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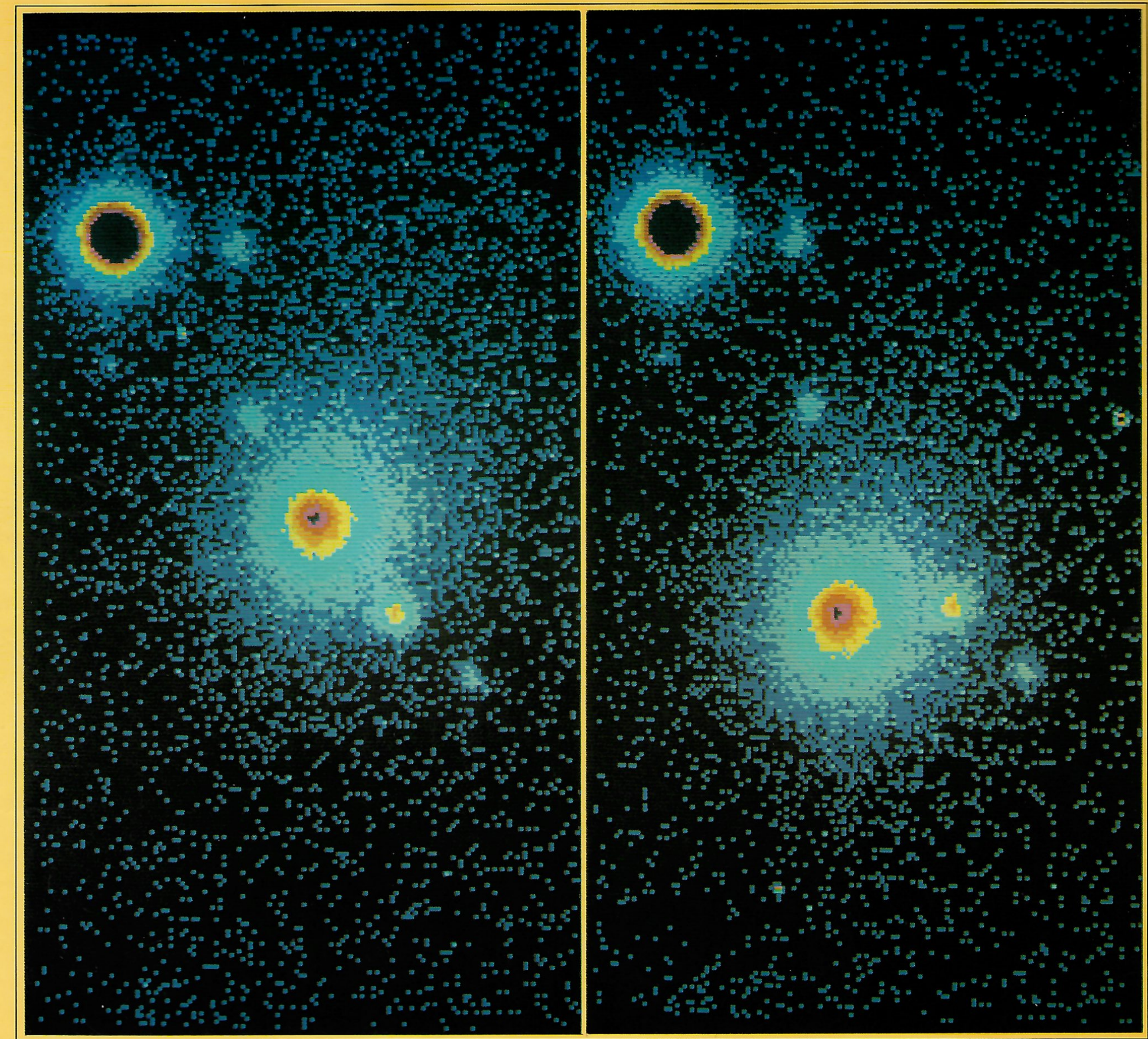
ROYAL GREENWICH OBSERVATORY



TELESCOPES INSTRUMENTS RESEARCH AND SERVICES

October 1 1980 – September 30 1985

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Royal Greenwich Observatory

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Observatorio del Roque de los Muchachos
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Tenerife, Canary Islands

Contents

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Five years of transition

At the end of 1980, the Royal Greenwich Observatory was constructing the Isaac Newton Telescope, Jacobus Kapteyn Telescope and Carlsberg Automatic Meridian Circle on La Palma in the Canary Islands. In this, the RGO was beginning to carry out the promises which it had made with its international partners such as the Netherlands Organisation for Pure Research (ZWO), the Dublin Institute for Advanced Studies, the Copenhagen University Observatory and the Instituto de Astrofisica de Canarias, as well as with the British astronomical community.

In 1981, when I became Director of the RGO, I made it my prime aim to speed the La Palma programme to completion and in the process to turn the RGO almost totally towards La Palma.

In 1985 I look back with pride at the astounding progress which the RGO has made in the last five years. The three telescopes have been operating for more than a year, and now have a full complement of scientific instruments. The first results from the telescopes have already appeared in the astronomical literature. The international collaborations are in full swing, and the astronomers and engineers of the RGO work in close partnership with their colleagues and counterparts in universities at home and overseas.

The end of this transition period in the history of the RGO was marked in June 1985 by the Royal Inauguration of the Canary Island observatories. This report records the achievements of this five-year period. It serves also as a statement of the RGO's present facilities which it operates for the benefit of users in universities in its national and international communities.

In looking back, I am conscious also that the RGO is beginning a second, equally momentous, five-year transition. The William Herschel Telescope is poised for erection on La Palma. By 1987 it will begin operating, and by 1990 it should be fitted with all its instruments. I look forward to the success of this fine telescope with an optimism which is solidly grounded in the achievements of the last five years of the Royal Greenwich Observatory.

A. Boksenberg

1981–5

The diary for the five years sketches a representative selection of events at the RGO:

1981

March 1 m telescope installed at Herstmonceux for testing prior to shipping to La Palma
April Science Research Council changed its name to Science and Engineering Research Council
June Delivery of Satellite Laser Ranger telescope
July Isaac Newton Telescope installation began
Sept First RGO staff went to live on La Palma
Sept First light with Satellite Laser Ranger
Sept RGO CCD camera commissioned on the Anglo-Australian Telescope
Oct Alec Boksenberg became Director of RGO
Nov Contract placed for construction of Herschel Telescope

1982

Feb Commissioning of Steavenson Telescope on Sierra Nevada
March Delivery of VAX 11/750 computer
April 26th Herstmonceux Conference on 'Outer Regions of Galaxies'
April Last observations with Reversible Transit Circle at Herstmonceux
May First issue of RGO journal, *Gemini*
May Visit to Herstmonceux of President of the Maldive Islands
Aug Minor planet 2603 named after RGO astronomer Gordon Taylor
Sept 150th anniversary of Nautical Almanac Office
Sept First Dutch technician, Arie Doorduin, began work at Herstmonceux under Anglo-Dutch collaborative programme
Oct Installation of Hewitt satellite tracking camera in Dome C of Herstmonceux Equatorial Group
Oct Kitt Peak 2.1 m telescope operated remotely from Herstmonceux
Nov Award of Royal Society's Rumford Medal to Prof Charles Wynne
Dec INT primary mirror arrives on La Palma

1983

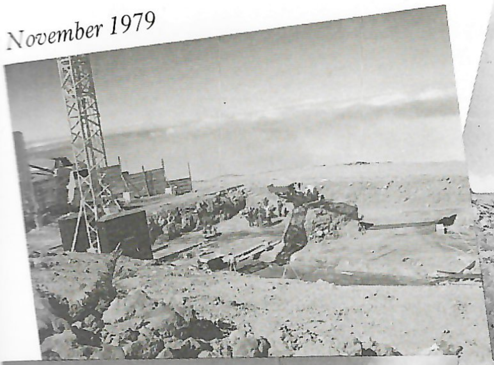
Jan Hand-over from the building contractor of INT building
March Closedown of ICL 1903T computer, RIP
March First returns of laser impulses using the Satellite Laser Ranger from satellites Lageos and Starlette
May Construction of William Herschel Telescope building began
May International MERIT Workshop at Herstmonceux
June Harrier jet from Royal Navy made an emergency landing on the SS *Alraigo*, a cargo ship carrying the 1 m telescope base plate
June 27th Herstmonceux Conference on 'Observational Cosmology'
July Rayner Review of RGO completed
Sept La Palma Observers' Guide issued
Oct 1 m telescope delivered to La Palma and erecte[illegible]
Oct Satellite Laser Ranger began routine observati[illegible]
Nov First light through the Carlsberg Automatic Meridian Circle
Dec ASRB Manpower Review Panel (Willmore Panel) at RGO

1984

Jan Major revision of Astronomical Almanac
Jan Versailles Working Group met at Herstmonceu[illegible]
Jan Jacobus Kapteyn Telescope first light
Feb Establishment of Redeployment List in order t[illegible] carry out large reduction in RGO staff number[illegible] (the 'buff envelopes')
Feb Isaac Newton Telescope first light
Feb 60th anniversary of BBC 'six pips' time signal
March First astronomical spectra obtained with INT Cassegrain spectrograph
April 26-inch telescope in Equatorial Group at Herstmonceux opened to public as part of the Exhibition
April Patrick Moore made *Sky at Night* on La Palma
May First photograph with JKT
May First scheduled observing on INT and JKT on La Palma
June Centenary of Greenwich Meridian
June Closedown of Photographic Zenith Tube at Herstmonceux
Sept Start of tests at Grubb Parsons of William Herschel Telescope
Nov First paper appeared using results from Isaac Newton Telescope on La Palma
Dec Herschel Telescope dismantled, packed and stored. Effective closure of Grubb Parsons
Dec Faint-object spectrograph commissioned on Is[illegible] Newton Telescope

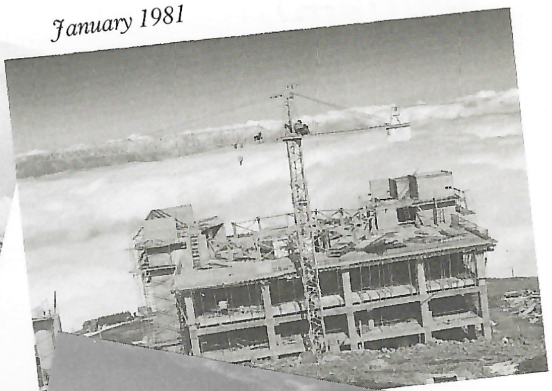
1985

Jan Privatization of RGO canteen
April TAURUS commissioned on Isaac Newton Telescope
April John Dunn show broadcast live on Radio 2 from Herstmonceux
May Setting up of the Council's Astronomy Review Committee to decide on the future of the Royal Observatories
June Completion of road to Roque de los Muchachos
June Royal Inauguration of the Roque de los Muchachos Observatory on La Palma
July First prime-focus images with Isaac Newton Telescope and CCD camera
Aug Opening of Residencia on Roque de los Muchachos
Sept CCD camera commissioned on Kapteyn Telescope



November 1979

mid 1980



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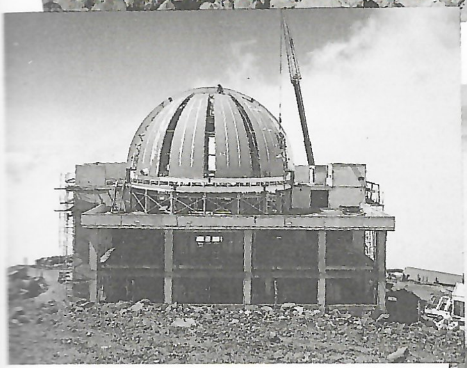

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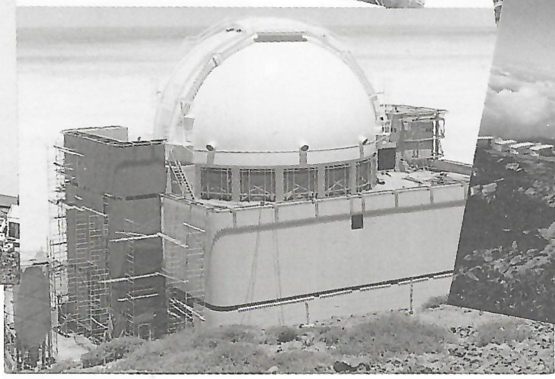

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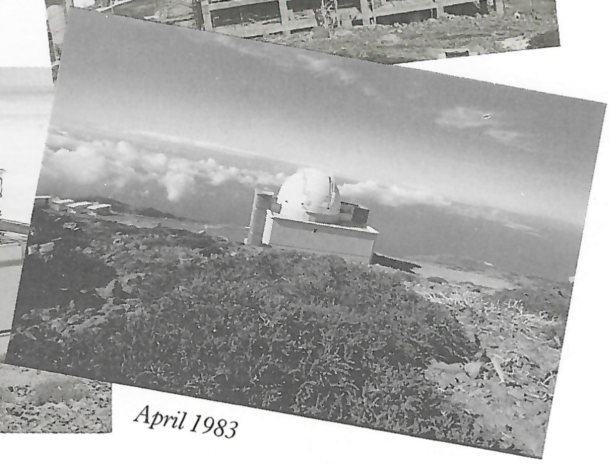


April 1983

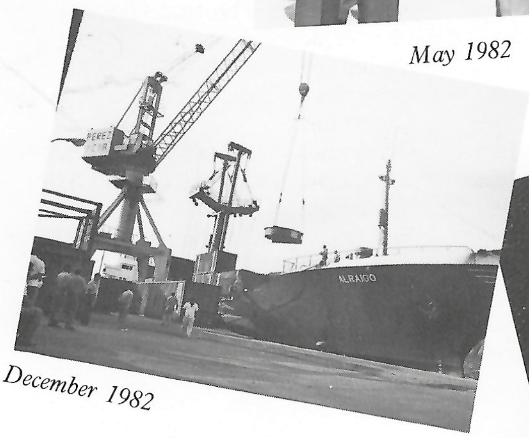
Growth of the Isaac Newton Telescope building on La Palma

March 1981

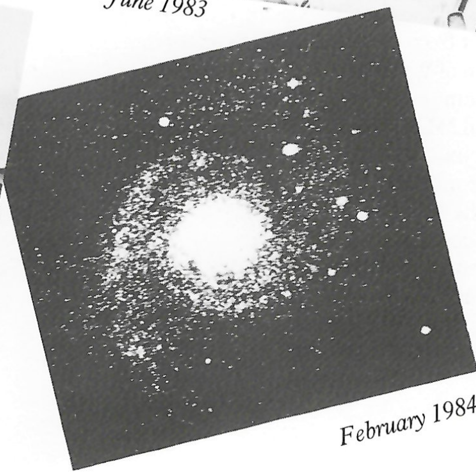
May 1982

September 1982

June 1983



December 1982



February 1984

Inauguration on La Palma

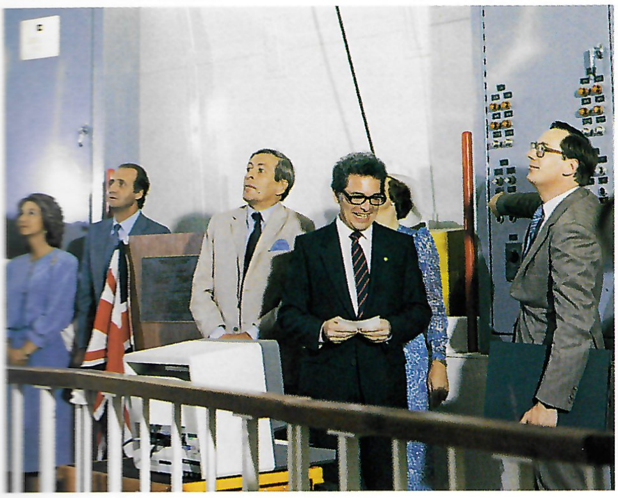
The observatories on La Palma and Tenerife, and the Instituto de Astrofisica de Canarias were inaugurated by seven heads of state, or their representatives, on June 28–9 1985. Attending were King Juan Carlos of Spain, Queen Beatrix of the Netherlands, Queen Margrethe of Denmark, King Gustav of Sweden, the Presidents of West Germany and of Ireland, and the Duke of Gloucester representing Queen Elizabeth of the United Kingdom. After ceremonies and banquets on Tenerife on June 28, the royal party and the guests flew to La Palma on the morning of the 29th, to ascend to the Roque de los Muchachos in perfect weather. The heads of state travelled from telescope to telescope, dedicating each in front of a small audience. The main ceremony, inaugurating the whole observatory, took place in a large open-air auditorium. The audience included royal guests, astronomers, engineers, Nobel Laureates, national and local dignitaries, Spanish, Dutch, Danish, Swedish and British staff on the Roque, civil servants, military officials and media representatives, in a gathering in which protocol played a relatively minor part. Other events on the island included the opening of the Convent of San Fernando in which there was displayed an exhibition of Hispano-Arabic astronomical instruments and maps, some loaned by the Old Royal Observatory, Greenwich.

National flags flew over the ceremonies for each telescope. The Spanish, Danish and British flags flew above the Carlsberg Automatic Meridian Circle as it was dedicated by the Queen of Denmark.

The 'flags of the cosmos', designed by Canarian artist Manrique, flew amongst the telescopes of the Roque, symbolically depicting worlds outside our own. Here Io's magnetosphere flies above the Herschel Telescope building.

(RIGHT) In recognition of the Anglo-Dutch partnership, the Duke of Gloucester asked Queen Beatrix to perform the second half of the INT dedication ceremony. The Queen used the computer terminal to type a command which, somewhat to her surprise, slewed the telescope to point out of the dome. The telescope motion and counter-rotating dome brought delight to all the onlookers.

(BELOW) After unveiling a plaque to dedicate the INT, the Duke of Gloucester opened the dome shutter to the directions of Prof Alec Boksenberg, as Queen Beatrix, Prince Claus, King Juan Carlos and Queen Sofia watched.



The observatory on La Palma was inaugurated by the King of Spain in ceremonies in an open-air theatre near to the INT with the heads of state and the royal guests and observatory dignitaries seated on the newly constructed platform.

The research programme of the RGO, as its main plank, is a set of selected, vigorous astrophysical investigations which, over the last few years, have turned more and more to La Palma. Other parts of RGO research are geared to ensure that the other facilities of the RGO – measuring machines, Satellite Laser Ranger, almanacs, time service – are similarly stimulated by the programme carried out by RGO's scientists. The astronomers of the RGO have used the practical knowledge which they gather in the course of their research programmes to feed, sustain and guide the La Palma programme to its present successful position: at first their skills have been used in the course of specifying equipment, and, now that La Palma is operating, their skills guide and maintain the operation and development for the benefit of all the telescope users.

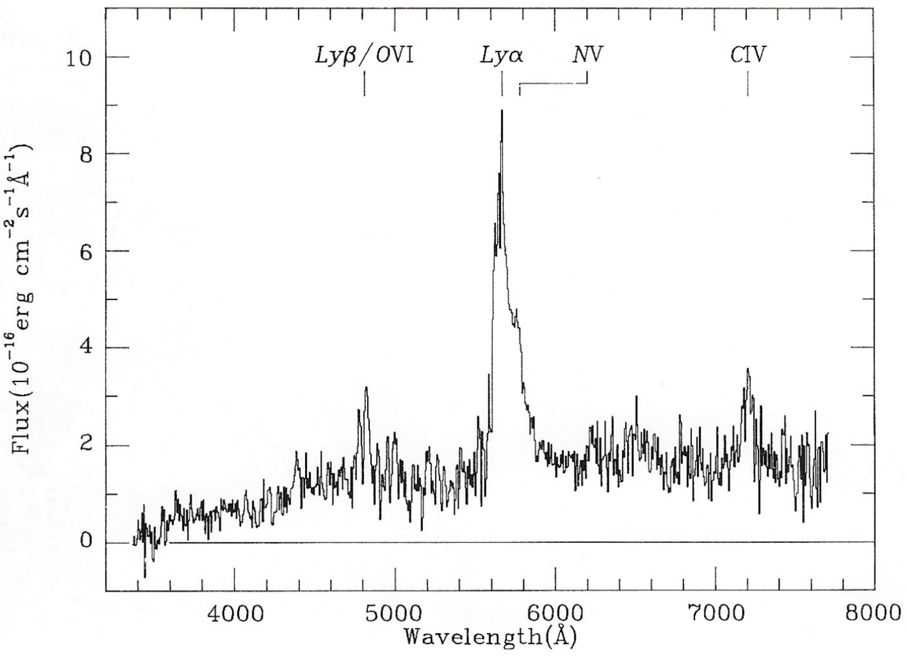
From here to quasars

Quasi-stellar objects, or quasars, are the most luminous sources in the universe. Most astronomers now share the view that quasars are the nuclei of distant galaxies where energetic processes, such as accretion of gas by a massive black hole, produce more light than the total amount emitted by all the stars in the galaxy (a typical galaxy contains about one hundred billion stars as luminous as our Sun). Because of the still mysterious nature of their central 'power-houses', quasars are objects of great interest at present. However, in recent years astronomers have devoted large efforts to the study of quasar spectra for an entirely different reason, which is the main theme of this article.

Being so luminous, quasars can be observed over much larger distances in the universe than any other class of object. We now know that the universe we live in is expanding in a manner analogous to a balloon being inflated – the further two points are on the surface of the balloon, or two galaxies in the universe, the faster the distance between them increases with the expansion, and therefore the faster they recede from one another. Proof of the extremely high velocities of recession of quasars is readily provided by the very high red-shifts of their spectra. As an example of this, Fig. 1 shows the optical spectrum of a quasar recently identified by Boksenberg and Sargent with the new Isaac Newton Telescope at the Roque de Los Muchachos Observatory on La Palma (the object was recognized as a quasar candidate by C. Hazard and R. McMahon.) The most obvious feature in the spectrum is the broad emission line of neutral hydrogen labelled Ly(man)α. The rest wavelength of this line – that is the wavelength at which it would be recorded in objects at rest relative to an observer on Earth – is 1216 Å, in the far ultraviolet. In the quasar in Fig. 1, the same spectral line is instead observed at 5691 Å implying that, since the time when the quasar light was emitted, the universe has increased in linear size in the same proportion as the wavelength of the Ly α photon, that is by a factor $(5691/1216) = 4.68 = (1+z)$. At a redshift $z = 3.68$, the quasar in Fig. 1 is one of the most distant objects in the universe known to date.

Because of the tremendous distance over which the quasar photons have travelled, the time taken to reach the Earth is a large proportion (about 9/10) of the total time since the expansion of the universe began. Furthermore, in its journey to the INT on La Palma, the light from the quasar has passed through intervening matter in the universe, matter which is too distant to be observed directly, but which has left its characteristic signature in the quasar spectrum in the form of *absorption* lines (see Fig. 2). It is easy to see now the importance of quasars as 'cosmic beacons': their spectra offer a unique opportunity to view the universe at much earlier times and provide clues as to how its properties have evolved over a significant fraction of its history.

Fig. 1 IPCS spectrum of the recently discovered quasar Q0055-269 obtained by A. Boksenberg with the Isaac Newton Telescope at the Roque de Los Muchachos Observatory on La Palma, and reduced with Starlink facilities by E. Bingham. The labelled ticks above the spectrum identify the most prominent ultraviolet emission lines which, in the quasar spectrum, are redshifted into the optical range. The redshift deduced, z = 3.68, makes Q0055-269 one of the most distant objects known in the universe.



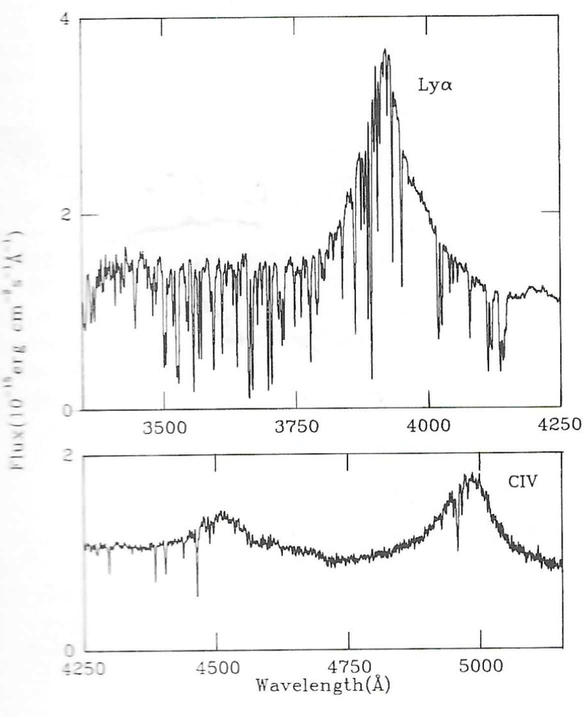
Over the last five years there have been several major steps forward in our understanding of quasar absorption spectra, made possible in large part by the availability of a new type of detector – the Image Photon Counting System (IPCS), developed jointly by University College London and RGO – on two of the world's most powerful telescopes: the 5 m Hale Telescope of the Palomar Observatory, in the northern hemisphere, and the Anglo-Australian Telescope at Siding Springs Observatory, in the south. The IPCS is particularly efficient at detecting faint light signals with the maximum possible accuracy; this is especially important for QSO absorption line work, since both high-spectral resolution and photometric accuracy are necessary to register the weak and narrow absorption lines seen in the spectra of generally faint quasars.

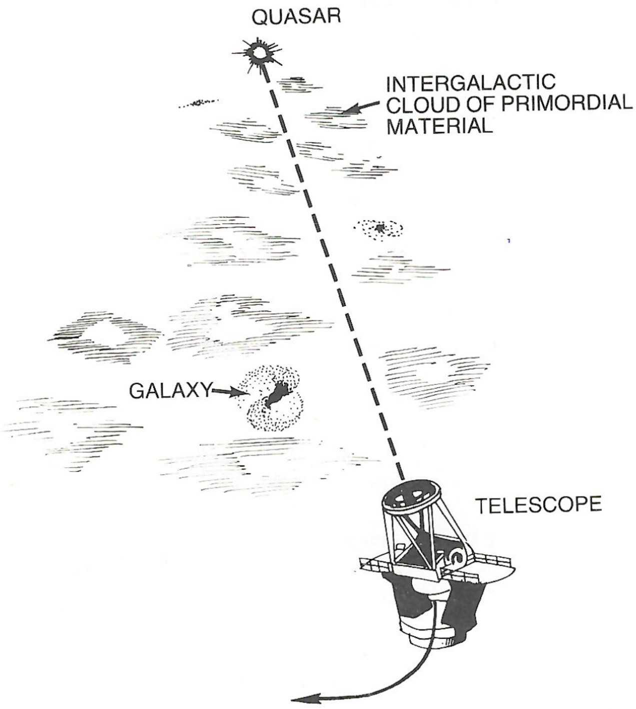
It now appears that there are at least two kinds of absorption lines, formed in physically distinct intervening regions. In a typical quasar spectrum (see Fig. 2) most of the lines at wavelengths longer than the emission Ly α line can be readily grouped in well-defined absorption systems, with all the lines within a system appearing at the same redshift, generally lower than that of the quasar itself. These lines can be convincingly identified with those of the most abundant elements – such as H, C, N, O and heavier species, up to and including Fe and Zn – in the stages of ionization prevalent in the interstellar medium of our Galaxy. Furthermore, the metal-line systems are clustered in redshift in a manner consistent with the present-day clustering of nearby galaxies. Thus, it appears that they are most likely formed in intervening haloes of galaxies randomly distributed in line of sight to the quasars. This in turn implies that galaxies possess tenuous gaseous haloes extending far beyond their optical dimensions, a conclusion supported by recent ultraviolet observations of the halo of our own Galaxy (see accompanying article 'The Gaseous Halo of our Galaxy'). Another important result deduced from studies of the quasar metal-line systems is that in a few cases where it has been measured with the required accuracy, the chemical composition of the interstellar gas in these distant galaxies has been found to be similar to that of the interstellar medium near our own Sun. This indicates that even when the universe was only 1/10 of its present age, at least some galaxies had already undergone a significant amount of metal enrichment via stellar nucleosynthesis.

The second class of quasar absorption lines is found only at wavelengths shorter than the emission Ly α and consists of single Ly α absorption lines, with no obvious associated heavy-element lines. As can be seen from Fig. 2, these Ly α lines are far more numerous, by a factor of about 50, than the metal-line systems. Furthermore, they are *not* clustered like galaxies, leading to the suggestion that they represent an intergalactic population of primordial clouds. Much effort is currently being directed towards determining stringent upper limits to the metallicity of the Ly α clouds. If this is indeed pristine gas, which has not condensed to form stars, it should still bear the imprint of the original composition determined by nucleosynthesis in the early universe and can thus serve as a powerful test of the predictions of the hot Big-Bang model. One result which has now been established beyond doubt is that the comoving density of the Ly α clouds exhibits a marked cosmological evolution, in the sense that the clouds became progressively less abundant as the universe expanded. This result has important implications for a problem of much current interest: how structure, in the form of galaxies, clusters and superclusters, formed and evolved from an initially smooth universe.

M. Pettini
A. Boksenberg

Fig. 2 The distances to the quasars are so great that, even at the speed of light, photons have travelled for a significant proportion of the age of the universe before reaching the Earth. In its journey from the quasar to our telescopes, the emitted light passes through intervening material randomly distributed along the line of sight. This matter is too distant to be seen directly, but leaves its signature in the quasar spectrum in the form of narrow, discrete absorption lines. Thus quasars are veritable 'cosmic beacons', offering us a unique view of the universe as it was at much earlier times. At least two different types of absorbing regions produce absorption lines: haloes of galaxies where the interstellar medium is broadly similar to our own, and intergalactic clouds of primordial gas, which has undergone little or no metal-enrichment through stellar nucleosynthesis. The quasar spectrum below is that of 0237–233 (z = 2·224) obtained by Boksenberg and Sargent with the Palomar 5 m Telescope.





Extragalactic HII regions and the primordial helium abundance

Visible matter is a mixture of chemical elements that exist by virtue of nuclear reactions in two kinds of sites. The hot Big Bang at the origin of the universe produced in the first five minutes primordial matter of which about 3/4 by mass was hydrogen, about 1/4 helium and traces of deuterium, helium 3 and lithium 7. Thereafter no nuclear reactions took place until the time when galaxies and stars were formed. Stars in advanced stages of evolution eject freshly produced carbon and heavier elements into the interstellar medium, as well as some more helium, and are held responsible for the existence in our neighbourhood of a mass fraction of 1 or 2% of 'heavy elements' consisting mainly of O, C, Ne, N, Mg, Si, Fe in descending order of abundance. Stars also 'process' the interstellar gas in the sense that some of the gas going into star formation is re-ejected without enrichment in heavy elements, but with loss of its deuterium, because the deuterium nucleus is so fragile that it is destroyed even in the outer layers of stars. Thus, according to how much of the present interstellar gas has been so processed (or 'astrated'), a proportion of the primordial deuterium has been lost and the present amount of deuterium is less than the original amount, whereas the present amount of ^{4}He is slightly more. For ^{3}He and ^{7}Li the situation is more ambiguous, however, because these can be both created and destroyed in the course of stellar activity.

Because the microwave background suggests that thermal equilibrium prevailed at some stage in the early universe, it is possible to make very precise predictions of the primordial abundances within the framework of the standard Big Bang model, especially in the case of helium. The predicted abundances depend on one free parameter, which is essentially the mean density of baryonic matter in the universe at the present time, and (in the case of helium) on the weak interaction rate (which is related to the half-life of the neutron) and on the number N_ν of lepton flavours or neutrino species which is usually assumed to be 3, corresponding to the electron, the muon and the tau-meson respectively (see Fig. 1). The predictions, however, naturally depend on the validity of the standard model, which assumes the truth of General Relativity, homogeneity, isotropy and zero lepton numbers, and so it is of importance to test whether one baryon density can be found that gives a set of abundances that agrees with observation. Furthermore, the resulting density is of great interest in itself because it can be compared with other methods of measuring the density, thus indicating whether appreciable amounts of non-baryonic matter exist, and with the closure density that is required to give a flat universe (Einstein – de Sitter model) that will just manage to expand indefinitely, which is currently favoured theoretically on the basis of inflationary universe models.

To carry out this programme evidently requires two steps: first, to measure the abundances of the relevant species in such objects as are accessible to observation or analysis and, second, to extrapolate back to the Big Bang. Both steps involve difficulties and uncertainties. Deuterium is quite abundant on the Earth and meteorites, but has been enhanced there by fractionation, and it is observed in the local interstellar medium, but with a large scatter which may or may not be real. The solar wind contains ^{3}He which is probably a combination of the proto-solar ^{3}He that was there when the Solar System was formed 4.7×10^9 years ago and proto-solar deuterium that has been burned into ^{3}He by the Sun in the meantime, so that the observed ^{3}He can be identified with D + ^{3}He in the interstellar gas at the time when the Sun was formed. The two components can be separated by observing gas released by heating from carbonaceous chondrite meteorites, which contains proto-solar ^{3}He alone, giving the proto-solar D by subtraction. Taking this value as a lower limit to the primordial D abundance, one obtains a firm upper limit to the baryonic density parameter $\eta = 7 \times 10^{-10}$, which is not inconsistent with the mass density of the universe deduced from the random motions of galaxies, but falls short of the closure density by a factor of at least 10. Observations of lithium 7 in subdwarf stars (which are deficient in carbon and heavier elements by a factor of the order of 100 and therefore represent matter that has undergone very little stellar processing) give a similar limit, and this agreement represents a considerable success for the standard theory.

The determination of a lower limit to the baryonic density parameter is more difficult because it requires assumptions about the amount of deuterium that was destroyed before the Solar System was formed. D. N. Schramm and his colleagues have argued that at least 25% of ^{3}He survives stellar processing, on the assumption that big stars destroy ^{3}He and small stars do not, and that the relative numbers of big and small stars formed has always been the same as we observe today. In this case, the sum D + ^{3}He gives a density parameter $\eta \geqslant 3 \times 10^{-10}$ and the baryonic density is constrained within quite narrow limits. Fig. 1 shows that this limit requires a primordial helium abundance $Y_p \geqslant 0.24$ for consistency, assuming 3 neutrino species. If $Y_p < 0.24$, either the argument about D + ^{3}He is invalid, or there is something wrong with the standard theory.

To check this prediction one needs to determine the primordial helium abundance to better than 5% – a formidable challenge. A variety of estimates exist, based on arguments ranging from the structure of the Sun and other main-sequence stars to the observed intensities of emission lines of hydrogen and helium in planetary nebulae and HII regions. All methods give $0.20 \leqslant Y_p \leqslant 0.25$, which is encouraging in the sense that a universal value of the expected order of magnitude does indeed seem to exist, but to find it with the required degree of precision is difficult and most methods involve a number of astrophysical assumptions which are open to doubt. Be this as it may, the different methods give an average value that is appreciably lower than 0.24.

A potentially quite precise method of determing Y_p was suggested by the Mexican astronomers Sylvia and Manuel Peimbert. Irregular and blue compact galaxies contain bright HII regions, i.e. gas clouds ionised by newly formed stars within them, and the heavy-element abundances are often very low, indicating relatively little stellar processing before the present burst of star formation. Assuming that additional helium is formed in a constant proportion to the total of heavy elements one can write for the helium abundance in one galaxy or HII region

$$Y = Y_p + Z(dY/dZ)$$

where Z is the mass fraction of heavy elements and is proportional to the oxygen abundance which is readily measured. dY/dZ is a parameter depending on the details of stellar evolution which can be determined empirically by plotting Y against Z and Y_p is the intercept on the axis $Z = 0$. The advantage is that both hydrogen and helium are represented by recombination lines with well-known recombination coefficients and that Z is often so small that relatively little extrapolation is needed. The difficulties are that the helium lines are weak, needing accurate spectrophotometry and allowance for underlying absorption lines (see Fig. 2), and that only the abundances of ionised hydrogen and helium are measured. If there is neutral helium in outer regions of the nebula where hydrogen is still ionised, or vice versa, then this has to be allowed for on the basis of theoretical models. Existing determinations covering between them about 20 extragalactic HII regions give results ranging from $dY/dZ = 3$, $Y_p = 0.23$ to $dY/dZ = 1$, $Y_p = 0.24$, and leave the crucial question of whether $Y_p \geqslant 0.24$ undecided.

Ionisation corrections become more uncertain the bigger they are, and so we have decided to make use of the extensive survey of blue compact galaxies made by R. Terlevich of the RGO and J. Melnick of the Universidad de Chile to find galaxies in which the ionisation corrections are predicted to be negligible. Combining these with the objects previously studied that satisfy the same condition, we have a sample of 28 galaxies for which a more precise solution can be obtained (Fig. 3). Our preliminary result is

$$Y_p = 0.230 \pm 0.003, \quad dY/dZ = 4.5 \pm 1.0$$

i.e. a low primordial helium abundance which raises questions about the standard Big Bang model. Whether there is something wrong with the model or a high degree of destruction of D and ^{3}He by astration remains an open question, but in the latter case one is driven to the conclusion that most matter in the universe is non-baryonic, whether or not the closure density is actually reached.

B. E. J. Pagel

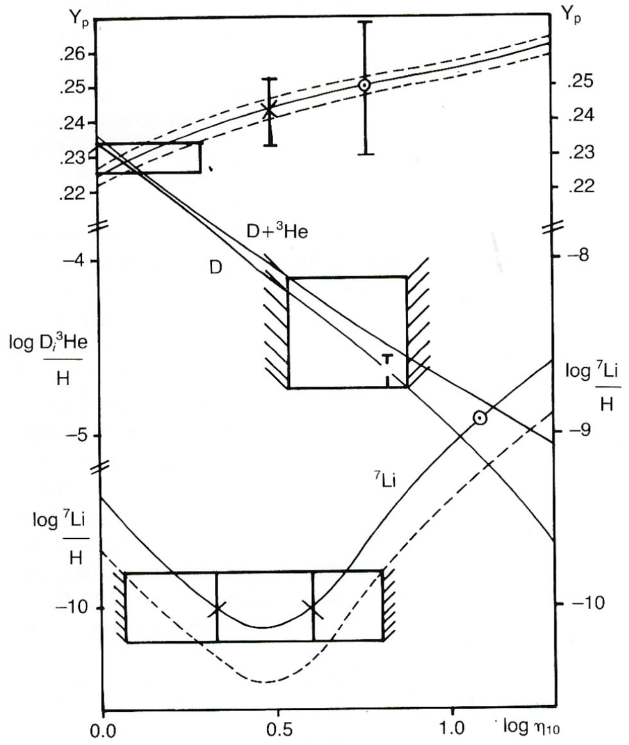


Fig. 1 Predicted abundances of helium 4, helium 3 + deuterium, deuterium and lithium 7, resulting from the standard Big Bang model with $N_\nu = 3$, as a function of $10^{10}\eta$ where η is the ratio of baryons to photons and is related to the present mean density of normal matter through the known temperature of the microwave background (2.7 K). Broken lines represent limits due to theoretical uncertainties. The 'Sun' symbol ⊙ represents abundances in the Solar System at the time of its formation, and crosses represent estimations of the primordial abundances. For helium, two results are given, the larger value resulting from the work of D. Kunth and W. L. W. Sargent (Astrophys. J., 273, 81, 1983) and the smaller one from the present work which is in agreement with the result derived earlier by J. Lequeux et al. *(Astr. Astrophys., 80, 155, 1979). Boxes represent limits on η resulting from the measurements and estimated uncertainties.*

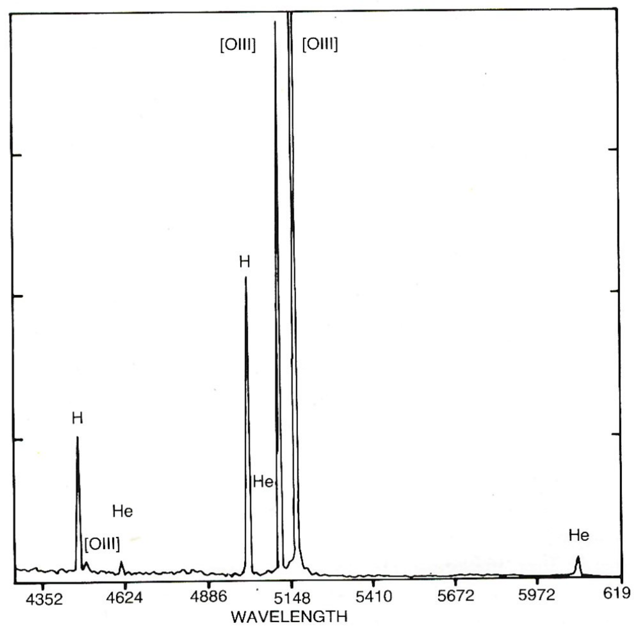


Fig. 2 Spectrum of blue compact galaxy CS 0102–3105 showing some of the helium lines used in abundance determination. The spectrum was taken at Las Campanas Observatory, Chile, by R. Terlevich and J. Melnick.

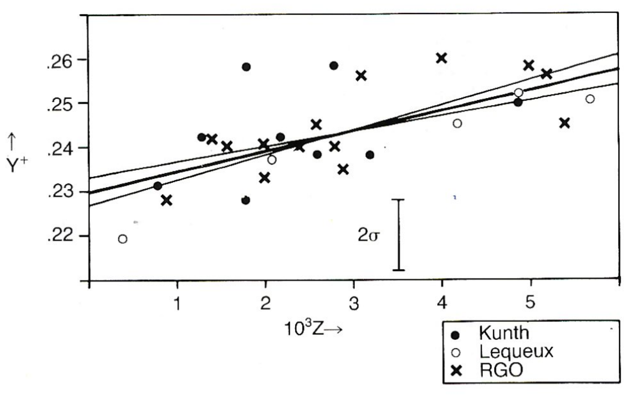


Fig. 3 Plot of Y^+, the mass fraction of ionised helium, against Z, the mass fraction of heavy elements, for extragalactic HII regions in which the ionisation correction is believed to be negligible. Sources of data are indicated. Straight lines show the least-squares solution with its 1 σ error limits.

HII regions and the chemical evolution of galaxies

The distribution of the chemical elements contains clues to cosmology and the evolution of stars and galaxies. Locally we have a mixture with about ¾ by mass of hydrogen, about ¼ helium and 1–2% of heavy elements, mainly O, C, Ne, N, Mg, Si and Fe in decreasing order of abundance. The hydrogen and most of the helium come from nucleosynthesis in the first five minutes after the Big Bang at the origin of the universe, whereas the heavies come from nuclear reactions in stars that have reached an advanced stage of evolution followed by ejection into the interstellar medium when the star either explodes as a supernova or ejects its outer envelope in the form of a stellar wind or planetary nebula (see box).

Stars exist in galaxies which themselves are collected in groups, clusters and superclusters and the precise way and order in which galaxies and their groupings were formed is not well understood. In one picture, large structures were formed first by gravitational instability and broke up eventually into individual galaxies, while in another, small structures about the size of a globular cluster were formed first and merged to form galaxies which then cluster together hierarchically into larger groupings. In either case there is good reason to believe that most galaxies established their identity before significant star formation and nucleosynthesis had occurred, because we shall see that the distribution of the elements is closely related to the structure and overall properties of the parent galaxy.

We consider, then, a newly formed galaxy consisting initially of primordial gas which then begins to form stars. How efficient is this process? The answer is that the efficiency is highly variable, because the star:gas ratio varies greatly along the sequence of morphological types distinguished by E. P. Hubble. Elliptical galaxies consist of old stars, comparable in age to the universe as a whole, and have little gas or dust, implying that stars were formed with high efficiency at an early stage. Measurements of colour, and of the strength of prominent absorption lines, indicate that large elliptical galaxies are richer in heavy elements than small ones and that their central regions are richer than the outer ones, i.e. there is a radial abundance gradient. Spiral galaxies have a central bulge with similar properties to ellipticals, surrounded by a flat disk in which star formation has proceeded continuously for nearly as long as the age of the universe, but the process has been so slow that considerable gas and dust are left over, and these are still forming new stars (mainly in spiral arms) at the present day. The size of the bulge relative to the disk decreases, and the proportion of diffuse matter in the disk increases, along the Hubble sequence from Sa to Sd, and beyond Sd we have irregular galaxies with no bulge, just a disk, and no spiral arms, but still more diffuse matter undergoing star formation.

The theory of the chemical evolution of galaxies aims to relate the distribution of the elements to the history of star formation and evolution and other relevant processes in the evolution of galaxies such as collapse, dissipation and exchanges of material with the environment. When a generation of stars is formed, with masses ranging from perhaps 0.1 to 100 times the mass of the Sun, various things happen. First, the most massive stars (over 10 times the mass of the Sun, say) send some material back in the form of stellar winds and shortly afterwards (within about 10 million years) they explode as Type II supernovae, leaving a neutron star as a remnant and ejecting oxygen and other elements into the gas (some of the ejecta, especially refractory elements like silicon, may arrive in the form of dust). The neutron star has a mass about equal to that of the Sun, so that most of the material from massive stars is returned to the interstellar medium. Intermediate-mass stars (say 1 to 10 times the mass of the Sun) also return gas to the interstellar medium, much of it in the form of planetary nebulae enriched in carbon and nitrogen, leaving behind a white dwarf remnant which again has about the same mass as the Sun. The time scale increases with diminishing mass from about 10^7 years for 10 solar masses to 10^{10} years for 1 solar mass.

Close binaries, in the same mass range, can in some cases undergo a more dramatic kind of evolution in which, after various episodes of mass exchange from one component to the other, they end up as two white dwarfs spinning round each other at close range. Through loss of angular momentum by the emission of gravitational waves they eventually coalesce producing a single white dwarf that has too much mass for stability and explodes as a supernova of Type I ejecting elements up to the iron group and leaving no compact remnant. Finally, stars of less than one solar mass (which account for about half the total mass of stars formed in each generation) have such long evolutionary lifetimes that they merely serve to lock up more and more diffuse material as time goes on. Thus the mass of gas is gradually depleted (unless more is supplied from outside the system) and the gas that remains acquires an increasing proportion of heavy elements which is reflected in the composition of later generations of stars relative to earlier ones. The relationship between gas depletion and enrichment in heavy elements is largely governed by a single parameter call the *yield*, which is the ratio of the mass of heavies newly synthesised and ejected to the mass locked up in small stars and compact remnants, by each new generation of stars. The yield depends on the relative numbers of big and small stars formed, and it is unclear whether the relative numbers are constant or variable at different times and places, but a reasonable guess is that the yield in the solar neighbourhood is of the order of 1%. In a closed system with no inflows or outflows and a constant yield the heavy-element abundance is simply related to the logarithm of the gas fraction, i.e. the degree to which the initial gas has been depleted by star formation.

The chemical composition of stars can only be studied in detail in the solar neighbourhood, apart from a few highly luminous stars in the nearby Magellanic Clouds, but spiral and irregular galaxies contain giant HII regions in which a vast cloud of gas is 'lit up' by ultraviolet radiation from a cluster of newly formed stars within it and accordingly shows emission lines of hydrogen, helium, oxygen, nitrogen and some other abundant elements (see Fig. 1). These HII

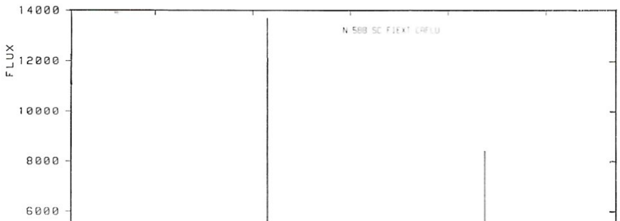


Fig. 1 IPCS spectrum of giant HII region NGC 588 in M33, taken with the INT on La Palma.

regions are so bright that they can be studied in detail in distant galaxies, revealing the distribution of these important elements over a substantial part of the universe. During the past five years at the RGO, Mrs A. I. Diaz and I have been investigating the chemical composition of extragalactic HII regions in collaboration with M. G. Edmunds of Cardiff University. Our investigations have addressed the following problems among others:

1 How is the overall heavy-element abundance related to the gas fraction? The answer is that in irregular galaxies there seems to be a simple relationship of the type predicted, but with a small yield of about 0.0025. This could be due to loss of enriched material from these relatively small and loosely bound systems. As we go from irregular to spiral galaxies (Fig. 2) the effective yield goes up, and spirals have an abundance gradient corresponding to an effective yield that increases inwards towards the nucleus. Both the abundance and the effective yield increase in the regular manner with the local surface density of mass in the disk, which suggests that the mass density controls the chemical evolution, perhaps by limiting the escape of supernova ejecta.

2 How are the abundances of different elements related? The ratio of helium to hydrogen increases only a little with heavy-element abundance because of the dominant contribution from cosmological production and elements like neon and sulphur vary in lockstep with oxygen because their nucleosynthetic origin is essentially the same. Nitrogen, on the other hand, can be expected to behave differently because it is in part at least a secondary product coming from carbon and oxygen that existed in the progenitor stars before nucleosynthesis took place. The abundance of secondary nitrogen would vary as the square of the abundance of oxygen, while that of primary nitrogen would be in simple proportion to oxygen and other elements. Our results (Fig. 3) show both trends, with primary nitrogen among irregular galaxies with low oxygen abundance, and some secondary nitrogen among spirals where, however, a large scatter is also evident. The scatter is probably related to the average age of the underlying stellar population, because much of the nitrogen comes from intermediate-mass stars, and the objects with the smallest ratio of nitrogen to oxygen may be identified as young – or at least youthful – galaxies.

B. E. J. Pagel

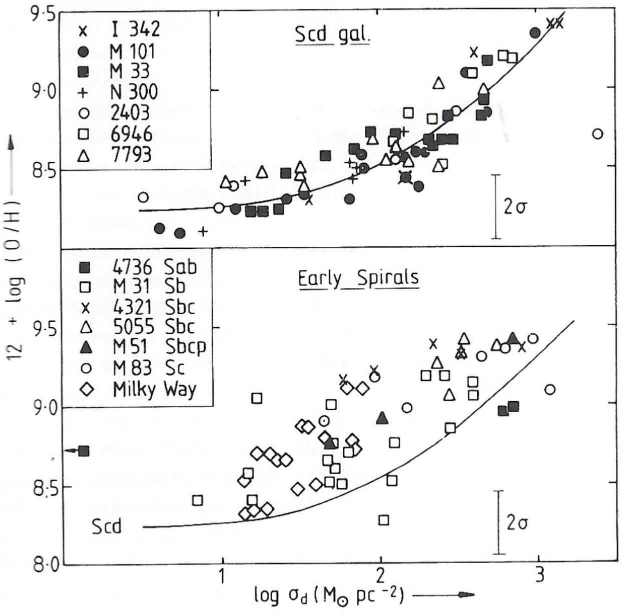


Fig. 2 Plot of oxygen abundance against surface mass density σ_d, in disks of spiral galaxies. The eye-fit curve to the Scd data points in the upper panel is repeated for comparison purposes in the lower panel.

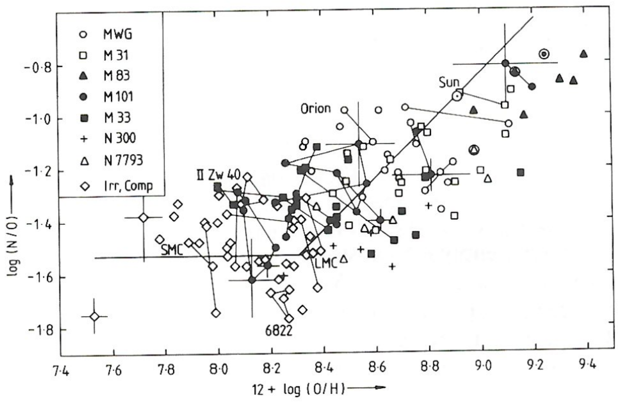


Fig. 3 Plot of N/O versus O/H in HII regions of irregular, compact and spiral galaxies. The strong horizontal and diagonal lines represent the corresponding relation for dwarf stars. Weak solid lines join alternative results for the same irregular galaxy, or (in spirals) for the same HII region.

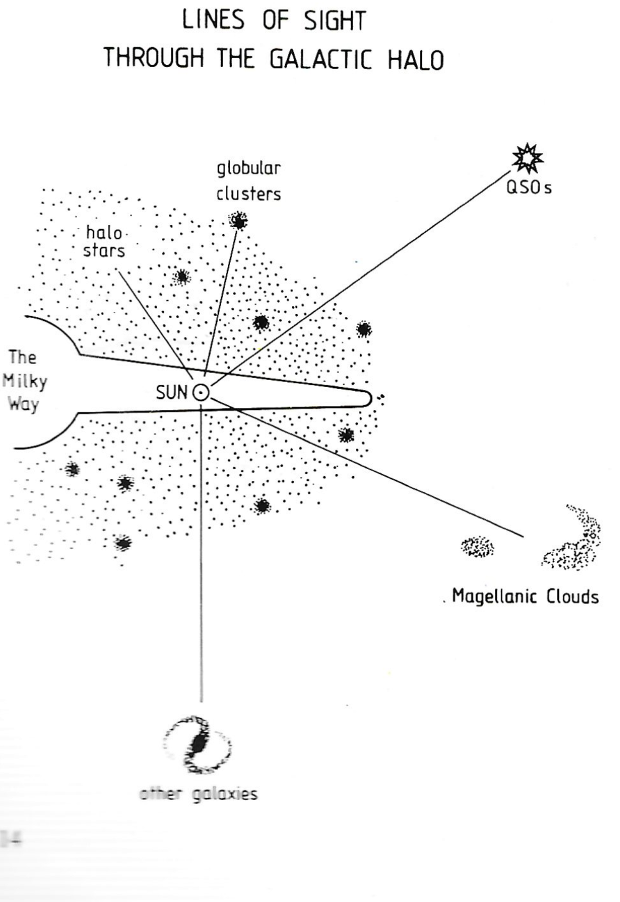
Origin of the chemical elements

Species	Nuclear reactions	Probable sites
H, D, ^{3}He, most ^{4}He	$^{1}H(n,\gamma)\,^{2}H(p,\gamma)\,^{3}He(n,\gamma)\,^{4}He$	Big Bang
^{12}C	$^{4}He(2\alpha,\gamma)\,^{12}C$	Supernovae; red giants expelling planetary nebulae
^{13}C, ^{14}N, some ^{4}He.	$^{12}C(p,\gamma)\,^{13}N(\beta^{+}\nu)\,^{13}C(p,\gamma)$ $^{14}N(p,\gamma)\,^{15}O(\beta^{+}\nu)\,^{15}N(p,\alpha)\,^{12}C$	Red giants expelling planetary nebulae
^{16}O	$^{4}He(2\alpha,\gamma)\,^{12}C(\alpha,\gamma)\,^{16}O$	Supernovae, especially Type II (over 10 solar masses)
^{20}Ne, ^{23}Na, Mg, Al	Carbon burning	Supernovae, especially Type II
Si, P, S, Cl, Ar, K, ^{40}Ca	Oxygen burning	Supernovae, especially Type II
Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn	Silicon burning Carbon deflagration	Type II supernovae Type I supernovae
Most heavy metals (Sr, Ba, Pb, etc)	Slow neutron capture (s-process)	Red giants; plantetary nebulae
Neutron-rich isotopes; radioactive elements.	Rapid neutron capture (r-process)	Supernovae

The gaseous halo of our Galaxy

Does our Galaxy, the Milky Way, possess an extended halo of diffuse interstellar matter? While the interstellar medium in the disk of the Milky Way (and nearby galaxies) is immediately evident from widespread radio emission and from conspicuous condensations – dark molecular clouds and bright HII regions near newly formed stars – its extension in the outer regions of the Galaxy is much more elusive. For over 30 years now, astronomers have been attempting to establish the extent, chemical composition and physical conditions – such as temperature, density and degree of ionization – of gas outside the Galactic disk. The scientific motivations for such keen interest are several. First, this information would provide valuable clues for theories of the formation and evolution of galaxies. Second, it is an important missing link in our knowledge of the cycle of galactic 'ecology'. We now realize that the interstellar medium in the disk, far from being in a quiescent state, is shaped by energetic processes which could have profound effects well away from the plane of the Galaxy. Third, and perhaps most importantly, an understanding of the properties of the halo of our own Galaxy is a prerequisite for interpreting the information on much more distant, and younger, galaxies provided by the study of quasar spectra, as discussed in the article 'From Here to Quasars'.

Fig. 1 The disk of the Milky Way is surrounded by an envelope of tenuous gas which extends much further than the optical dimensions of the Galaxy. This gaseous halo is too rarefied to be observed directly, but is sufficiently extended to produce interstellar absorption lines in the spectra of distant objects shining through it. This figure illustrates the different background sources which have been observed with the International Ultraviolet Explorer satellite to probe the extent, chemical composition and physical conditions of the Galactic halo. Other galaxies are also expected to have similarly extended gaseous envelopes.



The difficulty in studying the Galactic halo stems from the fact that it is so tenuous that it can best be detected by the ultraviolet absorption lines it produces in the spectra of distant objects (see Fig. 1). Fortunately for life forms on Earth, the atmosphere of our planet filters out ultraviolet radiation very effectively; this, however, does mean that ultraviolet astronomy can only be carried out from telescopes placed outside the atmosphere, mostly on satellites in orbit around the Earth. The Copernicus satellite, launched in 1972 and operating over most of the last decade, gave astronomers an unprecedented clear view of the local interstellar medium, but its sensitivity was insufficient to reach regions of the Galaxy outside the solar neighbourhood. All this changed dramatically with the advent of the International Ultraviolet Explorer (IUE) satellite which has the capability to observe objects more than a thousand times fainter than Copernicus, albeit at somewhat lower spectral resolution and photometric accuracy.

Blair Savage and Klaas de Boer, two astronomers working at the University of Madison in Wisconsin, were the first to capitalize on the very much greater sensitivity of IUE to obtain ultraviolet spectra of stars in the companion galaxies of the Milky Way, the Magellanic Clouds. These stars are more than 150 000 light years from the Sun and provide a highly suitable background against which the rarefied, but extended, halo gas which may be present along the line of sight can be detected via the absorption lines of its constituent atoms and ions. Considerable excitement accompanied the discovery by Savage and de Boer that towards the Magellanic Clouds the interstellar medium of our Galaxy indeed does extend far beyond the thin disk of stars, gas and dust in the plane. The velocities of the absorption lines they detected are precisely those which would be produced by the general rotation of our Galaxy, if the halo clouds are at distances of up to 15 000–30 000 light years from the plane. For comparison, the disk only extends about 1000 light years on either side of the plane. Furthermore, the observations suggest that the smaller Magellanic Clouds may themselves be surrounded by extended gaseous envelopes. Combining the IUE absorption data with later radio measurements of neutral hydrogen in the same directions allowed a direct determination of the chemical composition of the gas in the Galactic halo. The somewhat surprising result found is that, even though the gas is at large distances from the disk, where the chemical elements are manufactured in the interior of stars, it is in fact just as rich in processed material as the nearby interstellar medium observed with Copernicus. This finding provides strong evidence in favour of the viewpoint that the gaseous halo of the Galaxy originated from the disk, probably through violent events, such as supernova explosions. It now appears unlikely that halo gas is a remnant from earlier stages in the evolution of the Galaxy, or that it is material being accreted from the intergalactic medium.

Since these initial results, much effort has been directed towards the study of the Galactic halo in directions other than the Magellanic Clouds, to establish its global properties and check if the sight-lines to the Clouds are in some ways atypical, because of the gravitational interaction between our Galaxy and its companions. In the five-year period covered by this report, the author of this article, in collaboration with Kym West of University College London, completed a major survey of highly ionised gas in the halo using Galactic stars as background sources. Although suitable stars do not extend beyond about 13 000 light years from the plane, they are the only objects sufficiently bright to be observed by IUE over large scales in the Galaxy. Several important results were obtained with this survey. First, the extent of the gas towards the Magellanic Clouds is, by and large, typical of the halo as a whole. It now appears that the interstellar medium of our Galaxy is probably in the shape of a thick disk, surrounding the denser and much smaller disk of stars and bright nebulae which are directly visible by their emission. The tenuous disk of interstellar matter, as revealed by the absorption lines it produces, extends to about 15 000–30 000 light years on either side of the plane, over an area with a radius of up to 150 000 light years from the centre of the Galaxy. This in turn implies that our galaxy occupies a volume over 100 times larger than commonly thought only a few years ago, prior to the launch of the IUE satellite. By inference, this is also likely to be the case for galaxies in general; in fact it appears that smaller galaxies, like the Magellanic Clouds, have proportionally bigger haloes, probably because of the reduced gravitational attraction they are able to exert on the surrounding medium.

A second result of the survey by Pettini and West is that much of the gas in the halo is highly ionized, as demonstrated by the presence of significant amounts of triply ionized carbon (C^{3+}) and silicon (Si^{3+}). In analogy with the Sun, this led astronomers to speculate about the existence of a Galactic corona. In the disk, C^{3+} and Si^{3+} are found mainly in the immediate vicinity of hot stars, whereas in the halo they are widespread and, furthermore, occur in roughly constant proportion, irrespective of direction or distance from the plane. This last finding provides a clue to the physical processes responsible for producing (and maintaining) the coronal gas. One possibility is that the high degree of ionization results from a high temperature; in this case the narrow range of values for the ratio of C^{3+} relative to Si^{3+} would imply an essentially constant temperature of about 80 000°. This is an unexpected result, because gas at such a temperature cools very rapidly. Therefore, it appears that either some hitherto unrecognized heating process is operating to maintain the interstellar medium in the halo at 80 000°, or the temperature is in fact much lower (near the stable value of 10 000°) and the high ions are produced by photoionization. Recent calculations have shown that the cosmic background of far ultraviolet radiation, originating mainly from distant quasars, is in fact adequate to explain the observed degree of ionization. In such models the gas is kept at large distances from the plane of the Galaxy (which exerts a considerable gravitational attraction) by the pressure of cosmic rays streaming from the disk, rather than by thermal pressure, as in the high temperature case.

Whatever the origin of the Galactic corona, the IUE observations have demonstrated that it resembles closely, in several basic details, the gas producing the heavy-element absorption lines commonly seen in the spectra of distant quasars (see pp. 8–9). This realization provides compelling evidence to show that the latter are also formed in intervening galactic haloes, an interpretation made significantly more plausible by the much increased dimensions inferred for the Milky Way in absorption. Thus, the body of information now available for our own halo provides astronomers with a basic benchmark with which to compare the characteristics of galaxies at earlier times and explore the way they may have evolved up to now.

It is clear from this brief account that the last five years have seen some very major improvements in our understanding of the Milky Way halo. It is worthwhile to speculate, in closing, what further progress the next five years may bring. An obvious point is to extend the work described here to other, nearby, galaxies, as this will make it possible to investigate how the properties of the haloes depend on other characteristics of the parent galaxies, such as morphology, size, cluster membership, etc. To this end, a team of RGO astronomers have been collaborating with Chris Blades, from the Space Telescope Science Institute, on a programme aimed at identifying bright background sources (mainly quasars) in the fields of nearby galaxies. Fig. 2 shows a particularly good example of the generally high degree of success which this quasar search has enjoyed up to now. The numerous sources discovered within close range of the bright galaxy NGC 253 will allow us to probe the interstellar medium of this galaxy at many different locations within its halo, using both ground-based telescopes and the Hubble Space Telescope, due to be launched in 1986.

M. Pettini

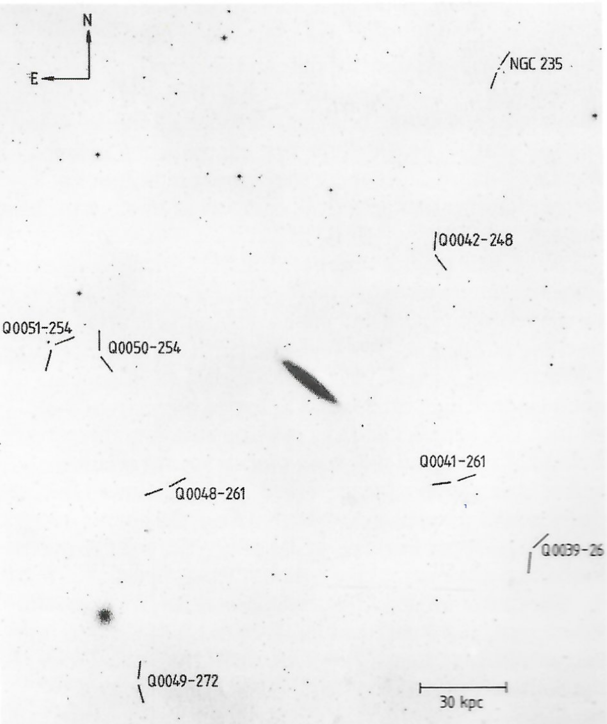


Fig. 2 In order to study the properties of the haloes of nearby galaxies it is necessary to identify bright background sources (mainly quasars) which can be used as probes of the intervening interstellar medium. An RGO–STScI collaboration, specifically aimed at this, has led to the discovery of many suitable quasars fortuitously located on the sky near some galaxies, such as NGC 253 shown here. The quasar candidates are first selected by inspecting UK Schmidt-objective prism plates and later confirmed by low-resolution slit spectroscopy. High spectral resolution observations of these background sources, to be carried out in the near future with large ground-based telescopes and with the Hubble Space Telescope, will give a full picture of the interstellar medium of NGC 253 at large distances from its luminous central regions.

The stars of the Galactic halo

The stellar populations of the Galactic halo provide one of the most effective mechanisms of probing the physical processes that governed the formation of the Galaxy. Stars form when gas clouds collapse and dissipate. After formation, although evolved stars return processed matter to the interstellar medium enriching its metal content, the individual stars themselves are essentially impervious to external influence. Hence in their spatial distribution, kinematics and composition, they carry the signature of the prevailing conditions at formation. So, just as palaeontologists use the terrestrial fossil record to trace the evolution of species, we can trace the evolution of the Galaxy.

Until recently the accepted evolutionary picture was that originally proposed by Eggen, Lynden-Bell and Sandage (ELS) which hypothesised a rapid collapse of the protogalactic gas cloud to form a disk system (see box). The last few years have seen a renewed attack on this problem driven by three main forces. First, the discovery of flat rotation curves in external galaxies, and the consequent inference of massive halos, revived interest in our own halo. Second, the development of automatic photographic plate scanning machines meant that star (and galaxy) number–magnitude–colour counts – the essence of statistical astronomy – could now both be more extensive and more accurate. Finally, the impending launch of Space Telescope provoked theoretical work on star count models – models based on discrete stellar populations and matched against the new star counts.

Initially this work did not contradict the ELS model. Using the deep star counts by Kron and Koo (Berkeley) and Tyson and Jarvis (Bell Labs), Bahcall and Soneira (Institute of Advanced Study, Princeton) found that the standard model, with an exponential disk and spherical, r^{-3} halo, represented the data adequately. Chiu (Berkeley) added proper motions for the brighter stars in the Berkeley fields, and this analysis provided the first contradiction of the standard picture, since there were strong indications of a flattened, rather than spherical, component amongst the halo stars.

All of these studies were based on PDS microdensitometer scans of 4-metre telescope plates and thus were limited, both by the scanning speed and plate availability, to areas of less than a square degree. The development of the faster scanning UK machines, GALAXY, COSMOS and APM, and the abundance of high-quality 6 × 6 degree plates from the 48-inch UK Schmidt added a new dimension to this work. Instead of relying on matching models against relatively sparse observations, the improved statistics allowed the deduction of the stellar distribution from the counts themselves, using intrinsic stellar properties to infer the individual distances.

The first of these studies, by Gilmore (Royal Observatory, Edinburgh) and Reid, used (V–I) colours to infer absolute magnitudes, and hence distances, for ~20 000 stars towards the South Galactic Pole. This method of photometric parallaxes is valid provided the SGP stars are unevolved and subsequent observations have confirmed that this is largely the case. Fig. 1 shows the inferred density distribution with height above the Galactic Plane for stars of $M_V \sim +5$. Over the initial ~ 1.5 kpc, the dominant population follows the 300–330 parsec exponential distribution classically associated with the old disk. However, traditional models predict a local halo star density of ~0.13% that of the disk and, with an ~ -3.5 density law, this cannot account for the higher-density (local density 1–2% of disk) second component evident in Fig. 1.

The second population in Fig. 1 also has a distribution that is flattened towards the plane of the disk, with an axial ratio of ~ 4:1. As such these stars are reminiscent of the extended component found in external galaxies by van der Kruit (Groningen) and Searle (Mt. Wilson) from surface photometry of edge-on spirals. The latter work shows a strong correlation with the prominence of the bulge. Given that our galaxy is an Sbc, it is therefore not surprising that it possesses a similar population.

These observations suggest the presence of an intermediate population, forming after the spherical halo and before the old disk. By mass it is not strikingly important, having ~ 10% the mass of the disk as judged from the relative density laws. However, in terms of the history of star formation in the Galaxy, an intermediate component is much more significant. With a second burst of star formation it becomes possible to explain the scarcity of metal-poor disk stars, since this intermediate burst may provide the requisite enrichment of the interstellar medium.

Current research, then, centres on the properties of the intermediate population. Gilmore and Wyse (Berkeley) have used photometry of G dwarfs to study the metallicity distribution to heights of ~ 1.5 kpc above the plane. They find evidence for a substantial number of moderately metal-poor stars, with metallicities ~ 25% that of the Sun. This compares with the much lower (< 10% solar) abundance associated with the classical halo. The obvious inference is that the intermediate population is intermediate between extreme halo and disk in composition as well as in spatial distribution.

To probe the halo at greater distances we require more luminous tracers – K giant stars. However, the predominance of red dwarfs fainter than V ~ 12 has always hindered the identification of these distant red giants. Recently, however, Ratnatunga and Freeman (Siding Spring) have used objective prism techniques to discriminate between dwarfs and giants, while Reid and Wegner (Dartmouth College) have used proper motions. The latter survey relies on the proximity of red dwarfs with V < 15 to give them relatively large proper motions and uses GALAXY measures of Kapteyn Selected Area plates to determine these motions with milliarcsecond accuracy. Follow-up spectroscopic observations show that this method is extremely effective, and the sample includes many giants with abundances close to the intermediate metallicity dwarfs found by Gilmore and Wyse. Fig. 2 contrasts one of these intermediate metallicity giants with a genuine halo giant from the same sample. Moreover, the kinematic data strongly suggest that these intermediate metallicity stars have significant rotation – the population is rotationally supported, like the disk, rather than pressure-supported, as is the extreme halo.

Considerable work remains to be done in untangling the properties of the different stellar populations. In particular, it is important to determine to what extent they are distinct populations, and to what extent they represent static points within continuous evolution. Only with the resolution of these questions will we be in a position to interpret the observations of galaxy evolution in stars at redshifts of more than 0.1.

N. Reid

Fig. 1 The stellar density distribution as a function of height above the Galactic plane's solid curve: exponential distribution associated with the old disk. Dashed curve: second (flattened) population, axial ratio ~ 4:1

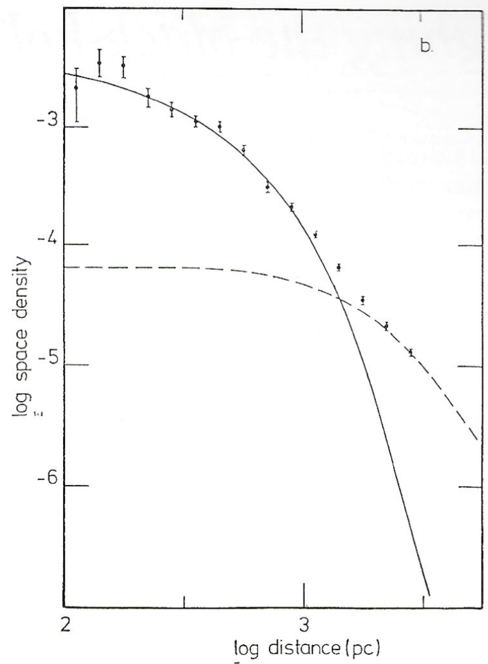
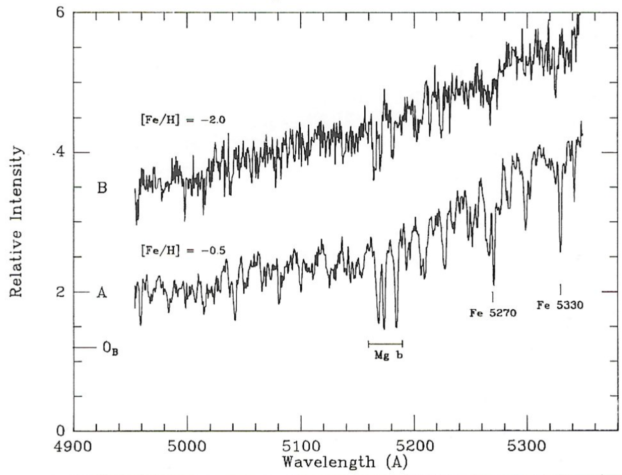


Fig. 2 The spectrum of an intermediate metallicity giant (lower) contrasted with that of a metal-poor halo giant. The observations were made with the Isaac Newton Telescope on La Palma.



The ELS Halo formation model

The ELS model was developed from photometric, astrometric and radial velocity observations of 221 stars – 108 bright (V ~< 6) stars and 113 with space motions (relative to the Sun) of >100 km/sec. All are within ~ 100 pc of the Sun. Adopting a mass model of the Galactic potential, ELS computed orbital parameters – in particular, eccentricities. Analysing these data, ELS found two apparently significant correlations. Ultraviolet excess – a measure of metallicity – was correlated with both eccentricity (such that low metallicity stars have highly eccentric (radial) orbits) and with w-velocity (perpendicular to the plane of the disk). The latter correlation is such that few metal-rich stars have high w-velocities (> 50 km/sec) while the low metallicity stars cover the range $0 < w < 250$ km/sec. Remembering that these stars are in the plane now, this means that the latter stars can reach heights of 10 kpc above the plane while the former are constrained to < 400 pc.

ELS interpreted these correlations as showing that the metal-poor (halo) stars formed during the rapid collapse of the protogalactic cloud. Hence the higher w-velocities of some metal-poor stars reflects the fact that these stars formed at large distances above the plane. The collapse must be rapid (few × 10^8 years) to explain both the shape of the UV-excess – w-velocity diagram and the highly radial orbits. ELS postulated that as halo stars form at height Z, material streams past substantially increasing the gravitational potential. Assuming conservation of angular momentum, the halo star will follow a more highly bound, radial orbit.

However, there are problems with this picture. First, the ELS observations were biased towards low metallicity stars with high space motions and against metal-poor stars with solar-like motions. These stars are rare, but they do reduce the impact of the UV excess eccentricity correlation. Second, and more important, if we make standard assumptions about metal recycling i.e. how processed material is returned to the interstellar medium for subsequent star formation, the short time-scale of the rapid collapse model requires that there should be a significant fraction of metal-poor stars in the disk. These stars do not exist. Finally, there is the general problem of time-scales. The oldest stars in the disk have ages of ~ 8 × 10^9 years while globular clusters have ages ~ 12 – 18 × 10^9 years. No direct estimate of the age of the halo in the field exists, but from star counts the halo star colour magnitude diagram resembles that of a globular cluster. The ELS model has no mechanism for switching off star formation between formation of the halo and formation of the disk.

Weighing the black hole

In 1982, an international research team, with leading members from the RGO, weighed the centre of a quasar, and the discovery strengthened the theory that the immense and concentrated power of a quasar is due to gas swirling around a very massive black hole in the centre of the host galaxy, NGC 4151.

The team have been studying the galaxy since 1978. To weigh its centre, they investigated gas clouds very close to the galaxy's core. They found that the clouds are moving at speeds up to 14000 km/sec. In a crucial new step, they also ascertained the distances of the clouds from the core by finding the time it took for a brightening of the core to 'light up' the clouds.

It turns out that the slower-moving gas clouds lie farther from the core – just as the slowest planets in the Solar System are those that are farthest from the Sun. This means that there is some very massive object at the centre of the galaxy NGC 4151 (analogous to the Sun at the centre of the Solar System). The speeds and distances of the gas clouds show that this object is 1000 million times heavier than the Sun – and the only kind of object which can be so massive, yet sufficiently small, is a black hole.

In 1969, Donald Lynden-Bell, then of the RGO (now Professor at the Institute of Astronomy, Cambridge), proposed that quasars are caused by black holes at the centres of galaxies. Gas from the galaxy spirals inwards, under the influence of the black hole's gravity, and in the process becomes hot and emits radiation (see Fig. 3). Many such galaxies should have central black holes, around 100 to 1000 million Suns in mass. Such a black hole could cause the quasar phenomenon at the centre of an otherwise normal galaxy.

NGC 4151 is a low-luminosity (mini-quasar) example of this phenomenon: it is a spiral galaxy, similar to our Milky Way, lying some 50 million light years away in the direction of the constellation Canes Venaticorum. But, unlike the Milky Way, NGC 4151 has a central mini-quasar core: a very small, very bright region where gas clouds move at high speed. Astronomers call such galaxies Seyfert galaxies (after the American astronomer, Carl Seyfert, who first studied them), and NGC 4151 is the nearest bright Seyfert galaxy.

The researchers, from the UK, France, Italy, Sweden and Germany, investigated the galaxy's core with the 45 cm telescope on board the International Ultraviolet Explorer satellite (a joint project of the SERC in the UK, NASA in the US, and the European Space Agency). Most of the ultraviolet radiation from the galaxy's core region arises in an extremely compact central powerhouse; but there are also spectral lines (at particular wavelengths) which come from gas clouds outside the core. The team identified three different types of gas cloud. One type emits strongly at a wavelength characteristic of carbon atoms, another at that of magnesium, and the third at another carbon wavelength. A detailed study of the spectral lines shows that the three kinds of cloud move at different speeds: up to 14000, 11000 and 4000 km/second respectively.

The core's radiation lights up the clouds, and the team discovered that there is a delay between the core flaring up and the clouds becoming brighter (Fig. 2). They were particularly lucky to pick up a major outburst in the galaxy in May and June 1979, which showed the effect clearly. The delay must be due to the finite time it takes the radiation to travel from the core to the clouds. The length of the delay thus reveals the clouds' distance from the core. The delays from the three types of cloud turn out to be different. The highest-speed clouds respond in about 13 days, meaning they lie some 13 light-days out (1/30 light year). The intermediate clouds take about 30 days to respond, and so lie about twice as far out. The slowest-moving clouds show very little sign of being affected by outbursts in the core, and probably lie much farther out, about a light year away from the core. For each type of cloud, an application of Newton's law of gravity to the speed and distance from the central object gives the mass of the latter. All three give very similar answers for the core: about 1000 million Suns.

The observations also support the black hole theory in another, completely independent, way. As the gas spirals into the black hole, it should form into a swirling accretion disc. The disc should be at a temperature of 30000°C, and stretch to about ten times the size of the black hole itself. The inner edge of the accretion disc, where gas is closest to the black hole, is the energetic powerhouse, producing most of the core's radiation. But the hot gas in the rest of the disc should produce characteristic ultraviolet radiation of its own – and the observations did indeed reveal radiation of roughly the correct intensity over the predicted range of wavelengths.

A central jet?

Since 1981, NGC 4151 seems to have entered a less active stage which has, in fact, thwarted attempts to confirm the above results.

However, it instead provided an opportunity to study fainter features in the spectrum which had previously been lost in the glare of the stronger components during the bright active phase. This led to the discovery of two new spectral lines whose behaviour seemed quite different from those described above. Lying on either side of a strong carbon line at wavelengths not associated with strong lines in other objects, these features appear to be emitted close to the nucleus because they vary rapidly and with little apparent delay (less than a day) between them (see Fig. 4). On the other hand they show only a small internal motion (speeds less than 1500 km/sec). Nor do they respond to changes in the brightness of the core.

The international research group has concluded that these lines are emitted by carbon atoms in two localized regions moving rapidly away from the core – a 'two-sided jet' very similar to that described in the section on SS 433. This result has also excited astronomers because it is the first evidence of jets on such small scales in galactic nuclei.

Size and variability

Variation of the brightness of distant objects is an extraordinarily powerful tool enabling astronomers to measure the size of the spatial relationship between components of a single source. For example, halving or doubling the brightness within a day implies the source cannot be bigger than a light-day or the spread of arrival times of the light would smear out the variations (see Fig. 1). The RGO has long been involved in the study of variations of quasars and related objects since the mid-1960s when a monitoring programme was started on the Herstmonceux 26-inch refractor. In recent years, however, more elaborate facilities, including the International Ultraviolet Explorer (IUE) satellite and the Isaac Newton telescope (INT), have made important discoveries by studying the variations of the galaxy NGC 4151 – a Seyfert galaxy containing a 'mini-quasar'.

Fossil Quasars

Another exciting result, made possible by the fading of NGC 4151, followed the first spectra taken with the resited Isaac Newton telescope at the Observatorio del Roque de los Muchachos on La Palma. These showed an enormous change in NGC 4151 compared to spectra taken ten years previously when the INT was at Herstmonceux (see Fig. 5). In 1974, the spectra showed clear signs of the rapid motions in the centre of the galaxy mentioned above. In 1984 these had all but disappeared and the spectral classification of the galaxy had changed from Seyfert Type 1 (broad spectral lines, indicating rapid motions) to Type 2 (strong narrow emission lines but no evidence of rapid motions). This result then suggested to RGO astronomer, Michael Penston, and his Spanish student, Enrique Perez, that other Type 2 Seyfert galaxies might all be presenting fossilized evidence of previous quasar-type activity in their centres. In the Seyfert Type 2 galaxies, the emission lines were known to come from volumes hundreds or thousands of light years in size, and so of course cannot change rapidly even if the original activity in the core completely stops. The fossil activity would continue for hundreds or thousands of years.

With so many interesting results from studies of variations in this galaxy, astronomers would be rash to suppose NGC 4151 has yet exhausted its capacity to surprise us!

M. V. Penston

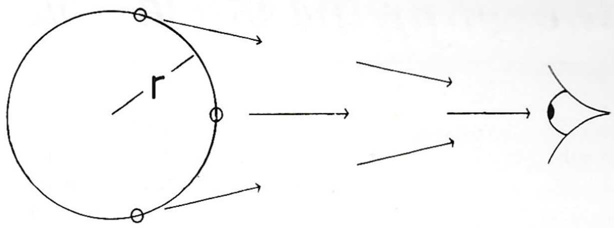


Fig. 1 Even if all parts of a sphere of radius r brighten (or get fainter) simultaneously, light from parts at the extremities of the sphere has to travel a distance r further than light from the front of the sphere so the simultaneous brightening is smeared into a pulse of width r/c. Thus the sphere cannot change instantaneously, and r/c is a lower limit to the time scale of variability.

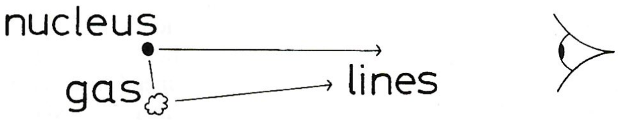


Fig. 2 Light from a galaxy nucleus can travel direct to the Earth and be detected as a continuum in the spectrum of the galaxy. Light can also travel to a gas cloud and cause the gas to give out emission lines, whose light also travels to Earth. Any variability in the nucleus also shows up in the gas but is delayed by the time it takes light to travel from the nucleus to the gas cloud.

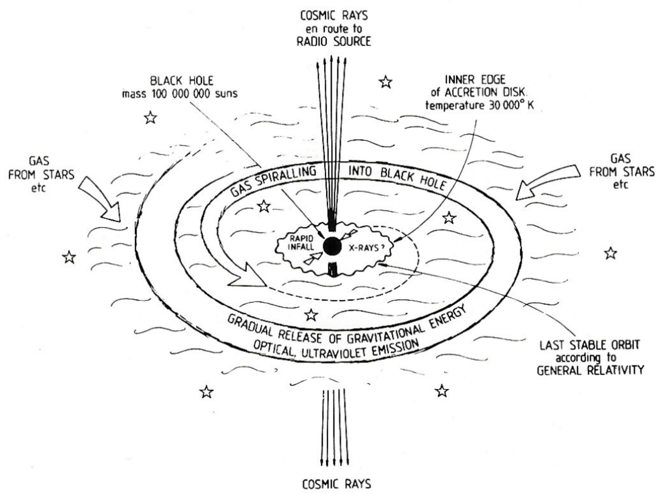


Fig. 3 Lynden-Bell's model of the black hole in the centre of a galaxy.

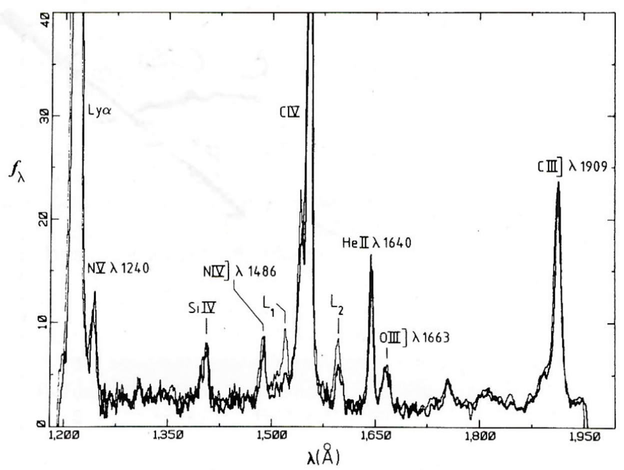


Fig. 4 Spectra of NGC 4151 with the IUE satellite show emission lines from gas orbitting the central black hole. L_1 and L_2 are emission lines from a jet in the galaxy's centre, arising from red- and blue-shifted CIV.

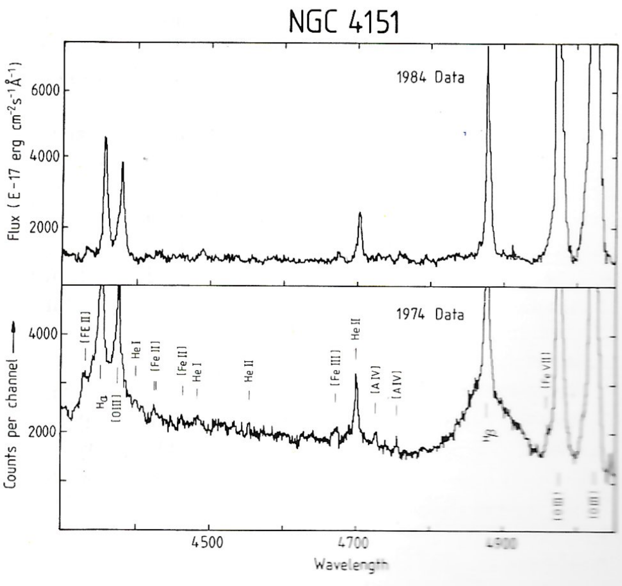


Fig. 5 Spectra of NGC 4151 with the Isaac Newton Telescope before and after its transfer to La Palma.

Power for LINERs: A black hole in every galaxy?

The nuclei of galaxies display a variety of types of 'activity' including strong radio sources, X-ray emission, infra-red emission and optical emission lines (see box). In extreme cases (Quasi-stellar objects or QSOs), the total power radiated exceeds the luminosity of a normal giant galaxy by a factor of 100 or more and much of it comes from a very compact central power-source with a diameter of much less than a light-year, giving rise to the favoured model of a massive black hole (10^6 to 10^9 times the mass of the Sun) gobbling up matter from a surrounding accretion disk and releasing gravitational energy in various forms that include relativistic jets and non-thermal radiation.

QSOs are relatively rare objects except perhaps at large red-shifts; the nearest object powerful enough to be so classified is IC 4329A with a red-shift of 0.016, although it is natural to speculate that nearby radio galaxies like M87 and Cen A are closely related and could actually have been QSOs in cosmologically recent times. However, about 1% of early-type spiral galaxies ('early type' is equivalent to having a large bulge: disk ratio, Hubble classes Sa, Sb, Sbc) have very bright nuclei with an emission-line spectrum resembling that of QSOs and are known as Seyfert galaxies after the astronomer who studied a nearby sample in 1948. These have been classified into two main types: Sy 1 nuclei, like QSOs, have a strong featureless continuum, and very broad permitted lines of hydrogen, helium I and II, carbon IV, iron II and other ions indicating the presence of high-density gas ($\sim 10^{10}$ cm^{-3}) ionised by a power-law radiation spectrum and moving with velocities of up to 7000 km s^{-1}. Sy 2 galaxies (and some Sy 1 galaxies) show much narrower permitted lines and also forbidden lines of [Ne V], [OI], [OII], [OIII], [NII], [SII] etc. indicating a more extended region of low-density gas ($\sim 10^4$ cm^{-3}) ionised by the same power-law spectrum roughly $F_\nu \sim \nu^{-1.5}$. Strong radio galaxies, which are invariably elliptical, show similar spectra. It is the character of the ionising radiation that makes the emission-line spectrum different from that of classical HII regions like the Orion nebula, in which the gas is ionised by the more black-body-like radiation from newly formed hot stars and displays a much narrower range of degrees of ionisation. Supernova remnants, which excite the interstellar medium by radiative shocks, display spectra that are qualitatively more like those of Sy 2 galaxies, but differ significantly in the line ratios observed, e.g. [OIII] is not as strong relative to hydrogen lines.

However, nuclear activity, defined by phenomena ranging from emission lines to significant X-ray, infra-red and radio outputs, is not confined to QSOs and Sy galaxies, but turns out to be the rule rather than the exception in otherwise normal spirals. In many cases (particularly late-type spirals) the nucleus is a giant HII region or 'starburst' emitting amounts of energy that are quite comparable to those of Seyferts. Other galaxies, when observed with modern linear detectors, show the presence of a faint Seyfert-like nucleus, often associated with a surrounding region of star formation. Early-type spiral galaxies, such as M81, most commonly display what is known as a 'LINER', which is an acronym coined by Tim Heckman for 'Low Ionisation Nuclear Emission-line Region'. The spectra of LINERs (which are also seen in some elliptical galaxies) have [OIII]/Hβ intermediate between nuclear HII regions or starbursts and Sy 2 galaxies, [OI] similar to the latter and very strong [NII], so much so that [NII]λ6584 exceeds the neighbouring Hα line λ6563. LINERs, again, are often surrounded by HII regions of star formation when they occur in spiral galaxies but not in ellipticals as a rule.

How are the spectra of LINERs excited? Some years ago, it was taken for granted that the chief mechanism was shock excitation, since there is some resemblance to the spectra of supernova remnants and measurements of the weak [OIII] line λ4363 appeared to indicate the presence of a high electron temperature ($\sim 2 \times 10^4$ K) in the more ionised region. However, in 1981 a much more interesting possibility was pointed out by G. Ferland and H. Netzer and by J. Halpern and H. Steiner: that LINERs are excited by a

Varieties of activity in galactic nuclei

Type	Subtype	Host galaxy	Effects
	Radio-quiet	Spiral?	(X-r), u.v., optical, i.r., broad and narrow absorption and emission lines
QSOs	Radio-loud	Elliptical?	γ-r, X-r, u.v., optical, i.r., broad and narrow emission and absorption lines, double radio sources, jets, superluminal expansion
	Optically violently-variable QSOs	Elliptical?	As above; strong variable polarisation
Blazars	BL Lac objects	Elliptical	X-r, u.v., optical, i.r., narrow absorption lines, strong variable polarisation (jets seen end-on?)
Broad-line radio galaxies	N-galaxies	Elliptical (peculiar)	U.v., optical, i.r., dust, double radio source, jets, broad emission lines.
Seyfert	1 to 1.8	Spiral (Sa, Sb)	γ-r, X-r, u.v., optical, i.r., broad and narrow emission lines
Narrow-line radio galaxies		Elliptical (peculiar)	Radio sources, jets, narrow emission lines
Seyfert	2	Spiral (Sa, Sb)	Radio, u.v., optical, i.r., narrow emission lines, HII regions, stars
LINERs		Ellipticals and early-type spirals	Stars, nuclear radio source, broad and narrow emission lines (lower excitation), HII regions in arms near spiral nuclei), some X-rays.
Starburst galaxies		Irregulars and late-type spirals (Sc, Scd, Sd)	Stars, HII regions, dust, i.r., supernovae, some radio and X-r
Centre of our Galaxy		Sb	Weak radio source, winds, shocks, i.r., stars, HII regions

power-law continuum in the same way as Seyferts, but with a lower value of the ionisation parameter which is the ratio of density of ionising photons to electron density. In this case LINERs are simply a milder extension of Seyfert galaxies and hence of QSOs. The frequency of QSOs at high red-shifts suggests that many galaxies still have black holes in their centres, the intensity of activity depending on how rapidly they consume matter from their surroundings, and in this case one can understand the existence of varying degrees of activity on the basis of a single unifying hypothesis.

Various tests have been considered as a means of distinguishing between photo-ionisation and shock hypotheses for the excitation of LINERs. The strength of [OIII]λ4363 has been shown to be unsatisfactory because it can be excited by high density as well as high temperature and its intensity is uncertain in any case because it is seen superposed on an absorption-line spectrum from the underlying stellar population, which has to be subtracted off. However, in the course of my collaboration with Mrs A. Diaz (University of Sussex), M. G. Edmunds (University College, Cardiff) and M. M. Phillips (Cerro Tololo Inter-American Observatory) I have argued in favour of photo-ionisation models on the basis that, with those, the strong [NII] lines can be understood without invoking a large overabundance of nitrogen (such as is required in shock models), as we find no evidence for such an overabundance in the surrounding HII regions.

At the RGO, I. R. G. Wilson and myself, in collaboration with Mrs E. Terlevich of Sussex University, have exploited the potentialities of CCD detectors in the far-red region of the spectrum to make a more definitive test by observing the strength of [SIII] lines at λ9069 and λ9532, which are predicted to be strong in photo-ionisation models; under shock-excited conditions they appear only at large shock velocities where a strong emission-line spectrum also appears in the ultra-violet. We have detected [SIII] lines in a number of LINERs including notably the much-studied elliptical radio galaxy NGC 1052, which used to be regarded as the classic example of shock excitation; in most cases the [SIII] lines are consistent with photo-ionisation models and in NGC 1052 shock excitation can be ruled out on the basis of the combination of [SIII] intensity and the ultra-violet spectrum. The ionising continuum is too weak to appear in the visible, which is consistent with the low ionisation parameter that is required; but it does appear at the short wavelength end of the ultra-violet spectrum observed with the IUE by T. Snijders *et al.*

We conclude that most LINERs are indeed excited by photo-ionisation, implying that massive black holes are common in galatic nuclei if they are indeed the main source of power-law-like continua with soft X-rays. The latter assumption, however, might not be true, since R. Terlevich and J. Melnick have shown that very massive stars with the large abundance of heavy elements that is characteristic of galactic nuclei lose enough mass in the course of their evolution to expose their hot cores and deliver collectively a hard spectrum resembling a power law and capable of causing the ionisation of Sy 2 galaxies as well as LINERs. The choice between these so-called 'Warmers' and massive black holes remains open for the present.

B. E. J. Pagel

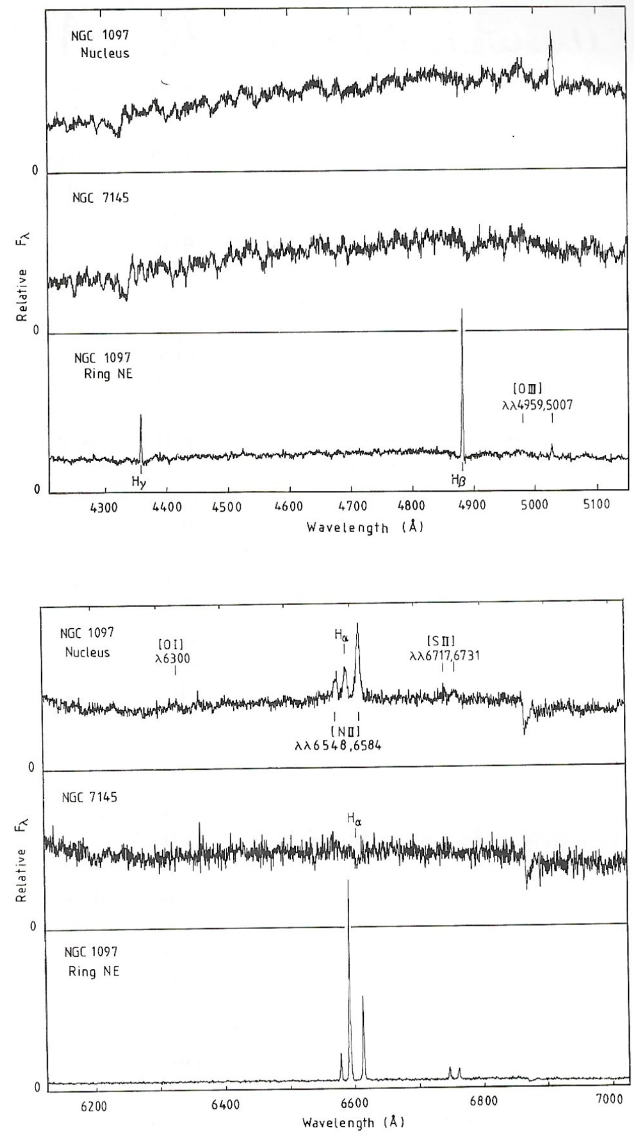


Fig. 1 Portions of the nuclear spectrum of NGC 1097, compared to the emission-line free elliptical galaxy NGC 7145. The upper spectrum shows that the lines are broadened (FWHM = 300 km s^{-1}) and that, relative to hydrogen lines, [OIII] is enhanced and [NII] very greatly enhanced compared to the surrounding HII regions due to star formation in the spiral arms, shown in the bottom panel. The spectra were taken with the RGO spectrograph on the Anglo-Australian Telescope by M. G. Edmunds and M. M. Phillips.

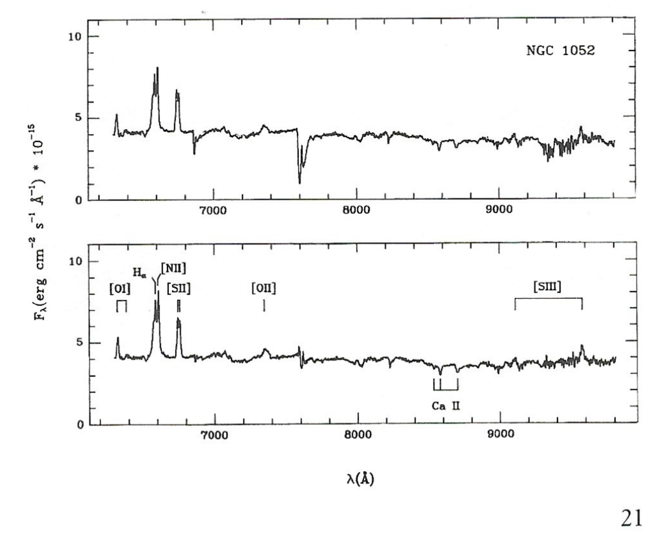


Fig. 2 Red spectrum of the nuclear region (1.5 × 10 arc sec^2) of NGC 1052 taken with the Isaac Newton Telescope, with major telluric absorption bands divided out in the lower version. Wavelengths are in the observer's frame.

Cen A – the nearest active galaxy

Centaurus A is an extraordinary galaxy when viewed at any waveband, from X-ray to the radio wavelengths, yet this extraordinariness is primarily the result of its proximity to us rather than its uniqueness. Indeed, were we to view Centaurus A at 50–100 Mpc rather than its actual estimated distance of 3–5 Mpc, we would see, in the optical, an elliptical galaxy with a dust band. In the radio we would see the double-lobe source centred about an unresolved point source defining the active nucleus of the galaxy, which would also emit in X-rays, and the infra-red. None of these features are unique, indeed they place Centaurus A into a well-populated class of dust-lane radio ellipticals.

However, it is the proximity of Centaurus A which makes it such an important member of its class, since it allows a uniquely detailed view of the physical processes which are characteristic of radio ellipticals. Indeed we can ask of it two fundamental questions.

(i) What is the origin of the gas and dust which fuel the nuclear activity?

(ii) What does the orbit of the dust band tell us about the three-dimensional shape of the gravitational potential formed by the stars which make up the elliptical galaxy?

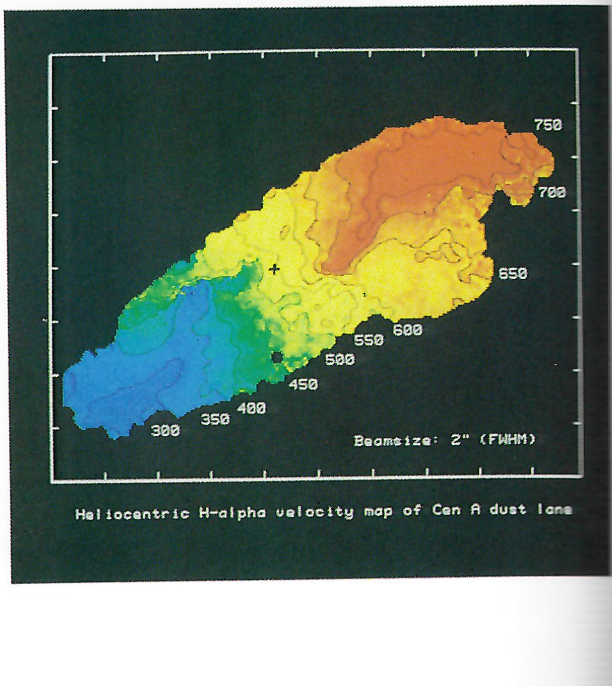
The question of the origin of the gas comprising the dust band, so clearly visible in Fig. 1, has been actively at issue since the discovery that the gas was rotating much faster than the stellar component. This led, not unnaturally, to the view that the gas and dust were the remnants of collision between the dominant elliptical galaxy and a smaller gas-rich disc galaxy, somewhat like our own. The chaotic appearance of the dust, together with multi-band imagery of the galaxy, led to the view that the accretion of material from the collision, which presumably fueled the nuclear activity, was a relatively recent phenomenon so that the material had not had time to relax into a stable configuration.

However, TAURUS, with its unique ability to map the kinematics of the gas in entirety at a spatial resolution limited only by the seeing, gave a completely new view of the object as revealed by the Hα emission from the HII regions embedded in the dust bands. For the first time it became clear that we were seeing a complete disc of gas rotating about the nucleus of the gravitational potential. We were able to see the motion of the disc unencumbered by the obscuration of the dust or dilution by star light from the elliptical component. These results are presented in Fig. 2.

What is immediately obvious from an analysis of these results is that, far from the dust band in Centaurus A being a chaotic recent encounter with a spiral galaxy, the gas, as revealed by its motions, is in an extremely well-settled state. The degree of symmetry in its rotation implies that the encounter happened a long time ago. Many rotations of the captured material about the elliptical have taken place and the material has acquired stable orbits within the potential well of the stars.

Fig. 1 Centaurus A shows as an elliptical galaxy crossed by a complex dust lane in this picture from the Anglo-Australian Telescope. The dust reddens the starlight from the elliptical galaxy behind it, and a haze of blue stars has formed on the fringe of the dust, and within. These blue stars ionise the gas mixed with the dust, and the HII nebulae which are thus formed show as pink patches. It is the velocity of the HII nebulae which TAURUS measures.

Fig. 2 The red area is receding and the blue approaching, relative to the centre (+) of this map of the dust lane crossing Cen A. The velocity contours are labelled in km/s. The dust shows an orderly, rotating velocity field, not the chaotic jumble expected from a recent collision.



A more thorough analysis of the TAURUS results allows one to disentangle from the velocity, flux and line-width maps a model of the dust and gas lane which gives us a three-dimensional view of the shape of the disc. Indeed, as indicated from deep prime-focus plates of these objects, the disc is not a flat structure but is severely warped in its outer radii. This appearance has led many to suppose that the dust band is not a plane structure but a thick swathe of material crossing the face of the elliptical. However, a three-dimensional structure of the dust band revealed by the TAURUS Hα data is consistent only with a thin disc passing through the nucleus which is severely warped, not only in the plane of the sky but also in the line of sight.

Indeed the warp may be represented by a fairly simple analytic expression. Its complexity is only a result of seeing the structure in projection on the sky. The prominent dust bands are due to dust in the outer radii of the disc crossing in front of the elliptical body.

We are thus led to an interpretation of Centaurus A as a stable configuration of stars and dust, with the gas component mapping out the three-dimensional potential of the stars.

This brings us to the second question. The very lack of a significant rotation in the stellar component gives us a clue to the three-dimensional structure of the potential. The apparent ellipticity, whose inner axis is coincident with the dust band, is not, as had been originally supposed, a simple rotational flattening. Indeed its elliptical shape is simply a reflection of a more general triaxial geometry seen in projection onto the sky. Again, this characteristic is not unique but is shared by the majority of elliptical galaxies whose stellar rotation has been determined, and we can assume that triaxiality is a general property of such objects.

The study of stable gas orbits within such a potential is a fairly new field; however some general cases have been analysed. In order to obtain objects which are warped as in the case of Centaurus A, the Triaxial potential has to be undergoing a slow tumbling motion whose time scale is long in relation to the orbital time scale of the individual stars. In this case a warping of the stable orbits about one of the preferred plans of the triaxial can be induced. From the sense of the warp and the direction of the angular momentum vector of the orbits one can predict the direction of tumbling. In the case of Centaurus A the direction and amplitude of the tumbling is measured. Unfortunately the theory does not predict either the shape or direction of the warp which the TAURUS observations reveal. Indeed the complexity of the warp is such as to rule out all simple theories of this type and we are clearly forced by the present data into looking for new models.

K. Taylor

TAURUS

TAURUS is an imaging Fabry–Perot interferometer which is used in conjunction with a photon-counting area detector like the IPCS to obtain three-dimensional images of galaxy in their emission lines. Two of the three dimensions are spatial while the third is a spectral dimension equivalent to velocity, which allows us to map the motions within galaxies to an unprecedented level of accuracy and detail.

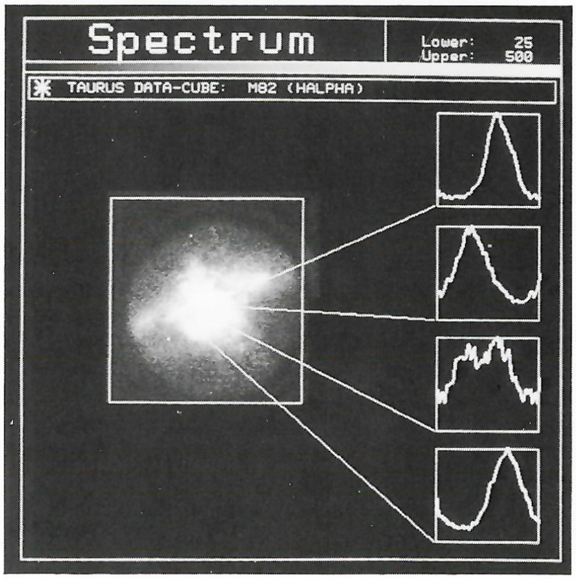
At the heart of TAURUS is a new type of Fabry–Perot whose accurately plane-parallel reflecting faces are maintained to an accuracy of 200th of a wavelength, even while the instrument is supported at the back of a constantly moving telescope. The means by which dynamical parallelism is maintained is that of capacitance micrometry, a technique perfected by a group at Imperial College. TAURUS creates its three-dimensional cube by stepping the gap between the parallel plates 100 times through a distance of half a wavelength, each time a new image of the galaxy under study is formed.

Although TAURUS has been in operation now for three years at the AAT and has since been put into service on the new INT on La Palma, it is still a unique instrument, being the only one of its type in regular use on a large telescope world-wide. Its efficiency in gathering kinematic data on galaxies outstrips conventional spectroscopy by two orders of magnitude with its ability to create 30 Mbyte data cubes on objects in a matter of a few tens of minutes.

Indeed its vast data rate has been a driver for the need for fast computers in the reduction of astronomical data. The Starlink network computers which now embody approximately 10 networked VAX computers, arrived just in time for the onslaught of TAURUS data reduction. Each three-dimensional data set can now be reduced to a set of two-dimensional images coding the flux, velocity and line-width of each point in an emission-line galaxy.

With the advent of this type of detailed kinematic data, new techniques have had to be developed to handle and interpret the information.

The figure is taken from newly acquired data on the active galaxy M82. The image is that seen through a direct interference filter while the spectra represent spectra on four separate positions on the galaxy. Clearly seen is the region of line splitting to the south of the nucleus, first identified by Axon and Taylor in 1978, and interpreted as an expanding hollow cone of material emanating from the nucleus.



Are elliptical galaxies really dead?

I suppose that one of the properties of a living thing is the ability to defend itself against change by its own internal processes. By analogy with this, for years elliptical galaxies were regarded as being pretty nearly dead; and as a consequence, they were thought to be simple and rather dull objects. The main reason for this is that they show little sign of the vigorous metabolism of spiral galaxies (see box) where new stars are constantly being formed as the debris of old ones is recycled, and the whole process is mediated through elaborate dynamical structures, the spiral arms. By contrast, the classical picture of ellipticals is that they consist of coeval stars, all growing old together. The gas in these galaxies, which should be the material to make new stars, is too hot and tenuous to do anything but hover in the potential well of the galaxy, slowly streaming away and emitting X-rays. The main reason for this depressingly monotonic picture is that ellipticals have small amounts of angular momentum compared to the random internal motions of the stars (see box).

For many years, however, there was at least one piece of evidence to show that there was more to ellipticals than decline. In 1918 Curtis found the famous jet in the giant Virgo elliptical M87 (Fig. 1).

Curtis had discovered a totally new constituent of elliptical galaxies, although for decades M87 was a unique curiosity. However, in the 1960s and 70s the use of aperture synthesis in radio astronomy showed that 'jets', rather like M87's, were extremely common in ellipticals. These radio jets can be detected in about a quarter of ellipticals, but are extremely rare in spirals. They emit strongly-polarized radiation by the synchrotron process, showing that they contain relativistic particles and magnetic fields. The energy of the particles is drained away rapidly by radiation and M87 is one of the few cases where there are still enough particles present at high enough energies to radiate in the visible. It seems that jets represent a short-lived, but possibly recurrent, phenomenon; streams of highly energetic material are squirted out of the nuclei of ellipticals in a remarkably collimated manner.

Radio interferometry over continental baselines has shown that the nuclear engine is tiny; certainly less than a parsec in size. In extremely luminous radio ellipticals and quasars, the engine can dominate the host galaxy's starlight with a rapidly flickering output of non-thermal radiation. The time-scales of these variations, the huge energies which can be involved, the collimation, and the impossibility of explanations based on familiar stellar nucleosynthesis, have lead towards the idea that many (perhaps all) ellipticals contain a massive black hole in their nuclei. In some (unknown) circumstances the gravitational energy of this object can be tapped and released in the form of relativistic plasmas. It is the observation of radiation associated with these plasmas that leads the classification of a given elliptical as an 'active galaxy'.

We can now appreciate the strange dichotomy of ellipticals. On the one hand we have a collection of stars, placidly proceeding towards extinction in 10^{10} years or so; on the other, the ephemeral radio sources, lasting only 10^8 years at most, and the whole collection of short-lived energetic phenomena associated with the nucleus itself. Does the nucleus 'know' that it is an elliptical galaxy? If it does, what is the physical link between the sedate processes in the great bulk of an elliptical, and the bizarre activity in its nucleus? At the RGO, a large part of the work on active galaxies has been trying to answer questions like these. The hope underlying the research is that we can understand the events in the nucleus as a consequence of the metabolism of the galaxy as a whole. Notice that we already think that there *is* a metabolism, rather than death!

For some years it has been known that the probability of an elliptical being a radio source is proportional to its total *stellar* luminosity. This shows that the nuclear object, ultimately responsible for the energy released at radio frequencies, knows how big its host galaxy is. It certainly knows that it is an elliptical, since radio jets occur so very rarely in bona fide spirals. Recently at the RGO, another early (but controversial) result has been vindicated – the radio emission depends on the shape of the galaxy, with apparently round ellipticals being stronger radio-emitters than 'elliptical' ones. Moreover, from a dynamical analysis it seems likely that radio ellipticals carry more angular momentum than their radio-quiet peers. Adding these results to the black hole hypothesis suggests two alternative interpretations. The pessimistic one is that the existence of the central engine and the large-scale structure of its host galaxy are related in that they were both made during the epoch when galaxies were formed, an epoch both observationally and theoretically rather inaccessible. If the black hole can be fuelled from it's *immediate* environment, for example by its tidal demolition of passing stars, then the current state of the host galaxy is pretty unimportant to any explanation of active galaxies.

We take the alternative view, that the host galaxy *does* matter, and the reason it matters is that it is a source of fuel for the nucleus. Thus we visualize, for example, that some of the mass lost from stars as they age can be channelled into the nucleus, there to release its potential energy in an accretion disc near a black hole. Evidently the shape, size and dynamics of the galaxy would be important to such a process, although we have not yet been able to calculate their precise

Elliptical and spiral galaxies

Elliptical and spiral galaxies differ in most major observational respects. Spirals have prominent discs, flattened by rotation, within which are the striking spiral arms. They have plenty of gas, dust and young stars. Ellipticals by contrast have little angular momentum and their flattened spherical shape is a consequence of the anisotropic 'pressure' of the random motions of their constituent stars. Classically, they contain very little cool or tepid gas, no dust and are not forming significant quantities of stars. The major reason for all these differences is angular momentum. In a spiral there is a large amount of organized motion, and clouds of cool matter and dust are not dissipated by colliding with other clouds. The material lost in the form of stellar winds does not have a high velocity with respect to other components of the interstellar medium. In an elliptical, the large random motions of the stars ensures that material processed through them ends up at a temperature (about 10^7 K) corresponding to the stellar velocity dispersion, usually about 300 km s^{-1}. Thus the gaseous environment in an elliptical should be totally hostile to the condensation of new stars, as the gas is hot and tenuous. It may even be flowing right out of the source galaxy, if there is enough extra heating from exploding stars. So in an elliptical, its constituents are used to build a single generation of stars, which then gradually burn out with no progeny.

role. There is however one piece of evidence to suggest that the interstellar gas influences the behaviour of the nucleus, and this is the discovery by astronomers at ROE that distant, energetic radio ellipticals are forming new stars very rapidly. It seems quite likely that the condensation of new stars would be associated with cooling of the interstellar gas and rapid flows into the nucleus. The gas in an elliptical's 'atmosphere' is supported against gravity solely by its thermal pressure, and since stars can only form in cool dense gas it follows that star formation and inflow must go hand in hand. We therefore have been examining the gaseous and stellar content of ellipticals with the hope of discovering processes going on over the bulk of the galaxy which will deliver material into the nucleus. What we expect to be able to detect is a low level of star formation and clouds of tepid (10^4 K) gas. An early interpretation of the statistics of radio ellipticals, in terms of a model of gas flowing in from all over the galaxy, was produced at the RGO two years ago. Since then we have had two new unexpected results. The first was the discovery of *dust* in elliptical galaxies. One of the classical distinctions between ellipticals and spirals is that the latter are dust-free; clouds of cool gas and dust are where stars are formed (see box) so it seemed sensible that ellipticals should have neither. Yet modern techniques of image processing reveal dust in many 'normal' ellipticals. This surprising discovery shows that there is a great deal yet to be learned about what goes on in ellipticals' atmospheres. During the lifetime of a galaxy, perhaps 10^9 solar masses of gas is blown into these atmospheres by dying stars. Most of it probably starts in a hot phase at 10^7 K, cooling very slowly by radiating X-rays. Only when the gas reaches 10^4 K will it radiate in optical emission lines. Yet in a recent large survey, looking for the Hα Balmer emission line, we have found such 'tepid' gas in the nuclei of more than half of all ellipticals. One possible explanation is that compression of the hot atmosphere as it (somehow) flows into the nucleus pushes up the gas density to the point where rapid cooling down to 10^4 K becomes possible.

So far, we have identified some elements of a metabolism in ellipticals, which we expect to be linked to their active nuclei. A hot atmosphere certainly exists, and within it there are tepid clouds of gas. Dust near the nucleus is not unusual. The processing of gas into new stars is an element expected, but not yet found. Research continues to discover how material is cycled through the evolution of an elliptical galaxy, and whether the life found in their active nuclei can be tied in to an understanding of their large-scale physical processes. However it seems pretty clear, to paraphrase the curate's expression, that ellipticals are only 'dead in parts'.

C. Jenkins

Fig. 1 The jet in M87, a picture obtained with the RGO's CCD camera at the prime focus of the Anglo-Australian Telescope. The image has been processed on a Starlink VAX–780 to subtract the bright, fuzzy image of the galaxy within which the jet is embedded. The nucleus of the galaxy is the faint stellar object at the narrow end of the jet. The other stellar objects dotted about the image are part of M87's swarm of globular clusters.

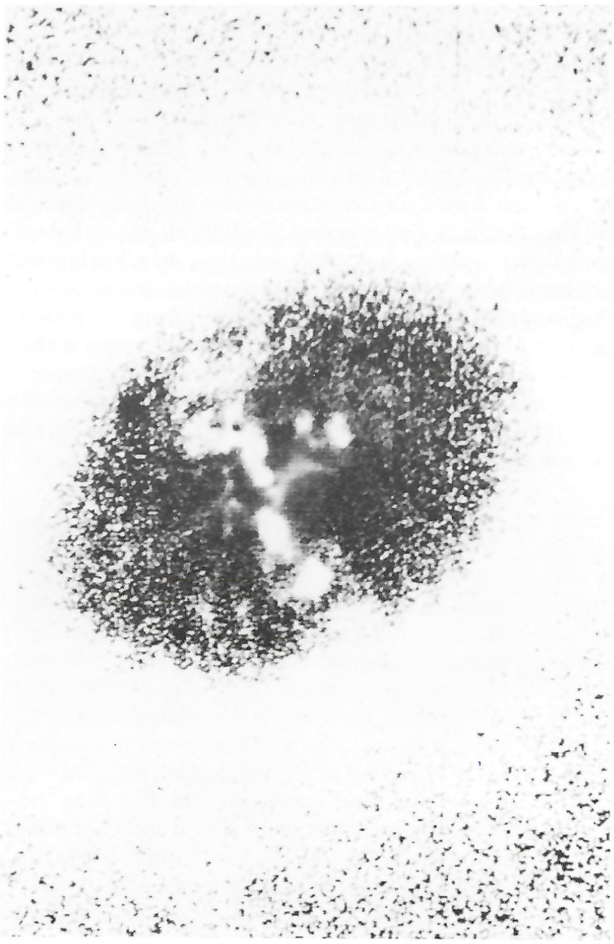


Fig. 2 A dust lane in an elliptical galaxy, NGC 1316. In this map of optical depth, regions of dust show up white. The data were obtained with the RGO CCD camera on the Danish 1.5 m telescope in Chile.

Ellipticals and doubles

What makes a galaxy into a radio galaxy? What persuades its nucleus to beam energy to two giant radio lobes in precisely opposite directions, lobes which may be distant from the galaxy by 10 times the galaxy's optical diameter? It is surely reasonable to suppose that the galaxy hosting such an amazing nuclear engine should show distinctive optical characteristics. But in fact there are not many correlations between the radio and optical properties, so that the few which exist are treated with extreme reverence.

One of the most revered is that the large double-lobed radio sources are associated *only* with elliptical galaxies. There are a few other well-established relationships between optical and radio properties which must be fundamental to any successful theory: the brighter the elliptical, the more likely it is to be a radio-emitter; and the presence of emission lines in the optical spectrum likewise increases the probability of radio activity. In addition, some radio galaxies are rapid rotators: detailed measures of the spectral shift of the starlight at points across galaxian images has shown that they spin rapidly despite having high optical luminosities, whereas the trend among radio-quiet ellipticals is for the luminous ones to be the slower rotators. Recently a series of observations involving M. J. Disney (University College, Cardiff), W. B. Sparks (University of Sussex), and RGO astronomers has yielded further correlations: radio-emitters are *redder, rounder*, and *more sociable* in that they have a greater tendency to have galaxies nearby than do radio-quiet elliptical galaxies.

We can draw a very tentative picture which incorporates all these findings. Suppose that *all* ellipticals are capable of generating nuclear activity, but only those which achieve an adequate fuel supply for the nucleus succeed. Interstellar gas fuel may find its way to the nucleus either from accretion of gas outside the galaxy, or from loss of gas from stars within the galaxy. Either way, so-called galactic winds (pressure from supernova explosions) will try to prevent this putative fuel from getting to the fire, the 'monster in the middle', the central black hole with its accretion disk, or whatever it is.

But gravity can overcome; and it is probably the depth of the gravitational potential well, the summed total of all contributions to gravitational pull at the centre, which decides whether the fuel arrives. Galaxies with deep gravitational wells hang on to the gas, which eventually accretes onto the nucleus to power radio activity. On this simple model, both the old and the new correlations can be accounted for like this:

1 Radioactivity and optical luminosity: it is known that the most luminous galaxies are the most tightly bound; the stellar velocities are highest.

2 Sociability: more neighbours – the galaxies in the richer environments – will provide an increased gravitational well. Gas which cannot escape the group or cluster is likely to cool and accrete onto the dominant elliptical at the centre, and this galaxy is invariably the radio-active one.

3 Ellipticity: it is known from other observations that elliptical galaxies with smallest axial ratios (the 'roundest ellipticals') are the most tightly bound and have the deepest potential wells.

4 Colours: extra reddening associated with radio-emitting ellipticals may be due to higher dust content. Dust and gas are generally found in association in the interstellar medium in galaxies – and extra dust may be a tracer of the extra gas fuelling the radio activity.

5 Rotation properties: rapid rotation for radio ellipticals shows that there is an intimate connection between the bulk dynamics of the stars and the nuclear activity. The stars know that the galaxy is a radio galaxy. How? Theoretical investigations provide a strong indication: the effectiveness with which both lost stellar mass and accreted extragalactic matter reach the nucleus has been shown to depend on galaxy shape and on stellar orbits.

These first stumbling steps towards an understanding of why a galaxy is a radio galaxy beg many questions. Large programmes of observations to address these are in progress, involving RGO astronomers, M. J. Disney, W. B. Sparks and A. E. Sansom (University of Sussex). Some early results are shown in Fig. 1. If the tentative picture holds under this intensive scrutiny, then we have come some way to understanding the radio-galaxy phenomenon: the amazing ability of ellipticals to generate doubles.

J. V. Wall

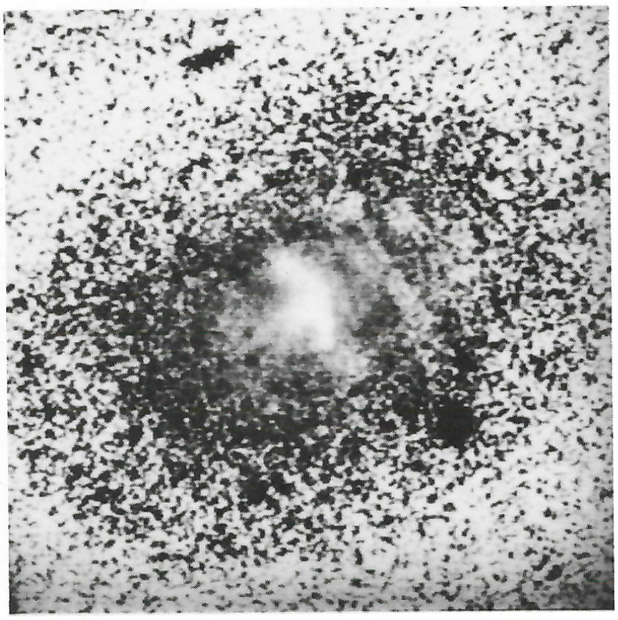


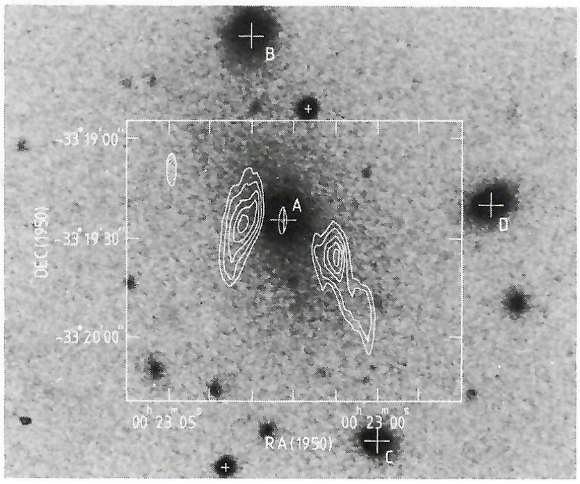
Fig. 1 Is the redness of radio galaxies due to dust (correlation 4) which could be a tracer of gas fuelling the nucleus? Or is it due to a different star population? CCD observations by W. B. Sparks and RGO scientists have been analyzed with a novel technique to enhance red features outlining dust lanes; several new dust features have been detected in radio ellipticals. The structure of dust lanes in NGC 1052 is now found to be particularly complex.

New elliptical radio-galaxies . . .

Radio-emitting galaxies are discovered in two different ways. Either the radio telescope is pointed at individual bright galaxies to try to detect their radio emission, or it is scanned to survey a patch of sky and optical plates are searched at positions where radio sources are detected. Because the catalogued galaxies are bright and relatively close, the first method finds radio sources of low luminosity. In contrast, radio sources found in sky surveys are usually identified with faint galaxies at large redshifts, the big distances implying high radio luminosities. These generally show the classical double-lobed structure, while the low-luminosity emitters are either point-sources coincident with the nucleus of the bright galaxy, or of diffuse shape, asymmetric and perhaps poorly collimated. The difficulty is that the high-luminosity radio emitters are too faint optically for detailed studies. The correlations discussed here are therefore of necessity from studies of relatively bright galaxies of low radio-power. Are these correlations telling us about the *true* radio galaxies, the powerful double-lobed objects?

Intermediate-luminosity samples hold the key, samples in which the galaxies host powerful radio sources, but are not too distant to prevent detailed optical studies. RGO astronomers, together with P. A. Shaver and A. M. Moorwood (ESO), W. M. Goss (Groningen), R. D. Ekers (NRAO VLA), and D. A. Malin (AAO) have obtained optical and radio data for about 90 such objects. The radio observations, obtained with the VLA, show that many of the sources have classical double structure; but many others do not, the variety of radio structures demonstrating the transition nature of the sample. Precise comparison of the properties at radio and optical wavelengths will establish whether the correlations persist from low to high radio-luminosities. First indications are that they do.

PKS 0023–33, a member of the intermediate-luminosity sample which is essentially a double radio source, but with the lobes swept back into a trailing form due to motion through the intergalactic medium.



. . . and one which isn't?

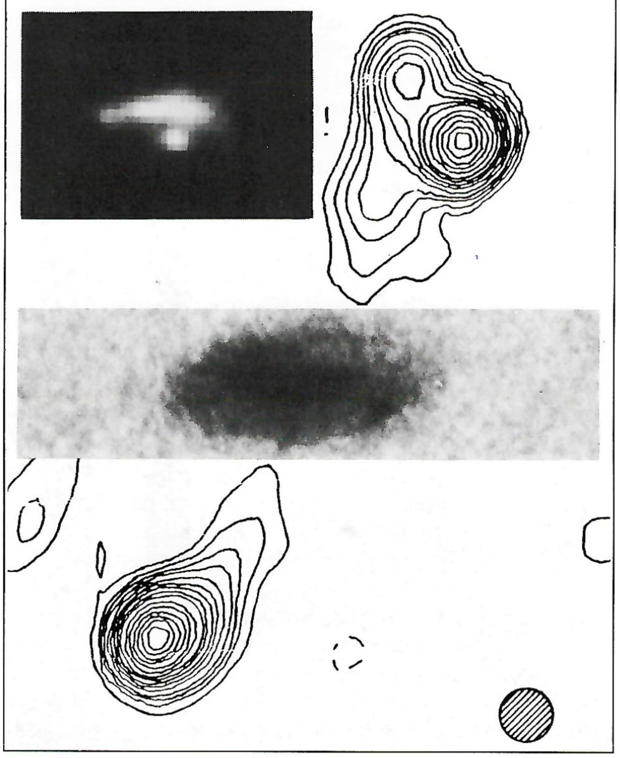
PKS 0400–181 is a faint little radio source which had the temerity to challenge one of our most cherished beliefs about double radio-sources: that they are always produced by giant ellipticals, and never by spirals. For spirals, it is 'well-known' that the radio emissions are weak, and smaller in extent than the optical disks.

The figure demonstrates the cause for concern. In the course of the study of the sample of intermediate–luminosity radio galaxies, an early VLA observation showed PKS 0400–181 to be an edge-brightened double radio source whose centroid coincided very closely with the optical centre of a faint (16 mag) late-type barred spiral. Many observations at many wavelengths of this apparently unique spiral subsequently were made. It turned out to be normal in every respect other than its apparent radio emission.

One possibility remained in order to preserve conventional wisdom. Could the spiral be an innocent foreground object, sitting accidentally on the line of sight to a distant elliptical? To test for this unlikely event, RGO astronomers obtained deep images of the object while commissioning the CCD camera which RGO built for the AAT. The images revealed a faint object just to the South of the bar, lying within one arc sec of the radio centroid. The object is very red, and in fact it has the right shape, size, colours and magnitude to be a giant elliptical at a redshift of 0.5. The distance corresponding to such a redshift implies a high-luminosity radio source for which the collimated edge-brightened double structure of PKS 0400–181 would be typical.

It therefore seems likely that the double source 0400–181 is produced by a distant elliptical. This leaves the foreground spiral with only one distinction: that of being the most thoroughly observed faint barred spiral in the sky.

VLA map at 1.4 GHz of PKS 0400–181, and a red-band CCD image of the bar of the spiral with a faint elliptical image below it. The radio lobes are probably associated with the distant elliptical, not the large foreground spiral.



Violent star formation

Violent Star Forming Regions are regions in which thousands of massive stars (masses larger than 20 solar masses) recently have formed in a very small volume of space (a few parsecs in diameter) and over time-scales of only a few million years. The term 'Violent Star Formation Region' (VSFR) seems appropriate to characterize the extremely short time-scales, small dimensions, and large luminosities involved.

VSFRs are present in a variety of extragalactic systems, the best-known examples being the giant extragalactic HII regions like 30 Doradus in the LMC and NCC604 in M33, the extragalactic detached HII regions or HII galaxies like IIZW40 and IZW18 (in which very luminous bursts of star formation take place inside low-luminosity galaxies) and the Star-burst Nuclei, i.e. VSFRs in the central region of luminous spiral galaxies.

HII galaxies are characterized by emission-line spectra similar to those of individual giant HII regions in luminous spiral galaxies, superposed on continua which appear to be mainly due to O–B stars and which unlike Star-burst Nuclei, show no evidence of stellar absorption features from a population of late-type stars. The remarkable stellar make-up of these isolated objects, combined with the very low heavy-element abundance deduced from their emission-line spectra, lead to the conclusion that some of them can be truly 'young' galaxies forming their first generation of stars. In any case they represent the youngest galaxies that can be studied in any detail.

The study of these galaxies is particularly important for models of galactic chemical evolution because we can observe the activity which was extinguished long ago in our Galaxy. From their emission-line spectra it is relatively straightforward to derive precise abundances of elements He, N, O, Ne and S. From the comparison between helium and metal content we can deduce the primordial helium abundance. This is perhaps the most important parameter in order to choose among the many possible cosmological models describing the early phases of the Universe. Moreover, within the canonical Big-Bang model, these studies could also provide some insight into the physics of elementary particles. By studying the systematic properties of VSFRs it is possible to place stringent constraints on the theory of formation and evolution of massive stars. The whole-sky spectroscopic survey of the optical spectra of about 700 giant HII regions, HII galaxies and Star-burst Nuclei recently completed by R. Terlevich, J. Melnick (ESO) and collaborators has discovered, among other things, the presence of large numbers of Wolf-Rayet stars in many of these objects.

These luminous Wolf-Rayet stars are believed to be the product of the evolution of very massive stars under the influence of mass loss in the form of stellar winds. Recent theoretical studies indicate that massive stars may go through very different evolutionary sequences depending on their initial mass, mass-loss rate and metallicity. Stars with masses in the range 25 solar masses to 60 solar masses may go through a red supergiant phase and then become a Wolf-Rayet star during the last part of the core helium burning, whereas stars more massive than 60 solar masses never reach the red supergiant phase, evolving directly into the Wolf-Rayet phase.

The discovery of Wolf-Rayet stars in VSFRs may have far-reaching consequences. In the past decades, astronomers have come to invoke the presence of a massive black hole surrounded by an accretion disk to try to explain any unusual activity in the core of luminous galaxies.

Of particular importance in this respect are the enigmatic Seyfert type 2 and LINER galaxies (acronym for Low-Ionization Nuclear Emission-line Region). They are the most common type of galaxy with active nuclei representing about 2% and 30%, respectively, of all giant spirals with Hubble type earlier than Sbc.

Seyfert galaxies are defined as having bright compact nucleii and emission-line spectra with broad lines covering a wide range of ionizations. Two main types are distinguished. Seyfert type 1 galaxies have very broad (FWHM > 1000 km/s) permitted lines, and narrower forbidden lines. Seyfert type 2 galaxies on the other hand are defined as having permitted and forbidden lines of the same width.

Since most observational evidence indicates that the high-excitation emission-line spectra and wide range of ionizations found in Seyfert Type 2s cannot be produced by photoionization by normal O stars, most students of active nuclei assume, probably as an extrapolation of what is believed to happen in the most active Seyfert type 1 or quasars, that a very hot accretion disk circling a black hole is responsible for the properties of the emitting gas and all the nuclear-associated phenomenae.

But recently, R. Terlevich and J. Melnick have suggested that the emission-line spectra of Seyfert type 2s do not require a black hole but are instead the normal late stage of evolution of a large nuclear burst of star formation (the so-called 'Star-burst' Nucleus).

They also pointed out that the recent developments in the theory and understanding of evolution of massive stars have shown that as a consequence of mass loss in the form of stellar winds, stars more massive than 60 solar masses do not expand and become a cool red supergiant at the end of the core hydrogen burning as was previously thought. Instead, these evolve towards higher temperatures and end their evolution as bare helium, carbon and oxygen cores, with effective temperatures up to 300 000 K and several million solar luminosities. These bare cores are 'hotter' than normal stars but 'cooler' than a black hole centre; we dubbed them WARMERS. They heat up the surroundings quickly, and the calculated spectrum of the VSFR becomes identical to that of a Seyfert type 2 galaxy.

These WARMERS are not hypothetical stars. They do indeed exist; Barlow (University College London) recently demonstrated the existence of extremely hot Wolf-Rayet stars, named WO stars, characterized by the presence of high-ionization emission lines (OVI, CIV) in the optical and UV spectra. Their effective temperature is probably higher than 100 000 K.

There are two main reasons to expect large numbers of WARMERS in the nuclear regions of early-type spirals:

1 The gas can be accreted in the core of an early-type spiral to form a cloud far more massive than possible in the outer disk.

2 The nuclear region of an early-type spiral contains a higher proportion of metals than the outer disk, and a star with more heavy elements will expel its outer regions more efficiently and therefore live longer as a WARMER.

The evolution of the spectrum of the ionized gas associated with a VSFR will depend strongly on the mass-loss rate of the hottest stars and therefore on chemical composition. In the case of a metal-poor burst with sub-solar abundances, like all HII galaxies, giant HII regions and most Star-burst galaxies, the emission-line spectrum remains essentially unchanged during the first 2.5 million years. Then, as the most massive stars begin to evolve off the main sequence, the effective temperature and total ionizing flux decrease, and thus the strength of the emission lines becomes steadily smaller. Eventually, the emission lines disappear when all the ionizing stars become red supergiants and the gas is dispersed by stellar winds and supernovae shocks, leaving behind a populous blue cluster of young stars.

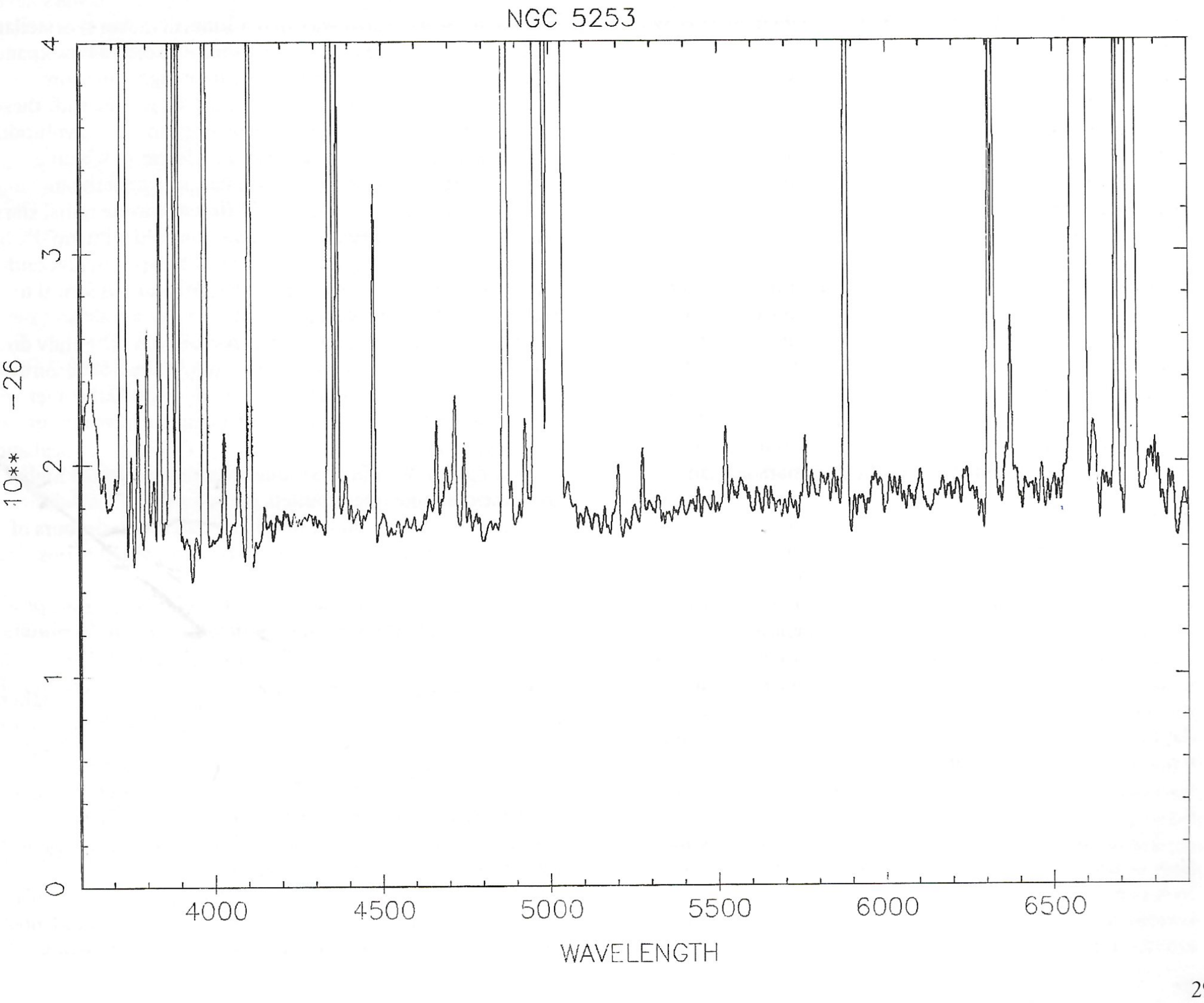
The evolution of a metal-rich VSFR is not substantially different from that of a metal-poor one during the first 2.5 million years. The evolution becomes dramatically different, however, when the most massive stars reach the WARMER phase. In a very short time the ionizing spectrum of the cluster is fundamentally modified by the appearance of a luminous and hot component, the WARMER component. Consequently the emission-line spectrum is transformed from that of a typical low-excitation HII region into a high-excitation Seyfert type 2. Following the evolution further shows that after 5 million years the Seyfert type 2 nucleus becomes a LINER.

The model computations shows that while a large star-burst will follow the sequence HII region – Seyfert type 2 – LINER, a smaller one will never become a Seyfert, evolving after 2.5 million years directly into the LINER phase.

If this model is supported by further observations, it will go a long way towards establishing the first physical theory of active galactic nuclei. The study of VSFRs appears to hold the key to understanding a wide range of phenomena running from the formation and evolution of stars to the formation and evolution of galaxies.

R. J. Terlevich

Fig. 1 Optical spectrum of a region of violent star formation in the galaxy NGC 5253. The intensity scale of the spectrum has been enlarged to show the weak spectral lines and the tips of the strongest lines are 100 box heights out of scale. There is a large number of well detected weak lines, such as HeI 4026, 4471; [SII] 4068 + 4076; [SIII] 6311; [AIV] 4711, 4740; [OI] 6300, 6363; [OIII] 4363 (reaches full scale!); [FeIII] 4658, 4881, 5270; [CIIII] 5518; [NII] 5755; [NI] 5200. The blend of broad lines between 4600 and 4800 corresponds to features found in Wolf-Rayet stars. There are no strong stellar absorption features.



The jets of SS433

SS433 is the 433rd entry in a catalogue by N. Sanduleak and C. Stephenson of stars having emission-line spectra. Such stars have a spectrum consisting of an underlying essentially black-body component – the optically-thick surface layer of a star – plus emission lines coming from an optically thin gas surrounding the star. The stars are catalogue-worthy because the gas represents some interesting interaction between the star and its neighbourhood.

The interaction causing an emission-line spectrum may have any of many causes. Some of the stars in the SS catalogue are rotating so rapidly that centrifugal force at their equators counteracts their attractive gravitational force, so that the stars shed an equatorial disk of gas which shows as the emission-line region. Some, like SS433, are binary stars with matter flowing around and between the two stars. Since hydrogen is the most common element in the Universe, the stars in the SS catalogue typically show hydrogen emission lines, the strongest line of which is Hα at 6563 Å. Helium lines are also typical.

SS433 languished as one star among many hundreds in the SS catalogue until its re-discovery in 1978. Spectra taken then show the Balmer series and spectral ines from neutral helium, both arising from the circumstellar material ripped from one star by its companion. There were also present in its spectrum other lines which were unidentified, particularly because they seemed to come and go sporadically.

It was only after several months of monitoring the spectrum of SS433 that the pattern became apparent. The unidentified lines appear in pairs, the most prominent of which shift cyclically in position about a wavelength which is somewhat to the red of the Hα line. The cycle has a period of 164 days, and the range over which each member of the pair shifts is more than 1000 Å. The lines are antiphased. With this clue to the interpretation of the two strongest of the unidentified lines, the other unidentified lines could then be paired off. They show similar behaviour, oscillating in antiphase about wavelengths which lie to the red of the other Balmer lines and the neutral helium lines.

Thus the emission line spectrum of SS433 consists of three components – a stationary set of Balmer and helium emission lines arising from the interaction of a double star, and two antiphased oscillating sets of moving spectral features associated with the Balmer and helium emission, and arising from a new phenomenon.

The interpretation of the moving features is in terms of a pair of equal and opposite jets of material shooting from SS433. Because of the speed of outflow of material, the spectral emissions of hydrogen and helium gases in each jet are Doppler-shifted from their rest wavelengths, one (the approaching jet) generally to the blue and the other (the receding jet) generally to the red. The jets precess like a spinning top in a conical motion with period 164d and so the features move in antiphased cycles of this period.

Curiously, even at the moments when the jets are in the plane of the sky, with no component of speed towards or away from us, there is a shift. It has its origin in the phenomenon of relativistic time dilation. The fast-moving hydrogen atoms in the jets have 'clocks' – the natural time-scales of atomic phenomena – which are running slow with respect to ours and so emit Hα photons of lower frequency. The speed of the material in the jets is an astonishing one quarter the speed of light!

Interest was focussed in SS433 because it was identified with an X-ray star centrally within a spherical radio supernova remnant called W50. This led to the suggestion that SS433 is the stellar remnant of the same supernova explosion which gave rise to W50. Perhaps SS433 contained a black hole produced in a supernova explosion on one of a pair of stars. In this model, the black hole accretes material expelled by its companion (this material gives rise to the stationary emission lines which earned SS433 its place in the SS catalogue). As it approaches the boundary (event horizon) of the black hole, in-falling material is accreted in a disc around the black hole and compressed by its gravitational field. Accretion yields the X-rays which are the reason why SS433 is an X-ray star. The accretion is over the rate which would generate the Eddington luminosity of the black hole, and pressure of the radiation generated by heating of the in-falling material drives the relativistic jets, which are collimated by the holes in the accretion disk.

Not only is SS433 an X-ray star, it is also a radio star – indeed, not knowing of its SS designation, the rediscoverers of SS433 used the *radio* coordinates to point the Anglo-Australian Telescope to the *optical* star which they anticipated was the stellar remnant of the supernova. Techniques of Very Long Baseline Interferometry have resolved the radio image of SS433 into a blobby, elongated structure in which the blobs move out in a cone, with transverse speeds of 0.0088 arc sec day^{-1} – matching the 0.26*c* jet speed at the 5 kiloparsec distance of the star.

One interesting question to which the Isaac Newton Telescope on La Palma was put in June 1985 was to attempt to link the optical jets directly with the radio ejection process. The star was followed on 14 consecutive nights to show the evolution of the moving features, at the same time that the radio star was observed across the European VLBI network. The optical data show two events (the clearer of which appears in the graphs with this article), in which the moving features break up and re-form at different wavelengths. On night A of the accompanying spectra, obtained with the IPCS and the Intermediate Dispersion Spectrograph, the two jets are represented by emission lines at 6790 and 6880 Å. On night B the jets had changed orientation just a little and the emission lines had moved to 6795 and 6860 Å. On night C, faint emission lines can still be seen at 6790 and 6860 Å, but the main lines are at 6695 and 6900 Å. By night D the original jets are only faintly present and the main jets have opened to 6660 and 6930 Å.

The picture behind this sequence is that the jets of SS433 are somewhat like tracer bullets in the sweep of a machine gun. Once fired, the bullet flies in its trajectory, decoupled from the subsequent behaviour of the gun, which is revealed by later bullets. Between nights B and C therefore, on this interpretation, the machine gun had shifted to a different position, and a bullet was fired, with an orientation in the sky defined, through the projected radial velocity, by the wavelengths of the main emission lines on night C. The bullet is predicted to appear in the VLBI observations at that orientation after the appropriate time delay, and to coast outwards from the central radio image. The prediction is currently being put to the test by analysis of the huge volume of VLBI data.

P. G. Murdin

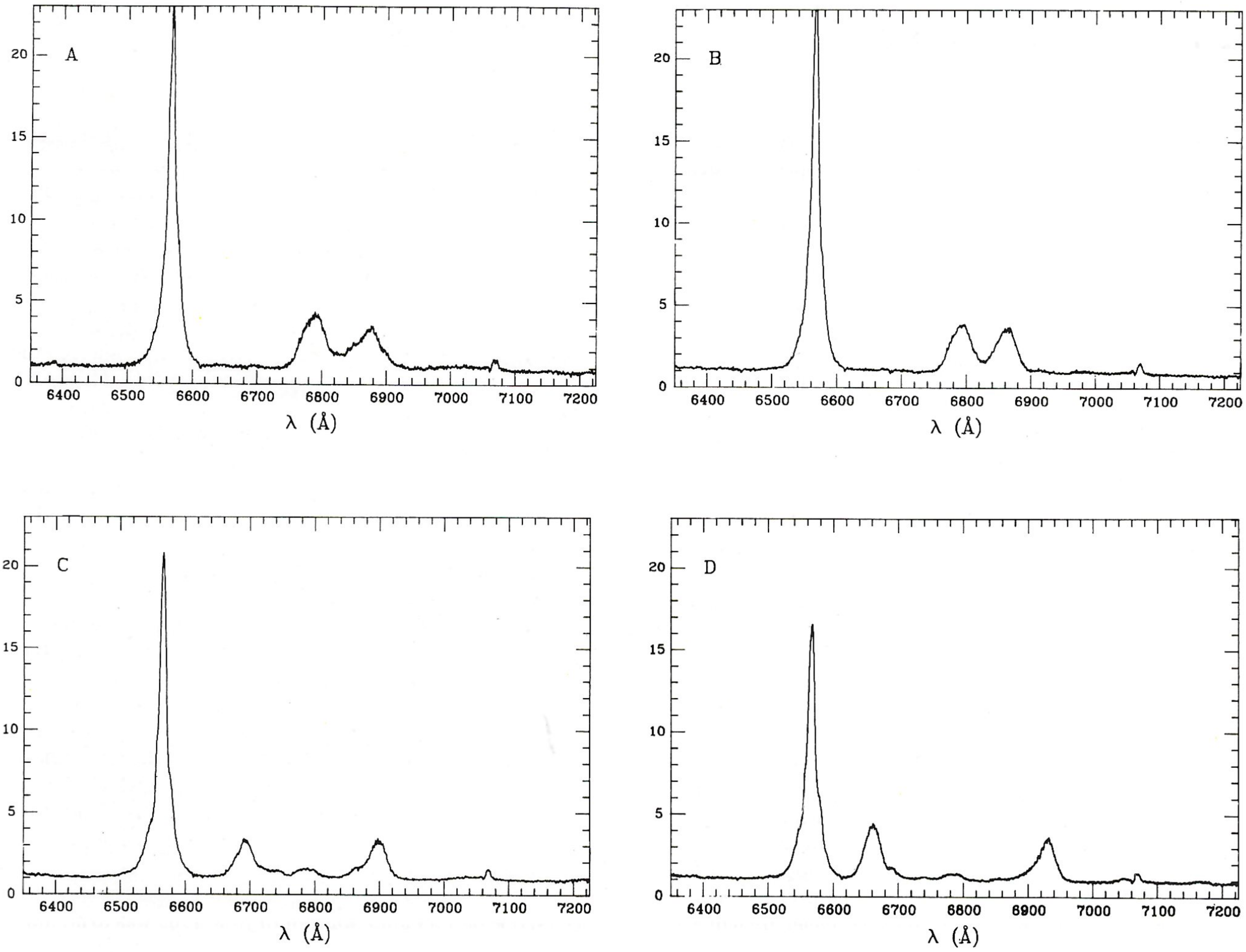


Fig. 1 The sudden appearance, between spectra B and C of this series of four spectra of SS433 made with the INT, of two new spectral lines, while the previously existing pair fade away, represents the firing of two new 'bullets' in the jets of SS433.

Star clusters – snapshots of star evolution

The study of individual members of star clusters depends entirely upon a good segregation of members from field stars: the first of the basic problems why relatively so little work is being done in this field. Selection of cluster members requires the measuring at extremely high accuracies of proper-motions of very many stars, of which only a small proportion belongs to the cluster. In order to detect approximately all 300 Pleiades stars brighter than m(pg) = 14.5, proper motions of some 20 000 stars are to be measured with accuracies better than 0.001 arc sec/annum. Going still 1.5 magnitudes fainter, another 40 000 stars are to be investigated with still higher accuracies, just to find 100 members. Still, these 100 members are equally needed in building up the picture of stellar evolution: they will be less massive and therefore less evolved stars. Proper motions cannot easily be improved by using bigger telescopes, they are mainly in need of longer time-base-lines and thus require mainly a lot of patience and very long time-scale planning. The best proper-motions currently available, which were obtained at the RGO with the GALAXY measuring machine, are based upon a set of photographic exposures covering the Pleiades cluster over a period of more than 80 years. These exposures were all taken with the same instrument, the still-operational photographic refractor of Leiden Observatory. Only because of the fact that for all exposures the same instrument could be used, the accuracy of 0.0002 arc sec/annum was reached, which allowed for a study of the internal dynamics of this cluster. At the distance of the Pleiades (130 pc), 0.0002 arc sec/annum corresponds to a velocity of 120 m/sec, half the cruising speed of a conventional aeroplane. The velocity dispersion in the core of the Pleiades cluster is only 700 m/sec, as was found from these measurements.

The proper-motions of nearby clusters, such as the Pleiades and the Hyades, separate these clusters quite well

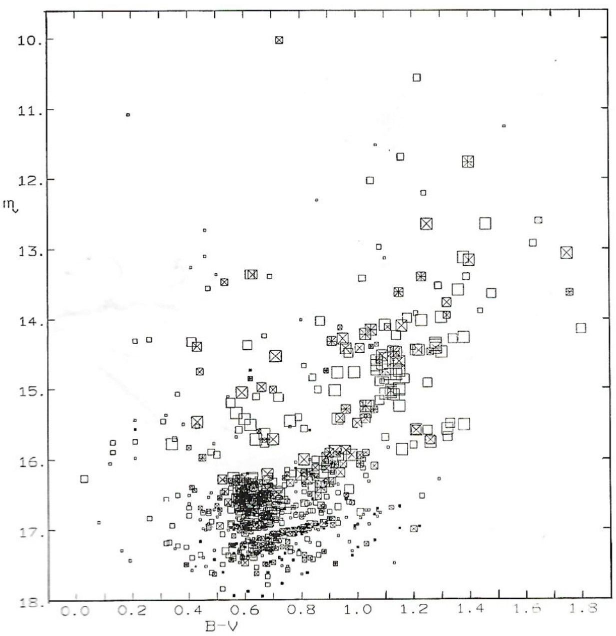


Fig. 1 Colour-magnitude diagram of the Melotte 66 star cluster members (as defined by GALAXY measurements) shows curious gaps, which represent sudden and rapid changes in the structures of stars as, in their evolution, they get to these areas of the diagram.

from the background field-stars. This is due mainly to the reflection of the solar motion; the cluster proper-motion is largely only a parallactic motion. This parallactic motion gets smaller for objects further away from the Sun. The proper-motion separation for most of the clusters beyond the Pleiades is much less obvious, in particular with the usual measuring accuracies of 0.002 arc sec/annum. This is the second reason why these objects are neglected: even if you could measure the proper-motions fairly accurately, you still do not know whether each individual star is a member or not. There is nothing more one can do about this other than trying to improve the proper-motion accuracy to a level well below 0.001 arc sec/annum, which means providing now the first epoch material with which future astronomers might be able to reach it. For the time being we have in many cases to deal with membership probabilities, which do already allow some interesting studies, but from which it is almost impossible to detect a single peculiar cluster member.

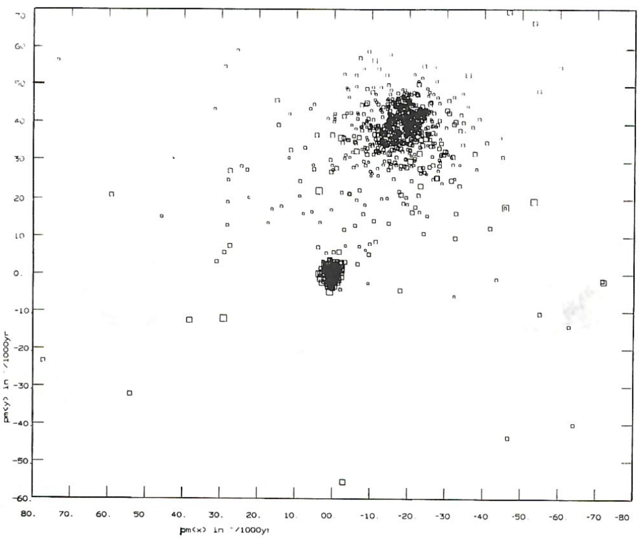
When individual cluster members have been selected, we would like to know whether these stars are singles or doubles, what their photometric characteristics are, and what their spectra look like. If we found only single, non-variable stars then this investigation could be rounded off within a fairly short time-span. Most astronomers did not expect to find much more than possibly a few double stars, which was the third reason not to bother about star clusters. A much closer look at individual cluster members in the Pleiades has revealed, however, that many stars in such a young open cluster are variable. This has since been confirmed by observations of stars in Alpha Persei. Variability adds another dimension to our picture of these stars. In fact, the variability which I discovered together with P. Alphenaar and J. J. M. Meys was the onset of a complete change in the current picture of the early evolution of low-mass stars. It takes, however, a lot of observing time to find out not only that a star is variable, but in addition to determine its period and light curve with sufficient accuracy to use it for some physical interpretations. The only way to improve upon this situation is the development of multi-star photometers such as the instrument built at Leeds University. With this type of instrument it becomes possible to monitor a large group of stars in a cluster simultaneously and with a high photometric accuracy. It then becomes possible to perform statistics on the type of light curves, periods, stability and possible correlations with flare activity for stars like the Pleiades K-dwarfs. In addition it becomes possible to find at the same time occultation binaries and Delta Scuti stars among the A, F and G dwarfs.

Not only at the bottom end of the main-sequence is there still a lot to discover, also the picture of post-main-sequence evolution is still incomplete. This is shown by photometric data on the brighter stars in old rich open clusters such as M67 and MEL66, both of which have been studied at the RGO. The combination of good membership segregation and good photometry shows in these clusters many details in the temperature-luminosity diagram. During its evolution a star describes a track. Some parts of this track are covered in a short time interval, others take considerably longer. Stellar evolution theories predict a few of these accelerations and decelerations, but the observational data seem to show many more. In a group of stars of the same age but with some spread in mass, an acceleration along the evolution-track is shown as a gap, while a deceleration is shown as a concentration of stars. This is similar to a group of cyclists cycling as a small dense group against the wind at low speed, or as a long string with the wind in the back at high speed. Every acceleration and deceleration is an indicator of a major change in the stellar constitution. Such changes are usually caused by transitions in the stellar energy supply between nuclear fusion and gravitational contraction. So far nobody has performed a systematic and detailed photometric and spectroscopic investigation of stars within different concentrations in the brightness temperature diagram of an older open cluster. Still, this could be at least as promising as the pre-main sequence investigations performed in recent years. In addition, there are likely to be between the two groups very many related processes: both contain very rapidly rotating stars with deep convective envelopes, and in both cases the BY Draconis syndrome of non-axial symmetry of the surface flux has been observed as well as rapid loss of angular momentum.

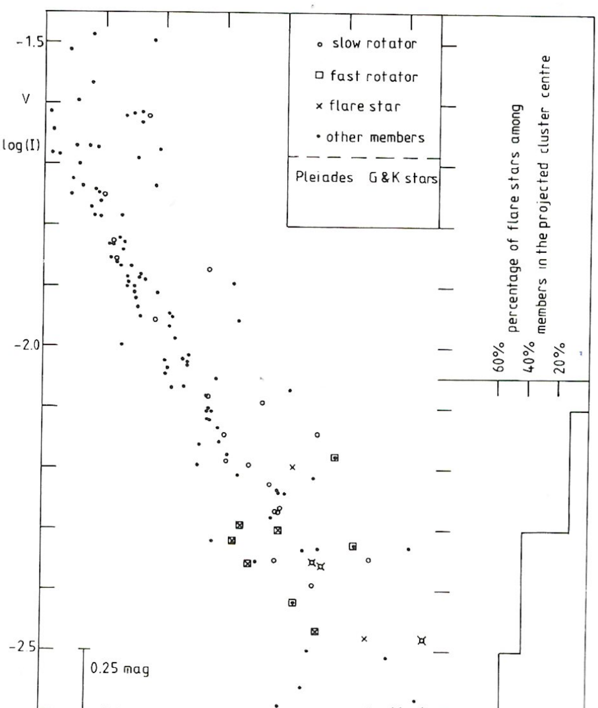
F. van Leeuwen

Planetary formation in the Pleiades

The Pleiades K dwarfs have shown in recent years most spectacularly how much there is still to discover about star evolution. According to the age of the Pleiades, as derived from the evolved B stars, the Pleiades K and M dwarfs should be pre-main sequence stars. They are found, however, very near to, and often even below the main sequence, while theoretical models predict that these stars should be found well above the main sequence. This led to theories in which the low-mass stars in this cluster are up to five times older than the massive stars, which would create severe difficulties in the formation of a star cluster. In 1980 I discovered, together with two students from Leiden Observatory (P. Alphenaar and J. J. M. Meys) that a large number of the Pleiades K dwarfs are variable due to rotational modulation. This has triggered off a vast amount of follow-up observations, which together indicate that the Pleiades K dwarfs are most likely pre-main sequence stars, showing many unexpected phenomena such as very rapid rotation after a spin-up during the last contraction phase (but not for all stars!), non-axially symmetric modulation of the surface flux with an amplitude increasing with increasing angular velocity, flare activity which seems to cover entire stars in single outbreaks, modulation of the stellar wind to a bi-polar outflow which rotates synchronously with the stellar flux modulation, calcium and hydrogen emission from the stellar atmospheres and polarization of the stellar light. The only phenomenon that was not observed is also the only one which was predicted by theory: these stars are not brighter than main-sequence stars of the same temperature. They only show considerably more intrinsic spread in the luminosity-temperature relation, probably due to the influences of the various phenomena on the spectrum. There is an abrupt change in the main sequence in the Pleiades as can be seen in the figure: from the very regular appearance on the top left for the F and G dwarfs to the very disturbed appearance in the bottom-right where the K dwarfs are found. The disturbances coincide with the occurrences of flare activity and rapid rotation, but without a further correlation between these phenomena. An interesting side aspect of the current discoveries is that we are looking at stars very similar to our Sun at the time of establishing themselves as main-sequence stars. The formation of the planets is supposed to take place during this period too, and the strong bipolar stellar wind produced by the stars during this phase of evolution could have had a significant influence on the formation of the planets. The fascinating thing here is, that in open clusters we are able to observe stars in which the planetary systems are currently created, thanks to which it will become possible to put much tighter and realistic constraints on theoretical models describing these events.



The proper motions of 840 stars in the direction of the Pleiades separates two groups. A mass of stars, tightly clumped and therefore with the same motion through space, lies at the origin of this diagram and represents the cluster members to be studied astrophysically. A broader distribution of stars of various motions represents stars lying by chance in the direction of the Pleiades but not connected with it and to be disregarded. These data were obtained by comparing two photographs taken at different times, with measurements made by the RGO's GALAXY machine.



Colour-magnitude diagram of the Pleiades star cluster members shows how fast rotators and flare stars concentrate in the K-dwarf area (bottom right), as these stars form planetary systems.

Probing the South Galactic Cap

In studying the space distribution of stars in our Galaxy, the basic source of uncertainty is our knowledge of stellar distances. If colours, or better still, spectral types, are known, then distances can be estimated from assumed luminosity and apparent magnitude, but this is complicated by intrinsic dispersion of luminosities for a given colour and also by interstellar absorption. Nevertheless, ideas of the distribution of stars at faint apparent magnitudes have hitherto been based entirely on star counts and photometry in selected regions of the sky, combined with models of the stellar populations in the Galaxy such as those of Bahcall and Soneira (Princeton), and Reid (RGO) and Gilmore (ROE).

The most direct method of measuring stellar distances is by trigonometric parallax, but from ground-based observations this can only give reliable results for individual stars within about 20 parsecs of the Sun. The parallaxes which will be obtained from the HIPPARCOS Satellite will extend this limit of reliability to nearer 100 parsecs. Alternatively, if we know the kinematic behaviour of a group of stars, their mean velocity relative to the Sun and their velocity dispersions, then the mean distance of the group can be estimated statistically from measured proper motions.

Both these astrometric methods are very laborious, using classical measuring techniques and photography taken with long-focus telescopes. An individual parallax requires some 20 or more plates extending over two or three years, and, in order to obtain proper motions of reasonable accuracy, observations over a time interval of a decade or more are needed.

The advent of automatic plate-measuring machines, such as GALAXY, raised the possibility of measuring large numbers of Schmidt plates, thus reducing dramatically the labour and time-scale for observing proper motions and parallaxes for many thousands of stars.

The UK Schmidt parallax and proper motion programme

Soon after the UK Schmidt telescope at Siding Spring Observatory was commissioned, a programme of plates on a region near the South Galactic Cap was undertaken. The results reported here were obtained from measurements made with the GALAXY machine at RGO, on two independent series:

(a) 40 unfiltered B plates taken between 1975.0 and 1977.0

(b) 33 filtered V plates, from 1978.6 to 1980.9

Series (a) was taken through the original single-element corrector plate and series (b) through the doublet achromatic corrector. The complete measuring list contained more than 16500 objects. Photometric calibration in B and V was obtained from more than 150 photo-electric standards, for over 6000 stars with $B < 17.5$ $V < 17$ mag, the limits of the present discussion.

Reduction of measurements was carried out using the central overlap technique in which the relative scale, orientation and zero points for each plate, and the five astrometric parameters (coordinates, proper motion components, parallax) for each star are estimated in a single least-squares solution. For convenience the data were divided into eight groups according to B–V colour, each containing less than 1000 stars; series (a) and (b) for each group were reduced independently, transformed to a homgenous coordinate frame, and then combined. For the initial analysis, the stars in each group were binned according to apparent B magnitude, in intervals of one magnitude for $B < 13$ and half magnitudes for $B > 13$ mag. Mean values and dispersions of the proper motion components and parallax were calculated for each bin.

Now if the average volocity of the stars in each bin, relative to the Sun, were the same, then the mean proper motion would be proportional to distance, and in particular, the plot of mean proper-motion components should be a straight line. As an example, Fig. 1 shows this plot for all bins containing more than 50 stars, in the colour range $0.65 < B - V < 1.2$; the linearity is evident and the slope, estimated from a two-error regression, is -0.41 ± 0.05. However the mean velocity of the nearby bright stars relative to the Sun, corresponding to the so-called standard solar motion, has components $U = -10$, $V = -15$ km s^{-1}, where U, V axes are positive in the directions towards the galactic centre and in the direction of galactic rotation respectively. These axes are also shown in Fig. 1, together with the direction of motion of the nearby stars, which is almost identical with that of our bin means; it is therefore safe to assume that their mean velocity is the same as that for the nearby stars. We can therefore use the mean proper motions for these bins to calibrate our measured trigonometric parallaxes.

Having identified bins of stars which are kinematically homogenous, we can analyze the observational data, proper motion, parallax and apparent magnitude, to estimate mean absolute magnitude, dispersion of absolute magnitude, and space distribution as characterized by a central density and exponential scale height, as outlined in the box. The colour/mean – absolute-magnitude diagram for these common stars is shown in Fig. 2; the agreement with the zero age main sequence is excellent. It must be emphasized that these absolute magnitudes have been derived entirely from kinematics, and are quite independent of observed colours.

That not all the stars partake of the same motion is illustrated in Fig. 3, which shows the proper-motion plot for bins containing more than 20 stars, in the photometric range $B > 13.5$, $0.45 < B-V < 0.65$. In this case the average direction of motion is almost parallel to the X-axis (right ascension). There is however a good correlation between proper-motion in the X-direction and the mean trigonometric parallax of each bin, as calibrated by means of the common stars. This strongly indicates that these stars are not distant giants, for which the parallaxes would be very small, but must have luminosities similar to the common stars discussed above. In fact the direction of motion is very close to that of the Hyades cluster, and the speed of that cluster ($\sim$43 km s^{-1}) is not inconsistent with the observed bin mean parallaxes and proper motions. Furthermore, if we do adopt this speed in analyzing the data for these stars we derive absolute magnitudes which also lie close to the main sequence. It is tempting to suggest that, in addition to the common stars sharing the same motion on the nearby stars, there is also a significant population of main-sequence stars within a radius of several hundred parsecs, which shares the motion of the Hyades cluster.

This investigation is still in progress. Apart from the quite unexpected problem of Hyades-like population already mentioned, there are red giants whose kinematics and luminosities have yet to be studied. Nevertheless the results so far illustrate the enormous potential of GALAXY machine, coupled with large Schmidt plates, to probe the stellar content and kinematics of our own Galaxy well beyond the limits which have been reached hitherto from studies of nearby and bright stars.

C. A. Murray

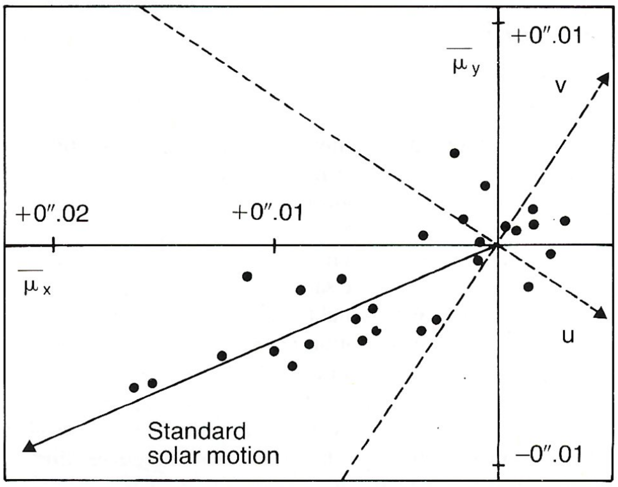


Fig. 1. The proper motion components of groups of similar stars of increasingly fainter magnitude should decrease towards zero because the stars are, statistically, increasingly further away. The relation between the two proper motion components should be a reflection of the motion of the Sun relative to the nearby stars. In this figure, the points represent the mean proper motion of groups of stars with 0.65 <B–V <1.2 binned according to magnitude and the points indeed define a straight line along the standard solar motion.

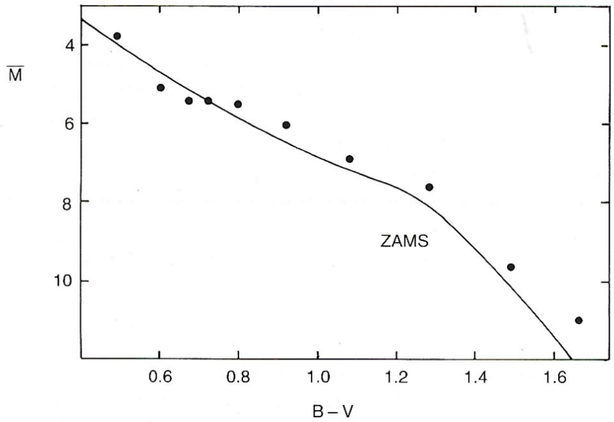


Fig. 2. The data of Fig. 1 can be analyzed to determine the mean absolute magnitude of each colour group. The data should form a sensible colour-magnitude diagram, and in fact agrees with the Zero Age Main Sequence.

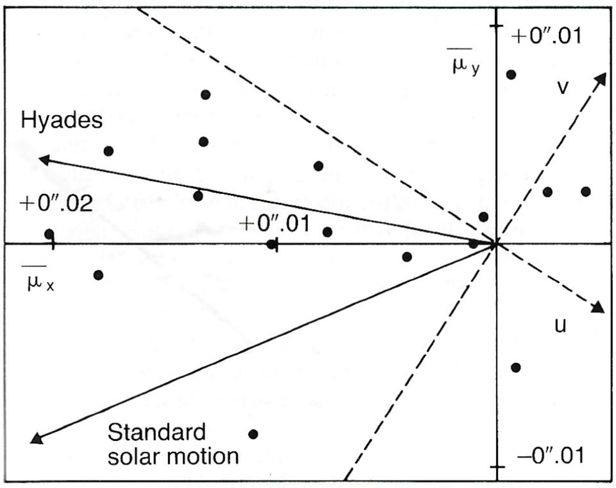


Fig. 3. Not all groups of stars show the behaviour of Fig. 1. If a group of stars is streaming through the solar neighbourhood independently of most of the nearby stars then the proper motion components of the group should show the motion of the Sun relative to the star stream. The group of stars with B >13.5, 0.45 < B–V <0.65 shows the motion of the Hyades star cluster. The Sun seems to be passing through a star stream representing the far-flung members of the Hyades.

Estimation of stellar luminosity and density

This analysis applies to a kinematically homogeneous group of stars which are assumed to have a Gaussian distribution of absolute magnitudes about a mean $\overline{M}$ with dispersion σ_M and an exponential density distribution with scale parallax (inverse length), P_0. For simplicity we assume that the kinematics can be represented by a common mean velocity with speed $\overline{T}$ transverse to the line of sight, and a circular Gaussian spread with dispersion σ_T about the mean.

The kinematic parameters $\overline{T}$, σ_T are adopted a priori and the parameters P_0, $\overline{M}$, σ_M are estimated from the observed parallax π_i, total proper motion μ_i, and apparent magnitude m_i for N stars i = 1 . . . N.

We express the joint probability density of the three observables for star i, within solid angle ω, in the form

$$J_i = \omega n_0 A_i$$

where

$$A_i = \int_0^\infty r^2 \rho(r)\, C(\pi_i|r)\, C(\mu_i|r)\, C(m_i|r)\, dr$$

and $C(X|r)$ denotes the conditional density of variable X at distance r, $\rho(r)$ is the density law and n_0 the central density at r = 0.

The total number of stars in the sample, between apparent magnitudes m_0, m_i, is

$$N = \omega n_0 B$$

where

$$B = \int_0^\infty r^2 \rho(r) \int_{m_0}^{m_i} C(m|r)\, dm\, dr$$

so that the logarithmic likelihood function for all N stars is

$$l = \sum_{i=1}^{N} \ln J_i = \sum_{i=1}^{N} \ln A_i + N(\ln N - \ln B)$$

The integrals and their first and second derivatives with respect to p_0, $\overline{M}$ and σ_m can be evaluated for each star and the values of these parameters which maximise l are obtained by iteration.

Stellar cataclysms

Stars may be considered as self-gravitating spheres of gas where the central energy and pressure are sufficient to promote nuclear reactions. The energy from these reactions makes its way to the surface where it emerges as starlight. For a stable star the pressure gradient at each point is balanced by gravity. If this condition receives a small perturbation it is possible that the star will go into a stable oscillation; many such cases are known, typically the Classical Cepheids. However it is equally possible that the star could suffer from a catastrophic instability. These catastrophes can be of many different types. A simple example is the catastrophe which would ensue if the energy souce were removed from the Sun. It would take several million years before any decrease in surface brightness became apparent. On the other hand if the pressure support were removed the Sun would go into free-fall on a time-scale of hours. The catastrophes suffered by the stars discussed here are mostly more complicated than these but the time-scale on which the perturbation grows is always a valuable diagnostic.

Different types of cataclysmic variable are listed in the box, in approximate order of discovery or reverse order of energy released. In this short article we concentrate on the dwarf novae and AM Herculis stars which have attracted most attention at the RGO in the last few years. The interest has been fueled by the flow of data and discoveries from X-ray satellites and the International Ultraviolet Explorer satellite and by the vigorous research effort into accreting viscous discs undertaken in British universities.

The nature of these stars can best be understood by forgetting the outbursts to begin with. When in quiescence there is good spectroscopic evidence that the great majority, probably all, are double. Either two distinct spectra can be distinguished or a single spectrum shows cyclic variations in radial velocity symptomatic of a spectroscopic binary. If the light curve of a dwarf nova in quiescence is plotted as a function of the period then most of them fall in to one of the categories in Fig. 1. The evidence of these light curves together with the spectroscopic evidence, leads us to the widely accepted model in Fig. 2. A hydrogen-burning star, with a temperature around 4000 K (a red dwarf) revolves about a degenerate white dwarf in a period of a few hours. Although the white dwarf is comparable to the Earth in size it is nearly always more massive than the red dwarf, which is pulled into a tear-drop shape by the gravity of the other star. The apex is the inner Lagrangian point which is a position of unstable equilibrium in the problem of three bodies from whence material flows towards the white dwarf. Because the inner Lagrangian point is not at the centre of gravity this material has angular momentum which puts it into orbit about the white dwarf. It would remain there indefinitely were it not for viscosity. The physics of the viscosity displayed by this material are not generally agreed but it can be demonstrated mathematically under very general assumptions that viscosity transports the material inwards and the angular momentum outwards. The energy liberated by the viscosity is stolen from the binary system and escapes as thermal radiation. The temperature of the disc increases inwards so that the outer parts radiate mostly in optical wavelengths while the inner parts radiate predominately in the ultraviolet.

This model explains the light curves in Fig. 1 very easily. The dominant source of radiation at optical wavelengths is the bright spot where the gas stream strikes the disc. Although usually termed a bright 'spot', in fact it must be extended around the white dwarf in order to explain the phenomena. If one views Fig. 2 face-on no variations are expected. Viewed at moderate angles the bright spot is hidden behind the disc for half the period. When it emerges it is first seen end-on and then gradually turns across the line of sight so that the chief characteristic of Fig. 1(a) is simply a geometrical foreshortening. Moreover the gas stream from the red dwarf is unstable so that material arrives in blobs giving rise to the flickering which varies in sympathy with the bright spot. As one moves towards higher inclination angles the red dwarf begins to eclipse the bright spot giving a curve like Fig. 1(b). At inclinations near 90° both the bright spot and the white dwarf are eclipsed, giving a light curve similar to Fig. 1(c).

Although the behaviour of dwarf novae at minimum light is comparatively well understood, there is still no generally accepted theory of the outburst. There are two schools of thought; one sees the outburst as a mass-transfer instability and the other as an instability in the structure of the disc. Unfortunately both theories give rise to time-scales roughly in accord with the observations so neither can be eliminated for this reason. A valuable diagnostic is to study the onset and decay of outburst at different wavelengths. Because of the strong temperature gradient across the disc, each wavelength can be identified with an approximate radius. To get a sufficient range in wavelength it is necessary to combine IUE observations with ground-based optical ones. The RGO has been heavily involved in several such campaigns in association with many University colleagues.

With a few strategic alterations, Fig. 2 can be used to explain other types of variable star. A few percent of isolated white dwarfs show strong circular polarization indicative of magnetic fields around 10^8 Gauss. Such stars in close doubles like Fig. 2 would prevent the formation of an accretion disc because the gas stream would be channeled by the magnetic field directly to the magnetic poles. Immediately above the magnetic pole a cyclotron column is formed whose light is both circularly and linearly polarized. The exact amounts are a function of the inclination of the column to the line of sight so that the polarization is a powerful diagnostic of the geometry of the system. Cataclysmic variables with strong circular polarization are termed AM Herculis stars; their brightness depends on the mass transfer rate and whether one or both poles is accreting. It is believed that the magnetic field in AM Her stars is sufficiently strong to force the rotation of the white dwarf into synchronism with the binary orbit. However it is now realized that there is a class of intermediate polars combining an outer accretion disc with a magnetic field. Here the white dwarf spins faster than the binary period and the radiation from the cyclotron columns illuminates the disc at the same frequency. This gives rise to the highly coherent variations seen in stars like DQ Herculis, shown in Fig. 1(d).

The cyclotron columns in polars and intermediate polars are rich sources of X-rays, making them prominent objects in the X-ray sky. However there is an an alternative mechanism for producing X-rays without invoking magnetic fields. If the compact object in a close binary is a neutron star rather than a white dwarf, the gravitational potential well will be much deeper. Thus material in the inner regions of the accretion disc becomes much hotter and emits X-rays. The transient X-ray source A0620–00 is believed to be such a case.

D.H.P. Jones

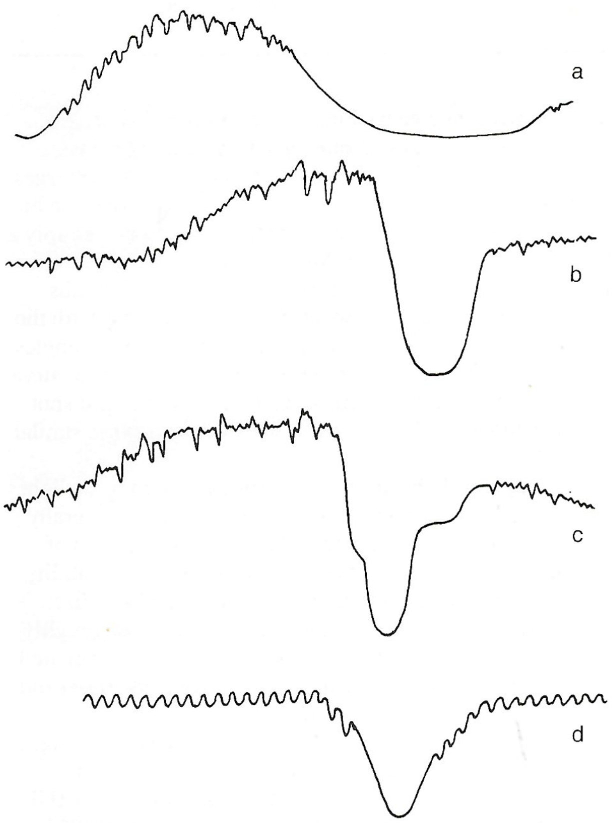


Fig. 1 Orbital light curves of typical dwarf novae in quiescence. (a,b,c) represent the system in Fig. 2 viewed at angles of about 30°, 60° and 90°. (d) represents an eclipsing intermediate polar.

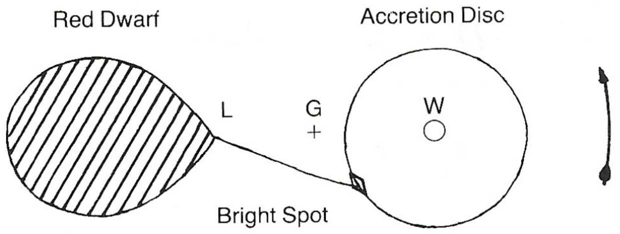


Fig. 2. The model for cataclysmic variables. Gas streams from the inner Lagrangian Point L to the Bright Spot. W is the white dwarf and G is the centre of gravity.

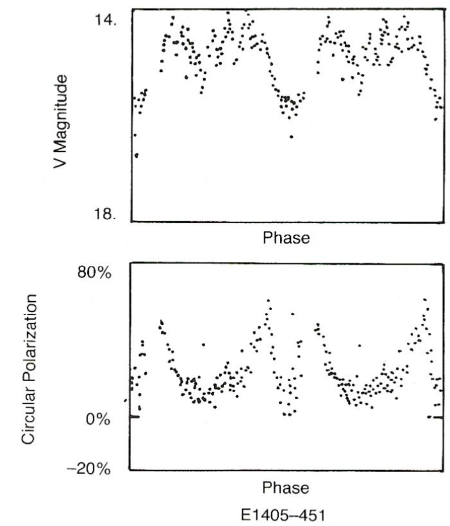


Fig. 3. The AM Her variable E1405–451 observed by Jones and Dick. The upper panel is the light curve and the lower panel is circular polarization. The abcissa is two binary periods and each point is plotted twice.

Types of Cataclysmic Variable

Type	Example	Range (Max/Min)	Remarks
Supernovae	SN1054 (Crab Nebula)	10^8	Remnants are gaseous debris and pulsars; never recur
Classical Novae	Nova Aql 1918	10^4	Probably recur in about 10^5 years
Recurrent Novae	T CorB	10^3	Recur at about 30-year intervals
Dwarf Novae	SS Cyg	10^2	Recur at about 100-day intervals
Nova-likes	TT Ari	10	Sporadic high and low states
X-ray transients	A0620–00	10^4	First discovered in X-rays by Ariel V
Polars	AM Her	10	Known to be a sporadic variable for many years before its discovery as an X-ray source
Intermediate Polars	H2215–035	2	First discovered as an X-ray source

The different classes of cataclysmic variable are not mutually exclusive, e.g. Nova Aquilae 1918 now shows outbursts reminiscent of a dwarf nova. Also A0620–00 was an X-ray and optical nova when discovered in 1975 but an earlier outburst in 1917 was later discovered on old plates, thus relating it to the recurrent novae.

Motions of natural satellites

Recent work at RGO has concentrated on testing and improving the mathematical models, i.e. the 'theories', of the orbital motions of Titan, Hyperion and Iapetus. These 3 satellites are at the outer part of the Saturn system. They only receive small perturbations from the inner satellites, which can be easily modelled, and so it is reasonable to consider these 3 satellites in isolation.

Titan has a large mass relative to that of Saturn, $\sim 2 \times 10^{-4}$, and is the most massive satellite relative to its primary, apart from the Moon and Triton. It causes large perturbations on the other satellites, but is not very much perturbed itself, so the theory of its orbit is fairly simple. Hyperion is in a deep orbital resonance with Titan, as it makes 3 orbits for every 4 of Titan, and the perturbations of Hyperion are very large and difficult to model. The theory of Hyperion used was developed by Woltjer in the 1920s. Iapetus is at a large distance from Saturn, of 59 equatorial radii, which is the relevant scaling factor for considering the perturbing effect of the flattening of Saturn. As a result the solar perturbation on its orbital plane is comparable to that of the flattening, causing a rather complicated motion. (The Moon is at a similar relative distance from the Earth of 60 equatorial radii, but as the Sun is closer to the Moon than it is to Iapetus the solar perturbations dominate, and the Moon's orbit plane is locked to the ecliptic.) The theory of the orbit of Iapetus used is one developed at RGO a few years ago.

The constants of these theories have been improved by comparing with recent photographic astrometric observations (many taken at RGO), spanning about 16 years. The typical accuracy of these observations is about 0″.15. The theories of Titan and Iapetus gave fits to the observations of about this accuracy, suggesting that the theories are at least as good as the observations. The fit of Hyperion's theory was 0″.6, and this is probably an underestimate of the real error, since the least-squares process always gives an artificially good fit to any particular data set. So clearly the theory needs improvements, but how can they be determined? The traditional method is to divide the data into subsets, usually each opposition, and determine corrections to the constants of the theories from each data subset. Observations indicated that one of the long-period terms affecting the longitude of the apse of the orbit needed correction. When this correction was solved for, the fit to the observations was improved to 0″.4.

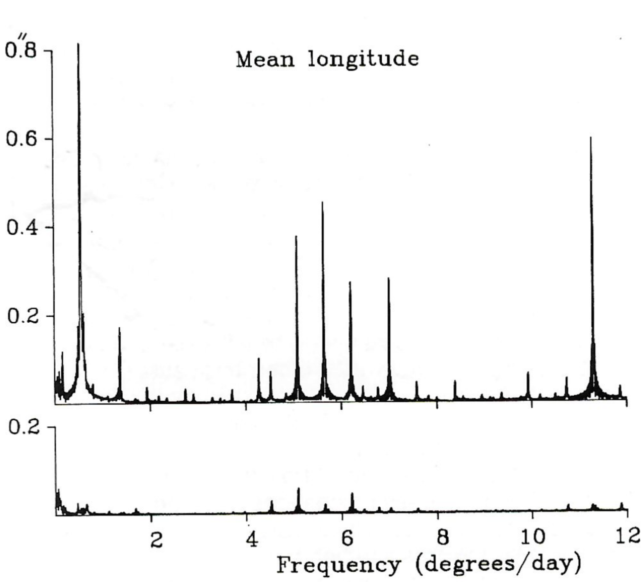


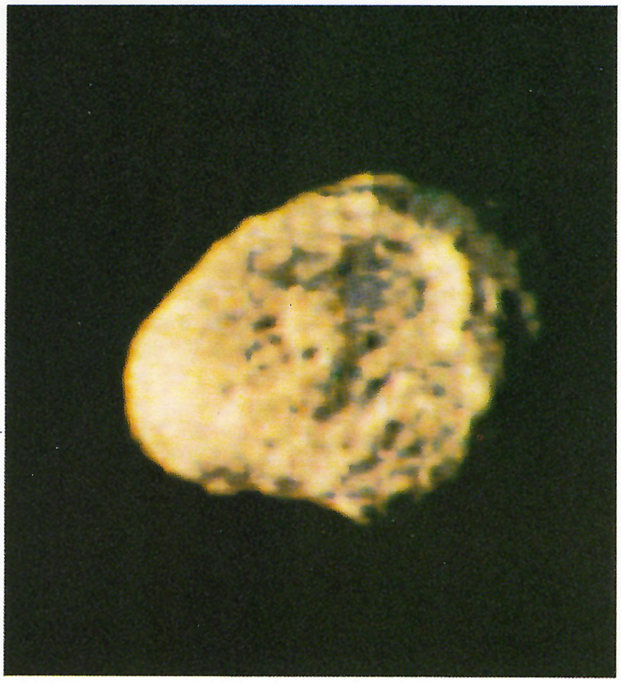
Fig. 1 Spectrum of the residuals of the theory of Hyperion's orbit from a precise numerical integration before and after correction.

An alternative method of computing the orbit of a satellite is to solve the differential equations of its motion by numerical integration instead of analytical techniques. This is now done for the planetary orbits, because the analytical theories were becoming excessively complicated to construct and use, and were still not achieving the accuracy of the observations. It is not usually done for satellite orbits; in most cases it is unnecessary as the accuracy of observation can be achieved with fairly simple analytical theories, and there are also numerical problems in computing an orbit over the number of revolutions needed to span the observations. However a numerical integration over a short time-span is a powerful tool for checking the accuracy of a theory, and this has been done for Titan, Hyperion and Iapetus.

For 3 satellites there are 9 second-order differential equations of motion, which can be easily solved by a standard numerical integration package. The problem is to determine the initial values of the positions and velocities, and the values of the constants in the equations. There are 22 of these parameters; 18 components of the positions and velocities, the flattening coefficient, and the masses of Titan, Iapetus and Saturn (the mass of Hyperion is negligibly small). These have to be determined by fitting the integration to the observations, and to do so we need, at each instant of an observation, the values of the rates of change of the 22 parameters. These are obtained by integrating a set of $22 \times 9 = 198$ differential equations. The computer job is now quite large, and an efficient purpose-built integrator should be used.

This has been done, and the integration was fitted to the same recent observations as the theories. Good determinations of the parameters were obtained; in particular a very accurate value of the mass ratio Titan/Saturn of $(2.3678 \pm 0.0006) \times 10^{-4}$ was obtained (the Voyager I tracking data gave 2.3664 ± 0.0008). The fits to the observations were of accuracy 0″.16 for Titan and Iapetus, but only 0″.29 for Hyperion. This suggests that the earlier problem of fitting Hyperion is not entirely due to the theory, but also partly the observations (the possibility of some unknown satellite causing the perturbations has been examined and eliminated). Hyperion is much fainter than the other satellites, so photographic plates exposed for the brighter satellites will give a larger measurement error for Hyperion.

Comparisons of the integration and the theories give RMS differences of: for Titan 0″.01, so the theory is very good; for Iapetus 0″.13, so the theory is just about adequate; and for Hyperion 1″.04, which is poor. (The differences have all been converted to the angular displacement as seen from the Earth.) The differences of the theory from the integration can be formed at equal intervals of time, and are free from observational error. Hence they are suitable for spectral analysis. The spectrum of the differences for one of the orbital elements, the mean longitude, is shown in the upper graph, where the amplitudes of periodic terms present in the differences are plotted against the frequency of the term. It is important to note that for this plot the short-period terms (frequency > 1°/day) of Woltjer's theory have been omitted, so all of these appear in the plot. The reason is that Woltjer recommends a complicated numerical averaging procedure to calculate the short-period terms, and until now it has not been possible to test the effectiveness of this procedure. In fact several modifications were found to be necessary.



Hyperion from 500 000 km, as seen by Voyager I.

The largest short-period term in the differences has amplitude 0″.6 at frequency 11.3°/day, and the next largest 0″.45 at 5.65°/day. These frequencies can be identified as $2n^1 - 2n$ where $n^1 - n$ are the mean motions of Titan and Hyperion. The largest long-period term has amplitude 0″.8 at frequency 0.56°/day, and this term is by far the largest correction needed to Woltjer's theory. In fact this term represents a phase correction to a term of the same frequency with amplitude 38″ in Woltjer's theory (all amplitudes are expressed as angular displacement seen from Earth), which is an oscillation of the system about an exactly resonant state. The frequency of the oscillation has a complex theoretical dependence on principally the mass of Titan, the eccentricity of Hyperion and the amplitude of the oscillation, but in practice it has to be determined empirically from the observations. So inevitably Woltjer will have made an error in his determination of this frequency, and what we are seeing now is the accumulated effect of the frequency error appearing as a phase error in modern observations. Other long-period terms in the longitude and the other orbital elements can mostly be identified as corrections to periodic terms already in the theory. The coefficients of these terms were determined by Woltjer by a mixture of theoretical and empirical methods, and it is not surprising that some of them should need correcting. In total about 12 corrections larger than 0″.05 were found. When these are applied to the theory, and also the improved method of calculating the short-period terms is used, the differences between the integration and the theory are greatly reduced, to an RMS value of 0″.22. The spectrum of the new differences in longitude is shown in the lower graph, and there are no terms bigger than 0″.06.

The corrected theory has almost reached the accuracy of observations. It is good enough for most practical requirements but many of the corrections made are empirical, and theoretical justification is desirable to give greater confidence in the corrections. The development of a new theory of Hyperion's orbit is in progress at Liverpool University, and preliminary comparisons have confirmed some of the corrections found.

These studies have been part of a general programme for improving our knowledge and understanding of the motions of the natural satellites. Some observations of the positions of the satellites of Saturn have been made using the 26-inch refractor at Herstmonceux and data have been collected from the literature for the period from about 1870 onwards. Unpublished data have also been obtained from other astronomers, especially from D. Pascu of the US Naval Observatory. The extensive database that is now available covers the satellites of Uranus as well as 8 satellites of Saturn. All published observations since the discovery of the first satellites of Uranus in 1787 have been collected and those since 1948, the year of the last discovered satellite of Uranus, have been reduced. Observations of the satellites of Uranus made at Mt Stromlo, Australia, by Dr P. Ianna of the University of Virginia, USA, during the oppositions in 1982, 1983 and 1984 have been reduced here; the data consist of x,y plate-measures of Uranus, the satellites and reference stars and have been reduced using a new catalogue of southern-hemisphere stars.

A. Sinclair
D. Taylor

Evolution of satellite orbits

The orbit of a natural satellite can be represented as a precessing ellipse, plus a number of periodic perturbations caused by other satellites and the Sun. This mathematical model is termed the 'theory' of the satellite's orbit. The various constants in this theory have to be determined by observation.

The theories of most satellites had reached a satisfactory state by the 1930s, and for the next 30 years or so little further work was done. With the advent of the space age further improvements of the theories of the orbits of most satellites have been found to be necessary. The major practical requirement for this was to enable spacecraft to pass close to the satellites. Accurate values of the orbital elements can also give an insight into any evolutionary mechanisms that have affected the system, and hence perhaps into its origin. For example, various damping mechanisms tend to reduce the eccentricity of an orbit to zero, but many satellites have orbital eccentricities significantly different from zero, and these are probably caused by a recent capture into or passage through an orbital resonance with another satellite. There is also considerable interest in the mathematical techniques that are needed to construct theories of the orbits to the accuracy required.

At RGO the orbits of the Moon and of the satellites of Mars and Saturn have been studied, and work on the orbits of the satellites of Uranus has recently been started. In the last few years the main effort has been on the satellites of Saturn, both to improve the accuracy of the orbits, and to analyse possible evolutionary mechanisms. In Saturn's system there are 3 pairs of satellites in orbital resonance, where the period of one orbit is a simple multiple of the other. This causes large perturbations of the orbits, and in particular the resonance of Hyperion with Titan makes the orbit theory of Hyperion probably the most technically complex of any satellite apart from the Moon. It is unlikely that all of these resonances were formed by chance. It has been shown at RGO that if one satellite orbit evolves towards another, perhaps due to tidal action, then when a resonance is encountered they can become trapped. This mechanism probably explains 2 of the 3 resonances.

Inertial frames

An inertial frame is established by analysing the motions of a mechanical system, the coordinate frame of which is non-rotating in Newtonian mechanics. In astronomy there are three ways in which this is pursued at present:

(1) Study of the celestial mechanics of the solar system.

(2) Study of the dynamics of the motions of stars in the Galaxy.

(3) Measurement of positions of extragalactic objects.

The third case is also really a dynamical one, but the apparent translational motions (less than 0″.002 per century) are negligible due to the great distances to the extragalactic nebulae. According to Mach's principle these frames should be identical (see box), and there is currently much interest in linking and intercomparing them. The RGO plays an active role in establishing the non-rotating frames (1) and (2) and in linking these to (3) (see diagram).

The technique of Very Long Baseline Interferometry (VLBI) has established the radio positions of a few hundred extragalactic sources with milliarcsecond (0″.001) accuracy. Intuitively, this should provide the best realisation of a non-rotating coordinate frame. However, it is sparse, only available at radio wavelengths, and very faint optically. On the other hand, the analysis of optical positions and proper motions of the stars in the Galaxy provides a much denser network which can be used in practice; but it has disadvantages. It is only available at optical wavelengths (being remedied by the Very Large Array); it is restricted to relatively bright stars; and it is model-dependent, in the sense that it requires a model of galactic rotation. It also has inherent defects due to systematic errors in proper motions which give rise to spurious rotations of the frame. Clear evidence for a spurious rotation (1″.1 per century) in the right ascension coordinate of the FK4 was found from the analysis of occultations of stars by the Moon.

In the last 5 years the RGO, through the use of meridian circles and photographic astrometry, has contributed to the improvement and extension of the FK4 which defines the galactic reference frame. The FK4 catalogue itself has a density of about 1 star per 5° × 5° and is limited to stars brighter than $m_v = 7$. Meridian circle observations were made at Herstmonceux and in Denmark using the Carlsberg Automatic Meridian Circle (CAMC) in collaboration with Copenhagen University Observatory. Observations of solar system objects were made in order to improve the link with the galactic frame.

The RGO has made a major contribution to the extrapolation of the FK4 frame in the southern hemisphere through the use of photographic astrometry. The widely-used catalogues, AGK3 and SAO, extend the FK4 to $m_v \sim 9.5$ and have a density of about 10 stars per 1° × 1°. The weakness of the positions in the southern hemisphere is evident from a plot of some of the first results obtained from La Palma in 1984 with the CAMC. This bad situation in the southern hemisphere has been improved at RGO by using the GALAXY measuring machine to measure the positions of 275 000 stars (14 stars per 1° × 1°) in the southern hemisphere. The declination zone −40° to −52° has been published.

Linking the relatively bright galactic frame with the faint extragalactic frame has been furthered at RGO by using photographic astrometry to measure the positions of about 200 Seyfert galaxies and 65 quasars. In this astrometric work the link is not made directly between the FK4 and the galaxies, but between the extrapolations, AGK3 and SAO, and the galaxies. A tighter link between FK4 and the galaxies can be established by starting with CAMC positions of reference stars with $m_v \sim 12$ which are obtained directly in the FK4 frame without photographic extrapolation.

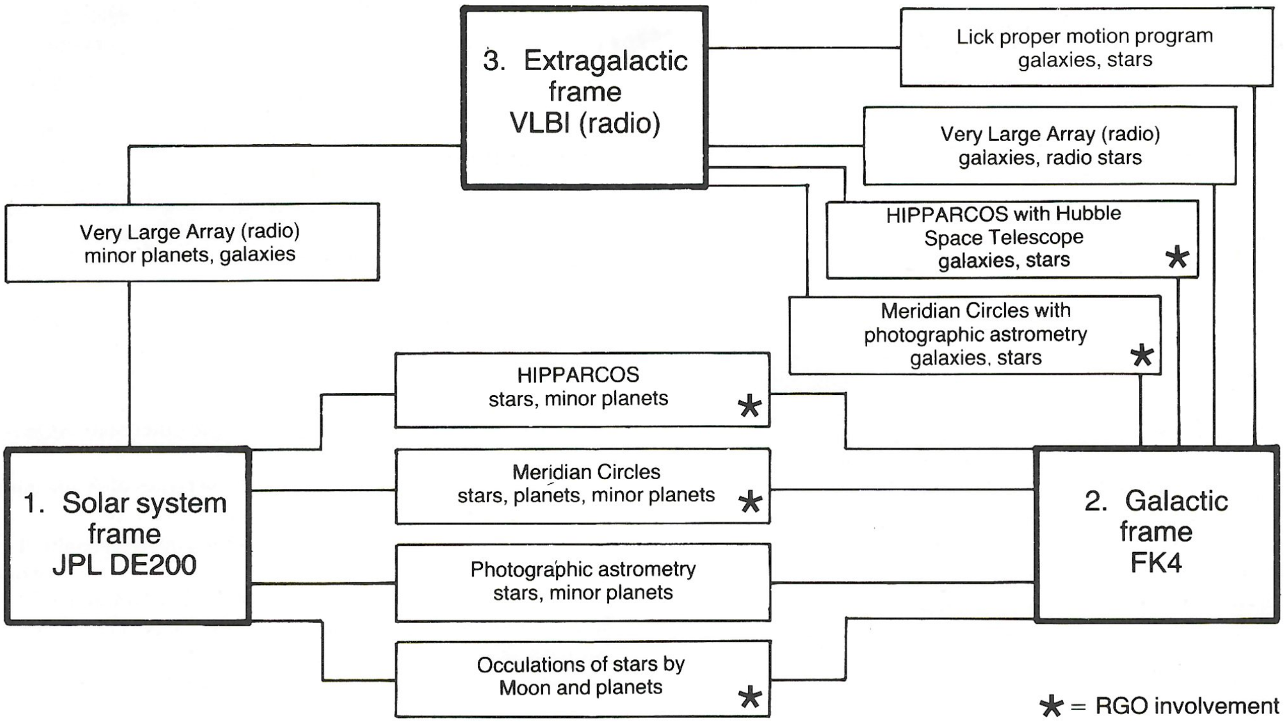
The Very Large Array is now able to establish a direct link at radio wavelengths between the extragalactic frame and radio stars in the Galaxy. So there is now much interest in obtaining accurate optical positions and proper motions for these stars in order to link the FK4 frame to the extragalactic frame. RGO has measured the positions of 69 radio (or suspected radio) stars using photographic astrometry. Again, the basic reference frame was not the FK4, but its photographic extrapolation, AGK3. The CAMC on La Palma is currently observing about 200 suspected radio stars in furtherance of this programme.

The astrometric satellite HIPPARCOS, in conjunction with the Hubble Space Telescope (HST) will provide an excellent link between all three reference frames, as shown in the diagram. The HST will measure to milliarcsecond accuracy the relative positions of extragalactic nebulae and nearby reference stars with $m_v \sim 11$. HIPPARCOS will determine the positions and proper motions of these reference stars to milliarcsecond accuracy relative to the HIPPARCOS reference frame which will be linked to the FK4. RGO participates in HIPPARCOS through the Northern Data Analysis Consortium (NDAC) and the Input Catalogue Consortium (INCA). The CAMC measures positions of stars with poor positions for INCA.

L.V. Morrison

Mach's Principle

The Austrian physicist Ernst Mach provided in 1883 a critique of Newtonian dynamical theory which greatly influenced Einstein in his development of the theory of general relativity. Einstein never provided a precise statement of what he understood Mach's Principle to be, but Mach recognised the essential difference between a kinematic frame of reference in which there only exists motion of one body relative to another, and a Newtonian inertial frame of reference in which Newtonian dynamics is true. For example, in a kinematic frame of reference, the rotation of a planet can be equivalently interpreted as the counter-revolution of the distant stars. In an inertial frame of reference the stars must be stationary and the fact of whether the planet is rotating or not can be judged by physical effects, such as its oblateness. Newton's 'absolute space', which is how he defined the inertial frame, is operationally realised by taking dynamical motion to be measured relative to the so-called fixed stars and asserting that in this frame Newtonian theory is true. In the usual interpretation, Mach's Principle postulates that a consistent theory of dynamics (to which the general theory of relativity approximates) would not allow this arbitrariness, and the frames of reference defined by the fixed stars and by the dynamics of, for example, the solar system or the Galaxy are identical.



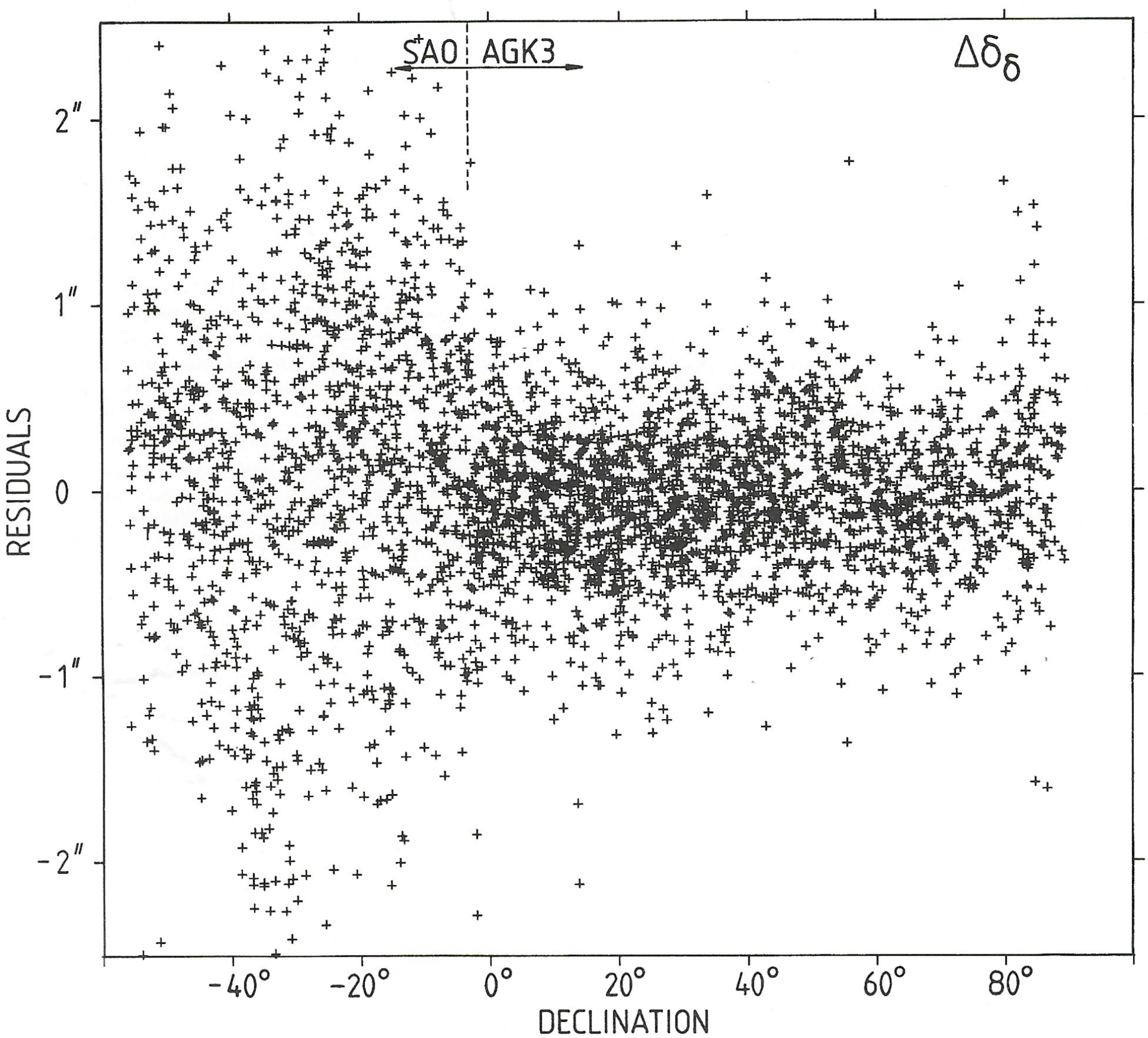


Fig. 1 Differences of star positions in declination between the CAMC and the AGK3 catalogue in the northern hemisphere and the SAO catalogue in the southern hemisphere.

Astrometric and space geodesy

The techniques of astrometry and satellite tracking are used to discover more about the Earth; information is obtained directly about the positions of the observing sites, about the rotation of the Earth with respect to the celestial reference system, and about the gravity field of the Earth. The results are made available for use in studies of the Earth's interior, crustal movements, the oceans, the atmosphere and the Earth–Moon system. The RGO activities in 1980 were based largely on the observations by the photographic zenith–telescope (PZT) and on the provision of an international service for the prediction and reduction of occultations of stars by the Moon. The PZT was used until 1984 to monitor universal time and the variation of the latitude of Herstmonceux, but has now been superseded by the satellite laser ranging system (SLR), which has a much wider range of applications. The responsibility for the lunar occultation service was transferred from HM Nautical Almanac Office to the Astronomical Division of the Hydrographic Department, Japan, as from January 1 1981.

PZT results

The photographic observations of stars passing through the zenith were measured and reduced to provide local estimates of universal time and of the latitude of the instrument with respect to the axis of rotation of the Earth. These basic results were transmitted to the Bureau International de l'Heure in Paris, where they were combined with similar data from other observatories to provide standard data on the variations of universal time (UT) with respect to international atomic time and on polar motion, that is on the motion of the axis of rotation within the Earth with respect to the conventional international origin. The results of the BIH Rapid Service were distributed in RGO Time Service Bulletin Series A. The mean observed values of time and latitude for each night up to the end of 1982 were published in Greenwich Time Reports. The observations since 1980 have been reprocessed using the MERIT standards and the results have been supplied to the International Polar Motion Service in Japan.

The PZT was in operation at Herstmonceux from 1955 to June 1984. Another PZT was installed in Canada at Calgary, at the same latitude as Herstmonceux, in order that UT and both components of the motion of the pole could be obtained from observations of the same catalogue stars. The analysis of data from these two stations could lead to improved positions and motions for these stars and to the determination of tidal and refraction effects at each station.

Lunar occultation results

The main motivation for the international lunar occultation programme was the study of the rotation of the Earth (see page 44) and observations predating the new techniques are still valuable, but current parameters are now better determined by other methods. The occultation data also provide, however, information about other contributions to the residual differences between the predicted and computed times of the occultations. Unfortunately it has not been possible to make a full analysis of all the data that have been collected since the NAO took responsibility for the programme in 1943, but a further four short papers were published by Morrison and Appleby on such topics as: the personal equations of the observers, the corrections to adopted limb profiles for the Moon, and the rotation of the FK4 reference frame. The final catalogue of observations (up to the end of 1980) was published in *RGO Bulletin* No. 192.

SLR analyses

Most of the observations with the satellite laser ranging system have been of the ranges to the geodetic satellites Lageos and Starlette. The data have been sent to the NASA centre for SLR data at the Goddard Space Flight Centre, which has forwarded them to the Centre for Space Research at the University of Texas at Austin for use in Project MERIT for the determination of Earth-rotation parameters, especially length-of-day and polar motion. In exchange the RGO has received data on request for the other stations that contribute to MERIT, and has, in turn, forwarded data for analysis to other UK groups at the Universities of Aston and Nottingham and to the RAE.

The RGO has developed a general purpose program package (SATAN) for the analysis of SLR data. The main components of the package are an orbit generator and a least-squares analysis subroutine. The orbit generator uses a numerical integration technique to compute the ranges to the satellite at the times of observation (or rather at the times of about 20 normal points that are formed to represent the observations of a satellite pass). At the same time it computes the partial derivatives of the range with respect to the parameters that specify the orbit of the satellite and the motion of the station in the dynamical reference frame to which the orbit of the satellite is referred. At present, the orbit generator takes into account about 2000 terms in the expression for the gravity field of the Earth and it includes a modelling of drag and radiation-pressure effects. The effects of solid Earth and ocean tides are taken into account in computing instantaneous coordinates of the station. The effect of time-delay (refraction) in the atmosphere is taken into account in computing the range residuals. The package has been designed so that the individual components of the modelling can be extended, and other parameters can be added and solved for special investigations. Copies of the package have been supplied to the University of Aston and to the Royal Aircraft Establishment for use in their analyses of the SLR data.

The analyses at the RGO have so far been limited to: using Lageos data for determining the coordinates of Herstmonceux and all other SLR stations to form a global reference frame; developing the techniques for determination of Earth rotation parameters; and testing the extent to which the observations at Herstmonceux alone can be used to improve the current estimates of the earth-rotation parameters. So far the analysis of the world-wide SLR data for one month allows the coordinates of the SLR stations to be determined with a precision of 20 cm but it is expected that eventually the coordinates of the SLR stations will be determined with a precision that will allow relative motions to be determined with a precision of 1 cm/year or better. The position of Herstmonceux is particularly important since it provides the fundamental reference point for Great Britain and it is tied accurately to Europe through ground-based surveys and through the use of the Transit (doppler-tracking) systems in several campaigns of simultaneous observations from many sites.

The accuracy of the estimates of earth-rotation parameters depends critically on the number and distribution of the passes used in the analyses; clearly these parameters are much better determined in arrears when data from a widely distributed set of stations are available. Similarly, studies of the motions of the stations, of tidal effects, of the gravity field (and its changes with time) and of the other factors that affect the ranges, which are already determined with a precision of the order of 1 cm, will require the use of worldwide data over extended periods and will require further refinements of the analysis programs.

The SATAN satellite analysis package developed at RGO has been extended at Aston University to allow for the simultaneous solution of station coordinates, geopotential coefficients and tidal parameters, and has been used at Aston for the analysis of Starlette laser ranging data. The station coordinates obtained were in close agreement to those obtained using Lageos data by RGO and other groups, and in particular there was very close agreement in the origins of the coordinate systems. Amplitudes and phases for ten constituents of the ocean tide model were solved, and the values obtained were in fair agreement with values from global tidal models derived from other satellites, thus demonstrating the usefulness of Starlette data for these studies.

Nottingham University have developed, in conjunction with RGO, their own analysis package for SLR data, and they have used this to determine Earth rotation parameters and station coordinates from the Lageos data obtained during the MERIT campaign.

The SLR activities in the UK are coordinated in the UK by the SLR Users Advisory Committee that reports to the Solar System Committee of SERC.

G.A. Wilkins
A.T. Sinclair

Centenary of the International Meridian Conference of 1884

On the 13 October 1884 the delegates to an 'International Conference for the purpose of fixing a Prime Meridian and Universal Day' held in Washington, DC, USA adopted the following resolution:

'That the conference proposes to the Governments here represented the adoption of the meridian through the transit instrument of the Observatory at Greenwich as the initial meridian for longitude.'

The next day the Conference proposed 'the adoption of a universal day for all purposes for which it may be found convenient . . .' and eventually it resolved:

'That this universal day is to be a mean solar day, is to begin for all the world at the moment of the mean midnight of the initial meridian coinciding with the beginning of the civil day and date of that meridian, and is to be counted from zero up to twenty-four hours.'

The choice of the meridian through Greenwich as longitude zero was a consequence of the adoption by Nevil Maskelyne of Greenwich (apparent) time as the argument of the tabulations in *The Nautical Almanac and Astronomical Ephemeris*, which provided data for determining longitude from observations of lunar distances (angular separations of bright stars from the Moon). This led in turn to the use of the Greenwich meridian on many navigational charts, including those for the east coast of North America, and then to the use of Greenwich (mean) time as the reference scale for the system of standard times adopted by the railways of North America. (GMT had been adopted in 1880 as the time-scale for legal purposes in the UK.) At the time of the 1884 Conference it was estimated that 72% of the world's shipping tonnage was using Greenwich, and after much argument the crucial resolution was adopted with only one objection and two abstentions. Some countries have been very slow in putting the recommendations into effect, and 'the hope that studies designed to regulate and extend the application of the decimal system to the division of angular space and of time shall be resumed' has not been realized.

The prime focus of the celebration of the centenary of the Conference was quite naturally at the Old Royal Observatory at Greenwich. 'Meridian Day' was marked (rather prematurely) on June 26 1984 by the issue in the UK of a special set of postage stamps, by a large gathering of school children (and others) in Greenwich Park where the meridian had been marked, and by other smaller celebrations at places on the meridian. An International Symposium was held at the National Maritime Museum at Greenwich on July 9–13; and the participants visited the RGO at Herstmonceux on July 11, and saw both its current work and a display of material from the archives. The Royal Institute of Navigation held a special meeting on November 14 and the Ordnance Survey published a booklet written by S. R. C. Malin and C. Stott on *The Greenwich Meridian.* Past and present members of the RGO staff participated in various ways, some cycled along the meridian and others walked to Greenwich from the meridian marker on the cliffs at Peacehaven.

Project MERIT

Project MERIT is a special programme of international collaboration to Monitor Earth Rotation and Intercompare the Techniques of observation and analysis. It is being organised by a Joint Working Group of the International Astronomical Union and International Union of Geodesy and Geophysics that was set up in 1978 under the chairmanship of G. A. Wilkins (RGO). The first objective of the Group was to foster the development and regular use of new techniques of observation, such as laser ranging and radio interferometry, so that they could contribute high-precision data to a new international service on earth rotation. An accurate knowledge of universal time, polar motion and other aspects of the rotation of the Earth are required for use in current applications (navigation, geodesy, astronomy and space technology) and for scientific research in such diverse fields as the properties of the interior of the Earth, the interaction between the atmosphere, the oceans and the crust of the Earth, the motion of the Moon and the theory of gravitation. The Group organised two observational campaigns: a short campaign from August to October 1980 and a main campaign from September 1 1983 to October 31 1984; these campaigns were preceded by periods for planning and preparation and were followed by periods for analysis and review. A further objective of these campaigns, which involved six different techniques of observation (optical astrometry, doppler tracking of satellites, satellite laser ranging, lunar laser ranging, connected-elements radio interferometry and very-long-baseline radio interferometry), was to provide high-quality data sets for research purposes. These techniques can also be used to determine positions on the Earth's surface and/or inter-station vectors with high precision, and so the MERIT Group cooperated closely with another IAU/IUGG Joint-Working Group on the establishment and maintenance of the conventional terrestrial reference system (COTES). Intensive campaigns of observation were organised bewteen April and June 1984 and May and July 1985 in order to provide additional data that could be used to determine the differences between the reference systems that are implicit in the current reduction procedures used by each technique.

The preliminary results from the main campaign and the first intensive campaign were reviewed at a Workshop held at Columbus, Ohio, USA on July 29–30 1985 and it became quite clear that the principal objectives of the project had been successfully achieved. The new techniques of VLBI and SLR are now regularly producing data of much higher quality than was previously available from optical astrometry and doppler tracking; the data show that the motion of the pole of rotation within the Earth is much smoother than had been previously supposed and that the rate of rotation (and hence the length of day) is subject to short-period variations that are very closely correlated with the variations in the angular momentum of the atmosphere; the data show variations with periods of only a few days and there were abnormal changes at the time of the El Niño phenomenon in the Pacific Ocean. It has also become clear that it is necessary to take into account the relative motions of the stations when analysing SLR data over periods of a year or more.

The MERIT and COTES Groups are recommending that there should be a new international service for both Earth rotation and the terrestrial reference system; the reference frame should, in future, be specified in terms of a catalogue of positions and motions of a set of reference stations used in the monitoring of Earth-rotation. The service should be based on both VLBI and laser ranging and the organisational structure should be similar to that which was used during the MERIT main campaign.

Rotation of the Earth

The length of the day

The Earth varies in its rate of rotation due to the external influence of the Moon and Sun, operating through the tides, and also due to the internal re-distribution of angular momentum between the core, mantle and atmosphere. Astronomical observations analysed at RGO and Durham University have revealed variations in the rotation on timescales of decades to millenia. These results have importance in the study of the long-term evolution of the Earth-Moon system and the geophysical constitution of the Earth.

A convenient unit of measure for the rotation of the Earth is the length of the day. The standard of reference is the day of 86 400 atomic seconds in the Système International d'Unités which was introduced with atomic clocks in 1955. Traditionally, astronomers have measured the actual length of the day by timing the successive passage of stars across the N–S meridian. Until recently, the Photographic Zenith Tube was used at the RGO for this work. Recently, it was superseded by Satellite Laser Ranging. These instruments are part of a world-wide collaboration to measure the Earth's rotation. The results are collated at the Bureau International de l'Heure, Paris.

The change in the observed length of the day compared with the fixed atomic standard is shown in Fig. 1. This shows a clear annual variation of about 1 millisecond (ms). The RGO in collaboration with the Meterorological Office confirmed that the annual variation in the rotation of the Earth and its associated angular momentum are equal and opposite to the changes of angular momentum in the global circulation of the atmosphere. However, the more gradual changes over decades in Fig. 1 cannot be explained by the interaction between the mantle and the atmosphere. We have to look within the Earth itself for the explanation.

Let us trace the decade variations back in time using astronomical observations collected at the RGO. Before the introduction of atomic clocks in 1955, man-made clocks were not as stable as the clock based on the length of the day. So, astronomers had to look elsewhere for a time-standard against which to measure the length of the day. They had recourse to the 'celestial clocks' defined by the regular and predictable motions of the Moon and planets. In particular, at the RGO we have used the Moon's motion relative to the stars as a clock. The Moon was, so to speak, the clock's hands and the stars were the markers around the dial. A particularly accurate way of determining the Moon's position is to time when it moves in front of a star and occults it.

Records of occultations of stars by the Moon since the early part of the 17th century have been collected and analysed at the RGO. These revealed the changes in the length of the day shown in Fig. 2. The fine detail in Fig. 1 has been smoothed out in Fig. 2 because the observations are less accurate and do not give such good resolution: but the figure clearly shows the decade fluctuations going back to AD 1800. The comparatively large fluctuations are explained by the transfer of angular momentum between the dense core and the surrounding mantle from which the astronomical observations were made. Electromagnetic coupling is thought to be the most likely physical mechanism to transfer the angular momentum, but this is still a matter for debate.

The dashed line in Fig. 2 shows that there is an underlying trend for the length of the day to increase by 1.4 ms per century. Over a few centuries, this trend is not very convincing because it is masked by the large decade variations. To derive an accurate value for this and other long-term trends we have to use observations of lunar and solar eclipses made centuries before the invention of the telescope (circa AD 1600). These observations have been collected by Dr F. R. Stephenson at the University of Durham and analysed in collaboration with RGO. The results are plotted in Fig. 3. The eclipse observations were made principally by Arabic astronomers around AD 1000 and Babylonian astronomers between 700 BC and AD 1. The average change in the length of the day from AD 1000 to the present is 1.4 ms per century which is shown in Fig. 2 as a dashed line. Between 700 BC and AD 1000, however, the increase is greater, some 2.4 ms per century. There are no data available to tell us how quickly the change around AD 1000 took place, but it was probably gradual rather than sudden.

The tides raised by the Moon and Sun should lead to an increase in the length of the day of 2.4 ms per century. This was indeed the case between 700 BC and AD 1000. But in the past thousand years or so, the Earth has departed from the expected value. The torque caused by the tides could not have changed appreciably over the past 2000 years, so there must be some other mechanism contributing to long-term changes in the length of the day. The changes could be caused by a long-term component of the electromagnetic coupling, between the core and the mantle; or they may be a result of an alteration in the Earth's moment of intertia, produced by a change in the distribution of the Earth's mass. For example, a global change in sea-level of 1 metre would alter the length of the day by 15 ms.

L. Morrison

Angular momentum budget

The Moon and, to a lesser extent, the Sun exert an external torque through the tides which transfers angular momentum from the Earth to the Moon. As a consequence, the day gets longer by 2.4 milliseconds per century and the Moon's orbit expands by about 4 metres per century. This may seem small, but in the long-term it is the dominant effect in the evolution of the Earth-Moon system.

After allowing for this net loss of angular momentum from the Earth, it is found from observation that the remaining balance within the Earth behaves in a complicated way. The Earth is not a homogeneous body, but consists of a core, mantle and atmosphere; and the angular momentum, though conserved within this system, is not constant in any one of the three constituent parts. Angular momentum is transferred between the three regions by physical mechanisms.

The atmosphere exchanges angular momentum with the mantle mainly through the force of the winds on mountain ranges, whilst the core and mantle may exchange angular momentum through electromagnetic coupling at the core-mantle boundary. Observations of the Earth's rotation (made from the mantle), set important constraints on the geophysical models which attempt to explain the global behaviour of the Earth.

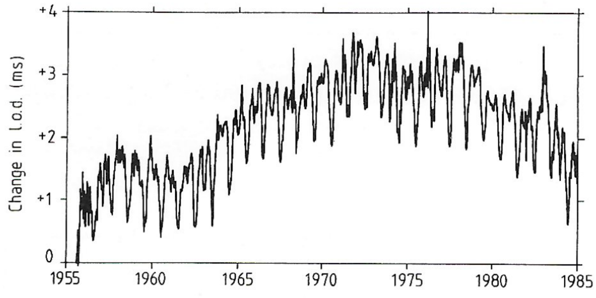


Fig. 1 Since 1955, atomic clocks have revealed that the Earth's rotation changes with the seasons, and from year to year.

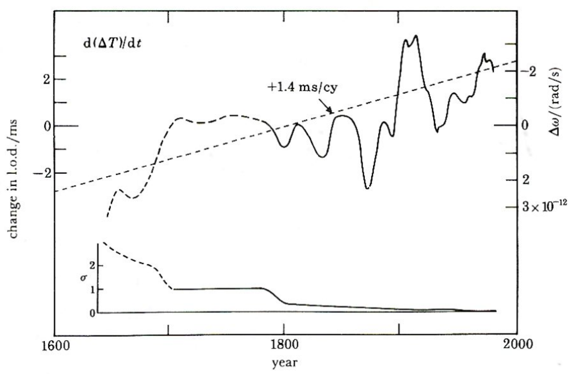


Fig. 2 Before atomic clocks, the Moon's motion showed the changing length of the day. Early results (dashed) were fairly imprecise.

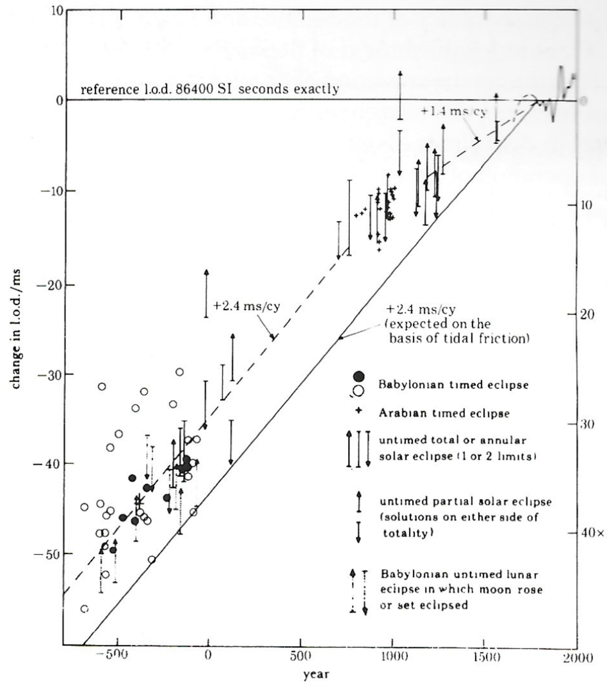


Fig. 3 The times of eclipses seen by the Babylonians, Chinese and the Arabs reveal the length of the day in the more distant past.

Eclipses and the length of the day

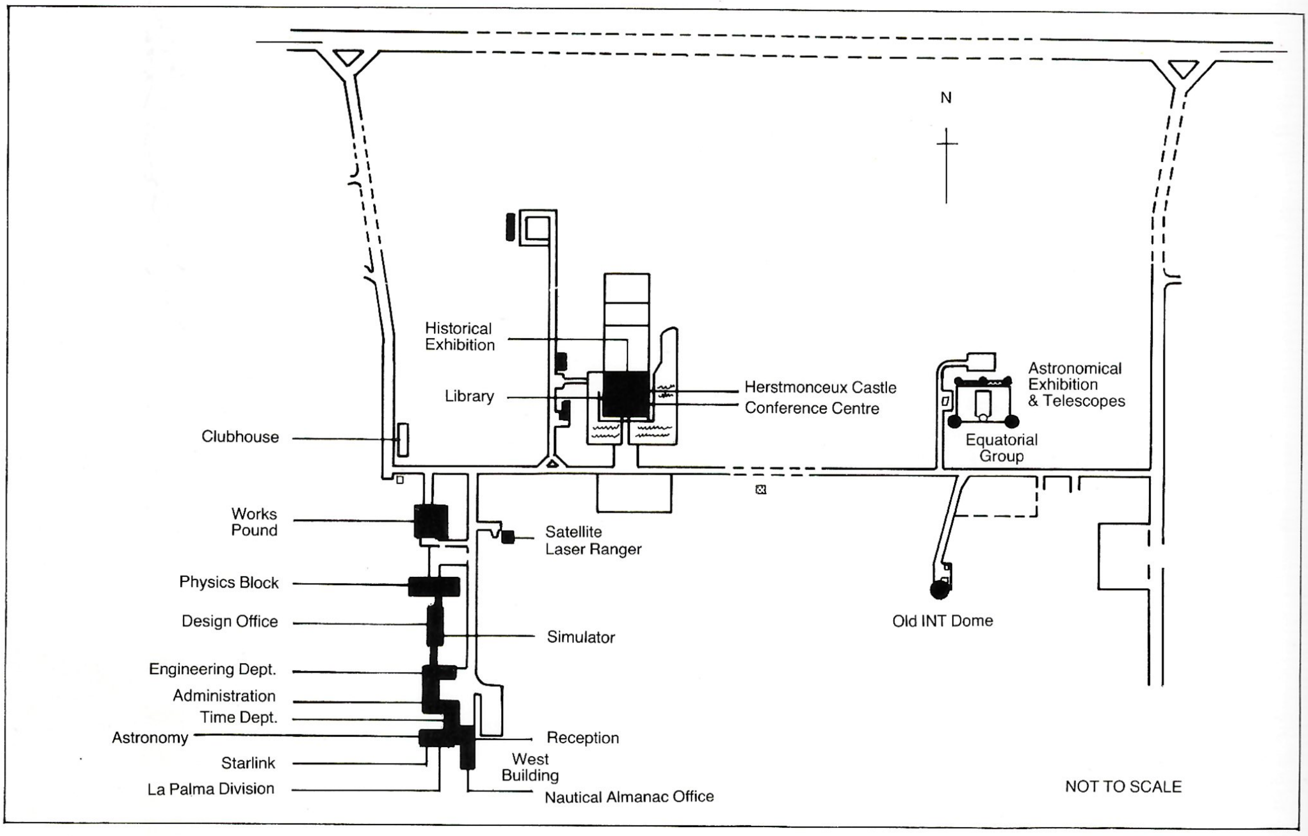
How we can derive small changes in the length of the day from ancient, relatively crude observations of eclipses? The long time-span gives us surprising accuracy. Suppose the length of the day increases steadily by 2 milliseconds per century between 500 BC and the present – an interval of 25 centuries. The actual day would be 50 milliseconds longer now than it was in 500 BC, and the average change would be 25 milliseconds over the period. Multiply this average change by the number of days in 25 centuries (about 900,000), and you find that the accumulated difference between an atomic clock and a clock running at the Earth's average rate amounts to 6.3 hours.

So we can expect large discrepancies when we analyse ancient observations of eclipses, such as the Babylonian timings of the interval between sunset and the beginning or end of a lunar eclipse. These observations were timed to the nearest 4 minutes and recorded in cuneiform script on clay tablets which are preserved in the British Museum. From a knowledge of the apparent motions of the Sun and Moon, we can calculate what these intervals should have been and, unless we make allowance for the changing length of the day, we do indeed find discrepancies between our results and the observations of around 5 hours.

Fragments of Babylonian clay tablets recording a vivid report of a total solar eclipse in 136 BC and lunar eclipses in 240, 154 and 143 BC.

The primary policy of the Science and Engineering Research Council is to aid research in the universities, and the RGO, as an establishment of the SERC, has played a major part in this policy over the last five years by procuring and beginning the operation of its telescopes on La Palma in the Canary Islands for a wide community of university astronomers. The telescopes have been and are supported by a coherent programme of professional engineering effort in disciplines of optical design, electronics, mechanical design, and computing, all targeted to the production and operation of first-class national and international facilities.

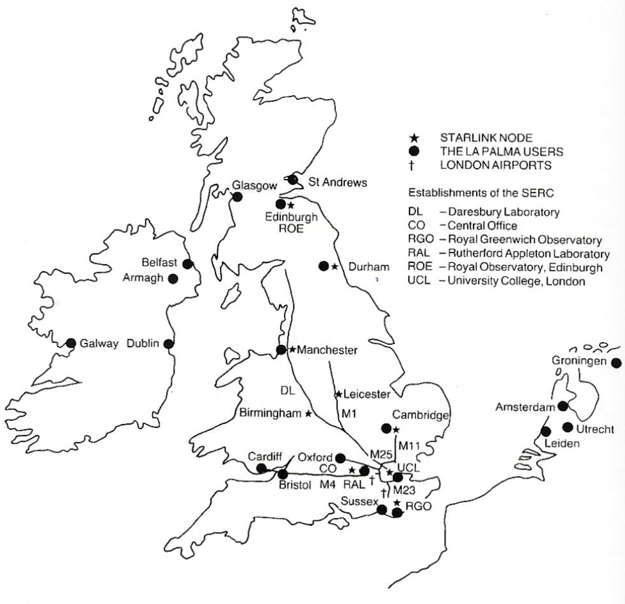
Telescopes, instruments and facilities



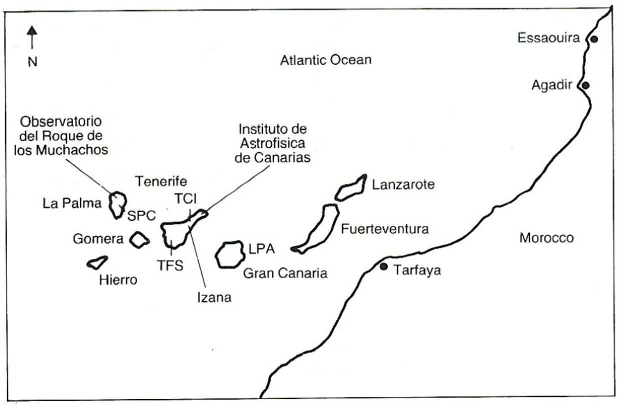
Herstmonceux Castle: plan of site.

Location of the RGO

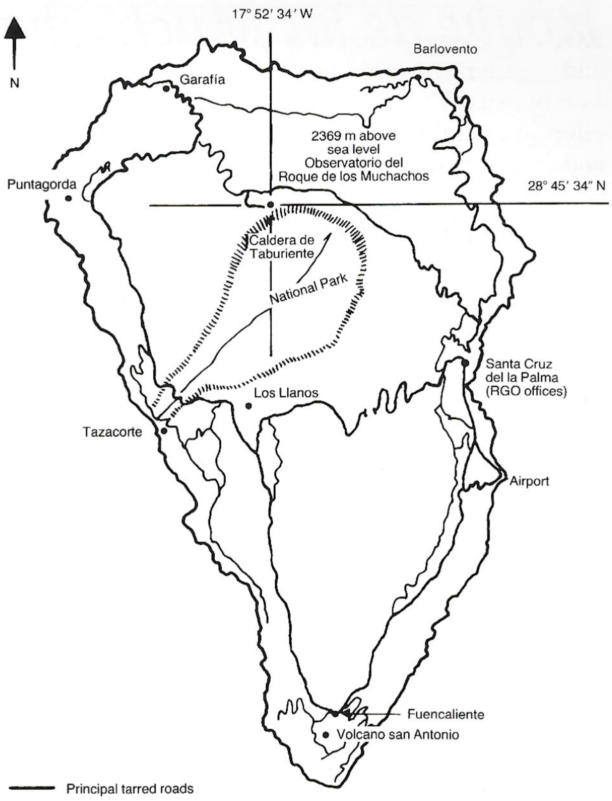
The RGO is located at Herstmonceux Castle in Sussex and on La Palma in the Canary Islands. Its user community consists of university departments and establishments in Britain, the Netherlands, Ireland, Denmark and Spain. The map of Northern Europe shows the location of the non-Spanish institutes which have used the La Palma telescopes, and the nodes of the Starlink computer network. La Palma data and reduction programmes are available through this network. In 1985 Herstmonceux became linked to its community by motorways connecting to London's outer ring-road motorway, the M25, giving access to the two London airports of Gatwick and Heathrow in one and two hours respectively. Flights to the Canary Islands from these airports take place several times per day, and of course there are numerous flights to European centres from both airports. Two ports on the south-east coast of England handle freight to the Canaries. The Canary Islands lie off the north-west African coast and international flights are frequent to southern Tenerife (TFS) and Las Palmas (LPA). Several inter-island flights per day connect these airports, and the northern Tenerife airport (TCI), to Santa Cruz de La Palma (SPC). The RGO maintains an office in this city. Access to the Observatory and telescopes on La Palma is via 44 km of tarred road to the Roque de los Muchachos at 2400 m. At Herstmonceux there are offices, laboratories and workshops, principally in the West Building, as well as the Castle, grounds and public exhibitions.



RGO related to the communications network.

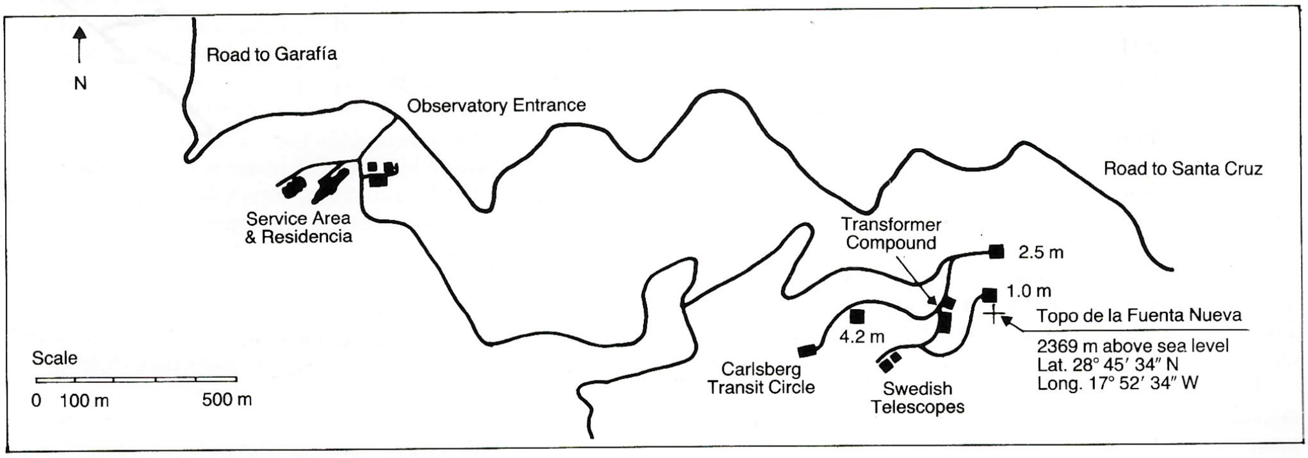


Location of La Palma and the Instituto de Astrofisica de Canarias.



La Palma: main localities and connecting roads.

Aerial view of the telescopes on the Roque de los Muchachos shows the edge of the caldera and the southern end of the island.



Observatorio del Roque de los Muchachos: plan of site.

Roque de los Muchachos

The Canary Islands were discovered, astronomically, by C. Piazzi Smyth in 1856. Newton had written: '[Telescopes] cannot be so formed as to take away that confusion of rays which arises from the tremors of the atmosphere. The only remedy is a most serene and quiet air, such as may perhaps be found on the tops of the highest mountains above the grosser clouds.' Following this principle Smyth tested El Teide, the main peak of Tenerife, for its suitability to sustain astronomical observations. In 1975 El Teide and La Palma, the island to the north west of Tenerife, were tested during the campaign to determine the site of the Northern Hemisphere Observatory, and as a result the RGO has, on the main peak of La Palma, the Roque de los Muchachos, erected and brought into operation three telescopes, with a fourth, the largest, in the final stages of construction. The telescopes are:

The 2.5 m Isaac Newton Telescope
The 1.0 m Jacobus Kapteyn Telescope
The Carlsberg Automatic Meridian Circle
The 4.2 m William Herschel Telescope

The first three having been in operation for a year, there is now a chance to check the observing conditions on the mountain top. The results from the first year confirm the excellent status of the site – undoubtedly one of the best in the world for astronomy.

Proportion of clear sky

The minimum requirement for an observatory by an astronomer is to be able to see stars. Between 29 May 1984 and 28 February 1985 the Isaac Newton Telescope was scheduled on 178 nights for spectroscopic observations which can use clear and partially clear nights. It made observations for 74% of the time available; 6% of time that was otherwise clear was lost by equipment breakdowns in this, the first year of operation, and would otherwise have been available for use.

Clarity of the sky

How clear is the sky when stars can be seen? There are two possible reasons for the sky at an observatory to be of less than perfect transmission. Air molecules scatter light as it passes the atmosphere, and the column density of air above the 2400 m height of the Roque de los Muchachos sets a theoretical minimum to the extinction above the site at different wavelengths. Larger particles than molecules will also absorb light as it passes through the atmosphere. These include ice crystals (cirrus cloud), water droplets (cloud generally, or water spray from the ocean) and dust. It is important to choose as observing sites places where these additional effects are at a minimum. The easternmost points of the Canary Islands are particularly prone to dust from the Sahara Desert during the southern Sirocco wind, but the eastern islands, like La Palma, are much more free from dust. A sample of dust collected from the Roque de los Muchachos was analysed by D. Jackson in the RGO laboratories. It was characterised by orange, yellow and transparent quartz-like particles of remarkably uniform particle size, in the range 20 microns to 60 microns.

Night-time extinction has been measured during 1984 by the Carlsberg Automatic Meridian Circle (CAMC) now in operation on La Palma. Between May 11 and December 17 1984 the CAMC was in operation on 194 nights for long enough so that a programme of measurements could be completed. The extinction measurements were distributed as shown in the following table. Half the nights were photometric, 81% usable.

CAMC extinction measurements 1984

Extinction	No. of nights	Proportion (%)
$V < 0.12$	4	2
$0.12 \leq V < 0.17$	59	30
$0.17 \leq V < 0.22$	38	20
$0.22 \leq V < 0.27$	17	9
$0.27 \leq V < 0.32$	7	4
$0.32 \leq V < 0.37$	6	3
$0.37 \leq V < 0.42$	5	3
$0.42 \leq V$	22	11
Clouded out	36	19

Atmospheric extinction on La Palma was measured in June 1984 with the People's Photometer on the Kapteyn Telescope by D. Jones of the RGO and published as a La Palma Technical Report. Half the time was completely clear but the period covered two major incursions by Sahara dust. The nights formed two distinct groups in extinction (see the following table). Also shown are the expected values for an aerosol-free atmosphere from 2400 m. The match between the aerosol-free atmosphere and the good nights is excellent, proving the clarity of the atmosphere above the island. It is striking that the extinction coefficients in colour are the same on both the clear and dusty nights. If the wavelength dependence of the additional extinction due to dust is $\lambda^{-\alpha}$, then $|\alpha| < 0.02$. In other observatories $0.49 < \alpha < 1.52$. The implication is that, as determined from the laboratory measurements, Sahara dust is of size much larger than the wavelength of light and that, though the dust extinction makes absolute photometry less accurate, measurement of colours and relative spectrophotometry are unaffected.

Median extinction coefficients on La Palma

	V	B–V	U–B	range in V
7 good nights	0.15	0.11	0.38	0.08 to 0.17
5 poor nights	0.40	0.11	0.38	0.33 to 0.70
Aerosol-free atmosphere from 2400 m		0.11	0.13	0.37

Seeing

The most critical parameter for astronomers while observing is 'seeing' the size of the stellar image. The size of a stellar image in a telescope is a matter of fundamental physical limitations, construction technique and the optical clarity of the atmosphere. Seeing can be measured with the Isaac Newton Telescope during the procedure by which the astronomer sets on his star. The image of the star is detected by an intensified TV camera system built by the RGO. The digitised image is analysed by a microprocessor responding to a pushbutton command panel and joystick controller, and its Full Width Half Maximum is determined. The median seeing for the measurements recorded during the summer of 1984 was 1.1 arc sec FWHM and for the winter months of 1984/5 was 1.4 arc sec, confirming or exceeding the site testing results of 1975 (median value 1.3 arc sec).

A point on which data had never been collected before 1984 was whether there are any asymmetries in seeing due to the influence of a steep vertical cliff face to the south of the

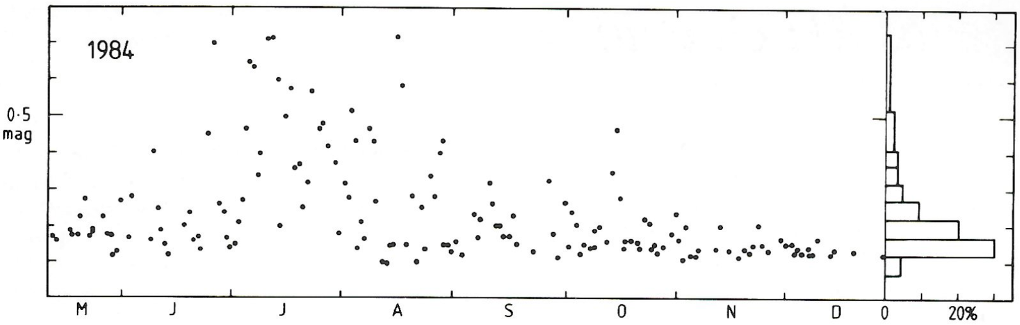


Fig. 1 Mean zenith extinction measured by the CAMC nightly throughout 1984. In the right-hand panel the data are binned into a frequency histogram.

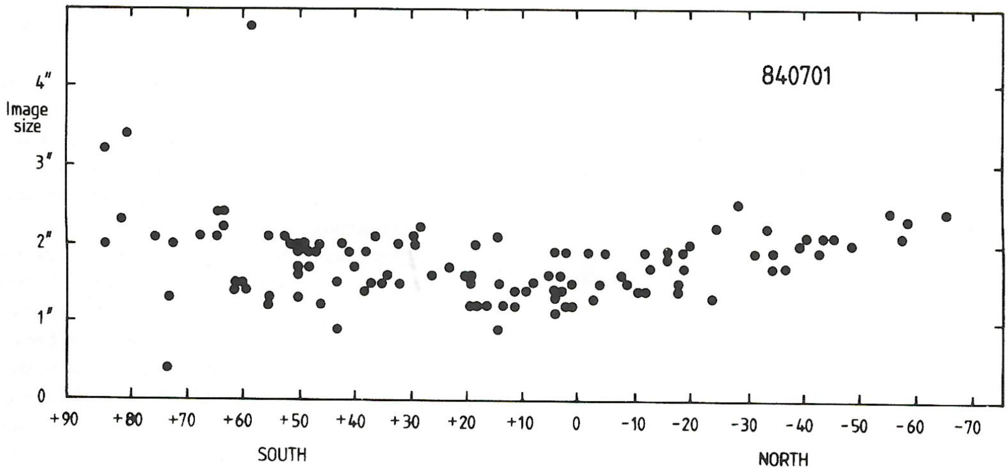


Fig. 2 Image size in the CAMC on a typical night in 1984 showing no effect of the Caldera on seeing for zenith distances of 50° or less.

Roque de los Muchachos. The drop of 1.5 km is the edge of a very prominent volcanic caldera which is the dominant geological feature of the island of La Palma. The CAMC on La Palma measures the width of star images as the telescope moves along the meridian and so it samples the sky in a north-south plane. The data typically extended from $z \sim 50°$ in the north to $z \sim 80°$ in the south. Studying a sample from June and July 1984, Murdin and Thoburn of the RGO, writing in a La Palma Technical Report, could find no north-south asymmetry in seeing for stars with $z < 50°$.

Infra-red conditions

Measurements of infra-red and millimetre radiation from stars is affected by water vapour content of the air. It is important to determine the behaviour of the infra-red transmission of the La Palma sky not only to find out whether to site specially constructed infra-red or millimetre wave telescopes there, but also whether to equip the optical telescopes with infra-red equipment.

From November 12 to 30 1980 millimetre-wave night time and daytime observation of the water vapour content above the Roque de los Muchachos were made by a team from Queen Mary College and the Rutherford Appleton Laboratory. A 230 Hz heterodyne receiver took the beam from the sky at any chosen elevation angle in two othogonal vertical planes (NS or EW). During the same period a calibrated infra-red water vapour monitor was used to determine water-vapour levels around midday by measurement of line-of-sight transmission from the Sun. The measurements showed horizontal stratification of the atmosphere (within 1°), even though the scale height of water vapour (1–2 km) is expected to be comparable to the height of the mountain, with little sign of azimuthal asymmetry. The infra-red measurements implied water vapour content as low as 0.9 mm precipitable water. Half of the measurements were below 5 mm. The study concluded that the atmosphere over La Palma was well-behaved and it was a good millimetre-wave and infra-red site.

Sky brightness

To detect faint stars, astronomers look for observing sites with a dark sky. Night-sky background on La Palma has been measured by D.H.P. Jones, with the Kapteyn Telescope in June 1984. All-sky average values measured while executing a photometry programme, from periods without Moon or twilight were U = 21.4, B = 22.3, V = 21.4, R = 20.4 and I = 19.3 mag. per square arc second.

The best observatories are located to avoid or minimise deterioration of the sky by pollution, particularly that due to light, radio and industrial activity. The absence of a coastal plateau around the steep-sided shores of La Palma means that urban development, with the pollution that it brings, will be naturally limited. From the Roque de los Muchachos, urban lights cannot be detected at significant levels above 20° elevation. Mercury emission at 4360 Å is detected fairly weakly in zenith spectra obtained with the Isaac Newton Telescope, except on the numerous occasions when clouds cover the Island below the observatory. A law to protect the observatory from light and industrial pollution was passed by the Canary Island government in 1985 and sent for ratification to the national authorities.

P.G. Murdin

The Isaac Newton Telescope

The Isaac Newton Group of optical telescopes, named after Britain's greatest scientist (see box), consists of the 4.2 m William Herschel Telescope (WHT), the 2.5 m Isaac Newton Telescope (INT) and the 1.0 m Jacobus Kapteyn Telescope (JKT) in the Observatorio del Roque de los Muchachos on La Palma.

The born-again INT, at La Palma, differs significantly in its mechanics, electronics and optics from the earlier incarnation at Herstmonceux. The change in latitude to 28° 45′ has resulted in a large change of angle to the polar disc which stands almost on edge. A segment was removed from the disc in order to allow operation to a declination of −30°. New encoders and drive electronics were fitted and a new computer control system was written. The primary mirror was replaced with a slightly larger one of considerably higher optical quality made of low-expansion material. The old prime-focus assembly, which required a caged observer, was replaced with one operated entirely by remote control; similarly, the Acquisition and Guidance Box at the Cassegrain focus is completely new. The telescope is housed in a new dome, the old one being left as a landmark for channel shipping. Finally, there is a suite of new instruments and a computer system to control them.

The telescope has a polar disc/fork type equatorial mounting supported by five axial and three radial hydrostatic oil bearing pads. The tube, a conventional open Serrurièr truss structure, supports the prime-focus assembly or secondary mirrors for Cassegrain and Coudé operation. Drive limits are currently set at −30° Declination, 70° zenith distance and $\pm 6^h$ Hour Angle (operation below the pole is also possible).

DC servo motors with integral tachogenerators are used for the slow-motion drives on both arms. The RA axis is driven by a worm/worm-wheel assembly and the Declination axis by a recirculating ball screw and nut. Preload and quick motion drive are provided by a pair of motors driving through spur gearing. Problems were encountered during commissioning as a result of compliance in both slow-motion drive assemblies. Oscillations were observed in RA (a continuous wobble at about 1.3 Hz with an amplitude of a few arc sec) and in Declination (a 5 Hz vibration of similar amplitude excited from time to time by the dome rotation). The RA oscillation was removed by stiffening the drive assembly; that in Declination is still present at the time of writing (June 1985), but should be amenable to amelioration in a similar manner.

The telescope's position is determined by Moiré fringe grating encoders mounted on each axis. There are three reading heads per axis. One bit corresponds to 0.3 arc sec in RA and 1 arc sec in Declination, although systematic errors are considerably larger. These errors have been partially calibrated, but still limit the absolute pointing of the telescope. When the telescope is being driven by the slow-motion motors, optical incremental encoders are used, with resolutions of 0.01875 and 0.01 arc sec in RA and Declination, respectively, mounted on the drive shafts.

The computers which control the INT and the 1 m Jacobus Kapteyn Telescope are Perkin-Elmer 8/16Es. The code, which is written in FORTRAN IV with a minimum of assembler, is virtually identical for the two telescopes. The pointing model for the INT has 17 terms, comprising the standard errors of an equatorially mounted telescope (offsets in Hour Angle and Declination, collimation error, misalignment of the polar axis and non-perpendicularity of axes), together with an empirical (Fourièr series and polynomial) model of flexure in the telescope structure and large-scale errors in the encoder readings. The r.m.s. errors in the absolute pointing of the INT are always less than 5 arc sec; values between 2.8 and 4.5 arc sec were obtained during tests at Prime and Cassegrain foci during 1985. Short-term tracking errors are < 0.25 arc sec; longer-term drifts are removed by the autoguiders.

The astronomer or night assistant interacts with the control system either via a terminal or by pushing buttons on the Control Console (these initiate actions such as a telescope slew). The User Interface task allows positions to be set up for a catalogue of up to 200 sources, which is held in memory. The coordinates may be entered at a keyboard or read in from disc: catalogues of positional, spectroscopic and photometric standards are always available. In addition, telescope parameters such as guiding rates and aperture offsets may be set up and displayed. Command entry is by means of simple keywords, and it is an interesting comment on changing attitudes to telescope control that most users now prefer to type commands on a terminal rather than pressing the equivalent button.

The optical system of the INT is a conventional Cassegrain with a paraboloidal primary mirror and a hyperboloidal secondary. The primary has a diameter of 2.5 m and a focal length of 7.475 m, giving a focal ratio of f/2.94 at the uncorrected primary focus. It is made of Zerodur and has a negligible coefficient of expansion ($\sim 10^{-7}K^{-1}$). On axis, 80% of the light from a point image lies within a circle of 0.3 arc sec in diameter. A three-element corrector of the type described by Wynne (1974), but with a flat rear surface and increased back focal distance, is used at the prime focus to give an unvignetted field of 40 arc min at a scale of 24.68 arc sec/mm. The images are calculated to be smaller than 0.5 arc sec diameter everywhere over the unvignetted field for incident wavelengths in the range 3650 Å to 10140 Å. The two secondary mirrors give f/8 Cassegrain and f/50 Coudé foci (although the latter is not yet commissioned). The scale at the Cassegrain focus is 5.41 arc sec/mm and the unvignetted field is 20 arc min.

Low light-level, integrating television cameras are mounted on a finder telescope and at the Cassegrain and prime foci of the main telescope (the last is not normally used for acquisition). Picture integration is possible either on the camera target or in digital memory: the limiting magnitudes attainable are fainter than $V = 21^m.5$ and $V = 18^m.5$ for the Cassegrain and Finder cameras, respectively and approximate aperture photometry is possible. As the Cassegrain TV rotates with the instrument mount, and may view the sky either directly or by reflection off the jaws of a slit, the orientation of the field is not immediately obvious, so a scale and the cardinal directions are overlaid on the picture. The images may be archived; this is especially useful in exceptional seeing conditions, or for photometry and astrometry. Given that the INT points quite well, the most important use of the finder is in the selection of guide stars for the Prime and Cassegrain autoguiders. The Cassegrain camera is used for acquisition and for guiding on light reflected from the slitjaws.

Erection and commissioning

The mechanical structure of the INT was shipped to La Palma in 1981 and was re-erected into the bare frame of its building in 1982. The mirror arrived on the island on December 10 1982: the building was handed over by the contractors to the RGO on January 17 1983 and work began on preparing the laboratories and workshops for the commissioning of the telescope. The first of three direct air shipments of machinery, instruments and computers arrived on La Palma on January 25. By September the building was in full operation and the telescope was fully assembled, with a freshly aluminised mirror, by the end of the year. Problems in the telescope drive amplifiers which arose in September were solved by January 1984 and on the first night of February 1984 stars were first seen in the telescope, at the prime focus. The telescope commissioning programme had been targeted towards the completion of the Cassegrain spectrograph since this would be the most widely demanded instrument: it was also tolerant to telescope pointing and tracking.

Telescope tracking was brought within specification by November 1984. Telescope pointing relied on the new encoding system and this was brought to a satisfactory standard at the end of the year. Meanwhile in the spring of 1984 there was a concentrated effort to commission the Cassegrain instrumentation, including acquisition TV cameras, Intermediate Dispersion Spectrograph, IPCS and CCD detectors and ADAM the software environment which brings together this complex of instruments into one working station. This programme was completed in May. On May 29 1984, the telescope welcomed its first scheduled astronomer. It operated for astronomers for 47% of the time in the first six-month period (semester F), 50% in Semester G, 62% in Semester H and 73% in Semester I. The rest of the time has been used for engineering work.

R. Laing

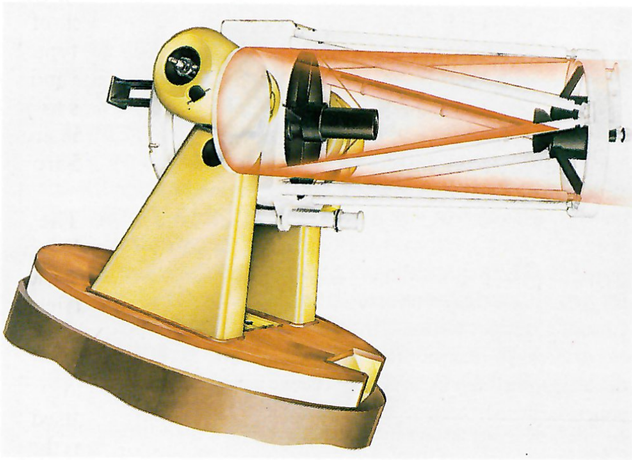


Fig. 1 Isaac Newton Telescope seen from the east, with the light path for the prime focus indicated in red.

Fig. 2 The observatory building of the Isaac Newton Telescope is protected by a solar screen against direct solar heating. A ventilation system uses the brown painted stairwells to the east and west. White chippings cover the black asphalt around the building, and the yellow flowers indicate the presence of the cordesa bushes which provide a natural solar screen for the rocky terrain. All these factors preserve the natural seeing against convection currents.

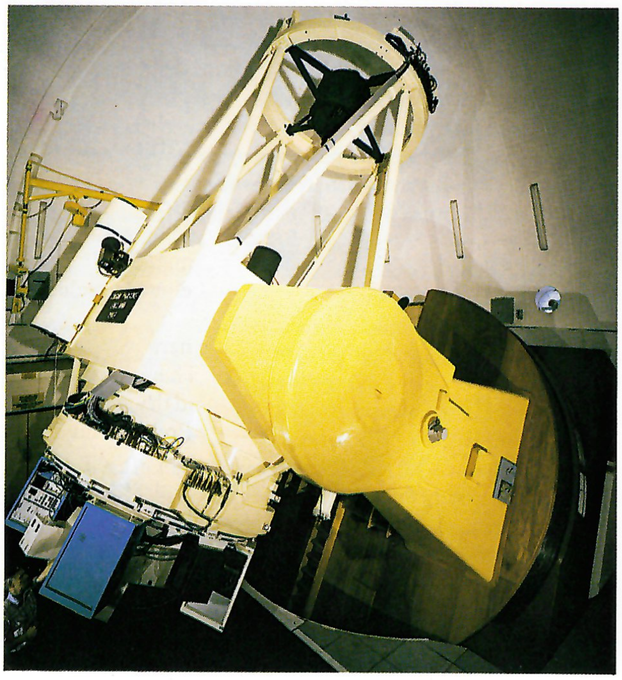


Fig. 3 The Isaac Newton Telescope carries blue painted electronics racks which control the Cassegrain instruments.

Isaac Newton (1642–1727)

Born into a farming family and first educated at Grantham, Isaac Newton was sent to Trinity College, Cambridge, where as an undergraduate, he came under the influence of Cartesian philosophy. When confined to his home at Woolsthorpe by the plague between 1665 and 1666 Newton carried through work in the analysis of the physical world which has profoundly influenced the whole of modern science.

On returning to Cambridge, Newton became a Fellow of Trinity College, and was then appointed to the Lucasian Chair of mathematics in succession to Isaac Barrow. In the 1670s lectures, demonstrations and theoretical investigations in optics occupied Newton, constructing in 1672 the reflecting telescope today named after him, but in the early years of the 1680s correspondence with Robert Hooke re-awakened his interest in dynamics. After Edmond Halley's visit to Cambridge to encourage him in this work, Newton laid the foundations of classical mechanics in the composition of his fundamental work *Philosophiae Naturalis Principia Mathematica.*

Newton seems to have come to a watershed in his career with the publication of *Principia* in 1687, after which he turned his back on academic pursuits. Appointed as Warden of the Mint in 1696 he diligently applied himself to the recoinage of the realm, though he of course maintained his position of scientific pre-eminence until the end of his life. In 1703 he was elected President of the Royal Society and the next year published his *Opticks*, containing the first full exposition of his method of fluxions.

INT imaging instruments

TAURUS

TAURUS is a wide-field, imaging Fabry–Perot interferometer designed to obtain seeing-limited spectral information of extended emission-line objects (in the wavelength range 4300 – 7100 Å). It produces monochromatic pictures of nebulae, which can then be interpreted to understand their motions and their three-dimensional structure. The telescope beam is collimated, passed through a piezo-scanned Fabry–Perot etalon and re-imaged onto the Image Photon Counting System. Depending on the choice of etalon, resolutions between 0.07 and 12 Å are available. The etalon is the active component in TAURUS; it is the means by which the light is dispersed (or, to be more accurate, interfered) into its component colours. It consists of two highly polished and reflective quartz plates, kept parallel by means of a technique known as capacitance micrometry. The surfaces are flat to 0.002 μm and have to be kept actively parallel to this same accuracy over their entire 60 mm diameter surface.

Each quartz plate weighs about 0.5 Kg and has to be kept parallel to this tolerance at all orientations of the telescope. The capacitance micrometry is a technique for determining relative distances extremely accurately and, within a feedback loop, allows one to drive a set of piezo stacks so that the parallelism is locked by means of an accurate servo. The separation of the plates has then to be changed through a distance of 0.25 μm – while, of course, maintaining their parallelism.

This stepping process has then to be synchronised with the IPCS camera TV frames time. After a predetermined number of TV frames have been accumulated in the external memory, the Instrumentation Computer has to send a message to TAURUS to move the etalon by one step (or 0.002 μm). TAURUS then responds, the external memory address is updated and a new picture begins to accumulate.

Applications of TAURUS include (in order of decreasing resolution): velocity fields in planetary nebulae, HII regions, supernova remnants, spiral, irregular and interacting galaxies, narrow-band photometry of distant galaxies and galaxy clusters, and QSO searches.

TAURUS is offered by the astronomers of the RGO as a service facility – this means that set-up, adjustment, scheduling and the carrying out of observations with

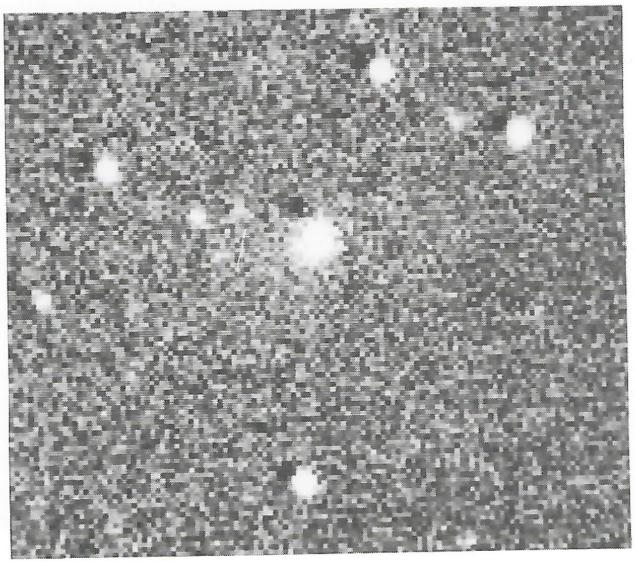


Fig. 1 Halley's Comet.

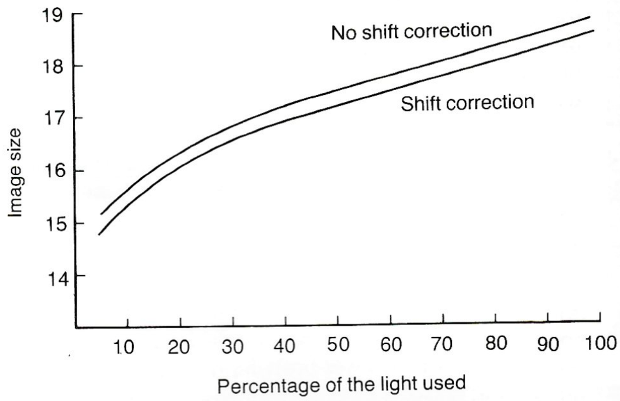


Fig. 2 Image size as a function of selection and shift correction, in the case of many seeing cells across the aperture.

TAURUS on the Isaac Newton Telescope, as well as initial data reduction, is carried out by RGO astronomers to the specification of the external users of the telescope who have been given time.

The Prime-Focus CCD Camera

A CCD camera at the prime focus of the INT was commissioned in July 1985. Two CCD chips can be used: RCA 58612 (thinned and back-illuminated) and GEC P8600 (front-illuminated). The former has a significantly higher detective quantum efficiency, especially in the blue, but higher readout noise. It is likely to be preferred for general-purpose imaging. On the other hand, the pixel size of the GEC chip is 22 μm, compared with 30 μm for the RCA chip (0.54 and 0.74 arc sec, respectively), so the former gives significantly better sampling in good seeing.

First light in the CCD Prime-Focus Camera during the commissioning run was from Halley's Comet. It is shown here in a double exposure (Fig. 1), one negative and one positive. The separation of the black and the white star images is at a different orientation to the separation of the Comet's image, because the Comet moved between exposures. In this picture, for the first time in this apparition of the comet, can be seen the comet's tail, extending to the south west.

R. Laing

Image sharpening

The availability of new technology, especially photon-counting detectors, has made it possible to improve the spatial resolution of ground-based optical telescopes. This makes sharper images, which not only reveal structures not previously identifiable but also produce more accurate spectra and other measurements by reducing confusion and background noise. If successful, image sharpening will have a large impact on the design and operation of optical telescopes and their instruments. Several groups around the world are engaged in research into image sharpening, including of course the RGO.

In its simplest form, the technique only corrects for image motion. The image is followed as it moves, and shifted into coincidence with the mean image before being recorded. This is called Image Stabilisation, and only gives a significant improvement if the primary mirror is smaller than an atmospheric 'seeing cell' (10–50 cm). If there are many seeing cells over the mirror, the image moves and blurs. Then it is much more effective to open the shutter only if the image of a reference star in the field is small (sharp), and then following and recording the field, correcting for its shift in position. This combination of two steps is called Image Sharpening. Because the field of interest and the reference star are viewed through slightly different paths of the atmosphere, the sharpening of the field is not quite as complete as the sharpening of the reference star. In the case of many seeing cells across the aperture, selection gives more improvement than shift-correction (Fig. 2). The reverse would of course be true in the case of one seeing cell in the aperture.

This can be shown by actual data as well as calculation. Fig. 3 shows the image of a double star with a separation of 5 arc sec. Data were recorded with the IPCS during commissioning of TAURUS on the Isaac Newton Telescope. The brighter object was used as the reference, but note that the other object is equally improved, indicating virtually complete correlation over that separation.

As the number of seeing cells across the aperture increases, the chance that their subimages coincide to produce a small image becomes smaller and smaller. This means that more and more light has to be thrown away. The efficiency can be improved by subdividing the aperture into smaller subapertures, each with its own shutter and shift-correction mechanism. Some early experiments with the 2.5 m INT have confirmed that the images of a star from different subapertures vary completely independently in size and position.

An obvious limitation of Image Sharpening is the requirement for a bright enough reference star ($m < 15$) not too far away (< 3 arc min) from the observed object. These requirements give access to 60% of the sky, and are less severe than would be the case for diffraction-limited restriction. This is reasonable for a technique that only aims at the intermediate resolution of 0.2 – 0.5 arc sec, determined by the size of the seeing cells rather than the telescope aperture.

The advance in telescope resolution by this technique is useful but not as spectacular as from interferometric techniques. However, image sharpening may improve the performance of speckle techniques and optical aperture synthesis by 'preconditioning' the incoming light.

J. E. Noordam

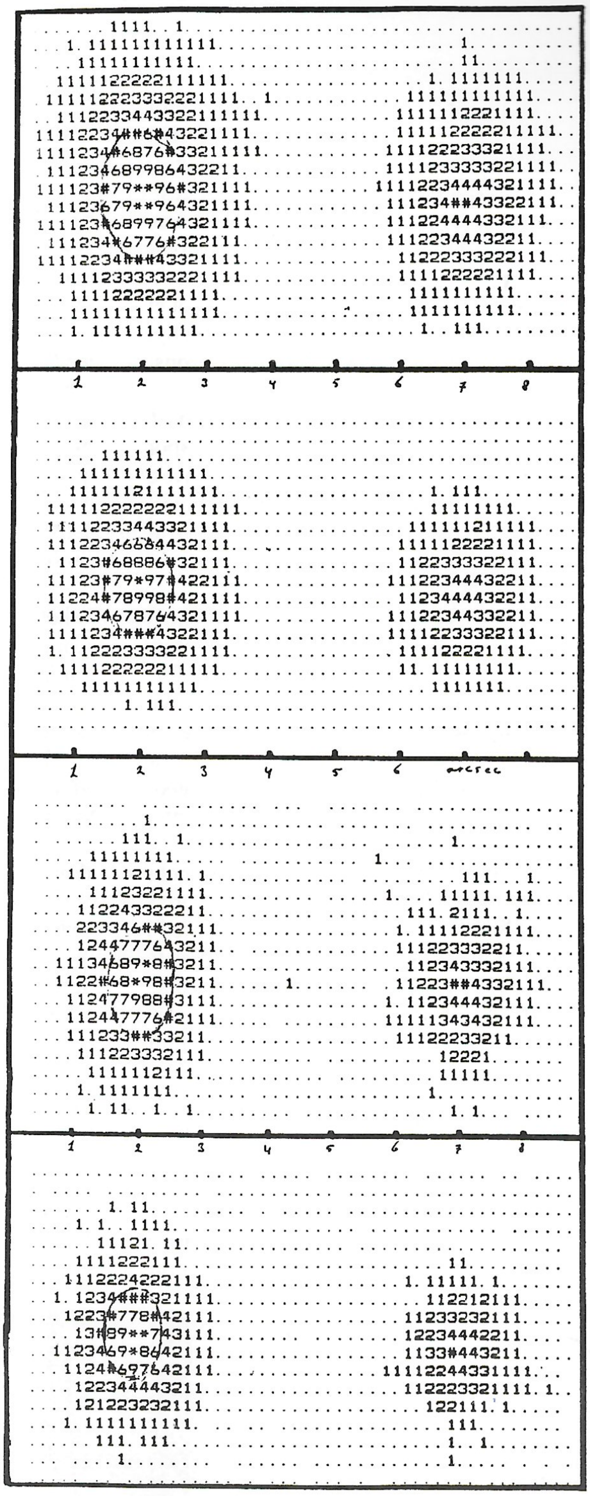


Fig. 3 (a) Passive image of a double star with a separation of 5 arc sec. (b) All exposures have been corrected for image-wander, by shifting the centroid of the bright star on the left to a fixed position. (c) Only 87 of 500 exposures have been used, selected for small horizontal size of the bright star on the left. No position-correction applied. (d) Full image sharpening: 87 out of 500 images were selected and added after position-correction.

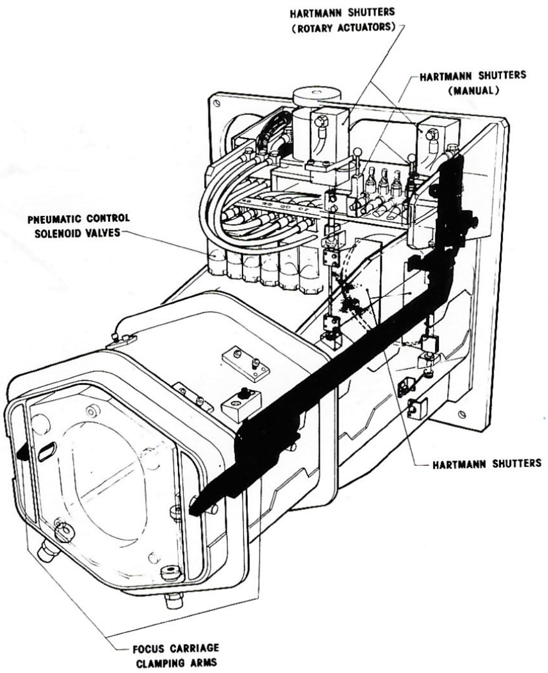
INT Cassegrain spectrographs

The principal common-user instrument at the Cassegrain focus of the INT is the Intermediate Dispersion Spectrograph (IDS), with a choice of two cameras of different focal lengths and two detectors: the Image Photon Counting System (IPCS) and a Charge-Coupled Device (CCD). It is combined with the Faint Object Spectrograph (FOS), a fixed-format, efficient spectrograph designed for low resolution work.

Both the IDS and the FOS are part of the same structure: a folded-input, flat-bed instrument, with the FOS occupying the 'straight through' position (Fig. 2). The spectrographs hang below an Acquisition and Guidance unit. Both cameras of the IDS (and indeed the FOS) may be used during the same night. Facilities for acquisition and guidance, calibration and comparison lamps, neutral-density and colour filters are located in the A&G unit to which the spectrograph is attached. Spectrograph and A&G functions are computer-controlled, although changes of grating and collimator are manual. The status of the system is indicated by a Mimic Display.

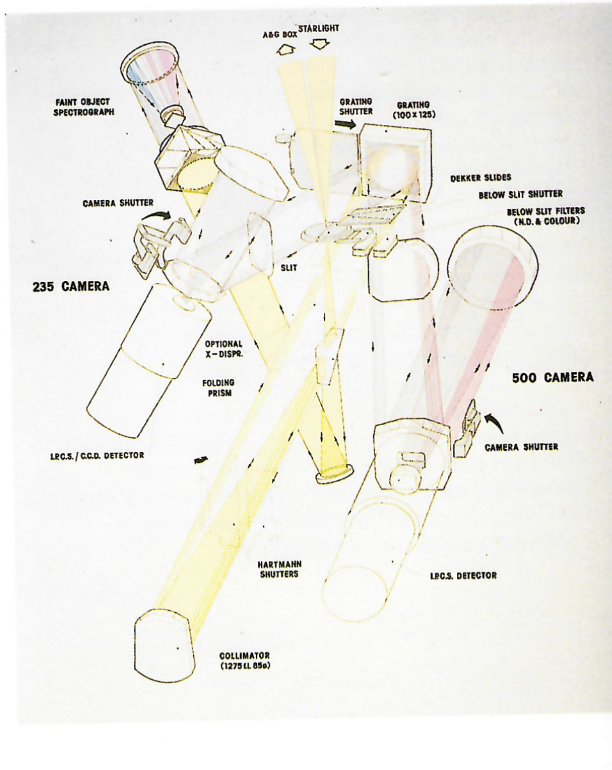
The IDS has a wide selection of first-order gratings giving dispersions in the range 7–140 Å/mm. Two cameras have focal lengths of 235 and 500 mm. The IPCS detects individual photon events by means of a four-stage image intensifier and lead oxide TV camera. The scintillation pulses are fed to a hard-wired signal processor and then to an external memory, which is read out by the instrumentation computer. Pixel size, and consequently resolution, are functions of the TV camera format, but 2048 15 μm pixels are generally used in the dispersion direction. A CCD camera is the alternative detector, generally used for spectroscopy in the red (the IPCS is more blue-sensitive than red-sensitive, although cathode sensitivity extends at least to 8000 Å). A front-illuminated GEC P8600 chip is currently available. It is superior to the RCA chip for spectroscopic applications because of its lower readout noise.

Fig. 1 Collimator support tube and Hartmann shutters in the Cassegrain Spectrograph. The Spectrograph design uses pneumatic control mechanisms (zero energy generation and long-action constant force operation) and involves numerous adjustments for the optical alignment.



The instrument control computer for the INT is a Perkin-Elmer 3220, programmed in FORTRAN VII under the OS/32 operating system and interfaced to the micros associated with individual devices via CAMAC. The software environment is provided by ADAM: the Astronomical Data Acquisition Monitor. The top level of ADAM is the command language, which consists of built-in commands, procedures (for example to carry out the sequence of operations that focuses the spectrograph) and program handling. Tasks are divided into two types: D-tasks (or line drivers), which are real-time programs in direct control of an instrument or detector and A-tasks (application), which are not concerned with control, but handle such jobs as data verification and graphics. A message supervisor controls the flow of information between tasks and the bulk data system provides a standard format for data stored on disc. All data produced by the telescopes, except for photographic plates, are copied onto magnetic tape, generally in FITS format, and retained in an archive at the RGO.

Fig. 2 Optical scheme of Cassegrain Spectrograph. The beam is folded to fit the limited space envelope, and to allow the spectrograph to be well supported by the Cassegrain turntable. Two cameras give two resolution ranges and support two detectors together with a Faint Object Spectrograph.



The Faint Object Spectrograph (FOS)

The FOS is an efficient, fixed-format spectrograph with a CCD detector used for low resolution (15–20 Å FWHM) spectrophotometry over the wavelength range 4000–10 000 Å. The optical design is a Schmidt camera without a collimator in the diverging beam from the Cassegrain focus (Fig. 3). The dispersion is provided by a transmission grating and a cross-dispersing prism, which give a two-order format. The detector is a GEC 6803 chip. The principal advantage of the FOS is its high throughput – 12% for the combination of atmosphere, telescope and FOS at 7000 Å – some three times larger than that of the IDS with the same detector. It is highly appropriate for the study of emission-line objects such as QSOs, radio galaxies, HII regions and planetary nebulae, but less useful for absorption-line objects (particularly those with narrow features) owing to its low resolution. There are four operating modes: beamswitching for point sources; beamswitching with a larger throw for extended objects; long slit (first order only) and 25 arc sec slit (both orders).

R. Laing

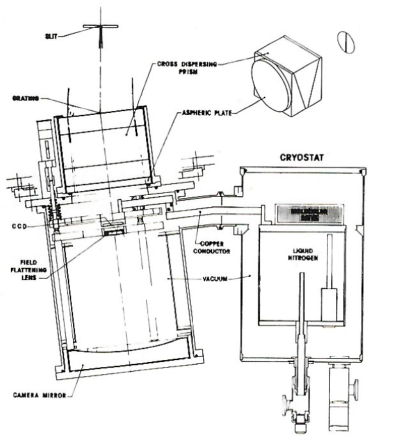


Fig. 3 Optical diagram of Faint Object Spectrograph.

Faintest stars

Using the UK Schmidt Telescope and infra-red plates, Neill Reid, Paul Hewett and I discovered a star, 2208 – 2007, with I = 16.6 mag. which is not visible on any V-band plates (fainter than 20.5). It was however visible on the acquisition TV of the Isaac Newton Telescope and, by comparison with published photometric sequences observed at the same time, I estimate V = 21.0 to 21.5. This implies a very red colour of V–I = 4.7. I obtained spectra on the night of June 27/8 1984 with the INT using the Cassegrain Spectrograph and the GEC CCD detector over the range 7200 – 8600. The project was a study of the space density of the lowest luminosity stars known to see if they could make up a substantial fraction of the mass of the universe. (They cannot.) The temperature sensitive features of the spectrum of 2208 – 2007 (top spectrum) are the shape near 8000 Å and the depth of the absorption feature near 8450 Å. These show the star to have an absolute visual magnitude of +18.5. Its distance is 30 pc. The bottom spectrum is of van Biesbrock 10, at absolute magnitude +19. Its spectrum was obtained as a comparison. 2208 – 2007 joins it as one of the half dozen faintest stars known.

G. Gilmore

Spectrographs in astronomy

A significant change has taken place in astronomy over the last decade. It has been most common for an observing astronomer to confine his investigations to the use of a single technique, which he used on a variety of different kinds of objects. The discovery of objects which emitted many different kinds of radiation – X-rays, radio waves and light – forced astronomers to single-object studies which deployed many instruments. Within optical astronomy the trend has developed. A common sequence of events would be for an astronomer to acquire the approximate position of an X-ray star sufficiently accurately to limit possible optical counterparts to just a handful. He would use a low resolution spectrograph like the FOS to take spectra of all the possible counterparts – the low resolution means that a high rate of photons fall into each element of the spectrum, so the spectra can be briefly exposed. From this rapidly obtained survey collection he can identify the X-ray object by its spectral properties. From a spectrum at intermediate resolution, which would take a longer exposure, he can map its spectral properties in some depth, isolating features of interest. If it is warranted these can be studied at even higher resolution (with correspondingly more effort) for, say, radial velocity information. As the resolution gets higher, the star light is spread thinly, and any noise which the detector creates gets more significant. CCDs are relatively noisy detectors, good for low resolution spectroscopes: for high resolution studies the low-noise IPCS is usually better. The INT's triple spectrograph is designed so that quick changes from one configuration to another are possible with minimum waste of time (~ 20 mins). Astronomers frequently elect to use more than one configuration from night to night, and often within one night.

JKT instruments

People's Photometer

The most often scheduled of the f/15 instruments for the Kapteyn Telescope has been the People's Photometer. It was designed a decade ago by R. Bingham at the RGO and five were built for various observatories throughout the world. These instruments are conventional two-channel photoelectric photometers, most frequently used in a star-sky mode where the separation of the two apertures is 172 arc sec. Each channel has an independent filter slide to take six filters; typically Kron Cousins ubvri or Strömgren uvby and Hβ When the transparency is variable it is possible to use only one aperture and put a neutral beam-splitter immediately behind it which sends the light into the two different photomultipliers. By selecting different filters for the two channels one may measure colours in non-photometric conditions even when it is impossible to measure magnitudes; the best example is the Hβ index. It is possible to replace the neutral beam-splitter with a Foster prism which forms a polarizing beam-splitter, and at the same time insert a rotating waveplate in the beam above the aperture. This combination modulates the light from a polarized source by an amount proportional to its polarization. A half-wave plate produces a modulation at four times the frequency of the plate rotation which is solely dependent on the linear polarization of the source. A quarter-wave plate is also sensitive to the linear polarization but the modulation has only half the amplitude; however there is an additional modulation at twice the plate frequency proportional to the circular polarization of the source.

The People's Photometer is controlled by a PE3220 computer which is the dedicated instrumentation computer for the telescope. The computer controls both filter slides, the apertures and the star-sky/beam-splitter selection by pneumatic pistons, colloquially known as digital trombones, interfaced like every other function, via CAMAC. This interface is likewise used to count the pulses from the photomultipliers and pass the counts to the computer which stores them first on disc and subsequently on magnetic tape. At the same time the computer provides approximate real-time reductions to inform the observer of the progress and accuracy of his observations so that he may pursue the most effective strategy. The speed at which the system works can be chosen to suit the programme. For constant or slowly varying stars a sampling period of one second is usual. When used as a polarimeter the wave plate rotates with a period of 960 ms and the data is read in samples of 10 ms so that the modulation is fully resolved. For particularly fast phenomena it is possible to use external memory in the CAMAC crate which can be addressed with sampling intervals of 4 ms in two channels.

Clearly the People's Photometer allows the astronomer to choose between a variety of configurations to study the particular problem he has in mind. Of the different investigations done on the JKT we present three, purely as examples (Figs. 1–3). The scientific background to these programmes is described on pp. 36–7.

Richardson–Brearley spectrograph

Another f/15 instrument is the Richardson–Brearley spectrograph built by R. Edwin at the University of St Andrews, following the original design by Richardson and Brearley. It is an efficient, lightweight, yet robust and stable, off-axis spectrograph, intended primarily for low- and medium-resolution stellar spectroscopy. It is operated manually and uses photographic plates to record the spectra.

Multi-purpose Photometer (MPF)

The telescope is provided with a multi-purpose photometer (known as MPF after its Dutch initials) built by J. Tinbergen at Leiden University. In this instrument light passes through an optional calibrator and is focussed on to a single or double diaphragm; the latter is for sky-chopping. After passing through an optional polarizer for linear polarimetry, the beam continues through two optional neutral density wedges and three optional neutral density filters to the collimator and an electro-mechanical shutter. The dichroic beam-splitter assembly yields up to six beams; three beams between 3000 and 6000 Å, the other three between 4500 and 9000 Å. Each of these beams is then split again, normally by a neutral beam-splitter, to form a pair for Hβ type photometry. The final beams pass through three-position filter slides and Fabry lenses to the photocathodes.

CCD camera

A direct CCD camera has been built for the JKT, similar to the prime focus of the INT but with a GEC chip. This came into use at the end of September 1985; later it will be fitted with an autoguider and low dispersion prisms. At its commissioning it recorded the Halley's Comet pictures on the front cover of this report.

Wide-field photographic camera

To take advantage of the high astrometric performance of the Harmer–Wynne optical system the JKT is provided with a wide-field photographic camera which provides an unvignetted field of 90 arc mins diameter on 250 × 200 mm plates (Fig. 4). The camera has an autoguider developed by D. Thorne very similar to those on the 2.5 m telescope. The wide band filters are the same size as the plates and the useful field is inscribed to one end of the plate leaving the other end free for the plate number and sensitometer spots. The sensitometer is of the 'Kitt Peak' design and shines light through the filter in use to the photographic plate. The camera is also provided with three fiducial lamps which expose small images on the plate which record the registration of the plate relative to the telescope. Thus the tangent point to the sky is known in principle which removes two degrees of freedom from astrometric reductions. Another novel feature of the camera is a roller shutter which always closes in the same sense as it opens so that all points on the plate receive equal exposure. The camera allows for nitrogen flushing so that the volume between the emulsion and filter is filled with dry nitrogen during exposure, thus guarding hypersensitized plates against degradation.

D.H.P. Jones

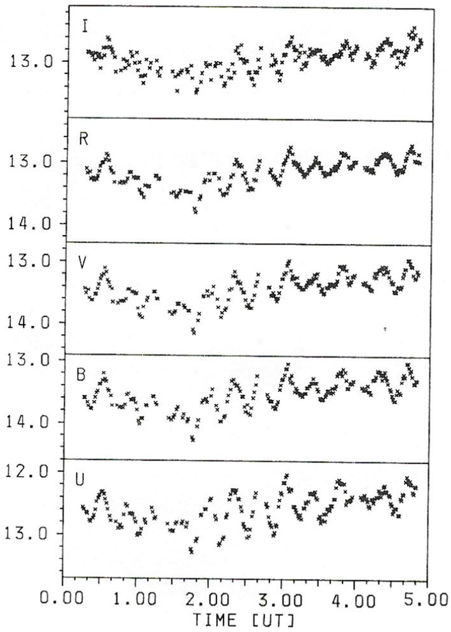


Fig. 1 Light curves of the X-ray binary H 2215–086 (FO Aqr) in UBVRI measured with the People's Photometer on the JKT by K. Mukai (Department of Astrophysics, University of Oxford) and co-workers. The four-hour binary period of the (red dwarf)–(white dwarf) pair produces only a modest modulation while the light curve is dominated by the 21-minute rotation of the white dwarf. Hard X-rays arising near one of the magnetic poles of the white dwarf illuminate other material in the system which re-processes the radiation into the optical region.

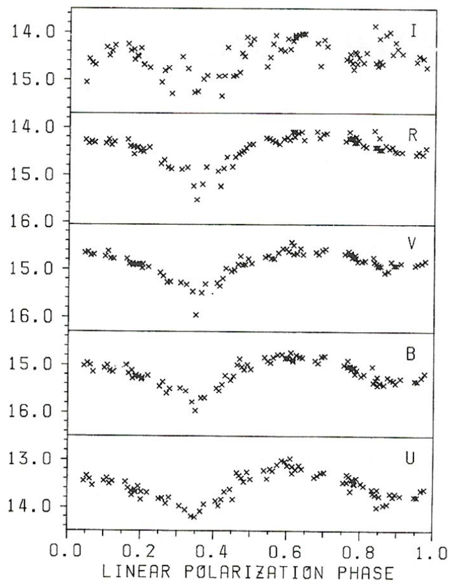


Fig. 2 Light curves of the X-ray binary E2003+225 (QQ Vul) in UBVRI observed by K. Mukai (Oxford) and co-workers. Because of its strong circular polarization E2003+225 is believed to have a stronger magnetic field than H2215–086 and magnetic braking has forced the rotation period of the white dwarf up to that of the binary orbit.

Fig. 3 Outburst light curve of SS Cygni observed by C. D. Pike and R. W. Argyle. The observations were made in search of rotational modulation by the red dwarf but none was found. Strictly speaking SS Cygni is also an X-ray binary but it was discovered to be an optical variable 80 years before its discovery as an X-ray source.

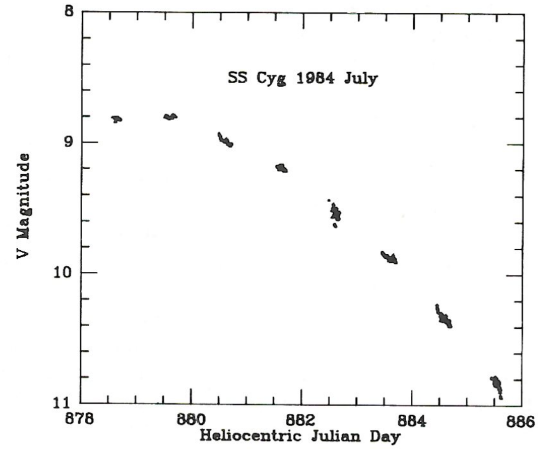
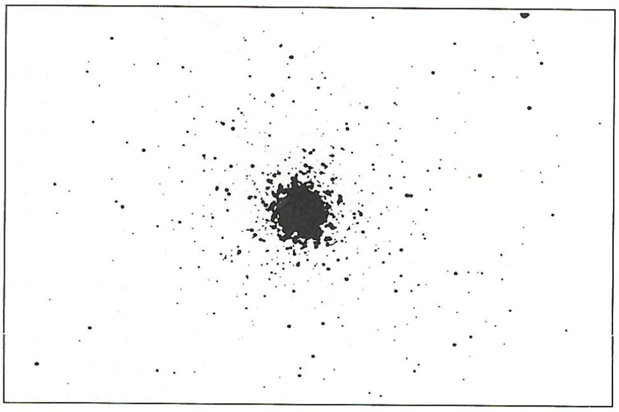


Fig. 4 First light with the f/8 Harmer–Wynne optics of the Jacobus Kapteyn telescope March 23/4 1984. The globular cluster M3 exposed for 60 minutes on unbaked unfiltered IIao by R. W. Argyle.



The Jacobus Kapteyn Telescope

In the early 1960s there was a flourishing school of photographic astrometry at the RGO. It was found that very accurate proper motions could be determined by comparing plates taken 50 or more years apart with the same telescope. Too strict a reliance on old telescopes was not a policy which could be pursued indefinitely and thoughts turned to the design of a dedicated astrograph incorporating the latest technology, especially in optical design.

The 1973 Scientific Case for the Northern Hemisphere Observatory called for three telescopes, the smallest to be a 1 m similar to the Boller and Chivens telescope of that size on Siding Spring Mountain. This telescope has f/8 and f/18 secondaries interchangeable with a flip top arrangement. The f/8 arrangement is a Ritchey–Chrétien which requires an elliptical primary. Thus the f/18 is not a true Cassegrain which requires a parabolic primary. The Ritchey–Chrétien is free from coma by design and the field is limited by astigmatism which amounts to an arc second 20 arc minutes from the axis. Moreover the optimal focal plane is curved concave to the secondary with a radius of 135 cm.

While this design is not the ideal astrograph it was quickly realized by those who had been urging the case for a new astrograph that the differences in specification were small enough to be negotiable. Nevertheless it was clear that there was no ideal astrograph and that each parameter of the final design must be a compromise between trade-offs in different directions.

The first parameter to establish was the effective focal length. f/8 had been chosen for the Siding Spring telescope because this matched a seeing disc of one arc second to the granularity of the Estman 103a0 emulsion. Since that time finer grain emulsions such as the Kodak III range have been introduced but by a happy accident the seeing on La Palma has proved better than anticipated so the 8 m focal length does not introduce a marked mis-match. If shorter focal lengths are moved to then the detector (photographic plate) for stellar images is undersampled but speed is gained on extended objects because each unit area of plate receives more photons. Unhappily this is also true of the brightness of the night sky which limits the exposure during which the emulsion can register fewer photons so that the signal/noise suffers. Because of its granularity the photographic plate can only store so much information per unit area, with fine grain emulsions able to store much more. As the focal length of the telescope is increased the seeing discs are spread over a greater area of emulsion which can contain more information if the exposure is long enough to gather it. This argument implies that the limiting magnitude of a telescope is purely a function of its focal length; the only limitation is the prohibitive length of the exposures.

Having decided on an overall focal length of 8 m we are still free to fix the focal length of the primary. A short focal length to the primary implies a shorter tube so that the telescope can be covered by a smaller dome. As the dome can cost a large fraction of the total cost of the project, and this cost rises sharply with size, this is a powerful consideration. Likewise, it is easier to construct the telescope tube with the requisite stiffness when it is comparatively short. The strongest argument for a longer focal length arises indirectly from the astrographic requirement that the field must be flat. With a curved focal plane the plate must be bent in two directions during exposure which results in internal stresses. These stresses are relieved when the plate is removed from the plate-holder for processing and ultimately for measurement. To reduce the measurements it is necessary to assume that both the glass plate and its thin coating of emulsion behave purely elastically under stress. This was felt to be a dangerous assumption in the most precise astrometry so it was specified that the field should be flat. Now Petzval's theorem implies a direct connection between the field curvature and the focal length of the primary in a two-mirror system so that a flat field requires a primary focal length of 4.6 m, a metre longer than the Siding Spring telescope. The astrographic requirement was felt to be the overriding consideration and the focal length of the primary was fixed at 4.6 m in spite of the contrary arguments rehearsed above. The only other argument in favour of such a long focal length was the reduced amount of ceramic which has to be ground away from the primary and the relative ease of polishing and figuring.

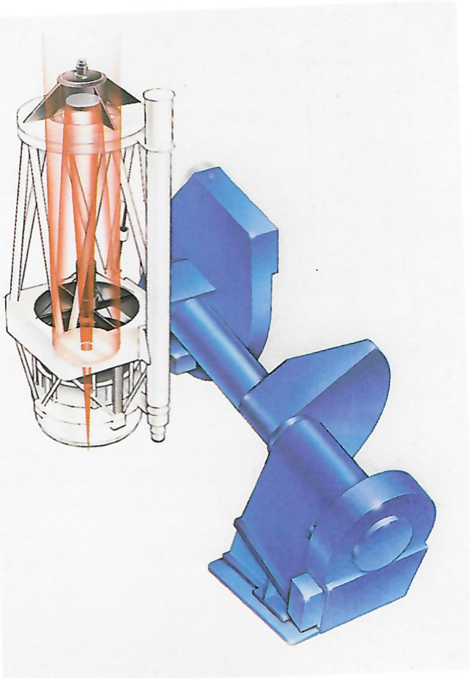


Fig. 1 Optical diagram of JKT in its f/8 mode.

With the focal lengths of the two mirrors fully specified the astronomer is still free to decide on the field size. Although he wants the biggest field possible, the larger the field the more difficult it is to design a system with acceptably small aberrations. For precise astrometry symmetrical aberrations like astigmatism are less dangerous than asymmetric ones like coma. Because the photographic plate is a non-linear detector the apparent centre of an asymmetric image varies with the length of exposure and this is quite unacceptable in an astrograph. Equally unacceptable is for the apparent separation of two stars to be a function of their colours. With these requirements in mind we embarked on a series of conversations with Prof C. G. Wynne FRS and C. F. W. Harmer to design a telescope with a field in excess of 1° and acceptably small, symmetric images whose positions were independent of colour. The outcome was a field diameter of 1.5° with symmetrical images nearly all smaller than 0″.5 over the wavelength range 365–852 nm. The parabolic primary could provide a conventional Cassegrain with a hyperbolic secondary but in the wide-field mode uses a spherical secondary, totally insensitive to disalignments about its centre of curvature. The wide-field correction is provided by an afocal doublet in the middle of the tube, with all surfaces spherical for ease of fabrication. Both components

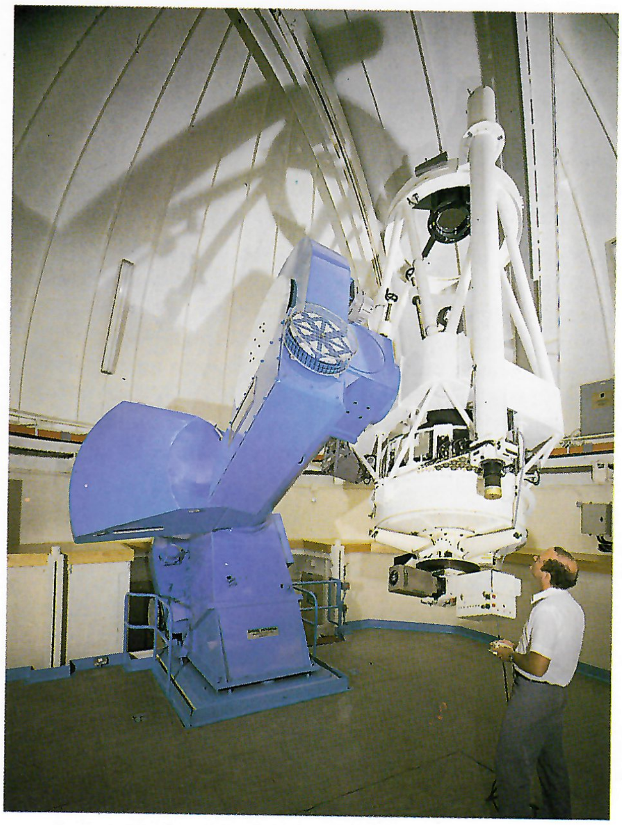


Fig. 2 The JKT in its dome on La Palma.

are of the same glass type so that there are no chromatic effects. For a 1 m telescope the corrector lens is 326 mm in diameter which implies that this design cannot be extrapolated to very large telescopes. The outline optical design for the f/8 and f/15 modes is shown in Fig. 1.

The design of the telescope was fixed by 1977 well in advance of the SERC decision to support the NHO project or the firm decision to site the observatory on La Palma. The order to build the telescope came from the Department of Trade and Industry, inspired by the then government of Great Britain in an effort to relieve unemployment in Newcastle-upon-Tyne. The firm of Sir Howard Grubb Parsons were asked for a conventional 1 m telescope suitable for sale to a wide range of customers. The RGO produced a User Specification for the instrument but the engineering specification was produced by Grubb Parsons. Their intention was to provide a conventional analogue control system which would operate by itself or which could easily be interfaced with a computer, whichever the customer wished. Thus the RGO had little control over the detailed design of the telescope and the adaptation of the design to computer control caused much more trouble than either party had expected.

The telescope was erected on the ground floor of the Isaac Newton Telescope building at Herstmonceux in 1982 and interfaced to its computer. It was shipped to La Palma in the summer of 1983; its base plate was the landing pad for a Royal Navy Sea Harrier which put down on the cargo ship Alraigo after losing its aircraft carrier. The telescope was built into the dome on La Palma in October 1983 and the building handed over in January 1984. The telescope control system was installed in February and March and the first plate taken in March 23/24 1984. The first scheduled astronomers used the telescope on May 29; for the first year of its use the JKT was successfully used for photometry, spectroscopy and CCD imagery. Photography was commissioned but could not be fully exploited due to residual problems of optics and tracking.

D.H.P. Jones

Jacobus Cornelius Kapteyn (1851–1922)

Apart from being an innovative astrophysicist, Jacobus Kapteyn was a considerable figure in the promotion of international cooperation in astronomy, and one of Holland's foremost men of science.

The abiding interest of his life was the investigation of the structure of the Universe and the list of his achievements reflects this. A doctor of physics, he only entered the astronomical field when aged 24, becoming Professor of Astronomy in the University of Groningen in 1878; his inaugural address on stellar parallax marked the keystone of his career.

The University of Groningen could boast no observatory at the time Kapteyn was appointed and, failing to obtain proper funding for observatory buildings, he established an astrometrical laboratory where he hoped to exploit the full potential of photography in astronomy, then in its early days. His association with David Gill at the Royal Observatory, Cape of Good Hope developed from his offer to measure and reduce plates taken there. Thirteen years of work yielded the *Annals of the Cape Observatory*, a catalogue of nearly half a million stars between 18°S declination and the Pole, work done with help only from unskilled assistants.

During the years of the measurement and reduction of the Cape photographic plates Kapteyn was also active in other fields, particularly the photographic determination of parallaxes. In 1882 the parallaxes of only 34 stars were known: by the end of his life the *Groningen Publications* had carried papers giving more than 10 000 parallax measures.

All this work tended to the general aim of improving our knowledge of the stellar system. Growing naturally from his work on annual parallax, the study of proper motion next claimed his attention. The determination of absolute proper motions of neighbouring stars will yield the Sun's motion towards the solar apex and in turn will give an ever-increasing baseline for the determination of secular parallaxes. This work directly led to the greatest single discovery of his life, that of 'star streaming'. It had previously been assumed that the proper motions of stars would be random. By analysis of proper motions in selected areas of the sky, Kapteyn showed that stars were moving in two streams 140° apart. This is today recognized as direct evidence of the rotation of our Galaxy, though the full significance of the discovery was not realized until after Kapteyn's death and the demonstration that some nebulae were extragalactic, being indeed galaxies in their own right.

Kapteyn proposed international collaboration in the analysis of the properties of the stars. Their magnitude, proper motion, parallax, spectral class and radial velocities were to be determined in measurements carried out according to his 'Plan of Selected Areas'. He selected 206 areas distributed uniformly over the whole of the sky and 46 areas near the galactic plane, and the results from all these zones were to be treated statistically to form a picture for the whole sky.

Only weeks before his death, some of the results of his 'Plan' were published under the title 'First Attempt at a Theory of the Arrangement and Motion of the Sidereal system' in the *Astrophysical Journal*. Though the general scheme of our Galaxy which Kapteyn outlined was shown to be erroneous by the work of Leavitt, Shapley and Hubble, the importance of the huge amount of work done by him was in the solid foundation of astrometric data and analysis on which later generations have built with confidence.

The 1 m wide field astrometric reflecting telescope built at the Observatorio del Roque de los Muchachos on the island of La Palma, a joint Dutch/United Kingdom/ Irish project, has been fittingly named after this pioneering Dutch astrophysicist.

Remote operation of telescopes

The SERC and its international partners invested large capital sums during the 1970s and early 80s in building telescopes in favourable sites, including the four on La Palma: Isaac Newton Telescope, Jacobus Kapteyn Telescope, Carlsberg Automatic Meridian Circle and finally the William Herschel Telescope. Cheap and reliable international air travel also made it possible for astronomers to fly around the world for those precious few nights on a good site with world class instrumentation. In one sense though, the astronomer had already started to withdraw from the telescope. He had moved from the end of the telescope to the control room. There are even stories of astronomers going to the foreign sites, running the experiment and never seeing the telescope at all!

The costs of this kind of travelling over the whole of SERC now amount to over £500 000 per annum and there are still telescopes to come into operation. It thus seems appropriate to see if this work could be done, at least in part, in a more economical way without sacrificing any science.

There are several ways of 'remote observing'. One end of the spectrum is where the astronomer sends a written request and some time later has the data delivered to his doorstep. The other end of the spectrum has an astronomer in a similar control room to that at the telescope but located at his home institution. The former system is the way that most radio synthesis telescopes are run. This type of operation is usually classed as 'service observing'. The closest approximation to the other kind of remote observing system are the ground-base facilities of the satellites IUE or IRAS.

Experiments in remote observing

Major technological changes occurring in the late 1970s have started to alter the economic balance between sending the astronomer to the foreign site and sending the data from the foreign site back to the astronomer. The first attempts at remote observing were done as early as 1969 at the Kitt Peak National Observatory (KPNO) in which a fully automated telescope and photometer were used from Tucson. The real costs of telecommunications and microcomputers have fallen dramatically in the last decade. The earliest group to use this potential was again from KPNO who used the free overnight Federal Telephone Service (FTS) in the USA and some customised video transmission hardware. Their first observations were in June 1981. This equipment gave a picture from the acquisition TV every 38 seconds, a voice link and a graphical display on a simple terminal. The user was also allowed access to the sophisticated KPNO reduction software during the day. A workshop was held at the RGO in July 1982 as a result of the KPNO work and afterwards a number of groups attempted various approaches to the problems of remote observing.

The first international remote observing, from ROE to UKIRT in September 1982 used the International Packet Switched Service as a communications medium whilst the RGO used the KPNO equipment in October 1982 (see box). Further tests were done in 1982 to drive the AAT from the UK and ESO has run its own tests in June 1984. There were some hard lessons learnt from these experiments since although they were successful in a small way, they also clearly showed the deficiencies of the hardware, software and infra-structure needed for comfortable remote observing. Typical lessons were:

Error free communications are essential: The KPNO hardware lacked any error correction system whilst the ROE packet switched service had such facilities. Thus, interference from the dome motors in the KPNO experiment sometimes corrupted the data as it was being transmitted to the UK.

Acquisition TV image is needed for optical astronomy: The UKIRT system did not have a picture of the source being observed whilst the KPNO system did give a good quality acquisition image. This was felt to be a real advantage but there remained a problem of how to transmit quickly and cheaply two-dimensional images and then store them so some local processing could be performed to check for the faintest sources using simple image enhancement. The KPNO system did not allow for any storage of the target image to allow further processing.

Eavesdropping

The second type of remote observing now being developed may be entitled 'eavesdropping'. The astronomer stays at home and gets back over the telecommunications network sufficient information to ensure for himself that the experiment has been performed correctly. That means ensuring that the correct object was chosen and sufficient observing time was allocated to achieve the desired signal-to-noise ratio. The major problem to be overcome is the transmission of the target picture in an economical way. The literature has many examples of image compression algorithms but which technique is best is dependent on the type of observation. At the RGO we have been experimenting with a two-dimensional Haar transform to produce the compression (Fig. 2). Simple images are typical of many observations but there are losses associated with a complex picture containing lots of structure. (The Horsehead Nebula is a well known graveyard for 'general purpose' image compression techniques.)

Most telescopes now have control computing systems that correct for telescope structural deformations, and pointing accuracies inside ten arc seconds are normal. Thus only a fraction ($< 10\%$) of the full image need be sent in order to confirm acquisition. In this way the actual picture can be transmitted in less than a minute and the integration need not be held up at all. The AAT and UKIRT already have International Packet Switched System (IPSS) lines and the Spanish authorities say they are installing IPSS equipment on La Palma in 1985. It is therefore possible for the La Palma telescopes to have an eavesdropping system. The home institution can in principle be anywhere in Europe that is attached to the international networks and has a VAX computer with an image display. This includes all the STARLINK sites. It is easy to envisage the impact of this on the usage of remote observing. However, it is still the early days and there are many lessons to learn before we can do it well.

R. Martin
K.F. Hartley

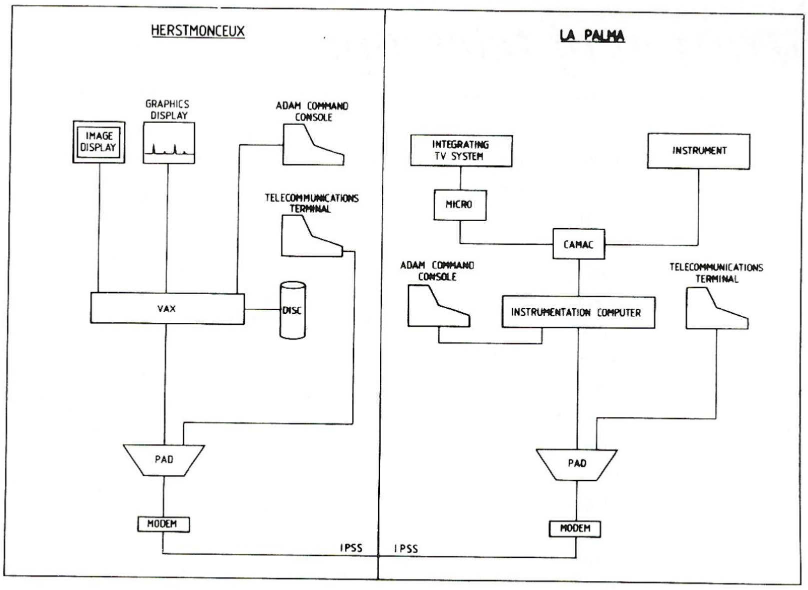


Fig. 1 Proposed remote operation facility for La Palma.

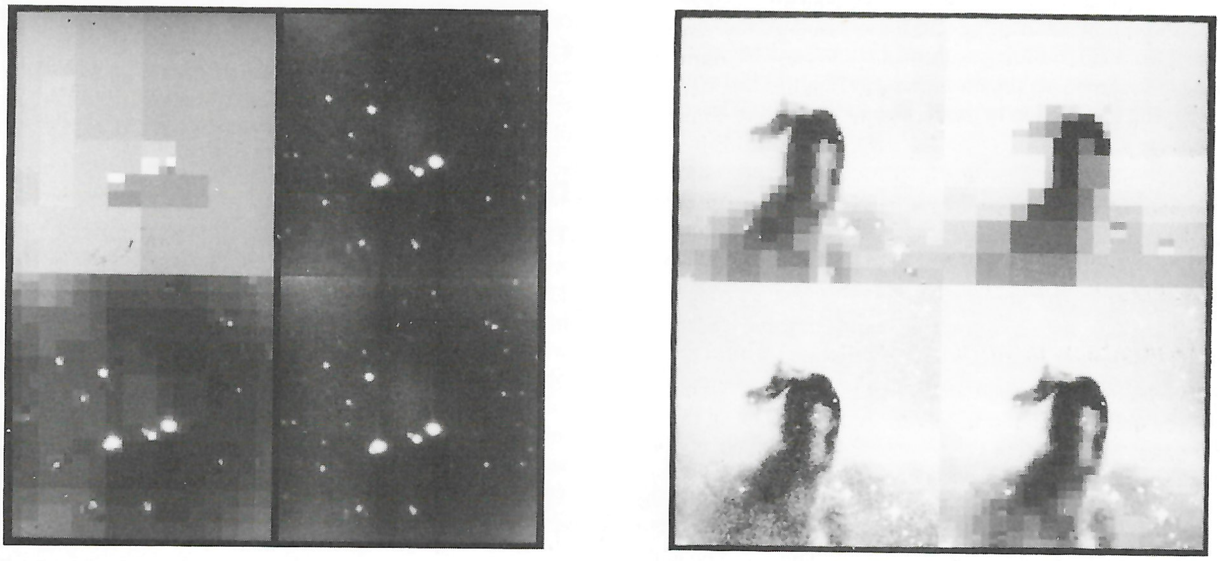


Fig. 2 The Haar Transform passes most of the information in an astronomical image even though it compresses the data by 10% or 1% but not by as much as 0.1%. Fields with star images are less affected than fields with nebulae.

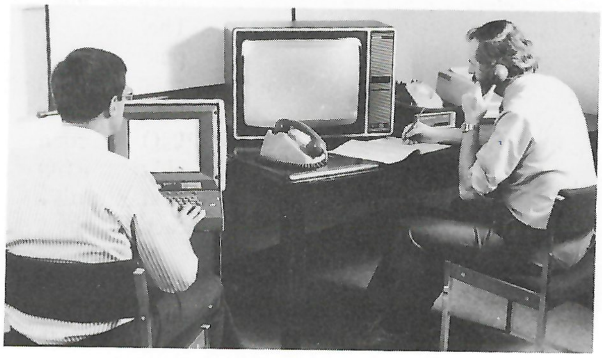
Operating the Kitt Peak 2.1 m

The first intercontinental optical astronomical observations using standard telephone links was initiated from RGO on the night of 25–26 October 1982.

One telephone line was used to send information to the computer for the 2.1 m telescope at Kitt Peak to set up the telescope spectrograph and to return the data. The other line was used to talk to the night assistants or to send two TV pictures a minute to the RGO control room.

The first object, SS433, was identified on the TV screen and positioned for a spectrum, which was beamed onto the Tectronix 4010 to cheers all round.

SS433 was followed by a radio galaxy red shift and a simultaneous remote RGO and IUE observation of NGC 1275. Once the links were set up the astronomy was easy and comfortable. The real work was put in by the communications people. They pioneered the way, ironing over the mountains of noise and nonsense which threatened to drown the faint light of truth flickering over the telephone lines.



The team dispersed into the cold light of an October dawn at RGO with the thought 'It wouldn't have been right if we had done it in daytime.' We realised just how hard it had been, and how much we had relied on using a well-tried instrument with very competent night assistants and a communications team who pushed everything to the limits.

J. Baruch
Leeds University

The William Herschel Telescope

As part of the Isaac Newton Group of telescopes based on La Palma, the RGO, on behalf of the UK Science and Engineering Research Council and the Netherlands Organisation for the Advancement of Pure Research, is installing a new 4.2 m altazimuth-mounted telescope. This telescope, known as the William Herschel Telescope, has been designed by the RGO in conjunction with Freeman Fox and Partners and manufactured by Grubb Parsons Ltd (Northern Engineering Industries plc) in Newcastle; it is due to become operational in 1987. A substantial complement of instruments is being prepared by the RGO and university groups in Britain and the Netherlands for general use.

The WHT will be the world's third largest telescope with a single main mirror (see box for optical design) and it is expected that the already-proven excellent observing conditions on La Palma, together with the most up-to-date instruments and detectors, will give it the edge over its larger rivals, the 5 m telescope in the USA and the 6 m telescope in the USSR. The telescope has been assembled and thoroughly tested, and is now dismantled and ready for shipping to La Palma. The WHT building with its distinctive dome now is nearing completion on the mountain site (Fig. 1) and will be ready for the installation to the telescope by the RGO, starting late in 1985.

Telescope drives and control

Identical precision straight spur gears are fitted to the two axes of the telescope. Maximum rotations are 0–95° from the horizontal and ± 270° about East.

For each axis, the servo control system has three feedback loops: (a) current or torque, which is generated within the control electronics, (b) velocity, from the tachogenerator and (c) precision rate, which is developed either from a 17-bit incremental shaft encoder driven through a pinion off the main gear or a 20-bit roller driven encoder, each giving the same accuracy of 0.03 arc sec. Absolute position is obtained from a pair of gear driven shaft encoders on each axis of the telescope. It is intended that the telescope pointing accuracy be 1 arc sec or better after compensation by the computer control system for all repeatable errors (see next page). The maximum slewing speed for both axes is 1° sec^{-1} with acceleration during slewing reaching a maximum of 0.3° sec^{-2}. For tracking, a local torque loop around the two motors in each axis maintains continuous gear tooth contact during all tracking accelerations up to a maximum of 0.02° sec^{-2}. On the rare occasions when tracking an object which passes closer to the zenith than about 0.2°, observing will have to cease temporarily while the telescope traverses a 'blind' region through which it will not be able to track continuously. During this time, which will be less than 3 minutes for the WHT, the telescope will slew through a large azimuth angle (180° if the object happens to pass through the zenith), to reacquire the object as it leaves the blind region.

In normal use, all the telescope drives are controlled from an operations desk by means of a computer system which communicates with each of the motors and encoders through a parallel CAMAC system. All the instrument turntables and cable wrap devices are controlled in sympathy with the telescope motion, as well as the positions of the dome observing slit and windscreen.

Dome and building

The telescope is supported by a reinforced concrete pier which puts the centre of rotation of the telescope at a height of 13.4 m above the ground. The dome is onion-shaped, of 21 m internal diameter, and a pair of up-and-over shutters with a windscreen coupled to the lower shutter will allow observations down to 12° above the horizon. The dome is supported on a rail set onto a cylindrical concrete building structure which internally is open to ground level. Set on one side of the cylindrical drum is a 3-storey rectangular annex of conventional construction (Fig. 2). This contains the mirror

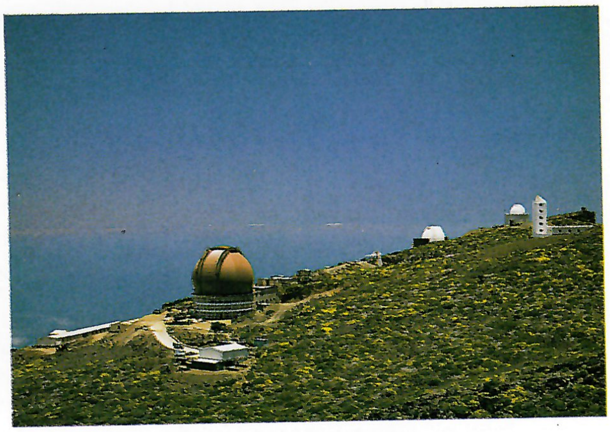


Fig. 1 The Herschel Telescope building looms above the Carlsberg Automatic Meridian Circle in the foreground.

Fig. 2 The Herschel Telescope building nears completion (summer 1985).

aluminizing plant, the operations control room, computer room, dark rooms, workshops, offices and various services. Because no unnecessary activity takes place in the dome there is very little thermal disturbance of the air near the telescope, which greatly improves the chance of achieving perfect 'dome seeing'. This is further facilitated by large extractor fans set into the cylindrical structure.

The budget for the design, erection and manufacture of the WHT, its control system, dome, building, aluminizing tank and other plant, and a full set of instrumentation is £15 million (October 1984 prices). The design is currently being brought to realization by a team of engineers and scientists at the RGO now led by Michael Morris, with Brian Mack as telescope project engineer, Rowland Milner as civil engineer and Neil Parker responsible for the instrumentation and its supporting infrastructure.

A. Boksenberg

Frederick William Herschel (1738–1822)

At the age of 19 William Herschel left his native Hanover, where he had been a regimental oboist, and came to England. His earlier life was devoted to music and it was as a chapel organist that he moved to Bath in 1766. He was, however, becoming increasingly interested in astronomy and mathematics, and he began serious observational work with telescopes he had made in 1773.

He had for some nine years been carrying out increasingly thorough sky surveys, where his purpose was the investigation of double stars, when he realized that one celestial body he had observed was not a star at all, but a planet. Uranus was the first planet to be discovered since antiquity and Herschel and his sister and assistant Caroline became famous overnight. George III appointed him 'Court Astronomer' and granted pensions to brother and sister.

This discovery is not, however, his only claim to pre-eminence; he was a great observational astrophysicist and it is for these achievements that the Herschel Telescope is named after him. Herschel's investigations into double stars enabled him to demonstrate statistically that these were not chance pairings due to a line-of-sight effect, but were physically linked binary star systems. The determination of their orbits was the first evidence that Newton's law of gravitation was universal, and was seen to be operating outside our own Solar System. Herschel also determined the motion of the Sun through space.

Herschel vastly increased the numbers of known nebulae, from Messier's famous list of 100 to the 5000 catalogued by Caroline and him by 1820, and his view that the nebulae were greatly distant aggregations of stars, which today we call galaxies, was more than a century before his time.

Telescope optics

The William Herschel Telescope is of classical Cassegrain optical configuration. The paraboloidal primary mirror is made of a glass-ceramic material (Cervit) having near-zero coefficient of expansion over the operating temperature range. It has a clear aperture of 4.2 m and a focal length of 10.5 m (f/2.5). Its diameter-to-thickness ratio of 8 makes it thinner than for most large telescopes built in recent years, but it is not classifiable as a thin mirror and raises no special problems for its support system. The precise diameter of 4.2 m was determined by the availability of the mirror blank, made by Owens-Illinois. The mirror is now undergoing its final stages of figuring at Grubb Parsons. It is believed that this will be the most accurate large mirror yet made, concentrating 85% of the light of a distant star into an area only 0.3 arc sec in diameter. As at the summer of 1985, interferometric tests indicated that its specification had been met. The mirror figure was specified by means of the irregularities in the wavefront reflected from it. It is necessary for the mirror to be very smooth and accurate on scales of 20 cm or less, since this is about the size of the atmospheric cells above the La Palma site. Portions on the mirror separated by larger distances than this may be tilted relative to one another so long as they direct the light within the 0.3 arc sec tolerance. Thus, the mirror is accurate to within 1/50 of the wavelength of light at a scale of 2 cm, about 1/15 wavelength at 8 cm and about 1/2 wavelength at 1 m or more.

The focus of the uncorrected primary mirror would show strong coma off-axis but the incorporation of a three-element correcting lens before the prime focus will give an unvignetted field of 40 arc min diameter extending to 60 arc min diameter at nominally 0.6 transmission. The effective focal ratio of the primary mirror with corrector is f/2.8.

When not operating at prime focus, a convex hyperboloidal secondary mirror, made of Zerodur, 1.0 m in diameter, directs the light through a central hole in the primary mirror to the main instrumentation mounted at the Cassegrain focus beneath the primary mirror cell. The telescope also incorporates a third main mirror, a flat, angled at 45°, which can be motor-driven into position at the intersection of the axes, just above the primary mirror, so that the light from the secondary is diverted sideways either through one of the altitude bearings to the Nasmyth platforms where particularly large or massive instruments can be placed, or to an intermediate, folded Cassegrain position for use of small, subsidiary instruments. As desired during the night, instruments mounted at any of these four stations can be selected within minutes by the motion of the single Nasmyth flat mirror. The effective focal length of the telescope for the Cassegrain and Nasymth foci is 46.2 m (f/11). The available unvignetted field diameters are 15 arc min at the direct Cassegrain focus and 5 arc min at the Nasmyth and folded Cassegrain foci.

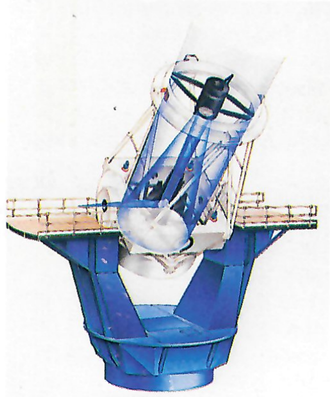


Diagram of the Herschel Telescope shows the light path (blue) directed to the Nasmyth focus.

Instrumentation for the William Herschel Telescope

The utility of any telescope depends hugely on the capability of the instruments it feeds. The continual, rapid increase in the functional sophistication of instrumentation for optical astronomy, and the frequent introduction of major enhancements or of fundamentally new instruments, means that a description of the suite of instruments now in preparation for the WHT should be taken in some respects as illustrative. Nevertheless, there is a basic requirement for versatile and efficient spectrographic instruments, these representing the major analytical technique of the astronomer, and for highly sensitive imaging detectors both to serve in such spectrographs and for direct imaging purposes. Such equipment for the WHT, in concept at least, will persist for the foreseeable future. There will be, of course, a continual trend towards higher optical efficiency and increased detector sensitivity; the clear potential for this can be seen from the fact that the overall efficiency of the telescope and a typical complex instrument with its detector rarely exceeds a few per cent, and that this is some orders of magnitude greater than was available just a few decades ago.

After a call for competitive tender to propose and produce instrumentation for the WHT, several groups in the UK and Netherlands astronomical communities are now involved in the production of the core instruments to be brought into use over the first few years of telescope operation. Production of some instruments, and the instrumentation support infrastructure including control system and acquisition and guidance facilities, together with the general coordination and management of all the instrument work, is the responsibility of the RGO.

The core instruments and related facilities now in production, design or planning stages are: a versatile intermediate dispersion double spectrograph (known as ISIS), a fixed-format highly efficient low dispersion spectrograph (known as the Faint Object Spectrograph, FOS) functionally integrated with ISIS, a polarization unit incorporated within ISIS and also available for the FOS, an imaging Fabry–Perot interferometer with additional imaging options (known as TAURUS II), a high-dispersion echelle spectrograph, a Fabry–Perot unit for the latter, infra-red instrumentation yet to be fully specified, a prime-focus camera for photographic plates or electronic detectors, an Image Photon Counting System (IPCS II) and a charge-coupled device (CCD) camera system both with several head units to operate with the above instruments as appropriate or to be used for direct imaging, and units to provide acquisition and guidance facilities for these instruments. These instruments and detectors are disposed around the four principal focal stations of the telescope. The rapid changes between Cassegrain and Nasmyth foci made possible by use of the movable Nasmyth flat mirror will allow, for individual objects, near-simultaneous observations with different instruments, as well as matching of the needs of different observing programmes with the prevailing conditions so facilitating 'flexible scheduling' of observing allocations.

The number of instruments and detectors that will be either in use or mounted and available for use at any one time, together with the problems of handling very large quantities of high-bandwidth data, require the adoption of an integrated system approach to the management of the observing functions. This is described elsewhere in this report.

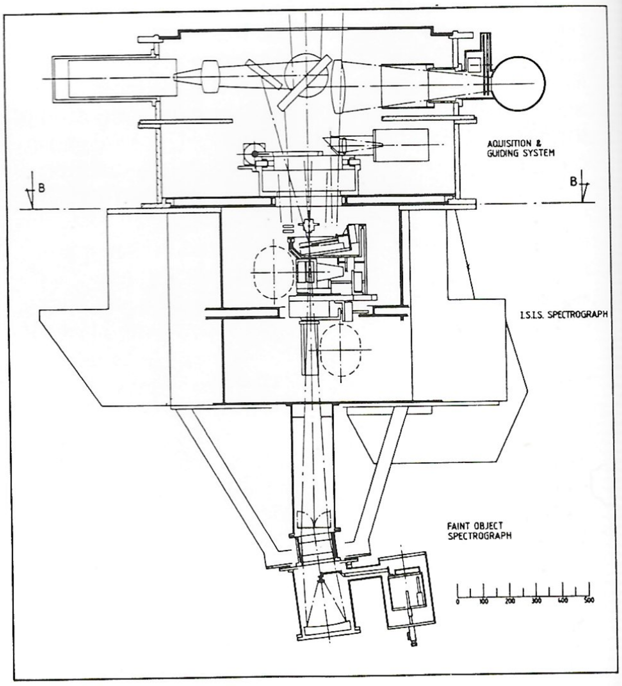
Like the telescope, all the instrumentation and related facilities are being built to be operated fully remotely. Initially the observers will be positioned inside the nearby control room as is now conventional, but it is planned that a substantial proportion of observing will be conducted from a control room in the RGO's home base in the UK, possibly also linked to the observers' home institutions. The need for travelling to the distant observatory site thus obviated, flexible scheduling of different programmes, according to observing conditions, becomes a practical proposition.

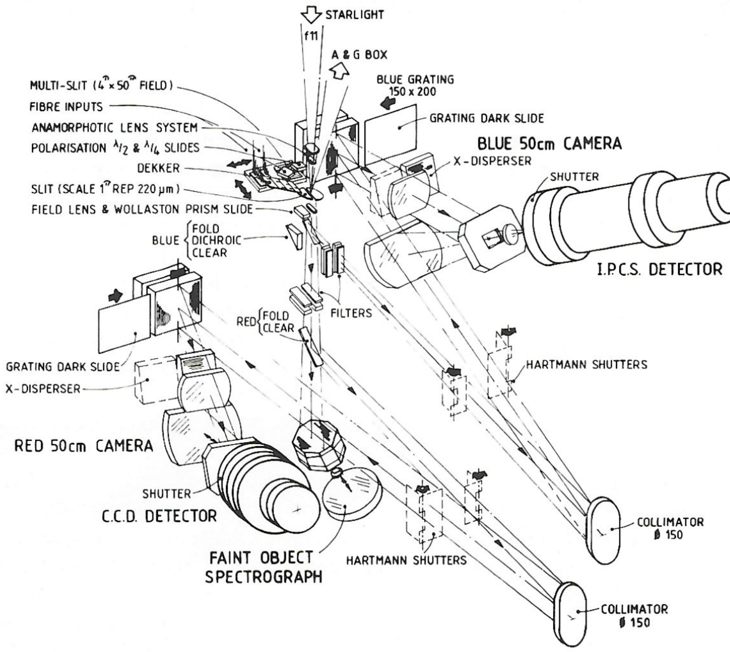
A. Boksenberg

WHT – the Cassegrain instruments

Cassegrain Acquisition and Guidance Unit

This unit, now in production at the RGO, provides a rigid support for the acquisition television camera and autoguider systems it contains, and a mounting for the Cassegrain instruments. The autoguider is based on the use of a CCD as detector, which is fed by means of a scanning prism assembly which can rotate about the instrument axis and be moved radially to acquire an appropriate guide star. In addition to the main instrument mounting face, the unit has an auxiliary focal station with the full unvignetted 15 arc min Cassegrain field available for multi-object spectroscopy using optical fibre probes. The future incorporation of an image stabilization system, basically a high-bandwidth autoguider probe and actuated mirror, is planned as an optional feed for the main instruments to take advantage of the marked reduction in instantaneous image size this gives. An atmospheric dispersion corrector will be mounted just above the unit, within the telescope tube. The A&G unit has been specified and final mechanical design began at RGO in the summer of 1985.





Faint Object Spectrograph

The FOS is a collimator-less dedicated (not versatile) spectrograph designed to have the utmost efficiency for use at low dispersion and covering the widest possible wavelength range. It employs a transmission grating whose substrate is cemented onto a cross-dispersing prism which in turn is cemented onto the aspheric plate of a Schmidt-type camera, so eliminating four glass-air surfaces. The grating lies in the divergent beam from the ISIS slit assembly when the straight-through mode is selected. The resultant complicated aberrations are satisfactorily corrected by appropriate adjustments in the separation, tilt and centering of the rest of the components of the system. A CCD detector is mounted on a cooled finger which supports it at the internal focus of the Schmidt-type camera so avoiding the need for a further reflecting surface to provide an external focus as for the ISIS cameras. A similar spectrograph, built jointly by the RGO and Durham University, is operating on the Isaac Newton Telescope. The WHT spectrograph has been optically designed and its integration with ISIS defined but no arrangements have been made (as of summer 1985) to make it.

TAURUS II

TAURUS is a wide-field (9 arc min) imaging Fabry–Perot interferometer originally developed jointly by the RGO and Imperial College, London to map velocity fields of extended or multiple astronomical emission-line sources. The original instrument is in use on the INT on La Palma. A new, fully automated version, TAURUS II, is being built by the Kapteyn Sterrenwacht Werkgroep in Roden, the Netherlands, with some technical input from the RGO. It is to be one of the Cassegrain instruments.

Detectors

The CCD camera system for the WHT is being developed jointly by the Radiosterrenwacht at Dwingeloo in the Netherlands, and the RGO. It is a development of the CCD camera designed by the RGO for the Isaac Newton Telescope. The new design retains the flexibility of programmable waveforms, but emphasis has been placed on the ability to drive and read out several different CCD chips either together or separately. Large format CCDs, now in development by more than one manufacturer, also can be accommodated.

The IPCS II is an evolution from the original IPCS developed at University College London. A new CCD-based readout system to replace the Plumbicon tube system, and new centroiding electronics employing an interpolative method, are under construction at UCL. This will be preceded either by the four-stage intensifier also used in the original system but with a new coupling lens or by a microchannel plate intensifier with tapered fibre optic or lens coupling.

ISIS

This versatile Cassegrain instrument consists of two intermediate dispersion spectrographs which can be operated one at a time or simultaneously, and are separately optimized for the blue and red spectral regions. This is to be the workhorse instrument of the telescope and is expected to be used for the majority of the observing programmes. It is being produced by the RGO and Oxford University in a collaborative effort with the design and construction carried out dominantly at the RGO.

The main design goals are to provide: a range of dispersions between 130 and 16 Å mm^{-1} in first order, corresponding to a range in resolving power respectively between 800 and 7000 when using a narrow (0.5 arc sec) slitwidth; maximum possible throughput; high operating efficiency in both the setting-up and observing modes, with the capability of operating the blue and red spectrographs as a single unit; rapid interchange between ISIS and the Faint Object Spectrograph, which share the same slit assembly; long slit (4 arc min), multi-slit and fibre optic feed capabilities; a cross-dispersed mode capable of recording the wavelength range from 300 to 1100 nm with a resolving power of about 2000; facilities for spectro-polarimetry; and full capability of being remotely operated. At the summer of 1985 ISIS was fully specified and in an advanced state of design, with some subassemblies manufactured.

Factory tests of the William Herschel Telescope

The telescope was fully assembled at the Grubb Parsons' factory in Newcastle in order to test the complete system and thus minimise the construction and commissioning period on the mountain site. Factory tests were carried out between August and November 1984 on the telescope, including its control system as built by Marconi.

The tests on the telescope have shown that the structure has a high natural frequency and negligible hysteresis. This confirmed the results expected from the extensive analysis of the telescope structure using the techniques of finite element analysis and various design optimisations of the total telescope mounting and tube. All the subassemblies which had been manufactured under separate contracts were individually bench tested prior to the full shop assembly. It is impractical to detail every one of these tests in this report. The weeks of testing which involved every last cable and connector are the unglamorous side of the job but the careful attention paid to the job in Newcastle will pay dividends in the commissioning period in the harsher conditions on the mountain top in La Palma.

Besides the RGO team, there was also an independent team of inspectors from the firm of Guthrie and Craig who provided valuable support on a day-to-day basis. After all the subassemblies had been tested, the computer was connected to the system and the performance of the servo-systems evaluated. The Grubb Parsons' factory was far from ideal for this testing for a variety of reasons. These included the vibrations coming from the heavy machines in the adjacent buildings, spikes down the mains and the high audio noise levels from the hydraulic pumps. Despite these problems it became clear that the tests were even more important than originally intended because NEI Parsons have announced that the William Herschel, whilst being the biggest telescope they ever built, would also be their last. The testing covered three main areas. These were:

Safety
Drive Controls and Stability tests
Soak tests

Safety tests

The movements of an alt-az telescope are all controlled by the computer systems. It is important however that the telescope is protected from hardware faults or programming errors. The WHT has a set of interlocks that protect the telescope from being operated in an unsafe way. Thus, any attempt by the computer to drive the telescope with too fast an acceleration or too low an altitude will invoke an interlock which takes control away from the computer and leaves the telescope in a safe condition. Proving that these interlocks work reliably is a delicate job and required the greatest cooperation between the mechanical, electronic, electrical and computer engineers of Grubbs, Marconi and the RGO. The other safety problem was that the WHT is so large that it only just fitted into the factory and this meant that not all combinations of the full alt-az range were available together.

Drive controls and stability tests

Once the telescope was shown to operate in a safe manner, the work commenced on checking the encoding systems that are on the various axes. The WHT will use in full operation the altitude, azimuth and focus drives plus one of either Prime or Cassegrain rotator drives. (The Nasmyth Rotator is a separate system.) Each of these drives has an absolute encoding system. In addition, there are fine resolution incremental encoding systems on the altitude and azimuth axes. These are of two types. The first encoding system is driven through a gearing system and is expected to be the normal encoding system in operation. The second system is an experimental friction driven encoder which may have potential use for large future telescopes. The servo-amplifiers were tuned by Marconi to give the optimal performance within the factory. Of course it was not possible to check the encoder systems against the external reference system of the sky. However the internal consistency of the two incremental systems shows the likely external consistency achievable. The two agreed everywhere to within 0.1 arc sec. The roller bearing appeared smoother than the gear driven system, which appeared to show tooth-to-tooth errors. Obviously, any errors affect the tracking of the telescope, which the tests showed everywhere to be just within specification. The performance on site should be better because the main pier in the telescope building is a lot stiffer than the floor at Grubb Parsons.

Soak tests

The final testing phase was to put the telescope through a soak test where as many mechanisms as possible were run simultaneously for many hours. In this way, faults that occur rarely or equipment that is of marginal reliability can be pinpointed and rectified before even leaving the factory. The total number of telescope slews performed was equivalent to many months of actual operation. One interesting test was of the azimuth tachometer where the drive was cycled at maximum acceleration between maximum positive and negative velocity whilst at the same time driving the Cassegrain turntable with a similar duty cycle. The abrupt change of velocity at maximum velocity is accomplished without noticable oscillation, which is evidently damped away within the resolution of this plot (about 0.1 sec).

There is a hysteresis, within tolerance, of a fraction of a second at zero velocity. This measures the stickiness of the azimuth axis: the test probes the performance of an altazimuth telescope at a velocity which is not used by equatorial telescopes except to set the declination. Problems of over- or under-shoot during the setting of declination axis of an equatorial telescope are merely irritating or inefficient. For an altazimuth telescope any similar problems in the azimuth axis would be fatal at maximum elongation of a star from the pole, and, for the altitude axis, at culmination. Again the telescope tracking was within the specification as it passed those crucial points, even at maximum deceleration.

The conclusions which resulted from all these tests are that the design of the WHT is satisfactory and within the specification in every way. Indeed, the Cassegrain rotation turntable was operated at double the original design load and still worked perfectly. The results of all these tests is that the telescope is expected to have an excellent pointing and tracking performance on site.

The WHT tests were performed by a team comprising R.H. Adams, S.M. Atkinson, D.J. Harman, B. Mack, R. Martin, K.R. Pope, J.V. Smith, H. Stevenson and P.B. Taylor.

The telescope was featured in TV programmes on Channel 4 and BBC's 'Tomorrow's World' during the tests. Finally, upon completion of the tests, the telescope was featured as part of the NEI's Open Day and attracted 600–700 visitors.

R. Martin

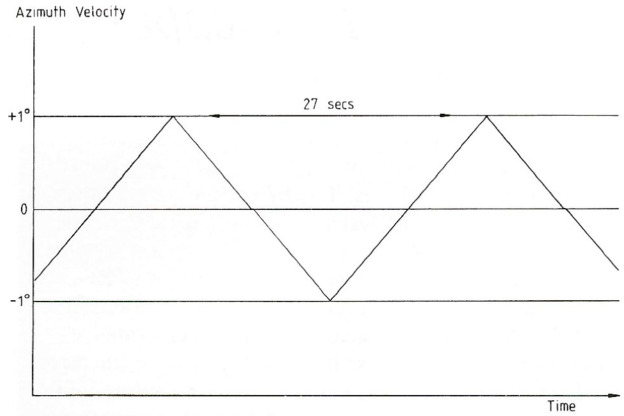
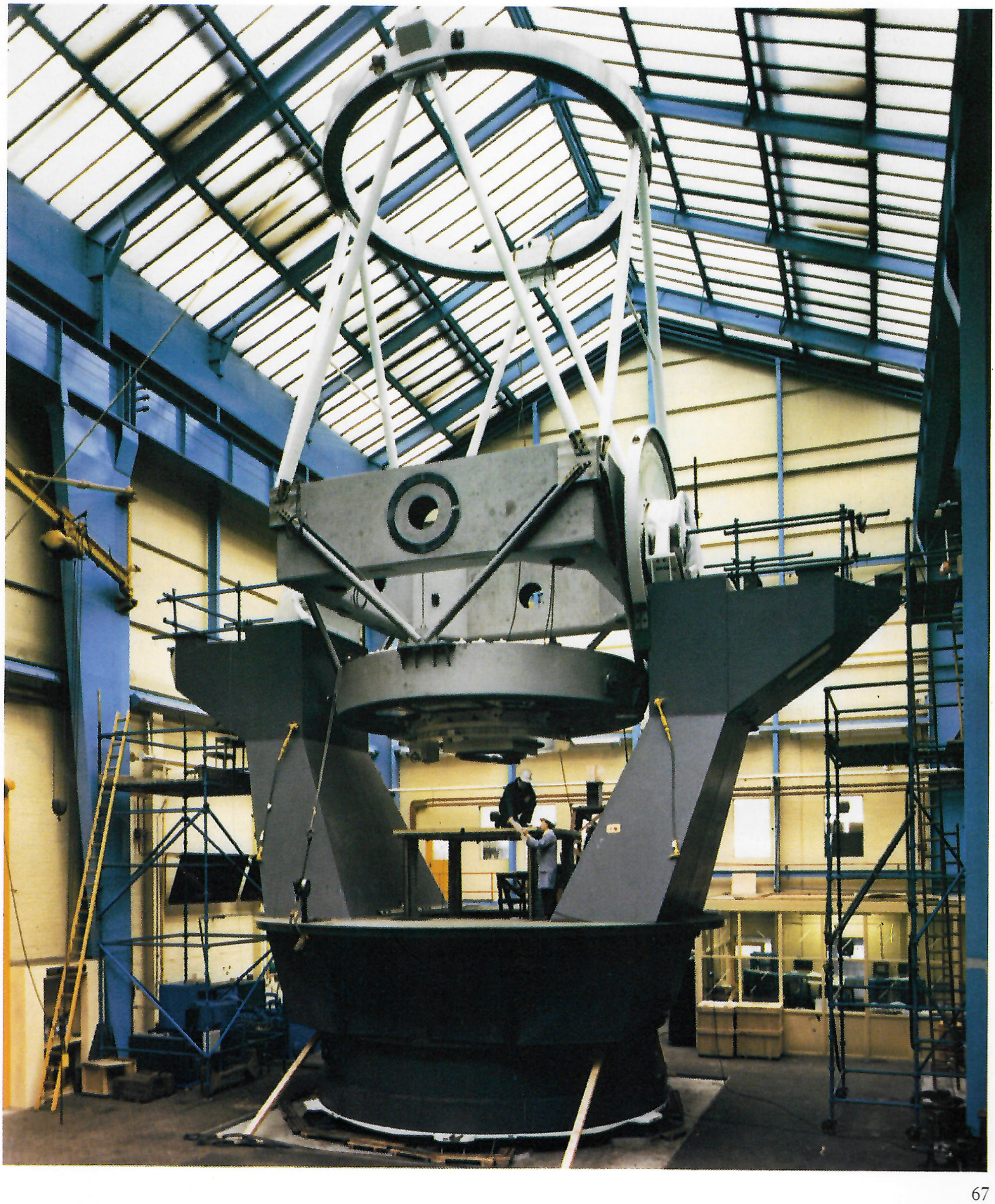


Fig. 1 The telescope axes were cycled at maximum acceleration with a period of 27 secs during soak tests, to check for oscillation and hysteresis. This plot of azimuth velocity shows no over- or under-shoot outside tolerance, but measures the small hysteresis at zero velocity.

Fig. 2 William Herschel Telescope in the factory.



Optical design

A new optical design is needed for most astronomical instruments: it is unusual to find standard lenses or existing optical designs which will suit. This is because any optics affecting the starlight are critical as regards performance. The optical design has to be matched to the properties of a particular detector, and in particular to function over a given range of wavelengths. The wavelength coverage required usually exceeds that available with existing designs and mass-produced lenses.

The RGO produces its own designs for optics and handles the procurement, testing and assembly of optical systems. Items which have been made for La Palma have included the optics for the telescopes, and instrumentation. Completed auxiliary instruments include the intermediate dispersion spectrograph for the 2.5 m Isaac Newton Telescope and the Faint Object Spectrograph. Major items currently being designed or procured include: the intermediate dispersion spectrograph (ISIS) for the 4.2 m telescope; the prime-focus corrector lens for the 4.2 m telescope; the optics for the TAURUS II interferometer and Low Dispersion Survey Spectrograph; the relay lens for the IPCS II detector system; and the image rotator for the Nasmyth focus of the 4.2 m telescope.

The RGO has no optical manufacturing facility. The lenses and mirrors which we require are produced by different companies as a result of tenders. However, testing, coating, mounting and adjustment are usually carried out by the RGO, particularly in view of the maintenance requirement associated with each of these functions. Also, we have frequently to specify and purchase the individual blanks of optical glasses and mirror substrate materials required to implement our designs.

The RGO coating laboratory

A specialised optical coating facility has been established in order to carry out the design and manufacture of optical coatings to satisfy the critical requirements of astronomical optics.

A BBC-microcomputer-based system provides a design facility for tailor-made coatings, which can then be produced in an advanced vacuum coating plant. This unit evaporates coating materials from electron beam sources onto optical components up to a third of a metre in diameter, rotated in a complex motion on a planetary mount, ensuring excellent coating uniformity. The evaporation processes are controlled by both an optical monitor and an automatic mass monitor. Coatings comprising up to 32 dielectric layers have been produced in this way. A simpler large rotating holder allows for coatings of less complexity and uniformity to be applied to substrates up to 800 mm in diameter. A semi-automatic ultra-violet/visible spectrophotometer is used to evaluate the completed coatings.

The coating laboratory has produced anti-reflection coatings, high reflectivity protected mirrors, dichroic filters and many other special coatings for the RGO, other SERC establishments and universities.

Optical fibres

Investigations have been carried out into the properties of optical fibres relevant to their use for feeding the light from many astronomical sources into a single spectrograph for simultaneous analysis. Our measurements have allowed us to select from the multitude of fibres available, those most suitable for our particular applications. Techniques have been developed for terminating the fibres with a better optical finish and precision than that generally required for communications applications.

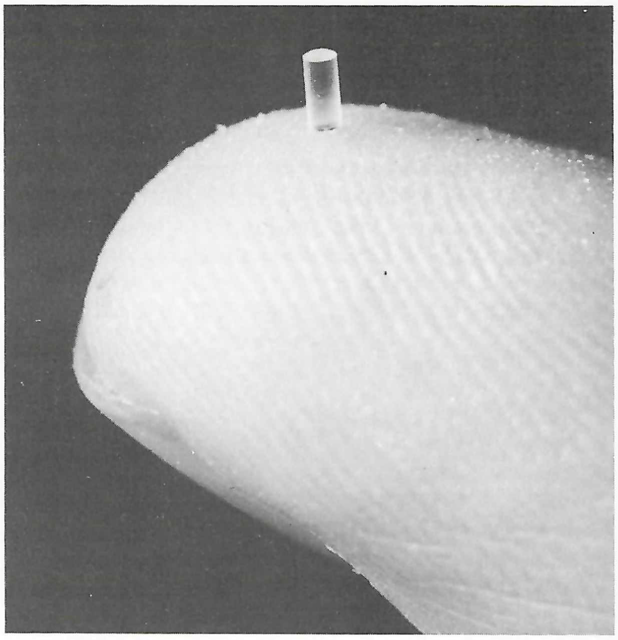


Fig. 1 The smallest optical components procured by the RGO in the last five years form a set of microlenses used to couple fibre optics to a spectrograph. The lenses convert the fast effective f-ratio of the fibres to the slower input f-ratio of a spectrograph collimator.

In order to maximise the optical coupling efficiency of fibres to spectrographs, we are pioneering the use of individual microlenses on each fibre.

A prototype system is being built, using microlenses and 15 metre lengths of fibre to feed simultaneously the Cassegrain spectrograph of the 2.5 m INT telescope from the images of 40 astronomical objects at the prime focus. This will give a large increase in the efficiency of telescope usage for particular applications. Multi-object spectrograph feeds are also being prepared for the 4.2 m WHT.

Substantial items of optics work 1980–5 at the RGO

Major telescope optics – inspection for progress and acceptance
ISIS spectrograph design
Cameras for echelle spectrographs for Anglo-Australian and 4.2 m telescopes
TAURUS II
25 cm spectrograph camera for Anglo-Australian Telescope
Coudé spectrograph for Isaac Newton Telescope
Future Large Telescope designs
Image rotator for 4.2 m Nasmyth focus
Prime-focus corrector for 4.2 m telescope
Scale-reducing lens for CCDs and TV cameras
FOS – Faint Object Spectrograph
LDSS – Low Dispersion Survey Spectrograph
FORS – Faint Object Red Spectrograph
Atmospheric dispersion correctors
Acquisition and Guidance box for 4.2 m telescope
Infra-red spectrometers
IPCS relay lens for CCDs

R. Bingham

Spectrograph cameras for ISIS

ISIS is the intermediate dispersion spectrograph for the William Herschel Telescope. It is a dual-beam system with 'blue' and 'red' channels being fed by a dichroic beam-splitter. During the design study phase of ISIS several camera designs have been investigated. They are all variations of the Wynne short Schmidt camera which yields good image quality over a wide wavelength range with an accessible focal plane provided by introducing a pierced folding flat mirror into the camera. A range of focal lengths, from 28 to 50 cm, has been considered with a view to optimum matching to detector resolution and field size. All designs are configured to accept, without vignetting, the 150 mm collimated beam which can be dilated at the grating to 200 mm.

In the early stages of the spectrograph design, the CCDs available as detectors for the red channel were all small in size and so shorter focal lengths were considered in order to increase spectral and spatial coverage at the expense of wavelength resolution. These faster cameras, f/1.4 and f/1.6, are more efficient if the CCD is mounted inside the camera, the obstruction from the detector and its associated support structure being considerably less than that produced by the pierced folding flat mirror required to produce an accessible back focal plane. With the advent of larger CCDs and the fall-back option of mounting two small chips side by side in the same cryostat the final configuration decided upon for both blue and red cameras is a 50 cm focal length which yields an image spread, in the wavelength range 300 to 1000 nm, of better than 15 μm over a field of 40 mm by 20 mm.

Camera designs of this type are also being provided for the high-resolution echelle spectrographs for the AAT and the WHT.

Image rotator for the William Herschel Telescope

To compensate for the rotation of the star field which occurs in an altazimuth-mounted telescope, motor-driven turntables are provided for the instruments at the prime focus and Cassegrain observing stations of the William Herschel Telescope. Instruments will not be rotated at the Nasymth stations but an optical image rotator will be introduced when required. To reduce both light loss and polarisation in the image rotator, prisms of fused silica with total internal reflection are used rather than mirrors. Fused silica lenses cemented to these prisms, with a final element of UBK7 glass, extend the optical path (as is necessary to provide an accessible focus) to give an effective focal ratio of f/11.2. With the telescope refocussed by moving the secondary mirror downwards by 3.82 mm, the position of the final focus is identical to that of the normal Nasmyth focus. The final image rotates at twice the angular speed of the rotator optics, which also change the image parity. The detailed geometrical-optics design was produced at the RGO, giving aberration correction, together with essentially unchanged image position focal length and exit pupil position.

The image rotator for the Nasmyth focus of the William Herschel Telescope is a new design which reduces light loss and polarisation and leaves the focus unchanged from the straight-through position.

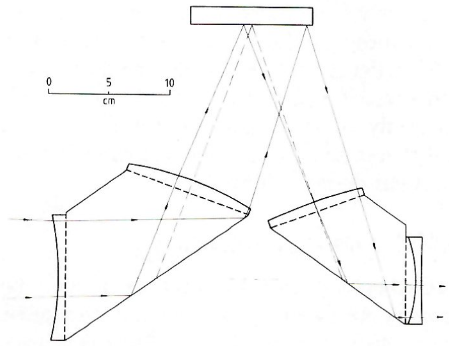
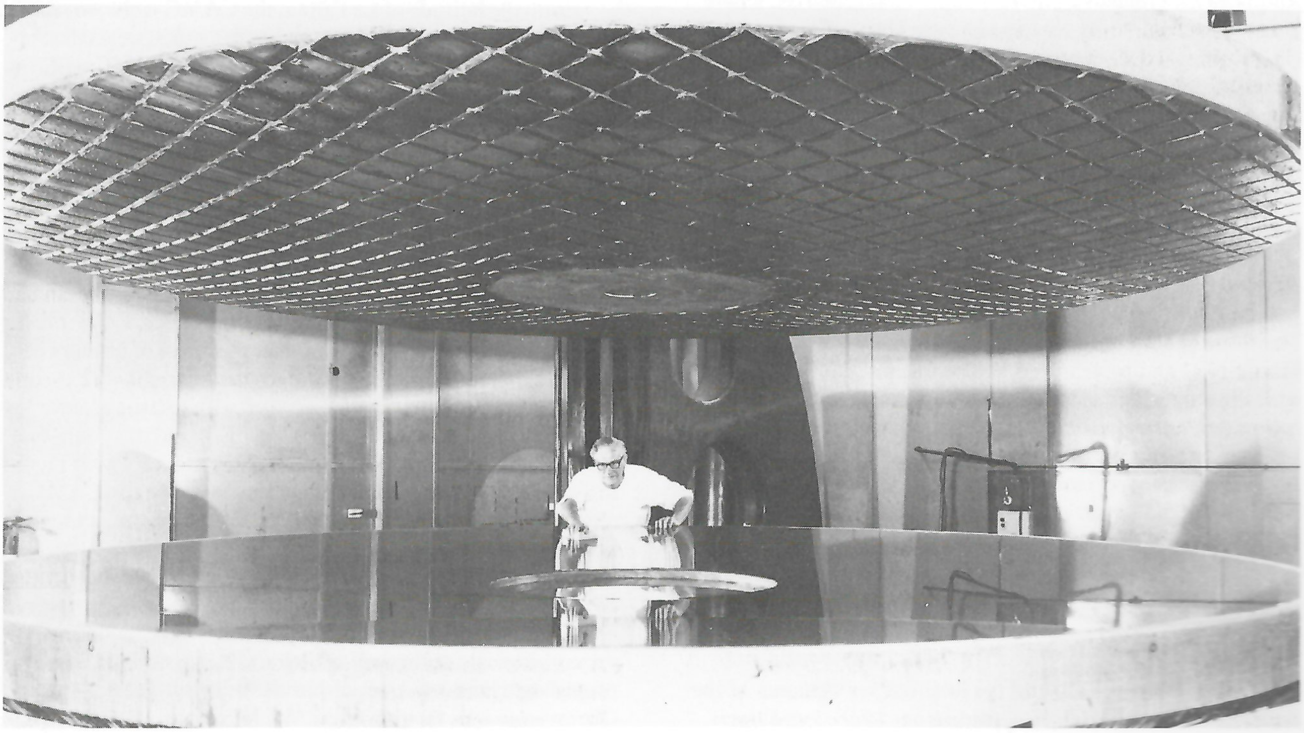


Fig. 2 The largest optical component procured by RGO is the 4.2 m mirror for the William Herschel Telescope seen here under its pitch lap in Grubb Parsons optical works.



Carlsberg Automatic Meridian Circle

The Carlsberg Meridian Circle was made by Grubb Parsons in 1952 to the same specification as the Cooke Reversible Transit Circle which was in operation at the RGO until 1982. It has a clear aperture of 178 mm and a focal length of 2665 mm.

The telescope was put into operation at Copenhagen University Observatory, Brorfelde, Denmark where it carried out observing programmes between 1964–76 using a photographic micrometer. On completion of these programmes a major overhaul of the instrument was undertaken in order to automate the observing process under the control of two HP minicomputers. A new type of impersonal, photoelectric micrometer replaced the photographic micrometer. With this micrometer being completely controlled by a computer, it was decided to automate the rest of the instrument, thus removing the observer completely from the telescope, and from having an influence on the observations. This completely eliminated such effects as heating the instrument or parts by the observer's proximity to the telescope, mis-setting of the circle and mis-reading of the meteorological data and last, but not least, the personal influence on measuring the photographic plates. Finally, from the financial point of view, for about one third to one quarter of the manpower involved in manual operation one could acquire several times as many observations in the same time and of consistent quality.

The CAMC incorporates: an automatic setting system; a new type of impersonal photoelectric micrometer; automatic meteorological data collection; a photoelectric collimation micrometer; and an improved circle-reading system. The computers control all the movements of the telescope, including the micrometer and the circle-reading scanners, and collect data from the various photomultipliers, limit-switches and other sensors.

In order to utilize the resultant increase in efficiency it was decided to move the CAMC to a better site. An agreement was signed in 1979 between the Science Research Council of the UK and Copenhagen University of Denmark to collaborate in moving the CAMC to the Observatorio del Roque de los Muchachos on La Palma, Islas Canarias, where it would be run jointly by Copenhagen University Observatory (CUO) and the RGO. In 1982, the Instituto de Astrofisica de Canarias delegated to the Instituto y Observatorio de Marina (IOM) its use of the observing time on the CAMC. The project then became a tripartite collaboration between CUO, RGO, and IOM.

Two short test programmes of observations were carried out in Denmark during the years 1981–83 before the telescope was dismantled and shipped to La Palma. These observations showed that the instrument met the expected standards of efficiency and accuracy.

The telescope was taken out of operation at Brorfelde in March 1983 and refurbished before shipping to La Palma with the computers in August 1983. The telescope and computers were assembled in the purpose-built housing on La Palma during the period September 1983 to February 1984. The telescope was aligned and tested during March and April 1984, and began regular operation on 1 May 1984.

The provisional geodetic coordinates of the CAMC are:

$$\left.\begin{array}{l}\text{latitude } 28^\circ\,45'\,31''\,\text{N}\\ \text{longitude } 17^\circ\,52'\,50''\,\text{W}\\ \text{height } 2327\text{ m}\end{array}\right\}\quad\text{geodetic position}$$

One of the first results to emerge during the alignment of the instrument were the values of the astronomical coordinates. These were found to be:

$$\left.\begin{array}{l}\text{latitude } 28^\circ\,45'\,52''\,\text{N}\\ \text{longitude } 17^\circ\,53'\,08''\,\text{W}\end{array}\right\}\quad\text{astronomical position}$$

These imply a deflection of the vertical of about 20″ in latitude and longitude. This is large, but not impossibly so for a small island in an ocean. A new survey of the island conducted in 1984 will confirm whether the deflection is indeed 20″, or whether the island is misplaced by 600 m!

The observations are reduced daily to the FK4 system. When a sufficient number of good observations is acquired (usually 4), the star is automatically removed from the observing programme.

The completed stars are to be published annually, together with revised values of their proper motions. The observations of planets and minor planets will also be included in these annals.

In the first period of operation 1 May 1984 to 12 December 1984 the CAMC made the following observations:

35 100 observations of 5292 programme stars in the magnitude range $3 < m_v < 13$
274 observations of Mars, Jupiter, Saturn, Uranus and Neptune
664 observations of 14 minor planets

The standard deviations, σ, for programme stars within 30° of the zenith are given below, showing the accuracy of the instrument on La Palma and in Denmark.

	La Palma	**Denmark**
$\sigma_\alpha \cos\delta$	$0^s.0129$	$0^s.0128$
σ_δ	$0''.184$	$0''.203$
σ_m	$0^m.054$	$0^m.1$

There is not a very strong dependence of σ on magnitude, except for the faintest stars around 13.0 which are near the limit of the telescope and detector system. The value of σ for these is about 50% greater than for stars brighter than 12.0. This near-independence on magnitude is the result of increasing the number of scans on fainter stars.

From the latitude of La Palma, the CAMC is able to reach a declination of − 45° without losing too much in accuracy (which is a function of zenith distance). The CAMC will, therefore, make an important contribution to improving the quality of the reference frame in the south.

An early result obtained in 1984 was the confirmation of the warping of the fundamental bright-star reference frame defined by the FK4 catalogue. The residuals, CAMC–FK4, in right ascension plotted against declination agree with the results of the PERTH 70 catalogue that the right ascension system of the FK4 is systematically shifted in some southern bands of declination by nearly 0″.2 at the epoch 1984. This means, for example, that the optical positions of quasars in right ascension at different southern declinations will certainly not agree to better than 0″.2 with quasi-absolute radio positions which are tied to the FK4 system at only one point in right ascension. About 700 reference stars with $11 < m_v < 13$ in the fields of quasars are included in the CAMC observations for 1984. These positions are not subject to this distortion in the FK4.

The good seeing and transparency on La Palma show the advantages of the site for the programme of global astrometry being carried out by the CAMC. The CAMC's records of meteorological conditions, seeing and extinction are also providing useful information for the other telescopes at the Observatorio del Roque de los Muchachos.

L. V. Morrison

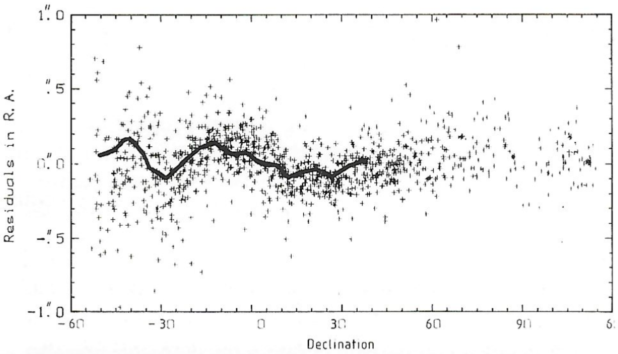


Fig. 1 Differences in right ascension between the observed positions (CAMC) and the positions from the FK4 catalogue, plotted against declination. The solid line is the systematic trend found in the PERTH 70 catalogue.

Fig. 2 The Carlsberg Automatic Meridian Circle moves in a north–south plane, looking through a slit which opens in a roll-off building to the stars which transit above the instrument.

Photoelectric moving-slit micrometer

An impersonal photoelectric moving-slit micrometer is used to record the transits of stars and planets. The slit plate is mounted on a carriage in the focal plane of the telescope. This slit plate contains a selection of slits and pin-holes used to view different objects such as nadir, planets and stars. The two slits (V-shaped) used for normal star observations are inclined at 45° to the meridian. The slits are 5″.5 wide in the east-west direction and cover 23″ in right ascension and declination.

Given the magnitude, right ascension and declination (δ) of an object, the process controller sets the telescope, including a correction for refraction, selects a filter, and calculates where to position the slits prior to making the observation. During a normal observation, the steadily-moving star image is scanned by driving the slits to and fro across the image. Normally, an observation consists of 8 traverses, each producing two 'peaks' in the photon counts from the photomultipliers.

When a star (or minor planet) is fainter than 10.0 magnitude (visual) the forward traverses are folded together and the reverse traverses are folded together. This increases the signal-to-noise ratio. The folding of profiles also helps to sort out the more complex signal received from double stars. The figure shows the folded signal obtained from the double star, Aitken 9728, components (A) 6.5 and (B) 6.6 magnitude, separation approx. 12″ in position angle 190°.

The total number of photoelectrons within each profile gives a measure of the total flux received by the passage of the slit across the star image and can be used to derive the stellar magnitude.

Part of the real-time reduction process includes deconvolving the stellar profile from the slit transmission function in order to obtain an estimate of the seeing.

Smaller telescopes

The Equatorial Group

The Equatorial (EQ) Group of Telescopes at Herstmonceux operates with a negligible input of resources. The four telescopes are used on an ad hoc basis by astronomers from UK universities and from the RGO. These telescopes comprise the 36-inch Yapp reflector, the 30-inch Thompson (Coudé) reflector, and the 26-inch and 13-inch refractors, the latter having the Franklin–Adams camera attached to its tube.

There are three principal functions for the EQ telescopes.

1 Test-beds. It is frequently beneficial to try new instruments or detectors near the home institution before taking them to a remote site, and both the 36-inch and the 30-inch telescopes have been used in this way. The list of instruments tested (since 1980) includes RGO CCD systems, most notably the 1500 × 1500 pixel GEC device, tested in contract with AAO; a reticon detector system built by the RGO for the spectrograph of the 74–inch reflector at SAAO and now in standard use there; a new spectrograph from Queen's University, Belfast; a CCD system from Durham; autoguiders for the INT and JKT on La Palma; the People's Photometer for the JKT; and an imaging photon detector from UCL.

2 Astrometry. The long-focus 26-inch and 13-inch refractors have well-established astrometric properties, and continue to be used for essential positional observations. For instance, a long series of plates with the 26-inch refractor has produced many accurate positions of active-galaxy nuclei, for comparison with radio and X-ray observations to provide precise coincidence of the celestial coordinate systems at each wavelength. The 26-inch telescope is also used to confirm supernovae detected by amateur astronomers, and to obtain astrometric positions for the supernovae. As an example of how such positions are used, the accurate position for Wild 1980, the supernova in NGC 6946, enabled the VLA to detect radio emission from it months before the current theories predicted that the radio emission should have reached detectable levels.

3 Monitoring of selected objects. A large programme of photographic photometry with the 26-inch refractor to obtain light-curves for many optically-variable QSOs was begun in the late 1960s and brought to a successful conclusion in 1982. At present, optical monitoring continues for a few selected objects such as the following:

NGC 4151: the optical light curve is essential in deducing the behaviour of the UV power-law continuum, in turn enabling a more detailed comparison between the emission-line and continuum variations.

PKS 0215–015: is the most distant BL Lac object known, and monitoring it has resulted in the identification of high-luminosity phases during which high-resolution spectra could be obtained with the AAT. The absorption-line systems in these spectra provided fundamental discoveries about the distribution of gas-clouds (proto-galaxies?) along the line-of-sight.

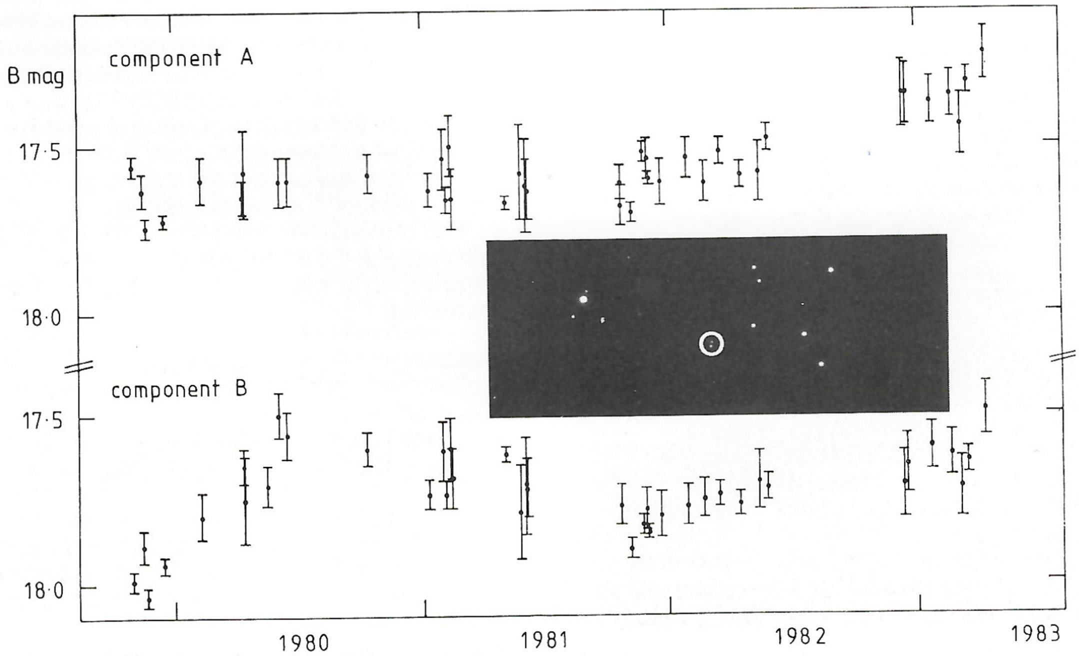
The double quasar 0957 + 561: has been monitored since 1979. The quasar pair is believed to be a double image of a single quasar seen behind a massive galaxy. The double image is produced by a lens effect of the galaxy gravitational field on the quasar light. The light-curves of the two images (Fig. 1) are plotted to determine the difference in light travel-time for the two components, essential in modelling the mass distribution lens producing the double image.

In addition the telescopes – and the 26-inch telescope in paritcular – carry out important cometary and planetary observations. Comets IRAS-Araki-Alcock (1983), Giacobini–Zinner (1985) and Halley (1985) are examples of the former, while examples of the latter are the set of observations of Saturn's satellites made to improve the orbit models, and observations made to predict star occultations by minor planets.

Future plans are to support the telescopes as part of the RGO astronomy exhibition, to make at least one telescope available to interested groups on a fairly regular basis, and to continue similar ad hoc scientific observations on short-term programmes of obvious scientific value.

J.V. Wall

Fig. 1 The double quasar 0957 + 561 from a 26-inch plate, and the light curves of its components. The brightening of B in 1970–80 does not appear simultaneously in A. When it becomes clear how one component follows the other, the gravitational lens can be modelled.



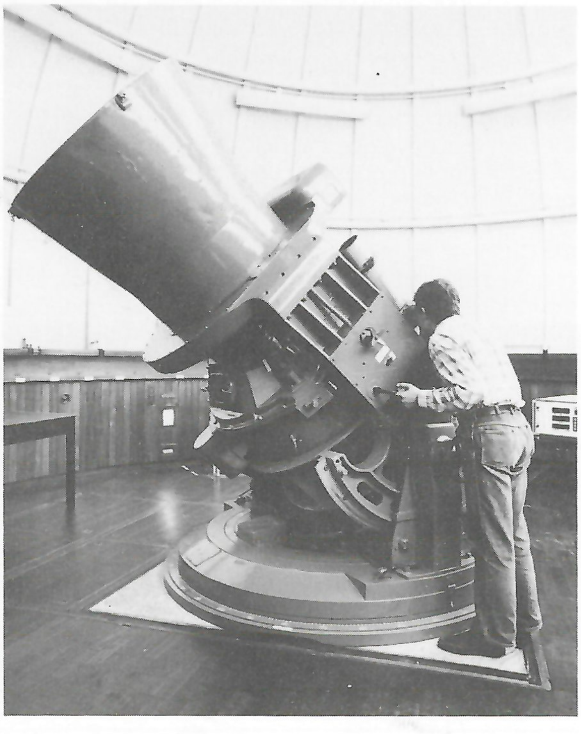
Hewitt satellite camera

The Hewitt satellite tracking camera was moved to Herstmonceux from a previous observing site at Evesham in Worcestershire, in the autumn of 1982. This was due to a desire to have the top UK satellite tracking instruments, consisting of the satellite laser ranger and camera, together at one location, where expertise could be shared.

The Hewitt camera now in Dome C of the Equatorial Group at Herstmonceux is one of a pair that was designed by the late Joseph Hewitt at the Royal Radar Establishment, Malvern, for use in tracking the Blue Streak ballistic missile. They were used at sites near Evesham and Edinburgh by the Ordnance Survey from 1967 onwards for geodetic triangulation using satellites. The cameras were transferred to the Earth Satellite Research Unit (ESRU) of the University of Aston in 1978 for geophysical research; positions of satellites are measured with an accuracy of 1 to 3 arc secs and are used to determine the changes of the orbital elements of selected satellites and hence the irregularities in the gravity field of the Earth and the variations in the density of the upper atmosphere. The Evesham camera was moved to Herstmonceux in 1982; the second camera, which had been mothballed since 1975, was moved to the Observatory at Siding Spring Mountain, Australia, and began operating again in 1980. ESRU provides a prediction service for the cameras and for amateur observers who make visual observations in support of the orbit analysis work carried out by ESRU and other groups. Financial support for the cameras is provided by the Department of Trade and Industry and by the Ministry of Defence, as well as by SERC and NERC.

Observations are often carried out on behalf of outside organisations, for example, the observation of geostationary objects for the Department of Trade and Industry. The re-entry of the Cosmos 1402 nuclear reactor in January 1983 gave much publicity to one of the more repetitive areas of space work, and showed worldwide the tracking capabilities of the camera based here at the RGO.

M. White



Spencer Jones Group

The Spencer Jones Group lies to the north-west of the Castle and contains pavilions for three astrometric instruments and an OS triangulation pillar. (The primary pillar for the Ordnance Survey triangulation of Great Britain lies to the south of the old Isaac Newton Telescope Building.) The main instrument is the Cooke reversible transit circle (RTC) which was brought into regular operation for the precise measurement of the positions (and proper motions) of the stars and of the Sun, Moon and planets. Operations ceased in April 1982 so that effort could be concentrated on the development of the Carlsberg Automatic Meridian Circle for La Palma. The RTC was used to make measurements of the positions of fundamental stars and members of the solar system. The observations of Uranus were used by JPL in calculations for the VOYAGER encounter in 1986, and the observations of the Sun were used by Dr Eddy of the National Centre for Atmospheric Research, Boulder, in his investigation of possible changes in the solar diameter.

The second major instrument is the photographic zenith telescope (PZT) which was in use to June 30 1984 for the determination of universal time (against atomic time provided by the Time Department) and latitude (by measuring, in effect, the angle between the directions of the zenith and of the axis of rotation of the Earth). The results are used for practical applications in navigation, land surveying, geodesy, and positional astronomy, while the corresponding variations in the length of (sidereal) day and in position of the pole of rotation with respect to the crust of the Earth are of great geophysical interest. The operation of the PZT for this purpose was stopped so more effort could be devoted to the operation of the new satellite laser ranging (SLR system, whose results are used in determining these variations with higher precision and for other purposes.

The RTC and PZT have been mothballed by the National Maritime Museum with a view to their being put on public exhibition in due course. The control building for the PZT (which was operated remotely) has been rented to a local firm for offices since October 1984.

The Danjon prismatic astrolabe, which is also used to study the rotation of the Earth, has been loaned to the National Observatory of Brazil and has been in use at the University Campus Natal, near the equator, where it is able to observe stars and planets in both celestial hemispheres.

The principal geodetic reference point at Herstmonceux is now the point of intersection of the axes of the SLR telescope. This point was connected by the Ordnance Survey in 1983, with a precision of about 1 mm, to the primary pillar south of the INT, to the other pillar near the RTC and PZT, and to other reference marks on the site.

Steavenson telescope

Under an agreement with the Instituto de Astrofisica de Andalucia (IAA) British astronomers have used the Steavenson telescope, of aperture 30 inches, at 10 000 feet in the Sierra Nevada near Granada in southern Spain. The telescope was refurbished at RGO prior to shipping to Spain; it is instrumented with photometers. The telescope was commissioned in 1982.

Satellite Laser Ranging

Laser ranging is the most accurate technique available for observing the orbits of artificial satellites. Although it can only be used with satellites carrying retroreflectors these are entirely passive, long-lasting, light and small and so are relatively easy to fit to satellites whose precise positions need to be known.

The satellite laser ranging system at the RGO obtained its first returns from the satellite Lageos (the Laser Geodynamic Satellite launched by NASA in 1976) in March 1983. More observations were made throughout the commissioning period and it has been in regular operation since October 1983. It is now recognized as one of the most effective and accurate installations in the global network that is needed to extract full benefit from the use of this technique.

The system was built jointly by the RGO and Hull University and its procurement was entirely funded by SERC. Hull's responsibilities covered the laser, timer, radar and receiver packages, while RGO dealt with the telescope, buildings and services, computers and almost all the software, and with their integration into the working system. Operation and maintenance are entirely the responsibility of RGO. There is, however, recognition that observations with the system are potentially valuable outside the normal fields of responsibility of SERC, and both DTI and MoD now contribute funds under a rolling 3-year agreement to support single-manned observing. NERC has also made a small contribution.

Since regular observing began operations have been scheduled to cover virtually all suitable passes of Lageos and Starlette, a similar but smaller satellite in a lower orbit. Both satellites are dense reflector-covered spheres dedicated to laser ranging. Their orbits are relatively insensitive to non-gravitational perturbations. Lageos, at a height of 6000 km, is observed primarily to obtain information about the rotation of the Earth and the geometry and deformation of its surface, while observations of Starlette are of greater significance for studies of the Earth's gravitational field, which is more irregular at lower altitude, and of orbital changes occurring as a result of tidal deformation of the Earth.

The SLR at Herstmonceux can work both day and night provided that the skies are clear. It is calibrated by regular ranging to local targets, and the effects of atmospheric refraction on measured range are computed from meteorological data with an estimated uncertainty of about 2 cm.

The instrument is intended for making very precise observations of satellites whose positions at the time of observation can be predicted to within a few tens of metres. Predictions are based on data distributed yearly (for Lageos) or weekly (for Starlette) by a coordinating centre and updated at RGO by using data from our most recent passes. A computer file of predicted positions is generated shortly before each pass and is used to control both the pointing of the telescope and the delay between emission of the laser pulse and re-arming of the timer. Close control of timer arming is essential for daytime operation, when it is typically done only 100 ns before the expected return.

The computer records the times of emission and of up to four photon-events that occur after re-arming. The timing resolution is 50 ps. Genuine returns lie on a smooth curve on a real-time display of observed residuals from the predicted range but are not otherwise identifiable.

During the pass the operator is responsible for maintaining a radar-assisted watch for aircraft approaching the emitted beam, but can glance quickly at the display to judge whether returns are being obtained. Controls are available to adjust instrumental settings if this seems appropriate.

After the pass the operator uses a cursor to define the shape and position of the best-fitting smooth curve on the display of residuals. Background points are rejected in an iterative procedure and a representative selection of observations is appended to data files maintained on an international computer system for use by the centres responsible for computing Earth-rotation parameters and updating orbit predictions. Full-rate data are submitted later, on tape, for archiving and distribution as standard data sets for more exhaustive analysis. Research aspects of the SLR programme are treated in a separate report.

The SLR telescope can also be used at night to make directional observations of sunlit satellites, whether or not these carry reflectors. In this mode it complements the Hewitt camera, which does not need such accurate orbital predictions but cannot provide immediate read-out of position. The telescope control software has recently been modified to improve its responsiveness to commands from the operator during tracking of less-well predicted satellites, but a sensitive wide-field TV camera will be essential for effective operations of this kind.

J.D.H. Pilkington

Aircraft safety

Although the average optical output power of the SLR laser is only about 200 mW, the short duration of the pulse, the small divergence of the beam and the focussing action of the eye could combine to produce damaging instantaneous power levels on the retina of an unprotected eye within the emitted beam. We therefore have to take precautions to ensure that the laser is never fired towards an aircraft, although the direct effect of the beam on the structure of an aircraft would be entirely negligible.

Protection is provided by a radar beam that tracks with the telescope and is arranged to disable laser action if an aircraft is detected. The radar system was assembled at RGO, using a radar dish and radome on long loan from RSRE Malvern and a commercial marine-band radar transceiver. The drive system for the dish was developed at RGO, as was the post-detector signal-processing unit that is needed to provide increased sensitivity and discrimination against direct reception of radar pulses from ships in the Channel. Pointing accuracy and sensitivity are checked regularly by using a target on the Downs, and the radar is always supplemented by a visual observer in the telescope dome whose main responsibility at this time is to inhibit firing if there is any doubt about laser safety.

Both the CAA and RSRE were consulted during construction of the SLR system and we are confident that the existing hardware and operating procedures provide full protection for the occupants of aircraft without unduly restricting ranging operations.

Fig. 1 The green beam of the stream of laser pulses sent to artificial satellites from the Satellite Laser Ranger is easily visible as the telescope works at night.

Time and Satellite Laser Ranging

It is appropriate that the satellite laser ranging (SLR) system is operated by the RGO's Time Department, but the relationship between the observations and time is no longer the traditional one. In earlier times the Department's role was to determine 'the time' by observations of the Earth's rotation, and to adjust the Observatory's master clock to agree with the results of the observations. Today the role is reversed; a world wide ensemble of atomic clocks defines the time and the observations quantify, among other things, the variability of the rotation of the Earth. Nevertheless, the link between today's observations and time is far more precise than could have been dreamed of in the older work.

The SLR system uses time information in several distinct ways. Most obviously, it uses precise measurements of time interval, and the known speed of light, to determine the distance between the reference point of the tracking instrument and the reflector on the satellite. The instants of emission of the light from the laser, and that of detection of the output pulse from the photomultiplier mounted on the receiving telescope, are each recorded in terms of a local continuous time-scale with a resolution of 50 ps, and the time-of-flight is deduced by subtraction. This technique allows more flexible modes of operation than the alternative 'stop watch' approach in which the timer runs only during the interval to be timed; for example, it simplifies the examination of several possible 'returns' from each shot, which is important during daytime operation when many random events are produced by light from the bright sky, and it could also allow several shots to be 'in the air' at once. It is conventional (and in this case entirely appropriate) to visualize very short intervals of time in terms of the corresponding distance traversed by light. 50 ps corresponds to approximately 1.5 cm or (for cosmologists) 4.8×10^{-25} Mpc.

The timing unit, which was built at the University of Maryland, uses a time expansion technique in which a capacitor is charged at a pre-set high rate during a short but unknown time interval, and its subsequent discharge at a much slower rate is timed by a conventional fast counter. A computer-controlled calibration and correction technique developed at RGO has greatly improved the accuracy available from this unit, which would otherwise have limited the overall accuracy of the ranging system. The observed single-shot rms scatter of about 5 cm almost certainly originates mainly in the photomultiplier.

In most precise measuring systems one of the major difficulties lies in establishing the accuracy of the scale unit; in ranging this means ensuring that the 'metre rule' is of the correct length. This is not a severe problem for the RGO's SLR because the metre has recently been redefined in terms of the SI second and a specified velocity of light. The RGO's existing time links make the SI second accessible to us with a long-term uncertainty of around a part in 10^{13} and short-term irregularities around 100 times larger, corresponding to about 0.1 mm in 10000 km; these uncertainties are at present negligible.

A less obvious requirement of the SLR system for precise time is that the observations should be dated in terms of a globally accessible time-scale with a permissible uncertainty of only around 1 μs in order that they may be properly combined with those obtained elsewhere. This figure is obtained by combining the ultimate accuracy of ranging (about 1 cm, set by propagation uncertainties in the atmosphere) with the relative velocities of the lowest satellites, which are of the order of 10 km/s. This requirement for precise time at the RGO is expected to continue even in the absence of a continuing commitment by SERC to the maintenance of atomic time services for external users.

More demands on system timing arise in principle during the analysis of SLR observations, but in this case the concern is with the overall quality of the global time-scale rather than the uncertainty with which it may be accessed. The time-scale used to date the observations must be capable of being related to the one that is implicit in the equations of motion of the satellite. Current indications are that for objects in orbit near the Earth other factors limit the attainable accuracy of analysis long before the uniformity of TAI becomes a problem – but this will remain true only while the formation of TAI is adequately supported. Comparisons of atomic time and dynamical time are of fundamental interest but demand long-term commitment; recent pulsar studies have suggested that dynamical time-scales may still present a challenge to the uniformity of TAI.

HIPPARCOS

The RGO participates in two HIPPARCOS consortia, the Input Catalogue Consortium and the Northern Data Analyses Consortium. The latter, refered to as NDAC, is one of two data reduction consortia. It consists of people working at institutes in the UK (RGO and MSSL), Denmark and Sweden. The major task of NDAC is to produce and run software for the data-reduction, such that 1.5 years after the end of the mission a preliminary mission-catalogue can be produced. RGO is committed to the first stage in the data reduction, involving almost on-line large-scale data crunching for a period of 2.5 to 3 years.

The HIPPARCOS mission will produce the following data streams, which are of importance to NDAC and will be sent to the RGO:

1 The IDT photon-counts, which arrive at 1200 Hz, and from which transit times of program stars are derived.

2 The star-mapper photon counts, which come in samples of two times 200 read-outs at 600 Hz with average intervals of five seconds, from which the satellite attitude is derived.

3 Readings from three gyros at 15/16 Hz also incorporated in the satellite attitude.

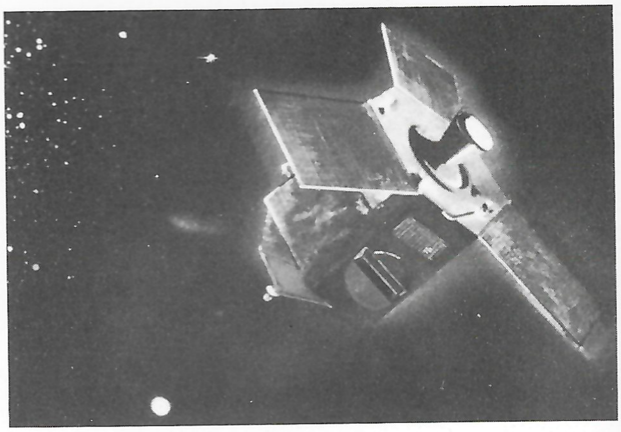
4 The real-time attitude determination (RTAD), three datapoints, once every 10 seconds.

5 Various items needed for calibrations and inclusion of minor planets, ephemerides, etc.

The data will arrive at the RGO once every week in batches of ten high-density tapes, 1000 Mbytes of data per week. At the RGO we are to reduce this data stream by a factor 25. Firstly data streams 2, 3 and 4 are used to derive at intervals of 32/15 seconds the satellite attitude with an accuracy of 0.1 arc sec in all three coordinates. Then data stream 1 is used to derive transit times for the program stars and to calibrate characteristics of the main detector-grid which are needed for double star segregation. Finally, using the reduced IDT data, improvements to the attitude will be applied and positional corrections for stars observed with the star-mapper incorporated in the star-catalogue. Every week two tapes with transit- and attitude-data will be sent to Denmark for further processing.

The writing of the Fortran modules will be rounded-off in the beginning of 1986. At that moment we will have available all the software needed to perform a basic data reduction. The last two years before launch, mid-1988, will be used for optimizing, documenting, standardizing and extensively testing this software package. In addition diagnostic software has to be written in order to keep sensible control over the reduction of the vast data stream, monitor programs are to be developed to keep control on the actual data-processing and arrangements in the software have to be made for system interrupts. When the input-tape formats have been finalized the TIO software, bringing data from tape to disk into our own format requirements, has to be written. Tests with simulated data will take place continuously, but in mid-1987 the more serious system tests will start, culminating in a number of simulated sets of 12-hour observations. These tests will take place till the beginning of 1988, when the last preparations for the actual implementations are to take place. Then, from mid-1988 till the beginning of 1991, we expect to be reducing the mission data.

F. van Leeuwen



Hipparcos

Parallaxes

Absolute distances to stars, which are of fundamental importance in astrophysics, can only be measured by triangulation, using the Earth orbit as base line and the stellar background as reference frame. Absolute distances with accuracies better than 10% are known for only 100 stars within 10 to 20 parsecs from the Sun. Calibrations of absolute magnitudes and other, indirect, distance indicators are therefore still quite inaccurate, but can no longer be much improved using ground-based observations.

The ESA HIPPARCOS satellite intends to improve considerably upon the present situation, measuring positions, proper motions and parallaxes of up to 100 000 stars with accuracies down to 0.002 arc sec, a general improvement by a factor five in accuracy and by a factor 100 in total volume within which stars with significant parallaxes are found. The most important feature of HIPPARCOS is the introduction of two telescopes separated by a fixed 'basic-angle' of 58°, and projecting on one and the same detector. Thus, while the satellite scans the sky, it will always observe two fields in which the parallactic displacements are different. This allows for the first time to derive absolute parallaxes. Unlike ground-based telescopes, this instrument observes stars in both hemispheres, providing a unique homogeneous covering of the sky in reference positions, proper motions and parallaxes.

Software Spin-off

The HIPPARCOS activities at the RGO have already created an interesting by-product: an extensive library of high-quality least-squares routines, suitable for a wide range of problems. Incorporated in the library are various types of matrix manipulations: Householder transformations, least-squares updating mechanisms and running solutions, least-squares chain solutions, inversion routines, Choleski factorization and so on. All of these routines are written in standard Fortran, available in single and double precision, thoroughly annotated and documented and extensively tested under various difficult conditions. This library is our versatile toolbox needed for the data-reduction, but is by no means specific to the HIPPARCOS problems.

Measuring machines

The RGO operates a suite of measuring machines as a national facility. These include two major installations, the GALAXY machine and the PDS microdensitometer, and several small machines – two coradograph X–Y tables, a Zeiss Ascorecord X–Y table, a Sartorius iris photometer, and a Joyce–Loebl microdensitometer.

GALAXY

The GALAXY (General Automated Luminosity and X–Y) measuring machine has the capability to measure precise positions, to 1 micron, for stellar objects over the entire (14 × 14-inch) area of a Schmidt plate. This accuracy is not equalled by any other machine in the UK, and is not surpassed anywhere. It results in unique scientific capabilities, which range from major improvements in stellar reference frames, to evolutionary studies of stars and star clusters, through to studies of stellar populations delineating the formation and collapse mechanism for our Galaxy.

For five years the major effort on GALAXY has been the Cape Photographic Catalogue, measurement of positions to ± 0.15 arc sec for 200000 stars on 6000 plates taken with the Cape Refractor in the 1950s (Fig. 1). Each star appears on an average of four plates, the total number of measures thus approaching 10^6. The project is an international one (plates from SAAO, measurements on GALAXY, reductions at Hamburg), requested and designed by several IAU commissions. Measurements are now complete and analysis is in progress. A first zone of the catalogue was published last year. The project is of crucial importance to the stellar reference frame, in turn vital to most branches of observational astronomy and cosmology.

At the moment there is a hiatus in GALAXY operation due to withdrawal of funding for the past two years. With the restoration of operating resources, it is planned to complete an electronic refurbishing and to be operational in 1986. This is timely for two reasons. First the 1.0 m telescope on La Palma, the JKT, is now fully operational, and GALAXY machine will be required to measure the wide-field plates to be taken as part of a large-scale international programme. Secondly, there is a resurgence of interest in stellar populations both nearby and in the Galactic halo, the mechanism of galaxy formation, dynamics and evolution of clusters and comparisons with N-body simulations. All these need major measurement programmes on a machine providing the micron-accuracy GALAXY achieves as a matter of course. An example of GALAXY capability is shown in Fig. 2.

PDS microdensitometer

The PDS machine is an automated microdensitometer, recording an array of densities over a defined area of a photographic plate. Unlike the other large measuring machines in the UK, it is 'hands-on', highly suitable for the casual user and for small projects. Of greater scientific significance is its dynamic range which much exceeds that of other UK measuring machines, and gives the PDS outstanding photometric performance. This has been used to great advantage in, for example, major programmes of galaxy surface photometry by Oxford astronomers, and electronographic stellar photometry by ROE astronomers.

Current plans for the PDS machine consist of completing an electronic upgrade, of providing a new carriage for handling 14 × 14-inch Schmidt plates with greater ease and safety, and of moving the machine to a new environment to improve user convenience and comfort.

J. Wall

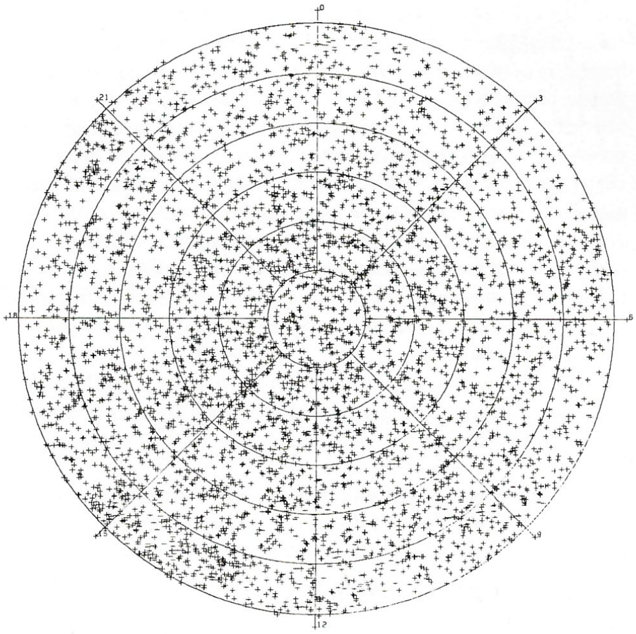
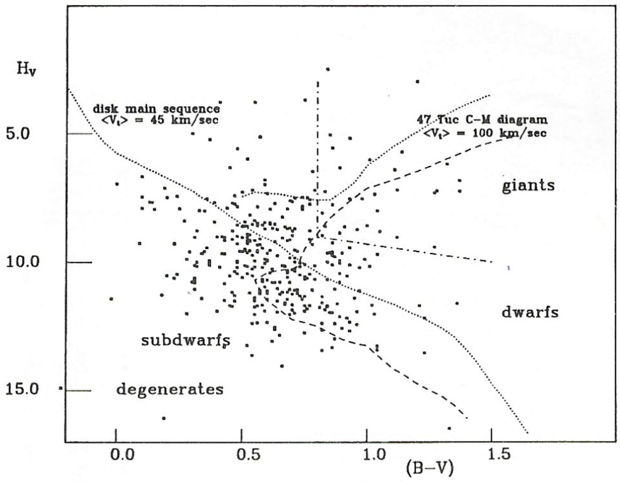


Fig. 1 The distribution of stars at the South Celestial Pole with accurate positions measured by GALAXY in the Cape Overlap Survey. The rings are every 2° in declination (–88°, –86°, –84° etc.) while the radial lines show right ascension. About 5100 stars are shown; surface density is 11 stars per deg^2, and each star is measured to an accuracy of ± 0.15 arc sec.

Fig. 2 Reduced proper-motion diagram for stars in Selected Area 68. Determining the kinematics and metallicity of the Galactic halo requires a method of identifying halo stars unambiguously. The diagram shows that precise proper-motion data enable a set of halo red giants to be delineated by eliminating sample contamination from nearby stars with large proper-motions.



Mechanical design

The optical performance of a telescope depends on controlling the deformation of the mirror surface when the mirror is contained in a mirror cell. In fact, a large mirror would bend by hundreds or thousands of times the optical tolerance if not mounted properly. The images would be useless. The problems for large telescopes become severe very rapidly, since the deflections of a structure increase with its weight multiplied by the lever arm at which the weight is applied, and divided by the cross-sectional area of its material, which provides the stiffness. The deflections of a telescope thus increase as the square of the telescope mirror size, so that in this sense a 4.2 m telescope is about three times more difficult to make than a 2.5 m telescope.

The mechanical engineer is therefore faced with the task of calculating the deformations of the structures proposed in order to see whether they will be adequate for the task, and which is the most cost-effective.

A technique that has gained popularity for the analysis of the deformation of solid bodies is the method of finite elements. This method was developed from research investigations into structures and uses the compatibility of displacements and equilibrium at nodes. Each element is connected to its neighbour by mutual nodes. The nodal displacements, forces, and bending moments are usually combined and equated using the principle of virtual work. Finite-element techniques have been employed successfully for a number of years, and it is now possible to construct an accurate mathematical model of a primary mirror with its supports (Fig. 1).

Such models were constructed at the RGO to check the design of the Isaac Newton Telescope and used extensively for the design of the William Herschel Telescope. The 4.2 m mirror of the WHT has a diameter to thickness ratio of 8:1, and classical flat-plate theory was simply not accurate enough. The primary mirror support system which evolved from the design work (Fig. 2) is described in the box.

The finite-element analysis technique has been used at the RGO to investigate the likely performance of a 7.5 m telescope. Such a large mirror cannot be made of a single, monolithic piece of glass. The primary mirror must be made of segments or a mosaic of independent smaller mirrors, or of thin glass, or of a honeycomb, hollow box-like structure. Once a 7.5 m telescope can be constructed, a series could be combined in arrays or into a huge telescope of, say 18 m diameter. Once the problem of the mirror support system is solved, then correcting lenses for imaging with the large mirror must also be modelled to see if they distort by unacceptable amounts while hanging from their circumferences. Design studies like these for future telescopes have been carried out at the RGO (Fig. 3).

Finite-element analysis was also used by the mechanical engineering group at the RGO to design the support structures of the La Palma telescopes themselves. The 4.2 m mounting structure carries the telescope tube of 82 tonnes on hydrostatic altitude bearings at the top of two mounting columns which rotate on an azimuth bearing: this bearing carries 160 tonnes. The deflections in the mounting structure are crucial to the pointing and tracking performance of the telescope principally because stiffening the structure raises its natural frequency and hence its responsiveness to control.

B. Mack

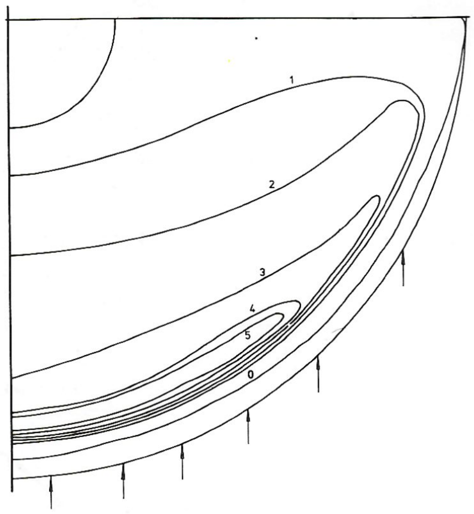
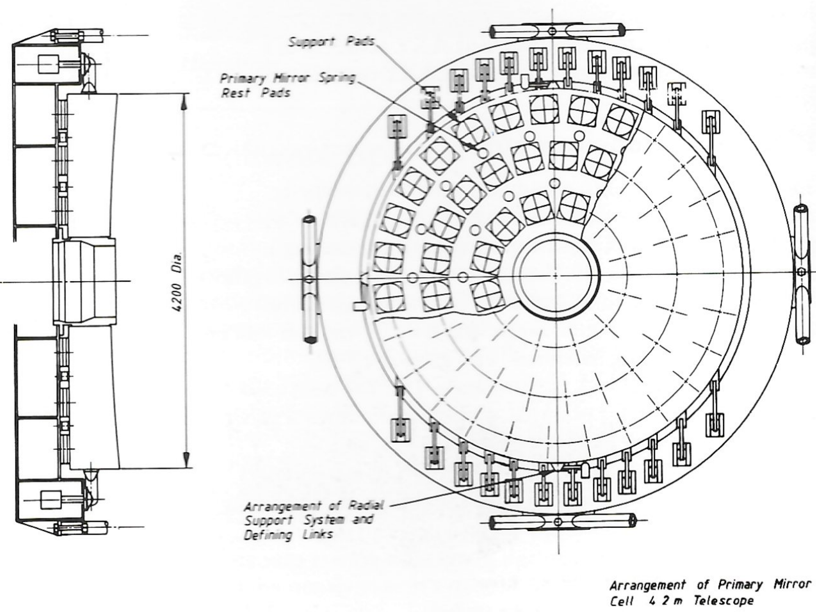
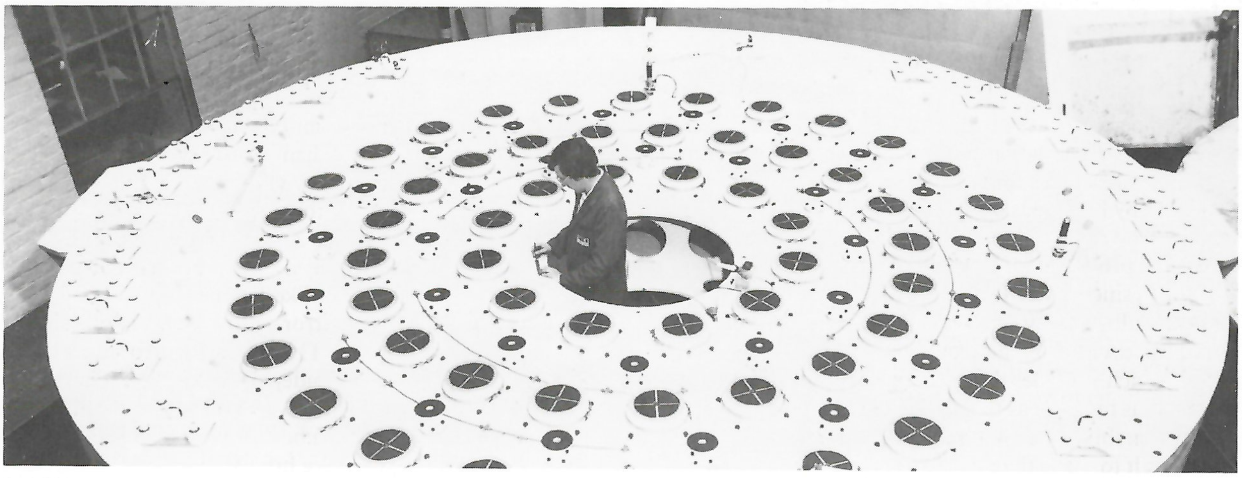


Fig. 1 In the most severe case, when the primary mirror of the William Herschel Telescope stands on edge in its cell, a ridge appears at the lower edge, of peak height 50 nm (about 1/10 of the wavelength of light). Finite-element calculations which generated contour plots like these were used to select the best and least expensive of the options for the cell structure.

Fig. 2 Finite element calculations led to the engineering design by RGO for the William Herschel Telescope mirror cell (right).





The cell was manufactured under contract by Grubb Parsons. Its final test in September of 1985 was to support the finished 4.2 m mirror in the Grubb Parsons optical test tower while interferograms of its figure were obtained, thus testing the mirror and cell as a system.

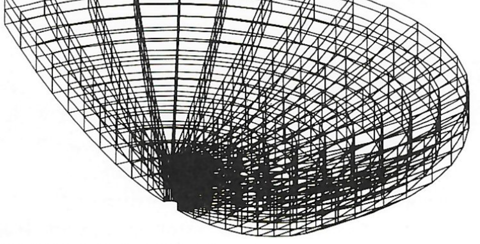
Mirror support systems

The primary mirror of the William Herschel Telescope has sophisticated axial and transverse support systems. The axial support system consists of two subsystems: an axial flotation system made up of an array of pneumatic cylinders employing roll-diaphragms as seals, together with a pumping system providing the gas pressure needed to support the full mirror weight; and an axial defining system which locates the mirror in its correct axial position at three points around the mirror edge. Load sensors in the axial definers provide signals which control the pressure in the pneumatic cylinders; the system also allows fine height and tilt adjustments to be made. A system of spring-loaded rest pads supports the mirror when the pneumatic system is not pressurized.

The cylinders of the axial flotation system, a total of 60, are arranged in three concentric rings on the floor of the mirror cell. The optimum arrangement was determined by use of a finite-element computer analysis of mirror deflections. The cylinders are divided into three sectors each of 120°, symmetrically disposed about a diameter perpendicular to the telescope's altitude axis. All the cylinders in each group are connected by a system of manifolds and pipes to an individual controller housed inside the mirror cell. Each of the three controllers have two sets of electrically-operated valves: one connects the cylinders to a pressurized nitrogen reservoir, the other opens the cylinders to a vacuum tank. The valves are controlled by the output of the associated load cell in such a way that the force exerted by the mirror on the defining point is maintained at 0 ± 5 kg during tracking at all angles of the telescope tube from the zenith down to the horizon. The total weight of the primary mirror is 16.5 tonnes.

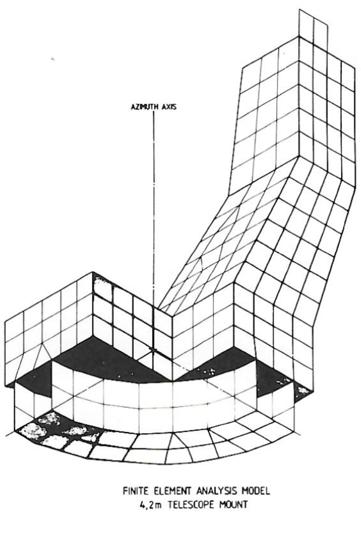
The mirror is supported in a transverse direction by weighted levers coupled by link arms to brackets connected to the edge of the mirror in much the same way as a conventional push-pull radial support system. However, as the mirror will not rotate with respect to the gravity direction, the weighted levers and linkages are arranged to act only in the vertical direction and are spaced unequally in such a way that each pair of weighted levers, one pushing and the other pulling, effectively supports a 'slice' of the mirror equal to 1/12 of its total weight. This efficient arrangement is only possible in an altazimuth mounting. In plan view the force applied by each pair of weighted levers acts through the centre of gravity of its slice, but in elevation all the forces are applied in the one plane containing the centre of gravity of the whole mirror. Transverse definers take the form of tangential links tying the mirror to its cell at three 90° positions.

Fig. 3 In finite-element analysis the structure is modelled by a 3D web which is loaded at its nodes. The web can be simplified if there are symmetries in the structure. Thus the support structure for the William Herschel Telescope mount can be halved because both halves are identical. Likewise a heavy circular lens such as an element for the prime focus of the telescope can be dealt with as a semi-circle.



WHT.PRIME.FOCUS.CORRECTOR.FRONT.ELEMENT

UNDEFORMEDSHAPE



FINITE ELEMENT ANALYSIS MODEL
4.2m TELESCOPE MOUNT

William Herschel Telescope – instrumentation system

The four principal foci of the William Herschel Telescope (WHT) together with the auxilary fifth focus and a number of instrument ports on the Cassegrain Acquisition and Guidance Unit provide the opportunity for a wide range of instrumentation to be installed and ready for use at any one time. Reconfiguring the telescope to switch between different instruments can be performed quickly, offering great flexibility. In order to exploit this flexibility and to handle the large amounts of data involved, it is necessary for an integrated system approach to be adopted. At the RGO we developed a model for the system in 1983 which represented a new approach to the provision of instrumentation for a major telescope. Over the last two years, in parallel with developing the instruments and detectors, we have begun work on the subsystems which make up the infrastructure.

Requirements of the infrastructure

The main role of the infrastructure is to allow an astronomer to control the operation of one or more instruments, several detectors, the telescope, dome and windshields in a simple and efficient manner to carry out the observing programme. In addition it must enable interaction with the data as it is received in order to make changes or reorder priorities in the remainder of the run.

The infrastructure must be sufficiently modular to allow individual subsystems to be developed, tested and maintained independently. Commonality of parts is also important to keep down the spares inventory and simplify maintenance.

Description of the infrastructure

To achieve these twin goals of providing an integrated single system whilst incorporating high modularity, we have adopted a distributed-intelligence approach (see box) with overall control being exercised by a system computer. Each subsystem has its own processor and is capable of operating in a stand-alone mode for engineering and maintenance purposes. During normal operation the subsystems and system computer are interconnected by a utility network which carries command and status messages.

The Utility Network is an important feature of the system and carries command and status messages beween subsystems. It is based on Ethernet, using commercial RS232 interface units to link in the microprocessors. The interface units provide, as standard, a virtual circuit type of connection. This has been modified by the manufacturer to provide an RGO-specified packet switched service and the first units are currently undergoing tests.

TV system

The acquisition television cameras are intensified SEC vidicons similar to those chosen for the 2.5 m and 1 m telescopes. They provide on-target integration and further integration in a digital memory. Earlier TV systems have made use of a commercial digitising memory incorporating recursive filtering and display. This system is no longer available so a new system based on VME modules is being developed at the RGO. It will incorporate more on-line image processing than was previously possible and will provide powerful facilities for image-sharpening experiments.

It is connected to the utility network to collect overlay information for the display and for archiving occasional acquisition pictures. Overlays are particularly useful during acquisition and usually show probe positions and turntable orientation.

Autoguider

The autoguider is based on a CCD detector which monitors the position of an object in the telescope field of view. Any apparent movement in the object is measured and output to the control computer as an error signal which is used to correct telescope tracking. Besides its main role in telescope guiding the autoguider will be an important diagnostic tool in commissioning the telescope control system.

It uses a VME system to analyse the CCD data and to interact with the observer in selecting a guide star. The CCD will be driven by a new controller being developed for CCD work on the WHT.

Detectors

Two main types of detector are planned for the WHT; one is the Image Photon Counting System (IPCS) which counts individual photons on a two-dimensional grid, accumulating the counts in a large histogramming memory. The other uses a CCD as a charge-accumulating detector which is read out at the end of an exposure. Both types of detector have large formats (2000 × 2000 CCDs are expected in the near future) and arrays of detectors will be used. The IPCS histogramming memory is based on VME and has been made general purpose to allow CCDs to be read into it. Incorporation of a detector processor into the external memory for laboratory development and for removing detector artifacts is thus possible and convenient.

The external memory will also contain a display driver (identical to that used for the TV and autoguider) which will be used by the detector processor to display detector data. In due course we shall produce a VAX driver to use this display with data reduction software.

Instrument control

Existing instruments on La Palma each have their own microprocessor to control the movement of elements in the optical path such as filters, gratings, shutters, mirrors, prisms and apertures. We developed a Modular Microprocessor System (MMS) many years ago to handle this type of work and it has been used as a standard for all Phase I instruments. For the WHT we have moved on to a new standard called 4MS (4.2 m Microprocessor System) which is based on commercially-available modules using the G64 bus. This change has allowed us to take advantage of the range of modules available for G64 but we have retained many of the concepts of MMS which have proved so successful.

Telescope control

The telescope has its own control computer which is capable of operating in a stand-alone mode for commissioning and diagnostic purposes. In normal operation it is treated as any other instrument and receives coordinating commands over the utility network from the system computer. It also uses the utility network to interact with acquisition and guidance units, television systems and autoguiders.

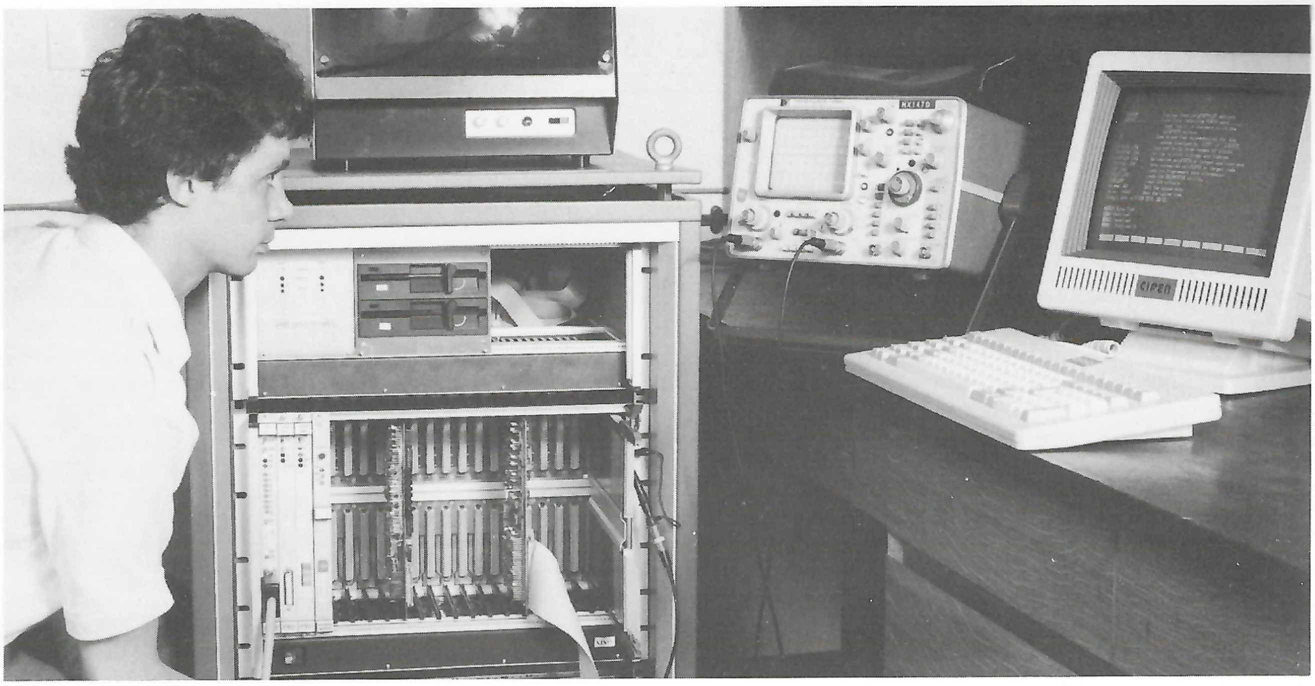


Fig. 1 VME microprocessor system under test in the RGO workshops.

System computer

A member of the VAX computer family running VMS will coordinate all the activities involved in observing and will handle data acquisition and first-line reduction. The data acquisition environment will be based on the Adam system which was developed at the RGO and is currently in use on the Phase I telescopes on La Palma. The Royal Observatory Edinburgh has adopted RGO's Adam for UKIRT and has ported it onto a VAX. A copy of this version is now running at RGO and is likely to be adopted for the WHT.

The VMS operating system will enable Starlink software to be used for data reduction during observations. The astronomer will thus be able to assess the quality of his data and modify his observing programme to make better use of telescope time.

Conclusion

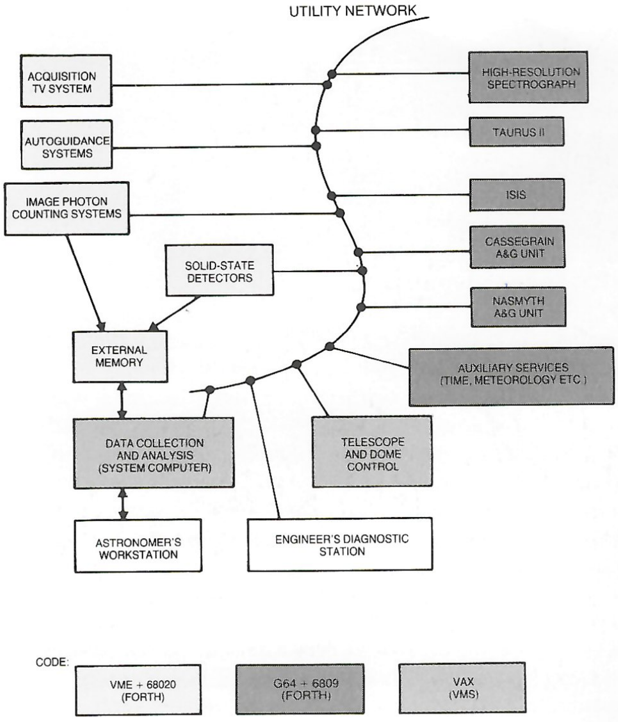
At the RGO we are using our long experience in optical astronomy and breadth of technical expertise to bring together a highly modular but integrated infrastructure designed to make the best possible use of the William Herschel Telescope. We believe we shall produce an astronomy machine which is second to none and which is capable of being enhanced to keep it in that position for many years to come.

N. Parker

Distributed intelligence instrumentation system

In this schematic diagram of the William Herschel Telescope instrumentation system, coded to indicate the use of common components, VME and 4MS refer to the two types of microprocessor system in use; both of these are RGO standards and represent the latest stage in a well-coordinated development policy which started in 1976.

The Utility Network is an important feature of the system and carries command and status messages between subsystems. It is based on Ethernet, using commercial RS232 interface units to link in the microprocessors. The interface units provide, as standard, a virtual circuit type of connection. This has been modified by the manufacturer to provide an RGO-specified packet switched service and the first units are currently undergoing tests.



FORTH and microprocessor applications

Since their introduction at the RGO in 1976, microprocessors have played an important part in data acquisition and control for astronomical instruments, as well as for data reduction and analysis. They have also become indispensable tools in the development cycles of instruments in the laboratory, and have found uses as logic replacements, intelligent instrument controllers, minicomputer replacements, personal computers and fast controllers; 8-bit, 16-bit and 32-bit devices have been used in addition to bit-slice chip sets.

In any microprocessor project, software and the choice of language are crucial. Some of the personal computers at RGO use BASIC but, for real-time applications, a more powerful interactive language was needed. FORTH was chosen for this purpose, because of its combination of high execution speed and powerful interactive command structure. Also, since it includes its own operating system, editor and assembler, it is probably the most highly standardised of all programming systems, making it simple to transport software between processors, and to adapt to new processors as they become available.

Although we have found it easy from the software point of view to transfer between processors we decided at a very early stage to choose a standard microprocessor in each class; this has kept the number of hardware learning cycles to a minimum and reduced spares holdings. We have stayed with each particular standard so long as it has been capable of performing the required tasks, moving on only when technological developments have offered a significant increase in performance.

The classes of microprocessor in which we have adopted standards are 8-bit, 16/32-bit and bit-slice; they are described here with some of the applications in which they have been used.

8-bit

Motorola 6800 8-bit microprocessors were the first microprocessors to be used at the RGO and were our first major standard. We used them in two forms, either as Motorola 'Exorciser' cards or as our in-house designed cards based around the Eurocard format. We called our system MMS (Modular Microprocessor System) and designed it into many applications over several years before replacing it with a new system.

MMS and Exorcisers were used for all 8-bit applications for the phase 1 telescopes on La Palma (i.e. the Isaac Newton and Jacobus Kapteyn). In addition they were used for several travelling instruments which were used in Chile, South Africa, Spain and Australia. Most of the applications are still in regular use and the microprocessor equipment has proved exceptionally reliable despite the rigours of foreign travel. Table 1 summarises the applications using the 6800.

Towards the end of our phase 1 work we decided it was time to replace our MMS by one of the commercial Eurocard-based systems now appearing on the market. We had already decided to upgrade to the Motorola 6809 and had started to use it in the form of Motorola 'Exorsets' which were used as intelligent controllers for engineering tests on new instruments.

We were unable to find an emerging 'industry standard' bus so chose the best manufactured bus we could find. This was G64 and is proving to have been a most fortuitous choice. It has now been adopted as a standard by CERN, Rutherford Appleton Lab, Daresbury Lab and many of our Dutch collaborators. At least a dozen manufacturers now make G64 cards.

Previously, software development had been carried out on Exorcisers with Motorola USE modules being used for in-circuit emulation for software/hardware testing. For 6809 and G64 work we put together a package called 4MS (4.2 m Microprocessor System) which incorporates a standard FORTH kernel in read-only memory, a standard chassis, power supply, processor card and, for development use, an IEEE 488 interface to a floppy disc. This forms the development system and the target hardware, with only the floppy disc being removed for the final application. The FORTH used is multi-tasking and applications normally run in one or more background tasks leaving the operator's VDU task active. It is thus possible to plug a VDU into a 'black box' application and access the FORTH dictionary as a very powerful set of diagnostic tools which essentially come free.

4MS is being designed into all the instruments for the William Herschel Telescope and into a new camera for the JKT. Table 2 summarises its applications to date.

16/32-bit

In 1978, work was begun at RGO on solid-state area detectors; in particular, charge-injection devices (CIDs) and charge-coupled devices (CCDs). These required two-dimensional image-handling software in addition to the more usual instrument control software. While the Exorciser could cope with instrument control, the 2D image software needed a more powerful processor. For this purpose the LSI-11 16-bit microcomputer was chosen. This choice was conditioned mainly by the fact that there was already a PDP–11/34 at RGO with FORTH imaging software for controlling a microdensitometer. Initially, the LSI–11/2 processor was used, but later this was largely superseded by the faster LSI–11/23.

LSI–11 systems have mainly been used in the laboratory for detector development work but travelling detectors complete with LSI–11s for control, data collection, display and image processing have been used on various telescopes around the world.

As detector sizes have grown (the next CCD on the horizon has more than 2000 × 2000 pixels) the problems of handling large images have increased. To cope with this we have moved on to more powerful processors with large addressing capabilities. As with the move from MMS to 4MS our decisions were driven by the choice of bus with VME being our adopted standard. As with G64 our requirements forced us to choose before it was clear which of the prospective buses would emerge as the industry standard. It seemed likely that there would be more than one and that VME would be one of them. It would satisfy our requirements and was available. Subsequently it has been chosen as a standard by CERN, Rutherford and Daresbury.

The choice of processor was more difficult; although 68000 seemed to be the natural choice there was a local preference for microVAX although, even now, we are not aware of any commercial VME card incorporating a microVAX. We are currently using 68000s for initial development work and will almost certainly settle on 68020 as the La Palma standard. Fortunately, the use of FORTH allows us to keep our options open.

Table 3 shows the LSI–11 and 68000 applications; the external memory mentioned there is part of the detector system for the WHT and it looks very likely that the Anglo-Australian Telescope will adopt the same system.

Table 1: 6800 Applications

Application	Format	Use
TAURUS Interferometer	MMS & Exorciser	INT (at Herstmonceux), Chile, South Africa, Australia, currently in use on INT
Four Star Photometer	MMS & Exorciser	Herstmonceux, Sierra Nevada in Spain
Cassegrain A & G Unit	MMS	INT
Cassegrain Spectrograph	MMS	INT
Prime Focus Assembly	MMS	INT
Auto-plate changer	MMS	INT (awaiting commissioning)
Autoguider	Exorciser	INT and JKT
Reticon Photon Counting System	Exorciser	South Africa
Integrating TV System	MMS	INT and JKT
Faint Object spectrograph*	MMS	INT

** Produced by Durham University*

Bit-slice

Bit-slice processors have been used for two applications requiring high-speed sequencers. The first was a CAMAC serial branch driver built into a Nova minicomputer for use in South Africa. It was designed around AMD 2900 family components and microcoded by hand. The second application was for a sequencer for CCD detectors. Again the AMD 2900 family was used but this time the microcode was written in FORTH using an RGO microcode compiler running on an LSI–11. This provided tremendous flexibility for laboratory development work and allowed waveform patterns to be optimised very quickly for different CCDs.

CCD cameras using this sequencer are now in operation in Australia and on La Palma as well as being used for continued development work. Although their flexibility allows them to handle any CCD (including the large new ones which are not yet available) a new design is in progress to handle multiple CCD arrays.

Conclusion

Microprocessors have played a major part in the development of new instrumentation and detectors at the RGO. That so much has been achieved by a relatively small group is due to our early adoption of FORTH and consistent development policy based on suitable standards.

N. Parker I. van Breda

Table 2: 6809 Applications

Application	Format	Use
CCD A&G Unit	4MS	JKT
ISIS Spectrograph	4MS	WHT
Cassegrain A&G Unit	4MS	WHT
High Resolution Spectrograph*	4MS	WHT
TAURUS II*	4MS	WHT
Engineers Controller	Exorset	INT, JKT
IPCS II†	4MS	WHT

** Being produced in the Netherlands* † *Being produced at UCL*

Table 3: LSI–11 and 6800 Applications

Application	Format	Use
CID detector	LSI–11	Lab development
CCD detectors	LSI–11, VME+68000	Lab development, travelling camera used at various telescopes around the world
Software Development	LSI–11	PDS plate measuring machine
CCD Autoguider	VME+68000	WHT
Integrating TV system	VME+68000	WHT
External Memory	VME+68000	WHT (possibly AAT)

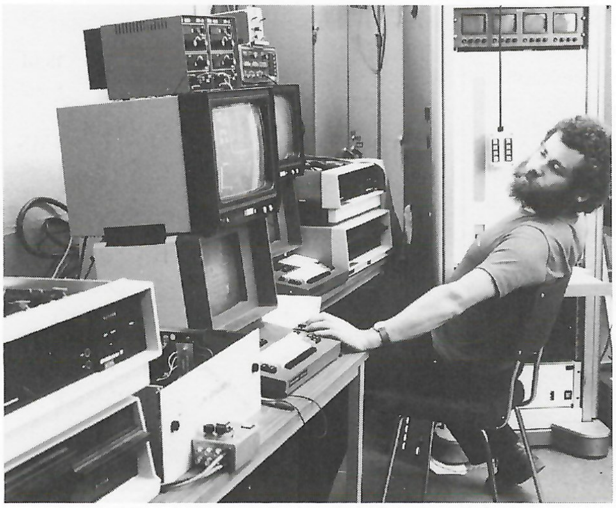


Fig. 1 The INT autoguiders and integrating TV system were commissioned by David Thorne on La Palma early in 1984. The first stage, illustrated here, was to integrate the complete system in the laboratory after shipping and then to install the equipment on the telescope. During the integration and the commissioning, the Exorcisers were used for microprocessor development. About a year later, the system had stabilised enough for the microprocessor programme to be burned into read-only memory; the Exorcisers could then be used for diagnostic tests or the next application.

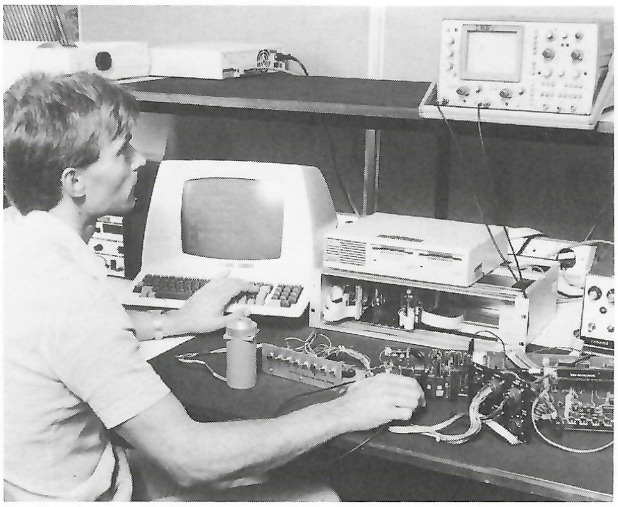


Fig. 2 As part of a pilot programme for the development of the 4.2 m instrument control system, the new JKT acquisition system was developed using FORTH software on the 4MS (4.2 Microprocessor System). The assembly shown is a general stepper motor-drive system specially developed for minimum heat dissipation inside the instruments, so as not to disturb astronomical images with air currents.

Mechanical construction

The design of an astronomical instrument requires the bringing together of many state-of-the-art technologies. Typically in the design of a spectrograph it is necessary to bring together optics, mechanics, electronics, computing, cryogenics and many other disciplines in order to optimise the performance of the new dynamic instruments. Once the astronomers have fixed the specification for an instrument, it then becomes necessary to establish the optical design based on the given parameters. The mounting, separation and movements of the optics needs to be defined and assessed for feasibility. The Design Office is the central point at which all the associated disciplines come together. Here the designs are interrogated for stresses, deflections, tolerances and material selection based on experience and the use of modern technologies such as finite-element analysis. The request for common user, remotely-operated instruments has added another dimension to the design process. In conjunction with the hardware design and manufacture the electronic status encoding, drives and controls are integrated into the instrument. In parallel component commissioning is undertaken together with the selection of operational computer systems and programs. The selection of detector systems for use on modern instruments has become a science in its own right. Within the visible band of the electromagnetic spectrum many detector systems have been designed to collect the very last photons available from an observational source. Image Photon Counting Systems (IPCS) and Charged Coupled Devices (CCDs) are used extensively. The design of ancillary equipment such as transportation and handling facilities is now of paramount importance as a modern instrument can be well over 1.5 m^3 in volume and 1.5 tonnes in weight. Close attention needs to be given to the requirements of the instrument whilst it is undergoing manufacture, commissioning and in its various operational states both on and off the telescope. No instrument is considered complete until all the commissioning, maintenance and operational documentation has been completed, which requires a combined effort of all the project team.

The Engineering Department is also available to trouble-shoot problems which may arise on the telescopes and instruments on La Palma. These may be of minor nature such as giving advice on day-to-day matters or providing solutions to very complex operational difficulties. A typical example of this was the investigation of the hour-angle oscillations produced in the 2.5 m INT drive system. Once the unacceptable oscillations, which were making first-class astronomy unattainable, had been identified, a team of engineers was rapidly brought together and dispatched to solve the problem. The solution required major surgery to be performed on the RA drive system. This provided greater stability and alignment of the drive unit, a greatly enhanced data encoding system and an improvement to telescope control loops. The modifications produced a drive system free from optically detectable errors thus establishing the INT's status as being one of the world's premier telescopes. The whole operation was successfully carried out in the space of only three weeks.

N. Snodgrass

The RGO Workshop

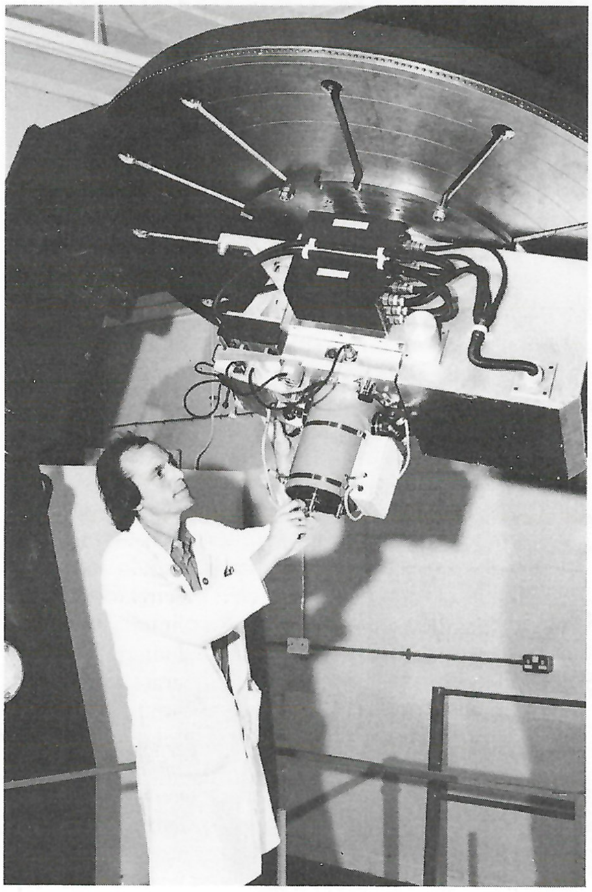
The Engineering Workshop provides a comprehensive service in support of the RGO's commitment to ground-based astronomy.

The large and varied machining capacity of the workshop enables the production of both large structures and small precision components required in modern astronomical instruments. The workshop personnel are trained in the specialist skills necessary for the manufacture, assembly and commissioning of complex mechanisms and components required by technically demanding instruments. Typically the slit area components of a modern spectrograph are not commercially available. This is due to the extreme technical demands made upon them. Hence this standard of work is highly sought after, and the RGO supplies precision items for instruments throughout the world. A large commitment has been made in support of the commissioning of the 2.5 m INT and 1 m JKT telescopes and associated equipment on La Palma. Teams of technicians and craftsmen worked in rotation to provide essential assistance to the operational personnel at the Roque de los Muchachos Observatory. The fruits of their work is now seen in the internationally acclaimed facilities on La Palma.

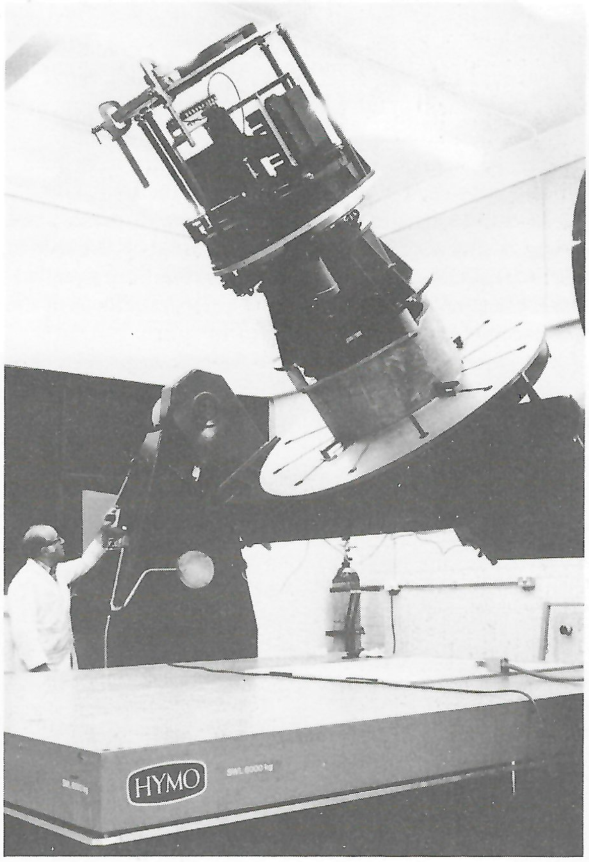
Telescope simulator

The RGO Simulator is designed to aid the commissioning, and perform analyses, of astronomical instruments. The unit is capable of simulating the principle foci of major telescopes and can be operated in modes typical of astronomical observing programmes. Instruments are attached to the turntable of the simulator where they may be rotated about their principal axis or an axis at right angles to the principal axis. This facilitates the analysis of instruments in all the attitudes they will see when functioning as part of an operational telescope. The stability of an astronomical instrument is essential, and by using the simulator to assess the flexure of an instrument, the impact on the optical performance can be anticipated.

The INT Spectrograph was analysed using the simulator, which proved extremely useful in establishing the performance of the unit and also in considerably reducing the on-site commissioning time. In conjunction with the simulator, HeNe lasers were used to establish and monitor the alignment of the optical components, and photographic plates taken to record the image shifts with respect to the instruments attitude. Modifications were then made to individual components and the resulting improvements measured until stabilities in the order of a few microns were achieved. Computer systems were also attached to the spectrograph and the preliminary programming undertaken. A recent example of the versatility and usefulness of the simulator was demonstrated in the assembly and testing of a new axial support system for the JKT primary mirror. Here a dummy mirror and support cell, complete with pneumatic support diaphragms, was mounted on the simulator and interrogated through all the possible attitude positions it would see on the 1 m telescope. The result was a greatly improved mirror support control system working within a tolerance band of a few grams.



The CCD camera and Acquisition and Guidance Unit for the Kapteyn Telescope were first assembled on the Telescope Simulator. In a device like the A & G Unit, or a spectrograph, it is particularly crucial that the mechanical deflections are within tolerance or else there are severe restrictions on instrument performance.



The Telescope Simulator is made from standard components, principally a handling frame for welding assemblies and a lift for access. Instruments can be attached to a turntable to simulate the upward-facing prime focus as well as the downward-facing Cassegrain focus. Here the plate camera and cone assembly for the INT prime focus are under test.

Detector developments

Since 1980, major strides have been made in charge-coupled devices (CCDs) and photon-counting detectors, as well as in the service detectors used for acquisition and guidance.

Development in the laboratory has relied heavily on the availability of Digital Equipment LSI–11 series and Motorola 6800 series microcomputers running FORTH software, and extensive application software packages have been written by those involved in detector development. Some progress has also been made towards introducing the 32-bit VME bus for high-performance imaging applications. The work has also made considerable use of an accurately flux calibrated low light-level source developed for RGO by Dr J. V. Jelley. This has enabled objective assessments to be made of the performance of a range of detectors. Photomultiplier counting efficiency measurements have been made on this apparatus in conjunction with EMI.

CCDs

Work on CCDs began in 1980, following the previous successful construction of a charge-injection device (CID) camera. The first CCD camera was a development of the CID design, and used the same RGO-designed cryostat (later superseded by a standard Oxford Instruments Ltd cryostat). This was built for the prime focus of the AAT and uses an RCA 320 × 512 pixel thinned chip; delivery was made in August 1981. This system formed the basis of the Phase I CCD cameras for La Palma.

The camera uses a bit-slice microprocessor to generate the clock sequences needed to extract data from the CCD and output from this is fed, via optical isolators, to a 'local driver box' located near the chip for generating the appropriate analogue signals for the chip; the same chassis also contains the analogue-to-digital converter needed to digitise the image. A microcode compiler was written that enables the waveform sequences generated by the bit-slice processor to be programmed in high-level FORTH, permitting rapid changes to be made in the waveforms during development and chip optimisation.

So far, RCA, GEC and Thomson-CSF chips have been set up and optimised in the laboratory. On the INT, GEC CCDs have been installed on the intermediate-dispersion and faint-object spectrographs along with a thinned RCA chip at prime focus; an interim GEC CCD camera has been installed for direct imaging applications at the Cassegrain focus of the 1 m telescope.

Laboratory work has been carried out on improving the noise-level of the pre-amplifiers used to read out the analogue data from the CCDs to the sub-two electron level (the precise figure depends on chip gain and pixel integration times). A study has also been made of the variation of chip noise with temperature and it has found that a significant optimisation can be obtained by working at the correct temperatures.

There have been collaborations with AAO and the University of Cambridge firstly on the AAO-funded project for a large 1500 × 1500 pixel GEC CCD, for which RGO has been carrying out initial tests. To date, the project has met with partial success in that chips have been made that can produce images, but none has had a satisfactory performance as a two-dimensional detector at low light levels. A second collaboration with the same group is now underway to produce a standard-sized GEC chip with better blue sensitivity.

In the 4.2 m telescope, there has been a collaboration with NFRA Netherlands, to build a new generation of CCD controller. This will be more compact than the Phase I design and will also be capable of driving several chips simultaneously. A prototype has been built in the Netherlands, and further development work is now being undertaken at RGO.

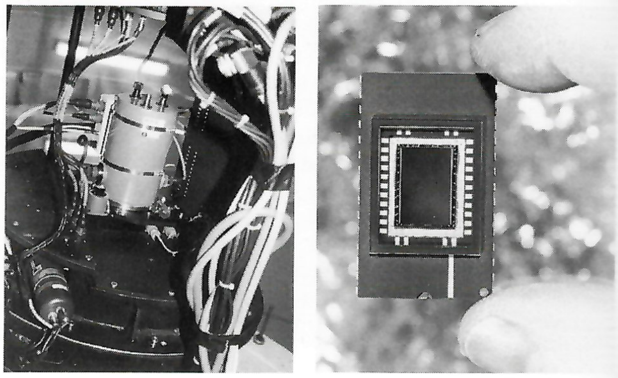


Fig. 1 A CCD microchip to record astronomical images must be cooled to liquid nitrogen temperatures and the small detector area is located at the front of a cryostat in order to do so. The cryostat was mounted at the prime focus of the Isaac Newton Telescope during the commissioning of the prime focus in July 1985.

During the period of this report, collaborative specialist observing programmes have been carried out with the University of Copenhagen on the 1.5 m telescope at ESO, for direct CCD imaging, and with the Queen's University of Belfast using a CCD mounted on the McKeith echelle spectrograph on the 1 m telescope on La Palma, following initial setting up tests on the 36-inch telescope at RGO.

Photon counting

Work on photon counting has covered a wide variety of aspects involving both IPCS and other work.

General support has been provided for IPCS I which, following its return from SAAO in 1981, was overhauled and re-commissioned. New facilities were added in collaboration with UCL, including improved external memory, increased spatial resolution, and new hardware and software interfaces for the La Palma computers. The detector was integrated with the intermediate-dispersion spectrograph for the INT using the telescope simulator at RGO, and commissioned on La Palma in 1984. Since then it has continued to be supported on La Palma, and upgrades have been made to include scanning of the image tube using magnetic coils to reduce the effect of tube granularity. Sequential tagged photon event recording has also been implemented for use in image stabilisation experiments. Further support at the RGO has been provided in the form of comprehensive image-tube calibration and testing.

The RGO has maintained close links with AAO to assist with the support of their IPCS, in conjunction with UCL. In particular, contracts have been placed for the RGO to procure and test intensifiers for AAO and to provide a copy of the magnetic scanning upgrade. A low light-level calibration source (Beta source) has also been designed and built for AAO and La Palma.

As a replacement for the IPCS on the 1.9 m telescope at SAAO, an intensified Reticon photon-counting system was developed and delivered in 1981. This uses the three-stage magnetically focussed intensifier, that was already in use with the spectrograph, lens-coupled to a three-stage Varo electrostatic intensifier stack, in turn fibre-optically coupled to a dual Reticon diode array. Events are recorded in an external memory mounted in a CAMAC crate. Development was carried out using a Motorola 6800-based microcomputer with FORTH imaging software transferred from the LSI–11/PDP–11 systems used for two-dimensional CCD imaging and the PDS microdensitometer. Subsequently, the detector was integrated into the SAAO computer systems in collaboration with SAAO staff.

A copy of the Reticon photon counter, this time interfaced to an LSI–11 microcomputer, was built at RGO to allow photon-counting experiments to be undertaken. This was built for the purpose of examining the possibility of using microchannel plate intensifiers for photon counting.

The principal reasons for doing this were:

1 Existing photon-counting systems are based on three- or four-stage magnetically focussed intensifiers. These are extremely bulky and difficult to keep mechanically and electronically stable.

2 The power supplies are correspondingly bulky and dissipate considerable heat.

3 Commercial considerations; the supply of EMI intensifiers is not guaranteed on a long-term basis.

4 It was considered highly desirable that university-users on La Palma should have ready access to high-quality detectors for mounting on specialist equipment, where small physical size would be a considerable advantage.

Two prototype microchannel plate intensifiers were obtained from Instrument Technology Ltd (ITL), which were tested by direct coupling to a Reticon diode array. These experiments showed that a viable detector could be produced in this form, and that satisfactory pulse-height distribution, counting efficiency and one-dimensional spectroscopic resolution could be obtained. The detector was tested on the Richardson–Brearley spectrograph, built for the 1 m telescope on La Palma by the University of St Andrews, by mounting it on the 36-inch telescope at RGO. This showed that high quality spectra could be obtained.

Following the prototype tests RGO provided funds to build a production chamber in collaboration with ITL, aimed at improving quality control during manufacture. The chamber has been recently commissioned and prototype tubes should be available in the near future. The collaboration has now been joined by Imperial College to examine the more detailed scientific aspects of MCP intensifier performance and production.

Collaboration is also under way with UCL on the development of IPCS II. This photon-counting system is intended for the 4.2 m telescope and is characterised by the use of a rapid-scanned CCD with event centring logic being developed at UCL. It is capable of being used either with a four-stage EMI intensifier, for which a fast coupling lens has been designed at RGO, or with a microchannel plate intensifier. The latter may be either lens-coupled or fibre-optically coupled using a tapered fibre bundle. Experiments with a Reticon array have shown that good resolution can be preserved through a taper, at least in the one-dimensional spectroscopic mode. Related work on evaluating fibre optic faceplates and tapers has been carried out at RGO. In addition, some collaborative work with ITL was done under contract to ESEC (ESA) to develop an MCP based photon-counting detector.

Acquisition and guidance sensors

In addition to detectors needed for obtaining actual astronomical data, work has been carried out on detectors for the acquisition and guidance facilities on La Palma.

Following a comprehensive evaluation of the various detector options, Westinghouse ISEC vidicon cameras were chosen for object acquisition. On the Phase I telescopes, these are coupled to Grinnell integrating TV memories. Extensive graphics software, including such facilities as seeing determination, have been written to assist the observer in using the acquisition facilities, and a simple guide star acquisition procedure has just been implemented.

The Phase I guidance sensors consist of microprocessor-controlled image dissector tubes, used to perform crossed scans on a reference star image to determine its centroid. This information is passed to the telescope computer to correct the tracking, where necessary. Again, extensive graphics software has been provided to enable the device to be used readily, and to enable the observer to obtain a sound appreciation of how well tracking is proceeding.

In the 4.2 m, work has just begun on a CCD guidance sensor which will use the same design of chip controller as that being built for the astronomical CCDs.

So far, TV cameras have been provided at the INT prime and Cassegrain foci and for the 1 m Cassegrain focus; a TV camera is also available on the INT finder. Commissioning and integrating these devices into the telescope control system has progressed well, and work is continuing to streamline the software to provide a well-integrated and easy-to-use system for the observer.

I. van Breda

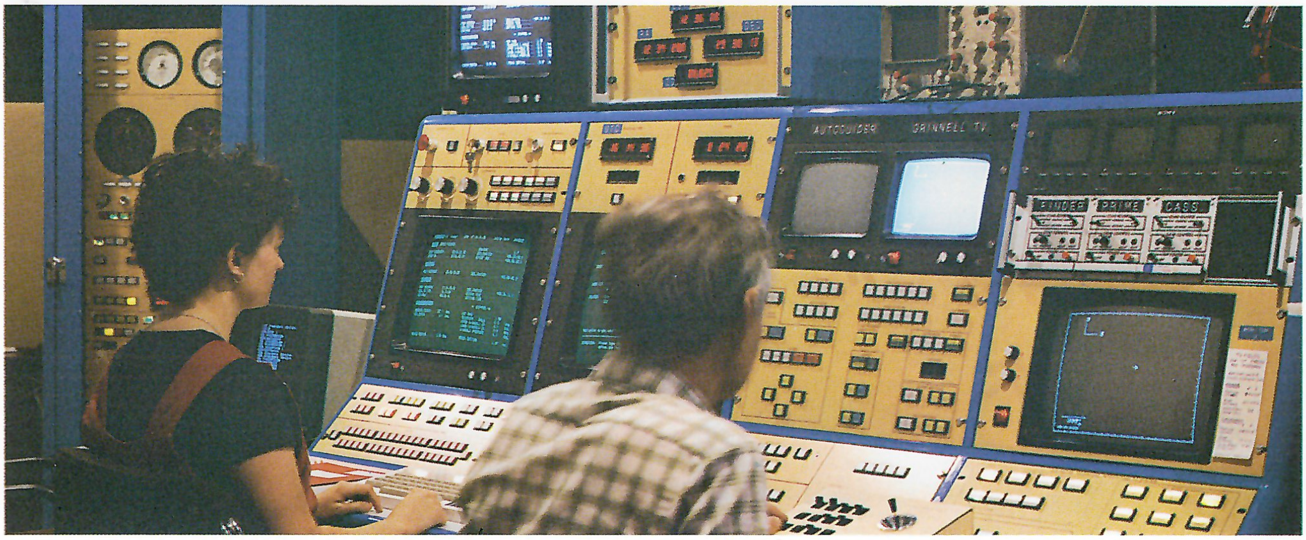


Fig. 2 At the Isaac Newton Telescope control desk, the astronomer and night assistant view displays from the intensified TV acquisition cameras and autoguider, to help set and control the telescope, and from the detector in the astronomical instrument, to evaluate and monitor the scientific result.

Computing at RGO

Of the three kinds of computing at RGO (central service, real-time control and administrative) this report concentrates on the first. In 1980, RGO was running a traditional closed shop mainframe system based on an ICL 1903T computer. There were some slow alphanumeric terminals but most of the work was performed in batch-mode. Jobs might be prepared at a terminal but they were scheduled and run by the computer in batch mode. Most of the work was still submitted on punched cards and output was invariably on a massive line-printer. The computer was completely isolated from its users and from all other computers. Access to SERC central computers was by means of a GEC 2050 remote job entry station.

At about the same time the Starlink project was getting under way and in May 1980 our node, a VAX 11/780, became operational. This brought with it interactive operation via fast graphics terminals, colour image and graphics display systems and various hard copy graphics and printing devices. All jobs were run from terminals. Memory size and disk capacity increased by an order of magnitude and the VAX was linked to the rest of Starlink by dedicated telephone lines using the proprietary DECNET software.

By 1981 the ICL 1903T was clearly overdue for replacement and in due course a VAX 11/750 was installed; after a year of dual operation the old machine was finally closed down on March 25 1983, and sold for recovery of its precious metals content. During the transition period substantial effort went into re-training users; the result was a smoother changeover than was expected with almost all users expressing satisfaction with the new service. It soon became clear that the new system, with its greater CPU power and virtual memory facility, meant that not only did jobs run faster but some work was now possible which had been unthinkable before. For example the maximum likelihood approach to astrometric analysis could never have been attempted on the 1903T.

These changes in hardware brought even more profound changes in the way that the computers were operated and managed. The ICL 1903T had two teams of dedicated operators, each made up of a shift leader and two operators, together with an operations manager. They were backed up by system and applications programmers. Only in exceptional circumstances were users allowed into the computer room – they peered through the glass trying to catch the eye of an operator or sat in their office awaiting delivery of the large brown envelope containing their printer output. The computer was switched off when the late shift went home. The Starlink machine is left running 24 hours a day, 7 days a week, 52 weeks a year and is unattended except disks, tear off their own printer output and take care of most of their own plotting. The need for user support and programming help and advice remains. The new mode of operation has caused some problems in re-deploying staff, which has been compounded by difficulties in recruiting staff against the competition of industrial and commercial salaries and in retaining staff in the face of poor promotion prospects and the lure of more exciting, though not more demanding, projects.
exciting, though not more demanding, projects.

As time passed DEC broadened their network protocol to use the X25 packet switched service and the Joint Network Team (JNT) released what is now known as the 'coloured book' network software. This has made it possible for the VAXs to communicate with each other and with all makes and types of computer supported by SERC. The JNT PAD has made it easy to put together complicated networks in a very flexible manner. The JNT has also provided gateways to PSS, IPSS and thus to worldwide networks. In the near future this facility will be extended by the Spanish telecom service to La Palma, providing the vital link which will make remote operation of the RDLMO telescopes possible.

This trend towards greater connectivity will continue. The benefits of the network are most visible in Starlink, where it binds the users and management together in a very real sense, but other examples include a daily electronic mail service to AAO and SAAO, the ability to compose telexes at standard computer terminals, access to the CDS astronomical database at Strasbourg and the chance to install and test Starlink software on a VAX in Granada. As we become more familiar with the advantages of local area networks it has become clear that a higher speed link between the two RGO VAXs would be of great benefit, sharing facilities between the VAXs rather than duplicating them. It is therefore expected that we will install a 10 Mbits/sec Ethernet link between the two machines. This will be followed by a similar service between the computers on La Palma and between the various sub-systems on the WHT.

More recently RGO has found increasing uses for BBC B personal computers as sophisticated, but low cost, terminals and as self-contained computers for limited scientific and managerial tasks. Software developed at RGO now makes it possible to make the full range of facilities of the BBC micro available, including colour graphics and image display, through the internationally accepted standard graphics language GKS. It has also been used for experiments in the use of the simple, free network protocol Kermit, which allows us to link in the La Palma Perkin–Elmer computers.

The main uses of the 11/750 continue to be the traditional work of the observatory – positional and dynamical astronomy. In particular, this includes processing and unprecedented data flow from the CATC on La Palma and generating predictions and analysing the results from the SLR. All data from GALAXY, particularly from the Cape Overlap project, are processed on this computer. At present a new major user is emerging – software development and testing for processing data from the Hipparcos satellite. During the three years 1988–91 this single project will require eight hours a day to process the data coming from ESOC before passing it on to Scandinavian colleagues.

These projects are putting increasing demands on the computer so that the response time during prime shift can become extremely poor. Users are therefore encouraged to prepare their jobs on-line, but then submit them to a batch queue, to ensure that users do not waste too much time. How ironic that the very success of these systems means that users are forced back into the ways of working which the new systems were intended to replace.

RGO and Starlink

Starlink grew out of the deliberations of the Disney panel, which had been convened to bring some order to the competing demands from many groups around the country, all of whom wanted (different) minicomputers to analyse the data coming from the new generation of digital detectors. RGO staff played a prominent part in the initial discussions and have since made very significant contributions to the growing body of Starlink software.

When the Starlink 'interim environment' was first released RGO staff started writing applications aimed at analysing 2D arrays of data. It soon became clear that a command language was needed to hold the applications together and so DSCL was written. The applications, of which there were over 400 at the last count, continued to be developed at RGO and elsewhere, becoming known as ASPIC, which was derived from AStronomical PICtures. RGO continues to be responsible for development and maintenance of DSCL and ASPIC, which remains the only substantial package written in the Starlink interim environment. Nevertheless the great strength of this approach can be seen from the fact that *all* 2D software has been written using that environment and has fitted neatly into the framework provided by DSCL.

Starlink eventually decided to adopt the UCL package SPICA for spectroscopy. RGO helped with the initial conversion (the original having been written for a Perkin–Elmer 16–bit machine), dropped its own package (RGODR), added new applications and for several years was responsible for maintenance of the whole package. At the same time other sites and individuals wrote and used many different packages, but RGO users remained faithful to the adopted standard.

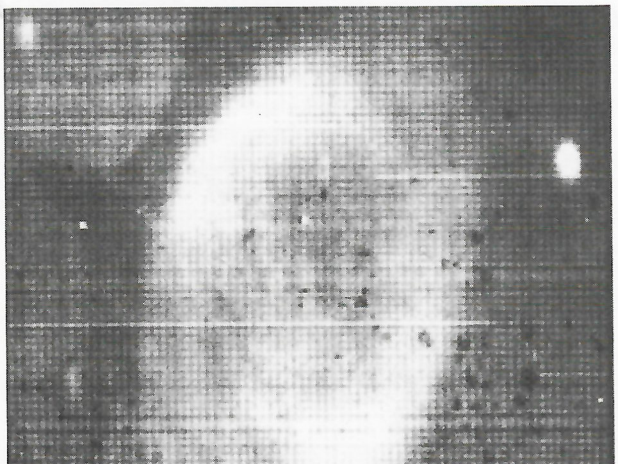
RGO has also supplied the official Starlink finding chart program, the latest version of which makes use of the interim environment and the official graphics standard GKS. In fact RGO has been one of the leading users of GKS, including writing new drivers for Calcomp plotters and BBC micro computers and adapting the packages Simpleplot and MONGO to work through GKS. When the new, but ill-fated, Starlink Software Environment (SSE) was released, RGO was one of the first groups to write real applications, based on improved versions of many ASPIC programs, using GKS for *all* line and greyscale graphics.

Throughout this period RGO has supported the ethos which led to Starlink, supported its adopted standards and contributed as much software as possible to the common pool. Now, when the major decisions about the 'final' environment are about to be made, shortage of experienced staff will mean that RGO can no longer continue to make the contribution which the community has come to rely on.

K.F. Hartley

The ICL 1903T computer (about 1979) was operator-manned, with a long time to turn around a job submitted on punched cards or paper tape and output to a massive line-printer. The more powerful VAXs are operated by the users themselves, with a concentration on interactive use from terminals.

A precursor to the modern generation of CCD cameras, the Charge Injection Device (CID) produced raw images such as the one on the left. The ASPIC software package (written at RGO) improves the images, removing fixed pattern noise and filtering to give images like that on the right (derived from the same data).



Greenwich Time Service

Throughout the period of this report the primary objectives of the Time Department have remained unchanged: to establish a stable atomic timescale, primarily for use as a reference in astronomy; to monitor the rotation of the Earth, on which timekeeping was originally based; and to make the results of both activities accessible to users of all kinds, both inside and outside the Observatory.

Today work in these 'service' activities is the subject of almost complete international coordination; the most generally useful results are produced in central bureaux by combining results submitted by many independent establishments. This cooperation has certainly improved the accuracy of the overall reference system, but it has also had the effect of reducing the unfavourable local impact of withdrawal of support from one contributor among many. During a period of increasing competition for resources this has been unfortunate for the RGO's atomic time service; in future the RGO must expect to be a customer for precise time rather than a major timing centre.

The activities of the RGO that relate to atomic time have been:

(a) Operation of a group of commercial caesium-beam clocks in a stable environment under conditions intended to justify as far as is feasible the assumption that each generates an independent good approximation to an ideal atomic timescale. The clocks are kept in six locked, temperature-controlled rooms in an air-conditioned sub-basement and have individually stabilized external DC power supplies.

(b) Evaluation of the performance of individual clocks and identification of any showing significant deviations from 'normal' behaviour. This requires the frequent precise intercomparison of at least three independent clocks of comparable quality. In principle they need not all be at the same site, but in practice the uncertainties introduced by external timing links still make it impossible to perform comparable evaluations of remote clocks. Methods now exist to reduce these uncertainties, but only after substantial investment of funds and effort.

(c) Formation of a composite 'paper' timescale by suitable combination of the readings of the clocks currently identified as being most predictable. This timescale, TA(RGO), is intended to be uniform, is not influenced by seasonal or other variations in the propagation of signals over long distances, and is immediately accessible. Because it is a free scale, not subject to control by an evaluable frequency standard, it must be subject to a slow random walk in frequency and will gradually diverge from other similar scales and from the internationally adopted reference timescale TAI. It is also potentially subject to ageing effects, or residual seasonal effects, which would invalidate the assumption that the clocks operate independently. But in the medium- and long-term its stability and uniformity are much better than those available from individual caesium-beam clocks. It can, at any time, be related to similar local timescales in Europe and North America with an expected uncertainty of less than 1 μs. It is a national facility and it is still in everyone's interest that it should be properly exploited.

(d) Use of this timescale as a reference in measurements of the reception of selected radio signals, and regular publication and distribution of the results. If the same signals can be received at other locations these results can be used there to obtain retrospective access to TA(RGO) and to other related timescales, time intervals and frequencies.

(e) Contribution of clock data and signal-reception data to the Bureau Internation de l'Heure for use in the computations defining TAI, which are currently performed two months in arrears. TAI in definitive form, and UTC which differs from TAI by an integral number of seconds, are thus accessible only after a two-month delay as time-offsets from the readings of real clocks participating in the scheme coordinated by the BIH. Times recorded in terms of a local clock that can be referred to TA(RGO) can be subsequently referred to TAI.

The signals that have been particularly relevant in (d) are those emitted from Rugby on 16 kHz (GBR) and 60 kHz (MSF), which were timed and phase-tracked at RGO, and the 100 kHz groundwave-propagated pulsed and phase-encoded emissions of the Loran-C navigation aid, which is still the mainstay of the international system of time comparisons and can yield total uncertainties of less than 1 μs. Four distinct Loran-C transmissions are monitored at RGO and our results are used in operational control of the Loran-C system for both time-transfer and navigation. We can also make measurements of TV synchronizing pulses for use in the calibration of precise timing equipment in southeast England, but at present we know of no demand for this service. Publication of GBR and MSF phase results ceased in June 1985.

This description of the work of the atomic-time service at RGO could have been given at any time during the past few years. Although a high-level meeting in 1982 between representatives of SERC and NPL concluded that RGO's atomic-time service complemented that provided by NPL, with parallel operation providing valuable insurance against technical or other difficulties at either establishment, funds and staff at RGO have both been reduced to a level that has enforced a fundamental revision of objectives and a concentration upon the RGO's own immediate requirements.

The Earth-rotation related activities of the Time Department have also undergone drastic revision since 1980, but here the changes have been more positive. The 'classical' photographic zenith telescope was removed from service in June 1984 because effort was no longer available to operate it and reduce the results. Instead the Satellite Laser Ranging system has been producing much more precise but not directly comparable observations of the Earth's rotation since October 1983. These observations are best analyzed in combination with similar observations made at other sites, and offer the prospect of a greatly improved understanding of factors influencing the Earth's rotation in the short term, as well as other topics. But they do not provide direct access to a non-rotating celestial reference frame; in future this will be primarily the responsibility of geodetic users of the radio astronomical technique of Very Long Baseline Radio Interferometry. The excellent quality and quantity of RGO's SLR data, and the fact that it can provide a basis for research in many fields, make us hopeful that this instrument will remain in operation, funded as it is now by MoD, DTI and NERC as well as SERC, for the foreseeable future. It is now the main on-site 'customer' of the atomic-time service.

J.D.H. Pilkington

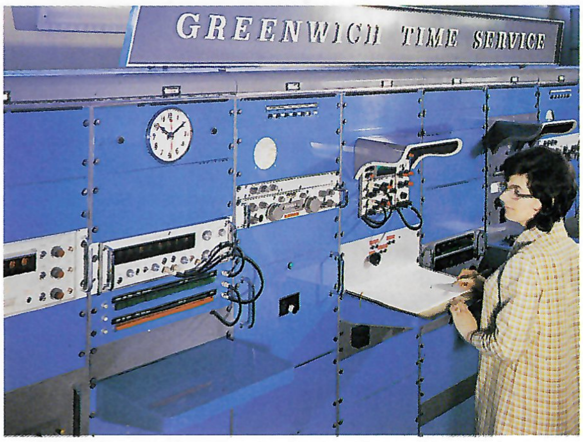


Fig. 1 Greenwich Time Service control desk monitors the RGO clocks.

The six pips

The Greenwich 'six-pips' time signal was first broadcast by the BBC at 9.30 pm on the evening of Tuesday, 5 February 1924. Sir Frank Dyson, the ninth Astronomer Royal, introduced the first signal, which was derived directly from the seconds-escapement of a long-case pendulum clock at the Royal Observatory at Greenwich. Electrical impulses were sent by land-line to the 2LO studio at 2 Savoy Hill on the Embankment for wireless transmission over the British Isles as six 'dots', the last of which indicated the beginning of the minute. Gradually the use of the signal spread and it is now broadcast throughout the world on the BBC Home and World Services.

In 1924 the timescale was derived from observations of the transit of stars across the meridian, but the signal is now derived from an atomic clock at the RGO at Herstmonceux Castle. Its availability, reliability and accuracy are now taken for granted by the many millions of persons who check their clocks and watches against it; its mode of distribution makes it unsuitable, however, for the most precise work. The timescale serves as a measure of rotation of the Earth around its axis and Greenwich Mean Time is used for the navigation of ocean-going ships as well as for many other useful purposes.

Timescales

Scientific timekeeping is now an international collaborative activity. It is based on results obtained from over a hundred atomic clocks and a much smaller number of evaluable atomic frequency standards which are operated in collaborating institutions around the world. Individual institutions (such as, within the UK, the RGO and the NPL) maintain local timescales based on one or more clocks and regularly provide the Bureau International de l'Heure (which now operates under the aegis of the CGPM) with precise measures of individual clock differences and signal-reception times. These are processed by the BIH to establish, in arrears, the relationship between the local timescale and International Atomic Time, which is usually denoted by the language-independent abbreviation TAI. TAI exists only in the form of these offsets from local timescales.

Coordinated Universal Time, UTC, is a timescale formed for general use which is commonly called GMT and forms the basis of the worldwide system of zone-times. It differs from TAI by a whole number of seconds and was designed to make both atomic time and Earth-rotation time easily accessible with appropriate accuracies. Adjustments of exactly one second are made at times published by the BIH at least eight weeks in advance in order to keep UTC within +0.9 s of UT1. UTC has had its present form since 1972. 'Leap second' adjustments have so far been necessary about once a year.

Universal Time, UT, is a time-like measure of the angular position of the Earth about its axis of rotation. Its value can only be established by making astronomical observations, and is calculated from a formula that perpetuates historical links with time-of-day at Greenwich. The designation UT1 indicates that the raw observations have been corrected for the site-dependent effects of the observed displacement of the pole from its conventionally adopted position. UT1R is formed from UT1 by the removal of some predictable short-term variations of rotation rate due to Earth tides. It forms a better basis than UT1 for the combination of observations made at different times, and for interpolation.

UT is needed by astronomers, surveyors and navigators, who use it to relate observations of celestial objects to their own position on or near the Earth's rotating surface.

Greenwich Mean Sidereal Time (GMST) is, like UT, a time-like measure of the angular position of the Earth about its axis of rotation; in fact UT is defined as a function of GMST, which is more directly related to the observations that establish them both.

Ephemeris Time, ET, was the timescale used prior to 1984 as the independent variable in gravitational theories of the solar system. The observational determination of ET was based in principle on the Earth's motion around the Sun and in practice on the orbital motion of the Moon. Since these motions are less affected by unpredictable forces than is the rotation of the Earth, observations of ET provided access to a timescale that was more uniform in the long term than UT. Determinations of ET were subject to uncertainties of order 0.1s and were consequently unsuitable for routine use as a standard of time.

Dynamical Time has now replaced Ephemeris Time in theories of the solar system. Terrestrial Dynamical Time (TDT) is the independent argument for geocentric ephemerides. For practical purposes it is TAI + $32^{s}.184$ although in principle TDT-TAI is still an observable variable. Barycentric Dynamical Time (TDB) is used in ephemerides and equations of motion that are referred to the barycentre of the solar system, and differs by only periodic terms from TDT. The variations arise from the varying gravitational potential of the Earth, and the clocks defining TAI, with respect to the barycentre; their amplitude is about 1.7 ms.

The work of HM Nautical Almanac Office

The preparation and publication of almanacs, ephemerides and tables for astronomy and navigation is carried out in close cooperation with the Nautical Almanac Office of the US Naval observatory. The volumes published are listed elsewhere in this report.

The content and arrangement of the *Astronomical Almanac* were subject to minor revisions from year to year and there were major changes in the basis of the ephemerides in the volume for 1984. These changes entailed major changes in the procedures and programs for the determination and use of the printed ephemerides and consequential changes in the explanatory notes and examples in the *Almanac*. The changes in the computer programs were first implemented on the ICL 1903T computer; some, but not all, of these programs have since been converted to Fortran 77 and otherwise adapted to run on the VAX 11/750 computer. The procedures and programs for the production of the other almanacs were also modified or redesigned to take into account the changes in the fundamental ephemerides and star catalogues and the change of computer. So far about 200 programs and subroutines have been changed.

There were no significant changes in the content of the *Star Almanac* but it was necessary to develop a new system of automatic typesetting for 1985 onwards. This new system has since been used for the production of pages for the *Astronomical Almanac* for 1987, for which there have been changes in the division of responsibility between RGO and USNO.

New publications

Planetary and Lunar Coordinates for the Years 1984–2000 is in continuation of the previous volume which covered only the years 1980–4. It follows the same general arrangement but the coordinates are all referred to the mean equinox and equator, or ecliptic, of the new standard epoch of J2000.0. Moreover, these coordinates are based on a new set of planetary and lunar ephemerides that have been prepared by numerical integration at the Jet Propulsion Laboratory, California, in cooperation with the United States Naval Observatory, Washington, DC.

Compact Data for Navigation and Astronomy for the years 1986–1990 contains in a convenient form the basic astronomical information that is needed by navigators who wish to be able to make effective use of small programmable calculators or personal computers. It may be used to calculate, without reference to the *Nautical Almanac*, the Greenwich hour angle and declination of the Sun, Moon, Venus, Mars, Jupiter, Saturn, the 57 bright stars used in navigation and the circumpolar stars Polaris and σ Octantis.

The data are mainly in the form of monthly polynomial coefficients and are ideal for use with small calculators. Daily coefficients have also been provided for the Moon, and positions of the bright stars are also represented by sets of eight coefficients covering the whole five-year period. Interpolation is automatic and does not require special techniques or tables. The precision is usually much better than $0'.2$ and is more than adequate for astronavigation at sea (or in the air) and for many other purposes. The explanation contains formulae for calculating position at sea without reference to the *Nautical Almanac* or Sight Reduction Tables.

The data will also be useful for astronomers, surveyors and others who are interested in calculating the positions and configurations of the Sun, Moon, planets and bright stars. Methods are given for calculating their times of rising and setting and for determining latitude and azimuth from sextant or theodolite observations of the circumpolar stars. The booklet wil be particularly useful for educational purposes, especially if used with a personal computer with a graphics display.

The *Explanatory Supplement to the Astronomical Ephemeris* is now obsolete and out of print. As an interim measure the principal changes in the bases of the ephemerides were described in a *Supplement to the Astronomical Almanac 1984*. Work on planning the new supplement has just recommenced; the work will again be shared with USNO and other astronomers may be asked to contribute.

Data services, 1981–5

The number of requests for astronomical data has continued to increase during this period and it has been necessary to automate the procedures still further in an attempt to keep pace with the demand; for example, the daylight and moonlight diagrams are now usually drawn directly by a Versatec plotter although this does not give the quality that is required for camera-ready copy for printing. Diagrams were produced at short notice for use during the conflict in the Falkland Islands. There has been a particularly large increase in the number of requests from Muslims for predictions of the dates of first sighting of the new moon, which marks the end of the period of fasting at Ramadan, and for prayer times that depend on the local direction of the Sun.

The Office issued worldwide predictions for the occultations of stars by the Moon up to the end of 1982 and it compiled and published the results of the observations made up to the end of 1980. The Office supplies to UK observers detailed predictions for grazing occultations and meets other special requests. Predictions are being prepared for occultations by Halley's comet as seen from both ground-based observatories and the IUE spacecraft.

Development of new techniques, 1981–5

Although the Almanacs continue to be widely used, they are not convenient (or are not available) for all purposes and so some effort was devoted to developing techniques that are appropriate for direct use with computers of various powers. A set of low-precision algorithms were developed for computing the coordinates of Jupiter and Saturn over long periods for use in historical and other investigations (NAO Tech. Note 56). Quite different techniques are required for the rapid reduction of navigational sights and so appropriate algorithms and data have been developed and published (NAO Tech. Notes 60–2; RGO Bull. 185; and *Compact Data, 1986–1990*).

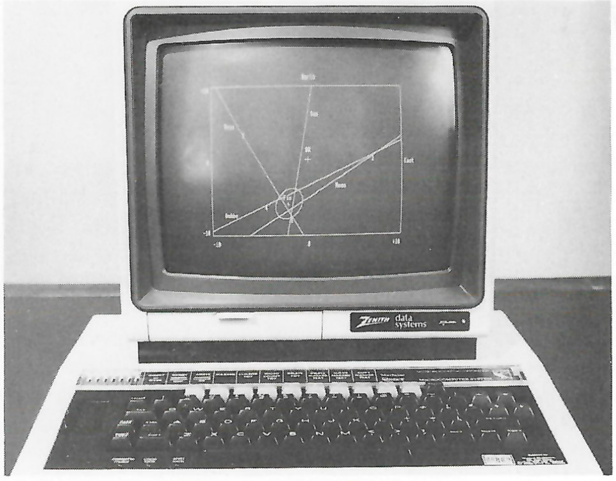
Procedures for other astronomical calculations have been developed and published in other NAO Technical Notes: physical ephemerides of planets and satellites (53), geocentric and heliocentric phenomena (54), phase corrections for Venus (55), solar rotation (58), and refraction (59, 63).

It was also necessary to develop a new system for automatic typesetting to replace that developed 15 years ago; this has been done in cooperation with staff of Her Majesty's Stationery Office.

Sesquicentenary

The 150th anniversary of the establishment of HM Nautical Almanac Office was celebrated at a Reunion Party held at Herstmonceux Castle on September 25 1982. The previous Superintendent, Dr D. H. Sadler, and nearly 50 other past and present members of the staff of the NAO attended; some of them had worked in the office over 50 years previously.

B. D. Yallop G. A. Wilkins



The TV monitor screen shows a navigational 'fix' that has been calculated directly by a BBC microcomputer using a program that was written in BASIC.

To find position at sea by astronavigation the navigator observes the altitude of a celestial body using a marine sextant, and he records the time of the observation using a watch which has been corrected to GMT. An initial estimate of position at the time of the fix is made, usually by dead reckoning, and the altitude and azimuth of the celestial body is calculated at the time of observation. The navigator's true position lies on or near to a position line which is plotted on a chart. The shortest distance from the estimated position to the position line is the difference between the observed and the calculated altitude of the body. If the altitudes are measured in minutes of arc the distance is in nautical miles. The position line is drawn at right angles to the direction of the calculated azimuth of the body. A minimum of two position lines is required to obtain a fix, but three or more sights are usually taken to reduce the effects of errors in the observed altitude.

1984: A year of change in the *Astronomical Almanac*

The International Astronomical Union adopted in 1976, 1979 and 1982 a series of recommendations concerning the introduction into astronomical practice of a new system of astronomical constants and units, new dynamical time-scales, a new standard epoch, a new fundamental reference system, and new procedures for the computation of apparent positions; the consequential changes were introduced into the *Astronomical Almanac* in the edition for 1984 and were described in a bound-in Supplement, which included the IAU recommendations. The published ephemerides of the Sun, Moon and planets are now based on a numerical integration of their motions with respect to the barycentre of the Solar System; this integration was carried out at the Jet Propulsion Laboratory, in cooperation with the US Naval Observatory and Naval Surface Weapons Center; the equations of motion included the effects of general relativity and the integration included also the librational motion of the Moon and the orbits of five minor planets. The computations of the published apparent geocentric coordinates (which were carried out at RGO) required the development of new procedures for the reductions for precession, nutation and aberration, for the inclusion of the effect of the bending of the light path in the gravity field of the Sun, and for the difference between the barycentric and terrestrial dynamical time-scales. Time in the new series for precession is expressed in units of Julian centuries, rather than of Besselian solar years, and the new standard epoch (denoted by J2000.0) is defined as a Julian Date. The new time-scales replace ephemeris time in high-precision applications, but are continuous with it for applications not requiring the use of relativistic theories.

The new fundamental reference system is that of the FK5 star catalogue that is being prepared by the Astronomisches Rechen-Institut, Heidelberg. The systematic differences between the FK4 and FK5 systems have been applied in computing the star positions given in the *Almanac*. New formulae, using vector and matrix techniques, for the computation of precise apparent positions from catalogue positions have been developed and published in the explanatory notes in Section B. Data and formulae for the day-number technique are still given for use in applications where full precision is not required. Changes have been made in the treatment of the E-terms of aberration and in the expression for the relation between universal time and Greenwich mean sidereal time.

Automatic typesetting of tables

The publication of an Almanac or similar book containing numerical data in tabular form requires that the printed information be accurate, easy to read, and in a convenient form for the user. In order to save time in editing and proofreading it is necessary to use an automatic typesetting system that will start from the numerical data in its initial form as simple lists without headings or spaces, and produce the coding that will drive a filmsetter (phototypesetter) to produce masters in final, paged form. A system of this kind was first developed in the NAO in 1968 on the ICL 1909 computer.

A completely new system has now been designed and developed. The first stage has been implemented in the NAO and involves a new command procedure known as TOPPS (Tables and Text from Computer Output for Printing System). The editor, who need not have a detailed knowledge of computer programming, specifies by a series of commands the exact format of the page (headings, founts, spaces, rules, leading-figure suppression, etc). This format statement is processed with the data for each page to produce a file containing a complete specification of what is to be printed. This filc is listed so that it can be verified that the headings, layout and numerical data are correct before the file is copied to magnetic tape. The second stage has been implemented by HMSO and consists of a program that starts from this tape and produces another that is used by the printer to drive a Linotron 202 filmsetter. This two-stage procedure has the advantages that the NAO output is device independent (and so will not have to be changed if a different filmsetter is used) and that it is, at present, acceptable to the printers' unions.

SUN – SEPTEMBER, 1986 19

U.T. d	h	*R* h m s	Dec. ° ′		*E* h m s		U.T. d	h	*R* h m s	Dec. ° ′		*E* h m s	
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Wed.	6	43 31.3	2 21.6	58	05 20.3	54	Thur.	6	15 03.7	0 44.8	58	08 10.2	52
	12	44 30.4	2 15.8	58	05 25.7	53		12	16 02.8	0 50.6	59	08 15.4	52
	18	45 29.6	2 10.0	58	05 31.0	54		18	17 02.0	0 56.5	58	08 20.6	52
18	0	23 46 28.7	N 2 04.2	58	12 05 36.4	54	26	0	0 18 01.1	S 1 02.3	59	12 08 25.8	51
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19	0	23 50 25.2	N 1 41.0	58	12 05 57.9	53	27	0	0 21 57.7	S 1 25.7	59	12 08 46.3	51
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20	0	23 54 21.8	N 1 17.7	58	12 06 19.3	53	28	0	0 25 54.2	S 1 49.1	58	12 09 06.6	51
Sat.	6	55 20.9	1 11.9	58	06 24.6	54	Sun.	6	26 53.4	1 54.9	59	09 11.7	50
	12	56 20.1	1 06.1	58	06 30.0	53		12	27 52.5	2 00.8	58	09 16.7	50
	18	57 19.2	1 00.3	59	06 35.3	53		18	28 51.7	2 06.6	58	09 21.7	50
21	0	23 58 18.3	N 0 54.4	58	12 06 40.6	54	29	0	0 29 50.8	S 2 12.4	59	12 09 26.7	50
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Library and Archives

The Library and Archives collections of the RGO are the most complete single source available for scholars, both for the current state of the art in astronomy, astrophysics and related subjects and for the history of those subjects. They are also a primary source in the history of science and, to a lesser extent, technology.

They consist of the contemporary publications available on two sites at Herstmonceux (the Castle and West Libraries) and the John Whelan Library of the Roque de los Muchachos Observatory on La Palma; the nineteenth-century printed material; the Airy Collection of Rare Books; the Archive collection of manuscripts relating to the history of the Observatory; the modern records, consisting primarily of post-World War II papers; the deposited archival collections of papers relating to, but not originated by, the Observatory and the collections of museum objects, three-dimensional archives and works of art.

Administratively, Library and Archives are part of Almanacs and Time Division, reporting through the Superintendent of the Nautical Almanac Office to the Director. The collections are available as a reference source to all members of the RGO and visiting staff and students, to the staff and students of the Astronomy Centre at Sussex University and other similar departments, to all Fellows of the Royal Astronomical Society and to other bona fide researchers on request. It is in fact true that all of the collections, with the exception of the contemporary publications, are used more by researchers not directly employed by SERC and this is particularly so of the Archives and the Airy Collection.

It was not until the late 1970s that any concerted attempt was made to introduce systematic cataloguing, indexing and arrangement to any of these collections and the sheer size of the problem has made progress somewhat slow. However, the results of the efforts made over the last six years are now becoming apparent.

In the Library, all of the twentieth- and the more used of the nineteenth-century publications have been catalogued, classified by UDC and rearranged on the shelves. The catalogue information is now being entered onto a computer data base. A short-title catalogue of the Whelan Library is already available, as is an interim card catalogue to the Herstmonceux collections. The periodicals catalogue is being put onto computer at ROE as part of a union list of UK holdings of astronomical serials. The Airy Collection of Rare Books is now housed in the Castle Chapel. All the titles in this collection have now been catalogued with a full bibliographic description. Thus far it exists in manuscript only but there are long term plans to publish it, possibly as a microfilm edition.

Dealing with the Archives is a much larger and more complex problem. Such lists as did exist had been produced in the late 1950s as a result of the Public Record Act, 1958: the Observatory's records are Public Record within the meaning of the Act and the Observatory itself is a Place of Deposit under Section 4 of that Act. The lists were of necessity brief and occasionally uninformative; in any event they dealt only with certain sections of the records, probably no more than one third of the total. Increasing interest in the collections made sorting and adequate indexing a real priority but the means of so doing were not immediately obvious.

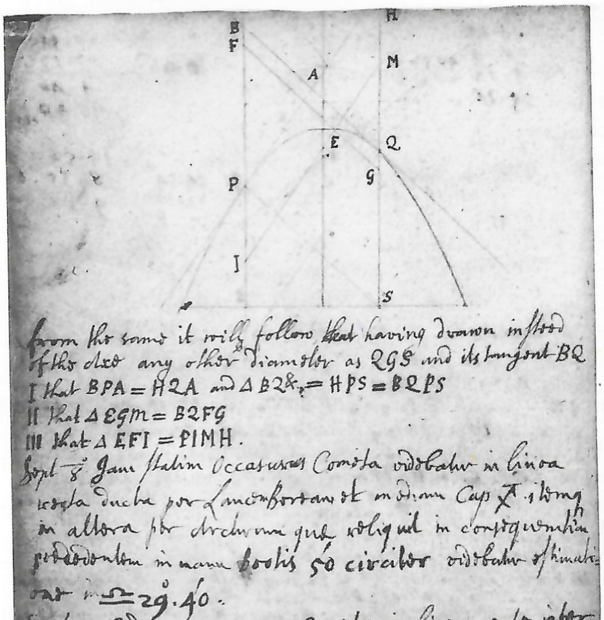
As funding from SERC budgets seemed unlikely to be approved, even in the long term future, the RGO approached the Manpower Services Commission (MSC) with the intention of setting up a team of cataloguers and indexers to be entirely funded by MSC under their Community Programme. Agreement was eventually forthcoming and, in April 1983, a staff of one supervisor, three full-time and five part-time assistants was appointed to form the Laurie Cataloguing Project. The first year of the Project, 1983–4, produced lists of the papers covering the first 200 years of the Observatory's life, together with some 10 000 entries in an index to the correspondence of G. B. Airy, Astronomer Royal 1835–81. Another index, to named chronometers mentioned in the collections, was also started.

During the second year, 1984–5, the Project tackled the Solar Plate collection, a unique run of daily Sun photographs on glass plates, where vital information would soon have been irretrievably lost and the plates spoilt had no action been taken. By the end of the year over 14 000 out of a run of 22 000 had been saved, the various indexes had doubled in size and the listings reached the twentieth century. To ensure continued MSC funding, the Project also planned and wrote a series of Educational Work Packs, intended for distribution to the many school parties visiting the Observatory. The staff in this second year grew to three full-time and seven part-time employees.

The MSC have now approved a third year, 1985–6, during which the educational aspect of the work will be expanded. It is also hoped to complete the transfer of all the archival listings to word processor disk: the Observatory was the first department to produce its listings in this way.

Although about 75% of the papers have now been listed, the huge indexing task is only 10% complete: to make this information immediately available it should be entered on computer, but financing on the scale required will not be available from MSC.

Fig. 1 Edmond Halley's common-place book in the RGO Archives shows how he calculated the orbit of the Comet of 1682 with the aid of Newton's theory, and predicted its return.



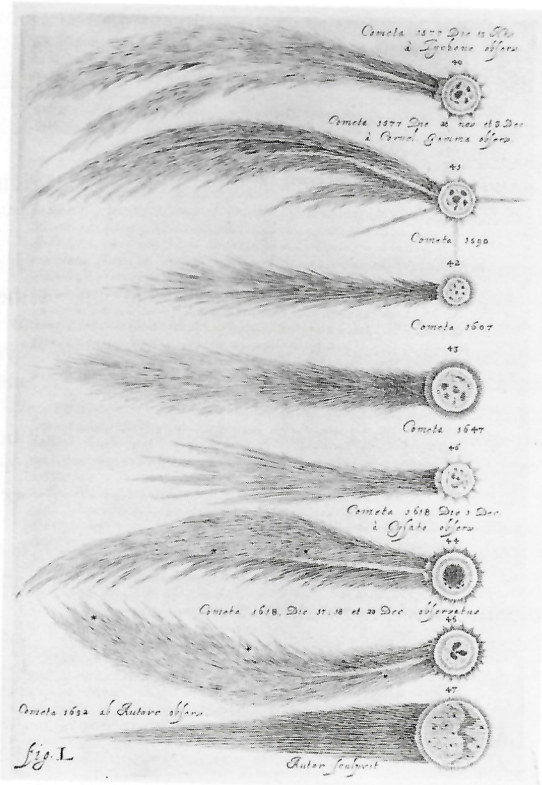


Fig. 2 Hevelius' Cometographia *of 1668, in the Airy Collection of Rare Books, depicts Halley's Comet on its 1607 apparition.*

Fig. 3 In the collection of pamphlets in the Archives is a Heath Robinson cartoon reproduced in The Sketch *of Nov. 17 1909 showing eccentric astronomers observing the 1910 apparition of Halley's Comet.*

As an example of the use to which all these data are put, material in the Archives and Airy Collection has been used by Yallop (RGO) and Clark (RAL) to study the rotation of the Sun. Records of observations made during the seventeenth and eighteenth centuries of the occurrence of sunspots have been used to look for variations with latitude and time on the rate of rotation of the Sun. They found no detectable change in the equatorial period of rotation but they confirmed that the differential rotation with latitude varies with the sunspot cycle.

Lesley Murdin based a study of the practice of astronomy in the time of Newton on the archive material, and gave an account of how astronomers lived, built instruments and were financed in *Under Newton's Shadow*, Adam Hilger, 1985.

The 1985 return of Halley's comet is resulting in a good deal of research being carried out at the Observatory and this precisely illustrates the unique character of the collections. We have in Archives both Edmond Halley's 1682 Islington observations of the great comet and the common-place book in which he later calculated its orbit. In the Flamsteed papers are the observations made from Greenwich, against one of which is a note to the effect that, on that occasion at least, Flamsteed and Halley observed the comet together.

In the Airy Collection is Halley's *Synopsis Astronomiae Cometicae* (London, 1680), his first attempt to bring his theories to the public's attention; his note in the *Philosophical Transactions of the Royal Society*, 1705, is in the Castle Library. Also in the Airy Collection are Newton's *Principia* (3rd ed., London, 1726) which first interested Halley in the calculation of orbits and a number of important early treatises on comets, most notably Hevelius' *Cometographia* (Danzig, 1668). Bradley's observations of the 1758 return from Greenwich are in Archives and much of the published French work of the period, particularly that by Clairault and Lalande, is in the Airy Collection. By 1835, the Royal Observatory, Cape of Good Hope, was operational and Archives has Maclear's important series of southern hemisphere observations of the comet as well as Pond's from Greenwich.

By 1910 it was possible to make photographic plates with the 26-inch refractor at Greenwich and these, together with other plates, most notably again from South Africa, are stored in Archives. Virtually all of the printed material (newspaper articles, pamphlets, journal articles and results) are also available as are, now, a series of files of secondary publications on the present return and of photographs taken at both the Roque de los Muchachos and Herstmonceux.

Many of the images seen on television and in print relating to Halley's comet come from the Observatory. Use of all the collections is increasing rapidly and, as better finding aids become available and the book and periodical catalogues are fully automated, this trend is undoubtedly set to continue.

J. Dudley

Conservation

One of the main causes for concern when the Archive collections were reviewed in the late 1970s was their extremely poor physical condition and the rate at which the modern records, particularly, were deteriorating. After lengthy discussions, a modern and well-equipped Conservation Laboratory was installed at Herstmonceux and a qualified paper conservator appointed. Although his task is primarily to deal with the Archive collections he carries out some remedial work on the rare books. The main programme dealing with the latter is, however, carried out under contract by individual craftsmen. The Observatory is one of the very few departments to have such a facility funded by central government and it is the only one supported within a research council.

The RGO actively maintains a close relationship with the communities which it serves. The national and international communities of astronomers and scientists in the UK, the Netherlands, Spain, and Denmark work with the RGO's own astronomers and scientists at all levels in a common purpose to use the finest telescopes with the best instruments on the clearest sites for the most stimulating research.

UK astronomy on La Palma

UK astronomy on La Palma

With the construction of the Anglo-Australian Telescope, an imbalance between the southern and northern hemispheres developed in British optical astronomy. In the north, radio astronomers were making demands for time on large optical telescopes and the rapid growth of astronomy as a whole was increasing the pressure for time on all large telescopes. In 1967 Prof H. Brück, Astronomer Royal for Scotland, proposed that a new observatory should be built for UK astronomers. It would be on an excellent site, yet to be identified, and it would have a large optical telescope as its central feature.

The Science Research Council decided in 1968 to review the possibilities for such a Northern Hemisphere Observatory (NHO). The Review Committee first met in 1969 under the Chairmanship of Sir Fred Hoyle. Its 1970 report stimulated a survey of possible sites. Advice was sought from Prof M. F. Walker of Lick Observatory who was interested in extending his objective assessments to a selection of good sites over the whole world. As a result, testing was concentrated on Tenerife, La Palma, Hawaii and Madeira. These tests showed that Madeira was an inferior site compared to the other three and that La Palma was preferable to Tenerife for night work because of the small amounts of dust and light pollution. Problems of working at altitude and at such a distance from the UK ruled out Hawaii for optical observing.

In August 1974 the Spanish authorities issued an invitation to form a Joint Astronomical Site Survey to undertake an international programme of site testing on the Canary Islands. Polaris trail telescopes and meteorological equipment were set up on La Palma and observation began on November 25 1974.

At a meeting in December 1974, representatives of Denmark, Sweden, Germany and the UK met the Spanish authorities: the meeting revealed the intention of the Spanish astronomers and authorities to provide the basic facilities, i.e. a road, electric power and water for the new observatory site. The project was to be regarded from the start as a cooperative venture, with the overseas participants providing telescope time and training for research astronomers in return for the use of the site and of its facilities. The formal agreements necessary to secure the rights and specify the duties of the international participants were formulated two years later, and signed in 1979.

In 1974, the RGO began to put its main efforts into the construction of the NHO, now designated the Isaac Newton Group, part of the Roque de los Muchachos Observatory.

F.G. Smith

Agreements on cooperation in astrophysics

On May 26 1979, after having overcome all kinds of difficulties, the 'Agreement on Cooperation in Astrophysics' was signed in the Cabildo of La Palma, by Spain, Denmark, the UK and Sweden. At the same time, the Spanish Higher Council for Scientific Research (CSIC), the Danish Research Administration, the British SERC and the Swedish Royal Academy of Sciences, signed the 'Protocol of the Agreement on Cooperation in Astrophysics'. Afterwards, the IAC also signed the Agreement with each of the User-Institutions of the Canarian Observatories, which are the aforementioned signatory bodies of the Protocol. These are the three formal levels around which the international scientific collaboration has been structured. In April of 1983, the German Federal Republic adhered to the agreements, which required some redrafting of the Protocol. The signing of the third level, the Agreement between the IAC and the DFG, took place in the La Orotava Town Hall. Britain, through the SERC, made separate agreements with the Netherlands Organisation for Pure Research (ZWO) and the Irish Dublin Institute for Advanced Studies and National Boards for Science and Technology to share its La Palma Telescopes.

International Observatories

Spain, through these Agreements, has internationalised the IAC's observatories, making them available to the scientific community. Therefore any scientific institution, established within the territory of a country which has signed the First Level, can install their telescopes there. The telescopes remain the property of those countries which originally installed them. Spain guarantees the research activity and the protection of the Observatories according to the IAU's guidelines. An effective participation in the adoption of all decisions concerning the Observatories is guaranteed to the signatory bodies through the International Scientific Committee, known by its Spanish initials as CCI.

The International Scientific Committee (CCI)

The CCI is the key factor in the international cooperation. Its agreements require the unanimous vote of all of the signatory bodies to the Protocol, and this provides an important guarantee.

The CCI is composed of one CSIC representative, one La Laguna University representative, one CNAE (National Committee for Spanish Astronomy) representative and a representative from each of the countries that sign the Agreement, and the European Science Foundation, plus the Director of the IAC.

The CCI elects a president and vice president every two years. Its functions are:

(a) To coordinate the 'Common Services' needs of the individual telescopic installations, and present proposals on their use or modification to the IAC

(b) To approve the expenses and other financial agreements

(c) To approve new agreements for telescopic installations, in relation to those aspects that could affect other users

(d) To coordinate the joint scientific activities within the observing time assigned for cooperative research projects

(e) To produce annual reports on the development of scientific activities in each observatory

(f) To prepare the norms for the distribution of the observing time

(g) Any other matter which might arise, with regard to the development and use of an Observatory.

The Committee meets twice every year and is assisted in its work by subcommittees. At present there are three in existence; 'Finance', 'Technical' and 'Operations'.

The Finance Subcommittee is responsible for preparing the budget and related matters so that the CCI can approve it, and also it supervises the accounts. It is made up of one representative from each signatory country to the Agreement, plus another from IAC.

The purpose of the Technical Subcommittee is to act as advisor on the technical aspects related to the common services of the observatories. Its composition is similar to the above.

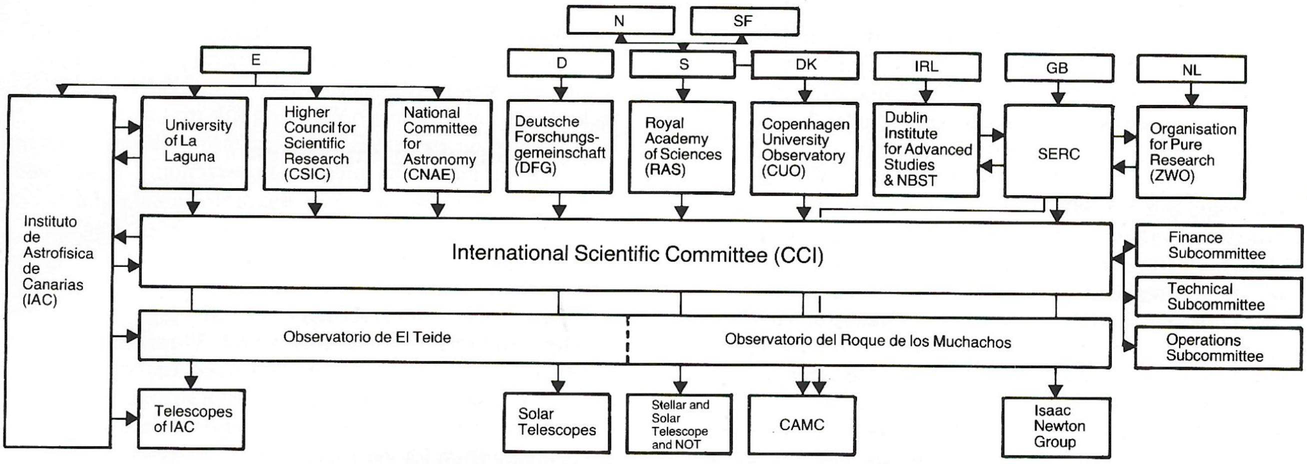
The Operations Subcommittee of the Roque de los Muchachos Observatory advises the CCI on the establishment, maintenance and administration of the common services of this Observatory and passes on any concrete recommendations to the Director of IAC. It meets almost every month and is responsible for the permanent control of the Observatory's operations.

CCI Presidents

1979–81	Prof F. G. Smith, Royal Greenwich Observatory
1981–3	Prof A. Wyller, Royal Academy of Sciences
1983–5	Prof H. Jorgensen, Copenhagen University Observatory
1985–	Prof A. Boksenberg, Royal Greenwich Observatory

CCI Vice-President

1979–	Prof F. Sanchez, Instituto de Astrofisica de Canarias



International structure of the Canary Island observatories

The Instituto de Astrofisica de Canarias (IAC)

The IAC is a research centre with a very special legal identity, unique among Spanish research institutes; it is responsible for three organisations: The Roque de los Muchachos Observatory on the Island of La Palma, the Teide Observatory on the Island of Tenerife, and the Instituto de Astrofisica located in the campus of La Laguna University of Tenerife. The IAC's administrative structure is called Consorcio Publico de Gestion (public management consortium) and is based on two fundamental governing bodies: first the Consejo Rector (governing council), which is the decision-making power in administration and finances, and, second, the Director of the Institute, who is competent in scientific matters and acts as the executive organ of the Consejo Rector.

The Consejo Rector, 'through which the organization composing the consortium exercise the necessary control' is presided over by the Minister of the Presidency of the Government and composed of the highest authorities of those organizations as well as by the Director of the IAC. The motivation for this special administrative structure given to the IAC is based on the intrinsic interest of the astrophysical research, and, beyond that, on the consideration of the Canary Islands' sky as a natural resource of the archipelago and on the International Agreements which establish the observations on La Palma and Teide. Therefore, 'the Spanish State, conscious of these realities', gave the IAC a special legal status by the Royal Decree Number 7/1982, forming thereby a Consorcio Publico de Gestion created by joint action of the State Administration, which acts through the Ministry of the Presidency, the Canary Islands Government, the University of La Laguna and the CSIC in order to:

(a) Carry out and promote all types of astrophysical or related research

(b) Disseminate astronomical knowledge, collaborate in University teaching of the speciality of astronomy and astrophysics in the University of La Laguna, train and prepare scientific and technical personnel in all fields related to astrophysics

(c) Administer the Centres, Observatories and astronomical installations that already exist and those that will be created in the future, or that are incorporated into its administration, and also those dependent on its services

(d) Promote relations with the national and international scientific community

In pursuit of the last aims, joint programmes with international groups including the RGO are being developed and the scientific production of the Institute increases steadily. The telescopes and instruments of the Observatories already included in the agreements with the UK are being finished, installed in their definitive sites and put into operation by the RGO. In spite of the natural complications inherent in an international venture of such dimensions, the joint work of the different members of this 'astrophysical club of the Canary Islands' is constantly improving. I would like to think that these Islands will become a fruitful meeting place for the astronomical community and offer a permanent example of the understanding and collaboration among the men of science of our nations.

F. Sanchez

Samenwerking

Astronomy in the Netherlands is first and foremost a university activity. The astronomy institutes at the Universities of Amsterdam, Groningen, Leiden and Utrecht, chaired respectively by Ed van den Heuvel, Hugo van Woerden, myself and Max Kuperus, are the centres for both research and training. All four have astronomy undergraduate as well as PhD programmes. The undergraduate training lasts between four and six years; the PhD candidate normally has a four-year junior staff appointment. The dissertations are substantial research contributions, properly printed and usually distributed around the astronomical world four- to six-hundred fold. By this means a large fraction of our research efforts finds its way into astronomical libraries in both journal and book form. The dissertations in fact are normally a bundle of refereed articles tied together by a prologue and/or an epilogue.

Dutch ground-based astronomy has only one 'establishment': the Netherlands Foundation for Radio Astronomy (NFRA) with headquarters at the Dwingeloo Radio Observatory and a most important facility at the Westerbork Radio Observatory. The NFRA employs just over 100 full-time equivalents, about 155 people, who are legally employees of ZWO, the Parent Organization for Pure Scientific Research. Optical instrumentation efforts were made by Groningen, Leiden and Utrecht separately till 1981. That year the Interuniversity Work Group for Optical Instrumentation was formed by Groningen and Leiden and five Leiden technical staff moved north; the group is housed in the Kapteyn Sterrewacht in Roden, near Groningen and is informally called the Kapteyn Sterrewacht Werkgroep (KSW). The KSW is directed by Harvey Butcher, professor of observational astronomy at Groningen; it is financed by the two participating universities. The Utrecht instrumentation efforts continue in their stand-alone mode. Utrecht is building the echelle spectrometer for La Palma as well as elements of the Maxwell telescope; the KSW is, among other things, building a scanning Fabry–Perot, developed at the RGO and called TAURUS, for both the WHT and the AAT.

The most substantial contributions to the La Palma and to the Maxwell telescope procurement phase come from the NFRA's Dwingeloo laboratory, workshops and software group. Jean Casse, head of NFRA's laboratory, coordinates all technical contributions from the Netherlands to the UK–NL astronomy collaboration. The chairman of NFRA's Management, a post that passed from Wim Brouw to Ernst Raimond on September 1 1985, monitors the manpower and financial aspects of our role in La Palma and Mauna Kea operations; he is assisted by Ton Schöller, head of NFRA's administration. Klaas de Boer is the liaison link for NL astronomy with RGO.

The formal partner of SERC in this enterprise is the Netherlands Organisation for the Advancement of Pure Research, ZWO. Hette Weyma, of the ZWO Directorate in The Hague, is the chief liaison link with SERC. ZWO has appointed Miller Goss, astronomy professor at Groningen and myself as its members in the SERC-ZWO Joint Steering Committee. Between semi-annual JSC meetings the coordinating role for our part of the effort is entrusted to the Stuurgroep Brits-Nederlandse Samenwerking which I chair and which reports to the Boards of both NFRA and the ASTRON Foundation; the latter is chaired by Max Kuperus, who is professor at Utrecht. ASTRON is ZWO's Foundation for administering astronomy grants to universities and it plays an advisory role in the tuning of all constituents of our astronomy community with the aim of achieving harmonious and mutually reinforcing policy and decision-making.

ZWO, the two foundations and the university astronomy institutes are all represented in the Stuurgroep. The Stuurgroep's assignment is to muster the collective capacities of both ZWO Foundations and of the university institutes in order to meet ZWO's obligations towards SERC and to optimise our use of La Palma and Hawaii facilities. Wilfried Boland, ASTRON's executive secretary, also handles the Stuurgroep secretariat. By gentlemen's agreement the university institutes are to provide about half the Dutch share of operational manpower as well as an agreed portion of the procurement programme. The SERC-ZWO agreement signed in June 18 1981 has meant an enormous challenge and a considerable burden for all of this country's astronomical teams. The new circumstances have turned the NFRA's technical talents towards optical and sub-millimetre instrumentation, inevitably at the expense of the development effort for centimetre/decimetre radio astronomy. It has been gratifying to see how effectively the professional skills developed in radio astronomy can be brought to bear on instrumentation and software tasks in the optical and submillimetre domain.

Our new obligations are not easily met, especially in this heavily committed procurement period. Three features have justified the burden: the lively and new colleague-to-colleague interaction at all levels between British and Dutch teams makes life interesting; the beautiful results astronomers are bringing from La Palma, tributes to RGO's world class performance under trying circumstances, are generating much enthusiam; a commitment to succeed through pooling talents and resources gives Dutch astronomy a convincing claim on support from ZWO and from the universities.

The UK–NL collaboration in astronomy completes our access to state-of-the-art equipment across the whole spectrum. For a small country with a great astronomy tradition that is a necessary ambition, as well as a privilege that cannot be taken for granted.

H. van der Laan
University of Leiden

The British and Dutch astronomical communities committed themselves with the signing in 1981 of agreements between SERC and ZWO to work together on the La Palma and Hawaii observatories. They chose to share all the parts of the projects, as far as was practical, including the construction, operation and use of the telescopes, each providing manpower, capital and running costs in the ratio 4:1, this number being representative of the sizes of the British and Dutch astronomical communities. The Netherlands sends Dutch staff to La Palma and Herstmonceux to operate the telescopes and provide infrastructure; instruments are built in Dutch institutions as in British; and Dutch organisations share the responsibility for the whole La Palma project with their counterparts in the UK. The collaboration (*samenwerking*) is supervised by the SERC–ZWO Joint Steering Committee; the collaboration actually occurs at numerous interactions of scientists, engineers, astronomers, programmers, technicians and administrators every day and night.

Anglo-Dutch instrument programme

The instrument programme for the William Herschel Telescope relies on Dutch institutions for the provision of approximately 25% of the common user instruments. The Dutch are highly respected as radio astronomers and are now increasing their interest in the optical field bringing with them much experience, particularly in computing.

These instruments are contracted out by the RGO to various institutes in Holland who are responsible for their design, development, construction and commissioning. Since the instruments are complex and require to be integrated into the WHT computing system, network and data aquisition system, frequent liaison is required between establishments. A good working relationship has developed between the institutes and the RGO during the early stages of the programme.

The institutes involved are the Kapteyn Sterrenwacht der Rijksuniversiteit te Groningen who are building TAURUS (an imaging Fabry–Perot interferometer) which, when used with a photon-counting area detector such as the IPCS, can create 3D images of emission line galaxies and galactic nebulae. This technique was pioneered in a collaboration between Taylor at the RGO and Atherton at The Imperial College of Science and Technology, and a first-generation instrument was produced for the INT. The Mark II common user instrument to be produced for the WHT is in production and will be available early in the telescope commissioning programme. The astronomical observatory *Sonnenborgh* and the Laboratory for Space Research at Utrecht, have carried out the design studies, for, and will be building the High Resolution Spectrograph. This instrument is an echelle-based system which will permanently occupy one of the f/11 nasmyth platforms. Its design is a result of a collaboration between UCL and the Utrecht observatory and uses large quartz prism cross-dispersers so that it can be used from the near IR to the UV atmospheric cut off, at resolutions of up to 20000. The design configuration has also been optimized to allow for both shorter and longer focal length cameras whilst permitting grating cross-dispersers as an option for experiments where larger order separations are required.

Development of the CCD control sequencer is being carried out at the Radiosterrenwacht at Dwingeloo; it will eventually be integrated into the overall RGO CCD system. This system will be capable of driving the largest of CCD chips 2048 x 2048 pixels and also large arrays of smaller chips 320 x 512 pixels. The Radiosterrenwacht are also developing the archiving system for La Palma.

M. Morris

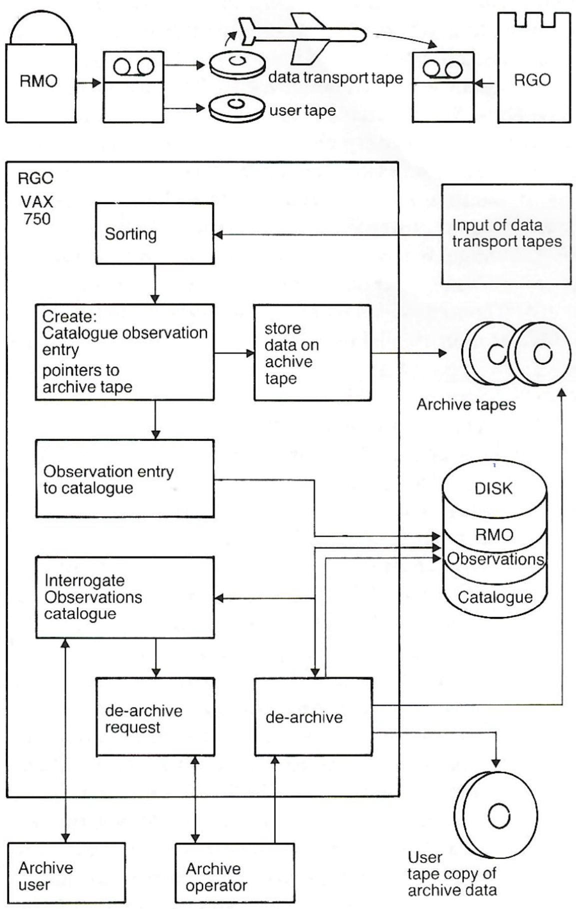
La Palma archive

Precious astronomical data have been carried away from observatories by the observers themselves since the beginnings of astronomy. Information may have been stored away in the memory of the astronomer, it may have been stored as notes, as strip charts or, as is normal today, on magnetic tape. With the coming of satellites measurements had to be processed by a control station to separate the astronomical data from the more technical satellite information. Thus such costly astronomical data was stored in a systematic way, and in particular the IUE satellite operation resulted in a public accessible data archive.

The high quality of the data coming from the advanced instruments on the excellent site of the Roque de los Muchachos Observatory on La Palma, together with the computer control of the observatory data flow, warrants the establishment of a data archive. Such systematic storing and accessing of data from an earthly observatory is a novum; the Roque de los Muchachos Observatory data archive will be the first of its kind.

The software to archive and re-access such data has been conceived and is developed in Dwingeloo, the Netherlands, as part of the Netherlands contribution to the Roque de los Muchachos Observatory project of the UK–NL *samenwerking*. Software to make telescope and instrument data available on tape is made at the RGO. The structure of the archive scheme is shown in the diagram. The observation catalogue, whose form has recently been defined, will allow easy access by archive-users to check on existing data and to retrieve observations relevant for further use and analysis.

K.S. de Boer



The flow of data from the telescope to the archive and the way of archive retrieval.

RGO and the universities

A main function of the Royal Observatories is to provide, maintain, and operate facilities for the university community, in accordance with the SERC charter. The RGO welcomes this role; from it, and from mutual research interests described here, stem a labyrinth of connections at all levels with the UK universities interested in astronomy.

One particular and highly complementary relationship is with the other major astronomy institute in Sussex – the Astronomy Centre at the University of Sussex. A second type of relationship concerns research, where mutual interests result in connections which may consist of single telephone calls, to large-scale programmes involving many individuals, large amounts of telescope-time at wavelengths from radio to gamma-rays, and years of continued efforts towards the solution of a major astrophysical problem. A third and distinctively different type of relationship derives from conception, design, construction, and operation of telescope instrumentation. To this, the RGO brings great experience in optical, mechanical, electrical, and electronic techniques for instrumentation to support astronomers who conceive instrumentation at the forefront of astronomical technology. Indeed, if the instrumentation is to become 'common-user', available for use (through competition) to all astronomers, the RGO will eventually be responsible for maintenance and operation; and collaboration through all stages of new-instrument production becomes an advantage for all.

How do such collaborations work? There is no fixed format, because they range from informal joint explorations of, say, physics of a particular detector, to formal contracts between RGO and universities for specific pieces of design or hardware, through to the complete specification, design, and construction of major common-user instruments. The collaborations are encouraged by the RGO, and the growth in number suggests that mutual benefits are widely recognized. Recent or continuing collaborations on astronomical instrumentation include the following universities: Cambridge, Copenhagen, Durham, Groningen, Imperial College of Science and Technology London, Leeds, Leiden, Oxford, St Andrews, University College London, and Utrecht.

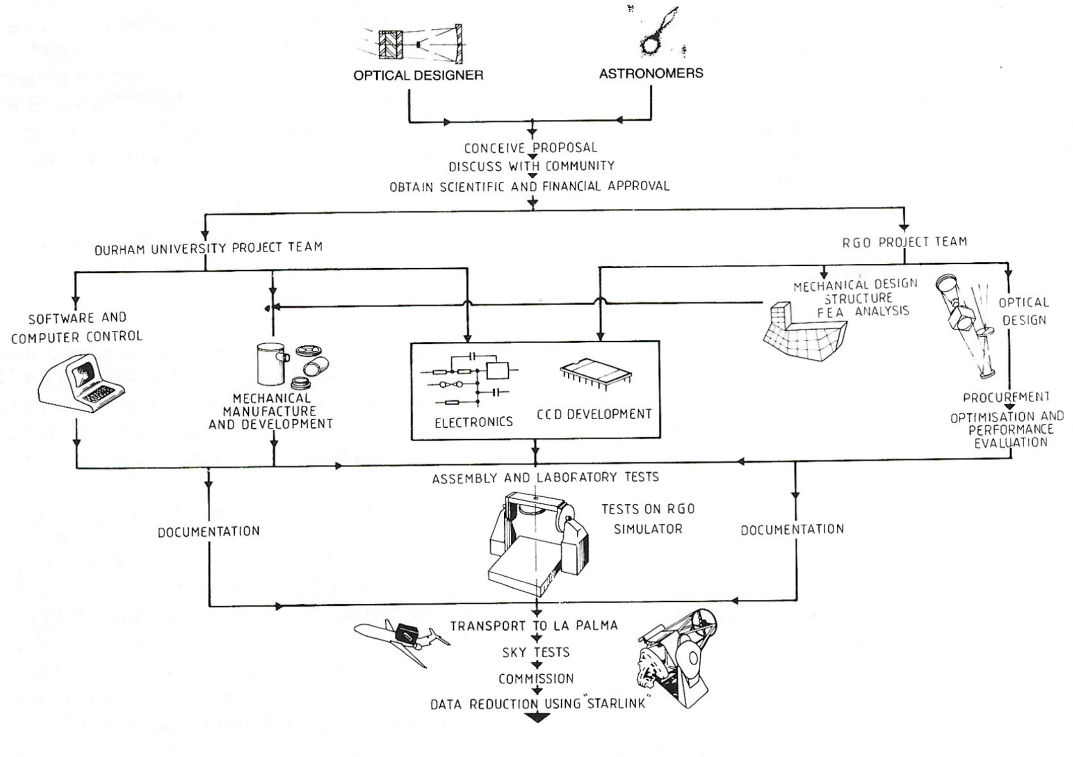
J. V. W

The Faint-Object Spectrograph

The Faint-Object Spectrograph (FOS), commissioned late in 1984, is now a common-user instrument on the INT at La Palma. Built in a close collaboration between the RGO and the University of Durham, it is a model of innovative design, cooperation between astronomers and technologists, and above all of how such collaborations run to the benefit of the astronomy community.

The FOS is a fixed-format highly efficient CCD spectrograph designed for low-resolution spectrophotometry over a wide spectral range. The optical design is based on a Schmidt camera working, without a collimator, in the diverging f/15 beam of the Cassegrain focus of the 2.5 m INT. Dispersion is provided by a transmission grating and a cross-dispersing prism giving a two-order format covering the spectral range 400–1050 nm. The small number of optical surfaces and the minimum vignetting, which results from placing the CCD chip inside the camera, means that throughput is very high.

The FOS has been described by a user – not from the RGO or Durham – as the 'world's best redshift machine'. This is arguable; but the FOS is without doubt one of the fastest spectrographs ever built. How it was built is indicated in the flow chart.



The RGO and the University of Sussex

In the past 18 years the collaboration between the RGO and the University of Sussex Astronomy Centre has been of essential importance to both groups, and to UK astronomy in the much wider sense. The Astronomy Centre was established as a group of theoretical astronomers with strong support from the SERC because of the proximity of the University of Sussex to the RGO at Herstmonceux. The collaboration provides a vital and healthy environment for balanced programmes in both teaching and research. It now provides a well-established astronomical entity – for instance, when the STARLINK computer network was constituted in 1981, a joint RGO–Sussex node was provided for the analysis of astronomical data obtained by scientists from both places.

The *teaching programme* has three components which concern RGO staff:

1 The MSc course consists of both thesis and lecture courses. Each year, RGO staff members provide one or two of these lecture courses, biased towards observational astronomy. For example, in the Lent term 1984, M. Pettini gave a 16 lecture course on The Interstellar Medium.

2 As part of the MSc programme, the RGO runs a residential course on Instrumental Astronomy. The students stay in Herstmonceux Castle for two weeks while carrying through four projects designed to acquaint them with the most modern optical instrumentation, detectors, data-capture and data-analysis techniques. The present course includes reduction and analysis of Image Photon-Counting System (IPCS) spectra and CCD images.

3 RGO staff members supervise a substantial proportion of the theses for MSc and DPhil degrees. For instance, in 1985 RGO staff supervised four of the eight MSc dissertations, and of the 16 DPhil students registered at the Astronomy Centre for October 1985, seven will be carrying out observational theses supervised by RGO staff members.

The teaching/supervising role of RGO astronomers is formalized by their appointments as visiting faculty members. At present A. Boksenberg and B. E. J. Pagel are visiting professors, C. A. Murray and J. V. Wall visiting readers, and R. A. E. Fosbury, D. H. P. Jones, M. V. Penston, M. Pettini and K. Taylor visiting lecturers.

The joint *research programme* has been fuelled by joint applications from Astronomy-Centre and RGO staff for research grants to fund Post-Doctoral Research Associates. A succession of able and successful astronomers have been employed on these grants (A. S. Wilson, D. J. Axon, M. J. Ward, C. P. Blackman, W. D. Pence, J. R. Lucey, I. N. Reid), every one of whom was subsequently awarded a competitive fellowship or permanent post in astronomy. The present recipients of these grants are C. Frenk, W. B. Sparks, and R. M. Smith.

Seminars, workshops and conferences form an essential part of an active research environment. Since 1968 a joint seminar series has run with lectures at both centres. Moreover, staff and students from each centre attend scientific meetings at the other – including informal seminars, the RGO workshop series, and the annual Herstmonceux Conference, the Anglo-Australian Telescope symposium of September 1982 and the BAAS meeting of August 1983, the latter two held at the University of Sussex.

The seminars, workshops and conferences bring eminent scientists into the Sussex–RGO community, and are of evident benefit to members of each institution. There is a considerable benefit to the visiting scientist as well, in that a single visit can encompass both an active university department with its emphasis on teaching and theoretical research, and an SERC establishment with its emphasis on observational research and the provision/operation of the very best optical facilities for the UK community.

The link allows RGO staff to see – continuously and at first hand – the commitments of Astronomy-Centre staff to research and to teaching, and to gain better appreciation of the needs and constraints of the university community towards which their supporting efforts are directed. Likewise, Astronomy-Centre staff may see directly the supporting efforts of the RGO, the technical and professional level of support which it is attempting to provide, and the immediate difficulties in doing so.

However, the real success of the relationship must lie in the environment which it provides. A simple measure of this is the quality of astronomer that the Sussex–RGO link has nurtured. Since the AAT was commissioned, more than half of the UK fellowships at the telescope have been held by DPhils and Research Associates from Sussex–RGO. There must be much merit in a system providing the basis for careers of astronomers of the calibre of Axon, Bailey, Barlow, Bath, Carswell, Dickens, Fosbury, Netzer, Penston, Reid, Savage, Stickland, Ward, Whelan, and Wilson.

RGO, the universities, and dynamical astronomy

In the past three years a strong link has been forged with the Department of Applied Mathematics and Theoretical Physics at the University of Liverpool. This link is based on collaboration in improving the theories of the motions of the satellites of Saturn, and especially of Hyperion. Currently a PhD student spends part of the year at Herstmonceux in order to use software and the RGO database of satellite positions. In addition RGO staff are participating in Project LONGSTOP, a study of the stability of the solar system via a numerical integration of the 100-million-year motions of the Sun, moon and planets. The project involves staff and research fellows from the Universities of Glasgow, London (Queen Mary College) and Liverpool, and the use of the Cray and ICL DAP computers.

The staff of the University of Aston who operate the Hewitt satellite-tracking camera are associated with the Satellite Laser Ranging (SLR) Group of the RGO, as part of the UK Facility for the Precise Tracking of Satellites. The UK Facility receives financial support from the Department of Trade and Industry and from the Ministry of Defence, as well as from SERC and NERC. The RGO has further links in space geodesy with the Department of Civil Engineering at the University of Nottingham and with other groups in universities and establishments. These include the Royal Aircraft Establishment and the Institute of Oceanographic Sciences (in connection with earth-ties and the future tracking of the ESR–1 satellite, for example). The first UK Summer School in Space Geodesy was hosted by the RGO in 1984.

La Palma telescope users

Telescope time on the three Anglo-Dutch telescopes on La Palma is shared between two user institutions: the UK Science and Engineering Research Council (SERC) and the Instituto de Astrofisica de Canarias of Spain (IAC). These institutions meet formally with other users of the Observatorio del Roque de los Muchachos as the International Scientific Committee (CCI). The SERC has made further collaborative arrangements with the Organisatie voor Zuiver Wetenschappelijk Onderzoek of the Netherlands (ZWO), The National Board of Science and Technology of Ireland (NBST) and the Dublin Institute for Advanced Studies (DIAS). The way the available observing time is shared between these international partners is the subject of a series of agreements, protocols and minutes summarized below.

Spain has at its disposal 20% of the observing time on each of the three telescopes: it is the responsibility of the IAC to make this time available to Spanish institutions and others. It does this through its Committee to Allocate Time (CAT).

An additional 5% of the observing time is for international collaborative programmes between member institutions of the CCI. It is intended that this time shall be used for the study of one, or a few, broad topics each year by several telescopes. No definitive arrangements have yet been made by the CCI as to how this time should be allocated.

The remaining 75% of the time is at the disposal of the UK. The SERC has agreed to share this time with foreign institutions under two separate agreements, one with the ZWO, the other with the NBST and DIAS. Under the first agreement SERC and ZWO agreed to share this observing time on all three telescopes in the proportions 80:20. The SERC-ZWO Joint Steering Committee has decided that time should be allocated to astronomers from the two countries by the UK Panel for the Allocation of Telescope Time (PATT) in the expectation that, due to the relative sizes of the British and Dutch astronomical communities, the ratio of 80:20 will occur spontaneously. Under the second agreement, the SERC has made available 27 nights per year of its share on the 1 m telescope to the NBST/DIAS. The Irish Advisory Committee for La Palma (AC) set up by the two Irish institutions has decided that proposals by Irish astronomers to take up this allocation of 27 nights per year should also be submitted to PATT. PATT includes two members from institutions in the Netherlands and an observer from an Irish institution.

All the above agreements envisage that observing time shall be distributed equitably over the different seasons of the year and phases of the moon.

There have been four six-month allocation periods so far. They are labelled F to I. The Spanish Committee for the Allocation of Time allocated almost exactly 20% of the time available in Semesters F, G, H and I. The error was entirely a matter of quantisation of the observing periods by days or weeks. Thus PATT allocated 80%.

Observing time allocated can be divided by the number of applicants on the proposal and summed by the applicants' home institutions. Institutions can be labelled by nationality. On this definition applied to the PATT allocation the INT was used in semesters F, G and H in the ratio 67% by the UK, 32% by NL; the JKT – 87% UK, 13% NL. About 7% of the time went to countries outside formal arrangements (Italy, France, Portugal, USA, Australia, Germany).

Telescope time is a commodity in fixed supply, and demand for large telescopes usually exceeds the time available, particularly during the time when the Moon does not interfere with observations.

Oversubscription can be measured in terms of the fraction of successful proposals (even though they may not get all the time requested) or in terms of the number of nights applied for compared with the number of nights available. The table shows the oversubscription for INT and JKT for PATT and CAT and for the Bright Grey and Dark time.

The La Palma Users' Community

Most astronomers in UK universities rely on national facilities to provide those research tools which it would be impractical, and uneconomic to provide individually. It would be difficult to over-emphasise the crucial importance of access to the La Palma observatory for UK astronomers, whatever the spectral region in which their principal interests lie. After many years of piecemeal begging of northern-hemisphere telescope time from generous foreign observatories, we are at last reaching a state where realistic allocations can be made on our own suite of instruments. This will make time available for those extensive cosmological and astrophysical observing programmes which have in the past been starved of observing time, but which are so vital in forming a solid observational basis (both in terms of data and experience) for UK astronomical research. Results from La Palma are already beginning to flow into the scientific journals and the response of users, despite the inevitable teething problems of a brand-new observatory has been very enthusiastic.

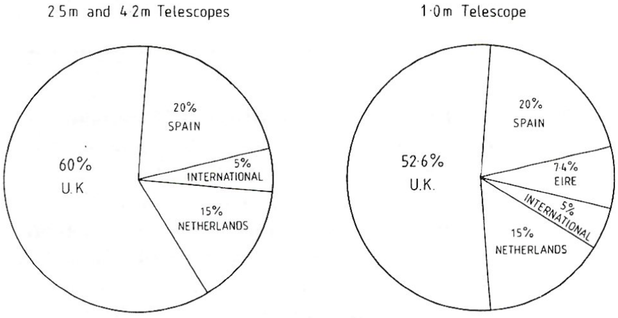
The telescopes also provide indispensable test-beds for innovative instrumentation developed in universities. With the excellent image quality at La Palma, the prospects for new techniques in high resolution imaging are particularly exciting.

La Palma gives a focus for fruitful international collaboration between groups. Strong links are springing up between universities and institutes in the UK and our partners Spain, Holland and Ireland. Such collaboration and interchange (including exchange of students) can only be of benefit to all concerned.

The William Herschel Telescope will give the whole UK astronomical community competitive access to what will be, for several years at least, the most powerful optical telescope in the world – given its site quality and advanced instrumentation. The potential for the enhancement of our worldwide reputation in original research, and for extending our firm knowledge of the universe, is immense. It is vital that La Palma continues to receive realistic support both from funding agencies and from our fellow scientists in other disciplines. The La Palma project is a unique opportunity for UK astronomical research. Its essential role, and the excellent support given by the RGO, is widely recognised within the university community.

M. Edmunds

Fig. 1 Time allocation on the La Palma telescopes



Oversubscription

A = *number of applications made/number of successful applications*
N = *number of nights applied for/number of nights available.*

INT

	PATT		CAT
Semester F	A = 3.4		3.9
G	2.7		5.4
H	2.6		3.1
I	2.3		2.6
	Bright	Grey	Dark
F + G + H + I	A = 1.7	3.4	3.9
	N = 2.1	4.3	3.8
	JKT		
F + G + H + I	N = 1.3	2.7	2.2

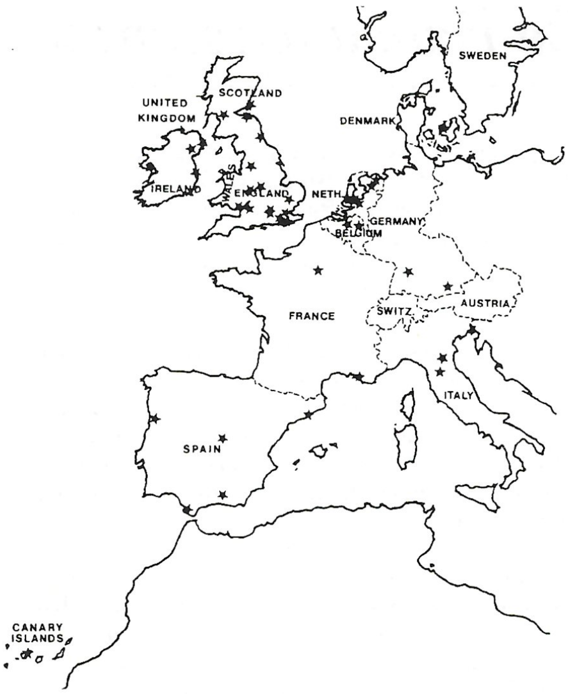
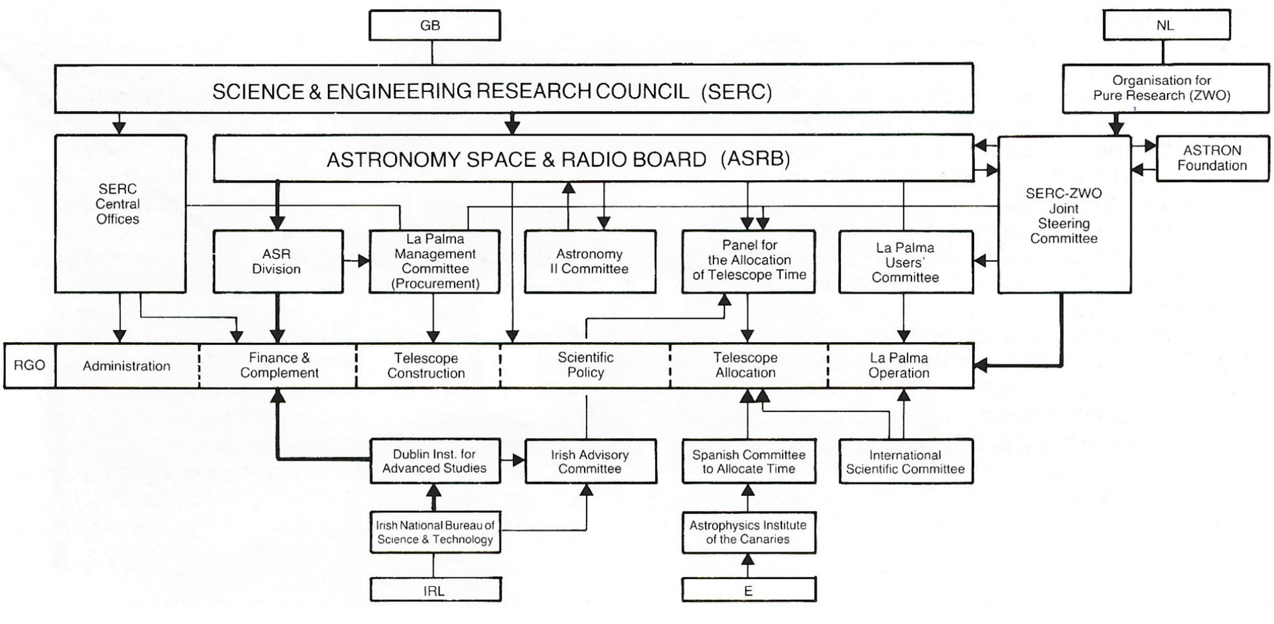


Fig. 2. RGO's European Astronomical Community. In this map, the stars indicate the 46 (to date) establishments of the users of RGO's telescopes at the Observatorio del Roque de los Muchachos on La Palma. In addition to the European connection there are users from some dozen establishments in other parts of the world, the majority of which are in Australia, USA and Canada (as indicated).

RGO and the SERC

The Science and Engineering Research Council was set up, according to its Charter, in order to make grants and disseminate knowledge, to carry out and support research and development in science and technology, and to provide and operate facilities for common use by universities.

In pursuit of the two latter objectives the RGO, an establishment of the SERC, makes, operates and uses major facilities for astronomical research, particularly the La Palma telescopes. The flow of money (represented in the figure by a thick arrow), control and advice from the SERC, and its partners including the Netherlands ZWO, to the La Palma project is shown diagramatically. The Astronomy Space and Radio Board of the SERC works through a Division of its officers and through subcommittees of astronomers to finance, control and advise the Director of the RGO in the procurement and operation of the telescopes. A separate group of officers of the Council provides the administrative structure and control required by the Council and the national authorities. The ZWO and SERC have formed a Joint Steering Comittee for the La Palma project; its terms of reference also include the Millimetre Telescope being built for Hawaii. Spain and Ireland have connections directly and via the committee structure to RGO.



Public information

The part that public information plays in the day-to-day activities of the RGO has increased dramatically over the last five years. Originally the Public Information Unit, as it was known, was part of the NAO as the majority of enquiries from the public related to sunrise and sunset times and other standard astronomical and calenderial data, which was and still is computed by them.

Nowadays the renamed Public Relations Unit is a part of Scientific Administration. Part of the work still involves passing on data supplied by the NAO but an additional role of the PRU is disseminating knowledge about astronomy, the SERC, and the work of the observatory both at a popular and scientific level. Press releases are compiled and issued in conjunction with SERC's PR unit at Swindon and the local press are kept informed of items of interest to them. Television and film crews are encouraged to visit and interview staff about their work and there is always a demand from various periodicals and newspapers for photographs and information, particularly of the Roque de los Muchachos Observatory. The number of unsolicited requests from the public continues to rise and the unit answers approximately 1500 telephone calls and 1200 letters each year on varying topics relating to astronomy.

Through the work of the PR Unit, the RGO has been able to provide material to the media on aspects of astronomical research of interest to the general public.

The BBCs *Sky at Night* programme devoted two broadcasts to the RGO in 1984: one about the Herstmonceux operational base and the other about a typical night's observing on the INT on La Palma. For the latter a full crew spent a week filming on the island.

At the time of 'first light' on the INT in February 1984 an ITN crew from Channel 4 visited La Palma, resulting in a nine-minute item on *Channel 4 News* and a condensed version on *News at Ten*. Nine minutes is a long time for a single news item and reflects the importance that ITN's Science Unit put on the opening of a major new British telescope.

Back at Herstmonceux, in 1983, Comet Iras–Araki–Alcock appeared in the skies, generating hundreds of telephone enquiries from the public and requests for information from both the local and national media. An ITN camera crew were able to mount an intensified camera on the 13-inch refractor and images of the comet were relayed to viewers of *News at Ten*.

Local radio stations frequently visit to interview staff on various aspects of astronomy and both they and the local press are interested to hear of RGO staff living in the area being involved in major contributions to astronomical research.

On La Palma, in late 1984, an Open University film crew spent time at the INT preparing material for a course in astrophysics. In this way we have been able to overlap the public relations work with our educational role.

The BBC World Service has devoted an entire programme to the Roque de los Muchachos Observatory and Television Espana has recently broadcast a four-part educational programme on the work being done there.

The list goes on and on: a CCD image of Comet Halley from the INT was shown on *News at Ten* in August 1985, and as interest in this and other astronomical phenomena increases, we aim to provide more and even better material, to help to convey the excitement and interest of astronomy to an ever-increasing audience.

C. Parker

One of the more unusual uses to which the Castle has been recently put was as a location for filming by Paramount Pictures for their major production Lady Jane. *The inner courtyard had wattle fencing and archery targets erected in it, barges moved majestically across the moat, and one entire room was transformed into an apothecary's. Although events such as this may seem well removed from serious scientific research, it is one way of earning income which in turn helps ensure that more funds are available for astronomy.*

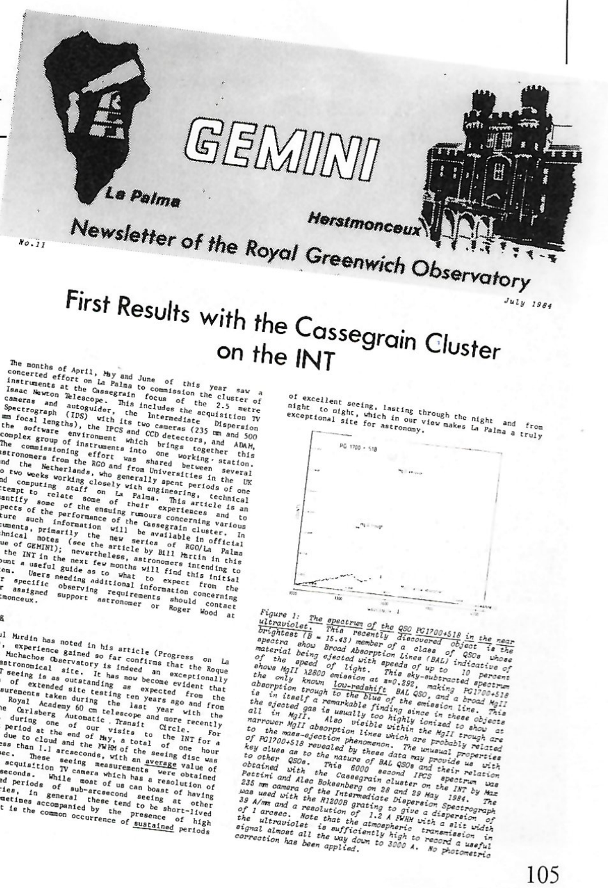
Workshops

Herstmonceux Castle has been used for a series of scientific workshops on such topics as 'Remote Operation of Telescopes', 'High Resolution Imaging for La Palma', 'Design of Large Telescopes', 'SLR Data and Active Galaxies' as well as for the annual Herstmonceux Conference. These workshops have been particularly successful in encouraging people from all over the world to discuss aspects of astronomy in the pleasant and relaxed atmosphere. The delegates are entertained in the evenings and accommodation is available in the recently refurbished Castle bedrooms.

The conference facilities in the Castle are also made available to a wider audience and rooms are regularly booked by a variety of outside organisations, for meetings, conferences, receptions and social functions.

Main scientific Conferences and Workshops 1980 – September 1985

1980	1/2 April	– Herstmonceux Conference – 'Interstellar Chemistry'
1981	7/8 April	– Herstmonceux Conference – 'Galactic Nuclei'
1982	20/21 April	– Herstmonceux Conference – 'The Outer Regions of Galaxies'
	7/8 July	– Remote Operation of Telescopes
	12/15 September	– The Intimate Environment of Seyfert Galaxies
	24/26 November	– Design of a Very Large Optical Infra-red Telescope
1983	5/7 January	– Satellite Laser Ranger Data
	8/10 February	– Applications of Low Resolution Spectroscopy to Cosmology
	6/7 April	– Ionization Mechanisms in Galactic Emission Line Nuclei
	18/22 April	– Faint Object Camera for the Space Telescope
	4/5 May	– Calibration of Stellar Luminosities from Astrometric Data
	28/29 June	– Herstmonceux Conference – 'Observational Cosmology'
	11/15 September	– Meeting of STARLAB Direct Imaging and Spectrograph sub-committees
	15/17 September	– Dynamical Problems in the Solar System
	10 November	– High Resolution Imaging for La Palma
1984	10/11 March	– Planetary Dynamics
	13/14 March	– Radio and Optical Observations of Active Galaxies
	15/16 March	– Meeting of European Range Observations of Satellites Group
	17/18 May	– Microprocessors and Standards in SERC
	20/21 June	– Herstmonceux Conference – 'Accretion (Discs)'
	17 July	– Image Stabilization
	27/28 July	– Meeting of Versailles Working Group
	22/24 August	– Science from Measuring Machines
	7/9 September	– BAA/IAPP meeting
	10/14 September	– Laser Ranging Instrumentation
	17/20 September	– Summer School in Space Geodesy
	1/3 October	– Project Longstop
1985	25/27 March	– Project Longstop
	16/17 July	– High Resolution Imaging on La Palma



First Results with the Cassegrain Cluster on the INT

The months of April, May and June of this year saw a concerted effort on La Palma to commission the cluster of instruments at the Cassegrain focus of the 2.5 metre Isaac Newton Telescope. This includes the acquisition TV cameras and autoguider, the Intermediate Dispersion Spectrograph (IDS) with its two cameras (235 mm and 500 mm focal lengths), the IPCS and CCD detectors, and ADAM, the software environment which brings together this complex group of instruments into one working station. The commissioning effort was shared between several astronomers from the RGO and from Universities in the UK and the Netherlands, who generally spent periods of one to two weeks working closely with engineering, technical and computing staff on La Palma. This article is an attempt to relate some of their experiences and to quantify some of the ensuing rumours concerning various aspects of the performance of the Cassegrain cluster. In future such information will be available in official documents, primarily the new series of RGO/La Palma technical notes (see the article by Bill Martin in this issue of GEMINI); nevertheless, astronomers intending to use the INT in the next few months will find this initial account a useful guide as to what to expect from the system. Users needing additional information concerning their specific observing requirements should contact their assigned support astronomer or Roger Wood at Herstmonceux.

Seeing

As Paul Murdin has noted in his article (Progress on La Palma), experience gained so far confirms that the Roque de los Muchachos Observatory is indeed an exceptionally good astronomical site. It has now become evident that the INT seeing is as outstanding as expected from the results of extended site testing ten years ago and from the measurements taken during the last year with the Swedish Royal Academy 60 cm telescope and more recently with the Carlsberg Automatic Transit Circle. For example, during one of our visits to the INT for a two-week period at the end of May, a total of one hour was lost due to cloud and the FWHM of the seeing disc was always less than 1.1 arcseconds, with an average value of 0.8 arcsec. These seeing measurements were obtained using the acquisition TV camera which has a resolution of ≈0.2 arcseconds. While most of us can boast of having experienced periods of sub-arcsecond seeing at other observatories, in general these tend to be short-lived events, sometimes accompanied by the presence of high cirrus. It is the common occurrence of sustained periods of excellent seeing, lasting through the night and from night to night, which in our view makes La Palma a truly exceptional site for astronomy.

Figure 1: The spectrum of the QSO PG1700+518 in the near ultraviolet. This recently discovered object is the brightest (B = 15.43) member of a class of QSOs whose spectra show Broad Absorption Lines (BAL) indicative of material being ejected with speeds of up to 10 percent of the speed of light. This sky-subtracted spectrum shows MgII λ2800 emission at z=0.292, making PG1700+518 the only known low-redshift BAL QSO, and a broad MgII absorption trough to the blue of the emission line. This is in itself a remarkable finding since in these objects the ejected gas is usually too highly ionized to show at all in MgII. Also visible within the MgII trough are narrower MgII absorption lines which are probably related to the mass-ejection phenomenon. The unusual properties of PG1700+518 revealed by these data may provide us with key clues as to the nature of BAL QSOs and their relation to other QSOs. This 6000 second IPCS spectrum was obtained with the Cassegrain cluster on the INT by Max Pettini and Alec Boksenberg on 28 and 29 May 1984. The 235 mm camera of the Intermediate Dispersion Spectrograph was used with the R1200B grating to give a dispersion of 39 A/mm and a resolution of 1.2 A FWHM with a slit width of 1 arcsec. Note that the atmospheric transmission in the ultraviolet is sufficiently high to record a useful signal almost all the way down to 3000 A. No photometric correction has been applied.

Information about RGO activities and research is disseminated through the magazine Gemini. *This appears every two or three months and is circulated to observatories, universities and other scientific establishments all over the world.*

Times of transition in RGO history

When Charles II signed the Warrant which, in 1675, officially gave birth to the new Observatory at Greenwich, that institution had a single, well-defined purpose. In the words of the Warrant itself, the King:

> appointed our trusty and well-beloved John Flamsteed, Master of Arts, our astronomical observator, forthwith to apply himself. . . to the rectifying of tables of the motions of the heavens, and the places of the fixed stars, so as to find out the so-much-desired longitude of places for the perfecting the art of navigation.

For the next 43 years Flamsteed, the first Astronomer Royal (AR), applied himself with great diligence to the most accurate and meticulous observational programme. His lasting monument is the great three-volume *Historiae Coelestis* (1725) which, with the companion *Atlas Coelestis* (1729), made scientifically accurate observations available to the astronomical community for the first time.

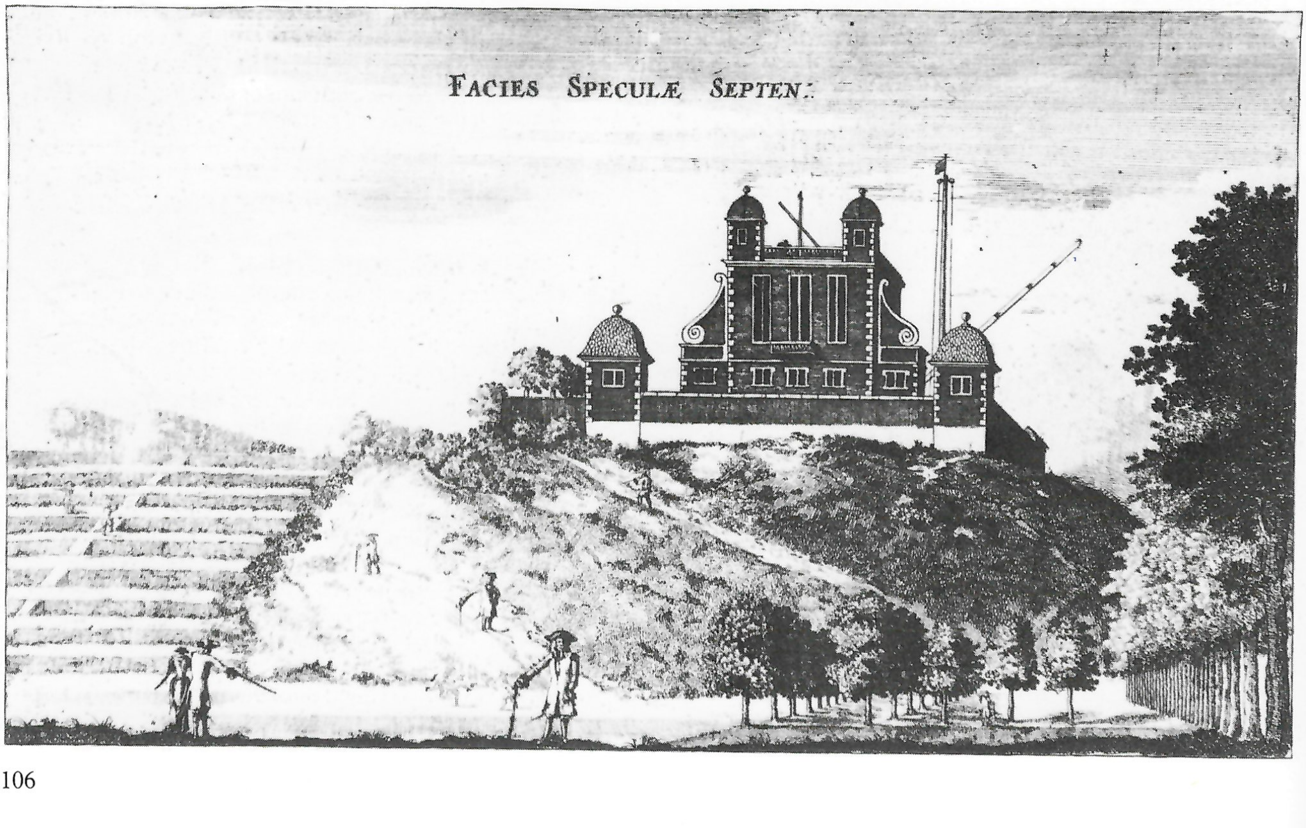
By the time Flamsteed died, however, the character of the Observatory was already changing. He had entered into often acrimonious public debate both with the Royal Society and with its Secretary (later President), Isaac Newton.

Fig. 1 Right from the incumbency of the first Astronomer Royal, the Royal Observatory constructed innovative instruments for astronomy. An engraving by Francis Place of the Royal Observatory at Greenwich about 1677 depicts two telescopes: one on the roof, is the 16-foot telescope and the other, of 60-foot focal length, is suspended from an otherwise unserviceable mast supplied by Navy Stores. The telescopes were used to make timings of celestial phenomena in order to construct ephemerides for use in navigation. The 60-foot telescope was successfully used in 1677 to observe Jupiter's satellites, but the mast suffered from resonant vibration, even in an apparent dead calm, and the project never worked as expected. The 16-foot telescope on the other hand was used to time phenomena of Jupiter's satellites from the founding of the Observatory until the replacement of the telescope by a 26-foot telescope in 1682.

Flamsteed's stormy relationship with Newton, Edmond Halley (who was later to become second Astronomer Royal) and Robert Hooke brought the Observatory into the public view and, in many minds, into disrepute. The Board of Visitors to the Royal Observatory was instituted by Royal Warrant in 1710, the first of many peer review committees that have continued until the present day.

In 1714, Parliament passed an Act setting up the Board of Longitude, which was to administer the £20 000 prize offered to anyone who could, to the satisfaction of the Board, finally solve the longitude problem. Science had become public.

Until the end of the nineteenth century, positional astronomy held sway at Greenwich. Successive Astronomers Royal obtained increasingly more accurate – and more complex – instruments and, more slowly, the additional staff to use them and to calculate the results obtained. Flamsteed was the first astronomer to make systematic observations using telescopic sights, most notably on the 7-foot mural arc. Halley commissioned two new instruments: a 5-foot transit circle and an 8-foot mural quadrant. James Bradley (AR 1742–62) brought into operation a 12½-foot zenith sector, an equatorial sectors, an 8-foot mural quadrant and an 8½-foot transit telescope. John Pond (AR 1811–35), whilst not renowned for his administrative abilities, was responsible for some outstanding new instruments: the 6-foot mural circle and 10-foot transit telescope by Edward Troughton and the mural circle by Jones. G. B. Airy (AR 1835–81) continued the trend with his altazimuth and transit instruments and the Great Equatorial (a 12¾-inch refractor). Between 1890 and 1899 W. H. M. Christie (AR 1881–1910) constructed the 13-inch astrographic, the 28-inch refractor, the Thompson 26-inch refractor and 30-inch reflector and the new Troughton and Simms altazimuth. This was to be the last great expansion of instrumental capabilities until the Yapp 36-inch reflector was installed in honour of Sir Frank Dyson (AR 1910–33) in 1933. In 1939 H. Spencer Jones (AR 1933–55) obtained the reversible transit circle by Cooke,



Troughton and Simms and, in the immediate post-war period, the construction of the 98-inch Isaac Newton Telescope (INT) began on the new site at Herstmonceux in 1949. The INT was inaugurated by the Queen in 1967 and it is this instrument which now forms the core of the new generation of telescopes being installed on the Roque de los Muchachos on La Palma.

Instrumental developments are only one thread, albeit the vital one, in the Observatory's history. As the information being obtained from increasingly accurate instruments became available that information in turn affected and altered the Observatory's programme. With better observations the existence of new problems and phenomena became apparent. Regular measurement of the motions of the stars led to investigations into the evolution of the stellar system. Spectroscopy was introduced to the RGO by Airy in 1873 as a measuring technique and led to the introduction of astrophysical research and thence to the study of galaxies outside the local group. By the beginning of this century, such interests were beginning to outweigh the more traditional occupations at Greenwich, a situation accelerated by Einstein's postulation of his special and general theories of relativity in 1905 and 1915 respectively. Dyson and Eddington, his former Chief Assistant, were instrumental in organising the test of general relativity at the eclipse of 1919 by measuring the gravitational deflection of light.

There have been a number of dramatic changes in the Observatory's history. Halley's successful attempts to rebuild its reputation after the Flamsteed–Newton quarrel, the solution of the longitude problem, the beginning of twentieth-century astrophysics, the move from Greenwich to Herstmonceux were all times of transition. The 1980s have undoubtedly proved to be another, with the development of the La Palma site and the beginning of the flow of astronomical discoveries from the Canary Islands.

J. Dudley

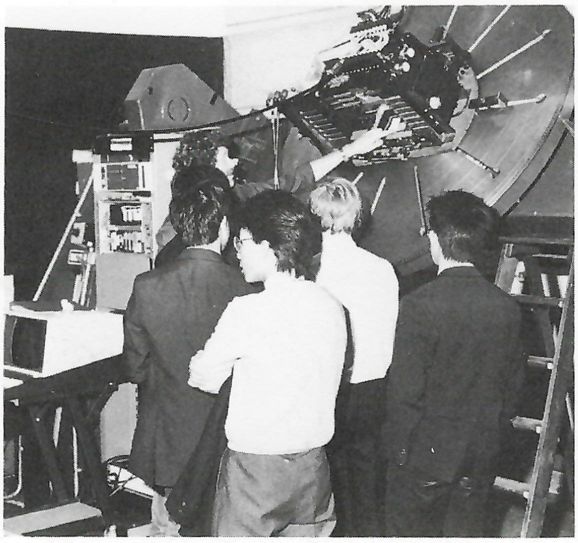
Students and the public

School visits

A large percentage of the total number of visitors to Herstmonceux are of course children, and in 1984 over 50 school parties, from many parts of the country, visited the observatory. RGO tries to liaise with schools in any way that can be of assistance. Leaflets on a variety of astronomical topics which are suitable for project work are available as are different tours for different age groups.

A typical tour comprises an astronomer demonstrating one or more of the equatorial group of telescopes and answering questions. There is a more detailed tour and talk for A-level students and adult groups with a serious scientific interest.

During the open day of 30 September 1985 1300 school children visited the observatory.



The Exhibition

Following the success of the open days held to celebrate the tercentenary in 1975, a permanent exhibition on both astronomy and the history of Herstmonceux Castle was established in two rooms of the Castle in 1977 and opened by Patrick Moore.

Over the years improvements have been made with exhibits constantly being updated as new and more relevant material becomes available and at the time of writing (August 1985) it is being expanded and relocated in the main building of the equatorial group of telescopes where the 26-inch Thompson refractor and 36-inch Yapp reflector are already on public display together with a video theatre. The Wealden District Council is assisting the move.

The Castle, grounds and exhibition attract over 55 000 visitors a year and gradually the available attractions have been increased. A nature trail extends through the grounds and woodland and a craft centre has been set up in collaboration with local people.

The new exhibition with the telescopes and existing attractions will, it is planned, be a leading astronomical visitor centre in this country, emphasising the role that RGO plays as, not only a centre for astronomical excellence, but also a populariser of science to schools and the general public.

Library and Conservation students

Since the academic year 1979–80, the Libraries and Archives Department has offered a place to one (or, in one year only, to two) students from Birmingham Polytechnic School of Librarianship. This is the only UK library school offering a four-year course, the penultimate year of which is spent gaining work experience in an approved library system. In every year but one, the RGO student has been awarded one of the two annual prizes offered by the publishing industry to students on the Birmingham Course.

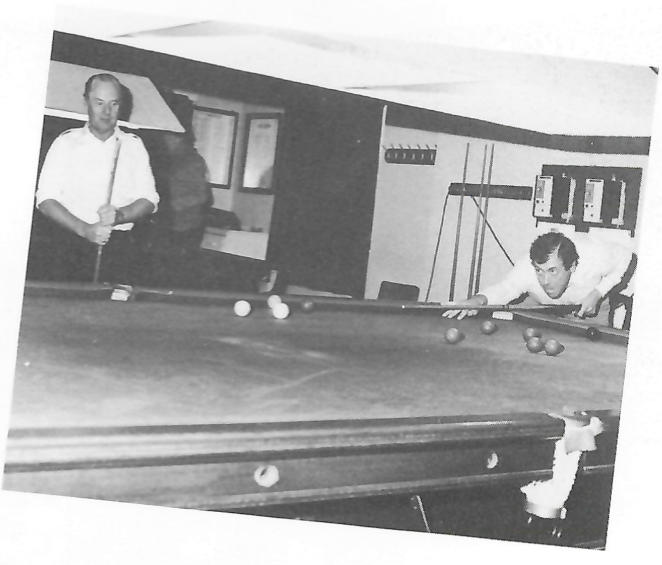
The Conservation Laboratory is approved as a training office for students taking the Society of Archivists' certificate in conservation. Students come to RGO for various periods of time to undertake instruction in specific subjects: bookbinding, traditional paper repair and so on. Of the six students so far instructed, all have subsequently been awarded their certificates.

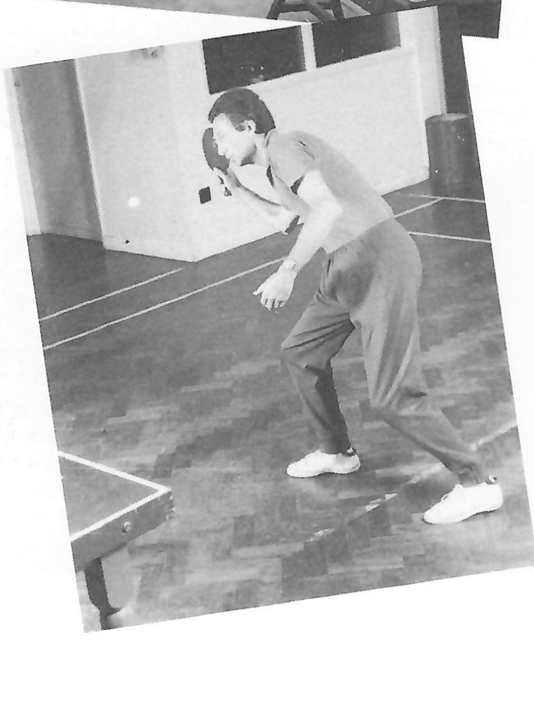
Twenty-fifth anniversary of the Clubhouse

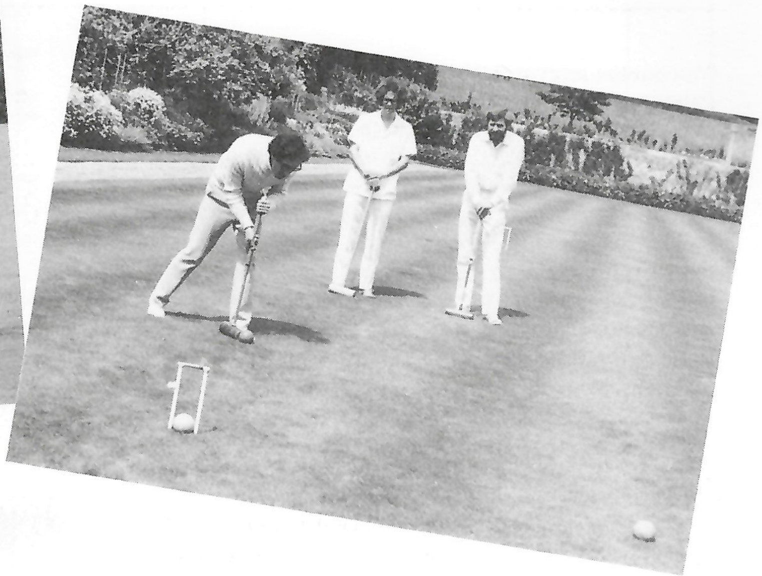
The Clubhouse at the West Gate of the Castle grounds was built by members in 1959 and opened in 1960. On October 1 1985, the Clubhouse celebrated its silver anniversary. The Club organises a full sports programme and the Clubhouse contains table tennis and snooker tables, with members successful in the local leagues. Activity in croquet, tennis, stoolball, archery and badminton has waxed and waned with individual enthusiasms. (Croquet might be introduced by Club members to La Palma if any flat ground can be found.) The cricket pitch east of the Castle witnesses friendly matches on most summer Sundays.

English country-dancing takes place every Wednesday evening, as regular as in the time of the last Herstmonceux Astronomer Royal. A nearly regular annual event is the Christmas pantomime, with script tailor-made to fit staff aspirations and fantasies.

For many years the Club entered a float in the Herstmonceux bonfire celebrations for November 5th, but its principal charity fund raising activities recently have been individual events, such as the fête in 1981, the Year of the Disabled, when large sums of money were made from an open day in the Castle grounds and presented to four charities for the disabled, the deaf, the blind and the diabetic.







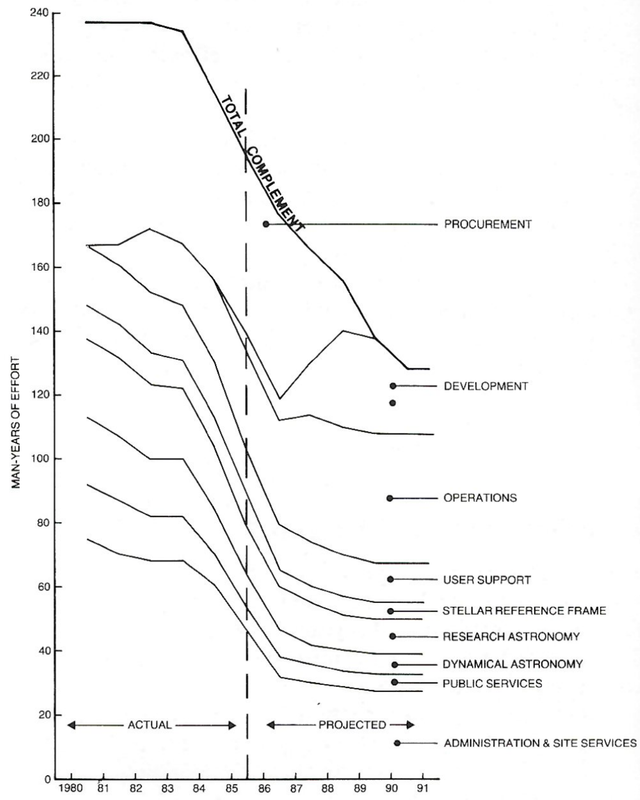

THE ROYAL GREENWICH OBSERVATORY
PREPARES TO STUDY VENUS

RGO manpower and budget

Procurement represents the construction effort for the La Palma telescopes, including the initial suite of instrumentation. It terminates at the end of the capital phase of the La Palma project. As the telescopes and instruments are brought into commission, the *Development* phase opens up during which they are improved and given new capability not defined in the original specification – for example, new detectors, unknown in the 1970s, are fitted to existing optical instruments; or software packages are installed for an advanced observational technique. The *Operations* manpower is in large part resident on La Palma in order to operate and maintain the equipment there, but certain skills and activity is more economically or appropriately resident in the UK and the profile includes such personnel, who commute to La Palma as needed. *User support* includes operation of measuring machines and data archives at Herstmonceux, all viewed as in support of the La Palma telescopes. The *Stellar Reference Frame* project to define star positions includes astrometry with the Kapteyn Telescope, meridian astronomy with the Carlsberg Automatic Meridian Circle and RGO's efforts in support of the ESA satellite Hipparcos. *Research astronomy* includes the RGO's astronomers who use SERC facilities, principally La Palma, to ensure they have the astronomical functions which all the users expect. *Dynamical astronomy's* principal facility is the Satellite Laser Ranger at Herstmonceux, and includes manpower used in computing the Almanacs. Much of this manpower is covered by receipts from MoD, DM and NERC, and by sale of the almanacs. *Public services* also includes manpower paid out of the receipts. *Administration and site services* is essentially the overheads line.

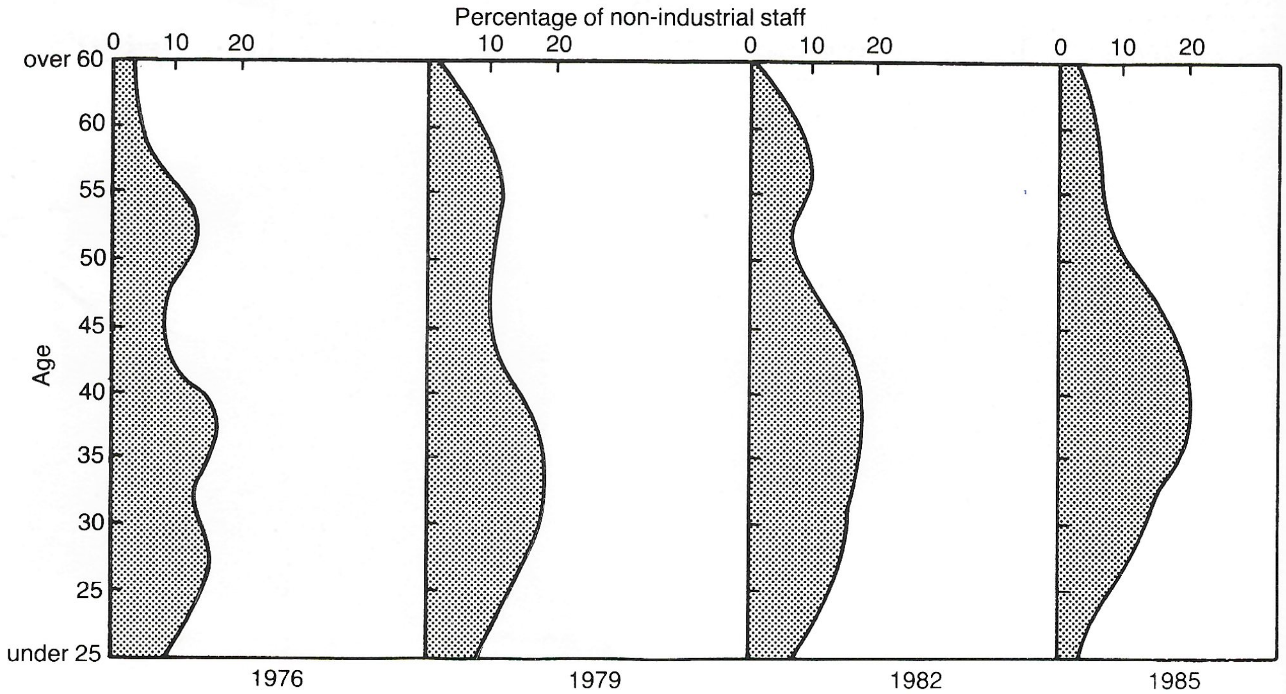
In 1983/84 the RGO was instructed to commence a rapid reduction in its staff numbers. This lead to the 'redeployment' exercise whereby numbers of staff were asked to take premature retirement. Others were compulsorily transferred to other SERC establishments or to posts within RGO falling vacant through natural wastage. Recruitment was held to the minimum.

The RGO total complement declines from 237 to 128 between 1980 and 1990, a fall of 46%.



Age profile of RGO staff

The accompanying figure shows the age profile at the RGO over the years as published in the *New Scientist* of 5 September 1985. In common with scientific institutions everywhere in the UK, according to the article, there is pressure on people over 50 to take early retirement, and a lack of opportunity for people under 30. At a period of declining complement, there is an enhanced tendency to hold back on recruitment of young people.

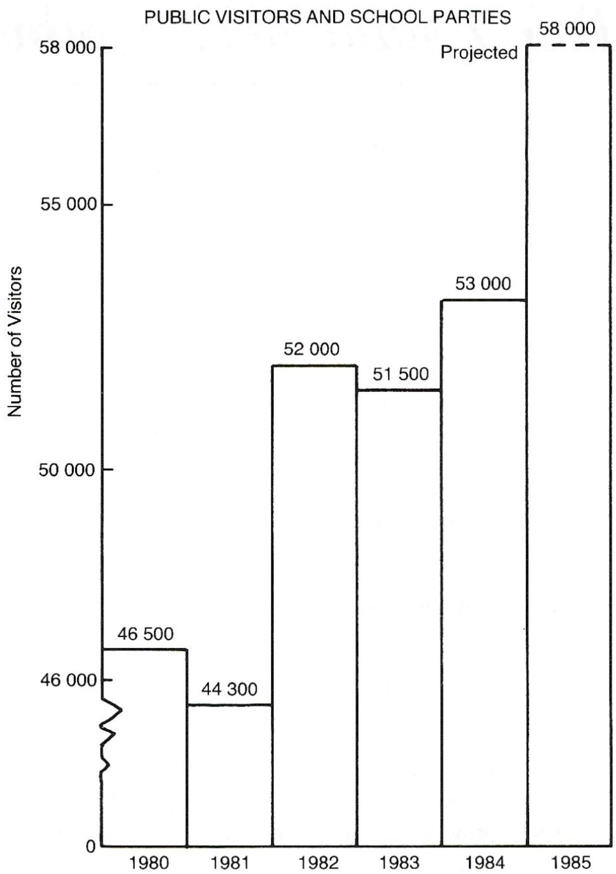


Growth of number of public visitors

The RGO has an exhibition in the Castle which is open to the public each year from Easter to the end of September. Local history is dealt with but the major section is on astronomy. It deals with the evolution of the science and with the latest concepts and techniques across the full wavelength range. An audio-visual theatre explains the RGOs programme in some detail.

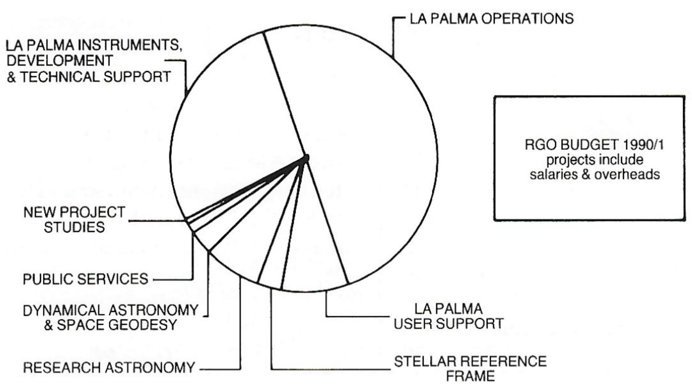
The grounds, including a nature trail, are also open to the public. On selective weekends there are displays based on the Observatory's 300-year-old archives and the collection of rare books. Approximately 50 school parties have guided tours each year and the number is rising fast.

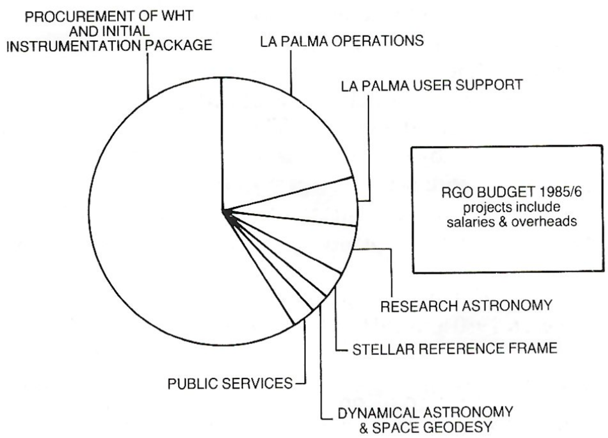
Prior to Easter 1986, the astronomical exhibition will be refurbished and moved to the buildings of the Equatorial Group of telescopes. The move is being supported by Wealden District Council, other agencies, and by companies.



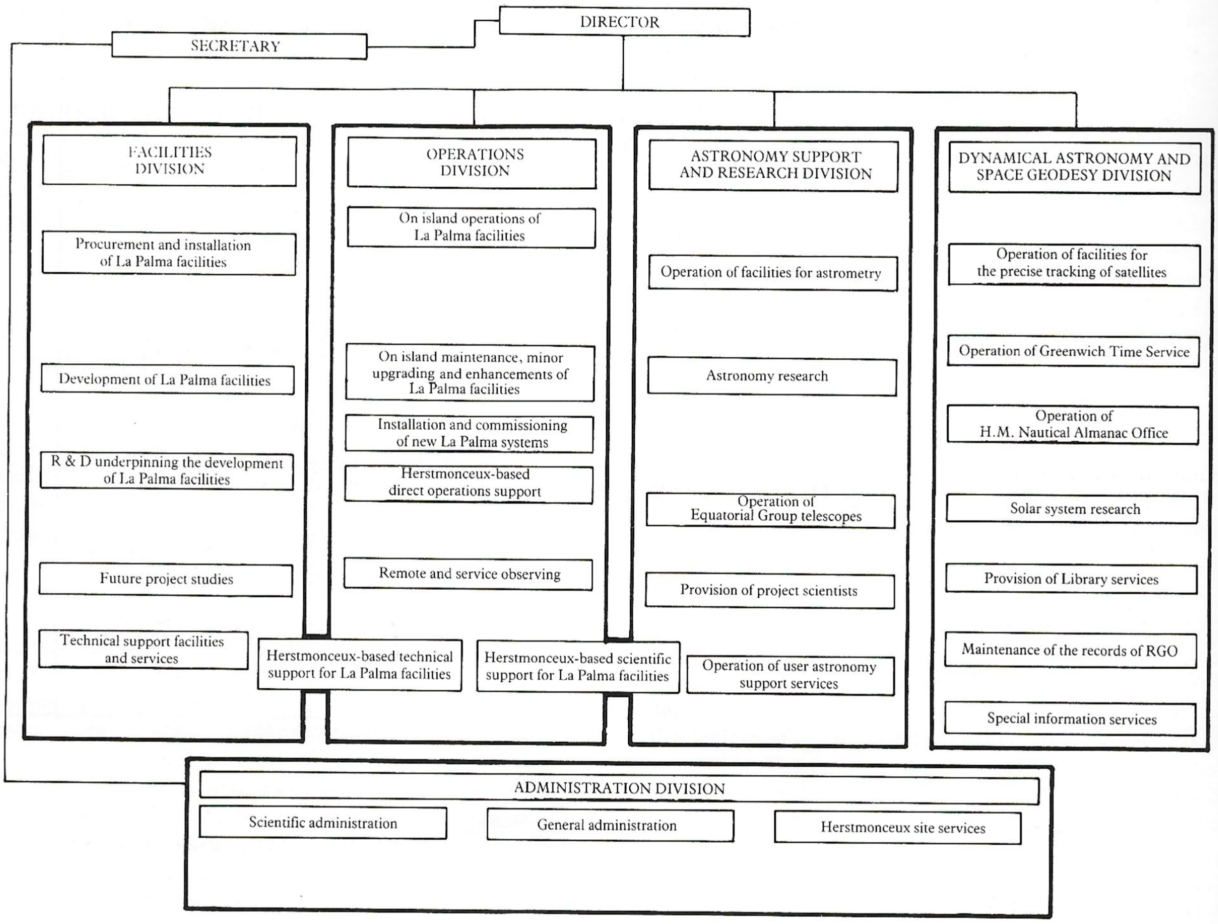
Distribution of RGO budget

1985/6 is a typical 'procurement' year for the RGO. That is, a major part of the funding is devoted to procuring new facilities on La Palma (in this year the William Herschel Telescope and the first suite of instrumentation) alongside the commissioning and generation of completed facilities. By the end of this decade, a new steady state will be reached for the operation and development of the telescopes. The budget will be reduced by 40% on its current level (£6.8 million in 1985–6) and the distribution will be as shown in the second pie chart.





The internal organisation of the RGO, 1985



Nominal Roll 31 August 1985

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Henbest Mr N. *N*

2 STAFF ON UNPAID LEAVE ON 31 AUGUST 1985
(not counted in with Staff-in-Post)

Site	Name	Grade	Divn
RGO	Brazier Mrs C.R.	*EO*	*ADM*
RGO	Fosbury Dr R.A.E.	*PSO*	*OPS*

ABBREVIATIONS

*	Repeated entry
GL	Group leader
H	Split function
M	Maternity leave
N	Non-complement
P	Part-time
S	Secondment
T	Temporary
LP	La Palma
U	Unpaid leave

Publications

Publications by RGO staff are listed below. The names of non-RGO staff are in italics.

Publications by HM Nautical Almanac Office

The preparation and publication of almanacs, ephemerides and tables for astronomy and navigation is carried out in close cooperation with the Nautical Almanac Office of the US Naval Observatory. The following volumes were published by Her Majesty's Stationery Office:

The Astronomical Almanac for 1982 to 1986

The Nautical Almanac for 1982 to 1986

The Air Almanac for 1981 to 1986 June, in two parts per year

The Star Almanac for Land Surveyors for 1982 to 1986

Astronomical Phenomena for 1983 to 1987

Sight Reduction Tables for Air Navigation, Volume 1, Epoch 1985.0, in 1983

Compact Data for Navigation and Astronomy, 1986–1990, in 1985

All but the last volume were published jointly with the US Government Printing Office. The *Nautical Almanac*, the *Air Almanac* and the *Sight Reduction Tables* were prepared under a contract with the Ministry of Defence.

The following volumes were edited by the NAO and published by the RGO:

The Report of the Royal Greenwich Observatory for 1979–80, in 1981

Royal Greenwich Observatory Bulletins, Numbers 185 to 193.

Of these, Number 185: *Compact data for navigation and astronomy for 1981 to 1985,* was the basis for a book on the use of hand-held calculators for navigation (H. Levison, 1984. *Astro-navigation by calculator: a handbook for yachtsmen.* David and Charles).

RGO Bulletins

185 Compact data for navigation and astronomy for 1981 to 1985. B.D. Yallop, 1981.

186 Catalogue of observations of occulations of stars by the Moon for the years 1623 to 1942 and solar eclipses for the years 1621 to 1806. L.V. Morrison, *M.R. Lukac and F.R. Stephenson, 1981.*

187 Third Greenwich catalogue of stars, Sun, planets and Moon for 1950.0. R.H. Tucker *et al,* 1983.

188 Fundamental data for southern stars (Seventh list). R.M. Catchpole *et al,* 1982.

189 First, second and third Herstmonceux catalogues of stars for 1950.0. R.H. Tucker *et al,* 1983.

190 Energy distributions of subgiant and giant stars. D.J. Stickland, 1983.

191 Narrow-band photometry of faint red stars, II. J.B. Alexander, D.H.P. Jones and J.E. Sinclair, 1983.

192 Catalogue of observations of total occultations of stars by the Moon for the years 1972 to 1980 and of grazing occultations for the years 1963 to 1980. G.M. Appleby, L.V. Morrison and M.T. White, 1984.

193 Herstmonceux observations of the sun, planets and Moon, 1957–1982. R.H.D. Swifte *et al.* 1984.

RGO Annals

14 Catalogue of radial velocities from Herstmonceux and Kottamia, 1964–1971, 1981.

Unpublished papers

The *RGO Preprint Series* publishes all papers accepted for publication in refereed journals and other selected articles. Preprints of papers and articles not yet published include:

Chemical evolution of galaxies. B.E.J. Pagel. Paper given at Symposium on cosmogonical processes, held in honour of A.G.W. Cameron, Boulder, Colo., March 1985.

Dust in elliptical galaxies. *W.B. Sparks et al* (including J.V. Wall). *Mon. Not. R. astr. Soc.*

Bowen fluorescence and HeII lines in active galaxies and gaseous nebulae. H. Netzer, *M. Elitzur and G.J. Ferland. Astrophys. J.*

Abundances of C, N, O in HII regions. B.E.J. Pagel. Paper given at ESO Workshop on production and distribution of CNO Elements, Garching, 13–15 May 1985.

The evolution of asymptotic giant branch stars in the LMC: II – Spectroscopy of a complete sample. N. Reid and *J. Mould. Astrophys. J.*

Abundances of O, Mg, S, Cr, Mn, Ti, Ni and Zn from absorption lines of neutral gas in the LMC in front of R136. K.S. de Boer, *E.L. Fitzpatrick and B.D. Savage. Mon. Not. R. astr. Soc.*

NAO Technical Notes

HM Nautical Almanac Office publishes a series of notes of special interest to those concerned with solar system calculations, numerical methods and navigation. *NAO Technical Notes* published since 30 September 1980 include:

52 Lunar occultations of the Crab Nebula, 1981–83. L.V. Morrison, 1980.

53 The computation of physical ephemerides of planets and satellites. A.T. Sinclair, 1980.

54 Geocentric and heliocentric phenomena. B.D. Yallop, 1981.

55 The phase correction for Venus. B.D. Yallop and B. Emerson, 1981.

56 Approximate coordinates of Jupiter and Saturn. B. Emerson, 1981.

58 Formulae for determining Carrington's elements and differential solar rotation. B.D. Yallop, 1982.

59 The effect of atmospheric refraction on laser ranging data. A.T. Sinclair, 1982.

60 A simple method of plotting position lines. B.D. Yallop, 1982.

61 Methods for calculating the time of meridian passage from polynomial data. B.D. Yallop, 1982.

62 Coefficients for calculating the GHA and DEC of Stars. B.D. Yallop and C.Y. Hohenkerk, 1985.

63 Computation of angular atmospheric refraction at large zenith angles. C.Y. Hohenkerk and A.T. Sinclair, 1985.

Notes and reports

Several series of limited distribution notes and reports are published within the RGO. The Electronics Department produces series of *Notes* and *Reports* on equipment which it develops and builds. Facilities Division produces *Technical Manuals* for the equipment on La Palma. Operations Division distributes *Technical Notes* on operating procedures on La Palma, or data necessary to reduce data. For copies contact, in the first instance, the RGO Library.

La Palma Technical Notes

1 UK optical telescopes on La Palma. R.A.E. Fosbury and W.L. Martin, May 1984.

2 Cleaning of optical components. D. Jackson and R. Powell, June 1984.

3 The series of NFRA notes. W.L. Martin, July 1984.

4 First results from the Cassegrain cluster on the INT. M. Pettini and R. Ellis, July 1984.

5 Seeing at the INT and CATC: First month. P.G. Murdin and C. Thoburn, July 1984.

6 Support astronomy: Observing run 1984 July 13–17. J.V. Wall, August 1984.

7 Telescope and instrument logbooks: Fault reporting procedures. K. Tritton, August 1984.

8 Safety of the IPCS on the INT on La Palma. C. Jenkins, September 4 1984.

9 General optical description of the 4.5 m William Herschel Telescope. R. Bingham, September 1984.

10 Count rates and extinction coefficients with the Peoples' Photometer. D.H.P. Jones, September 1984.

11 RGO/La Palma technical manuals. G.A. Harding, September 1984.

12 IPCS saturation. C. Jenkins, September 1984.

13 The use of CCD time on the night of 30–8–84 on the INT. T. Snijders, September 1984.

14 Recent changes to the INT control system, policy for future software releases and a plan for the next six months. R.A. Laing, October 1984.

15 Changes made to the Cassegrain cluster software (Sep 15 – Oct 3). W. Lupton, November 1984.

16 Current status and future policy of the location and distribution of documentation associated with the Isaac Newton Group of telescopes on La Palma. W.L. Martin, November 1984.

17 Changes made to the Cassegrain cluster software (Nov 2 – Nov 30). W. Lupton and P.B. Taylor, December 1984.

18 Utility network for the 4.2 m with choice of local area network. M. Johnson, February 1984.

19 Utility network for the 4.2 m with feasibility study: 4MS system: network interface to Ethernet. M. Johnson, February 1984.

20 Utility network for the 4.2 m with protocol architecture. M. Johnson, October 1984.

21 Commissioning results for the St Andrews spectrograph (July 1984). D.J. Stickland, October 1984.

22 New filters for the A&G unit of the INT in LP. D. Harmer, P. Ellis and L. Bell, January 1985.

23 Optical coating facility at the Royal Greenwich Observatory. D. Jackson, February 1985.

24 Software news. L. Bell, March 1985.

25 IPCS – selecting the spatial (X) resolution. A.R. Jorden, March 1985.

26 Focussing the INT. R. Le Poole, March 1985.

27 IPCS – scanning system to reduce granularity. A.R. Jorden, April 1985.

28 Hour angle limits of the JKT. D.H.P. Jones, May 1985.

29 CCD cryostat use. P. Jorden, June 1985.

30 Modifications to Fits tape Format to support the LP archive. W. Lupton, June 1985.

31 Atmospheric extinction at the Roque de los Muchachos Observatory, La Palma. D.L. King, October 1985.

32 Pointing of the INT and JKT. R.A. Laing, August 1985.

33 Use of LPINFO on the VAX 11/780. D.E. Hobden, September 1985.

34 Blemishes in IPCS flat-fields. A.R. Jorden and R. Collyns, October 1985.

La Palma Manuals

User's guide. M. Pettini (ed), October 1983.

1 ADAM manual [version 2.4]. L. Bell *et al*, December 1984.

2 IPCS users' reference manual [Issue No. 1]. W.L. Martin and P.B. Taylor, May 1984.

3 INT Integrating TV System: User guide [Version 1]. D. Thorne and P. Rudd, June 1984.

4 Peoples' Photometer: User and technical manual [Version 1]. D. Hobden, R. Wallis and D.H.P. Jones, June 1984. Updated August 1984.

5 A guide to the La Palma computer systems [Version R-02]. L. Jones, July 1984.

6 1–m darkroom manual [Version 1]. R.W. Argyle and B. Scales, July 1984.

7 1–m camera users manual [Version 1]. R.W. Argyle, July 1984.

8 Spectroscopy with the IPCS on the INT – a simple guide [Version 1]. C. Jenkins, August 1984.

9 Spectroscopy with the CCD on the INT – a user guide [Version 1.1]. P. Jorden and W. Lupton, December 1984.

10 INT faint object spectrograph – user manual [Version 1]. M. Breare *et al.*, May 1985.

11 Peoples' Photometer acquisition software (PPAS) [ADAM Version 1]. D. Pike, July 1985.

12 JKT user guide [Version 2.1] D. Pike, D.H.P. Jones and R.W. Argyle, July 1985.

13 JKT Richardson Brealey Spectrograph user manual [Version 1]. R. Edwin, October 1985.

14 MPF software manual [Version 1]. T. Schoenmaker, September 1985.

Electronics Notes

10 Programming of 32K and 64K EPROMS – MC68.000 Prom programming. A.C. Daly.

11 Compilation of PolyForth and New Prom programming software. N.M. Parker.

12 Recompiling PolyForth to gain memory space for the dictionary. A.R. Jorden.

13 Background tasks in PolyForth. N.M. Parker.

14 Interrupts and PolyForth on the 6800. N.M. Parker.

15 Interrupts (from CAMAC) with Exorciser and PolyForth. A.R. Jorden.

16 Storage of electronic circuit diagrams. A.R. Seabrook.

17 Driving the exorset parallel printer from ExorForth. N.M. Parker.

18 Modifications to Motorola Exorset 33. A.C. Daly *et al.*

19 Equipment documentation for PolyForth generated within the department. P. Wright.

20 MMS intermittent fault. Mods to 6800/02 processor and 8K/16 memory boards. P. Wright.

21 COMSOL. FORTH source layout standards. A.C. Daly.

22 Loading and running 'STEPPING FORTH' on Exorset and Exorciser. A.W. Thompson.

23 Instructions for up/down load of text between Exorset and Exorciser. A.W. Thompson.

24 Text handling and output on the Exorset running in PolyForth. A.W. Thompson.

25 Maintenance of an Electronics Notes/Reports index on a 5.25-inch floppy disk. A.W. Thompson.

26 COMPONENTS: An aid to the development of components lists. A.W. Thompson.

27 Two new FORTH commands: REPEAT and CHANGE. A.W. Thompson.

28 Electronics Department STANDARD POLYFORTH + standard software now available. A.W. Thompson.

29 RS 232 INTERFACE. M. Ingle.

30 Getting to grips with the FORTH FILES MANAGEMENT SYSTEM. A.W. Thompson.

31 SEE–FLOW: A useful tool in the development/debugging of FORTH software. A.W. Thompson.

32 Some comments on the Hettich SO 35 A/R inductive slot sensor. A. Doorduin.

33 Electronics Department universal IC sensor. P. Wright.

34 Wrong Exorciser glossary for ?DIGIT. A. Doorduin.

35 Adding an offset to the block numbers in a glossary. A. Doorduin.

39 TYPE and EXPECT on the 4MS. M.C. Vlot.

Electronics Reports

15 Exorciser operating summary. P. Wright.

16 Exorciser bus buffer card (Revision 2 by B.D. Slaughter). A.C. Daly.

17 PROMFORTH. N.M. Parker.

18 GALAXY: Microprocessor manual. A.C. Daly.

19 Analogue to digital converter card XEA 561. W. Bracey

20 Choosing a pattern 105 connector and its fittings. A.R. Seabrook and W. Bracey.

21 CASS SPEC local controller software handbook. P. Wright.

22 CASS SPEC local controller summary documentation. P. Wright and A.R. Seabrook.

23 Use of microprocessors to control a photographic plate measuring machine. A.C. Daly.

24 CASS SPEC local controller hardware documentation. P. Wright and A.R. Seabrook.

25 4.2 m instrumentation cabling. N.M. Parker.

27 2.5 m A&G box control commands and protocol (updates ER 009). R.C. Baker.

28 Forth to MDOS Prom programming manual. R.C. Baker.

30 Resistor card WEA 556/557. W. Bracey.

31 Stepping motor drive card report. A.C. Daly and N.A. Hall.

A

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