Chapter 1

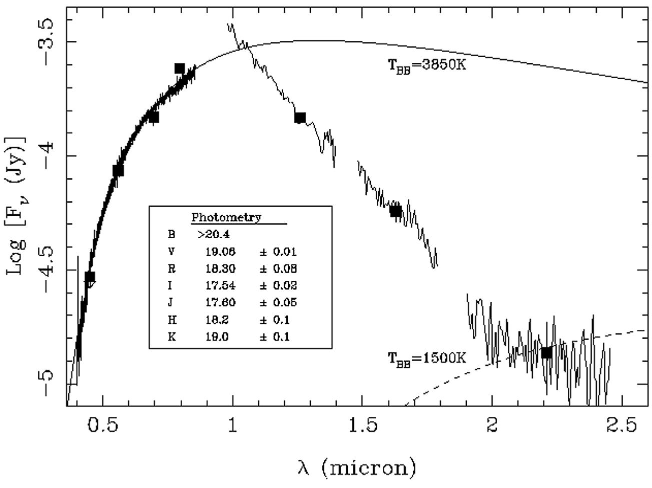
SCIENTIFIC HIGHLIGHTS

THE COOLEST KNOWN HALO WHITE DWARF

JKT+CCD, WHT+ISIS

White dwarfs are the remnant cores of stars that initially had masses of less than 8 solar masses. They cool gradually over billions of years, and have been suggested to make up much of the dark matter in the halo of the Milky Way. But extremely cool white dwarfs have proved difficult to detect, owing to both their faintness and their anticipated similarity in colour to other classes of dwarf stars.

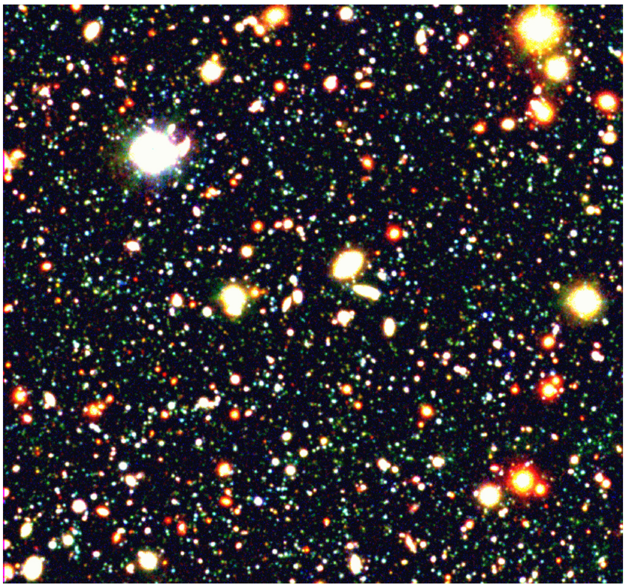
A white dwarf star, named WD0346+246, was serendipitously discovered as a faint, very fast moving star on a sequence of photographic plates. The high apparent velocity is a characteristic of stars which are very old and are traveling on inclined elliptical orbits through the Galaxy. Astronomers secured parallax measurements on the Jacobus Kapteyn Telescope to determine the distance to WD 0346+246 and confirm its low luminosity. They reported a distance of 28 parsecs. They also estimated a surface temperature of around 350 Kelvin. Thus WD 0346+246 has been shown to be one of the coolest and therefore oldest white dwarfs ever found, and has to be a member of a hitherto unobserved and possibly large population of faint stars in the Galactic halo.



This discovery has serious implications for our understanding of the Milky Way. The coolest white dwarfs provide a measurement of the age of the Galaxy, but they may also play a more important role. For the last thirty years, astronomers have found that most of our Galaxy seems to be invisible. In fact, as much as 90% of the mass in our Galaxy may be hidden in the form of dark matter. Dark matter theories fall into two broad classes. The first suggests that the dark matter is not really dark — but is composed of many faint stars such as cool white dwarfs and brown dwarfs. The second class of dark matter candidates are various elementary particles, left over from the Big Bang. Indirect evidence for the dark matter being comprised of cool white dwarfs first came from the MACHO gravitational microlensing experiment. The MACHO project monitored some ten million stars in the Magellanic Clouds in the hope of detecting the occasional brightening due to gravitational lensing effects caused by a dark halo object moving across our line of sight to one of the stars. The MACHO results suggest that these stars can be very numerous, and could contribute approximately 50% of the total mass of the Galaxy.

The discovery of one nearby, very old and cool white dwarf does not solve the dark matter problem. But it does lend weight to the MACHO scenario, and presents astronomers with an astonishing conclusion that the Galaxy may be full of extremely old white dwarf stars. The race is now on to count how many objects like WD 0346+246 exist in the Galaxy and to measure how much they weigh in total.

Figure 1. The spectrum of the halo white dwarf WD 0346+246 showing the dramatic effects of collision induced absorption by molecular hydrogen in the infrared. Thus the object appears red in the optical, but blue in the infrared.



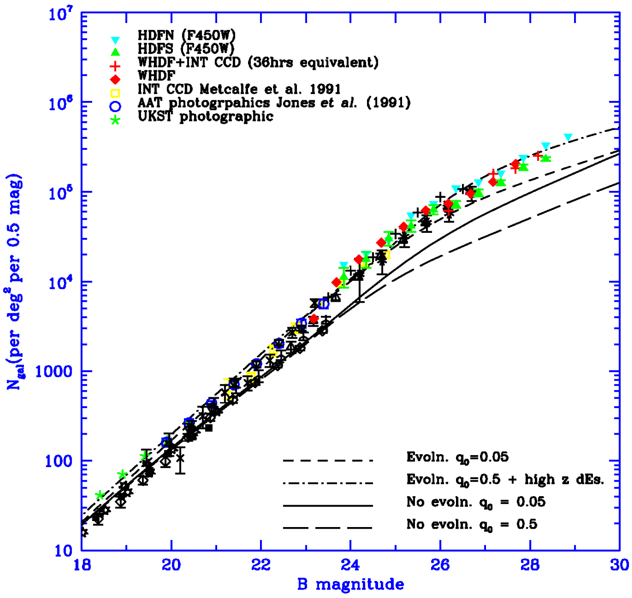


Figure 2. Left: A true colour image of the William Herschel Deep Field, formed by mapping U, B and R exposures onto blue, green and red respectively. The image covers 7×7 arcminutes. Right: This shows the B-band galaxy counts for the WHDF compared with other data, including the Hubble Deep Fields. Also shown are the predictions for a universe in which galaxies do not evolve with time, and those for which galaxies follow simple stellar population synthesis tracks. Two geometries are considered, q_0=0.05 (open) and q_0=0.5 (flat). It is clear that non-evolving models underpredict the counts from quite bright magnitudes (B~22). Even an open evolving model struggles to keep up with the sheer numbers of galaxies seen, although there are probably enough uncertainties in this model to 'tweak' it higher at faint magnitudes. Those who favour a closed universe have to relax the constraint that galaxy numbers are conserved (e.g. merging) or at the very least invoke a population at high redshift which has disappeared from view by the present day (e.g. fading dwarfs). The model shown is a version of the latter.

NEW EVIDENCE THAT GALAXIES FORMED EARLY IN THE HISTORY OF THE UNIVERSE

WHT+PFC

Ultra-deep imaging observations using powerful, ground-based telescopes such as the William Herschel Telescope have the capacity to probe the evolutionary history of galaxies back to their formation epoch. At the faintest galaxy magnitudes, we are looking out not only in distance but back in time to when the Universe was only a few percent of its current age.

Over the past few years, astronomers have used the WHT to produce the deepest ground-based image of the sky which they have called the William Herschel Deep Field (WHDF). With exposures of ~30 hrs in U and B, the resulting images reach magnitudes which are comparable to the Hubble Deep Fields (U~27, B~28) but covering a five times bigger area of the sky than the two HDFs combined.

For many aspects of the studies of high redshift galaxies, the bigger area of this Herschel Deep Field gives it a unique advantage over HST data. At intermediate redshifts ($1<z<3$) the larger numbers of galaxies means that they are more easily split into their various sub-populations by their colours. At high redshift, the big area means we have more chance of detecting candidates for galaxies in the redshift range $3<z<7$ which are within the magnitude reach of multi-object spectrographs on 8–10m class telescopes for obtaining spectroscopic confirmation of their photometric redshift. The bigger area also has advantages for studies of high redshift galaxy clustering, aimed at understanding how structure forms in the early Universe.

In 1996, the ultraviolet and blue pictures in the WHDF revealed so many faint blue galaxies at a redshift of 2 that they already challenged the claims of the most popular cosmological theory, which suggested that galaxies formed around a redshift of 1, when the universe was half as a big as it is now. Since then, observations carried out at other telescopes have confirmed these results by finding many galaxies at redshifts of 3 and 4. Now, applying similar techniques as before but to the new red and infra-red images from the WHT, astronomers find large numbers of galaxies at the even higher redshifts of 5 to 6 (as many galaxies as are found locally), pushing the epoch of formation of giant galaxies back even earlier.

COMET LINEAR BLOWS UP IN FULL VIEW OF THE JKT

JKT+CCD, INT+WFC

Nightly observations made since July 23, 2000 in different broadband filters with the Jacobus Kapteyn Telescope showed what appeared to be the complete disruption of the nucleus of comet LINEAR, the brightest comet of the year.

The central condensation was highly condensed and showed the typical 'teardrop' form in the evening of July 23rd and July 24th, although its brightness decreased by a factor of about 3 between the two nights. In the evening of July 25th something very odd was happening to the comet: the central condensation was seen to be strongly elongated, with a very flat brightness distribution. The condensation's brightness faded further and its length increased on the following nights. On July 27 there was no evidence of any local brightness peaks that would indicate the presence of sub-nuclei. In other words, it did not appear to have broken into individual fragments in the way that Comet Shoemaker-Levy 9 did in 1993. Instead, it had completely blown apart. The expansion velocity of the condensation was about 40 m/s, indicating that it consisted of solid particles and not just gas. The gas tail, which virtually had disappeared between July 23rd and 24th, had reformed as an extension of the major axis of the central condensation.

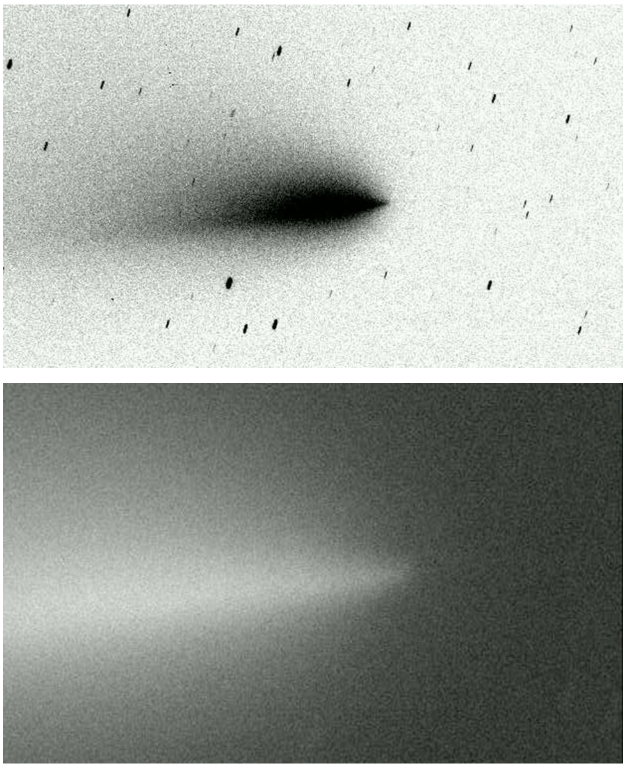


Figure 3. Above: This image, obtained on 1 August 2000 with the WFC on the INT, covers a field of view of 22 arcminutes and is processed to show the faint tail of the comet, which extends well beyond the edge of the field of view. Below: This image obtained on the same night is a 100-second exposure with the WFC on the INT. This section of the full image measures 4.5 arcminutes, equivalent to 110,000 km at the comet. Again the image was processed to show faint details in the coma of the comet. No features are seen in the image, which implied that no significant individual fragments more than a few metres across still emitted gas. This demonstrates the catastrophic disruption of the nucleus.

Further observations with the Isaac Newton Telescope confirmed the initial discovery and provided new insight into what the reason for the comet disruption could be: the evaporation of all the ice in the nucleus. Cometary nuclei are a mixture of solid lumps of material of various sizes, held together by a cement of ices. When comets pass close to the Sun during their journey across the solar system the icy elements (mainly water ice and carbon monoxide ice) sublime, leaving loose material behind that forms the dust tail of the comet, while the sublimed ice forms its gas tails. As a result of this process, or due to the strong gravitational pull from a planet such as Jupiter, or from the Sun, a comet nucleus may sometimes split into two or more fragments. What was seen in the case of Comet LINEAR, however, was different.

From analysis of the images astronomers concluded that this small comet probably ran out of ice altogether, leaving behind a loose conglomerate of particles that gradually dispersed into space. This model fitted the observations well, as measurements showed that the activity of the comet had been declining for several weeks as ice gradually sublimed away. During the comet's closest approach to the Sun, a burst of activity was recorded. Then, when all the ice was exhausted and nothing was holding together the solids, the nucleus began to fall apart.

The images taken with the Isaac Newton Telescope after break-up showed no sign of the comet's original nucleus, nor of any active sub-nuclei larger than a few metres across. Any large remnants of the nucleus that remained cannot be subliming significantly or they would have been detected in these images. Other comets are known to have disappeared, but Comet LINEAR is the first one to have been caught in the act.

DISCOVERY OF A TYPE IA SUPERNOVA PROGENITOR

INT+IDS

Type Ia supernovae (SNe Ia) are one of the most important tools for observational cosmology. Because these supernovae have a relatively small spread in their peak optical brightness and can be seen out to cosmological distances, they serve as standard candles and are used to measure cosmological parameters. However, the peak optical brightnesses of SNe Ia are not uniform; they are correlated with the shape of the light curve. Meaningful measurements of cosmological parameters require this variation to be calibrated. The corrections to peak brightnesses have to be empirical because the detailed physics of what causes SNe Ia is not fully understood.

All the most likely models for progenitors of SNe Ia feature an accreting white dwarf which ignites carbon in its core either because it has reached the Chandrasekhar mass or because ignition of accumulated helium causes compression of the core and a so-called 'edge-lit detonation'. This explains the fast rise times for SNe Ia, the lack of hydrogen and helium and the fairly uniform peak brightness. To initiate the explosion, the white dwarf must accrete material from a companion star. Two models for the companion star which have gained popularity in recent times are supersoft X-ray sources and double degenerates.

However, the possibility of a helium star companion to a white dwarf has not been widely considered as a source of SNe Ia. In particular, sub-dwarf B (sdB) star binaries might be good candidates. There are many white dwarfs which are known to accreate mass from a normal star, but these are made of hydrogen which causes a series of small explosions before the Chandresekhar limit is reached. This is what causes a nova explosion. To make a supernova, the white dwarf has to be supplied with helium, which explodes less easily but releases much more energy.

KPD 1930+2752 is a sdB star. It is about one fifth the size of the Sun and is about half as massive. Unlike normal stars, which are composed almost entirely of hydrogen, KPD 1930+2752 is made of helium. It is not entirely clear how sdB stars are made, but recent work suggests they are the remains of stars like the Sun which lose half their mass just before they complete the end of the red giant phase of their evolution. Only some small fraction of stars evolve this way and this is thought to be related to the fact that most sdB stars are binary stars.

KPD 1930+2752 was observed with the INT as part of a programme to study sdB stars to understand how they are formed. The Doppler shift shows that the star is orbiting an unseen companion every 137 minutes at a speed of 350 km/s. The unseen companion has almost the same mass as the Sun, but it is much smaller and fainter. The unseen companion star could be a neutron star or blackhole, but it is much more likely to be a white dwarf star.

When binary stars have orbital periods as short as two hours, they produce gravitational waves which drain energy from the orbit, so the stars gradually spiral in towards each other. KPD 1930+2752 will merge within 200 million years. The white dwarf will then gain extra mass from the sdB star and will exceed the Chandrasekhar critical mass. This is thought to lead to a Type Ia supernova explosion.

KPD 1930+2752 is the first star to be discovered that is a good candidate for the progenitor of a Type Ia supernova of this type, which may explode on an astrophysically interesting time-scale.

THE FIRST BLACK HOLE IN THE HALO OF OUR GALAXY

WHT+ISIS

X-ray novae or soft X-ray transients constitute a subset of low-mass X-ray binaries (LMXBs) that consist of a late-type secondary star and a neutron star or black hole exhibiting bright optical and X-ray outbursts that are recurrent on time scales of decades. During their outbursts, they resemble persistent LMXBs in which the light of the secondary star is overwhelmed by a luminous accretion disk surrounding the compact object. After a year or less in some objects, the system returns to quiescence. The secondary star now contributes a much larger fraction of the total light, and its atmospheric absorption lines become visible in optical spectra. Thus, quiescent X-ray novae provide the ideal opportunity to study the nature and dynamical properties of the binary system. These studies have demonstrated so far that the mass of the compact object in 10 X-ray novae exceeds the theoretical maximum mass of a neutron star and thus must evidently harbour a black hole.

A previously unknown X-ray transient, XTE J1118+480, was discovered by the Rossi X-Ray Timing Explorer all-sky monitor on 2000 March 29. An optical counterpart was then identified and confirmed spectroscopically. The shape of the light curve and its temporal evolution resembled those of superhumps observed during superoutbursts of short-period cataclysmic variables and outbursts of some other soft X-ray transients. The binary system was found at a distance of about 6000 light years in a direction pointing 62 degrees away from the Galactic plane.

From spectroscopic observations carried out by an international team of astronomers using a number of telescopes, including the WHT, and spanning a couple of months, the mass of the compact object was determined to be at least 6 times the mass of the Sun. This lower limit to its mass firmly implies that it is a black hole, the first one firmly identified in the Galactic halo.

Most compact objects are found close to the Galactic plane, which makes this discovery particularly interesting. It opens questions as to how this object was formed. The black hole could either have formed where it currently is found, or it could have been kicked out of the galactic plane during a violent stage of its evolution.

A SEARCH FOR PLANETARY NEBULAE IN M33

INT+WFC

Extragalactic Planetary Nebulae (PNe) are known in almost all galaxies of the Local Group. Most of them were discovered in the last decade by means of continuum-subtracted images in the bright nebular line of [OIII]. M33, one of the two other large spiral galaxies of the Local Group besides the Milky Way, was the only major nearby galaxy which had not been searched for PNe yet. Astronomers aimed to fill up this gap taking advantage of observational capabilities offered by the Wide Field Camera at the Isaac Newton Telescope. [OIII], Hα and continuum images allowed astronomers to detect 134 candidate PNe in M33 and a large number of other emission line objects (mostly HII regions).

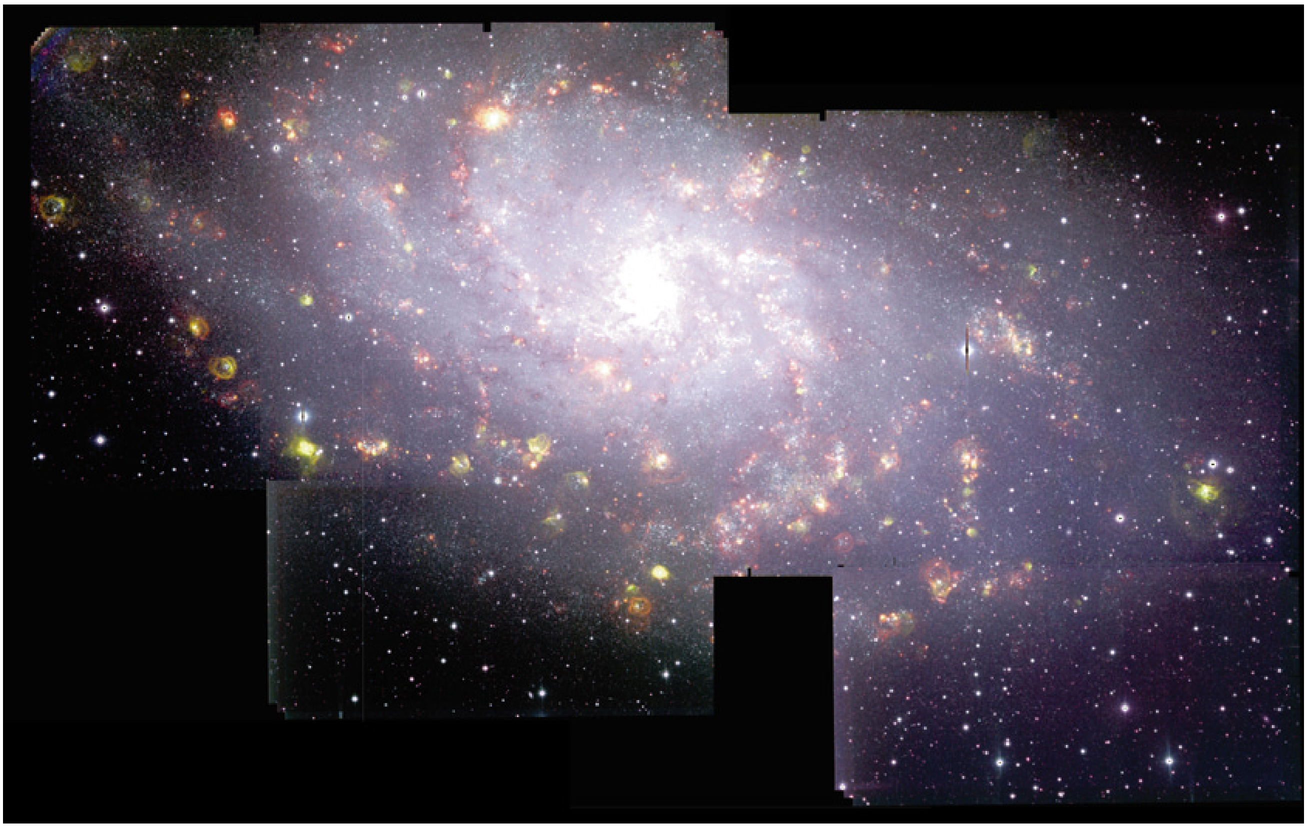


Figure 4. This image is a composition of frames taken in three narrow bands: the green colour represents the galaxian emission in a filter centred on the [OIII] nebular line at 500.7 nm, red is the Hα emission at 656.3 nm, while blue is mainly stellar light taken through a continuum filter centred at 555.0 nm (Stromgren Y). In only one observing night, and with two positionings of the telescope, it was possible to cover nearly the whole galaxy which has a size of approximately one degree in the sky.

FIRST CLEAR SIGNATURE OF AN EXTENDED DARK MATTER HALO IN A DWARF SPHEROIDAL GALAXY

WHT+AF2/WYFFOS

The central velocity dispersions of many Local Group dwarf spheroidal (dSph) galaxies are significantly larger than expected for self-gravitating systems. Assuming virial equilibrium, the implied mass-to-light (M/L) ratios reach as high as 250, making the dSph galaxies among the *most* dark matter-dominated systems in the universe. Given the apparent absence of dark matter in globular clusters, dSph galaxies are also the *smallest* dark matter-dominated stellar systems in the universe. As such, they have emerged as crucial testing grounds for competing theories of dark matter.

Despite their importance, dynamical models of dSph galaxies to date have been quite simple. Most analyses have relied on the use of single-mass isotropic King models, with their associated assumptions that mass follows light and that the stellar velocity distribution is isotropic. Hitherto, the validity of such assumptions has remained unchallenged because of the small size of the data sets. When only small numbers of radial velocities are available, there is a well-known degeneracy between mass and velocity anisotropy. An increase in the line-of-sight velocity dispersion at large radii may by due to either (1) the presence of large amounts of mass at large radii or (2) tangential anisotropy in the velocity distribution. This degeneracy could be broken by means of improved modelling and a larger data set with many more stars in the outer parts.

Observations were conducted from 2000 June 23 to 26 at the William Herschel Telescope using the AF2/WYFFOS multifiber positioner and spectrograph. A total of 284 stars were observed, spanning the magnitude range of V 17.0-19.8. Of these, 159 were Draco members (extending to 25') with spectra of sufficient quality to be included in the dynamical analyses. The median velocity uncertainty for these 159 stars was 1.9 km s-1. These are the first observations to probe the outermost regions of a strongly dark matter-dominated dSph galaxy.

From subsequent analysis, astronomers found that the velocity dispersion profile is flat or slowly rising at large radii, which provides the first clear signature of an extended dark matter halo in any dSph galaxy.

Further studies of this cocoon, whose composition remains a mystery, promise to illuminate the early history of our own Galaxy, which presumably built up from such dark-matter quanta. This result also fits with the bottom-up view of galaxy formation, in which the gravitational fields of big galaxies shred smaller ones and assimilate their stars, gas, and dark matter.

DISTANT GALAXIES ARE IN THE RED

INT+CIRSI

The panoramic IR camera, CIRSI has been used to carry out a large-scale survey of distant galaxies in the prime focus of the INT. The main goal of the project was to study the Universe when it was 7 billion years old, or around half its current age.

The recently completed infrared sky survey has detected over 50,000 galaxies in a patch of sky covering roughly the area of a full Moon. Although only one fifth of the data has been analysed so far, already three times as many very red galaxies have been found as was expected.

One possibility is that these galaxies have more old stars in them than expected. Old stars tend to be large and relatively cool, hence the red colour. A second possibility is that the galaxies are very dusty, where scattering by dust particles causes objects to appear red.

A second significant result is the discovery that these red galaxies seem to clump together much more than galaxies in the nearby Universe. One possible explanation is that these red galaxies are merging with each other to form single more massive galaxies.

This merging process would explain why astronomers are seeing more galaxies in the past than expected. If galaxies merge, their total number will decrease to the present-day value.

HIGH-SPEED ENERGY-RESOLVED STJ PHOTOMETRY OF THE ECLIPSING BINARY UZ FOR

WHT+SCAM

UZ For is a member of the AM Herculis type cataclysmic variables (CVs), in which a strongly magnetic white dwarf accretes material from a late-type companion that fills its Roche lobe. As material passes through the inner Lagrange point of the system towards the white dwarf, the magnetic field does not initially dominate the motion of the material. Closer to the white dwarf surface, beyond the stagnation region, the field threads and disrupts the flow, channelling infalling material into a funnel which terminates in a shock front at or near the magnetic pole(s). Shock-heated plasma cools via bremsstrahlung, Compton cooling, and cyclotron emission as it settles onto the white dwarf, with the accretion stream also contributing to the optical and ultraviolet emission. Magnetic interaction between the white dwarf and its companion keeps the white dwarf in rotational synchronism with the M dwarf companion, and the system rotation then leads to the coherent variability observed in these systems.

The orbital period of UZ For is 126.5 min, of which the white dwarf is eclipsed for approximately 8 min. The simultaneous rapid intensity and spectral variations which are characteristic of the eclipses of cataclysmic variables make these objects ideal targets for study with advanced photon-counting detectors which record the time of arrival and the energy of each incident photon. Although such detectors have long been available for high-energy studies (e.g. proportional counters or CCD detectors operated in X-ray photon-counting mode), they are only now becoming available for optical work, based on the new development of Superconducting Tunnel Junction (STJ) devices.

A photon incident on an individual STJ breaks a number of the Cooper pairs responsible for the superconducting state. Since the energy gap between the ground state and excited state is only a few meV, each individual photon creates a large number of free electrons, in proportion to the photon energy. The amount of charge thus produced is detected and measured, giving an accurate estimate of the photon arrival time as well as a direct measurement of its energy. Arrays of such devices provide imaging capabilities.

A 6×6 array of 25×25 μm^2 tantalum STJ device built at ESA was incorporated into a cryogenic camera operated at the Nasmyth focus of the William Herschel Telescope. The projected pixel size of 0.6×0.6 arcsec^2 results in an array covering a sky area of 4×4 arcsec^2. This camera, S-Cam2, is a development of the system first applied to observations of the Crab pulsar in 1999. Several modifications, including a new detector array, and improved detector stability and uniformity, result in an improved wavelength resolution of $\Delta\lambda$=30, 60, and 100 nm at λ=350, 500, and 650 nm respectively.

For each individual detected photon, the arrival time, x, y array element (or pixel), co-ordinate and energy channel are recorded. Photon arrival times are recorded with an accuracy of about ±5μs with respect to GPS timing signals, which is specified to remain within 1μs of UTC.

The characteristics of STJ arrays are ideally suited to the observation of CVs. The high time resolution, high efficiency, large dynamic range, and modest energy resolution afforded by the S-Cam2 system allow a direct probing of the energy dependence of the intensity variations across the eclipse, and investigation of the

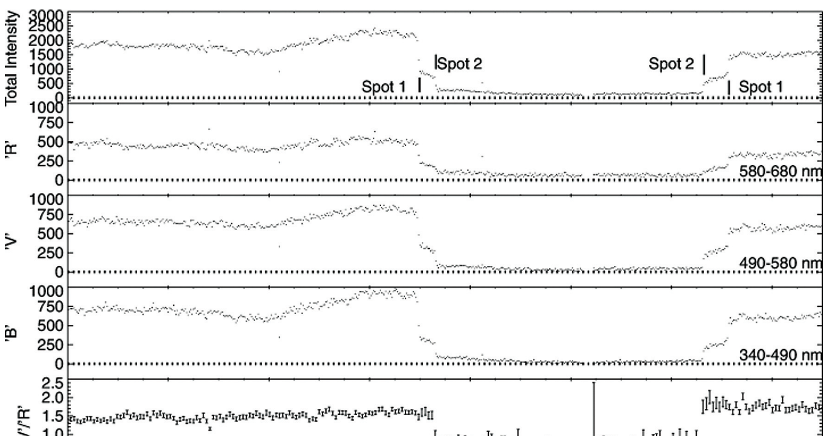


Figure 5. Sky-subtracted and flat-fielded total count s^{-1} (top), count s^{-1} in three bands: 340-490 nm (labelled 'B' for ease of reference), 490-580 nm ('V') and 580-700 nm ('R'), and two colour ratios constructed from the three energy-resolved light curves for the first observed eclipse of UZ For.

details of the ingress and egress light curves, whose structure provides important diagnostics of the emission mechanism.

Astronomers obtained data for three eclipses of UZ For. They attributed two sharp changes in brightness to the eclipse of two small accretion regions and localize them on the surface of the white dwarf primary. The first of these is in the lower hemisphere at the location seen by others in the optical, and in the EUV and X-rays. The second is in the upper hemisphere, near the rotation axis, and there is no evidence for any emission from this region in X-rays. The diameter of the accretion spots is less than about 100 km.

A NEW LOCAL GROUP GALAXY

INT+WFC

The Wide Angle Survey, one of the ING Wide Field Survey programmes, brings together a diverse range of scientific topics, merging the observational programme to increase scientific effectiveness.

As part of the Virgo survey component some 25 square degrees of Virgo were obtained in the B photometric band, and the pipeline processed object catalogues were analysed. More than 500 Low Surface Brightness galaxies $B_{tot}<21$ were discovered by comparing the light profiles of the millions of objects in the data frames with those of previously known template LSB galaxies.

Using this data astronomers at Cambridge discovered a new member of the Local Group of Galaxies in the constellation of Cepheus. This LSB dwarf galaxy is a typical example of previously unknown nearby galaxies, and it had been previously overlooked because of its low surface brightness relative to the night sky.

Most Local Group galaxies are satellites of the Milky Way and Andromeda systems leaving only a few outliers to use as probes of the dynamical evolution of the Local Group and for characterizing the unperturbed evolution of nearby dwarf galaxies.

The luminosity function in Virgo, when combined with the much flatter function found in the field, will enable the efficiency of low mass galaxy formation in differing environments to be investigated. First results are indicating a strong environmental dependence, which would need to be taken into consideration by Cold Dark Matter theories.

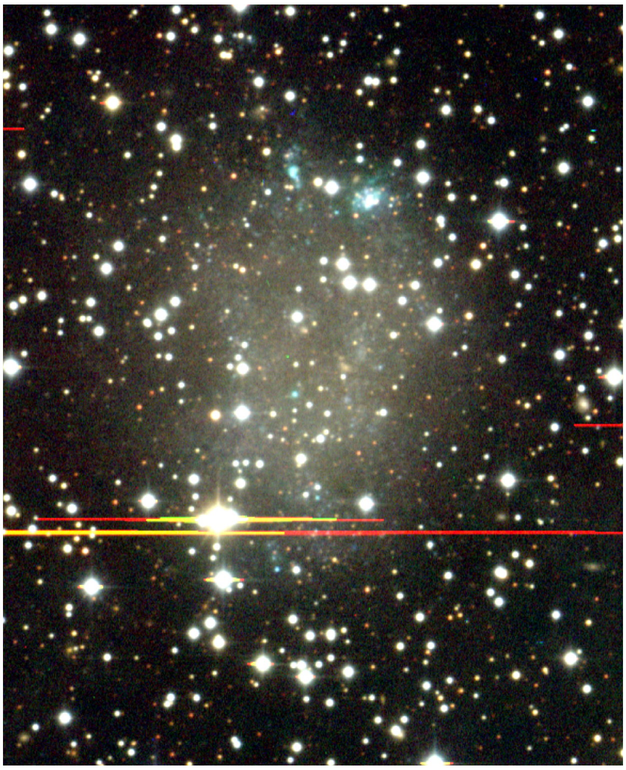


Figure 6. Colour composite of Cepheus galaxy created from 1200 second exposures in g', r' and i'-band images taken in sub-arcsec conditions using the Wide Field Camera on the INT.

A GIANT STREAM OF METAL-RICH STARS IN THE HALO OF THE GALAXY M31

INT+WFC

Within the framework of hierarchical structure formation, large spiral galaxies like the Milky Way or Andromeda arose from the merger of many small galaxies and protogalaxies. Later in their evolution, spiral galaxies become the dominant component in such mergers, cannibalizing smaller systems that fall within their sphere of influence. The complete destruction of the victim is usually progressive, and may take several orbits. However, the stellar debris from the destroyed dwarf galaxy follows a similar orbital trajectory to the progenitor, which is likely to have started life far away from the place of its final demise, and so the tidally disrupted matter tends to be deposited over a broad range in distance from the larger galaxy. Over time, with the accumulation of many such mergers, large galaxies develop an extensive stellar and dark-matter halo, the latter being by far the most massive component of the galaxy. Meanwhile, part of the (dissipative) gas component of the smaller galaxies

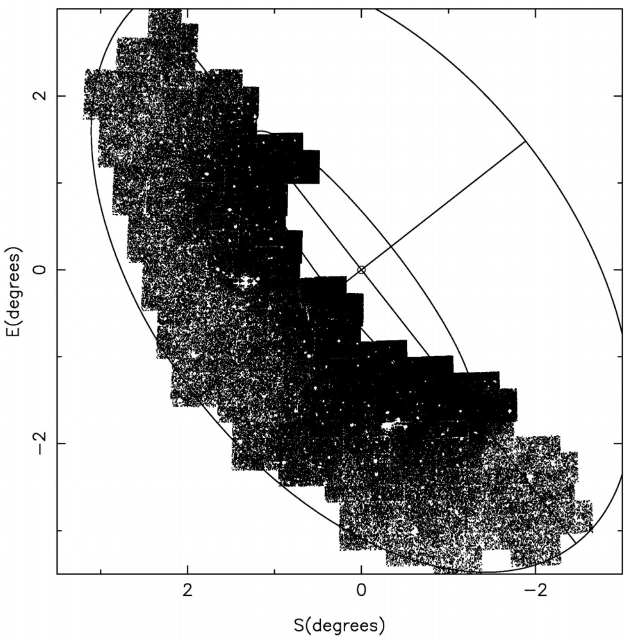


Figure 7. Surface density of RGB stars over the southeastern halo of M31. The over-density of stars is seen as a stream extending out of M31 close to, but distinct from, the minor axis.

feeds the growth of the disk of the larger galaxy. This is seen in numerical simulations of galaxy formation, which result in galactic haloes comprising clumps of dark matter. If this prediction is correct, then haloes should possess significant substructure — in contrast to previous suggestions, which predict the dark and luminous components of haloes to be distributed smoothly.

Andromeda or M31 galaxy is our Galaxy's "big sister", twice as large but otherwise very similar. It is the nearest large galaxy, lying only 2.2 million light-years away. Astronomers have known for some years that our own Galaxy is a cannibal. Its outer parts are threaded with tell-tale streams of stars from small galaxies it has engulfed.

The first sensitive panoramic wide field imaging survey of M31 using the Wide Field Camera on the Isaac Newton Telescope has unambiguously revealed the presence of a giant stellar stream within M31's halo. The source of the stream is likely to be either, or both, of the peculiar dwarf galaxies M32 and NGC205, close companions of M31, which may have lost a substantial amount of stars, gas and dust due to their tidal interactions with the massive host galaxy. The broad agreement of the metallicity distribution of the stream stars with these two dwarf satellites together with their alignment, physical proximity, and distorted morphological appearance, point to a common origin. The well-known disparity in properties between the Milky Way and M31 stellar haloes would be understandable if the majority of M31's stellar halo arose as relatively recent tidal debris from prolonged bouts of aggressive tidal interaction with its two nearest neighbour satellites. Together with recent observations of tidal debris in the Milky Way halo, these results clearly demonstrate that the epoch of galaxy building still continues, and that substructure in the form of huge, recently-deposited tidal streams, could be a generic feature of large galaxy haloes.

The new survey was possible only because the digital detector arrays such as the Wide Field Camera now cover fairly large areas of sky. Even so, more than fifty long exposures had to be pieced together to give a panorama of the halo on one side of Andromeda.

COMPLETELY DARK GALAXIES

INT+WFC

The universe could be harbouring numerous galaxies that have no stars at all and are made entirely of dark matter. Astronomers may ultimately discover that completely dark galaxies outnumber the familiar kind populated by shining stars and gas, perhaps by as many as 100 to 1. There is already a considerable amount of evidence that bright galaxies contain large amounts of dark matter, often ten times more than the mass of all their stars put together. There must be extra mass that we do not see to account for the observed movements of the stars under the influence of the gravity of the whole galaxy. In some galaxies we see so few stars they are incapable of holding themselves together as a galaxy. They would have long since scattered through space without the gravity of unseen matter to keep them together. But the question is: how do we look for these largely or even completely dark galaxies?

It's a difficult challenge, and the best technique will depend on the nature of the dark matter, which is still unknown. If the dark matter is composed entirely of fundamental particles, dark galaxies may act as gravitational lenses, distorting the appearance of distant galaxies that happen to lie behind them. If the dark matter includes some brown dwarfs their infrared radiation may be detectable. The same will be true if the galaxies contain any dead stars, such as white dwarfs or black holes. If they are nearby, it might be possible to detect these stellar remnants acting as gravitational lenses on the light of individual stars in other galaxies

Figure 8. From observations carried out as part of the ING Wide-Field Survey astronomers have been able to identify one place where a dark galaxy may exist. They noticed that the galaxy called UGC 10214, shown above, has a stream of material flowing out of it, as if it is interacting with another galaxy. In this case, the stream of material is apparently flowing towards nothing.

beyond them. Several lensing events in a small area of sky would suggest the presence of a dark galaxy.

One place where a dark galaxy may exist has been identified using images taken with the INT Wide Field Camera. A galaxy called UGC 10214 has a stream of material flowing out of it, as if it is interacting with another galaxy. But in this case, there is no other galaxy or source of visible light present, hence the companion galaxy may be completely dark.

TIDAL STREAMS IN THE GALACTIC HALO

INT+WFC

Standard cosmology theory predicts that dwarf protogalaxies were the first to born as individual systems in the universe. Afterward, many of these merge to form larger galaxies such as the Milky Way. The way in which this process takes place has consequences for the present-day structure of the Milky Way. The significant issues are how the merging efficiency compares with the star formation efficiency in the protogalactic fragments and how the fragment merging and disruption compare with the age of the Milky Way. If fragments are able to form stars before merging, they will collapse nondissipatively. If disruption was not complete, Galactic precursors should be visible today as dwarf galaxy satellites or as stellar streams within the Galactic halo.

The Sagittarius dwarf galaxy, the closest Milky Way satellite in an advanced state of tidal disruption, provides a "living" test for tidal interaction models and for galaxy formation theories. It was soon apparent that its extent was larger than at first assumed, and dynamical models predict that the stream associated with the galaxy should envelop the whole Milky Way in an almost polar orbit.

Using the Wide Field Camera on the Isaac Newton Telescope, astronomers detected a very low density stellar system at 50±10 kpc from the Galactic centre that could be related to a merger process.

The newly found system is 60° north and 46±12 kpc away from the centre of the Sagittarius dwarf galaxy. If it is really associated with this galaxy, it would confirm predictions of dynamical interaction models indicating that tidal debris from Sagittarius could extend along a stream completely enveloping the Milky Way in a polar orbit. However, the possibility that it corresponds to a hitherto unknown galaxy, also probably tidally stripped, cannot be rejected.

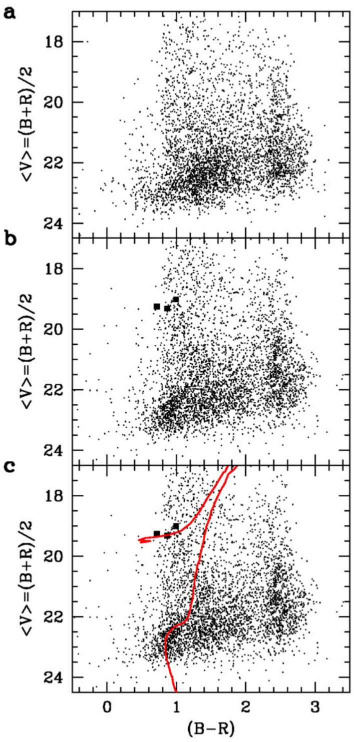


Figure 9. Color-Magnitude Diagrams (CMD) of the control (panel a) and target fields (panels b and c). Panel a provides the distribution of the foreground Milky Way stars. The overdense strip at (B–R)≃0.8, 22 ≤ V≤ 23.5 in panel b CMD is interpreted as produced by a stellar system at a distance of 51±12 kpc from us, which could make it part of the Sagittarius northern stream or, alternatively, could be the trace of a hitherto unknown tidally disrupted dwarf galaxy. Panel c shows the CMD of the target field with an old, low-metallicity (age: 12 Gyr; metallicity: 1/20 solar). The isochrone main sequence shape shows good agreement with the hypothetical target field main sequence.

THE LOCAL STAR FORMATION RATE

WHT+AF2/WYFFOS

There has been considerable progress in recent years in determining observational constraints on the cosmic history of star formation. Inevitably, most attention has focused on the contribution to the global history from the most distant sources, presumably seen at a time close to their formation. At more modest redshifts (z<1), it might be assumed that the cosmic star formation history is fairly well determined. However, the addition of further data to the low-redshift component of the cosmic star formation history has confused rather than clarified the situation. Using Autofib-2 on the William Herschel Telescope astronomers have conducted systematic spectroscopy of 305 low-redshift sources within two selected areas, updating the analysis of the ultraviolet luminosity function and star formation density presented in previous work.

The luminosity function measures the number of galaxies of different brightness in the sky, and, from such measurements, the density of ultraviolet light can be measured. Ultraviolet light is generated by massive short-lived stars, and consequently traces the star-formation rate of the surveyed galaxies. By combining with measurements of another star-formation tracer, Hα emission lines, the two tracers of star-formation can be compared. This allows astronomers to place constraints on how the star-formation rate of the universe has evolved over time, or redshift.

One of the main conclusions of this survey is that the local volume-averaged star formation rate is higher than indicated from earlier surveys. Moreover, internally within the sample, astronomers do not find a steep rise in the ultraviolet luminosity density with redshift over 0<z<0.4. These new data are more consistent with a modest evolutionary trend.

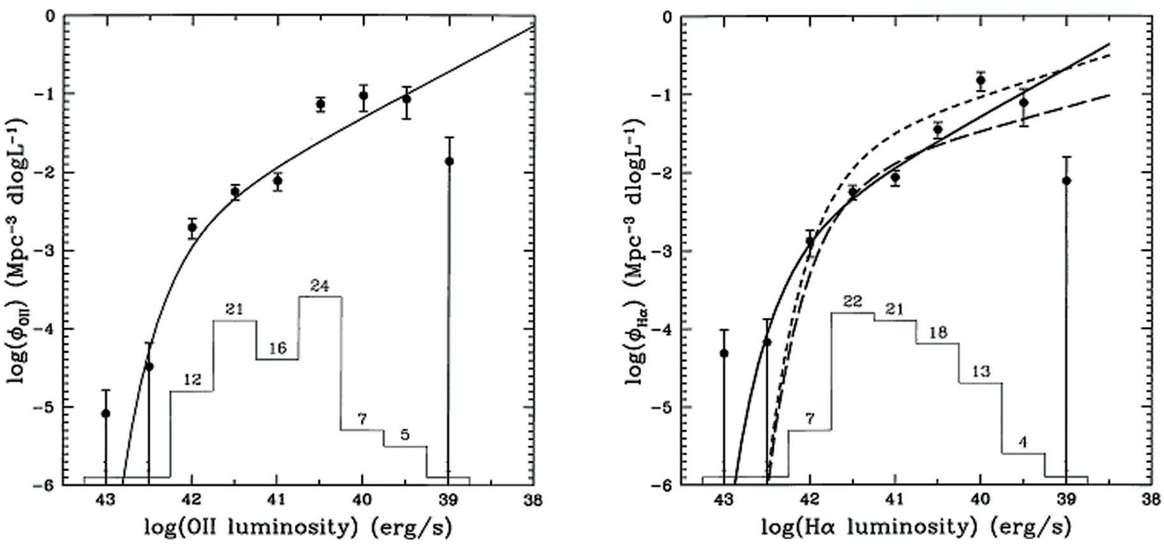


Figure 10. Left: The dust-corrected [O II] luminosity function derived from the AF2/WYFFOS sample (dots). The best fit is shown by the solid line. Right: The dust-corrected Hα luminosity function. The best fit is shown by the solid line. The short-dashed line is the Hα luminosity function derived by Tresse & Maddox, 1998 (ApJ, 312, 691) in a similar redshift range, while the long-dashed line shows the z≅0 estimate of Gallego et al., 1995 (ApJ, 312, L1).