Aust. J. Phys., 1990, **43**, 241–50

Flat-spectrum Radio Sources from the Parkes 2·7 GHz Survey —A Study of a Complete Sample*

Ann Savage,[A] *David L. Jauncey,*[B] *Graeme L. White,*[B] *Bruce A. Peterson,*[C] *W. L. Peters,*[C] *Samuel Gulkis*[D] *and J. J. Condon*[E]

[A] UK Schmidt Telescope, Anglo-Australian Observatory,
Private Bag, Coonabarabran, N.S.W. 2357, Australia.
[B] Division of Radiophysics, CSIRO, P.O. Box 76, Epping, N.S.W. 2121, Australia.
[C] Mount Stromlo and Siding Spring Observatories, Australian National University,
Private Bag, Woden, A.C.T. 2606, Australia.
[D] Jet Propulsion Laboratory, Caltech, Pasadena, CA 91109, U.S.A.
[E] National Radio Astronomy Observatory, Charlottesville, VA 22903, U.S.A.

Abstract

We describe our complete sample, taken from the Parkes 2·7 GHz catalogue, of flat-spectrum radio sources with flux densities > 0·5 Jy. The sample covers all right ascensions and declinations from $+10^o$ to -45^o, excluding the galactic plane ($|b| < 10^o$) and contains 403 sources. Attention is drawn to the advantages of radio surveys over optical surveys. The survey is used to highlight some selection effects found in optical surveys. We also discuss how this sample can be used to give us information on the early universe.

1. Introduction

We are investigating a sample of radio sources drawn from the Parkes 2·7 GHz survey (Bolton *et al.* 1979, and references therein) complete to 0·5 Jy. The basic sample comprises both steep- and flat-spectrum sources but we concentrated initially on the flat-spectrum sources. The compact nature of these means that accurate radio positions can be readily measured and thus unique optical identifications, based on positional coincidence alone, can be made to the 22·5 mag limit of the SERC J survey. The sample covers 4·5 sr of sky and comprises 403 sources. Accurate radio positions have been measured for all sources (McEwan *et al.* 1975; Condon *et al.* 1977, 1978; Jauncey *et al.* 1982; Condon *et al.*, unpublished data). Optical identifications were made from the SERC/UKST IIIa-J sky survey and from deep red CCD frames obtained on the Anglo-Australian Telescope (AAT). Redshifts were obtained with the AAT (White *et al.* 1988, and references therein), with results for 270 sources. The process above has been a 'bootstrapping' exercise as there is no well defined grid of radio calibrators, or precise optical astrometric grid, in the southern hemisphere. Gradual identification and confirmation has subsequently shown some adopted radio position calibrators to be misidentifications, resulting in a reanalysis of the radio position data.

* Paper presented at the joint Australia–USSR Workshop on the Early Universe and the Formation of Galaxies held at Mt Stromlo Observatory, 28–29 June 1989.

0004-9506/90/020241$03.00

The objects for which we have no redshift are either of the 'BL Lac' type and stubbornly refuse to show any features or are too faint to give a result with the AAT. The program is aimed at determining, in an unbiased manner, the space distribution of quasars over a large area of sky and in addition can be used in other ways to give us information on the early universe.

2. Completeness

Optical identifications have been made for 87% of the sample and redshifts have been obtained for 67%. We have excellent positional agreement for 27 stellar objects whose optical spectra show no features; these we have called 'BL Lac types'. Long integrations on three of the objects have eventually brought up extremely weak emission lines at low redshift. This content of BL Lac type objects is similar to the percentage of featureless-spectrum blue objects found in optical surveys (Boyle *et al.* 1988; Crampton *et al.* 1988) This percentage is, however, much lower than that of the BL Lacs found in X-ray surveys (Stocke *et al.* 1988). The total identification content is given in Table 1.

Table 1. Identification content

Type	No redshift	With redshift	Total	Percentage of sample
Galaxies	16	23	39	9·7
BL Lacs	24	3	27	6·7
Quasars	42[A]	244	286	71·0
Empty Fields	51	—	51	12·6

[A] These objects are claimed as quasars on the basis of the excellent radio–optical positional coincidence.

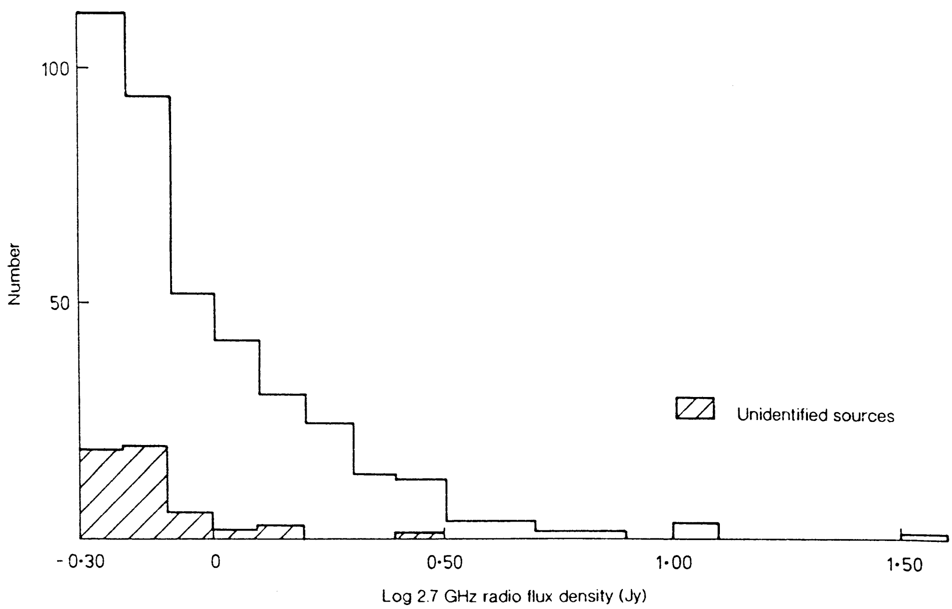

Fig. 1. Number–flux density distribution for all sources in the complete sample.

Fig. 1 gives the differential $N(s)$ distribution. It can be seen that it is predominantly the weaker radio sources that have not yet been identified to the magnitude limit of our CCD frames. A weak correlation between optical magnitude and radio flux has been found further confirming that the weaker radio sources will be the faintest optical objects.

3. Selection Effects

Our choice of radio-loud quasars may introduce a selection effect. Peacock *et al.* (1986) put forward a hypothesis for two distinct populations of quasars—'radio-quiet' and 'radio-loud'—according to the Hubble type of their underlying galaxy. In this scheme radio-quiet quasars are analogues of Seyfert galaxies—spirals—whilst the radio-selected quasars reside in elliptical galaxies. Further we have restricted our radio sample to contain only the flat-spectrum population. This excludes the steep-spectrum sources that can be identified as quasars and if there are any differences in the environment or the underlying galaxy for these two types of radio-selected quasars we will have introduced a further selection effect.

The optical identifications are not complete and because it is the weakest radio flux density sources that are the faintest optically, it may well be that the sample is missing some of the highest-redshift objects. Additionally the radio spectra of the highest-redshift quasars are not typical of those at a lower redshift (Savage and Peterson 1983). The spectra for our 10 objects with $z > 3 \cdot 0$ are shown in Fig. 2. Most of the spectra are peaked, indicating compact components that are synchrotron-self-absorbed at low frequencies and optically thin at high frequencies.

4. Advantages of this Survey

The survey uniformly covers a large area of sky and thus avoids both the small-area effects and large-scale non-uniform incompleteness found in optical surveys, and in some small area radio surveys. The identification rate is high, nearly 90%. Thus the large sample size reduces statistical fluctuations and provides reliable information on minority populations like the BL Lac type objects.

Accurate radio positions have been measured for all sources, allowing reliable optical identification to the $22 \cdot 5$ mag limit of the UKST IIIa-J plates and to the $24 \cdot 0$ mag limit of AAT CCD frames, without reliance on colour or morphology. This is particularly important in avoiding redshift-dependent effects of the type found in optically selected samples based on colour selection or emission-line selection.

5. Early Universe

This sample can be used to give us information on the early universe in many ways. It has proven efficient at finding bright high-redshift quasars (Jauncey *et al.* 1987). These quasars can then be studied at much higher dispersions as described at this workshop by Richard Hunstead and Max Pettini to reveal information on the conditions existing at these early epochs.

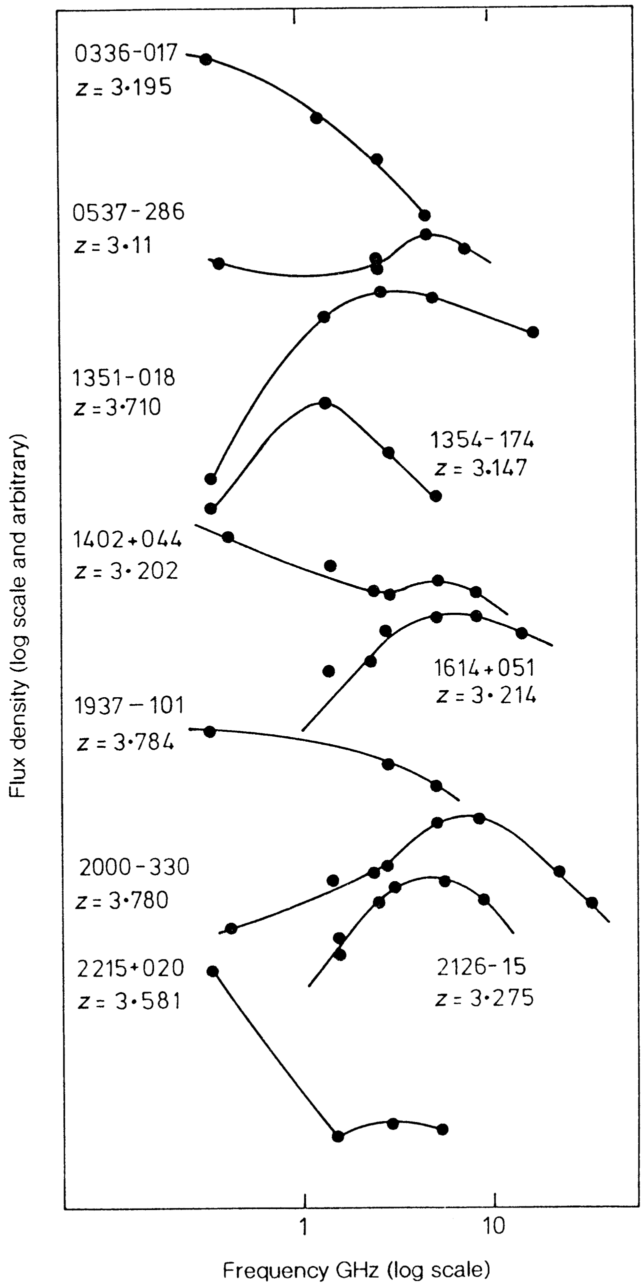

Fig. 2. Radio spectra for quasars with $z > 3 \cdot 0$, showing pronounced self-absorption peaks.

Such large scale radio surveys, together with the painstaking red-colour/prism searches of Hazard and McMahon (1985) are the only methods of finding bright high-redshift ($z > 3 \cdot 0$) quasars. The shape of the radio spectra (see Fig. 2) for these high-redshift quasars are not typical of radio quasars at lower redshifts.

These radio spectra themselves may indicate changes in the IGM at these early epochs or merely reflect the youth of the expanding source (Dunlop and Peacock 1990, paper in preparation).

We can study the change of the luminosity function of the components of this survey with epoch. The major component is the flat-spectrum radio quasars. However, before this is attempted one should be aware of the possible intrinsic differences between these and other quasars and the biases which may have crept into this sample. To illustrate this we compare this sample with some optically selected samples of quasars. We should not necessarily expect these groups of quasars to show the same luminosity function (Peacock 1988*b*).

6. Quasar Content

In our sample, 71% are identified with quasars and we have redshifts for 85% of these. We have already excluded some brighter (BL Lac) objects with no, or very weak, emission lines in their spectra. Magnitudes for all these objects have been estimated from the SERC IIIa-J survey following the method described in Downes *et al.* (1986). The overall error in the magnitudes should be <0·6 mag. We have obtained redshifts for a fairly representative sample although the fraction without redshifts increases at the faintest magnitudes. The higher redshift quasars are to be found predominantly amongst the weaker radio sources and the fainter identifications. It may be that both low-redshift objects and also very-high-redshift objects are to be found amongst those as yet without redshifts.

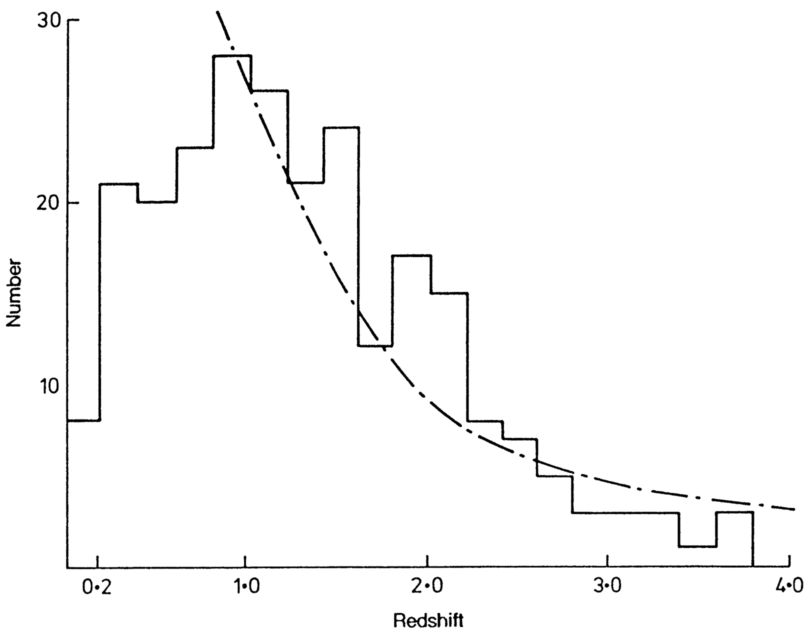

Fig. 3. Number–redshift diagram where the dot–dash curve is normalised for a comoving volume decreasing as $z^{-1\cdot 5}$ per unit interval of redshift.

7. Comparisons with Other Surveys

(a) Redshift Distribution

Fig. 3 gives the redshift distribution for this sample. Our redshift distribution appears to be consistent with a constant comoving density of objects with a broad range of absolute radio power. A comparison can be made between Fig. 3 and Fig. 1 of Wilkes (1986), which is a redshift distribution for a randomly selected sample of Parkes quasars studied by this group prior to 1983. Our complete sample confirms the Wilkes finding that there is no narrow peak at $z \approx 2$ as is found in emission-line selected samples. In fact, our new data further suppress any such peak, since the main difference between the Wilkes sample and ours has been an increase in the low-redshift objects, $z < 1 \cdot 6$, and a tripling of the number with $z > 2 \cdot 8$.

Peterson (1988) compared a model number–redshift diagram compiled from optical samples with this redshift distribution and found that apart from a slight excess of quasars with $z > 3 \cdot 0$ the radio number–redshift diagram is consistent with a model optical luminosity function that evolves to $z = 1 \cdot 4$ and then has a constant comoving density for all $z > 1 \cdot 4$. However, as stated earlier we should not necessarily expect radio selected quasars to show the same luminosity function as optically selected quasars.

(b) The V/V_m Test-Radioflux versus Redshift

The result for the banded V_e/V_a test for this sample using $\Omega = 1$ and $q_0 = 0 \cdot 5$ for a redshift band $1 \cdot 9$ to $3 \cdot 25$ is:

$$\langle V_e/V_a \rangle = 0 \cdot 429 \pm 0 \cdot 04 \text{ (53 quasars)}.$$

This can be compared with the values quoted by Peacock and Miller (1988) for samples compiled from a combination of the Parkes Selected Regions (Downes *et al.* 1986) and brighter complete Parkes radio samples (Peacock 1988*a*), also considering the same redshift band. Our value is higher than for their flat-spectrum quasars, again indicating a more uniform distribution for our sample. However, their samples of steep-spectrum quasars have still higher $\langle V_e/V_a \rangle$ values, again indicating a more uniform distribution. If we completed the steep-spectrum part of this sample and obtained redshifts for all objects then the combined $\langle V_e/V_a \rangle$ for all quasars could increase further to even closer to the $0 \cdot 5$ expected for a uniform distribution.

(c) Intrinsic Luminosity

The optical Hubble diagram has been plotted using magnitudes from the SERC IIIa-J survey. No correction has been made to transform to V magnitudes since the colours of these quasars are unknown. Our result is almost a scatter diagram because of the very broad range in optical luminosity for our identified quasars, with a very weak correlation for fainter sources to have higher redshifts in contrast to Fig. 2*b* of Wall and Peacock (1985) for a complete sample of radio-selected quasars with $S_{2 \cdot 7} > 2 \cdot 0$. Their figure shows a very tight correlation with small scatter about a line $\log z = 2 \cdot 23V - 4 \cdot 2$. We have tried to establish whether our result is due to: the broad intrinsic range in luminosity; an effect of poor magnitude estimates; emission lines in the

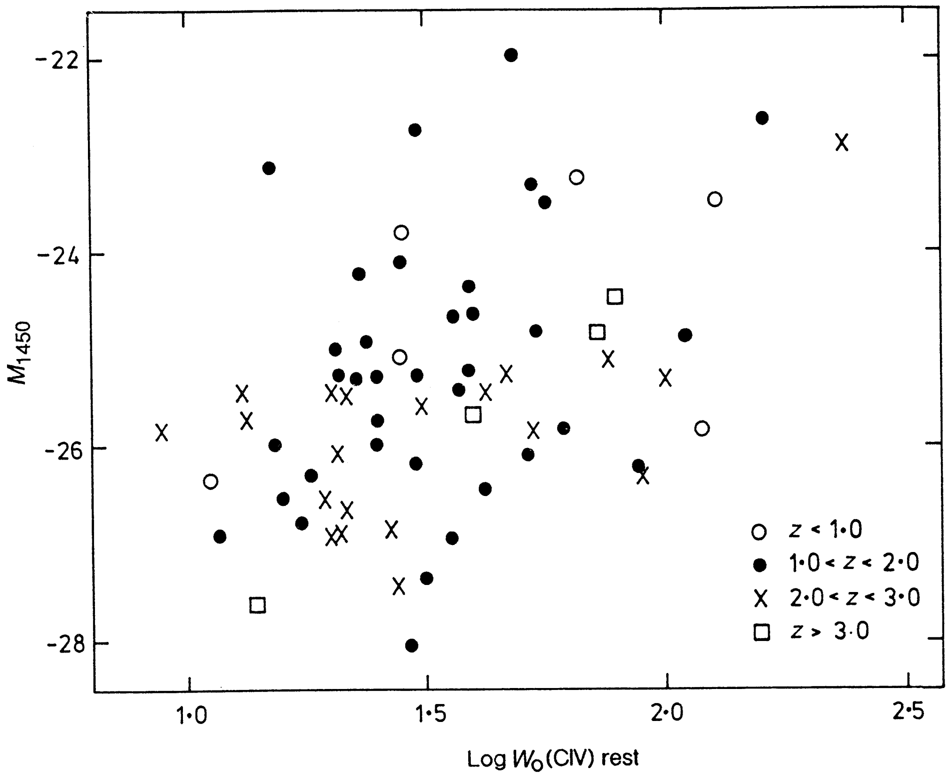

Fig. 4. The 'Baldwin effect' for quasars in our sample with measured CIV 1549 equivalent width.

broad-band colours or optical variability, by calculating continuum magnitudes at 1450 Å and replotting the data. We have used the published spectra in Wilkes *et al.* (1983) and our own unpublished spectra to estimate the continuum absolute magnitudes following the method of Wampler *et al.* (1984). The broad range in luminosities is still present and is therefore intrinsic. The scatter in our data is not a function of redshift, further confirming that the effect is not due to strong emission lines contributing to the broad-band colours, but intrinsic.

Our sample contains 10 quasars with $z > 3 \cdot 0$. We find a large range in optical magnitude, which is indicative of a broad spread in optical luminosity, consistent with the results of Anderson and Margon (1987). They found that 25% of the then-known quasars with $z > 3 \cdot 4$ fall beyond a line representing the then postulated evolution of maximum redshift with luminosity. In our sample 50% fall beyond the line. Our data increase the breadth and scatter in the diagram and are further evidence that low-luminosity quasars at high redshift are not rare.

Following Wampler *et al.* (1984), we have plotted in Fig. 4 the 'Baldwin effect' relation (Baldwin 1977) in order to compare objects in common and to use their data for the low redshift quasars. Yet again our complete sample increases the scatter and broadens the luminosity range; however, the correlation found by Wampler *et al.* (1984) is still apparent.

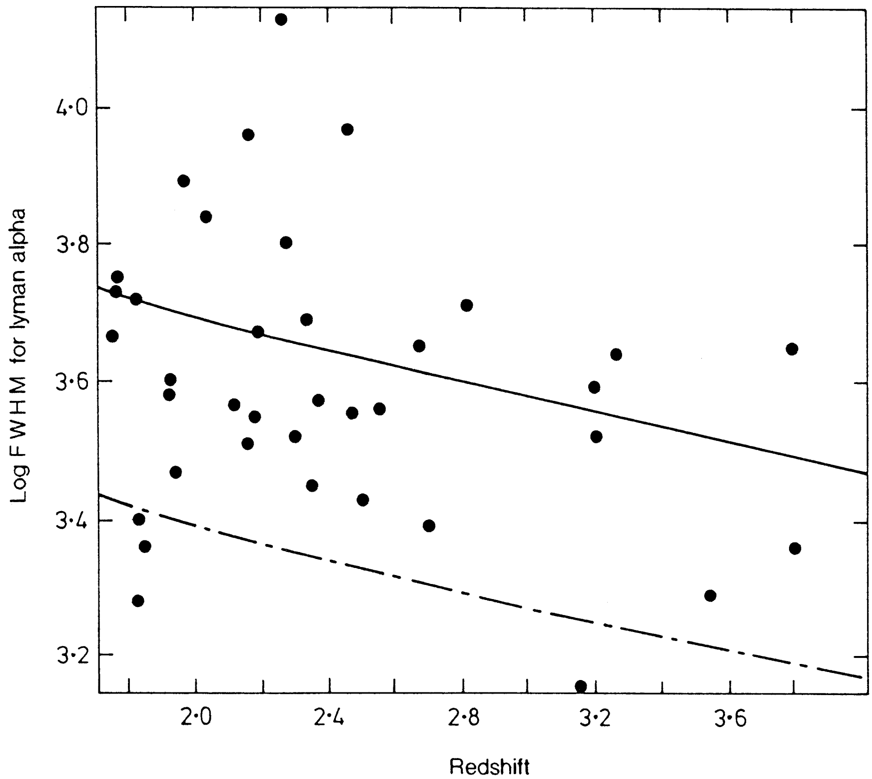

Fig. 5. FWHM of Lyα as a function of redshift for quasars in the sample with $z > 1 \cdot 7$. PKS 0528–250 has no Lyα emission for $z = 2 \cdot 76$, FWHM = 0. Note that an observed equivalent width of 50 Å corresponds to a rest-frame equivalent width of 12 Å of $z = 3$.

(d) Emission-line Widths

Fig. 5 presents a plot of rest-frame width (FWHM, km s^{-1}) of Lyα as a function of redshift for all the quasars in our sample with $z > 1 \cdot 7$. We can compare this figure with Fig. 4 of MacAlpine and Feldman (1982), which is for optically selected quasars. Of our quasars 56% have FWHM $< 3 \cdot 6$ (log scale) whilst only 42% of their objects fall in this range. Their lowest velocity width is $3 \cdot 4$ whilst seven (20%) of our quasars fall below this value. There is a tendency for the radio-selected quasars to have a narrower FWHM. Thus optical prism searches are biased towards stronger-lined quasars than radio surveys. Fig. 4 of MacAlpine and Feldman is consistent with a limiting observed FWHM of 60 Å whilst our radio-selected quasars are consistent with a limiting observed FWHM of $\sim< 30$ Å over all redshifts.

We have combined the rest-frame equivalent widths for Lyα from Wilkes (1986) and from data by this group to date (White *et al.* 1988). Wilkes used partially the same data base but re-reduced and remeasured all these data in order that her own measurements would be self-consistent. The Wilkes measures are generally higher than ours, presumably caused by setting the continuum at different levels. The value found by Wilkes is 65±34 Å. Our mean value of Lyα equivalent width from 38 quasars is 54±37 Å. The value adopted by Schmidt *et al.* (1986) of 75 ± 7 Å determined mainly from measures on optically selected quasars is higher than ours. Our distribution is significantly broader and our lines narrower than for the optical samples, again suggestive that optical surveys are missing weak, narrow-lined quasars.

(e) Optical Colours

Many colour–colour plots for all stellar objects in a variety of Schmidt fields have been made using different combinations of colours but usually only in one plot do quasars at a particular redshift stand clear of the main sequence. Our radio quasars are not selected by colour–colour techniques, and so a radio-selected sample is extremely useful to delineate those regions in the redshift/colour–colour space where multicolour searches may be incomplete.

8. Discussion

(1) These sources are drawn from a complete radio-selected sample which covers a large area of sky and thus avoids small-area effects.

(2) Even this radio-selected sample is not free from observational selection effects.

(3) Radio samples provide a method of detecting BL Lac and bright high-redshift quasars in significant numbers. These latter objects are very useful as probes of the early universe.

(4) Accurate radio positions have been measured for all objects, allowing reliable optical identifications to the $22\cdot5$ mag limit of the UKST IIIa-J survey without any reliance on colour or morphology. The discovery of PKS 2000–330 ($z = 3\cdot78$) in 1981 (Peterson *et al.* 1982) was instrumental in revealing the existence of such high-redshift objects and demonstrated the properties by which they are now found.

(5) We have optical spectral data on a large fraction of the quasar identifications. The redshift distribution shows no strong evidence for a redshift cutoff. Our Hubble diagram shows a large scatter in luminosity. We find equal numbers of low-optical-luminosity and high-optical-luminosity quasars at high redshift, at variance with some optical searches. The radio spectra of our high-redshift quasars are not typical of quasars at later epochs (now).

(6) Our sample contains more objects with narrow Lyα equivalent widths than are found in optically selected samples. The mean rest-frame equivalent width is narrower than that found for optical searches and has a very broad distribution. There is some evidence that the optical luminosity of these quasars also peaks at $z = 2$. Additionally, these quasars have a strong ultraviolet excess. Historically, a combination of these properties enhanced the number of quasars with $z = 2$ found in optical searches, and distorted the broadband number–magnitude counts. Additionally, it would produce spurious predictions for high-redshift quasar numbers in the extrapolations of evolutionary models from lower-redshift quasar data. A combination of the above factors would then serve to produce strong evidence for a steep-redshift cutoff in optically selected samples of quasars. Thus complete radio samples such as this also serve as an extremely useful tool in revealing incompleteness and bias in optical surveys.

Acknowledgments

This work was supported in part by the National Aeronautics and Space Administration under a grant to the Jet Propulsion Laboratory, California Institute of Technology. We thank the Anglo-Australian Observatory for the use of many of its facilities. GLW acknowledges the receipt of an Australian National Research Fellowship. Ann Savage would like to thank John Peacock for running these data through his banded V_e/V_a programme.

References

Anderson, S. F., and Margon, B. (1987). *Nature* **327**, 125.
Baldwin, J. A. (1977). *Astrophys. J.* **214**, 679.
Bolton, J. G., Savage, A., and Wright, A. E. (1979). *Aust. J. Phys. Astrophys. Suppl.* No. 46.
Boyle, B. J., Shanks, T., and Peterson, B. A. (1988). *Ast. Soc. Pac. Conf. Series* **2**, 1.
Condon, J. J., Hicks, P. D., and Jauncey, D. L. (1977). *Astron. J.* **82**, 692.
Condon, J. J., Jauncey, D. L., and Wright, A. E. (1978). *Astron. J.* **83**, 1036.
Crampton, D., Cowley, A. P., and Hartwick, F. D. A. (1988). *Ast. Soc. Pac. Conf. Ser.* **2**, 254.
Downes, A. J. B., Peacock, J. A., Savage, A., and Carrie, D. R. (1986). *Mon. Not. R. Astron. Soc.* **218**, 31.
Hazard, C., and McMahon, R. (1985). *Nature* **314**, 238.
Jauncey, D. L., Batty, M. J., Gulkis, S., and Savage, A. (1982). *Astron. J.* **87**, 763.
Jauncey, D. L., White, G. L., Savage, A., Peterson, B. A., Gulkis, S., and Batty, M. J. (1987). STScT QSO Absorption lines: Probing the Universe, p. 31.
MacAlpine, G. M., and Feldman, F. R. (1982). *Astrophys. J.* **261**, 412.
McEwan, N. J., Browne, I. W. A., and Crowther, J. H. (1975). *Mem. R. Astron. Soc.* **80**, 1.
Peacock, J. A. (1988*a*). *Mon. Not. R. Astron. Soc.* **217**, 601.
Peacock, J. A. (1988*b*). *Ast. Soc. Pac. Conf. Series* **2**, 203.
Peacock, J. A., and Miller, L. (1988). *Ast. Soc. Pac. Conf. Series* **2**, 194.
Peacock, J. A., Miller, L., and Longair, M. S. (1986). *Mon. Not. R. Astron. Soc.* **218**, 265.
Peterson, B. A. (1988). *Ast. Soc. Pac. Conf. Series* **2**, 23.
Peterson, B. A., Savage, A., Jauncey, D. L., and Wright, A. E. (1982). *Astrophys. J.* **260**, L27.
Savage, A., and Peterson, B. A. (1983). Proc. IAU Symp. No. 104 (Eds J. O. Abell and G. Chincarini), p. 57 (Reidel: Dordrecht).
Schmidt, M., Schneider, D. P., and Gunn, J. E. (1986). *Astrophys. J.* **306**, 411.
Stocke, J. T., Morris, S. L., Gioiia, I. M., Maccacaro, T., Schild, R. E., and Wolter, A. (1988). *Ast. Soc. Pac. Conf. Series* **2**, 311.
Wall, J. V., and Peacock, J. A. (1985). *Mon. Not. R. Astron. Soc.* **216**, 173.
Wampler, E. J., Gaskell, C. M., Burke, W. L., and Baldwin, J. A. (1984). *Astrophys. J.* **276**, 403.
White, G. L., Jauncey, D. L., Savage, A., Wright, A. E., Batty, M. J., Peterson, B. A., and Gulkis, A. (1988). *Astrophys. J.* **327**, 561.
Wilkes, B. J. (1986). *Mon. Not. R. Astron. Soc.* **218**, 331.
Wilkes, B. J., Wright, A. E., Jauncey, D. L., and Peterson, B. A. (1983). *Proc. Astr. Soc. Aust.* **5**, 2.

Manuscript received 3 October 1989, accepted 15 February 1990