THE ASSOCIATION OF GALAXY CLUSTERS WITH MODERATELY-HIGH-REDSHIFT QUASARS

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ABSTRACT. CCD images of quasars having redshifts between 0.3 and 0.65 are analyzed to study the association of galaxies with quasars. Average luminosity functions (LF) of the excess galaxies associated with the radio-loud quasars are determined. It is found that for the sub-sample with z>0.55, there is a significant brightening of the characteristic magnitude M^*, if q_o is assumed to be 0. Comparing computed quasar-galaxy spatial-covariance amplitudes, we can conclude, at the 0.025 significance level, that the spatial-covariance amplitudes of the sub-sample with z>0.55 are greater than those of the lower redshift quasars. This indicates that there has been a strong evolution of preferred sites for bright radio-loud quasars, implying some number-density evolution of quasars has taken place, and that some rich clusters at z~0.6, in comparison with the local rich clusters, have significantly different physical conditions.

In this paper, we present the analysis of the data collected from the Steward 2.3 m survey which provides preliminary evidence of the evolution of the global environments of quasars. Images taken through Gunn r (6500±450Å) and i (8200±600Å) filters of small fields around quasars were obtained using an RCA CCD camera on the Steward 2.3 m telescope. A semi-automatic procedure was used to identify, photometer and classify the detected objects. The sample consists of bright radio-loud quasars having 0.30<z<0.65 chosen from the 3C, 4C and Parkes radio surveys, and optically-selected quasars from the Palomar-Bright-Quasar Survey (PG) in the same redshift range. The completeness magnitudes for detected galaxies range from r=22.0 to 22.9. The field of view of the images is 91"x144". Observations through the r filter of control fields 1^o N of the quasars were also made to provide self-consistent background/foreground galaxy corrections.

For analysis, we shall assume cosmological redshifts for quasars, and derive properties of the excess galaxies in the quasar fields by assigning the redshifts of the quasars to them. Unless specified otherwise, H_o=50 km sec^{-1} Mpc^{-1} and q_o=0 are used throughout.

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To derive the differential luminosity function (LF) of the apparently associated galaxies, we use the following method: galaxies in each quasar field brighter than the completeness magnitude of the field are binned according to their calculated absolute luminosity with the assumption that they are located at the same distance as indicated by the redshift of the quasar. The K-correction term used is a combination of the K-corrections for elliptical-S0, SBc and Scd galaxies as given by Sebok (1982) for Gunn r. For each absolute magnitude bin obtained from each field, the corresponding apparent magnitude background counts are subtracted using the control field counts.

We can determine luminosity functions only for the radio-loud sample, as the PG sample quasars do not have enough excess galaxies to give useful results. The radio-loud sample is divided into two subsets according to redshift: 10 quasars with $0.3<z<0.5$ and 9 with $0.55<z<0.65$, with median redshifts of 0.41 and 0.61, respectively. For each redshift sample, an average luminosity function is calculated.

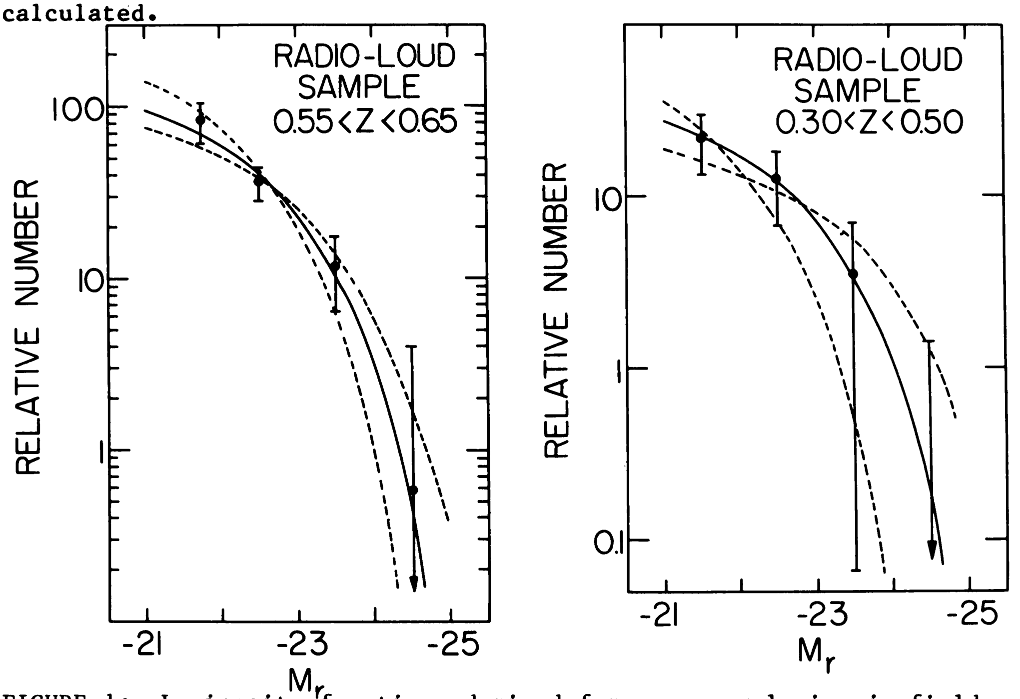

FIGURE 1: Luminosity functions derived for excess galaxies in fields of radio-loud quasars with (a) $0.55<z<0.65$ and (b) $0.3<z<0.5$ for $q_0=0$. The solid and dashed lines represent best fitting and limiting Schechter functions, respectively (see Table 1).

The results are shown in Figures 1a and 1b. To test for a possible evolution in M*, Schechter's (1976) analytical form for the galaxy luminosity function is fitted to the data by minimizing chi-square. By assuming the faint-end slope, α, of -1.2 (Sebok, 1982), we

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obtain M^* of −22.8±0.9 and −22.8±0.4 for the $\langle z\rangle$=0.41 and 0.61 samples, respectively. These are compared with an M^* of −21.96 for local galaxies (Sebok, 1982) and −22.3±0.3 obtained for the excess galaxies found in fields of radio-loud quasars with $0.15<z<0.3$ (Yee and Green 1984).

We conclude that for $q_o\sim0$, M^* for the $0.55<z<0.65$ sample is significantly brighter than that of local galaxies. An evolution in M^* of up to ~0.8 mag may have taken place. We note that this amount of luminosity + color evolution is comparable to that calculated by Tinsley (1980). If we assume q_o=1, the best fitting M^* is still brighter than that of the local galaxies, but the difference is not significant.

We derive the quasar-galaxy spatial covariance amplitude (B_{gq}) by assuming a standard power-law covariance function with index $\alpha=-1.77$. The method as prescribed by Longair and Seldner (1979) is outlined in Yee and Green (1984). To calculate B_{gq}, a proper LF must be chosen, since:

$$B_{gq} \propto A_{gq}/\psi(<M(m,z))$$

where A_{gq} is the angular covariance amplitude (which is proportional to the fractional excess of galaxies in the field), and ψ the LF of galaxies. We use two models for the LF: with and without evolution in M^*. The evolving model is based on the M^*'s derived for the LF of the associated galaxies themselves. We adopt an evolution of M^* of −0.5 mag at z=0.41 and −0.8 at z=0.6. Values for other redshifts are obtained by linear interpolation. The normalization constant for each LF model is determined by matching the counts derived by integrating the LF models in z-space, i.e.:

$$Ng(m)=1/4\pi \int dV\ \psi(<M(m,z))$$

to those of the observed control field counts. We note that the evolving M^* model with q_o=0 gives the best fit to the observed counts.

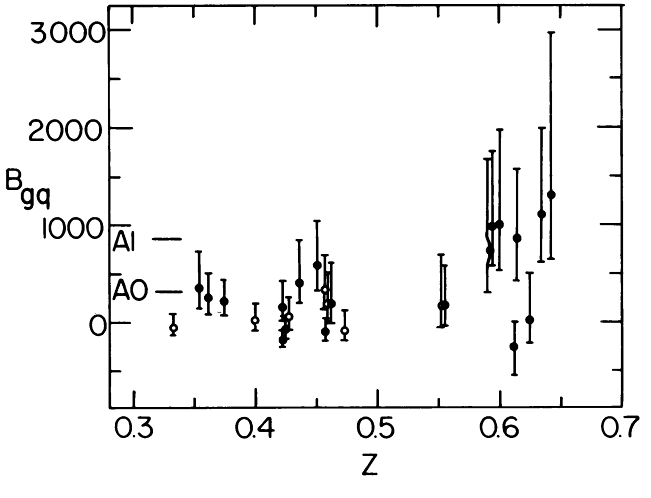

FIGURE 2: Spatial covariance function amplitude versus redshift, assuming an evolution in M^* as described in the text.

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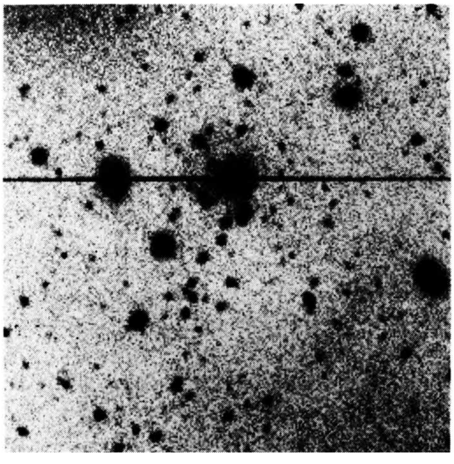
The resultant B_{gq}'s for the evolving M^* model are plotted against redshift in Figure 2. For both cases, using the one-sided Kolmogorov-Smirnov test, we can conclude, at a 97.5% confidence level, that the average spatial covariance amplitude for the $0.55<z<0.65$ sample is higher than that of the lower redshift sample. The results for the various redshift bins are summarized in Table 1 in the form of $\langle B_{gq}/B_{gg}\rangle$, where $B_{gg}=67.5$ Mpc$^{-1.77}$ is the average galaxy-galaxy covariance amplitude for normal galaxies (Davis and Peebles 1983). We also included B_{gq}/B_{gg} for quasars with $z<0.3$ from Yee and Green (1984). These values are scaled by a factor of 0.8 because of a different method used in deriving the angular covariance function.

TABLE I

Average Spatial Covariance Amplitudes

	$\langle B_{gq}/B_{gg}\rangle$		
Redshift	Radio-loud Sample		Optically-selected-sample
	$M^*=-21.96$	Evolving M^*	$M^*=-21.96$
0.00-0.15	—	—	1.51±0.58
0.15-0.30	2.76±1.01	—	1.57±0.74
0.30-0.50	2.78±1.27	2.54±1.13	1.32±1.14
0.55-0.65	20.43±6.34	9.64±2.69	—

For comparison, normalized covariance amplitudes of galaxies near the center of normal Abell classes 0 and 1 clusters are ~4.6 and 12.6, respectively (Longair and Seldner 1979). Thus quasars at $z>0.55$ have an average environment approaching that of the centers of Abell 1 clusters.



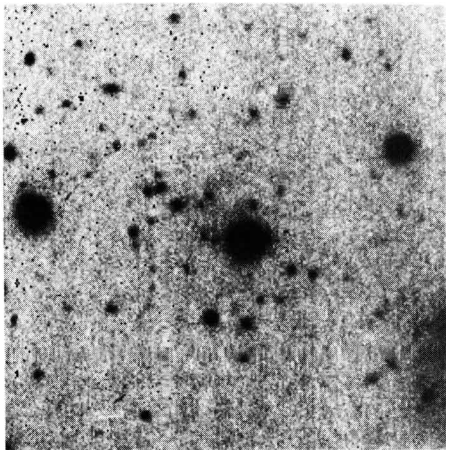


FIGURE 3: Example of deep CCD images of quasars apparently associated with rich clusters: (a) Pks 0405-12 (z=0.574) and (b) 3C263 (z=0.652). Images taken with prime-focus CCD camera at the CTIO 4 m and the CFH 3.6 m telescopes, respectively.

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From deeper CCD pictures that we obtained at the CFH 3.6 m and the CTIO 4 m telescopes (Figures 3a and 3b), this conclusion is visually obvious. So far, we have found over 10 quasars apparently associated with such rich clusters.

The apparent evolution of preferred quasar sites has two implications:

1) The physical conditions within some rich clusters at a redshift as small as 0.6 are already significantly different from those of nearby clusters, enabling them to support a bright quasar. Various models of triggering and fueling of quasars have predicted the existence of quasars in clusters at high redshifts (e.g., Stocke and Perrenod 1981, De Robertis 1985 and Roos 1985).
2) The fact that at higher redshifts there are more quasars existing within rich clusters indicates that some number density evolution of quasars must have taken place. This result suggests that the study of the evolution of the quasar luminosity function may have to take into consideration the physical environments of the quasars.

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DISCUSSION

Burbidge : How many redshifts have you got for the supposed galaxies in your sample ?

Green : We have 2-10 confirmations per field for about a dozen objects with $z < 0.45$. Even the brightest associated objects at $z = 0.6$ have $R > 21$ mag; we have not yet been successful in getting an absorption-line redshift.

Peacock : To prove you are seeing evolution of the environment, you must be sure the mean radio powers of the high and low-redshift bins are identical. Otherwise it could be that more powerful quasars lie in richer environments.

Blandford : How did you adjust the normalisation of your evolving galaxy luminosity function ?

Green : We normalised the evolving galaxy luminosity function by fitting to the number counts in the control fields, on the assumption that the field and the quasar host clusters evolve in the same way.

Tyson : This remarkable trend appears to continue to much higher quasar redshifts. A few years ago I made a CCD (unfiltered, back-illuminated RCA CCD) survey of 47 quasar fields. For the quasar field sample with quasar redshifts between 1 and 1.5, there is a statistically significant excess of galaxies (to $R = 22$ mag) nearby on the sky. The two-point angular correlation function implies extreme luminosity evolution of galaxies in these environments at $1 < z < 1.5$.

Van Heerde : By assuming luminosity function evolution you could reduce the excess of galaxies at the high redshift bin significantly. How much evolution do you have to assume to remove the excess completely ?

Green : To bring the excess number of galaxies down to the average value for the low redshift sample requires a change in m^* of > 3 magnitudes over a redshift interval as small as 0.3, with little change in intrinsic colour.

Alighieri : How did you consider the implication on your results of the fact that some of the galaxies around the quasar (after the background galaxies subtraction) might not be at the same redshift of the quasar ? The probability of getting galaxies at higher and lower redshift might not be the same and this might influence your conclusions on the luminosity function.

Green : To first order, any systematic biases from selection or measuring errors are cancelled because the control fields and the object fields are processed identically. If the quasar host clusters produce any gravitational lens amplification, then the background counts in the quasar fields would be slightly enhanced.

Hutchings : Do you see a dependence of your galaxy count excess on the luminosity of the quasars, either optical or radio ? Also, could you remind us of whether there is a difference in environment between radio and optical quasars in your $z < 0.4$ sample ?

Green : The abrupt change of clustering properties with redshift suggests that the dependence on optical luminosity is weak, given the small change in luminosity in this magnitude-limited sample for z going from 0.4 to 0.6.

There was a difference in environment for the lower redshift sample, in that the radio quasars showed a higher average clustering amplitude, because of brighter associated objects.

Turnshek : This is a comment. Foltz et.al. have just completed a spectroscopic survey at the MMT of both radio loud and radio quiet QSOs. The redshift range is about 1.4-1.9. They find that about 25% of the radio loud QSOs have $z_{abs} \simeq z_{em}$ systems, but that very few of the radio quiet QSOs do. This is evidence that radio loud QSOs have an excessive amount of material around them compared to radio quiet QSOs. This could be interpreted as radio loud QSOs being embedded in clusters, whereas radio quiet ones are not.

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"Untill we reach a deeper understanding of the physical evolution of quasars, we should be very cautious in drawing physical conclusions from successful mathematical representations of the quasar population ensemble properties."

- Richard Green (p.435)