QSO ENVIRONMENTS AT INTERMEDIATE REDSHIFTS

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Abstract

We have made a survey of quasar environments at 0.5 ≤ z ≤ 0.8, using a sample of both radio-loud and radio-quiet quasars matched in B-band luminosity. Our observations include images of background control fields to provide a good determination of the field galaxy counts. About 10 per cent of the quasars appear to live in rich clusters, whereas approximately 45 per cent live in environments similar to that of field galaxies.

The richness of galaxies within a 0.5 Mpc radius around the radio-quiet quasars is found to be indistinguishable from the richness around the radio-loud quasars, corresponding on average to groups or poorer clusters of galaxies. Comparing the galaxy richness in the radio-loud quasar fields with quasar fields in the literature, we find no evidence of an evolution in the environment with epoch. Instead, a weak, but significant correlation between quasar radio luminosity and environmental richness is present. It is thus possible that the environments of quasars, at least the powerful ones, do not evolve much between the present epoch and z ∼ 0.8.

Sample selection and observations

We report on a survey of the galaxy environments of intermediate redshift radio-loud and radio-quiet quasars (RLQs and RQQs, hereafter), described in more detail by Wold et al. (2000a; 2000b). The quasar sample was pulled from complete catalogues with different flux limits, in order to cancel the correlation between redshift and luminosity known to exist in flux-limited surveys. It contains 20 RQQs and 21 steep-spectrum RLQs within a narrow redshift range (0.5 ≤ z ≤ 0.8), but with a wide range in AGN luminosity, both optical and radio. The two
quasar samples are matched in both redshift and optical luminosity, and the distribution of sources in the redshift–optical/radio luminosity plane is shown in Fig. 1. Our assumed cosmology has $H_0 = 50 \text{ km s}^{-1} \text{Mpc}^{-1}$, $\Omega_0 = 1$ and $\Lambda = 0$.

![Figure 1](image-url)

**Figure 1.** Left: quasar absolute magnitudes as a function of redshift. Open circles correspond to RQQs, and filled circles correspond to RLQs. Right: radio luminosity as a function of redshift for the RLQs.

The RLQs were selected from two complete surveys limited both in the optical and in the radio; low radio luminosity quasars from the 7CQ survey (Riley et al. 1999) and high radio luminosity sources from the MRC-APM survey (Serjeant 1996; Maddox et al. in prep.; Serjeant et al. in prep.) The RQQs were selected from three different optically selected surveys, the faint UVX survey by Boyle et al. (1990), the intermediate-luminosity LBQS (Hewett, Foltz & Chaffee 1995) and the bright BQS (Schmidt & Green 1983).

Most of the quasar fields were imaged with the 2.56-m Nordic Optical Telescope on LaPalma, Spain, but there are also some data from the HST and the 107-in telescope at the McDonald Observatory. In addition to the quasar fields, we also imaged several background control fields by offsetting the telescope 5–10 arcmin away from the quasar targets. Our observing strategy was to use filters that target emission longwards of the rest-frame 4000 Å break at the quasar redshifts, and thereby give preference to galaxies with evolved stellar populations physically associated with the quasars. In some cases we also used two filters in order to straddle the redshifted 4000 Å break. Depending on whether the quasar had a redshift $z < 0.67$ or $z \geq 0.67$, we used $V$ and $R$, or $R$ and $I$, respectively.

Using the galaxy counts from the background control fields, we evaluated the number of excess galaxies within a radius of 0.5 Mpc centered on
the quasar, and thereafter converted to the ‘clustering amplitude’, $B_{\text{gq}}$, the amplitude of the spatial galaxy–quasar cross correlation function. The analysis involving the clustering amplitude is discussed elsewhere (e.g. Longair & Seldner 1979; Yee & Green 1987; Yee & López-Cruz 1999).

Figure 2. Clustering amplitudes as a function of quasar absolute magnitude (left) and redshift (right). The open circles correspond to the RQQs, and the filled circles are the RLQs. The dotted line indicates the clustering amplitude for local field galaxies (Davis & Peebles 1983).

Radio-loud vs radio-quiet quasars

The clustering amplitude for each quasar field is plotted as a function of quasar absolute $B$ magnitude and redshift in Fig. 2. As seen from the figure, there is a wide spread in the amplitudes. About 10 per cent of the quasars seem to live in very rich environments ($B_{\text{gq}} \gtrsim 700$ Mpc$^{1.77}$), in some cases perhaps corresponding to Abell class 1–2 clusters. Another 10 per cent live in fairly rich environments, with $B_{\text{gq}}$ between 500 and 700, and 45 per cent in environments similar to the field, $B_{\text{gq}} \lesssim 100$ Mpc$^{1.77}$.

Interestingly, we find that the average environment of the RQQs is indistinguishable from that of the RLQs. The mean clustering amplitudes for the RLQ and the RQQ samples are $210 \pm 82$ and $213 \pm 66$ Mpc$^{1.77}$, respectively. We thus find that the mean clustering amplitudes for the RLQ and the RQQ samples are statistically indistinguishable, implying that the RLQs and the RQQs live in similar environments at these redshifts. This result disagrees with Ellingson, Yee & Green (1991) who found that at $0.3 < z < 0.6$, the RLQs exist more often in rich environments than the RQQs, perhaps due to subtle selection effects in their somewhat heterogeneous sample. But our result is consistent with recent host galaxy studies finding that powerful RQQs exist in luminous,
massive elliptical galaxies similar to the RLQs (e.g. Bahcall et al. 1997; McLure et al. 1999). Other investigators are also finding similar environments for powerful RLQs and RQQs at $z \approx 0.2$ (Fisher et al. 1996; McLure & Dunlop 2000; these proceedings).

Note that both the quasar fields and the background comparison fields were obtained in exactly the same manner, and that we have applied the same analysis to both samples. The comparison between the RLQ and the RQQ environment is therefore direct and internally consistent. Straight number counts in the quasar and background fields show a clear excess of galaxies at faint magnitudes (see Wold et al. 2000a; 2000b), and we also find tentative evidence for clusters at the quasar redshifts in the form of a red sequence present in the richest RQQ fields, see Fig. 3.

![Colour-magnitude diagram of galaxies in the four richest RQQ fields (circles) and in the background control fields (diamonds). There is a hint of a red sequence (dashed line) in the quasar fields which is not present in the background control fields. The mean redshift of the four RQQs is 0.74, and the colour of the red sequence corresponds to the expected colour of galaxies at $z \approx 0.7$–0.8.](image)

**Figure 3.** Colour-magnitude diagram of galaxies in the four richest RQQ fields (circles) and in the background control fields (diamonds). There is a hint of a red sequence (dashed line) in the quasar fields which is not present in the background control fields. The mean redshift of the four RQQs is 0.74, and the colour of the red sequence corresponds to the expected colour of galaxies at $z \approx 0.7$–0.8.

**A link between radio luminosity and environmental richness?**

This section treats the environment of the RLQs. As discussed in the beginning, our aim with selecting sources from different surveys with different flux-density limits was to overcome the luminosity-redshift degeneracy.

In our data, we found a hint of a correlation between the clustering amplitude and the radio luminosity of the quasars. To further investigate this, we added 51 steep-spectrum quasars from the work by Yee & Green...
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Ellingson et al. (1991) and Yee & Ellingson (1993), mostly at redshifts \(0.2 < z < 0.6\). These data are plotted in Fig. 4, where it can be seen that the clustering amplitude correlates more with radio luminosity than with redshift.

To analyze this, we used Spearman’s partial rank correlation coefficients giving the correlation coefficient between two variables holding the third constant. The correlation coefficient between \(B_{gq}\) and \(z\), holding \(L_{408}\) constant, is 0.10 with a 0.8\(\sigma\) significance, whereas the correlation coefficient between \(B_{gq}\) and \(L_{408}\), holding \(z\) constant, is 0.4 with a 3.4\(\sigma\) significance. We thus find no evidence for the cosmic evolution in \(B_{gq}\) as has been claimed for RLQs and radio galaxies (Yee & Green 1987; Ellingson et al. 1991; Hill & Lilly 1991).

Figure 4. Clustering amplitudes in RLQ fields as a function of redshift (left plot) and radio luminosity at 408 MHz (right plot). Filled circles: this work, asterisks: Ellingson et al. (1991), open circles: Yee & Green (1987), diamonds: Yee & Ellingson (1993).

The correlation between \(B_{gq}\) and \(L_{408}\) is weak with much scatter, nevertheless, it is significant. Does this imply that the large-scale radio emission in the RLQs is affected by the environment? Models of radio sources certainly suggest this, where the minimum energy density in the radio lobes scales with the ram pressure at the working surface, implying that the synchrotron luminosity scales with the external gas density (Miller, Rawlings & Saunders 1993). Wold et al. (2000a) compare the data with a model which assumed \textit{all} the variation in \(L_{408}\) is due to the differences in the environments, but find that the predicted correlation is much steeper than observed. It is thus possible that both the environmental density and the bulk kinetic power in the radio jets determine the radio luminosity. Alternatively, the relation between \(B_{gq}\) and \(L_{408}\) may just reflect an increasing mass of the host. This is possible if the
radio luminosity is determined mostly by black hole mass, and if galaxies with massive black holes prefer rich environments.

Summary

1 Both the radio-loud and the radio-quiet quasars studied in this survey live in a diversity of environments, from field-like environments to what appears to be rich galaxy clusters. Only about 10 per cent of the quasars live in relatively rich clusters of Abell richness class 1–2, and approximately 45 per cent live in field-like environments.

2 The average environmental richness in the RLQ and the RQQ fields is statistically indistinguishable, corresponding to groups or poorer clusters. We therefore find that on scales of 0.5 Mpc there is no difference in the environments of the RLQs and the RQQs.

3 We find no evidence of an evolution with epoch in the environments of RLQs. Instead, the claimed evolution with redshift might have been caused by selection effects in flux-limited samples. The true underlying correlation may be that of environmental richness with radio luminosity.

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