The Astrophysical Journal, 706:657–664, 2009 November 20 doi:10.1088/0004-637X/706/1/657

ASSOCIATIONS OF HIGH-REDSHIFT QUASI-STELLAR OBJECTS WITH ACTIVE, LOW-REDSHIFT SPIRAL GALAXIES

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Received 2008 December 23; accepted 2009 October 5; published 2009 November 4

ABSTRACT

Following the discovery in the 1960s of radio and optical QSOs it was found that some of them lie very close to low-redshift ($z \leqslant 0.01$) spiral galaxies with separations of $\lesssim 2$ arcmin. These were discovered both serendipitously by many observers, and systematically by Arp. They are some of the brightest QSOs in radio and optical wavelengths and are very rare. We have carried out a new statistical analysis of most of those galaxy–QSO pairs and find that the configurations have high statistical significance. We show that gravitational microlensing due to stars or other dark objects in the halos of the galaxies apparently cannot account for the excess. Sampling or identification bias likewise seems unable to explain it. Following this up we selected all ~4000 QSOs with $g \leqslant 18$ from a catalog of confirmed QSOs in the Sloan Digital Sky Survey, and compared them with various subsets of galaxies from the RC 3 galaxy catalog. In contrast to the earlier results, no significant excess of such QSOs was found around these galaxies. Possible reasons for the discrepancy are discussed.

Key words: galaxies: general – galaxies: statistics – gravitational lensing – quasars: general

Online-only material: color figures

1. INTRODUCTION

The tendency of stars and galaxies to cluster is well known, and by using distance criteria it is possible to distinguish physical clustering from apparent groupings in the sky. In the case of extragalactic objects, the distance criterion is usually redshift. With the discovery of QSOs nearly 50 years ago the early results showed that there is only a weak correlation between apparent magnitude and redshift as compared with the results for normal galaxies and clusters of galaxies (cf. Hubble 1929; Humason et al. 1956). It was soon pointed out that this might mean simply that QSOs have a very wide range of intrinsic luminosities.

However, an alternative explanation was that the redshifts of the QSOs are not measures of distance. From the earliest days, the discoveries of Arp (Arp 1967) and statistical studies of samples of QSOs (cf. Burbidge et al. 1971) appeared to support this view. As the data accumulated, those who tended to believe in this radical view were encouraged, but the majority, who largely believe in the original continuity argument that QSOs are simply the nuclei of galaxies at cosmological distances (Kristian 1973), for which evidence has also grown, have prevailed. Thus at present astronomers in general assume that QSOs have cosmological redshifts, and use them for cosmological investigations.

But by now there is general agreement that there is observational evidence for the clustering of QSOs about much lower redshift galaxies (cf. Williams & Irwin 1998) and an overdensity of faint galaxies about QSOs (cf. Benitez & Martinez-Gonzales 1997). In all of the work along these lines, the authors tacitly assumed that all redshifts are cosmological in origin and attribute the effects to gravitational lensing due to foreground dark matter. This is the only way to explain the clustering on the conventional hypothesis since a wide range of redshifts of objects apparently close together is found. The galaxy–QSO correlations have however often been claimed to be unexpectedly strong; excesses of a factor of 2–10 have sometimes been claimed on angular scales of the order of an arcminute (e.g., Williams & Irwin 1998; Jain et al. 2003; Myers et al. 2005; Gaztañaga 2003). False correlations induced by Galactic extinction do not seem capable of explaining these phenomena (Nollenberg & Williams 2005). Scranton et al. (2005), on the other hand, in a large-scale study of QSO and galaxy observations from the Sloan Digital Sky Survey (SDSS), find good agreement with theoretical lensing expectations from *WMAP* concordance models on scales from 60 h^{-1} kpc to 10 h^{-1} Mpc.

In this paper, we first assess the validity of the early claims that there is a significant excess of bright QSOs close to nearby active spiral galaxies with low redshifts, beyond that expected from gravitational lensing. The dimensions which we are investigating are generally, although not always, smaller than the 60 h^{-1} kpc lower limit of Scranton et al. (2005). We test these claims by generating synthetic galaxy data sets, imposing them on the background distribution of bright QSOs extracted from the Sloan Survey QSOs, and counting these synthetic galaxies which have angularly close QSOs. We find a strong overabundance of close QSOs relative to chance expectations (Section 3). We show that microlensing due to material in the halos of the galaxies fails by four or five powers of 10 to account for these correlations (Section 4). Likewise, they appear not to be due to lensing due to large-scale structure.

A similar, puzzling result has been found by Benitez et al. (2001). These authors constructed a catalog of radio-loud QSOs and found that positive correlations with galaxy positions exist for the earliest QSOs discovered, with practically no correlation in the case of those identified later. The effect was significant at the 99.3% level, and they postulated the presence of an "identification bias" wherein the first radio sources to be spectroscopically identified tended to be those in regions of higher galaxy density. However, we find that this sampling bias, if it exists at all in the present data set, is weak and cannot account for the strong associations (Section 5).

The QSOs concerned are bright and the associated galaxies are generally spirals. Because of the large increase in QSO

Table 1
Cumulative Number Density ν of QSOs Per Square Degree Versus Magnitude m_v Adopted in this Study

m_v	ν
17.00	0.05
17.25	0.10
17.50	0.16
17.75	0.30
18.00	0.50
18.25	1.00
18.50	1.80
18.75	3.00
19.00	4.00
19.25	7.00
19.50	10.00
19.75	14.00
20.00	20.00
20.25	25.00
20.50	30.00
20.75	40.00
21.80	70.00

Note. Generally, only QSOs with $m_v < 18.5$ are used.

numbers arising out of the automated surveys, it is in principle possible to test the presence of anomalous associations using large amounts of new data. Furthermore, these new data sets have the advantage that human selection effects are not involved, and discovery bias is better understood. We have carried out tests using various subsets of the galaxies from the RC 3 galaxy catalog, comparing positions with all QSOs with $V \leqslant 18$ taken from the Sloan DR5 QSO catalog (Schneider et al. 2007). The test procedure is a quasi-Monte Carlo one which preserves the irregularities in both the RC 3 and SDSS QSO distributions. We found no evidence for anomalous correlations in these larger data sets (Section 6). Possible reasons for this, and future tests, are discussed in Section 7.

2. VERY CLOSE PAIRS OF QSOs AND GALAXIES: A BRIEF HISTORY

The first QSOs were found from very accurate radio positions, i.e., they were found as objects giving rise to non-thermal radio emission. Studies of the optical "stars" showed that they had large redshifts. The early radio surveys of the sky contained the radio-bright sources in the 3C catalog and the Parkes catalog. Thus, the numbers of sources over the whole sky were very small—only about 300 in the 3C catalog, out of which only 50 were found to be QSOs.

However, Sandage (1965) realized that there might be optically bright QSOs which were not radio sources. Following his lead many more QSOs were found, and it soon became clear that a large population of such objects was likely to be present over the whole sky. Surveys were begun, and it soon became clear that the number of QSOs is a steep function of apparent brightness (Table 1), the numbers increasing with faintness (Kilkenny, et al. 1997; Scranton et al. 2005). However, for the first decade after the discovery of QSOs, the emphasis was on optical identification and redshift measurement of the brighter radio and/or optical objects. Since the QSOs have large redshifts, most of the community, both observers and theorists, were most interested in using them for cosmological investigations.

In spite of this, in the first few cases it was found that some bright QSOs with high redshifts are remarkably close in the sky to very nearby low-redshift spiral galaxies. Given the rarity of the bright QSOs, and knowing that there are good estimates of the density of bright galaxies over the whole sky (de Vaucouleurs et al. 1991), it became clear that the probability that these pairs were due to accidental projections was very small.

However, the typical reaction when a close pair was found was, "This is remarkable but I shall suspend judgment until you find me another." Remarkably, this argument has continued to be used, for example, when an X-ray emitting QSO with a redshift $z = 2.1$ was found to lie only 8 arcsec from NGC 7319 (Galianni et al. 2005). Since the identifications went very slowly, by the time that another case had been found the previous one had been forgotten. Even when the first proper statistical study was made of the positions of 3C QSOs relative to the Shapley–Ames galaxies (Burbidge et al. 1971) showing a strong effect (five of the QSOs lie very close to NGC galaxies) this result, which remains valid, was largely ignored. Only Arp deliberately looked for pairings between high-redshift QSOs and radio sources, lying close to low-redshift galaxies. He found many of them and argued that they must be physically related (Arp 1967, 1987). However, this result became so unpopular with his observing colleagues that his observing program was stopped.

One result of this history is that there has never been a systematic statistical appraisal of the bright QSO–galaxy associations studied by Arp. In this paper, we attempt to remedy that deficit. Thus, we put together a large part of these data concerning very close pairs which came out of this period (Table 2) and carry out a conservative analysis. These early data sets are of course inhomogeneous and incomplete, but since QSO–galaxy correlations are now routinely observed in the large QSO data sets, it is worth revisiting these early claims of anomalies since they apply specifically to bright nearby galaxies, which form a unique data set and may yield new insights into the problem.

3. THE EARLY DATA SETS REVISITED

In Table 2, there are 39 QSOs very close to 33 galaxies, all of which have very small redshifts and all of which were discovered many years ago. The rms separations of the pairs are $\sim 2'.0$. While these data were taken from the original literature they have all been checked and are found in the most recent Veron-Cetty & Veron (2006) catalog.

The Veron-Cetty–Vernon catalog is inhomogeneous and incomplete and cannot be used to define a null hypothesis against which the suggested anomalies can be tested. We can however estimate the significance of the claimed overabundances as follows.

We first adopt a mean density for the background distribution of QSOs derived from, say, SDSS. We assume that the number density ν of QSOs over the region of celestial sphere occupied by these galaxies is not systematically different from that derived from the surveys (in fact, most of them lie in regions of sky covered by SDSS). Since we are considering only the expected mean, no assumption is implicit about the homogeneity or otherwise of the background counts. The probability of any prescribed departure from the mean may be obtained if we scatter synthetic galaxies randomly over a portion of sky covered by SDSS and count the number which has bright nearby QSOs. The assumption being made is that the background distribution of QSOs is statistically the same as that found in the region of sky covered by the SDSS.

From the pairs listed in Table 2, we first extract those QSOs which are brighter than some threshold magnitude V_t and which lie within some angular distance θ_i of each galaxy. This gives

Table 2
QSOs Close to Bright Galaxies ($m_v \leqslant 15.5$)

Galaxy	m_v	QSO	m_v	z	Separation ($''$)
UGC 0439	13.8	PKS 0038-019	18.10	1.674	72
NGC 470	12.5	(0117+0317g)	19.8	1.875	93
NGC 470		(0117+0317g) 68D	18.2	1.533	95
NGC 622	14.0	0133+004 (UB 1)	18.5	0.91	71
NGC 622		0133+004 (UB 1)	20.2	1.46	73
IC 1746	14.5	0151+048 (PHL 1226)	16.91	0.404	6.4
NGC 1073	11.3	BS0 1	19.6	1.945	104
NGC 1073		BS0 2	19.0	0.599	117
NGC 1073		RSO	20.0	1.411	84
NGC 1087	11.5	0243-007 (UB 1)	19.1	2.147	170
IC 2402	13.5	0844+319 (4C 31.32)	19.92	1.834	30
NGC 2534	13.7	0809+358 (UB 1)	18.5	2.40	121
NGC 2693	13.1	0853+515 (UB 1)	19.5	2.31	188
NGC 3067	12.8	0955+326	15.8	0.533	114
NGC 3073	14.1	0958+558 (UB 1)	18.8	1.53	144
NGC 3079	11.5	0958+559	18.4	1.154	114
ZW 1022.0-0036	15.5	PKS 1021-006	18.2	2.547	122
NGC 3384	10.8	1046+129	20.6	0.497	149
NGC 3407	14.3	1049+616 (4C 61.20)	16.3	0.422	173
NGC 3561	14.7	1108+289	20.0	2.192	66
NGC 3569	14.5	1109+357	18. 4	0.91	31
NGC 3842	12.8	QSO 1	18.5	0.335	73
NGC 3842		QSO 2	18.5	0.946	59
NGC 3842		QSO 3	21.0	2.205	73
NGC 4138	12.1	3CR 268.4	18.1	1.400	174
NGC 4319	13.0	Mk 205	14.5	0.070	43
NGC 4550	12.6	1233+125 (Wdm 8)	17.9	0.728	44
NGC 4651	11.8	3CR 275.1	19.0	0.557	210
NGC 5107	13.8	1319+38	19.5	0.949	40
NGC 5296	14.9	1342+440 (BSO 1)	19.3	0.963	55
NGC 5406	13.1	1358+392	18.5	3.28	95
NGC 5682	14.5	1432+489	19.2	1.940	95
NGC 5832	12.9	3CR 309.1	16.8	0.905	372
NGC 5981	13.9	1537+595	19.0	2.132	10.7
IC 1417	13.6	2158-134	17.8	0.73	76
Anon	15	2237+0305	17.3	1.41	$\leqslant$0.3
NGC 7465	13.3	2259+157	19.7	1.66	128
NGC 7413	14.8	3CR 455	19	0.543	24
NGC 7714	13.0	PB 5468	18.0	1.871	120

Table 3
QSO-Galaxy Pair Counts in Table 2

V_t	θ_i	r_{eff}	O	E
17.0	60	30.7	2	0.003
17.0	120	70.4	3	0.015
17.0	180	70.4	3	0.015
17.0	240	70.4	3	0.015
17.5	60	30.7	2	0.009
17.5	120	70.4	3	0.048
17.5	180	70.4	3	0.048
17.5	240	70.4	3	0.048
18.0	60	35.7	3	0.038
18.0	120	67.2	5	0.137
18.0	180	78.5	6	0.186
18.0	240	78.5	6	0.186
18.5	60	40.7	5	0.181
18.5	120	71.1	12	0.551
18.5	180	93.8	16	0.960
18.5	240	93.8	16	0.960
19.0	60	35.8	7	0.777
19.0	120	70.7	15	3.03
19.0	180	90.3	19	4.94
20.0	60	38.1	10	1.75
20.0	120	72.4	23	6.35
20.0	180	92.1	29	10.28
20.5	60	38.1	10	2.64

Notes. O is the total QSO count around the galaxies down to threshold magnitude V_t, the count being carried out to circles of radius θ_i'' around each galaxy. r_{eff} is the rms radius of the separations. Assuming that the number of galaxies investigated was 250, the expected total QSO count is given as E for the mean background densities given by Table 1.

us a total pair count x. We then calculate an effective radius for the extracted separations, being their root-mean-square sum

$$r_{\mathrm{eff}} = \sqrt{\Sigma(\theta_i)^2/N}. \qquad (1)$$

The mean number of pairs m expected may then be computed as a product of the mean background density ν of QSOs down to the prescribed threshold magnitude and the total area which was searched by the original observers. This latter area is obtained from all the N galaxies which they observed in arriving at the table:

$$m = N\nu \times \pi r_{\mathrm{eff}}^2. \qquad (2)$$

The actual number of galaxies searched deserves some discussion. From Table 2, we see that out of the 33 galaxies, seven have QSOs which were originally identified as radio sources. Thus, in this case the observers went directly to the galaxies. It is interesting to point out that in the case of 3CR 455 associated with NGC 7413 the original identification was with the galaxy and not the QSO. It was only when a more accurate radio position was made that E. M. Burbidge was able to show that the source was a genuine QSO only 24$''$ away from the galaxy (Arp et al. 1972).

In another case, IC 1746 and PHL 1226, it was the remarkable configuration which led to the identification of the very bright QSO. For many of the remainder of the pairs (about 20) Arp identified the optical object, and spectra were obtained. A good example is the triple system of QSOs around NGC 1073, which Arp & Sulentic (1979) identified and for which Burbidge et al. (1979) obtained spectra. Arp was the only observer who was trying systematically to identify QSOs very near to spiral galaxies. From the literature, and many discussions with Arp concerning his use of the catalogs, and the total amount of observing time that was made available to him, it is clear that he could not have surveyed in detail more than about 100 galaxies. This is in large part due to the fact that he was removed from the telescopes with his program incomplete.

Comparison between the cumulative number counts per magnitude per square degree ν given in Table 1, based on Kilkenny et al. (1997) data, with that obtained from analysis of Sloan data (e.g., Scranton et al. 2005) shows that the estimated QSO number counts have changed little, especially at the bright end, and we use the background count given in Table 1.

In Table 3, we give the results of these calculations. There is a large and systematic excess of close QSO–galaxy pairs, relative

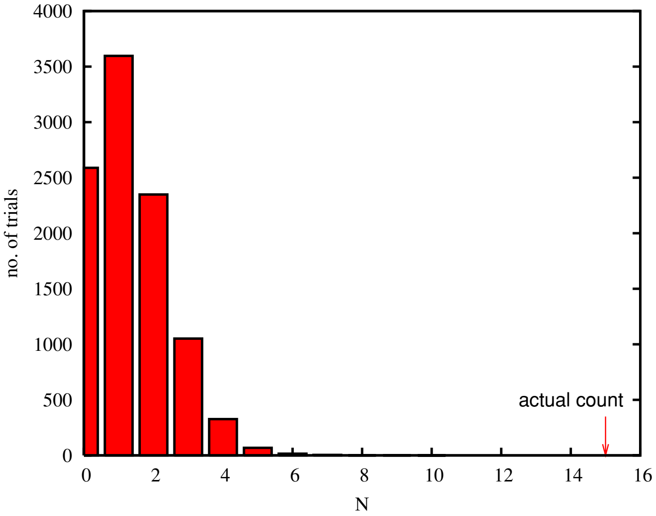

Figure 1. Ten thousand Monte Carlo trials in each of which 200 synthetic galaxies are spread randomly around the region of Galactic celestial cap covered by the Sloan Survey. The number of galaxies in each trial which have QSO companions $g \leqslant 18.5$ within $2'$ is recorded. The number shown in the real data is marked by the arrow.

(A color version of this figure is available in the online journal.)

to expectations, among the bright galaxies. For example, 15 QSOs with $V \leqslant 18.5$ are found within 2 arcmin of the galaxies listed; assuming a total of 200 galaxies were observed, there is an expectation of 1.26. Six QSOs brighter than 18.0 are found within 2 arcmin of the galaxies listed, as against an expectation of 0.34. This excess holds over the whole QSO magnitude range examined, out to at least $3'$ from the galaxy nuclei.

A number of Monte Carlo trials were carried out along the lines described above to test the significance of these apparent associations. For example, trials were carried out in which sets of synthetic galaxies (200 at a time) were scattered randomly over the "Galactic cap" region covered by the SDSS, and the number of galaxies with one or more QSOs in their neighborhood was counted. By using the observed QSO positions, we maintain the well-established clustering of QSOs which is normally attributed to cosmological large-scale structure (e.g., Shen et al. 2007; Ross et al. 2009 and references therein). The adoption of 200 galaxies is based on the estimate that Arp could not have surveyed in detail more than ~100 galaxies, and so is probably conservative. In 10,000 trials, in which a galaxy was counted if it had at least one QSO brighter than $V \leqslant 18.5$ within $2'$, the mean galaxy count per trial was 1.32 ± 0.02. This compares well with the expectation value 1.26 from Table 1. None of the trials yielded 15 galaxies having such close companions (Figure 1).

In these trials we ask: given a galaxy, what are the chances that a QSO of some magnitude will lie within a certain angular distance of it? However the discovery process seems not to have been purely of that character, we have seen that seven of the QSOs listed were identified first as radio sources and the proximity of a nearby galaxy was a post hoc finding. This would make no difference to the computed probabilities in the case of complete data sets, but that situation does not pertain here. We can assess the effect of this to an order-of-magnitude by assuming that the observational discovery process lay at the other extreme, namely, the QSOs were discovered first and a nearby galaxy was then identified within some angular distance. From the RC 3 catalog, there are 1770 galaxies brighter than $B = 14.0$ over ~30,000 deg^2 of sky (allowing for the Hubble zone of avoidance), whence their number density λ ~0.06 deg^{-2} and the mean nearest neighbor distance is $\sqrt{1/\pi\lambda}$ ~2.3 deg. To have an expectation of finding 21 QSOs in Table 2 having such a galaxy lying within $2' = 0.033$ deg, the total number of QSOs observed would have had to be $\sim 21 \times (2.3/0.033)^2 \sim 10^5$, greater than the QSO population identified from SDSS by Schneider et al. (2007). Trials were carried out in which synthetic QSO data sets were generated and a "nearest galaxy" count was carried out for the above 1770 RC 3 galaxies. The outcome of 10,000 trials is shown in Table 4. In these particular runs batches of QSOs were generated, 200 at a time, with a distribution mimicking the overall galaxy distribution. It is clear that an admixture of "QSO first, then galaxy" discoveries in the Table 2 data set makes no qualitative difference to its improbability.

Table 4
The Outcome of 10,000 Trials in Each of which a Set of 200 Synthetic QSOs was Generated as Described in the Text[a]

Trials	N_c
3764	0
3680	1
1803	2
582	3
136	4
26	5
8	6
1	7
0	8

Notes. The procedure falls well short of reproducing the 21 such close QSO-galaxy associations of Table 2.

[a] The number N_c having at least one bright RC 3 galaxy ($B \leqslant 14$) within $2'$ was recorded.

These trials thus confirm that the excess of bright QSO companions around the galaxies studied has extremely high statistical significance.

4. GRAVITATIONAL LENSING

Many years ago, Canizares (1981) suggested that the clustering of bright QSOs around nearby galaxies might be due to gravitational microlensing due to dark stellar objects in the halos of the bright galaxies. However, it was shown that in general even if the large numbers of faint halo stars exist, the argument fails quantitatively because it requires a much higher surface density of faint QSOs than observed (Arp 1990). We consider gravitational lensing here with particular reference to the Table 2 data set.

There is an extensive literature on the effect of gravitational lensing by distant cosmological objects in inducing QSO inhomogeneities and other distortions over the sky (see, for example, Jain et al. 2003 and Benitez et al. 2001 for a summary and model predictions, respectively). In the case of single QSO–galaxy alignments (as opposed to pairs or triplets of QSOs), the positional inhomogeneities of the QSOs are irrelevant and any magnification bias due to distant sources (e.g., Scranton et al. 2005) is automatically incorporated in the observed magnitude distribution of the QSOs. It thus appears that the cause of the QSO–galaxy pairings must lie within the nearby galaxies themselves. Bukhmastova (2007), for example, describes a model in which enhanced numbers of globular clusters in the halos of galaxies might create sufficient lensing to yield the galaxy–QSO pairs found by Arp and others.

A background QSO may be microlensed if it lies along the line of sight of foreground sources to within a few Einstein radii. On the cosmological interpretation of redshift z, the observer would be much closer to such lenses than the light sources, and in that case the Einstein ring has an angular radius, in microarcsec,

$$\theta_E \sim 3\sqrt{m/D}, \tag{3}$$

where m is the mass of the lens in solar masses and D is its distance in Gpc (Narayan & Bartelmann 1996). If there are n such lenses in the halo of the galaxy, then the total lensed area is, in square microarcsec,

$$A = n\pi\theta_E^2 \sim n\pi \times 9m/D = 9\pi M/D \tag{4}$$

from Equation (4), where $M = nm$ is the total mass of lensing objects in the halo. Thus, the proportion of QSOs lying within an Einstein ring is independent of the adopted lensing parameters (loc. cit.).

Consider for example NGC 1073, a face-on barred spiral of low surface brightness at a distance of about 16.4 Mpc (Kaaret 2005), with a triplet of close QSOs (Table 2). For lensing masses totaling $M = 10^{12}\,M_\odot$, the total lensed area is equivalent to a single disc of Einstein radius $\theta \sim 23''$ and area $\sim 10^{-4}$ deg^2. For comparison, there are about 100 QSOs per square degree down to magnitude 22 (Table 1; Myers et al. 2005). Thus, with these figures there is an expectation that $\sim$0.01 background QSOs with $V < 22$ lie within Einstein rings in the halo.

A microlensed QSO at an angular distance $\theta = \theta_E$ from a lens center will appear as two images brightened by $\delta V \sim 0.2$ mag, one within $0.1\theta_E$ by up to 2 mag. Thus to generate three QSOs of $V \lesssim 20$ around NGC 1073 by lensing a background population of $V \sim 22$ QSOs, one requires them to lie within $\sim 0.1\theta_E$ of the lens center, and so only $\sim 10^{-4}$ such QSOs are available. As one attempts to boost progressively fainter background QSOs, microlensing increasingly fails to account for the observed excess. The situation is even more extreme than this, since the argument neglects the lowering of density of background QSOs caused by the magnification: a deficiency arises from the increasing flatness of the slope of the QSO number–magnitude distribution with increasing V. Magnification by an amount μ increases the number count by a factor $\mu^{2.5s-1}$ where the slope $s = d\log N_0/dm$. Thus, an increase in the QSO count is expected behind lenses when the slope of the QSO number–magnitude count >0.4, a deficit otherwise. The break-even point occurs around magnitude 19.1–19.6 (Myers et al. 2005). The single-trial probability of the triplet configuration is $\sim 4 \times 10^{-7}$, neglecting any correlated lensing and distortion of the background density by intervening matter.

We might try to boost the shortfall of five or more powers of 10 by postulating that NGC 1073 is immersed in a dense mass of material. In fact, it belongs to a small group which includes NGC 1068, NGC 1055, and five small irregular galaxies. As the QSO triplets have projected separations $\sim$8 kpc from the nucleus, we would require say $10^{17}\,M_\odot$ of material to lie along a line of sight of this radius to NGC 1073, and this is plainly unrealistic. Thus, we have been unable to find any sensible model of microlensing capable of accounting for the Table 2 overabundances.

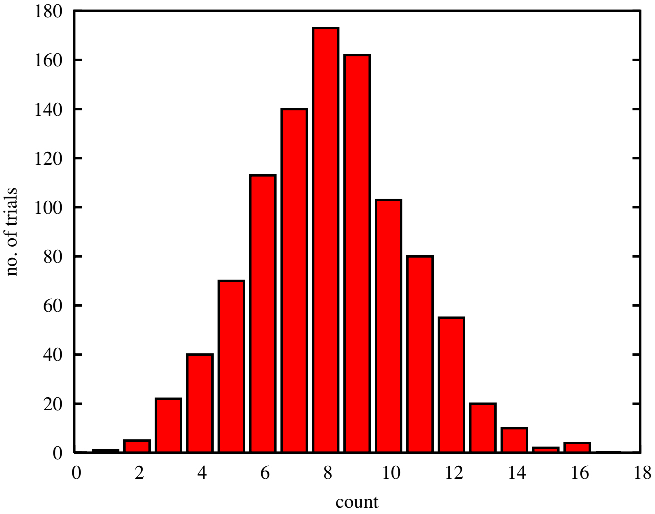

Figure 2. Galaxies in sets of 29 are extracted at random from the 1772 bright RC 3 galaxies ($B < 14$), and the number having at least one other RC 3 galaxy within 30 arc minutes is counted. From 1000 trials. The range encompasses the count observed for the Table 2 galaxies (11) and suggests that the latter simply follow the run of density of the field galaxies.

(A color version of this figure is available in the online journal.)

5. IDENTIFICATION BIAS

Benitez et al. (2001) have pointed out that the number of radio-loud QSOs around foreground galaxies is substantially higher than expected from weak lensing. They conjectured that there might have been an "identification bias" accounting for this and many other surprisingly strong QSO–galaxy associations found in the early literature. They suggested that the first radio sources to be spectroscopically identified as QSOs tended to lie in regions of higher than average galaxy density, facilitating the optical identification but creating a spurious correlation between radio-loud QSOs and nearby galaxies.

The excess of very close galaxy–QSO pairs in Table 2 is so extreme that it does not seem likely that such bias could account for it: there are simply not enough bright QSOs and nearby galaxies. Nevertheless, the hypothesis was tested as follows. If QSOs are intrinsically associated with individual galaxies, then any tendency for QSO–galaxy associations to lie in crowded regions would simply reflect that expected by random extraction from the galaxy distribution. Identification bias, on the other hand, would yield an anomalous concentration of such associations in dense regions. A thousand trials were carried out in each of which 29 galaxies were randomly extracted from 1772 RC 3 galaxies with $B < 14$, and the number having at least one neighboring galaxy within 30 arcmin was recorded. The outcome is shown in Figure 2. The number in the real data set having such a neighbor is 11, which is well within the random spread. Thus the Table 2 galaxies seem to simply follow the trend of galaxy counts, with little evidence for "identification bias."

6. THE SLOAN SURVEY BRIGHT QSOS

In the last 25 years there has been a vast increase in the number of QSOs which have been identified with measured redshifts. The most extensive surveys are the Two-Degree Field (2dF) survey (Croome et al. 2001, 2003) and the SDSS (Fan et al. 1999; Abazajian et al. 2003; Adelman-McCarthy et al. 2006). We also have the de Vaucouleurs catalog of Galaxies (RC 3), a

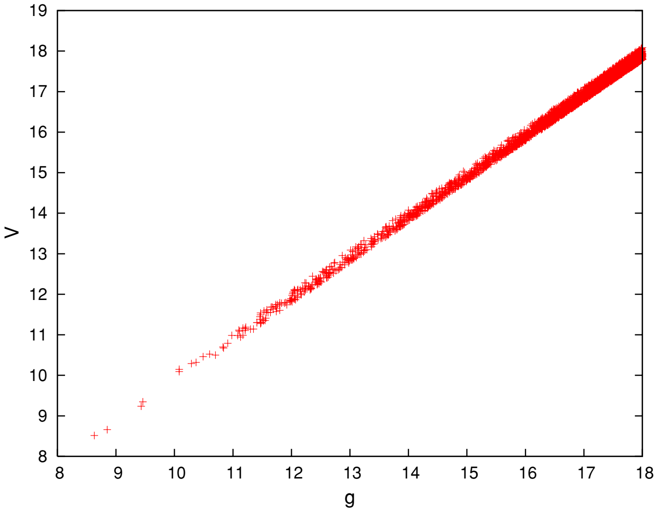

Figure 3. Conversion from Sloan Survey g-magnitude to V-magnitude, for the 4000 Sloan QSOs (Richards selection criteria) with $g < 18$.

(A color version of this figure is available in the online journal.)

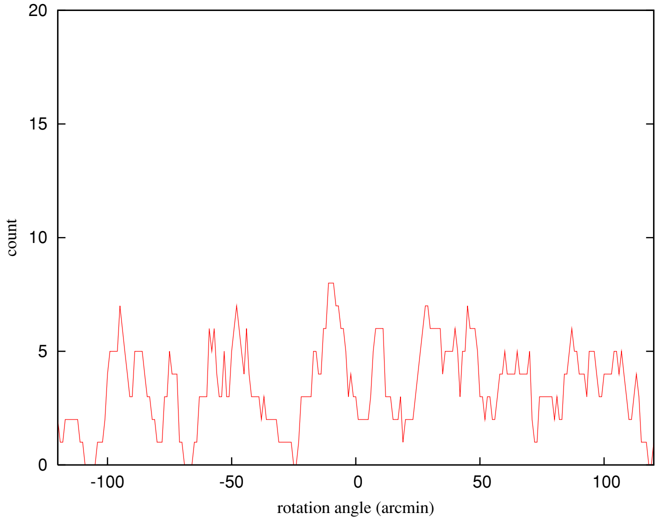

Figure 4. One thousand and forty five galaxies from the RC 3 catalog ($B \leqslant 14$, Hubble type Sa-Sc, $z \leqslant 0.05$), rotated about the celestial pole. For each angle of rotation, the number of galaxies having at least one QSO ($V \leqslant 18$) within 4′ is counted. For zero rotation, corresponding to the real configuration, no excess above chance expectation is found. The QSOs are extracted from the catalog by Schneider et al. (2007).

(A color version of this figure is available in the online journal.)

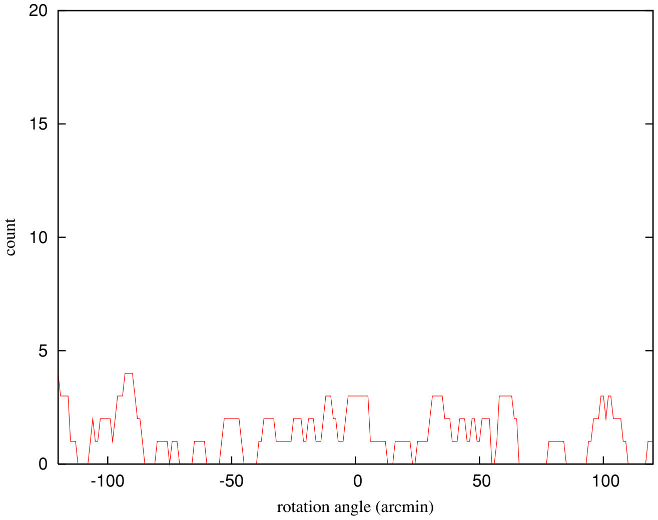

Figure 5. Same as Figure 4, but with 662 “active galaxies” from the Veron catalog ($V \leqslant 14$, $z \leqslant 0.05$).

(A color version of this figure is available in the online journal.)

whole sky survey, which contains about 23,000 galaxies brighter than 15.5 mag of which about 60% are classified as spirals. With the advent of these large-scale and automated surveys, the reality of the claimed QSO–galaxy associations could in principle be tested with much larger, relatively bias-free data sets. To do this, however, it is necessary to properly specify the type of galaxy for which the phenomenon is claimed to occur. In the early history of the subject, Arp was using his own catalog of disturbed and disrupted galaxies as a base for looking for QSOs. A fraction of those objects in Table 2 were found in this, but as was described in Section 1 several were found by first finding a radio source and then identifying a QSO near to the galaxy.

A number of trials were carried out to see whether specific types of galaxy can be identified as carrying the anomalous QSO excess. Firstly, 4019 QSOs with $g \leqslant 18$ were extracted from the Schneider et al. (2007) catalog (given that 7500 deg^2 are covered by the survey, this implies 0.54 such QSOs per square degree in good agreement with the Table 1 figure). A conversion between the Sloan g-magnitudes and V-magnitudes was applied to the data and the V-system was used throughout: the correlation is tight (Figure 3). These constituted the template against which galaxies of different morphological types were tested for association.

The procedure employed was to construct two concentric celestial spheres, with QSOs on one and the galaxies under test on the other, and rotate the spheres relative to each other about the polar axis of the equatorial system. For each rotation angle θ, the number of galaxies which had at least one QSO within a prescribed angular distance was found—typically the counting circles were 2 or 3 arcmin in radius. A significant excess of QSOs around galaxies would show up as a spike centerd on $\theta = 0^\circ$. This technique has the advantage that all inhomogeneities in both QSO and galaxy data sets are preserved, however they are caused.

A possible association with spiral galaxies in general was first examined by extracting 1045 galaxies from the RC 3 catalog, having $B \leqslant 14$, redshifts $z < 0.05$, and morphological types $1 \leqslant t \leqslant 7$ corresponding roughly to Hubble types Sa-Sc. These galaxies are generally nearby, the redshift distribution being concentrated around 1000–2000 km s^{-1} corresponding to distances ∼20–40 Mpc. The redshifts in the QSO data set are $\geqslant 0.078$ and so there is no overlap with the RC 3 galaxies. Figure 4 shows the result of this exercise. There is no evidence of a significant QSO excess around these spirals. Thus, the QSO excess found earlier does not apply to the population of spiral galaxies in general; any subpopulation carrying the signal is presumably lost in the noise.

The exercise was repeated using the galaxies classed as “active” by Veron-Cetty & Veron (2006) in their catalog. There were 662 of these with $V \leqslant 14$, redshifts $z < 0.05$ as before. Once again (Figure 5) there is no indication of a significant clustering of bright QSOs around these target galaxies, when counting circles of 4′ radius are employed.

These negative results suggest that the nature of the RC 3 galaxies showing the associations needs to be more precisely specified. Objects which are called active galactic nuclei (AGNs) or active galaxies were first defined to have broad emission lines in 1943 by Seyfert, but in recent years the term has been used with a much wider definition: if the galaxy has evidence for ejection of gas, bridges, etc., or if it is an X-ray source, it is now classified as an AGN. In fact, the X-ray astronomers have always defined the objects they find as AGNs, whether or not they are genuine QSOs. In the Veron-Cetty & Veron (2006) catalog, all of those objects which have been classified as "active" in whatever way with the proviso that assuming cosmological distances they have luminosities of minus 23 or less. They therefore include as "active galaxies" many objects which we and the Sloan authors classify as QSOs.

In the case of the de Vaucouleurs (RC 3) catalog of galaxies about 16,000 are spiral or irregular. It was long ago estimated by Woltjer & Setti (1982) that about 1% of spiral galaxies are active. This was based on the comparatively close by systems. This would suggest there are only about 150 active galaxies (AGNs) in the de Vaucouleurs catalog in the original sense. But even in this catalog most of the galaxies with redshifts have not been studied enough to know whether they are active in the broad sense or not. Without extensive study involving a great amount of spectroscopy these galaxies cannot be identified. It will take many years of observation of the details of these fainter objects to see whether they are really associated with active galaxies. Thus, the bulk of the spiral galaxies used in the previous section are not active in the sense originally used in constructing the hypothesis.

Thus, the astrophysics of the objects and the morphology of the parent galaxy are important parts of the apparent association being tested, and neither of these are sufficiently well defined in the large catalogs for a definitive test.

7. SUMMARY AND DISCUSSION

In summary, we find that the early claims of associations between particular active spirals and bright QSOs are statistically strong. Identification bias or similar observational artifacts do not seem able to account for them. Microlensing by objects within the halos of the galaxies is likewise inadequate to account for the phenomenon. Assuming that these QSOs lie in their associated galaxies and are not at cosmological distances, the QSO excess occurs on scales of a few tens of kiloparsecs; it is thus a halo phenomenon.

We have been unable to confirm this phenomenon in larger modern data sets. However, this may be because the phenomenon was found in the earlier samples through different techniques, namely observational searches around disturbed galaxies. Although the modern data sets are numerically much larger, they are less useful because the spectroscopic characteristics of the fainter galaxies are not known and it is not possible to extract from them galaxies comparable to the earlier data set. It has been pointed out that strong QSO–galaxy associations are almost routinely found in studies performed with radio-loud AGN samples (Benitez et al. 2001). Nevertheless, lacking a clear identification of the galaxy characteristics for which the associations occur, the results must be treated with caution, and the verification of apparently discordant redshifts around some nearby galaxies needs to be investigated in greater detail from an empirical point of view. Thus, one would like to know such features as the angular extent of the enhanced QSO distribution function around galaxies, and how the phenomenon varies with QSO magnitude.

Much of the material we have used is not new. This is particularly true when we restrict ourselves, for example, to one of the first catalogs of bright radio QSOs, the 3CR QSOs where it is now clear that at least 6 of the 50 QSOs (3C 455, 3C 232, 3C 268.4, 3C 275.1, 3C 345, and 3C 309.1) lie within 6′ of an active NGC spiral. Also the pair 3C 37 and 3C 39 lie almost symmetrically across the active spiral galaxy NGC 470 at distances of ∼30′. This galaxy also has two very close QSOs (Table 2).

These results are most easily understood by the hypothesis that some QSOs are physically connected to low-redshift active spirals. If so, a possible conclusion is that they have been ejected from the active nuclei of these galaxies, and have a non-cosmological component to their redshifts. If we assume that the QSOs studied here are at the same distances as the parent galaxies we find that their absolute magnitudes M_v lie in the range −11 to about −15.

Arguments in favor of cosmological redshifts for QSOs do exist. One of these is the time delay data for about a dozen apparently lensed QSOs (Saha et al. 2006); another is the apparently good evidence for cosmic magnification on cosmological scales (Scranton et al. 2005), and the loose correlation between QSOs and galaxies of similar redshifts. The results presented here represent a tiny fraction of the QSO population, and extrapolation of the non-cosmological interpretation to QSOs as a whole is another issue.

The major unsolved problem brought out here again is the nature of the anomalous redshifts of QSOs. This has always been the central problem since the QSOs were first discovered. A few of us have tried to solve the problem but have failed, and it is often said that observational data only begin to be accepted when there is a theory available to explain them.

We acknowledge and thank Peggy McCoy for her assistance in typing this paper, and an anonymous referee for many helpful comments.

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