THE STATISTICS OF RADIO GALAXIES & QUASARS AT HIGH REDSHIFT

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ABSTRACT. Evidence is now accumulating that the most powerful extragalactic radio sources display a cutoff in comoving density at relatively low redshift. For both radio galaxies and quasars, the luminosity function falls by a factor $\gtrsim 3$ between $z = 2$ and 4. We describe the data which lead to this conclusion, and discuss the prospects for studying the behaviour of low-luminosity active galaxies at high redshift. The strong evolution of highly luminous radio-quiet quasars at $z > 2$ may be an artifact of gravitational lensing.

1. EVOLUTION OF POWERFUL RADIO SOURCES

This paper is concerned with recent studies of the population evolution of extragalactic radio sources. We are now approaching a point where the empirical change of the Radio Luminosity Function with epoch is known: this will provide a firm constraint on physical mechanisms for the evolution. A good review of this field is given by Wall (1983); at that time the most recent study of RLF evolution was that by Peacock & Gull (1981). Since then papers by Condon (1984) and Peacock (1985) have appeared. All these workers use model fitting to derive their conclusions: there is no other way of combining partial data such as source counts with complete redshift data from bright samples. The problem with this approach is the non-uniqueness of the resulting model RLF. Condon (1984) gives only one model: from this, it is impossible to know whether any given feature is required by the data or whether it is an artifact of the model formulation. In contrast, Peacock (1985) considers an ensemble of 5 different consistent RLFs to estimate the uncertainty allowed by the data. Where these differ, we may be sure the data are inadequate. Where they agree, this may be fortuitous, but is more likely to be a hint that some feature is required by the data: we can then construct a specific test to see if this is the case.

Both Condon (1984) and Peacock (1985) confirm the main conclusions of Peacock & Gull (1981): the change with epoch of the RLF is differential in radio power, being greatest at high power. Also, both steep- and flat-spectrum sources behave similarly. Peacock & Gull,

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however, were unable to draw any conclusions about behaviour at high redshifts, z > 2: new data have improved this situation in Peacock's (1985) study. Figure 1 shows cuts through the RLF for two different values of q_0. The pairs of lines shown are the limits on ρ (in units of density per unit $\log_{10}(P)$, H_0 = 50 km s^{-1} Mpc^{-1}).

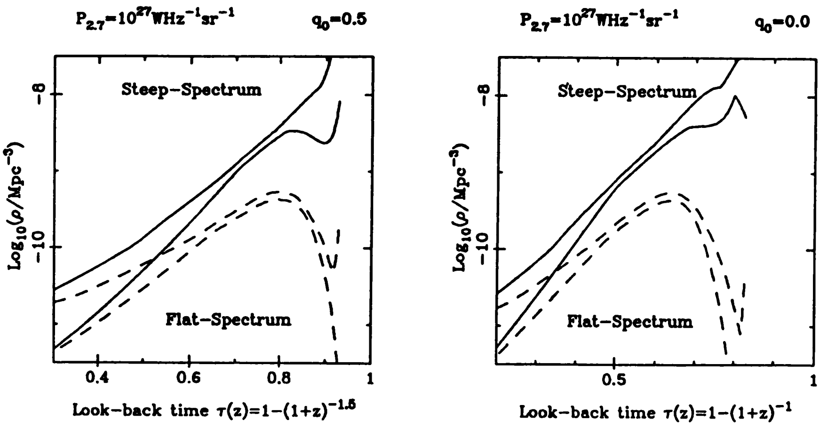

Fig. 1

Beyond z ≃ 2, all models agree that the flat-spectrum RLF falls, independent of q_0; conversely, the steep-spectrum RLF is still uncertain at these redshifts. This difference may be understood when we consider the redshift data used by Peacock (1985). Figure 2 shows a plot of radio power against flux density at 2.7 GHz (Ω_0 = 1 assumed). The vertical lines distinguish different flux-density limits; the steep-spectrum data go no lower than 1.5 Jy, whereas complete flat-spectrum samples exist down to 0.5 Jy. In this context, the term 'complete' means $\gtrsim$ 95 percent of the sources are identified and $\gtrsim$ 70 percent have spectroscopy. The missing redshifts can generally be estimated reliably from apparent magnitude.

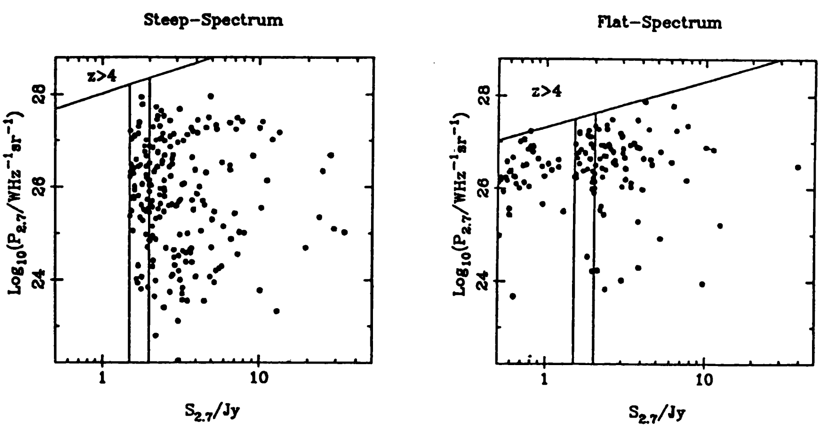

Fig. 2

Figure 2 makes clear the extra strength of the flat-spectrum data: objects of a given luminosity at z ≃ 1 can be compared with their counterparts at z > 4. As none are seen, we deduce a limit on the density at high redshift. This can be quantified through the V_e/V_a test

(Avni & Bahcall 1980). Considering $z > 1.9$ only, the combined flat-spectrum data yield $\langle V_e/V_a \rangle = 0.315$ ($\Omega_o = 1$) or 0.352 ($\Omega_o = 0$). With 24 sources in this range, these results lie respectively 3.1σ and 2.5σ below the expectation of 0.5 for a constant comoving density.

2. THE PARKES SELECTED REGIONS

To test the above conclusions and investigate whether powerful steep-spectrum sources also display a redshift cut-off we need redshift data on a deeper sample. This has been tackled by a collaboration at Edinburgh and Cambridge. The Parkes Selected Region surveys provide 178 sources (allowing for confusion) complete to 100 mJy at 2.7 GHz. VLA maps and sky-survey identifications are reported by Downes et al. (1985): even using UKST material reaching $J > 22$, only 56 percent of the objects were identified, with only 22 percent having redshifts in the literature. This is much as expected from previous RLF models: samples such as this were expected to be biased to high redshifts.

During 1985, we have greatly improved the data base. We have CCD data on all fields in two colours, reaching $B \simeq 25$ and $R \simeq 24$; at this level, $\gtrsim 96$ percent of the sample is identified (3 sources are affected by bright stars). We have also added 31 new redshifts. The remaining sources are almost all galaxies, for which photometric redshift estimation should be possible. The most spectacular result of the spectroscopy programme was the spectrum of 1351-018 (Dunlop et al. 1985). This flat-spectrum quasar has a redshift of 3.71 - the highest in any of the complete samples considered here.

With this exception, however, the highest redshift quasar in the Selected Regions is at $z = 2.8$ - which fits in with our previous idea of a fall in density for $z > 2$. We can test this by performing the V_e/V_a test again. (Now considering quasars only). There are a total of 163 quasar candidates in the complete samples used by Peacock (1985) plus the Selected Regions (60 steep- and 103 flat-spectrum). Figure 3 shows the analogous plot to Figure 2 for these objects.

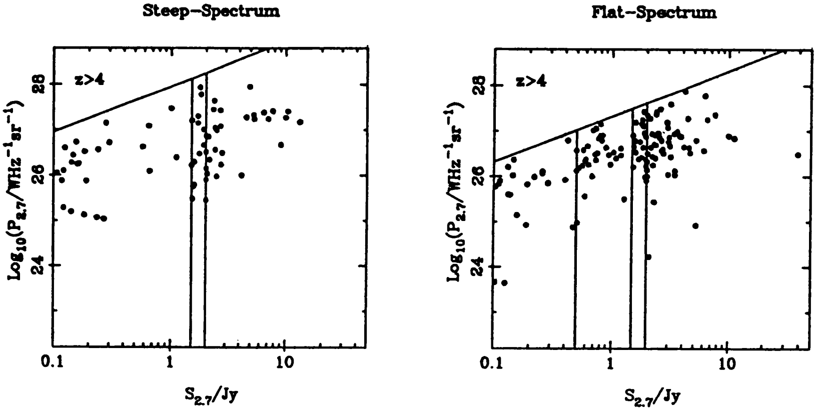

Fig. 3

The results of the V_e/V_a test are given in Table 1.

Table 1: $\langle V_e/V_a \rangle$ values

	Flat-Spectrum			Steep-Spectrum		
	n	Ω_o=1	Ω_o=0	n	Ω_o=1	Ω_o=0
$z > 1.8$	30	0.391	0.431	12	0.501	0.543
$z > 1.9$	27	0.362	0.395	12	0.442	0.459
$z > 2.0$	22	0.351	0.399	10	0.448	0.465

The statistics for the steep-spectrum case are poorer, but the overall trend is similar. However, we do not yet have conclusive evidence for a cutoff for steep-spectrum quasars alone (particularly considering that ~ 15 percent of our candidates still have unknown redshifts, which may affect the result). Also, the V_e/V_a test is imperfectly efficient, as it rejects all low-redshift data; a fuller analysis is needed.

We are now left with important question of whether similar behaviour applies for the radio galaxies. We have seen that essentially all objects are detected; according to the study of 3CR galaxies by Djorgovski & Spinrad (1985) this should not be a surprise. They found a convergence of apparent magnitude at $z \simeq 1$, largely attributable to stellar evolution, so that no galaxy was fainter than B = 24 or R = 23. Better constraints will come from infrared observations (cf Lilly et al. 1985); we have so far obtained K photometry for > 50 percent of the sample, and found no objects fainter than K = 19. As discussed by Lilly et al. (1985), this probably corresponds to $z < 3$. In fact, Peacock (1985) showed that the steep-spectrum RLFs in Figure 1 without a turndown predicted ~ 20 percent of selected-region sources to have $z >$ 3. If they do not, we will have evidence for a cutoff for powerful radio galaxies.

Following the refinement of the above conclusions, the next step must be to compare with the behaviour of low-luminosity sources. This will be possible given complete optical data for the 5C12 survey (Benn et al. 1984), ~ 50 times deeper than here, and the Leiden-Berkely Deep Survey (Windhorst 1984), ~ 300 times deeper. At present, however, > 50 percent of these objects are unidentified so firm conclusions are not possible. Windhorst (1984) claims to show that the RLF for $P_{2.7} \sim 10^{24}$ $\mathrm{WHz^{-1}\ sr^{-1}}$ falls beyond $z \simeq 1$, which would be important if true. However, this is only achieved via an extreme extrapolation of low-redshift evolution; the crucial range $z \simeq 1$ has not yet been probed directly.

3. COMPARISON WITH OPTICAL STUDIES

The behaviour of powerful radio quasars provides an interesting contrast with optically selected quasars. There are results in the literature on the high-redshift behaviour of the optical LF at high and low optical luminosities. At the high end, Osmer & Smith (1980) presented a V/V_{max}

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test over the redshift range 1.9 - 3.25 for 14 luminous objective-prism quasars with $M_B > -28.5$ (Ω_o=0). Their (corrected) result was 0.651 (Ω_o=1) or 0.595 (Ω_o=0) - indicating an increasing LF over this redshift range, Conversely, using faint quasars selected by non-stellar colours, Koo (1985) argues that, for $M_B > -26$ (q_o=0), the LF at $z > 2$ is either constant (q_o=0.5) or decreasing (q_o=0). There are several interesting points to make about this differential behaviour:

First, the behaviour of optically weak quasars is similar to that suggested above for radio-loud quasars (the match is better for low Ω_o). Given that radio-loud quasars generally have $M_B > -27$, radio and optical studies 'agree' on the redshift cutoff, with high-luminosity quasars being a special case. However, note that there is no reason why the behaviour of LFs in different wavebands should agree.

Second, the behaviour at low optical powers may be affected by incompleteness. Dunlop et al. (1985) show that objects with weak lines like 1351-018 will tend to have stellar UJF colours at $z \gtrsim 2.5$, and so be missed. We must await confirmation of Koo's result from CCD grism surveys sensitive to Lyα equivalent widths $W < 100$Å.

Finally, the most luminous optical quasars may be affected by gravitational lensing. Lensing by galaxies is insufficient to cause important perturbations to the LF (Peacock 1982), but for optically-selected quasars minilenses with $M \ll M_\odot$ can be important (e.g. Vietri 1985). We report here some calculations by Peacock (in preparation) which modify those of Vietri by consistent inclusion of flux conservation. As an illustration, we show in Figure 4 a Schechter-type LF and the results of mini-lensing at z = 1.9 and 3.25 for Ω_o = 0.1 (all in minilenses). The Schechter parameters were chosen to agree with Koo's results at the lower redshift.

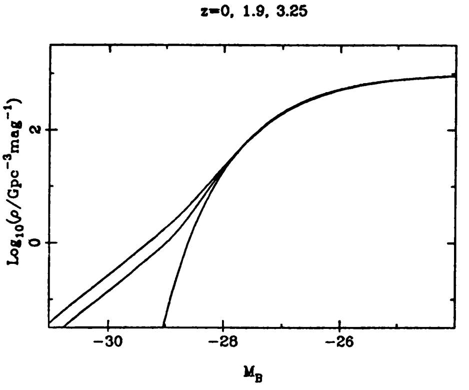

Fig. 4

At Osmer-Smith luminosities, the change in the LF is a factor 2 over this range. We can convert this to $\langle V/V_{max} \rangle$ by the approximate relation

$$\langle V/V_{max} \rangle \doteq 0.5 + \frac{\Delta \ln \rho}{12}$$

the effect is large enough to make quasars of all luminosities consistent.

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4. CONCLUSIONS

We end with a few points about interpretation of these results. The evolution of LFs is governed by a conservation equation:

$$\dot{\rho} + \frac{\partial}{\partial P} (\dot{P}\rho) = Q$$

Physically, what we would like to know are the terms $\dot{P}$ (invididual light curves) and Q (rate of creation). It has been conventional to relate a lack of quasars at high redshift to quasar (or galaxy) formation - i.e. low Q at high z - but it is equally possible that $\dot{P}$ is high - i.e. objects go through their life cycles faster at high z. Similarly, there is a tendency to invest some significance in 'Luminosity Evolution' models with $\rho(P,z) = \rho(P/F(z))$. However, such a form need not satisfy the conservation equation with Q = 0. Indeed, unless the individual source lifetimes are ~ the Hubble time (which is certainly not the case for radio sources) Q must be non-zero. Similar comments apply to the model of Condon (1984): he fits $\rho(P,z) = g(z)\rho(P/F(z))$ so that sources of all luminosities 'evolve' the same way. Nevertheless, this says nothing about the luminosity dependences of $\dot{P}$ and Q.

Although a start to physical LF modelling has been made (Cavaliere et al. 1983), perhaps the best way of interpreting the redshift cutoff is the direct one: if the radio galaxies at $z \simeq 2$ are truly young, we should be able to tell by observations of their colours and dynamics. This will be an exciting challenge for some years to come.

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DISCUSSION

Kapahi : When the luminosity function is expressed as a polynomial it may be dangerous to extrapolate it outside the range of parameters of the data that went into fitting the polynomial. I wonder if the cutoff in z implied by your models results merely from the fact that the input data contains few large redshifts.

Peacock : I completely agree. Using one polynomial would be meaningless. When you try 5 different ones and get the same behaviour, however, this may be the data telling you something. In any case, I have only used the models as a hint of what aspects to examine in a model - independent way.

Barthel : Basically we differ in approach. You study the high z behaviour statistically, I am trying to 'see' what is (or better : was) going on. You are right that selection effects have an influence on my conclusions, but it remains to be seen to what extent. I am convinced that the truth lies in between our two results. Meanwhile, until further notice I still offer a beer for every new QSR having $\alpha^{3}_{1.4}$ or $\alpha^{5}_{.408}$ steeper than 0.6 at z exceeding 2.5.

Peacock : My point is that steep-spectrum quasars at high redshift are going to be rare anyway through selection effects. Therefore, I believe it is hard to be sure that your potentially very important physical effect is operating. We need larger samples to see if you keep your beer.

Shanks : In the radio samples where you have applied the V/V_{max} tests, what is the redshift completeness ?

Peacock : About 80 percent. There is then a worry if the remaining ones are at redshifts high enough to remove the result. We have looked into this and find that most of them would need to have $z \gtrsim 3$. Since the objects are generally neither faint nor red, I think this is very unlikely.

Swarup : Could you comment on your results for redshift cutoff of steep spectrum quasars vis-a-vis those deduced by Windhorst for steep spectrum radio galaxies based on deep surveys at 1.4 GHz.

Peacock : Windhorst claims in his thesis to show that low power radio galaxies cutoff at $z \simeq 1$. This is clearly important if true, but I do not think it is firm yet. His argument is that extrapolation of evolution from $z < 0.6$ to > 1 exceeds the number counts. However, he only does one rather extreme extrapolation. I think we need to wait until some redshifts around 1 are measured.

Baldwin : The discrepancy does not, I believe, exist. Windhorst's cutoff referred to radio galaxies of <u>much</u> fainter radio luminosity (by a factor of 10^2-10^3). His cutoff for high power sources is also at $z \gtrsim 2$.

Peacock : I agree there is no contradiction. However, if you think the cutoff is related to galaxy formation, you might expect it to be independent of radio power.

Owen : The redshift estimates by Windhorst are also based on infrared colors as well as direct redshifts.

Peacock : These must be new data. I was talking about the arguments that have been written up.

Roberts : Burke, Turner, Gott, and I observed a sample of the most-optically-luminous radio quasars with the VLA at 0.5 resolution in a search for multiple images which could show that some apparently-luminous QSOs were the result of gravitational lens amplification. No multiple images were found.

Peacock : This interesting observation does not affect my point for two reasons. First, you have looked at radio-selected quasars : the radio luminosity function is less steep than the optical and the selection effects are reduced. Second, the optical depth for lensing by galaxies is known to be small : I was considering a low-mass component of the dark matter which will lens up the optical continuum source only, producing unobservably small splittings.

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