Radio-quiet objects in the 2QZ survey

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ABSTRACT

Co-addition of blank-field FIRST data at the location of over 8000 QSOs in the 2QZ survey has yielded statistical detections of radio quiet QSOs with median flux levels of 20–40\mu Jy. We show that the total radio flux of radio-quiet QSOs in the 2QZ is consistent with a smooth extrapolation of the 2QZ radio-loud QSO number-flux distribution based on the slope of the relation flattening near the FIRST flux limit. However, we are unable to distinguish a smooth extrapolation of the luminosity function to faint levels from a bimodal luminosity function with a break close to or below the FIRST radio detection limit. We also demonstrate that the redshift dependence of the median radio-to-optical spectral index $\alpha_{\text{RO}}$ for these radio quiet QSOs is consistent with that obtained for individual radio-loud 2QZ QSOs detected by FIRST.

Key words: active – quasars: general

1 BACKGROUND

The debate over whether the observed properties of radio-loud and radio-quiet QSOs are consistent with a single population of objects, albeit with a broad range in radio properties, or two distinct populations is more than thirty years old (see e.g. Schmidt 1970). Evidence for bi-modality in the radio properties of QSOs claimed by a number of authors (see e.g. Kellerman et al. 1989, Miller, Peacock & Mead 1990) has been challenged more recently using data obtained from the deeper, more extensive radio and optically-selected catalogues (White et al. 2000, Hewett, Foltz & Chaffee 2001) that are increasingly becoming available. However, recent claims for bi-modality have also been made based on QSO samples drawn from the extensive Sloan Digital Sky Survey (Ivesic et al. 2002, although see Ivesic et al. 2004 for a reassessment of this result) In contrast, a statistical analysis of the 2dF QSO redshift survey (2QZ, see Croom et al. 2004) and LBQS optically-selected survey and FIRST radio surveys has yielded no evidence for any gap in the distribution between radio-loud and radio-quiet populations (Cirasuolo et al. 2003).

Due to the intrinsically low radio flux of radio-quiet QSOs $< 100\mu$Jy, most previous analyses have been based on statistical arguments applied to upper flux limits inferred from non-detections, as opposed to detection, of radio quiet QSOs. In this paper, we adopt a different approach by directly trying to obtain a detection for an ‘ensemble’ average of radio-quiet QSOs in the 2dF QSO survey by stacking radio data from the FIRST survey. The combination of the 2QZ sample size ($\sim 10000$ QSOs in the area of overlap with FIRST) and the moderate depth of the FIRST survey (0.15mJy rms) suggest it should be possible to achieve reliable detections (> 5\sigma) for a number of 1000-2000 QSO ensembles at a level of a few tens of \mu Jy. Indeed, this method has already been successfully pioneered on the Sloan QSO sample by Glickman et al. (2004).

We describe the data and method used in Section 2 and present our analysis of the radio-quiet QSO flux distribution derived directly from the coadded images in Section 3. ‘Standard’ cosmological parameters: $\Omega_m = 0.3$, $\Omega_{\Lambda} = 0.7$ and $H_0 = 70\, \text{km\,s}^{-1}\,\text{Mpc}^{-1}$ are used throughout this paper.

2 METHOD

We used the 2QZ to obtain accurate (0.2-0.3 arcsec) positions for 8741 optically-selected QSOs within the 75-degree x 5-degree wide 2QZ equatorial strip ($9^h40^m < \text{RA} < 14^h40$) that overlaps with the FIRST survey (White et al. 2001). To ensure maximum data integrity, we used only QSOs with ID and redshift quality 1 in the 2QZ, and restricted our analysis to QSOs in the redshift range $z < 2.3$ where the survey completeness is over 50 per cent (Croom et al. 2004). We did not exclude the lowest redshift QSOs ($z < 0.25$) from the analysis where the completeness is also less than 50 per cent. However these objects only comprise 3 per cent of the QSOs in the lowest redshift bin under study.
Table 1. Radio properties of composite QSOs

| $z$ range | $z_{\text{med}}$ | $N_{\text{QSO}}$ | $f(1.4\,\text{GHz})_{\text{med}}$ (µJy) | rms (µJy) |
|-----------|-----------------|-----------------|---------------------------------|------------|
| $0.12 \leq z < 0.85$ | 0.65 | 1666 | 41.8 | 8 |
| $0.85 \leq z < 1.23$ | 1.01 | 1665 | 29.8 | 7 |
| $1.23 \leq z < 1.55$ | 1.39 | 1666 | 23.2 | 6 |
| $1.55 \leq z < 1.89$ | 1.72 | 1666 | 28.6 | 6 |
| $1.89 \leq z < 2.30$ | 2.05 | 1646 | 31.3 | 5 |

Figure 1. Images from co-added redshift bins. Increasing redshift bins run from left to right and top to bottom. The image in the lower right part of the figure is the sum of all redshift bins.

Figure 2. Stacked images from both white dwarfs (left) and galactic subdwarfs (right), from FIRST cutouts at positions from 2QZ.

3 ANALYSIS

3.1 Number counts

We first calculated the observed radio number-flux relation, $n(s)$, for both the radio-loud and radio-quiet QSOs in the 2QZ to determine whether there is evidence for any bi-modality or discontinuity in the flux distribution which might be indicative of a two-population model. We used the catalogued FIRST 20 cm fluxes for the individual radio-loud 2QZ QSOs. The resultant $n(s)$ is shown in Fig. 3.

We wish to test whether the observed total flux in the stacked images is inconsistent with a smooth extrapolation of the observed radio-loud $n(s)$. We know that the total flux of the radio-quiet population can not exceed the total flux, $f(1.4\,\text{GHz})_{\text{tot}}$, obtained by summing the median fluxes detected in each of stacked images over all redshift bins, scaled by the number of QSOs in each stack i.e. $f(1.4\,\text{GHz})_{\text{tot}} = \sum_{i=1}^{n} N_{\text{QSO}}(i) \times f(1.4\,\text{GHz})_{\text{med}}(i)$.

On the basis that the radio $n(s)$ may be extended below the FIRST completeness limit, we can obtain a prediction for the total QSO radio flux based on a smooth extrapolation of a fit to the radio $n(s)$ above the FIRST completeness limit. We adopt a completeness limit of 5σ (7.5 mJy) for the FIRST survey, and fit the the $n(s)$ between the 7.5 mJy in each co-added QSO image, but no source detection was made in either the galactic subdwarf or white dwarf control stacks. Images were modelled as point sources, and a gaussian fit was used with a 4-pixel (7.2-arcsec) diameter aperture. This aperture is consistent with the 5-arcsec resolution of the FIRST survey and with the Gaussian 5-arcsec FWHM aperture used to derive the FIRST point-source fluxes used for the radio-loud objects in this analysis. The flux estimate was robust against the choice of the precise centring (±0.5 pix) of the aperture. Furthermore, increasing the radius of the aperture produced no significant change in the total derived flux.

The median QSOs in the redshift bins were found to range in flux from $f(1.4\,\text{GHz})_{\text{med}} = 23\,\mu$Jy to 42µJy. This point-source flux corresponds to angular scales of between 20 kpc ($z = 0.65$) and 45 kpc ($z = 2.05$) for the median redshift bins used in this analysis. Given that, the vast majority of quasars is this survey will be compact flat-spectrum sources (see below) this ‘point source’ flux should represent an unbiased estimate of the total radio flux, independent of redshift. We note that derived fluxes for these stacked sources are similar to those obtained in the similar analysis made by Glickman et al. (2004) on the stacked radio-quiet QSOs in the Sloan QSO survey.
and 20 mJy. Compared to higher fluxes, the slope of $n(s)$ for radio-loud QSOs 'flattens-off' at these flux levels. Fitting of the $n(s)$ relation suggests the radio counts may be extrapolated below 7.5 mJy by a fit ranging from a flat slope, $n(s) = constant$, to shallow slope $n(s) \propto s^{-0.30}$, with a best-fit $n(s) \propto s^{-0.15}$ (see Fig. 3).

Table 2 presents the comparison of the integrated flux as a function of depth for these fits between these models and stacked observations. The errors on the integrated flux in both radio-loud domain and radio-quiet domain are approximately 10 per cent. Both model extrapolations converge rapidly at fluxes less than 0.1 mJy, with integrated flux predictions for slopes of 0.15 and 0.30 bracketing the observed integrated flux from the 2QZ radio-quiet QSOs. We thus conclude that the flux distribution of radio-quiet QSOs in the 2QZ is not inconsistent with a smooth extrapolation of the 2QZ radio-loud QSO number-flux distribution, on the basis that the slope of the relation flattens at faint flux levels.

This is a necessary but not sufficient condition for a single population model; more detailed modelling of the source counts based on fitted radio-loud and radio-quiet LFs will be presented elsewhere (Miller et al. in preparation). We note that the cosmological luminosity evolution of QSOs in both optical (Croom et al. 2004) and radio (Dunlop & Peacock 2004) tends to cancel out the effects of cosmological dimming over a significant range in redshift ($0.5 < z < 2.5$). This results in luminosity function features such as the break, $L^*(z)$, exhibiting the same observed flux over these redshifts. Thus a simple bimodal luminosity function model with a redshift-dependent break between radio-loud and radio-quiet QSOs that maintains an observed flux close to or below the FIRST radio detection limit over the range in redshifts sampled here could reproduce the current observations.

We also note that the two-population model favoured by Miller et al. (1990) was based on a carefully-selected sample of QSOs at $1.8 < z < 2.5$. We therefore looked to see if there was any evidence in any of our redshift ranges for the integrated radio-quiet flux below the FIRST completeness limit departing from a smooth extrapolation of the radio-loud $n(s)$. Due to reduced numbers of objects, the faint slope was much more difficult to constrain in these narrower redshift bins and we retained the values of 0.0 and 0.3 derived for the full $n(s)$ above. The results are reported in Table 3 based on an integration from the FIRST $5\sigma$ limit down to $10\mu$Jy.

As an illustration the $n(s)$ relation for the $1.85 < z < 2.30$ range is plotted in Fig. 4. Although hampered by larger measurement uncertainties, ($\sim 20$ per cent), we found the total integrated observed flux below the FIRST completeness limits ($0.35 - 0.48$ mJy deg$^{-2}$) at these redshifts were consistent with our extrapolation of the radio $n(s)$. In the lowest redshift bin, the total observed flux marginally exceeds the predicted flux with the fitted 0.3 slope, but only at the 1\sigma level.

### 3.2 Spectral Index

We also investigated the dependency on redshift of the radio-to-optical luminosity ratio for the radio-loud and radio-quiet QSO populations. We characterised the radio-to-optical luminosity ratio by $\alpha_{\text{ro}}$, the notional spectral index between the radio and optical bands, $\alpha_{\text{ro}} = -(\log L_{440nm}/L_{1.4GHz})/(\log \nu_{440nm}/\nu_{1.4GHz})$ where $L$ refers to the luminosities in both optical (440nm) and radio (1.4GHz) bands. Luminosities were calculated using a spectral index of $-0.5$ in both the optical and radio bands. The assumption that the mean radio and optical spectral indices are independent of the radio 'loudness' is implicit in our calculations. Studies of composite optical spectra for radio-loud

![Figure 3](image-url) Number-flux relation, $n(s)$ for the 2QZ radio-loud (filled squares). Fits to the $n(s)$ used in the text are indicated by the dotted lines (slopes of 0.0, 0.15 and 0.30 respectively). The 5\sigma completeness limit and 20 mJy fitting limit for the FIRST radio survey are shown by the dotted lines. Also shown in the corresponding $n(s)$ relation for the range $1.89 < z < 2.30$ (open squares).

![Figure 4](image-url) Radio to optical spectral index as a function of redshift for both radio-loud (crosses) and radio-quiet QSOs (filled circles).
and radio-quiet quasars confirm that the optical spectral index in the range 1200 \AA\ < \lambda \ < 4400 \AA\ is very similar for both populations (Cristiani & Vio 1990, Zheng et al. 1997). Although there is no information of the radio spectral index of radio-quiet QSOs, at the redshifts under consideration here, evolutionary models of the radio source population suggest that the vast majority of the objects will be flat radio spectrum QSOs largely independent of redshift (see e.g. Jackson & Wall 1999); steep spectrum sources only dominating at low redshifts z < 0.5.

In Fig.4 the derived $\alpha_{\rm ro}$ for radio-loud and the composite radio-quiet QSOs are shown. Although the absolute redshift trend in $\alpha_{\rm ro}$ is dominated by the choice of spectral index, the relative trend between the radio-loud and radio-quiet QSOs (which is independent of radio or optical spectral index) is similar. This is confirmed in Figure 5 where we plot the difference in $\alpha_{\rm ro}$ between the radio-loud and radio-quiet QSOs as a function of redshift. Error bars are determined from the errors on the flux determinations in both optical and radio. We can express the relation thus:

$$\frac{L_{\text{RQ}}(z)}{P_{\text{RQ}}(z)} = A \frac{L_{\text{RL}}(z)}{P_{\text{RL}}(z)}$$

where the subscripts refer to the radio-loud (RL) and radio-quiet (RQ) populations respectively and, for clarity, we denote the optical luminosity ($L_{4400}$) and radio luminosity ($L_{1.4\text{GHz}}$) as $L$ and $P$ respectively.

Over the redshift range of interest (z < 2.3) the observed radio flux evolution of the radio-loud population and the the optical flux evolution of the radio-quiet populations can be parameterised by luminosity evolution model as follows:

$$L_{\text{RQ}}(z) = L^* 10^{k_1 z + k_2 z^2}$$

and

$$P_{\text{RL}}(z) = P^* 10^{k'_1 z + k'_2 z^2}$$

where the optical evolution fit to the radio-quiet population yields $k_1 = 1.39$ and $k_2 = -0.29$ (Croom et al. 2004), similar to the radio evolution fit to radio-loud QSOs $k_1 = 1.18$ and $k_2 = -0.28$ (Dunlop & Peacock 1990). By combining these relations and expressing the functional forms for the optical and radio evolution as $f_{\text{opt}}(z)$ and $f_{\text{rad}}(z)$ respectively, we obtain:

$$P_{\text{RQ}}(z) L_{\text{RL}}(z) = \text{const.} f_{\text{rad}}(z) f_{\text{opt}}(z)$$

We can use the observation by Padovani (1993) that the optical evolution of radio-loud and radio-quiet QSOs are identical ($L_{\text{RL}}(z) = L_{\text{RQ}}(z)$) to yield:

$$P_{\text{RQ}}(z) = \text{const.} f_{\text{rad}}(z)$$

i.e. that the radio evolution of radio quiet QSOs is identical to the radio evolution of radio loud QSOs. As indicated above, this is predicated on the assumption that the mean optical and radio spectral indices of QSOs are independent of their radio-loudness. However, if this were not the case, the observation result would itself rely on some fine tuning.

### Table 2. Integrated Flux density for observed QSOs and extrapolated $n(s)$

| Flux Limit (mJy) | $n(s) = $ const (mJy deg$^{-2}$) | $n(s) \propto s^{-0.13}$ (mJy deg$^{-2}$) | $n(s) \propto s^{-0.2}$ (mJy deg$^{-2}$) | Observed (mJy deg$^{-2}$) |
|-----------------|-------------------------------|---------------------------------|---------------------------------|-----------------------------|
| 5.0             | 0.50                          | 0.62                            | 0.76                            | 0.64                        |
| 3.2             | 0.82                          | 1.03                            | 1.31                            | 0.93                        |
| 2.0             | 1.02                          | 1.32                            | 1.71                            | 1.13                        |
| 1.2             | 1.14                          | 1.50                            | 1.99                            | 1.23                        |
| 0.8             | 1.22                          | 1.63                            | 2.20                            | 1.27                        |
| 0.6             | 1.20                          | 1.60                            | 2.10                            | 1.20                        |

### Table 3. Observed and predicted integrated flux densities at f(1.4GHz) > 0.01 mJy for different redshift bins

| z range         | $n(s) = $ const (mJy deg$^{-2}$) | $n(s) \propto s^{-0.3}$ (mJy deg$^{-2}$) | Observed (mJy deg$^{-2}$) |
|-----------------|-------------------------------|---------------------------------|-----------------------------|
| 0.12 < z < 0.85 | 0.24                          | 0.40                            | 0.48                        |
| 0.85 < z < 1.23 | 0.30                          | 0.50                            | 0.40                        |
| 1.23 < z < 1.55 | 0.32                          | 0.53                            | 0.38                        |
| 1.55 < z < 1.89 | 0.32                          | 0.53                            | 0.34                        |
| 1.89 < z < 2.30 | 0.26                          | 0.43                            | 0.38                        |
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Figure 5. The difference between $[\alpha_{\text{ro}}]_{RL}$ and $[\alpha_{\text{ro}}]_{RQ}$, as a function of redshift.

i.e. the relative difference in spectral indices between radio-loud and radio-quiet QSOs would have to be equal and in the opposite sense to the difference in evolution between the radio-quiet and radio-loud populations. This is consistent with the results of Glikman et al. (2004) who found that the radio-to-optical luminosity ratio of the stacked radio-quiet QSOs in the SDSS sample exhibited the same dependence on redshift as the radio-loud SDSS QSOs.

4 CONCLUSIONS

We have demonstrated that the co-addition of blank fields in the FIRST survey provides a robust detection of an ensemble average of radio-quiet QSO flux distribution below the FIRST threshold, and that the flux properties are consistent with a smooth extrapolation of the radio-loud QSO flux distribution detected above this threshold. It would be straightforward to apply this technique to other extensive deep optical surveys, (2dFGRS, SDSS galaxies) comprising tens to hundreds of thousands of objects, thus potentially moving into the sub-$\mu$Jy detection limit. With the advent of next generation wide-field radio facilities such as the Square Kilometre Array, the nanoJansky detection limits proposed for surveys could be similarly transformed into sub-nanoJansky limits using these stacking techniques, providing the confusion limit is not reached and suitable object catalogues exist at deep levels in other passbands.

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