Scientific impact of large telescopes

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ABSTRACT

The scientific impacts of telescopes worldwide have been compared on the basis of their contributions to (a) the 1000 most-cited astronomy papers published 1991-8 (125 from each year), and (b) the 452 astronomy papers published in Nature 1989-98. 1-m and 2-m ground-based telescopes account for $\approx 5\%$ of the citations to the top-cited papers, 4-m telescopes 10%, Keck I/II 4%, sub-mm and radio telescopes 4%, HST 8%, other space telescopes 23%. The remaining citations are mainly to theoretical and review papers. The strong showing by 1-m and 2-m telescopes in the 1990s augurs well for the continued scientific impact of 4-m telescopes in the era of 8-m telescopes. The impact of individual ground-based optical telescopes is proportional to collecting area (and approximately proportional to capital cost). The impacts of the various 4-m telescopes are similar, with CFHT leading in citation counts, and WHT in Nature papers. HST has about 15 times the citation impact of a 4-m ground-based telescope, but cost > 100 times as much. Citation counts are proportional to counts of papers published in Nature, but for radio telescopes the ratio is a factor ~ 3 smaller than for optical telescopes, highlighting the danger of using either metric alone to compare the impacts of different types of telescope. Breakdowns of citation counts by subject (52% extragalactic), and journal (ApJ 44%, Nature 11%, MNRAS 9%, A&A 6%) are also presented.

Subject headings: telescopes

1. Introduction

New telescopes are funded on the basis of the expected yield in terms of new science, so it is of interest to compare the current scientific impact of different kinds of telescope, e.g. small vs large, optical vs radio, ground-based vs space. Scientific impact can be measured in a number of ways, including (1) counting published papers, (2) counting publications in high-impact journals, and (3) counting citations to published papers. (1) Counts of papers are easy to make, and several observatories maintain lists of papers based on data obtained with their telescopes, but such counts give equal credit to papers of different scientific merit. (2) Alternatively, one can look at the origin of only the highest-cited papers, or of papers appearing in journals with the highest impact, but the statistical noise is then higher. Lamb (1990) used this approach to chart the changing strength of biological research in different countries. (3) Citation counts provide a fairer measure of the amount of interest generated by papers, and are often used to assess the performance of individuals and organisations, but suffer from a number of biases:

• Geographical bias arises from the tendency of each community to over-cite its own results e.g. through reading and citing national journals (Abt & Liu 1989, Schoonbaert & Roelants 1998), or e.g. through prefentially citing results first heard at regional conferences.

• Language bias arises from the tendency of English-speaking scientists not to read or cite papers written in other languages (noted e.g. by Rees 1997) and, more subtly, from citation errors (Abt 1992, Kotiaho et al 1999) which may cause non-English citations to be missed more often by automatic searches.

• Different scientific disciplines cite at different

rates (Abt 1987), and this may be true of different sub-disciplines within astronomy as well. Also, minority fields may be under-cited, and popular topics over-cited, relative to real scientific impact.
• High citation rates for technical papers may reflect usefulness rather than scientific impact.
• Self-citations (Trimble 1986) are included in citation databases, although for highly-cited papers they are only a small fraction of the total. Mutual-citation networks (Coghlan 1991) can also bias the statistics.
Another disadvantage of citation statistics is the long time lag between data being taken at the telescope, and citations being made. Citation rates peak about 5 years after publication, according to Abt (1998), and it might take much longer for the significance of seminal results to be widely recognised.

Finally, scientific impact is not the only measure of success for a telescope. Continued funding, whether by the taxpayer or from private sources, depends in part on public interest in individual telescopes, as reflected e.g. in articles in popular journals.

1.1. Previous studies

Abt (1985) compared counts of citations of papers generated by two telescopes run by national observatories (the CTIO and KPNO 4-m) with those from two telescopes run by private observatories (the Lick 3-m and Palomar 5-m), and found them to be statistically indistinguishable.

Trimble (1995) compared the impacts of large US optical telescopes, using the 1993 citation rates of papers published in 1990-91, and extended this analysis in Trimble (1996) to include 29 telescopes worldwide. The telescopes yielding the most citations were, in decreasing order, the AAT 3.9-m, CTIO 4-m, KPNO 4-m, CFHT 3.6-m, Palomar 5-m and Isaac Newton 2.5-m (see Table 4 for a list of abbreviations), with a factor of 2 between the first and sixth ranked.

Leverington (1996) looked at samples of the 15% most-cited papers in ApJ and MNRAS taken every 4 years between 1958 - 1994, and found the six most productive ground-based optical telescopes to be the Palomar 5-m, AAT, Lick 3-m, KPNO 4-m, CTIO 4-m and Palomar Schmidt. The VLA, and the Einstein, IUE, CGRO and ROSAT satellites were comparably productive. He found that paper counts for space telescopes peak about 4 years after launch, and fall to half that rate about 9 years after launch. In Leverington (1997a), he showed that 4-m-class ground-based telescopes were about 50% more cost-effective (in terms of cost per paper) than 2-m-class telescopes. Leverington (1997b) extended this analysis to radio and space telescopes, finding that ground-based optical telescopes were (up to 1994) 2 - 3 times as cost-effective as space telescopes. HST appears particularly inefficient when judged by this metric, but as Pasachoff (1997) pointed out, this may highlight the limitations of paper-counting rather than indicate a poor return on investment.

Gopal-Krishna & Barve (1998) analysed astronomy papers published in Nature 1993-5 and found that of the 51 based on data from ground-based optical telescopes, 45% used only data from telescopes with mirror diameter < 2.5 m. They concluded that much front-rank science is still done by modest-sized telescopes, and that the productive life of optical telescopes is long.

Bergeron & Grothkopf (1999) ranked selected telescopes by publication counts, and found the order for 1997/8 to be WHT, ESO 3.6-m, NTT, AAT, ESO 2.2-m, INT, CFHT, CTIO 4-m, KPNO 4-m.

Massey et al (2000) used counts of papers from the KPNO 4-m and WIYN telescopes to compare the scientific impact of classical and queue observing, and found no evidence that the latter has higher impact.

Citation analyses of the productivity of US, UK and Dutch astronomers of different standing were made by Trimble (1993a), Trimble (1993b) and Spruit (1996) respectively.

1.2. This paper

We made two independent analyses of the scientific impact of telescopes of different sizes and types. (1) For a citations-based metric, we drew on a list of the 125 most-cited astronomy papers published in each year 1991-8 (1000 papers in all), calculating the fraction of citations attributable to papers based on data from each telescope. (2) For a metric which is free of some of the biases affecting citation counts, and which responds faster

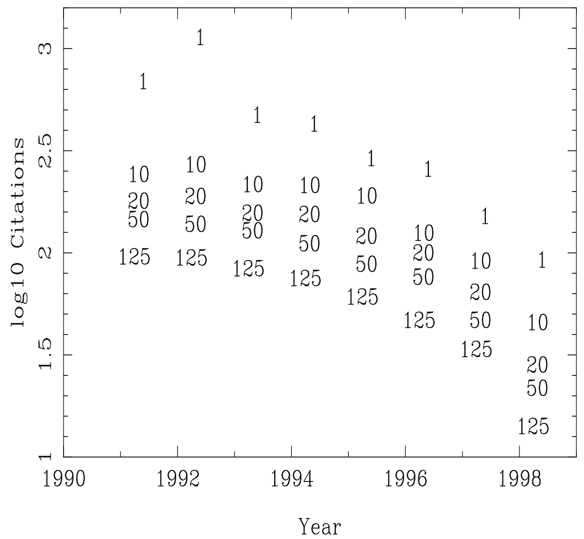


Fig. 1.— Number of citations, up to June 1999, for the 1st, 10th, 20th, 50th and 125th ranked papers published in each year.

to scientific trends (but which may still be affected by regional and subject biases), we analysed counts of papers in the journal Nature, to which much of the best science is submitted. Nature has the highest impact factor (citations/article) of any journal, about 8 times greater than that of MNRAS or ApJ. In addition, for a metric reflecting public interest, we counted mentions in the journal Sky & Telescope.

Throughout, we use the word 'impact' (unless otherwise qualified) to refer to the normalised fraction of citations to the 1000 most-cited papers.

2. Data

A list of the 125 most-cited astronomy/space papers for each year 1991-8, 1000 papers in all, was obtained from David Pendlebury of the Institute for Scientific Information (ISI) in Philadelphia.

The ISI list covers 21 journals, including A&A, A&AS, ApJ, ApJS, AJ, ARA&A, MNRAS, Nature, PASP, Science, and Solar Physics (using the standard abbreviations). For each paper the list gives the name of the first author, an abbreviated title, and the count of citations to that paper up to June 1999. We added the names of the telescopes which furnished the data on which each paper was based, and a subject code: sun, solar system, exoplanets, cool stars, hot stars (including gamma-ray bursts), the Galaxy, galaxies, active galaxies or cosmology. 450 of the 1000 papers were not classified by telescope, being theoretical (27%), or reviews (6%) or using data from many (> 5) telescopes (8%) or telescopes which could not be identified (5%). The fraction of theoretical papers is similar to that found by Abt (1993) for US astronomical journals as a whole, 28%. Citations of reviews comprise about 1% of all citations (Abt 1995).

The number of citations decreases with increasing year of publication (Fig. 1, see also Abt 1981), e.g. the 20th ranked paper of 1998 has only 26 citations, whereas the 20th ranked in 1991 has 158. In order to give equal weight to similarly-ranked papers published in different years, we expressed the citation count for each paper as a fraction of the total of citations for the 125 top papers published that year. With this normalisation, the highest-cited paper of 1991-8 is that by Smoot et al (1992) (COBE results).

For each telescope, we summed the number of papers, and calculated the average citation fraction, for the periods 1991-4, 1995-8 and 1991-8. About 1/3 of the observational papers are based on data from more than one telescope (this figure rises to 2/3 for papers based on data from 4-m telescopes). In each of these cases, the count of papers for each telescope i was incremented by a weight w_i where $\Sigma w_i = 1$, and where the relative weights used for different types of telescope were 1 for 1-m ground-based optical/IR, 4 for 2-m, 10 for 4-m, 50 for 10-m, 10 for sub-mm, 10 for radio, 100 for HST, and 30 for other space telescopes. E.g. if a paper used data from a 4-m class telescope and from ASCA (space telescope), the count of papers for the 4-m telescope was incremented by 0.25, that of ASCA by 0.75 (and similarly for the citation count). The relative weights of optical ground-based telescopes were estimated assuming that scientific impact $\propto$ collecting area, justified by examination of Fig. 2. The relative weights of ground-based optical and other telescopes were based on average impacts deduced from Fig. 3. Initially, the counts were calculated with all weights set to 1. The weights were then estimated from Figs. 2 and 3 and the analysis repeated, this time with weighting. The new versions of Figs. 2 and 3 were then found to be consistent with the applied weighting.

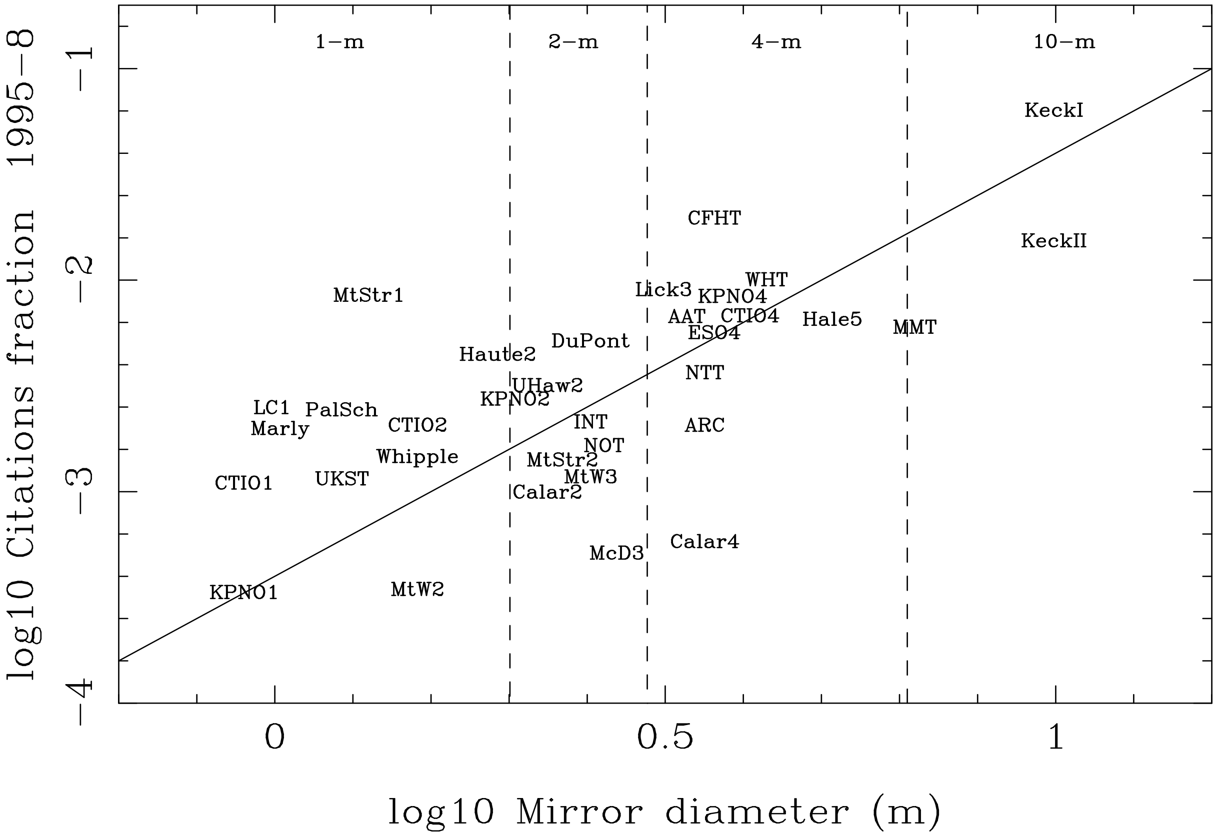


Fig. 2.— Citations fraction 1995-8 vs telescope diameter, for ground-based optical telescopes. The straight line corresponds to citation fraction = 0.6% *(diameter/4 m)^2. Statistical errors $N_{papers}^{-0.5}$ are $\sim$ 0.2 in log10 for typical 4-m telescopes, $\sim$ 0.3 for 2-m. In this figure, and others in this paper, a few points have been displaced slightly to avoid overlap of labels.

It should be emphasised that that changing all the weights to 1 significantly changes the counts for only a few small telescopes. The weights were used principally to avoid over-estimation of the contribution from 1-m telescopes, since these are often cited in conjunction with larger telescopes. The other conclusions of this paper are not affected by the choice of weighting.

For none of the large ground-based or space telescopes are the counts dominated by citations to only one or two papers. Nor are the citation statistics much affected by technical papers and catalogues receiving unusually large numbers of citations. A rare example is Landolt's (1992) paper on photometric standards, the second most-cited paper of that year, which accounts for the high 1991-4 impact of the CTIO 1-m.

Impacts as measured by counts of papers in the ISI database, and counts of citations to those papers, are similar, since there is only a weak dependence of citation count on rank in the ISI database (e.g. a factor of two between 20th and 125th ranked).

We made a similar analysis of the 452 observational astronomy/space papers (including letters, articles and reviews) published in Nature during the 10 years 1989-98, again distributing counts between telescopes where more than one contributed to a given paper. The number of astronomy papers published in Nature each year did not change significantly during this period. The slightly earlier start date than for the citations analysis allows coverage of a similar sample of new science, since publication in Nature is rapid. Approximately 100

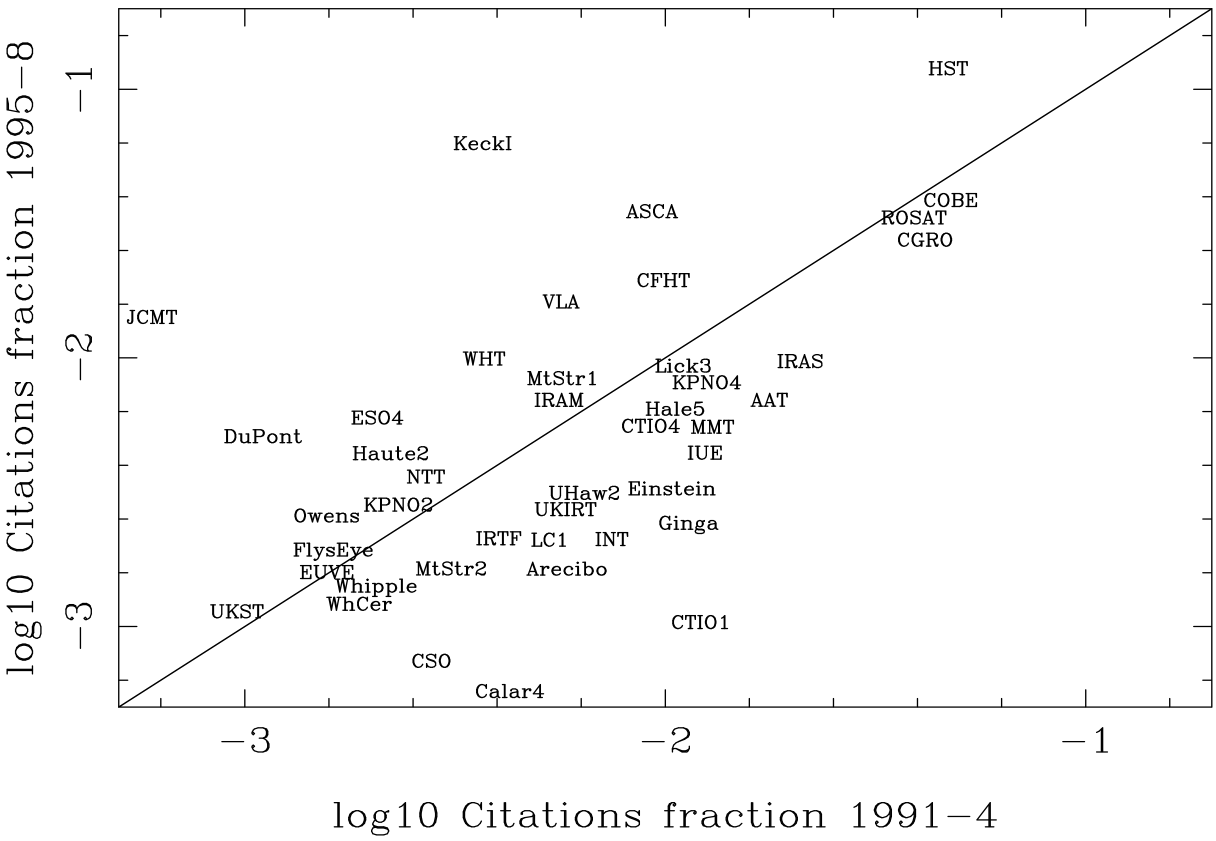


Fig. 3.— Citations fraction 1995-8 vs 1991-4, all telescopes. The straight line has slope 1. The telescopes with no citations 1991-4, but log10 citations fraction (1995-8) > -2 are BeppoSAX, Hipparcos, ISO, Keck II, RXTE, and SOHO.

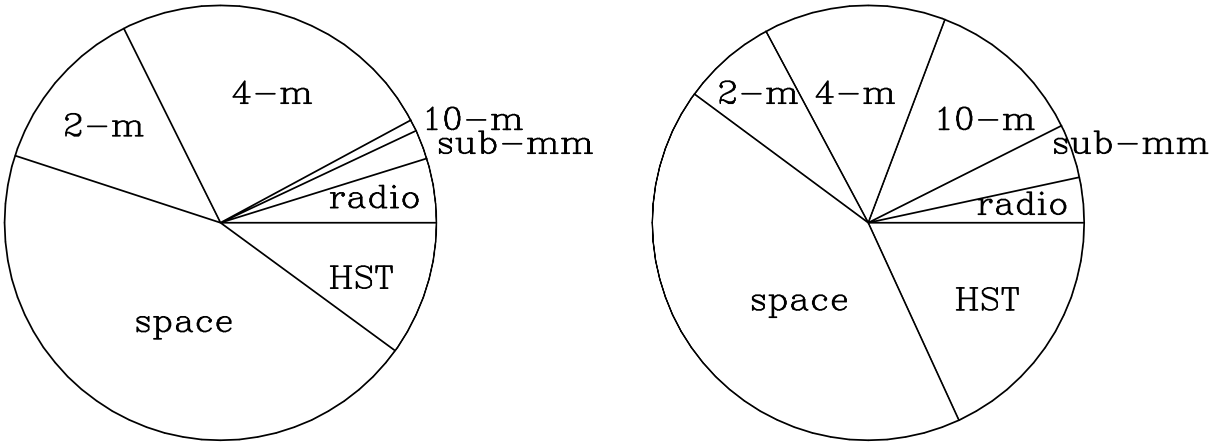
of the Nature papers appear also in the sample of the most-cited 1000 papers.

Finally, in order to gauge public interest in different telescopes, we counted mentions in the 'News Notes' section of Sky & Telescope during 1989-98.

3. Results

For each telescope, counts of papers from the 1000 most-cited, average citation fractions (to these papers) for 1991-4 and 1995-8, and counts of papers in Nature and of mentions in Sky & Telescope are given in Tables 1 (ground-based optical), 2 (other ground-based) and 3 (space). The tables include all telescopes with a total of more than 1.0 paper in the top-cited 1000, or in the Nature sample, or generating more than 0.1% of citations in either period. For reference, Table 1 also lists all ground-based optical (non-military) telescopes with primary-mirror diameter > 3.5 m which had been commissioned by 1996. The numbers of theoretical and review papers (and citations to them) are included at the bottom of Table 1. The counts in Tables 1 - 3 are sums of fractions (as discussed in Section 2 above). Fractional statistical errors on the telescope citation counts are thus $< 1/\sqrt{N}$, where N is the number of papers to which citations are made.

The relationship between 1995-8 citation count and telescope diameter for optical telescopes is shown in Fig. 2. A comparison between 1991-4 and 1995-8 counts, for all telescopes, is shown in Fig. 3. The fractional contribution of different types of telescope to the totals, for each period, is shown in Fig. 4. The ground-based optical telescopes can conveniently be divided into four class-



(a) 1991−4 (b) 1995−8

Fig. 4.— Shares of citations for telescopes of different types, for 1991-4 and 1995-8. '2-m' in this figure includes both 1-m and 2-m class telescopes. The area of each Venn diagram represents the citations to the 55% of the 1000 papers for which contributing telescopes could be identified (i.e. excluding review papers etc.). The 1991-8 averages are: 1-m + 2-m 9%, 4-m 18%, 10-m 7%, sub-mm + mm 3%, radio 4%, HST 15%, other space telescopes 44% ($\Sigma = 100\%$).

es: 1-m (diameter < 2 m); 2-m ($2.0 \leq$ diameter < 3.0 m); 4-m ($3.0 \leq$ diameter < 7 m, mostly 3.5 - 4.2 m); and 10-m (mirror diameter ≥ 7 m, i.e. Keck I/II, the only ones in this class commissioned by 1996).

Of the 14 4-m-class optical telescopes (i.e. excluding IRTF, UKIRT), 8 have similar 1995-8 impacts, between 0.55 and 0.95% of citations. They are the AAT 4-m, CTIO 4-m, ESO 4-m, Hale 5-m (50 years old), Lick 3-m (40 years old), KPNO 4-m, MMT 6-m and WHT 4-m telescopes. We confirm Abt's (1985) finding that the impacts of privately run telescopes (Hale, Lick) are not significantly different from those of national facilities. The CFHT 4-m has particularly high impact, with 1.8% of citations. The WHT ranks second. The CFHT citations are to a total of 18 papers, 10 with first authors at Canadian institutions, 6 US, 1 French, and 1 UK. The Calar Alto 4-m yields a factor of ~ 4 fewer citations than the average. The ARC and WIYN 4-m telescopes have low impact, perhaps because they were not commissioned until 1993, 1994, and citations have yet to appear in the literature. The other telescopes were all in regular use by 1990 (MMT was in its multi-mirror incarnation throughout this period). No papers from the Mt. Pastukhov 6-m telescope appear in the citations database. In Fig. 3, ~ 0.2 of the scatter in log10 is due to small-number statistics, but the impact of several telescopes has changed significantly between 1991-4 and 1995-8 (Figs. 5, 6).

The Keck I 10-m telescope, which has been in use since 1993, has an impact of 6% of all 1995-8 citations, 8 times that of typical 4-m telescopes. This factor is similar to the ratio of collecting areas. The (noisier) statistics for Keck II are consistent with similar impact per unit time. 29 of the 34 cited Keck papers are on extragalactic topics. No papers from other 8-m - 10-m telescopes appear in the citations database (most were commissioned after 1998).

The mean citation impact of 2-m class telescopes is a factor ~ 4 lower than that of 4-m telescopes, again reflecting the ratio of collecting areas. Comparison of individual telescopes is difficult because the numbers involved are small (Table 1).

Little can be said about the mean impact of 1-m telescopes because of poor statistics, but the distribution in Fig. 2 is consistent with mean impact being roughly proportional to collecting area. Ci-

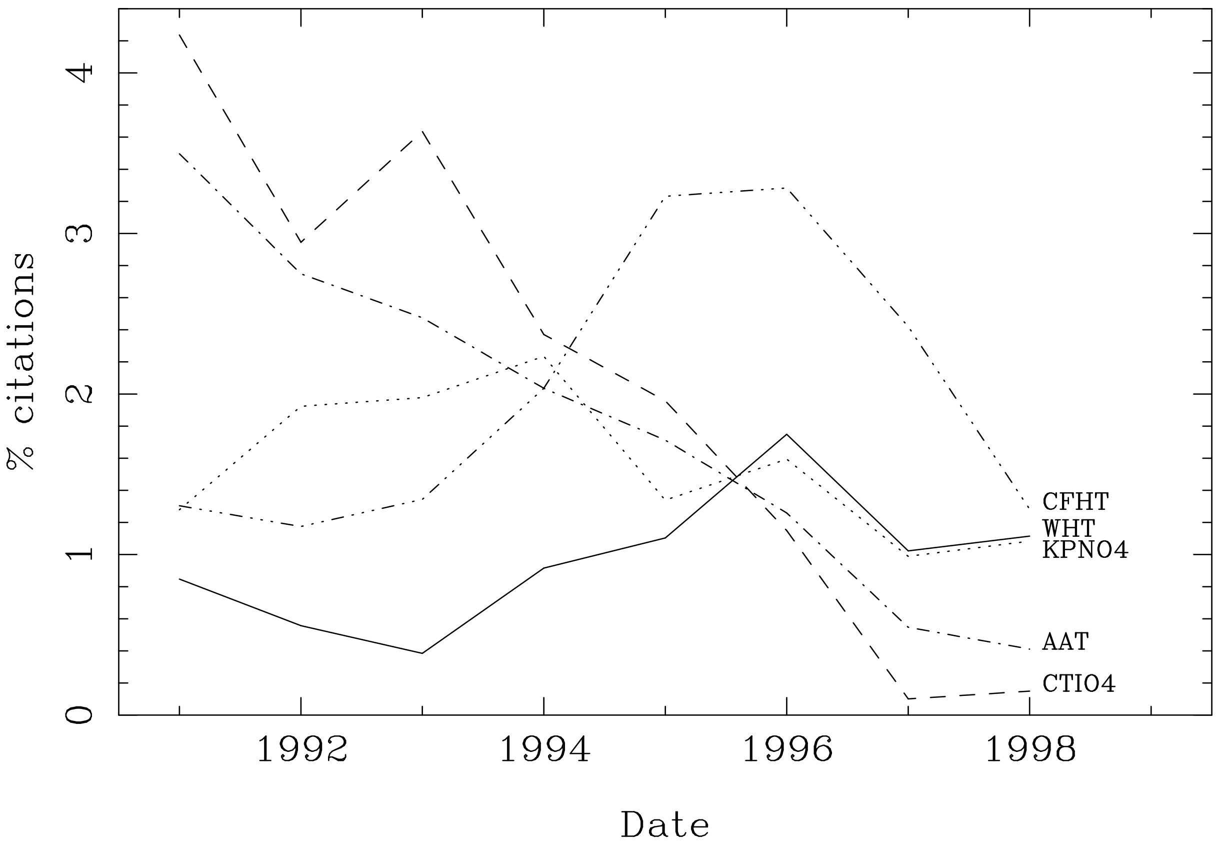


Fig. 5.— Citations fraction (3-year running mean) vs time for five 4-m telescopes. All were commissioned in the 1970s, except the WHT (1987). In this figure and Fig. 6 (only), the fractions are of all observational papers, i.e. excluding theoretical papers, to eliminate the effects of year-by-year fluctuations in the number of citations to the latter. The steady decline in citation fraction for most 4-m telescopes reflects a corresponding rise in citations to HST and Keck I/II.

tation counts may underestimate the scientific usefulness of small telescopes because they often provide uncited survey material on which are based discoveries (e.g. of high-redshift objects) made by large telescopes.

The 1-m and 2-m telescopes together contributed one half as much science (4.4%) as the 4-m telescopes (8.5%) during 1995-8 (the ratio was similar in 1991-4; Fig 4). Three of the top 40 most-cited papers are based on data from 1-m telescopes only, including two from the microlensing survey carried out with the Mt. Stromlo 1.3-m (hence its high impact, Figs. 2, 3). Extrasolar planets were also discovered using a small telescope: the Haute Provence 1.9-m (Mayor & Queloz 1995, the 9th most-cited paper of 1995).

The capital costs of telescopes of primary mirror diameter D scale approximately as $D^{2.6}$, for $D < 7$ m (Schmidt-Kaler & Rucks, 1997). 8-m - 10-m telescopes currently cost about 1/3 as much as predicted by this scaling. Running costs dominate total cost, and scale as a similar (slightly smaller) power of D as do capital costs (Abt 1980, although he only explored the relation for $D < 2.1$ m). The year-2000 capital costs of 2-m (median size 2.5 m), 4-m and 10-m class telescopes are $\sim$ \$5M, 18M and 80M, while the citation rates are in the approximate ratio 1:3:25 (Fig. 2). Therefore 2-m telescopes are roughly as cost-effective as 4-m telescopes. Keck I (10 m) is twice as cost-effective, but is the first of its size, and may have a bigger scientific impact than any of the 11 8-m - 10-m telescopes now coming online: 4 VLT, 2 Gemini,

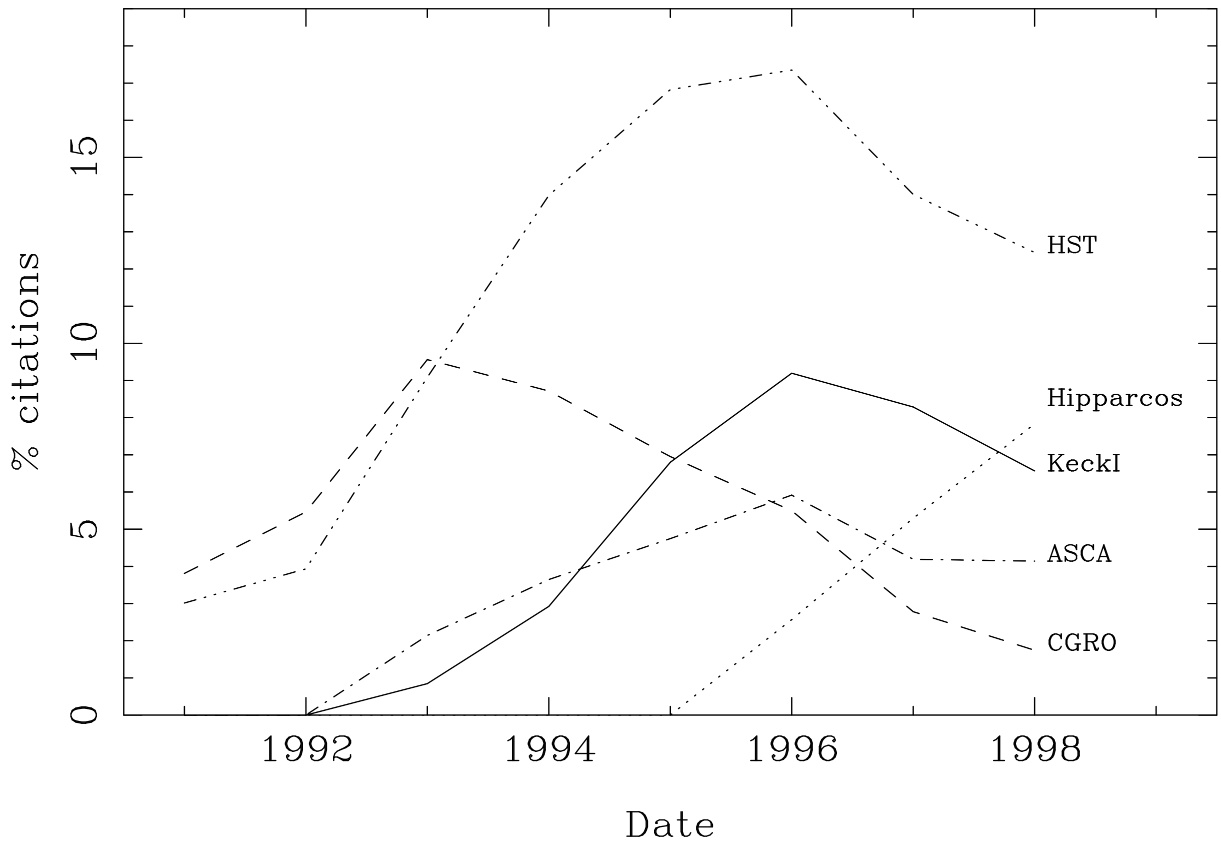


Fig. 6.— As Fig. 5, but for ASCA, CGRO, Hipparcos, HST and Keck I (and with different vertical scale). After 1996, the satellites BeppoSAX, Hipparcos and RXTE receive an increasing fraction of the citations.

Subaru, LBT, HET, SALT and Grantecan.

The citation counts for the UKIRT 3.8-m and IRTF 3.0-m IR telescopes are a factor ~ 3 lower than for the ground-based 4-m optical telescopes, perhaps reflecting a smaller user community (fewer citers), see later discussion of Fig. 7.

The sub-mm telescope JCMT generated 1.3% of 1995-8 citations, nearly twice as much as a typical 4-m, due largely to 6 1997/8 papers based on data from SCUBA, the innovative sub-mm imager. No papers from ESO's SEST appear in the citations database. The mm telescope IRAM is highly productive, with 0.8% of citations.

The VLA generated 1.5% of 1995-8 citations. It cost $\sim$ \$80M in the 1970s. All other radio telescopes combined generated 0.6% of 1995-8 citations (but 1.4% in 1991-4). Radio telescopes are more prominent in the counts of Nature papers (see discussion below of Fig. 7). No papers from the ATCA, Effelsberg, MOST or WSRT radio telescopes appear in the citations database. The VLBI observations were typically made with $\sim$ 10 - 20 telescopes across the globe, but the contributing telescopes are often not identified in the published papers.

HST, launched in 1990, generates 15 times as many citations as a 4-m telescope (11% of the 1995-8 total), but cost $\sim$ 100 times as much, $\sim$ \$2000M (a lot more, if the cost of servicing missions is taken into account). ASCA, BeppoSax, CGRO, COBE, Hipparcos, ROSAT all yielded citation fractions between 2.6 and 3.8% of the total, $\sim$ 4 times higher than a 4-m telescope, but cost $\sim$ 15 - 30 times as much. Comparison of the cost-effectiveness of ground-based and space telescopes is not straightforward. Some space telescopes (e.g. COBE, Hipparcos) are launched to solve a specific scientific problem which can't be tackled from the ground and they may have a short-lived community of citers, so it's not clear that citation counts are a fair measure of scientific impact. Others, such as HST, compete more directly with ground-based facilities (particularly now, with the advent of adaptive optics), and can be used to tackle similar problems, so a citation-based comparison of cost-effectiveness is fairer. In HST's case, the cost per citation is probably $\sim$ 10 - 20 times that for a ground-based optical telescope. The citation shares of ASCA, CGRO, COBE and HST peaked respectively 3, 2, 3 and 6 years after launch.

In Fig. 7 the citation counts are compared with counts of papers in Nature. Most of the telescopes contributing more than one paper to the top-cited 1000 have also generated Nature papers. There is a positive correlation between citation fraction and Nature counts, and a line of slope 1 is shown. However the constant of proportionality is different for different kinds of telescope. The line shows the approximate relation for ground-based optical telescopes. The ratio between citation fraction and number of Nature papers is $\sim$ twice as high for space telescopes as for optical telescopes. For radio telescopes, the ratio is *lower* than for optical telescopes. For the VLA, the ratio is a factor of $\sim$ 3 lower, while for ATCA, Effelsberg, MOST, Parkes, VLBA, VLBI and WSRT, the factor is $>\sim$ 10. This is not due to a regional bias in publishing practice, because the counts for optical telescopes from all countries cluster closely about the line in Fig. 7. If one assumes that publication in Nature is a reliable measure of scientific worth, this result indicates that citation counts undervalue radio work relative to optical work (alternatively, radio work may be over-represented in Nature). This highlights the risk of incurring metric-specific biases when comparing the scientific impacts of telescopes of different kinds.

For IR, sub-mm and mm telescopes (UKIRT, IRTF, JCMT, IRAM, Nobeyama, Owens Valley), the relation between citation fraction and Nature counts lies between those of optical and radio telescopes.

In terms of Nature papers, the most productive 4-m class optical telescope during 1989-98 was the WHT (11.5 papers), followed by the AAT (8.5).

Counts of mentions in Sky & Telescope and counts of papers in Nature are proportional (with a tighter correlation than that of Fig. 7), suggesting that the editors of Nature and of Sky & Telescope agree on what makes interesting science.

The citations database can also be used to break down scientific impact by region (of institution hosting first author), subject and journal. 61% of the citations to the 1000 most-cited papers are to papers with first authors at US institutions, 11% UK, 20% European (non-UK) and 8% other (mainly Australia, Canada, Japan). A detailed breakdown by country is reported elsewhere (Sánchez & Benn, in preparation). Breakdowns by subject and by journal are given below.

3.1. Citation counts by subject

Counts of citations to the 1000 most-cited papers, broken down by subject and date, are shown in Table 5. Papers on hot stars, galaxies and cosmology account for most of the citations to papers in the top 1000. There was a significant decline of interest in AGN between 1991-4 and 1995-8. 80% of the solar-system papers (excluding those on the sun) were published from the USA. Regionally, citations to work on cool stars, hot stars and our galaxy, each break down approximately as: 62% to papers from the USA, 2% UK and 36% other countries. For papers on galaxies, the split is 56% USA, 21% UK, 23% other. For papers on AGN and cosmology the split is 65% USA, 12% UK, 23% other. The USA is relatively strongest in cosmology, the UK in studies of galaxies, other countries (mainly Europe) in studies of cool stars.

For the 4-m telescopes whose users are predominantly from North America, 98 of the 134 cited papers (73%) are on extragalactic topics. For the UK (WHT, AAT), the fraction is 28 out of 33 (85%). At the 4-m telescopes whose users are predominantly from continental Europe, i.e. the Calar Alto 3.5-m, NTT 3.5-m and ESO 3.6-m, only 8 of the 18 cited papers (44%) are extragalactic. These regional (or cultural) differences in preferred subject area are also reflected in the extragalactic fraction in different journals: 62% for ApJ, 83% for MNRAS, 30% for A&A, 47% for Nature. If galactic and extragalactic astronomers had different citation practices, these differences could induce a regional bias in the citation counts. To test this, we counted the number of references in 25 of the papers in the database from each of the US, extragalactic and European (non-UK), stellar communities. The extragalactic papers had between 37

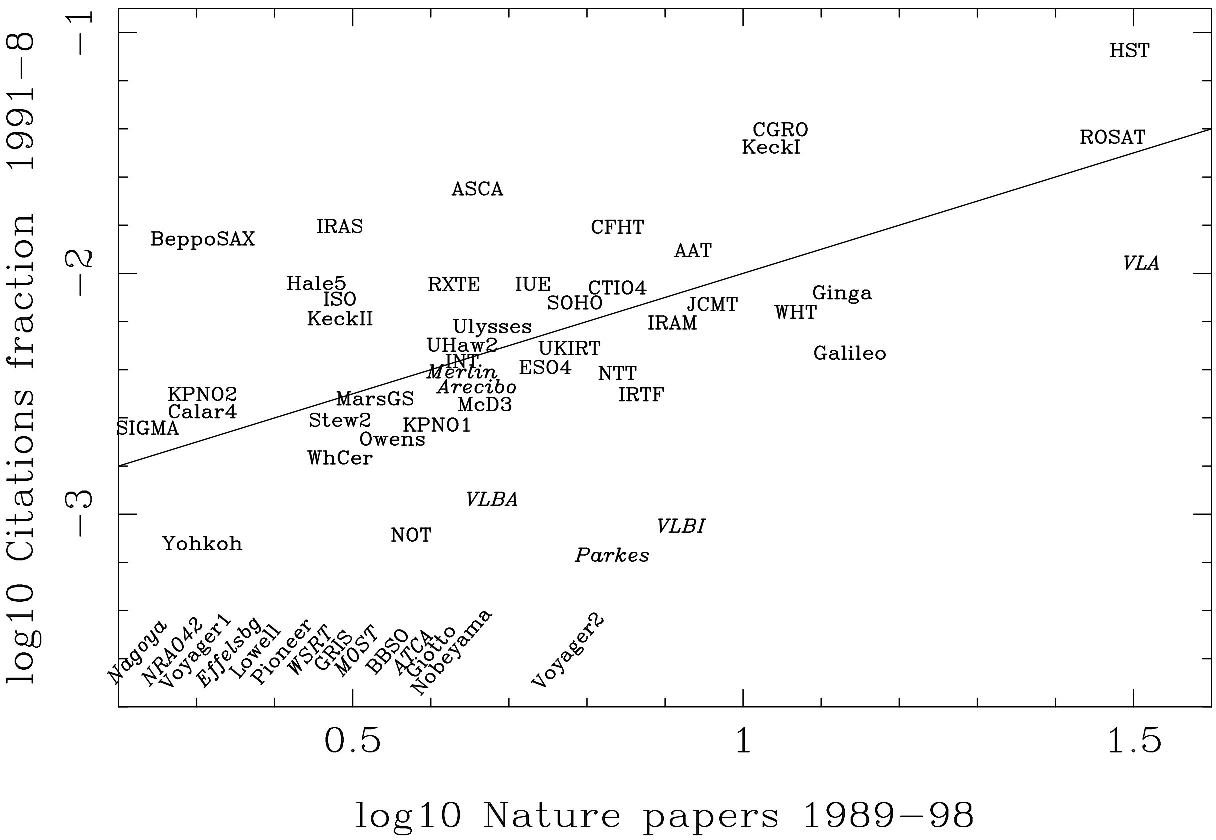


Fig. 7.— Citations fraction 1991-8 vs number of papers in Nature, all telescopes. The names of long-wave radio telescopes are italicised. The straight line has slope 1. The telescopes appearing along the bottom edge of the diagram contributed data to none of the top 1000 papers, but did generate Nature papers.

and 79 references (range excluding smallest and largest 1/6, i.e. approximating ± 1 standard deviation for a gaussian), the galactic ones 24 - 78. This suggests that any difference in citing rate between the two communities is small, and that the regional difference of subject area won't bias the citation count.

The subject breakdown for Nature is broadly similar to that given in Table 5, except that a larger fraction (≈ 20%) is devoted to solar-system work.

3.2. Citation counts by journal

Counts of citations to the 1000 most-cited papers, broken down by journal and date, are shown in Table 6. The US journals (ApJ/S, AJ, PASP) receive 60% of the citations, MNRAS 9%, A&A/S 10%, Nature 10%, Science 2%. Most of the journals publish papers on a broad range of astronomical themes, but 22 of the 26 papers from Science are on solar-system work (nearly all based on data from space probes). Most of the technical papers are published in ApJS, A&AS or PASP.

The citation shares of most of the journals have not changed significantly with time. The ApJS share dropped from 10 to 2% between 1991 and 1998. Nature's share of the top 10 papers each year was 2% in 1984-9 (1 paper), 20% in 1990-8 (17 papers). Since there are ≈ 50 space and astronomy papers published each year in Nature, 4% of them are amongst the top 10 most-cited. About 5% of the citations in Annual Reviews of Astronomy and Astrophysics are to Nature.

4. Conclusions

The scientific impacts of telescopes worldwide have been compared on the basis of their contribution to (a) the 1000 most-cited astronomy/space papers published 1991-8 (citation fraction), and (b) the 452 astronomy/space papers published in Nature 1989-98 (paper count). The conclusions below are subject to the caveats about citation bias made in the introduction.

• During the period 1991-8, approximately 5% of the citations were generated by 1-m and 2-m ground-based optical telescopes, 10% by 4-m, 4% by Keck I/II, 4% by sub-mm and radio, 8% by HST and 23% by other space telescopes. Most of the remainder were to theoretical papers and reviews. The strong showing by small optical telescopes suggests that cutting-edge science doesn't always require the largest aperture available, and this augurs well for the continued scientific impact of 4-m telescopes in the era of 8-m telescopes.

• Most 4-m optical telescopes have citation-fraction and Nature-paper impacts within 30% of the median for telescopes of this size. For 1995-8, CFHT is the most-cited (and joint-third most prominent in Nature). WHT is the most prominent in Nature (and the second most-cited).

• Citation counts correlate with counts of papers published in Nature, but the ratio is a factor 3 smaller for radio telescopes than for optical telescopes, suggesting either that the former are under-cited relative to scientific impact, or that radio work is over-represented in the pages of Nature.

• The citation impact of ground-based optical telescopes is proportional to collecting area and approximately proportional to capital cost. Space telescopes are less cost-effective in terms of citation counts.

• There is a strong correlation between counts of papers in Nature and counts of mentions of a telescope in Sky & Telescope.

• 61% of citations are to papers with first authors at US institutions, 11% UK, 20% European, 8% other.

• 52% of citations are to extragalactic papers, 34% stellar/galactic, 7% solar-system, 7% technical. At 4-m telescopes whose users are predominantly from North America or the UK, 75% of the cited papers are on extragalactics topics. For European (non-UK) telescopes, the fraction is 44%. The citations to ApJ are 62% extragalactic; to MNRAS 83%; to A&A 30%.

• The shares of the citation count by journal are: ApJ 44%, MNRAS 9%, A&A/S 10%, Nature 11%, others 29%.

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Table 1

Scientific impact of ground-based optical and IR telescopes

Telescope	Date	Diameter (m)	ΣPapers 1991-4	1995-8	1991-8	ΣCitations % 1991-4	1995-8	1991-8	Nature 1989-98	Sky&Tel 1989-98
10-m class:										
KeckI	1993	9.8	1.0	25.1	26.1	0.36	5.96	3.16	10.7	10.8
KeckII	1996	9.8	0.0	2.8	2.8	0.00	1.44	0.72	3.0	0.0
4-m class:										
MMT	1979	6.5	7.4	3.8	11.2	1.26	0.56	0.91	1.3	1.5
Bolshoi	1975	6.0	0.0	0.0	0.0	0.00	0.00	0.00	1.0	0.0
Hale5	1948	5.1	6.5	3.3	9.8	1.03	0.61	0.82	2.8	5.5
WHT	1987	4.2	1.6	3.9	5.5	0.36	0.94	0.65	11.5	8.3
CTIO4	1976	4.0	4.9	3.0	7.9	0.90	0.64	0.77	6.8	9.3
AAT	1975	3.9	8.3	3.5	11.8	1.72	0.63	1.18	8.5	7.3
KPNO4	1973	3.8	7.2	4.5	11.7	1.22	0.82	1.02	0.8	6.8
UKIRT	1978	3.8	3.1	2.0	5.1	0.56	0.26	0.41	5.9	10.3
CFHT	1979	3.6	4.6	8.4	13.0	0.96	1.84	1.40	6.8	17.1
ESO4	1977	3.6	1.0	2.5	3.5	0.20	0.57	0.38	5.5	8.6
Calar4	1984	3.5	2.6	0.2	2.7	0.42	0.05	0.23	2.0	1.3
NTT	1989	3.5	2.0	1.3	3.3	0.26	0.34	0.30	6.8	8.8
ARC	1993	3.5	0.0	1.0	1.0	0.00	0.19	0.10	0.0	0.0
WIYN	1994	3.5	0.0	0.0	0.0	0.00	0.00	0.00	0.7	1.0
Lick3	1959	3.1	7.0	4.4	11.4	1.07	0.85	0.96	0.5	0.5
IRTF	1979	3.0	2.4	1.2	3.6	0.39	0.20	0.30	7.3	9.5
2-m class:										
McD3	1969	2.7	0.8	0.3	1.1	0.49	0.05	0.27	4.6	3.0
NOT	1989	2.6	0.0	0.6	0.6	0.00	0.15	0.08	3.7	3.0
DuPont	1976	2.5	0.6	2.7	3.3	0.11	0.48	0.30	0.0	0.0
INT	1984	2.5	2.8	0.9	3.7	0.58	0.20	0.39	4.3	4.8
MtW3	1917	2.5	0.0	0.8	0.8	0.00	0.13	0.07	0.5	1.0
Hiltner	1986	2.3	0.0	0.0	0.0	0.00	0.00	0.00	1.5	0.0
Stew2	1969	2.3	2.6	0.0	2.6	0.46	0.00	0.23	3.0	3.5
MtStr2	1984	2.3	0.7	1.1	1.8	0.26	0.16	0.21	0.8	0.0
ESO2	1984	2.2	0.5	0.0	0.5	0.10	0.00	0.05	1.3	7.7
UHaw2	1970	2.2	4.5	2.0	6.5	0.65	0.30	0.48	4.3	6.2
KPNO2	1964	2.0	1.3	1.9	3.1	0.23	0.27	0.25	2.0	7.0
1-m class:										
Haute2	1958	1.9	0.5	1.0	1.5	0.22	0.42	0.32	0.0	0.0
Whipple	1970	1.5	1.0	1.0	2.0	0.20	0.14	0.17	0.8	2.0
CTIO2	1968	1.5	0.0	1.1	1.1	0.00	0.19	0.10	0.3	1.2
Pal2	1908	1.5	0.0	0.0	0.0	0.00	0.00	0.00	1.3	0.0
MtStr1	1941	1.3	1.0	3.0	4.0	0.55	0.80	0.68	1.0	0.0
UOWO		1.3	0.0	0.0	0.0	0.00	0.00	0.00	1.3	0.0
LC1		1.0	2.0	1.4	3.4	0.52	0.23	0.38	0.0	0.0
Marly		1.0	0.0	1.0	1.0	0.00	0.19	0.09	0.0	0.0
CTIO1	1967	0.9	2.0	0.5	2.5	1.18	0.10	0.64	1.3	0.5
KPNO1	1960	0.9	2.9	0.2	3.2	0.41	0.04	0.22	4.0	5.4
Lowell		0.5	0.0	0.0	0.0	0.00	0.00	0.00	2.3	0.0
PalSch	1948	1.2	0.0	1.1	1.2	0.01	0.23	0.12	0.0	0.6
UKST	1973	1.2	0.6	0.8	1.3	0.09	0.11	0.10	1.5	4.3
Solar:										
BBSO	1969		0.0	0.0	0.0	0.00	0.00	0.00	3.0	1.0
Theoretical			160.3	114.4	274.6	31.79	21.84	26.82		
Reviews			38.0	18.0	56.0	7.91	3.53	5.72		

Note.—The telescope abbreviations are those used in the figures, and are explained in Table 4. Column 2 gives the date of commissioning. Columns 4 - 6 refer to counts of papers (sums of fractions) from the 1000 most-cited, and columns 7 - 9 to citations of these papers.

TABLE 2

SCIENTIFIC IMPACT OF GROUND-BASED SUB-MM, RADIO AND COSMIC-RAY TELESCOPES

Telescope	Date	ΣPapers			ΣCitations %			Nature	Sky&Tel
		1991-4	1995-8	1991-8	1991-4	1995-8	1991-8	1989-98	1989-98
Sub-mm and mm:									
CSO	1988	1.4	0.5	1.9	0.27	0.07	0.17	1.0	1.0
JCMT	1987	0.2	6.0	6.2	0.06	1.34	0.70	9.0	4.0
SEST	1987	0.0	0.0	0.0	0.00	0.00	0.00	0.5	0.0
IRAM	1979	3.2	4.6	7.8	0.54	0.78	0.66	8.0	1.0
Nobeyama	1989	0.0	0.0	0.0	0.00	0.00	0.00	3.3	0.0
Owens		1.0	2.0	3.0	0.16	0.28	0.22	3.5	1.0
Radio:									
Arecibo	1963	3.0	1.0	4.0	0.48	0.16	0.32	4.5	6.4
ATCA	1988	0.0	0.0	0.0	0.00	0.00	0.00	3.3	1.0
Effelsberg	1972	0.0	0.0	0.0	0.00	0.00	0.00	2.2	2.0
GB91	1978	2.0	0.0	2.0	0.40	0.00	0.20	0.5	0.0
Merlin	1990	3.0	0.0	3.0	0.74	0.00	0.37	4.0	5.0
MOST	1967	0.0	0.0	0.0	0.00	0.00	0.00	3.0	1.0
Nagoya		0.0	0.0	0.0	0.00	0.00	0.00	1.8	0.0
NRAO42	1965	0.0	0.0	0.0	0.00	0.00	0.00	2.0	0.0
Parkes	1961	1.0	0.0	1.0	0.13	0.00	0.06	6.7	0.0
VLA	1980	2.4	5.6	8.1	0.55	1.54	1.04	31.9	33.4
VLBA	1993	0.0	1.2	1.2	0.00	0.22	0.11	4.7	2.8
VLBI		0.0	1.2	1.2	0.00	0.17	0.08	8.2	2.5
WSRT	1970	0.0	0.0	0.0	0.00	0.00	0.00	2.2	1.8
Cosmic-ray:									
FlysEye		1.0	1.0	2.0	0.16	0.17	0.16	0.0	0.0
WhCer	1992	1.0	1.0	2.1	0.18	0.14	0.16	3.0	2.0

NOTE.— The telescope abbreviations are those used in the figures, and are explained in Table 4. Column 2 gives the date of commissioning.

TABLE 3
SCIENTIFIC IMPACT OF SPACE (AND AIRBORNE) TELESCOPES

Telescope	Date	ΣPapers			ΣCitations %			Nature	Sky&Tel
		1991-4	1995-8	1991-8	1991-4	1995-8	1991-8	1989-98	1989-98
γ-ray:									
BeppoSAX	1996	0.0	9.5	9.5	0.00	2.63	1.31	2.0	0.5
CGRO	1991	19.4	14.7	34.1	4.04	2.93	3.48	11.0	14.0
GRIS	1988	0.0	0.0	0.0	0.00	0.00	0.00	3.0	0.0
X-ray:									
ASCA	1993	2.5	16.5	19.0	0.90	3.33	2.12	4.5	3.8
Einstein	1978	4.9	1.3	6.2	1.01	0.31	0.66	1.0	1.7
EXOSAT	1983	4.0	0.0	4.0	0.81	0.00	0.41	1.0	1.5
Ginga	1987	6.0	1.5	7.5	1.10	0.23	0.67	13.2	1.3
HXT	1991	1.5	0.0	1.5	0.23	0.00	0.11	0.0	0.0
ROSAT	1990	18.7	18.3	37.0	3.79	3.15	3.47	29.3	16.8
RXTE	1995	0.0	10.6	10.6	0.00	1.70	0.85	4.2	4.3
SIGMA	1989	3.0	0.0	3.0	0.43	0.00	0.22	1.7	2.3
SXT	1991	1.5	0.0	1.5	0.53	0.00	0.26	0.0	0.0
Yohkoh	1991	0.0	1.0	1.0	0.00	0.14	0.07	2.0	0.5
Optical/UV:									
HUT	1990	0.0	1.6	1.6	0.00	0.38	0.19	1.5	0.0
Hipparcos	1989	0.0	13.0	13.0	0.00	3.14	1.57	1.0	2.0
HST	1990	25.5	55.9	81.5	4.58	11.33	7.95	30.8	72.1
IUE	1978	6.1	2.5	8.7	1.21	0.49	0.85	5.3	2.8
KAO	1995	0.0	0.0	0.0	0.00	0.00	0.00	1.5	2.0
IR:									
IRAS	1983	10.3	4.3	14.6	2.04	0.92	1.48	3.0	10.7
ISO	1995	0.0	7.1	7.1	0.00	1.48	0.74	3.0	1.5
Radio:									
COBE	1989	16.4	12.9	29.3	4.64	3.34	3.99	1.0	7.5
Solar:									
SMM	1980	2.0	0.0	2.0	0.29	0.00	0.15	1.0	1.0
SOHO	1995	0.0	8.8	8.8	0.00	1.42	0.71	6.0	3.5
SUMER		0.0	1.3	1.3	0.00	0.25	0.13	0.0	0.0
Ulysses	1990	4.0	2.0	6.0	0.67	0.30	0.48	4.7	3.0
Planetary missions:									
Galileo	1995	0.0	5.0	5.0	0.00	0.88	0.44	13.5	5.0
Giotto	1985	0.0	0.0	0.0	0.00	0.00	0.00	4.0	0.0
Magellan	1990	2.0	0.0	2.0	0.27	0.00	0.13	0.0	0.0
MarsGS	1998	0.0	0.0	0.0	0.00	0.00	0.00	4.0	0.0
Pioneer	1972	0.0	0.0	0.0	0.00	0.00	0.00	2.3	0.0
Voyager1	1977	0.0	0.0	0.0	0.00	0.00	0.00	2.0	3.0
Voyager2	1977	0.0	0.0	0.0	0.00	0.00	0.00	6.0	4.0

NOTE.— The telescope abbreviations are explained in Table 4. Column 2 gives the date of launch (or of arrival at planet).

Table 4

Telescope abbreviations (as used in the figures)

Abbrev.	Telescope, and location (if ground-based)
AAT	Anglo-Australian Telescope, Siding Spring
Apollo	Apollo solar-wind mission
ARC	Advanced Research Consortium telescope, Apache Point, New Mexico
Arecibo	Arecibo radio telescope, Puerto Rico
ASCA	Advanced X-ray Satellite for Cosmology & Astrophysics
ATCA	Australia Telescope Compact Array (radio), Narrabri
ATT-horn	AT&T Bell Labs 20-ft horn antenna, New Jersey
BBSO	Big Bear Solar Observatory, California
BeppoSAX	BeppoSAX γ-ray telescope
Bolshoi	Mt Pastukhov telescope, Georgia
Calar4	Calar Alto 3.5-m telescope
CFHT	Canada-France-Hawaii Telescope, Mauna Kea
CGRO	Compton Gamma Ray Observatory
COBE	Cosmic microwave Background Explorer
CSO	Caltech Sub-mm Observatory, Mauna Kea
CTIO1	0.9-m telescope, Cerro Tololo
CTIO2	1.5-m telescope, Cerro Tololo
CTIO4	Blanco 4-m telescope, Cerro Tololo
DuPont	du Pont 2.5-m telescope, Las Campanas
Effelsberg	Effelsberg 100-m radio telescope, Germany
Einstein	Einstein X-ray telescope
ESO2	ESO 2.2-m telescope, La Silla
ESO4	ESO 3.5-m telescope, La Silla
EXOSAT	X-ray telescope
FlysEye	Fly's Eye air-shower detector, Utah
Galileo	Galileo mission to Jupiter
GB91	Green Bank 91-m radio telescope
Gemini	Two 8.1-m telescopes, Mauna Kea and Cerro Pachon
Ginga	X-ray telescope
Giotto	Giotto mission to comet P/Halley
Grantecan	Gran Telescopio Canario (10-m), La Palma
GRIS	Gamma-Ray Imaging Spectrometer (balloon-borne)
Hale5	Hale Telescope, Mt Palomar, California
Haute2	Haute Provence 1.9-m telescope
HET	Hobby-Eberly Telescope, Davis Mountains, Texas
Hiltner	Hiltner telescope, Kitt Peak
Hipparcos	Hipparcos astrometry mission
HST	Hubble Space Telescope
HUT	Hopkins UV Telescope (on the Space Shuttle)
HXT	Hard X-Ray Telescope
INT	Isaac Newton Telescope, La Palma

TABLE 4—*Continued*

Abbrev.	Telescope, and location (if ground-based)
IRAM	French mm telescope, Pico Veleta, Granada
IRAS	IR Astronomy Satellite
IRTF	NASA IR Telescope Facility, Mauna Kea
ISO	IR Space Observatory
IUE	International UV Explorer
JCMT	James Clark Maxwell Telescope, Mauna Kea
KAO	Kuiper Airborne Observatory
KeckI	Keck I, Mauna Kea
KeckII	Keck II, Mauna Kea
KPNO1	0.9-m telescope, Kitt Peak, Arizona
KPNO2	2-m telescope, Kitt Peak, Arizona
KPNO4	Mayall 4-m telescope, Kitt Peak, Arizona
LBT	Large Binocular Telescope (2 8.4-m), Mt Graham, Arizona
LC1	1-m telescope, Las Campanas
Lick3	Shane 3-m telescope, Mt Hamilton, California
Lowell	Lowell Observatory 0.5-m telescope, Arizona
Magellan	Magellan mission to Venus
Marly	Marly 1-m telescope, La Silla
MarsGS	Mars Global Surveyor
McD3	McDonald 2.7-m telescope, Davis Mountains, Texas
Merlin	Merlin radio interferometer, UK
MMT	Multiple-Mirror Telescope, Mt Hopkins, Arizona
MOST	Molonglo Observatory Synthesis Telescope (radio), Australia
MtStr1	1-m telescope, Mt Stromlo
MtStr2	2.3-m telescope, Mt Stromlo
MtW2	1.5-m telescope, Mt Wilson, California
MtW3	Hooker 2.5-m telescope, Mt Wilson, California
Nagoya	University of Nagoya 4-m radio telescope (solar), Japan
Nobeyama	Nobeyama mm array, Japan
NOT	Nordic Optical Telescope, La Palma
NRAO42	NRAO 42-m radio telescope, Green Bank, West Virginia
NTT	New Technology Telescope, La Silla
Owens	Owens Valley mm array, Big Pine, California
Pal2	60-in telescope, Mt Palomar, California
PalSch	Oschin 48-in Schmidt Telescope, Mt Palomar, California
Parkes	Parkes 64-m radio telescope, Narrabri
Pioneer	Pioneer 10, 11 space probes
ROSAT	Roentgen X-ray Satellite
RXTE	Rossi X-ray Timing Explorer
SALT	South African Large Telescope (modelled on HET)
SEST	Swedish / ESO Sub-mm Telescope

TABLE 4—*Continued*

Abbrev.	Telescope, and location (if ground-based)
SIGMA	X-ray telescope
SMM	Solar Maximum Mission
SOHO	Solar and Heliospheric Observatory
Stew2	Steward 2.3-m (Bok) telescope, Kitt Peak, Arizona
Subaru	Japanese 8.3-m telescope, Mauna Kea
SUMER	UV telescope on SOHO
SXT	Soft X-ray Telescope
UHaw2	University of Hawaii 88-inch, Mauna Kea
UKIRT	UK Infrared Telescope, Mauna Kea
UKST	UK Schmidt Telescope, Siding Spring
Ulysses	Ulysses Solar Satellite
UOWO	1.3-m telescope, University of Western Ontario
VLA	Very Large Array radio telescope, New Mexico
VLBA	Very Long Baseline Array, USA
VLBI	Very Long Baseline Interferometry
VLT	Very Large Telescope (4 8.2-m telescopes), Mt Paranal
Voyager 1,2	Voyager missions to outer solar system
WhCer	Whipple Cerenkov telescope, Mt Hopkins, Arizona
WHT	William Herschel Telescope, La Palma
WIYN	Wisconsin/Indiana/Yale/NOAO telescope, Kitt Peak, Arizona
WSRT	Westerbork Synthesis Radio Telescope, Netherlands
Whipple	1.5-m Whipple Telescope, Mt Hopkins, Arizona
Yale	Yale 1.0-m telescope, Cerro Tololo
Yohkoh	X-ray telescope

Table 5
Citation % by subject (including theoretical papers)

Subject	1991	1992	1993	1994	1995	1996	1997	1998	Total
Technical	6.7	11.7	5.0	4.9	6.4	6.7	7.5	4.9	6.7
Sun	8.4	1.1	3.1	2.4	4.9	2.4	3.4	1.8	3.4
Solar System	3.5	4.7	3.7	1.6	2.0	2.5	2.7	5.7	3.3
Exoplanets	0.0	0.0	0.0	0.0	1.7	2.3	1.9	0.0	0.7
Cool stars	8.5	14.8	12.2	12.5	5.9	9.3	4.9	3.5	9.0
Hot stars	7.4	12.2	20.2	14.8	12.7	8.0	19.6	23.8	14.8
Our galaxy	11.5	5.8	10.2	11.0	6.8	7.9	11.9	7.9	9.1
Galaxies	20.8	21.7	14.9	16.1	21.1	31.5	19.4	24.1	21.2
AGN	21.3	7.1	15.0	12.5	21.4	6.2	8.7	3.0	11.9
Cosmology	11.9	20.9	15.8	22.8	16.5	22.7	20.1	24.3	19.4

Table 6

Citation % by journal (including theoretical papers)

Journal	1991	1992	1993	1994	1995	1996	1997	1998	Total
ApJ	48.6	40.4	39.0	36.4	37.0	48.8	49.8	55.0	44.4
Nature	7.6	9.1	6.9	13.8	13.0	8.3	13.7	13.7	10.7
MNRAS	9.7	7.5	11.0	7.9	6.7	11.1	9.3	7.6	8.8
ApJS	7.4	13.2	8.7	13.6	12.2	3.9	2.6	1.8	7.9
A&A	7.5	5.3	11.5	2.9	2.7	7.2	3.0	9.8	6.3
AJ	3.3	7.1	5.0	3.6	7.6	6.4	5.1	4.1	5.3
ARA&A	3.4	5.7	6.3	6.5	2.6	4.6	2.0	0.6	4.0
A&AS	0.9	7.1	4.6	3.1	0.0	1.2	8.3	0.8	3.3
Science	0.0	0.0	2.1	0.5	3.6	5.3	2.7	3.7	2.2
PASP	0.9	1.9	1.9	2.8	7.1	1.2	0.0	0.6	2.1
Other	10.8	2.8	2.9	8.4	7.6	2.0	3.5	2.3	5.0