ASSOCIATIONS BETWEEN QSOs AND GROUPS OF GALAXIES

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ABSTRACT

Evidence that *most* presently known low-redshift QSOs are associated with groups of galaxies has led to a program aimed at determining the typical properties of these groups. For the 3C273 field, observations of essentially all galaxies with $m_B \lesssim 21.5$ over a region 10.1' (~1.5 Mpc) in diameter yield four galaxies having redshifts close to that of the QSO. Consideration of the present evidence concerning the richness of groups associated with QSOs leads to the conclusion that, for at least those QSOs that are radio sources, their galactic environment is similar to that of radio galaxies, except that they seldom, if ever, occur in the centers of rich clusters of galaxies.

I. INTRODUCTION

If QSOs are events occurring in the nuclei of galaxies, and if their redshifts are cosmological in origin, the known clustering properties of galaxies make it virtually inevitable that at least some QSOs should be found in association with other galaxies. The first positive evidence for such associations came with Gunn's (1971) discovery of a galaxy near PKS 2251+113 with a similar redshift. Other fairly bright QSOs found to be apparently associated with galaxies were 3C323.1 (Oemler *et al.* 1972) and 4C37.43 (Stockton 1973). A few years ago, I undertook a systematic survey of galaxies near low-redshift QSOs, the results of which were published last year (Stockton 1978, henceforth LRQ survey); since I shall be referring to this study in what follows, let me quickly recapitulate its main features.

The QSO sample for the LRQ survey comprised all those known to me as of mid-1976 with: (1) $z \leq 0.45$, (2) V (as listed by Burbidge *et al.* 1977) $< 19.12 + 5 \log z$, and (3) $-15° < \delta < 55°$. Around each of the

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27 QSOs meeting these criteria, all galaxies brighter than the red Sky Survey limit within 45" of the QSO were selected for the spectroscopic program: a total of 29 galaxies were found in 17 fields, the other 10 fields having no qualifying galaxies.

At the time the results of this survey were submitted for publication, definite redshifts had been obtained for 25 of the 29 galaxies along with a tentative redshift for one more. Of these, 13 galaxies in eight fields had redshifts within 1000 km s^{-1} of their respective QSOs. Two of the three galaxies for which no redshift information was available are of relatively minor interest as far as the identification of groups is concerned, since they occur in fields which already have at least one galaxy agreeing in redshift with the QSO. Further observations of the one remaining galaxy, Q1048-090(1), show it to have a redshift of 0.3456, where that of the QSO is 0.344. Thus nine of the original 27 fields have at least one galaxy meeting the specified selection criteria and agreeing in redshift with the QSO.

It is important to recognize the limitations of this survey. It was designed, not to find all the associations between QSOs and galaxies that might exist for this particular sample of QSOs, nor to determine the detailed properties of those that were found, but simply to test the cosmological hypothesis for the redshifts of QSOs. In order to cover as many fields as possible in a tractable observing program, both the field size and the galaxy magnitude limit were severely restricted. At the low-redshift end of the QSO sample, a 45" radius samples only a few percent of the total volume over which a typical group of galaxies is spread. At the high-redshift end, this radius samples something like half the volume of such a group; but in this case only the very brightest galaxies will be members of the galaxy sample. The importance of this magnitude cutoff in limiting the detectability of associated groups is demonstrated by Table I, which shows the number of fields in the sample and the number of detected associated groups for different intervals in QSO redshift. Note that 13 of the QSOs in the sample have redshifts above 0.35, but for only two of these have associated galaxies been found, whereas below this redshift fully half of the QSOs have detected associated galaxies. It is clear that, once the limitations and selection effects inherent in the survey are taken into account, the evidence is that *most* QSOs selected in a manner similar to the LRQ sample will be located in groups of galaxies.

II. THE 3C273 FIELD

As a first attempt to explore further the properties of groups around QSOs, the fields of five low-redshift QSOs have been selected for more detailed study. The intention is to obtain redshifts and magnitudes for all galaxies brighter than $m_B \sim 21.5$ within a radius of 0.8/z arcminutes (~750 kpc for $H_o = 75$) of each QSO. The only QSO field for which the observations are substantially complete is that of

3C273. This field is of particular interest not only because 3C273 is by far the brightest of the very low redshift QSOs, but because, among the six lowest-redshift QSOs in the LRQ survey, only for 3C273 and PG 0026+129 were no associated galaxies found.

TABLE I

STATISTICS OF DETECTION OF QSO-GALAXY ASSOCIATIONS AS A FUNCTION OF QSO REDSHIFT

z_{QSO}	Number of Fields	Detected Associations
< 0.20	2	0
0.20--0.25	3	3
0.25--0.30	5	2
0.30--0.35	4	2
0.35--0.40	7	1
0.40--0.45	6	1

The field of 3C273 is shown in Figure 1, and the galaxies for which spectroscopic observations were undertaken are indicated. The observed magnitudes and redshifts for these galaxies are given in Table II. Four of the galaxies - nos. 2, 3, 4, 5, - have redshifts agreeing with that of 3C273 to within reasonable limits (the association of no. 2 with 3C273 has already been reported [Stockton 1978b]). Figure 2 shows the spectra of these four galaxies, and Table III lists their absolute blue magnitude, M_B, their projected separation from 3C273, R_p, and their radial velocity difference with respect to 3C273, ΔV_r.

TABLE II

DATA ON GALAXIES IN 3C273 FIELD

No.	m_B	z	No.	m_B	z
1	20.5	0.248	7	20.6	0.21:
2	19.9	0.1577	8	20.4	0.1698
3	20.6	0.1592	9	20.0	0.180
4	19.6	0.1601	10	20.5	0.322
5	20.1	0.1600	11	18.5:	0.0895
6	21.6:	--	12	19.2	0.1778

This group around 3C273 is an example of one that probably would not have been detected at any redshift by the LRQ survey. The galaxy with the smallest angular separation, no. 2, would only come within the 45" radius field for redshifts > 0.26, at which point it would be over a magnitude fainter and would probably have been eliminated by the magnitude limit of the galaxy sample.

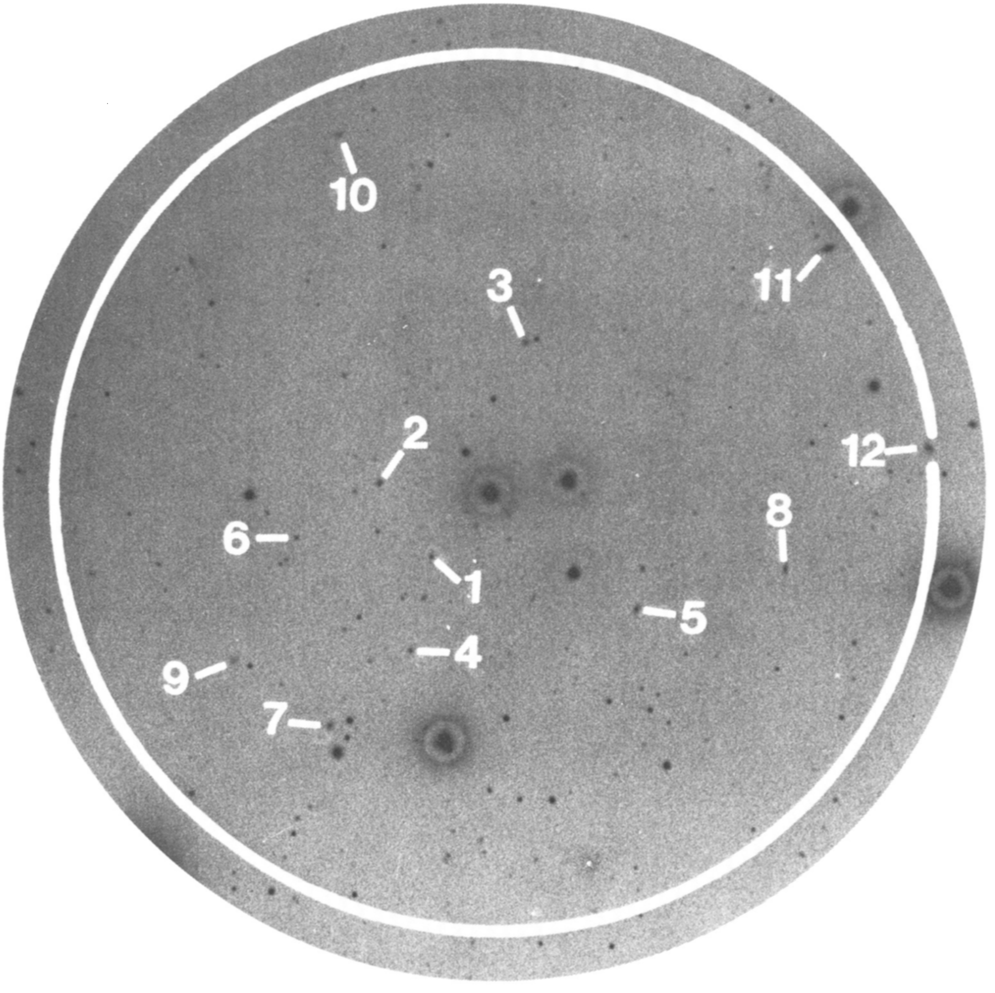

Figure 1. The field of 3C273 (centered), taken from an 098 plate exposed through an OG570 filter. The white circle has a radius of 5.06', and all galaxies within that radius with $m_B \lesssim 21.5$ are marked.

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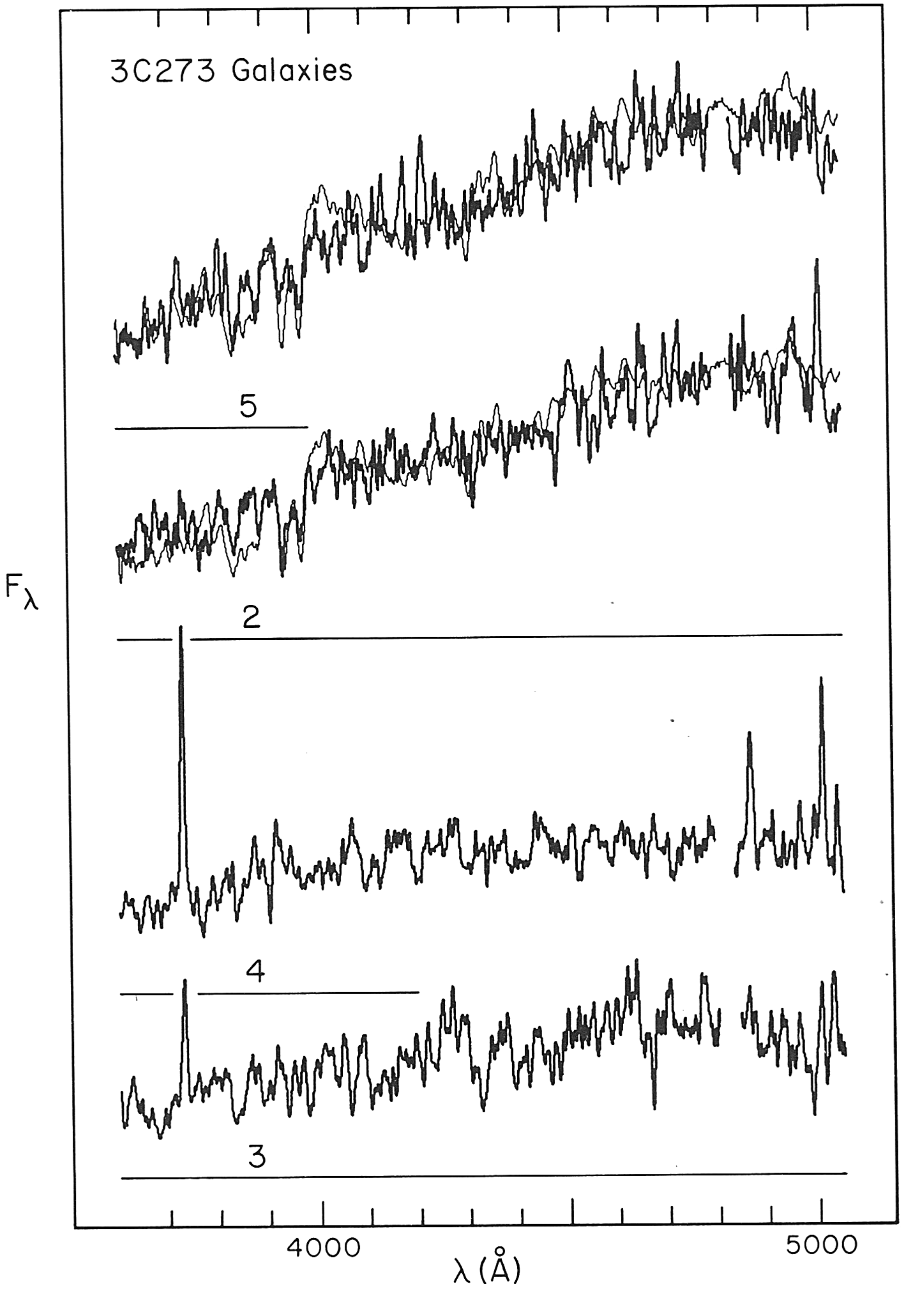

Figure 2. Spectra of the four galaxies with redshifts near that of 3C273, reduced to the rest frame. The light trace on the two upper spectra is Spinrad's spectrum of the inner region of M31, shown for comparison.

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TABLE III

PROPERTIES OF GALAXIES ASSOCIATED WITH 3C273

(H_o = 75, q_o = 0)

No.	M_B	R_p (kpc)	V_r (km/s)
2	-19.8	185	-80
3	-18.8	260	300
4	-19.8	295	530
5	-19.5	310	510

III. PROPERTIES OF GROUPS ASSOCIATED WITH QSOs

Only after several groups around QSOs have been surveyed in detail will we begin to realize fully the possibility of learning, through the study of their galactic environment, something about the nature of QSOs and their relation to other forms of energetic phenomena occurring in galaxies. But even with the sketchy information available now, it is possible to arrive at some interesting tentative conclusions and to isolate some of the research areas that seem most worth following up over the near term.

A. Richness of Associated Groups

No QSO has ever been found in a rich cluster of galaxies (although Butcher *et al.* (1976) have found a distant cluster centered on the BL Lac object 3C66A), and it has therefore long been suspected that QSOs do not occur in rich clusters with any great frequency. From QSOs and 3CR galaxies covering the same range of redshift and distribution on the sky as Abell clusters, Roberts *et al.* concluded at a 95% confidence level that QSOs are associated less frequently with clusters of Abell richness class 1 or greater than are strong radio galaxies. This conclusion is strengthened by the fact that none of the QSOs in the LRQ sample, which is largely disjunct from the Roberts *et al.* sample, occurs in a rich cluster.

On the other hand, Weymann *et al.* (1978) have shown that if the galaxy-QSO correlation for the LRQ sample of QSOs were the same as the average galaxy-galaxy correlation, the survey of galaxies that was carried out would have been expected to find only 2.4 correlated galaxies rather than the 14 actually found. They therefore concluded that galaxies are correlated more strongly with this sample of QSOs than they are, on the average, with each other.

The LRQ sample of QSOs is biased strongly towards radio sources, and it is well-known (see, e.g., Seldner and Peebles 1978) that radio galaxies show a similar tendency to be galaxies with which other galaxies are strongly correlated. The present evidence, then, is that, *while both radio galaxies and radio QSOs preferentially occur in regions where the density of galaxies is significantly higher than average, radio galaxies often are located at the centers of rich clusters but radio QSOs seldom, if ever, are.*

It is important to emphasize, however, that any conclusions reached from a sample of low-redshift QSOs may not have universal applicability. For example, even an unequivocal demonstration that QSOs occurring near our own epoch *never* are found in the centers of rich clusters would not prove that those at a redshift $z = 2$ are not found in rich clusters: with the evolution of conditions in clusters, there might very well have been a corresponding evolution of the characteristic locus of QSO activity with respect to cluster richness.

B. Effects of the Intracluster Medium

For radio galaxies there is a correlation between the richness of the cluster in which the galaxy lies and its radio spectral index, in the sense that the steeper index sources are in the richer clusters; this correlation is interpreted as being due to the influence of the density of the intracluster medium on the development of the radio source. Guthrie (1977) had suggested that radio spectral indices of QSOs might be useful as a means of detecting QSOs in clusters, but he was unable to find any QSOs with the very steep indices characteristic of radio galaxies in rich clusters. However, there is some indication that QSOs that are flat-spectrum radio sources are systematically in poorer groups that are steep-spectrum QSOs: considering QSOs in the LQR sample with $z < 0.35$, four of the five with steep spectra but only one of the five with flat spectra were found to have associated galaxies in the original survey. If this effect is real, it might also indicate an influence of the ambient gas density in these groups.

Another effect involving the intracluster gas may have some promise as a means of detecting QSOs in rich groups or in clusters, even at redshifts beyond those for which the cluster galaxies can be seen. Hintzen and Scott (1978) have proposed that distortions in the morphology of double radio sources associated with QSOs be used as an indicator of the presence of surrounding ambient gas and thus, presumably, a cluster. This technique does have limitations: it cannot detect the presence of gas that has both zero relative velocity and a symmetrical density gradient with respect to the source, so it would miss any QSOs that are analogous to the central radio galaxies in rich clusters. In addition, any attempt to compare, say, the relative frequency of QSOs in groups above a certain richness for two different epochs using this approach would have to deal not only with selection effects (which probably are manageable) but a number of presently unknown evolutionary effects.

C. Future Observations

It will be important to continue observations of groups associated with QSOs with a coverage comparable to that obtained for the 3C273 field in order to determine typical properties for such groups. Otherwise, the greatest need is for similar observations for a sample of radio-quiet QSOs. If they should be found to be distributed (as the radio QSOs are) in regions of higher-than-average galaxy density, then arguments that they are closely related to the classical Seyfert galaxies will have to be re-examined, since it appears that Seyferts tend to be, if anything, *more* isolated than the average galaxy (van den Bergh 1975).

Finally, the fact that radio QSOs tend to be found in environments similar to those of radio galaxies, except the centers of rich clusters, indicates that it would be worthwhile to attempt to delineate as carefully as possible the differences between radio galaxies in the centers of rich clusters and radio galaxies found elsewhere. The center of a rich cluster is a unique environment, and at least the cD galaxies found in cluster centers have apparently had a unique evolutionary history. It is therefore at least conceivable that radio galaxies in and outside of cluster centers have arrived at similar physical states along different paths, only one of which can sometimes lead to the QSO phenomenon.

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DISCUSSION

Longair: M. Seldner and I have studied the clustering of galaxies about strong extragalactic radio sources using cross-correlation functions. We study the cross-correlation of the positions of 3CR radio galaxies in a complete statistical sample with the Lick counts of galaxies. We set up a scale of clustering in terms of the amplitudes of the spatial cross-correlation function. For galaxies selected at random, the scale of clustering is 1. For Abell clusters, the scale has value 13. Intermediate scales of clustering are defined on a linear scale between these values. For 3CR radio galaxies in the redshift range $z < 0.1$ to which this technique is sensitive, the average clustering lies intermediate between the Abell clusters and galaxies selected at random. However, when one splits the sample into classical double radio sources and more complex radio morphologies, the complex sources lie in much higher regions of galaxy clustering than the classical doubles. In fact, the clustering about the classical doubles is not significantly different from galaxies selected at random in the universe.

The significance of this result for the quasars is that the quasars found most frequently in low-frequency radio surveys are classical double sources and, consequently, we would not expect them to lie in regions of strong clustering of galaxies. This is consistent with the lack of prominent clustering of galaxies about low redshift quasars. We discuss the implications of our results in a paper soon to be published in Monthly Notices of the R.A.S.

It will be most interesting to express the strength of the clustering of galaxies about quasars found by Dr. Stockton in terms of cross-correlation functions to find if our very different approaches are in agreement.

Stockton: I think that this sort of investigation is very important, and I am glad to hear of what you have done. I understand that you also have found a relationship between the optical spectra of radio galaxies and the strength of the clustering around them, which I believe is an important result.

The result of Weymann et al. for the LRQ sample of QSOs would, I believe, indicate a galaxy density enhancement of about a factor of 5 above that found around a typical galaxy, but I am not sure how this value would translate into your clustering scale. It will certainly be ironic of galaxies should turn out to be more strongly correlated with radio QSOs than with radio galaxies having similar radio structures, after we have supposed the contrary for so many years!

Jaffe: A number of studies have shown that the probability of a radio galaxy occurring in an optical galaxy of given magnitude does not depend on whether that galaxy is in a rich Abell-type cluster or not.

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