

redshift which in turn will allow a fuller understanding of the contribution of quasars to the extra galactic background light and the re-ionization of the Universe. The faint measurements facilitated by the INT WFS are vital as they help to pin down the shape and normalisation of the faint end of the luminosity function. The region where the luminosity function turns over will delineate those objects that contribute most to the energy budget of the early universe.

We can extend this work to even higher redshifts, i.e. by looking for i' -band dropouts. The detection of even a single quasar at $z > 6$ will allow the Gunn-Peterson measurement to test current predictions for the onset of re-ionization.

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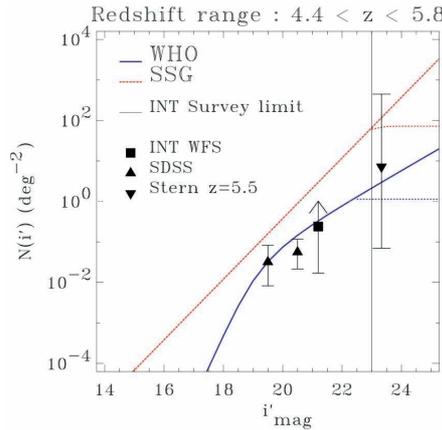


Figure 5. The comparison between two integrated quasar luminosity functions shows the extent of the current uncertainty over the redshift range for which the riz selection technique is sensitive. There is an order of magnitude discrepancy between the extrapolations of these two parameterizations in the apparent magnitude range where most of the energy is contributed to the ionizing background light. SSG — Schmidt, Schneider, Gunn, 1995, *AJ*, **110**, 68; WHO — Warren, Hewett, Osmer, 1994, *ApJ*, **427**, 412.

Name	z	Mag.			Ref.
		r'	i'	z'	
wfsj2245.6+0024	5.15	23.96	21.43	21.19	1
wfsj1612.7+5255	4.90	22.21	20.15	19.89	1
SDSS 1044-0125	5.80	>22.83	21.40	18.67	2
RD J0301+0020	5.50	26.2	23.38	22.84	3
SDSSp J1208+0010	5.27	22.66	20.37	20.17	4
SDSSp J1204-0021	5.03	20.72	18.89	18.56	5
SDSSp J0338+0021	5.00	21.61	19.54	19.19	6
SDSSp J1605-0112	4.92	22.42	19.36	19.37	5
SDSSp J0211-0009	4.9	21.97	19.51	19.26	6

Table 1. Known high redshift ($z > 4.9$) quasars. Refs.: 1. Sharp et al., 2001; 2. Fan et al., 2000b; 3. Stern et al., 2000; 4. Zheng et al., 2000; 5. Fan et al., 2000a; 6. Fan et al., 1999.

Scientific Impact of Large Telescopes

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Some telescopes clearly have higher scientific impact than others, but there have been few attempts to quantify this, or to compare impact with cost. Are 4-m telescopes a better investment than 2-m telescopes? Are space telescopes as cost-effective as ground-based telescopes? Recently, we obtained, from the Institute of Scientific Information (ISI), Philadelphia, a list of the 1000 most-cited astronomy papers published worldwide during 1991–8 (the top 125 papers each year). Although high citation isn't an infallible guide to scientific impact, and citation counts are subject to a number of biases (e.g. UK/US astronomers tend not to cite foreign-language publications), most of the hottest new science of the last decade

will be represented in this sample of papers. We determined which telescopes were used to obtain the data on which each of these papers was based, and thus measured the impact (fraction of total citations generated) of each telescope averaged over 1991–4 and 1995–8.

The impacts of ground-based optical telescopes are shown as a function of mirror diameter in Figure 1, and the 1991–4 and 1995–8 impacts are compared in Figure 2. Amongst 4-m class telescopes, CFHT has the highest impact, with the WHT in second place, but the differences between individual telescopes are small. Keck I, in use since 1993, has an impact 8 times larger than that of typical 4-m telescopes, and this factor is similar

to the ratio of collecting areas. No papers from other 8-m–10-m telescopes (apart from Keck II, commissioned 1996) appear in the list, since most were commissioned after 1998. The mean impact of 2-m class telescopes is a factor ~ 4 lower than that of 4-m telescopes, again consistent with the ratio of collecting areas. Comparison of individual 2-m telescopes is difficult because the numbers of papers involved are small.

The citation shares of different types of telescope are compared in Figure 3. 1-m and 2-m telescopes together contributed half as much science as 4-m telescopes during 1991–8. Three of the top 40 most-cited papers 1991–8 are based on data from 1-m telescopes only, including two from the microlensing survey carried out with the Mt. Stromlo 1.3-m. Extrasolar planets were also discovered using a small telescope: the Haute Provence 1.9-m (Mayor & Queloz, 1995, the 9th most-cited paper of that year).

The year-2000 capital costs of 2-m, 4-m and 10-m class telescopes are $\sim \$5$ M, $\$18$ M and $\$80$ M, while the impacts are in the approximate ratio 1:3:25 (Figure 1). If one assumes that running costs scale roughly as capital cost (Abt, 1980), then the data of Figure 1 indicate that 2-m telescopes are roughly as cost-effective as 4-m telescopes. Keck I 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, Subaru, LBT, HET, SALT and GranTeCan.

Notably productive non-optical telescopes (Figure 2) include JCMT (\sim twice the impact of a typical 4-m, largely thanks to SCUBA), IRAM and the VLA. The space telescopes ASCA, BeppoSax, CGRO, COBE, Hipparcos, ROSAT all have impacts ~ 4 times higher than a 4-m telescope, but cost ~ 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

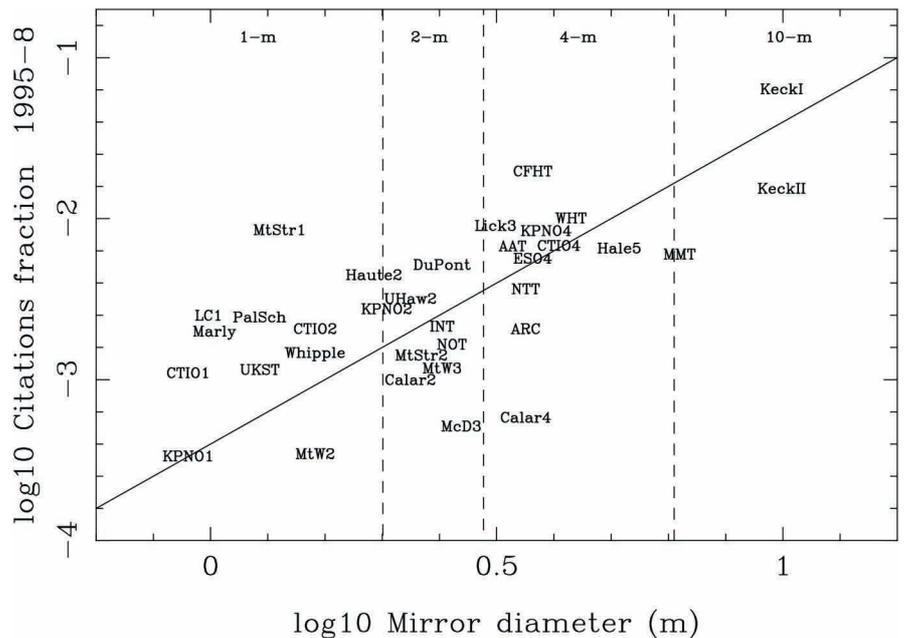


Figure 1. Citations fraction 1995–8 vs telescope diameter, for ground-based optical telescopes. Most of these telescopes were in use throughout 1991–8. The straight line indicates citation fraction = $0.6\% \times (\text{diameter}/4 \text{ m})^2$. Statistical errors $N_{\text{papers}}^{-0.5}$ are ~ 0.2 in \log_{10} for typical 4-m telescopes, ~ 0.3 for 2-m. In this figure, and Figure 2, a few points have been displaced slightly to avoid overlap of labels. Digits suffixed to the abbreviations distinguish telescopes of different size at the same observatory.

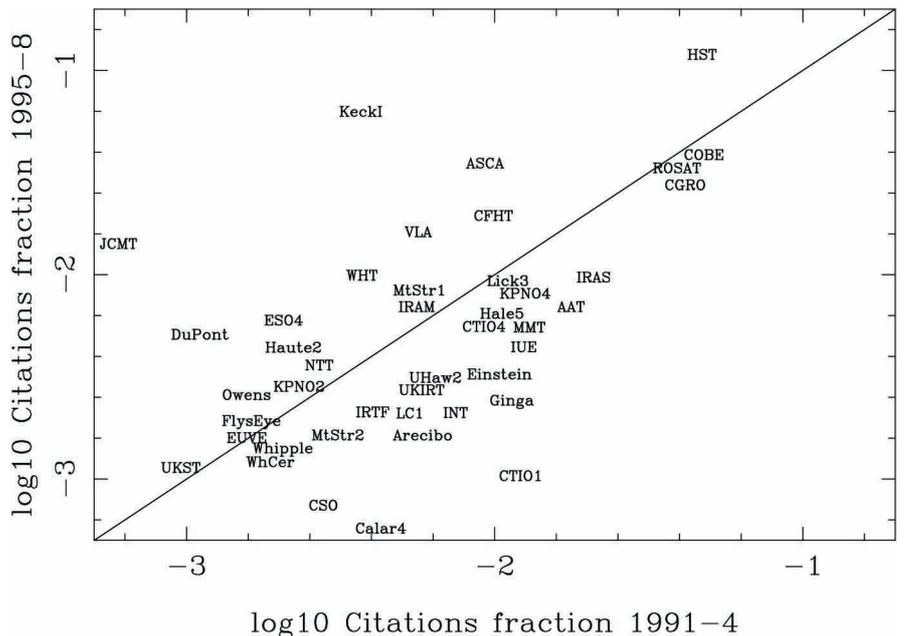


Figure 2. Citations fraction 1995–8 vs 1991–4, for both ground-based and space telescopes. The straight line has slope 1. Only telescopes with significant impact in both 1991–4 and 1995–8 appear on the plot (e.g. BeppoSax, Hipparcos, ISO, KeckII, RXTE, and SOHO all have citation fractions $> 1\%$ in 1995–8, but zero in 1991–4).

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. HST, launched in 1990, generated 15 times as many citations as a typical 4-m telescope but cost ~ 100 times as much, $\sim \$2000$ M (much more, if the cost of servicing missions is taken into account).

For an independent measure of scientific impact, we repeated the above analysis using the 452 observational astronomy papers published in *Nature* 1989–98, reasoning that only papers of the highest scientific merit make it into *Nature*. We found a close correlation between citation fraction and count of papers in *Nature*, except that radio telescopes are over-represented in *Nature* by a factor >3 relative to optical telescopes (or, to put it another way, radio telescopes are under-represented in the citation counts). This discrepancy highlights the risk of incurring metric-specific biases when comparing the scientific impacts of different kinds of telescope or community. The numbers of *Nature* papers generated by ground-based optical telescopes during 1989-98 are compared in Figure 4. The WHT was the most productive ground-based optical telescope during this period.

For each of the highest-cited and *Nature* papers generated by the WHT, we checked the instrumentation used. During most of 1991–8, observers were offered a choice of between 6 and 8 instruments at the WHT. However, 28 of the 31 WHT papers used data obtained with the intermediate-resolution spectrograph ISIS (21) or with an optical imaging camera (7).

The list of the 1000 most-cited papers can also be used to break down scientific impact by region, subject, journal or host institution (of first author). 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). 52% of the 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 (and 29 of the 34 Keck papers) are on extragalactic topics. For European (non-UK) 4-m telescopes, the fraction is 44%. The shares of the citation count by journal are: *ApJ* 44%, *MNRAS* 9%, *A&A/S* 10%, *Nature* 11%, others 26%. The most-cited host institutions in the UK

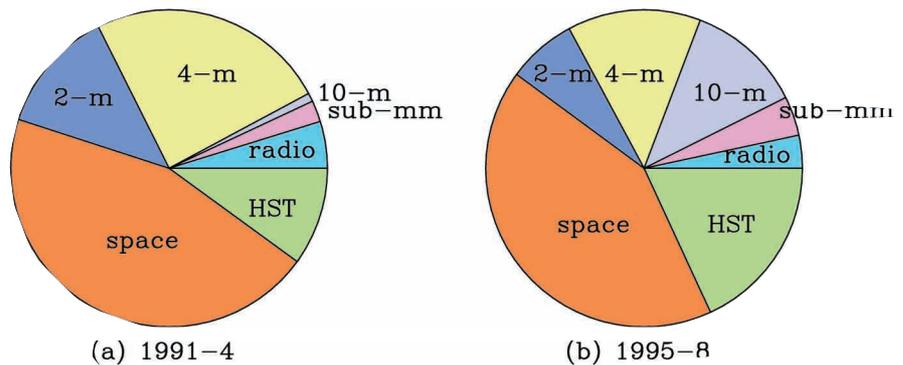


Figure 3. Citation shares of different types of telescopes, for 1991–4 and 1995–8. ‘2-m’ in this figure includes both 1-m and 2-m class telescopes.

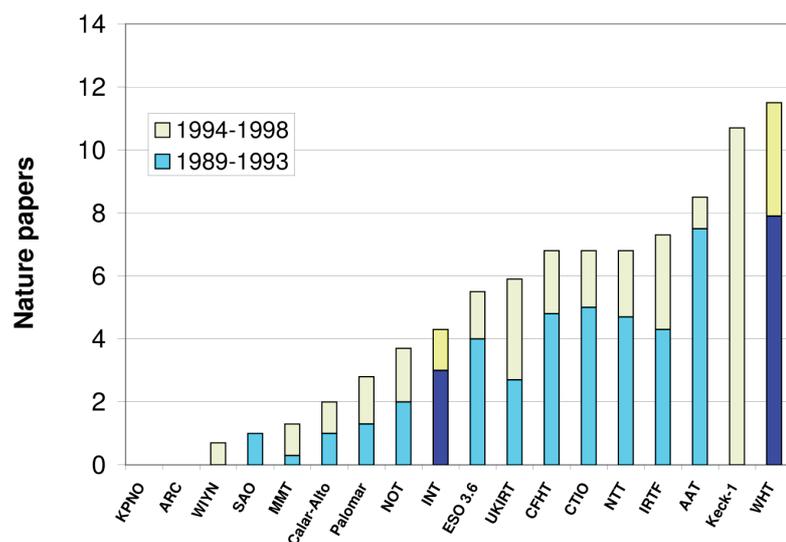


Figure 4. Number of *Nature* papers generated 1989–98 by ground-based optical telescopes with mirror diameter >3.5 m (for comparison, figures for the 2.5-m INT and Nordic Optical Telescope are also included).

were IoA Cambridge and Durham (with Durham creeping ahead in 1995–8).

Perhaps our most interesting conclusion is that during 1991–8, the era of 4-m telescopes, a substantial fraction of the science was generated by 1-m and 2-m telescopes (Figure 3). This 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.

For further statistics, and full details of the analysis, see our article in press at *PASP* (Benn & Sánchez, 2001). A recent feature article in *Nature* (2000) discusses these results further. We

thank ING summer students Ed Hawkins, Samantha Rix and Dan Bramich for their help with this project.

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