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The Cosmic Evolution of Quasars

Carole Jackson

CSIRO Australia Telescope National Facility, PO Box 76, Epping, NSW 1710, Australia

Jasper Wall

Department of Physics & Astronomy, University of British Columbia, Vancouver, BC V6T 1Z1, Canada

Peter Shaver

European Southern Observatory, Karl-Schwarzschild-Str. 2, 85748 Garching bei München, Germany

Ken Kellermann

National Radio Astronomy Observatory, Edgemont Road, Charlottesville, VA 22903-2475, USA

Isobel Hook

Department of Physics, University of Oxford, Denys Wilkinson Building, Keble Road, Oxford OX1 3RH, UK

Abstract. The form of the quasar luminosity function and its redshift dependence to z∼1 has long been established; powerful evolution is required so that by z=1 there is an increase of order 10^2 - 10^3 in the space density of the most luminous sources. However it is more difficult to deduce the form of the LF at high redshifts. In this contribution we discuss how a sample of relatively bright radio sources has been used to determine the high-redshift behavior of the radio-loud quasar luminosity function, and the particular advantages of using a radio-selected sample. Our results illustrate how radio-loud quasar samples can be an efficient probe of the high-redshift Universe.

1. Introduction

Historically, the study of the quasar luminosity function (LF) and its evolution over cosmic time has centered on large spectroscopic samples of optically-selected bright stellar objects from photographic plates. Since the ultraviolet-excess samples of the 1980s (Marshall et al. 1983, Green, Schmidt & Leibert 1986, Boyle et al. 1990) it has been known that luminous quasars have undergone strong cosmic evolution to z∼2.2. The extension of the color-selection technique to six optical band passes with the large bright quasar survey yielded confirmation, first deduced by Schmidt & Green (1983), that the optical quasar LF declines in the range z = 3.5 – 4.5 (Warren, Hewett & Osmer 1994). However this decline could be induced by intervening dust absorption, rather than representing a real decline in the space density.

More recently the 2dF Quasar survey team (2Qz: Boyle et al. 2000) obtained spectra for an optically color-selected sample of more than 23,000 quasars. This huge sample yields a clear determination of the LF and its evolution between z$\sim$ 0.35 and 2.3 (Boyle et al. 2000). However, at low redshifts ($z < 0.35$) and and at high luminosities, the quasar population is poorly sampled: low-redshift objects appear non-stellar and are rejected, whilst the high-luminosity objects have too low a space density to figure in the modest-area 2Qz survey.

The difficulty in determining the behavior of the quasar LF at redshifts between $\sim$2.3 and $\sim$4 is that quasars at these redshifts have the same colors as Galactic stars. Whilst the three-band color selection of 2Qz was highly efficient - with $\sim$50% of all targets found to be quasars - the extension of the 2Qz sample-selection technique to z $\sim$3.3 results in only 2% of the color-selected objects being quasars (Chiu et al., private communication).

To detect quasars at very high redshift, extremely red color selections can be used. From the Sloan Digital Sky Survey (SDSS, York et al. 2000, Stoughton et al. 2002), Fan et al. (2003) selected i-band drop-out objects with red z-band colors in order to find quasar candidates at $z > 5.7$. To date Fan et al. have detected 3 quasars above $z = 6.0$, all with luminosities brighter than $M_{1450} = -26.8$. Their results confirm that there is apparently a much reduced space density of quasars between $z = 5.7$ to 7 compared to that at $z = 2.2$.

2. Radio-selected quasar samples

Optically-selected quasar samples trace clearly the evolution of the LF from z$\sim$0.4 to z$\sim$2. Assuming that radio-loud and radio-quiet quasars race the same phenomenon, at either side of this redshift range the subset of *radio-loud* quasars provides an efficient probe of the LF. In particular, the radio-quasar LF spans a very wide range in luminosity – over more than six magnitudes, compared to two in the optical passband – allowing straight-forward selection of both local and distant quasar samples.

At the low-to-moderate power end of the LF large samples of radio galaxies and quasars can be extracted from optically-bright galaxy catalogues to reveal their absolute *local* space density. Condon, Cotton & Broderick (2002) determined the local radio LF for galaxies in both the Uppsala Galaxy Catalog (UGC: Nilson 1973) and the NRAO VLA Sky Survey (NVSS: Condon et al. 1998). Furthermore the 2dF Galaxy Redshift Survey (2dFGRS: Colless et al, 2001) and NVSS sample of radio galaxies and quasars have been used to map the radio LF between $0.05 < z < 0.3$ (Sadler et al. 2002). The results show the extent of the local evolution in a redshift range poorly represented in optically-selected quasar samples.

At the other end of the radio LF, high-power radio quasars provide an efficient probe of the very distant Universe. Compared to the optical passband, the radio regime is un-obscured and there are no 'color' degeneracies by which bright radio-loud quasars might overlap radio properties with other known cosmic objects. In the flux-density range 100 mJy to 10 Jy and at survey frequencies of between 1 and 5 GHz almost all radio sources are radio-loud galaxies and quasars. This means that bright radio sources can be used to trace the LF of powerful radio quasars; as long as we optically-identify *all* sources in a radio-selected sample we can avoid any optical bias which might be due to intervening obscuration.

To this end we set out to obtain a completely-identified sample of radio-selected quasars, large enough to map directly their space density behavior and to decide whether the optically-selected quasar LF turnover is real or induced by dust obscuration. To ensure that our initial sample was dominated by quasars, we use the 'flat-spectrum' criterion – compact radio-loud quasars characteristically have flat, undulating or inverted spectra at GHz frequencies (Kellermann & Pauliny-Toth 1969, 1971) due to synchrotron self-absorption. The advantage of this class of source is the relative ease of determining the arcsecond radio position of the bright quasar core, and hence the ease of making a secure optical identification of the host object.

We selected our sample from the machine-readable version of the Parkes radio source catalogue (PKSCAT90: Wright & Otrupcek 1990). The catalogue contains radio and optical data for 8264 radio sources south of +27° and was compiled from a series of surveys at 2.7 GHz performed by John Bolton and colleagues between 1969 and 1979 (Bolton, Savage & Wright 1979 and references therein). PKSCAT90 also contains data from 5 GHz flux-density measurements, compiled within a few months of the original 2.7 GHz surveys. As described in detail in Jackson et al. (2002) we selected all flat-spectrum sources from PKSCAT90 with $\alpha_{2.7GHz}^{5GHz} > -0.4$, where $S \propto \nu^{\alpha}$, yielding an initial sample of 878 sources. Imaging and spectroscopy campaigns (Jackson et al. 2002; Hook et al. 2003) yielded a final sample of identifications. We found that 677/878 sources had stellar host objects (quasars and BL Lac objects). From this resulting set of quasars we selected a complete sub-sample to map the high-redshift LF.

3. Radio quasar cosmic evolution

In calculating the high redshift LF we had to allow for the fact that 'flat spectrum' radio sources in reality have curved radio spectra. This could have a large biasing effect, particularly if many sources have radio spectra which steepen at high frequencies. In our sample, a number of quasars are only marginally flat-spectrum between 2.7 GHz and 5 GHz, i.e. $-0.4 < \alpha < -0.3$. Using cataloged data at other radio frequencies we devised a methodology to predict the number of quasars expected at large redshifts based on the number seen at lower redshifts. The procedure accounts for the individual spectra of each quasar and maximizes the number of sources available to our analysis. We named this procedure, a variant of the $V_{\max}$ method, the 'single source survey' ('*sss*', Wall et al., in preparation): each individual source is considered a 'complete survey' if it lies above the Parkes survey limit relevant to its area.

Our first *sss* analysis used only the PKS 2.7 GHz and 5 GHz survey data, and predicts 53.5 sources lying between $3 \leq z \leq 8$ if the space density found between z = 1 and 3 remained constant out to z = 8. We improved our analysis by tracing the spectral shape of each source using data from two lower-frequency surveys – Texas at 365 MHz (Douglas et al 1996) and the NVSS at 1.4 GHz (Condon et al. 1998). This modified the 'observable volume' for a number of sources up to their observed redshift. The adjustments work in both the positive and negative senses so that the overall result is only marginally amended to 54.0 sources at $3 \leq z \leq 8$. With some additional analysis based on higher-frequency radio data (Wall et al. in preparation) we concluded that our sample should have contained 40 to 50 quasars with redshifts 3 to 8, if the quasar space density between $z = 1$ and 3 remained constant to $z = 8$. In the redshift range 3 to 8 we actually found 16 quasars and we infer another 1.8 from the small (unbiased) set of candidate quasars with no spectroscopy. Given that the difference between the observed and predicted quasar number is significant at the $> 3\sigma$ level, we conclude that the space density of our radio-loud quasar sample shows a real diminution at $z > 3$. The similar high-redshift results from optically-selected samples thus are not induced by dust obscuration.

The LF results for our radio quasar sample are shown in Figures 1 and 2. The strong evolution in space density is clearly seen for the LFs of Figure 1 (left) computed in redshift bands from 0 to 2; Figure 1 (right) shows that this evolution has reached a plateau at $z = 2$, with the LFs for the ranges $2 < z < 3$ and $3 < z < 5$ lying successively lower.

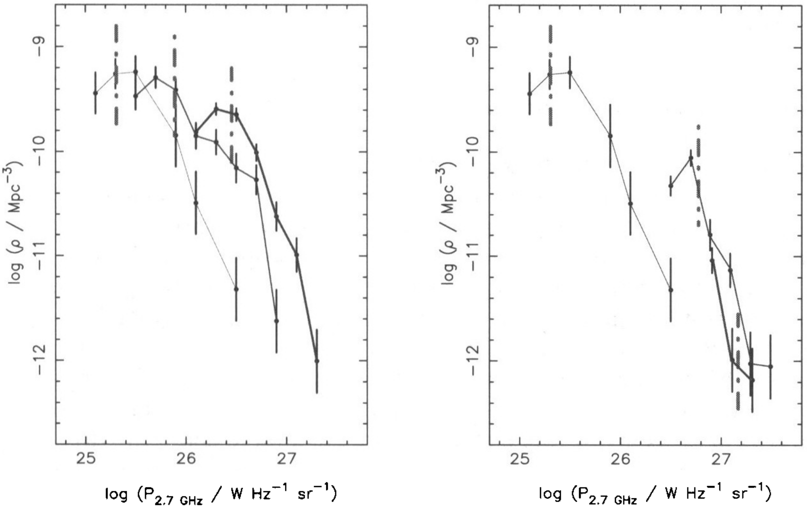

Figure 1. The radio luminosity function ($h_0 = 0.5$, $\Omega_m = 1$, $\Omega_\Lambda = 0$) for the quasars of the Parkes 0.25-Jy flat-spectrum sample, in log (number per Mpc^3 per $\Delta\log(P_{2.7\mathrm{GHz}}) = 0.2$ per $\Delta z = 0.5$). Left: computed in three redshift ranges, $0 - 0.5, 0.5 - 1.0$, and $1.0 - 2.0$; right: in redshift ranges $0 - 0.5$ (repeated from the left diagram), $2.0 - 3.0$ and $3.0 - 5.0$. Increasing line weight represents increasing redshift. Dash-dot vertical bars indicate lower limits of completeness for each redshift range, due to spectral-index spread.

The quasar LF as a function of redshift for different radio luminosities is shown in Figure 2. Numbers are small for each power range; but in general the space density is seen to decrease at redshifts greater than 2, mirroring the results from our *sss* analysis described above.

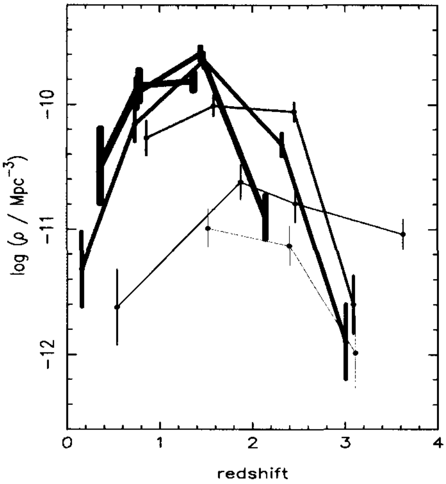

Figure 2. The space densities of Figure 1 shown as a function of redshift for 6 power ranges, $\log P_{2.7}$ = 26.0 to 26.2, 26.2 – 26.4, 26.4 – 26.6. 26.6 – 26.8, 26.8 – 27.0 and 27.0 – 27.2, distinguished by decreasing line weight. Abscissa values are at the mean redshifts in each of the 5 redshift ranges in the caption to Figure 1.

4. Future quasar LF studies

Our radio-selected sample demonstrated the utility of bright radio samples to probe the high redshift quasar LF. The selection function ensured that most objects in our initial sample were quasars whose radio positions were readily measured to arcsec accuracy. Even though the quasars are radio-bright, a 4-m class telescope was required for the optical identifications and spectra.

The greatest lesson we learnt with this sample is the necessity for contemporary flux-density measurements. At GHz frequencies, a large fraction of quasars – perhaps 30% or more – are variable. It is vital to sample the population at one state, whether it is in the 'up', 'down' or 'intermediate'; and the problem is that surveys of objects obeying a steep power-law source count are dominated by objects in the 'up' state. Our use of survey data from one epoch and flux-density measurements from later epochs means that we do not have a clean sample of radio spectra from which to trace the high redshift LF. The range of our results, e.g. the prediction of 40 to 50 quasars at $3 < z < 8$, reflects the uncertainty in taking this bias into account (Wall et al. in preparation), and highlights the dangers in using different-epoch data for any study of quasar attributes. The bias may well explain the much lower significance ascribed to a redshift cutoff from a similar sample by Jarvis and Rawlings (2000).

Current and future multi-wavelength large-survey-area campaigns covering radio to X-ray pass bands (SWIRE, CDFs, ELIAS-S1, etc.) promise that much will be learnt about the quasar LF. Radio surveys and radio-selected quasar samples have a major role to play in these projects. In the course of these, to obtain single-epoch radio spectra we propose to exploit the wide field of view and multi-frequency agility of modern interferometers such as the Australia Telescope Compact Array.

The refined definition of the quasar LF will lay a foundation for understanding the physical nature of the evolution of these objects as well as the relation between radio-loud and radio-quiet quasars. More detailed knowledge of the internal quasar mechanism would provide important insights into the feedback loop with the IGM, particularly for studying the re-ionization epoch. Before this, we have to determine how best to recognize these rare objects at such epochs.

References

Bolton, J.G., Savage, A., Wright, A.E., 1979, AuJPA, 46, 1B

Boyle, B.J., Fong, R., Shanks, T., Peterson, B.A., 1990, MNRAS, 243, 1

Boyle, B.J. et al., 2000, MNRAS, 317, 1014

Colless, M.M. et al., 2002, MNRAS, 328, 1039

Condon, J.J., Cotton, W.D., Greisen, E.W., Yin, Q.F., Perley, R.A., Taylor, G.B, Broderick, J.J., 1998, AJ, 115, 1693

Condon, J.J., Cotton, W.D., Broderick, J.J., 2002, AJ, 124, 675

Douglas, J.N., Bash, F.N., Bozyan, F.A., Torrence, G.W., Wolfe, C., 1996, AJ, 111, 1945

Fan, X., et al., 2003, AJ, 125, 1649

Green, R.F., Schmidt, M., Leibert, J., 1986, ApJS, 61, 305

Hook, I.M., Shaver, P. A., Jackson, C.A., Wall, J.V., Kellermann, K.I., 2003, A&A, 399, 469

Jarvis, M.J. and Rawlings, S., 2000, MNRAS, 319, 121

Jackson, C. A., Wall, J. V., Shaver, P. A., Kellerman, K. I., Hook, I. M., and Hawkins, M. R. S., 2002, A&A, 386, 97

Kellermann, K.I., Pauliny-Toth, I.K.K., 1969, ApJ, 155, L71

Kellermann, K.I., Pauliny-Toth, I.K.K., 1971, ApJL, 8, 153

Marshall, H.L., Tananbaum, H., Avni, Y., Zamorani, G., 1983, ApJ, 269, 35

Nilson, P., 1973, Uppsala General Catalog of Galaxies (Uppsala: Uppsala Astron. Obs) (UGC)

Sadler, E.M. et al., 2002, MNRAS, 329, 2276

Schmidt, M., Green, R.F., 1983, ApJ, 269, 352

Stoughton, C. et al. 2002, AJ, 123, 485

Warren, S.J., Hewett, P.C., Osmer, P.S., 1994, ApJ, 421, 412

Wright, A.E., Otrupcek, R.E., 1990, Parkes Catalogue Australia Telescope National Facility, CSIRO

York, D. G. et al. 2000, AJ, 120, 1579