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Quasar–galaxy associations revisited

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ABSTRACT
Gravitational lensing predicts an enhancement of the density of bright, distant QSOs around foreground galaxies. We measure this QSO–galaxy correlation w_{qg} for two *complete* samples of radio-loud quasars, the southern 1Jy and Half-Jansky samples. The existence of a positive correlation between $z \sim 1$ quasars and $z \approx 0.15$ galaxies is confirmed at a $p = 99.0\%$ significance level ($> 99.9\%$ if previous measurements on the northern hemisphere are included). A comparison with the results obtained for incomplete quasar catalogs (e.g. the Veron-Cetty and Veron compilation) suggests the existence of an 'identification bias', which spuriously increases the estimated amplitude of w_{qg} for incomplete samples. This effect may explain many of the surprisingly strong quasar–galaxy associations found in the literature. Nevertheless, the value of w_{qg} that we measure in our complete catalogs is still considerably higher than the predictions from weak lensing. We consider two effects which could help to explain this discrepancy: galactic dust extinction and strong lensing.

Key words: quasar galaxy associations; gravitational lensing

1 INTRODUCTION

Canizares (1981) showed that if gravitational lensing effects are considered, an enhancement in the density of QSOs close to the position of foreground galaxies is expected (see also Keel 1982; Peacock 1982). This effect, known as 'magnification bias' can be characterized by the overdensity $q = \mu^{\alpha-1}$ (Narayan 1989), where μ is the magnification and α is the logarithmic slope of the number counts distribution. Depending on the slope α, an excess ($q > 1$) or even a defect ($q < 1$) of background sources around the lenses will be observed. Galaxies and clusters trace the matter fluctuations (up to a bias factor b), and therefore, we may observe positive ($\alpha > 1$), null ($\alpha = 1$) or negative ($\alpha < 1$) statistical associations of these foreground objects with distant, background sources.

The evidence for association between high–redshift AGNs and foreground galaxies has steadily accumulated during the years (see Schneider, Ehlers & Falco 1992 for a detailed review). However, the results are sometimes apparently contradictory and quite often difficult to accommodate within the gravitational lensing framework. For instance, the strength of associations depends on the AGN type and in particular, the studies performed with radio-loud AGN samples, or with heterogeneous samples, usually extracted from early versions of the Veron-Cetty & Veron or the Hewitt & Burbidge catalogs, (which contain a high proportion of radio–loud QSOs) almost routinely find significant excesses of foreground objects around the quasar positions (Tyson 1986; Fugmann 1988,1990; Hammer & Le Févre 1990; Hintzen et al. 1991; Drinkwater et al. 1992; Thomas et al. 1995; Bartelmann & Schneider 1993b, 1994; Bartsch, Schneider, & Bartelmann 1997; Seitz & Schneider; Benítez et al. 1995; Benítez & Martínez-González 1995, 1997(BMG97); Benítez, Martínez-González & Martín-Mirones 1997; Norman & Williams 1999; Norman & Impey 1999). Although these results are qualitatively in agreement with the magnification bias effect, in most cases the amplitude of the correlation is much higher than that expected from gravitational lensing models.

On the other hand, the studies carried out with optically selected catalogs are less consistent. Positive correlations have been found by Webster et al. (1988), Rodrigues-Williams and Hogan(1991) and Williams & Irwin (1998). In all these cases, the amplitude of the correlations is more than an order of magnitude stronger than the predictions from the magnification bias effect. On the other hand, Boyle et al. (1988); Romani & Maoz (1992); BMG97; Ferreras, Benítez & Martínez-González (1997) and Croom & Shanks (1999) found null or even negative correlations, which in some cases are expected from the magnification bias effect due to the shallowness of the QSO number counts. However, there are certain instances in which the differences in the QSO–galaxy correlation w_{qg} between radio–loud and radio–quiet QSOs cannot be explained by the lensing hypothesis: BMG97 found a negative correlation for the optically selected Large Bright Quasar Survey (LBQS) catalog (Hewett,

Foltz & Chafee 1995), which has a steep slope $\alpha \gtrsim 2$. The most likely explanation for this is that the LBQS catalog is affected by a selection bias which hinders the detection of high-z QSOs in regions of high projected galaxy density (see Romani & Maoz 1992, Maoz 1995). Further evidence was obtained by Ferreras, Benítez & Martínez-González (1997) which found that CFHT/MMT QSOs (Crampton, Cowley & Hartwick 1989) were strongly anticorrelated with low redshift galaxies, contrary to what was expected from the magnification bias effect. The amplitude of the anticorrelation is stronger for lower redshift QSOs which practically excludes dust in foreground galaxies as its cause and strongly suggests a dependence on the strength of the emission lines used to identify the QSO. From these results it may be concluded that until the selection effects operating on optically selected QSO samples are not better understood, one should be wary of the gravitational lensing inferences obtained from them.

As Bartelmann & Schneider (1993a) pointed out, the scale of some of the positive correlations reported above (several arcmin) is difficult to explain considering lensing by isolated galaxies or microlensing, and apparently has to be caused by the large-scale structure. Bartelmann (1995) showed that in the weak lensing regime

$$w_{qg}(\theta) = b(\alpha - 1)C_{\mu\delta} \tag{1}$$

where $C_{\mu\delta}$ is the correlation between magnification and matter density contrast $C_{\mu\delta} =< \delta\mu\delta_m >$, b is the biasing factor $b = \delta_g/\delta_m$, where δ_g and δ_m are respectively the galaxy and dark matter overdensities. Sanz et al. (1997) and Dolag & Bartelmann (1997) have calculated $C_{\mu\delta}$ for several cosmological models taking into account the non linear evolution of the power spectrum of density perturbations. In Benítez & Sanz (1999) it was shown that the expected value of w_{qg} can also be estimated as

$$w_{qg} = Q(z_b, z_f)\Omega_m b^{-1} w_{gg} \tag{2}$$

where z_f and z_b are the typical redshifts of respectively the galaxy and quasar samples. For low redshift galaxies and relatively high-z QSOs like the ones considered in this paper, the factor Q is approximately independent of the cosmological model.

Any radio–loud quasar is detected in the optical, with e.g. magnitude B, and in radio with flux S. For a sample with independent optical and radio fluxes, the effective slope α_e (Borgeest et al. 1991) takes the form

$$\alpha_e(S, B) = -\frac{d\ln N(>S)}{d\ln S} + \frac{2.5 d\log N(<B)}{dB} \tag{3}$$

where $N(> S)$ and $N(< B)$ are the cumulative number counts distributions. This is known as the double magnification bias effect. It holds if the optical and radio fluxes are independent, and also if the source sizes are considerable smaller than the lens in both bands, what ensures that both fluxes are equally magnified. Both conditions are reasonably fulfilled for QSO–galaxy associations: radio and optical fluxes are practically uncorrelated for radio quasars (see e.g. Fig. 10 of Drinkwater et al. 1997) and the large scale structure weak lensing field is smooth enough to magnify similarly the sizes of the optical and radio emitting regions.

Therefore, to compare the model predictions with the observations, it is necessary to know in detail the unperturbed number counts distribution of the quasar sample. However, practically all the radio–loud samples mentioned above are incomplete (e.g. BMG97) or have heterogeneous photometrical information in the optical (e.g. Benítez & Martínez-González 1995). Here we intend to remedy this situation by measuring w_{qg} using two *complete* radioloud quasar samples.

The outline of the paper is the following. In §2 we describe the galaxy and QSO samples used to estimate w_{qg}. §3 deals with the statistical analysis. §4 presents two theoretical estimations of w_{qg} and compares them with the observational results. §5 discusses the puzzling results of the previous section and §6 summarizes our main results and conclusions.

2 THE DATA

Our galaxy sample is obtained from the ROE/NRL COSMOS/UKST Southern Sky catalog (see Yentis et al. 1992 and references therein), which contains the objects detected in the COSMOS scans of the glass copies of the ESO/SERC blue survey plates. The UKST survey is organized in $6 \times 6\,\mathrm{deg}^2$ fields on a 5 deg grid and covers the zone with declination $-90\,\mathrm{deg} < \delta < 0\,\mathrm{deg}$ and galactic latitude $|b| > 10\,\mathrm{deg}$. The catalog supplies several parameters for each detected object, including the centroid in both sky and plate coordinates, B_J magnitude and the star-galaxy image classification down to a limiting magnitude of $B_J \approx 21$. Drinkwater et al. (1997) quote a calibration accuracy of about ± 0.5mag for the COSMOS B_J magnitudes. As in BMG97, we include in our sample galaxies brighter than $B_J < 20.5$ and within $0.2' < \theta < 15'$ of the quasars selected as we describe below. The median redshift of the B_J galaxies is $z_g \approx 0.15$.

In BMG97 we studied the quasar-galaxy correlation for a sample of 144 $z > 0.3$ PKS quasars with a 2.7GHz flux $S_{2.7} > 0.5$Jy, extracted from Veron-Cetty & Veron (1996). This sample was shown to be strongly correlated with foreground galaxies, but its incompleteness precluded a detailed comparison with theory. Thus, we now consider two well defined and practically complete radio loud quasar catalogs to assess the incompleteness of the BMG97 sample and its effect on the estimation of w_{qg}: the 1Jy catalog (Stickel, Meisenheimer & Kühr 1994; Stickel et al. 1996) which includes radiosources with a 5GHz flux $S_5 > 1$Jy, and the Parkes Half-Jansky Flat-Spectrum sample (Drinkwater et al. 1997) which contains flat-spectrum sources detected at 2.7GHz and 5GHz, with $S_{2.7} \geq 0.5$Jy, spectral index between 2.7GHz and 5GHz $\alpha_{2.7/5.0} > -0.5$, galactic latitude $|b| > 20\,\mathrm{deg}$ and declination $-45\,\mathrm{deg} < \delta < 10\,\mathrm{deg}$.

Both the 1Jy and Half-Jansky catalogs are almost 100% identified and have spectroscopical redshifts for $\geq 90\%$ of the sources. To try to work with samples as similar as possible, we have extracted from the three catalogs those objects classified as QSOs. VC classify as QSOs those objects with absolute magnitudes brighter than $B = -23$ and the 1Jy catalog uses the same classifications as the original discovery papers. For the HJ we have selected those objects classified as "stellar", excluding the BL LACs to get a more homogeneous sample. Drinkwater & Schmidt 1996 showed that the original Parkes catalog classification was made in a non-uniform way, resulting in false large-scale correlations

among quasars drawn from that catalog. The HJ classification seems to be free of this problem (Drinkwater et al. 1997) and even if the 1Jy presents a similar defect, it would not affect the measurement of w_{qg}, since we normalize the galaxy density locally in a 15' circle around each quasar. It should also be kept in mind that the optical classification of radiosources may be affected by crowding effects (an example are the 'merged' objects in Drinkwater et al. 1997), and that this could tend to eliminate from the sample QSOs in fields with higher than average galaxy density, biasing low the measured value of w_{qg}.

Our analysis will be performed within basically the same area defined by Drinkwater et al. (1997), except for three additional constraints imposed by the characteristics of the COSMOS/UKST galaxy catalog:

i) Declinations $-45\,\mathrm{deg} < \delta < 3\,\mathrm{deg}$, as the COSMOS/UKST plates only reach up to $\delta < 3\,\mathrm{deg}$.

ii) Galactic latitude $|b| > 30\,\mathrm{deg}$. It was shown in BMG97 that the "galaxy" density in COSMOS fields is significantly anticorrelated with galaxy latitude, clearly due to an increase in the numbers of stars misclassified as "galaxies" when we approach the galactic disk. In fact, COSMOS fields with $|b| < 30\,\mathrm{deg}$ have on average 75% more objects classified as "galaxies" than the $|b| > 30\,\mathrm{deg}$ fields. Although excluding these fields does not affect strongly the results (BMG97), they would dilute the galaxy excess and bias low the amplitude of w_{qg}.

iii) $|\Delta x|$,$|\Delta y| < 2.25\,\mathrm{deg}$, $\sqrt{\Delta x^2 + \Delta y^2} < 2.5\,\mathrm{deg}$. As in BMG97, these cutoffs avoid the outer regions of the plates, with worse image and photometric qualities. We also exclude a few fields from the sample because they are affected by meteorite traces.

There are also other three general constraints based on the quasar characteristics:

iv) A faint threshold on the quasar B_J magnitude, $B_J < 20.5$, the same as for our galaxies. We also set an upper threshold of $B_J > 15$, brighter of which the photographic magnitudes are not reliable. We use only COSMOS B_J magnitudes obtained from Drinkwater et al. (1997), or directly from the ROE/NRL COSMOS/UKST Southern Sky catalogue. This ensures photometrical bandpass homogeneity. At the chosen magnitude limit, it can be reasonably expected that any radio source candidate is bright enough to be detected, correctly identified on a photographic plate and have its redshift determined spectroscopically. Up to this limit, the quasar catalogs should be practically complete.

v)A lower redshift cutoff, $z > 0.3$. Only 5% of the COSMOS/UKST galaxies with $B_J < 20.5$ have $z > 0.3$, so we exclude the possibility of "intrinsic" quasar-galaxy correlations contaminating the result. Setting a higher redshift cutoff does not affect significantly the results.

vi)A 2.7GHz flux cutoff: $S_{2.7} \geq 0.5$ Jy. This is the flux limit of the Half-Jansky catalog. The $S_{2.7}$ fluxes are obtained from Drinkwater et al. (1997) and from the Veron-Cetty & Veron compilation. Objects from the 1Jy catalog also have $S_5 > 1$ Jy. We do not set any constrains on the steepness of the radio spectra for the Veron-Cetty & Veron and 1Jy samples. The Half-Jansky sample has $\alpha_{2.7/5.0} > -0.5$.

The Veron-Cetty & Veron (VC) sample is very similar to the PKS sample used in BMG97 except for the exclusion of 23 quasars with $|b| < 30\,\mathrm{deg}$ and $B_J < 20.5$, and the inclusion of 12 objects which belong to the Veron-Cetty & Veron (1997) catalog and comply with criteria i-vi) but were not included in BMG97 because their names do not start with "PKS", or have $S_{2.7}$ exactly equal to 0.5Jy (the flux limit in BMG97 was $S_{2.7} > 0.5Jy$ and here it is $S_{2.7} \geq 0.5Jy$). The VC sample thus defined contains *all* the quasars in the 1Jy sample and 91.5% of the Half-Jansky (HJ) sample (86 out of 94).

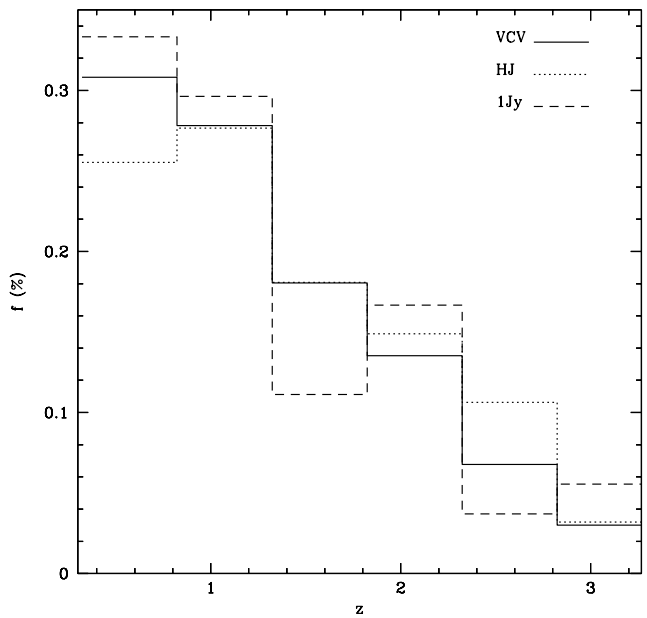

Figure 1. Redshift histograms for the VC (solid line), HJ (dashed line) and 1Jy (dotted line) samples. The vertical axis show the fraction of quasars in each redshift bin.

There are 35 VC quasars which do not belong to the HJ or 1Jy sample. They are steep-spectrum quasars fainter than the 1Jy catalog $S_5 > 1$ Jy limit, and are slightly brighter in the optical ($< B_J >= 17.50$) than the HJ sample. On the other hand, there are 8 HJ quasars which are not included in the VC sample. They are considerable fainter than the rest of the HJ sample, with $B_J > 18.6$ and $S_{2.7} < 0.8$.

The redshift distributions of the HJ, VC and 1Jy samples are shown in Fig 1. The distributions look rather similar, although the HJ quasars apparently tend to have slightly higher redshifts than the 1Jy ones. However, a Kolmogorov-Smirnov test shows that the difference between both distributions has only a 69% significance level. As Drinkwater et al. (1997) showed, the redshift distribution of the HJ catalog is very similar to that of optically selected samples, as the LBQS (Hewett, Foltz & Chafee 1995). Fig 2 displays the B_J histograms of the HJ, VC and 1Jy samples. Although VC and 1Jy quasars are slightly brighter than HJ ones, the difference is again not statistically significant. The cumulative number distributions $N(< B_J)$ of the $z > 0.3$ quasars in the HJ and 1Jy samples are shown in Fig. 3. They are much shallower than the corresponding distribution for optically-selected QSOs (Hawkins & Veron 1995). This fact was also noticed in BMG97 but since we were using a subsample of an incomplete catalog, it was not possible to distinguish between the effect of incompleteness and the intrinsic differences in the luminosity functions. The number

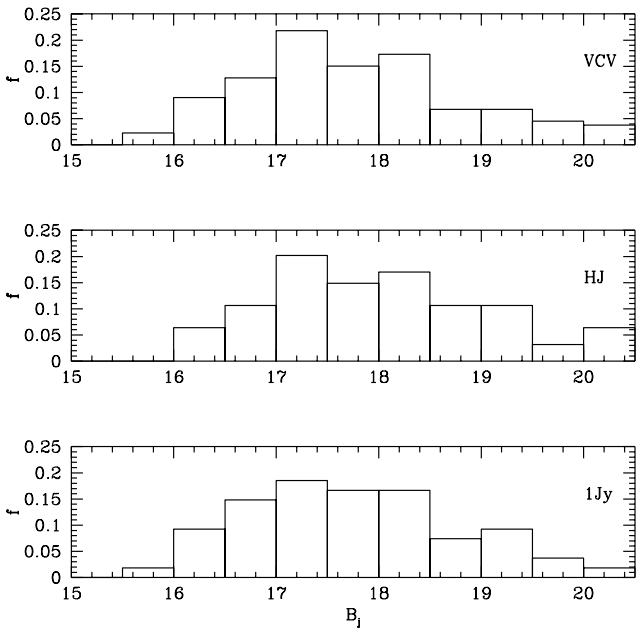

Figure 2. B_J histograms for the VC, HJ and 1Jy samples. The vertical axis show the fraction of quasars in each bin.

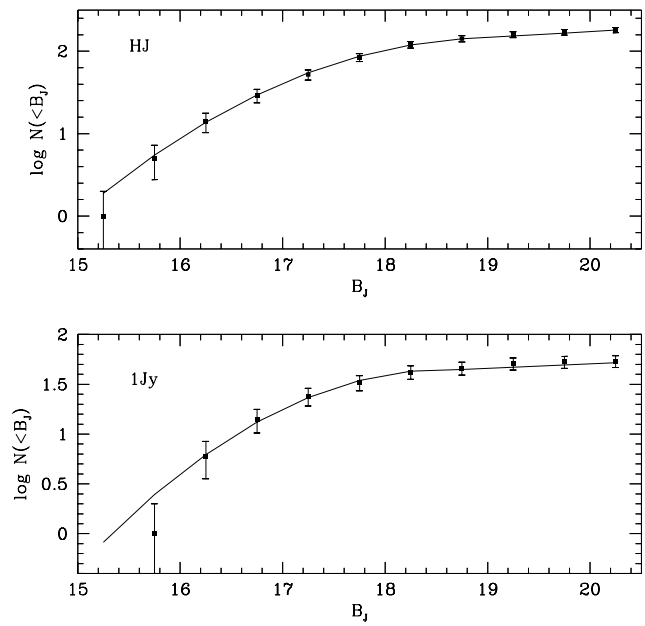

Figure 3. Cumulative number counts–magnitude distribution for the HJ and 1Jy samples. The solid lines are the least squares fits described in Sec 2

counts $N(< B_J)$ for the quasars are well fitted by a law of the form

$$\log N(< B_J) = \log N_B + a_1 \Delta B_J - a_2 \Delta B_J^2, \qquad \Delta B_J \leq 0$$

$$\log N(< B_J) = \log N_B + a_1 \Delta B_J, \qquad \Delta B_J \geq 0$$

where $\Delta B_J = B_J - 18.75$ and N_B is an arbitrary normalization. For the 1Jy sample $a_1 = 0.19$, $a_2 = 0.66$, whereas for the HJ sample, $a_1 = 0.11$, $a_2 = 0.77$. The above fits are plotted in Fig. 3.

The cumulative flux distribution of the $z > 0.3$ quasars in the HJ and 1Jy catalogs are shown in Figure 4. For the HJ sample

$$\log N(> S_{2.7}) = \log N_0 - 1.46 \log S_{2.7} - 0.36 (\log S_{2.7})^2 \quad (4)$$

and for the 1Jy sample

$$\log N(> S_5) = \log N_0 - 1.82 \log S_5 \quad (5)$$

where N_0 is an arbitrary normalization.

Therefore, at the flux limits of the HJ sample, $B_J = 20.5$ and $S_{2.7} = 0.5$Jy, we have that $(\alpha_e - 1)_{HJ} = 0.18 + 1.24 - 1 = 0.42$. For the 1Jy sample, $(\alpha_e - 1)_{1Jy} = 0.11 + 1.82 - 1 = 0.93$. The real value of $\alpha_e - 1$ is therefore $2 - 4$ times smaller than the values so far considered in the estimation of w_{qg} and q for the PKS sample (BMG97, Dolag & Bartelmann 1997), $\alpha_e - 1 = 1.8 - 2.2$.

3 STATISTICAL ANALYSIS

Spearman's rank order test has often been used to study the statistical significance of QSO-galaxy associations. For instance, in the implementation of Bartelmann & Schneider (1993a, 1994), all the individual galaxy fields around the quasars are merged into a single 'superfield', which is subsequently divided into N_{bins} annular intervals of equal surface. The rank order test determines whether the number of galaxies in each bin $n_i, (i = 1, N_{bins})$ is anticorrelated with the bin radius r_i. Here we have applied a variant of this test described in detail in BMG97. The field is divided into rings of fixed width $\Delta\theta$ and distance θ_i from the QSO, and the variables to be correlated are $w(\theta_i)$, the value of the empirical angular correlation in the $i-$bin, and θ_i. The results of several binnings are averaged to reduce the dependence of the significance on the particular choice of $\Delta\theta$. Extensive Montecarlo simulations show the robustness of this approach.

Table 1. Results of the weighted average test

Sample	N_Q	N_g	r_w	p_w
VC	133	12662	1.01375	99.55%
1Jy	54	5339	1.01537	97.09%
HJ	94	9243	1.01178	97.33%
HJ + 1Jy	106	10415	1.01200	97.84%
VC+HJ+1Jy	141	13577	1.01134	98.57%
VC "faint"	8	553	1.03805	93.43%
HJ "faint"	14	1309	0.99953	50.37%
"non-VC" HJ	8	915	0.97132	6.72%

N_Q is the number of QSOs in each sample, N_g the number of galaxies for which the w_{qg} is measured, r_w is the value of the normalized correlation coefficient (see text) and p_w the corresponding significance associated to the value of r_w.

The main advantage of this test is that it does not rely on any particular shape of the correlation function w_{qg}. It just tells us whether the distribution of galaxies is correlated with the positions of the QSOs. From it we find that the 1Jy sample shows a positive correlation with galaxies at a 99.0% confidence level. Note that the 1Jy 'North', $\delta > 0$ sample which is also practically complete and does not overlap with

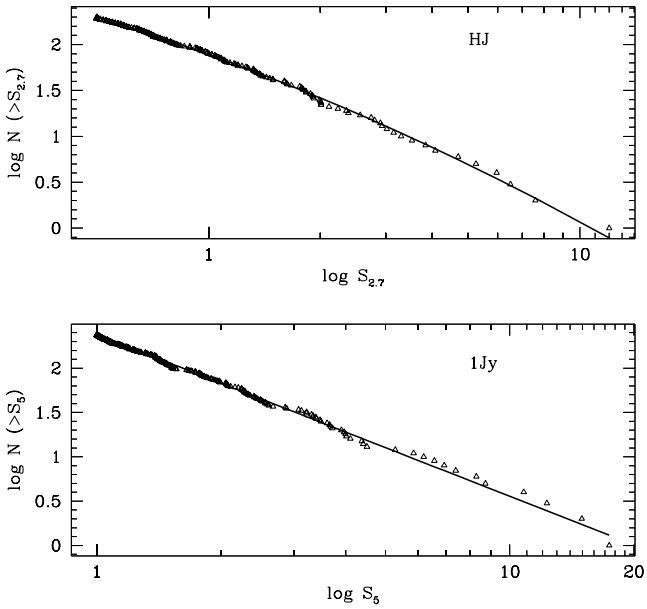

Figure 4. Cumulative number counts–flux distribution for the HJ and 1Jy catalogs (we include all the $z > 0.3$ quasars in the original Half-Jansky and 1Jy catalogs). The solid lines are least squares fits

the sample considered here, was found to be correlated with foreground APM galaxies at a 91.4% level (99.1% for the red galaxy sample Benítez & Martínez-González 1995; see also Norman & Williams 1999). A naive but conservative combination of both results yields $p > 99.9$ for the existence of positive correlations between the whole 1Jy catalog and foreground galaxies. The existence of correlation for the HJ sample is detected at a smaller significance level, $p = 84.1\%$.

To compare among the different samples we found more convenient the weighted average test of Bartsch et al. (1997). This test is based on the estimator r_g,

$$r_g = \frac{1}{N}\sum_{i=1}^{N} w_{qg}(\theta_i) \tag{6}$$

where N is the total number of galaxies and θ_i are the quasar-galaxy distances. Bartsch et al. (1997) showed that r_g is optimized to distinguish between a random distribution of galaxies around the quasars and a distribution which follows an assumed w_{qg}.

We will slightly modify the procedure of Bartsch et al. (1997) and use a normalized value of r_g, which we define as $r_w = r_g/I_{w_{qg}}$ where

$$I_{w_{qg}} = \frac{2\pi}{N}\int_{\theta_{min}}^{\theta_{max}} w_{qg}(\theta)\theta d\theta \tag{7}$$

Values of $r_w > 1$ will indicate a positive correlation, $r_w < 1$ negative, and $r_w = 0$ absence of correlation. If the galaxies are exactly distributed following w_{qg}, then r_g happens to be the Monte-Carlo integral of w_{qg}^2, i.e., $r_g \equiv I_{w_{qg}^2}$. Unlike Bartsch et al. (1997) we do not merge all the fields into one single superfield, but calculate r_w for each quasar and then found an average $< r_w >$ over all the sample. This avoids giving more weight to a field just because its galaxy density is higher, which could be due to star contamination.

We set $w_{qg} \propto \theta^{-0.688}$ as predicted by Benítez & Sanz (1999), and proportional to the galaxy angular correlation of the APM galaxies (Maddox et al. 1990). This test is very robust in the sense that it is only sensitive to changes in the shape of $w_{qg}(\theta)$; if we multiply this function by an arbitrary amplitude, the significance will not change. The values of r_w together with their significance level p_w, are listed in Table 1. The significance is established with 10000 sets of simulated fields each with the same number of randomly distributed galaxies as the real fields.

3.1 Is there an 'identification bias'?

From Table 1 we see that the VC sample, the one more similar to the PKS sample used in BMG97, has the higher significance level, $p_w = 99.55\%$ (the PKS itself has $p_w = 99.78\%$ using this test). However, the union of the VC, HJ and 1Jy samples, which includes only 8 more HJ quasars has a considerable lower value of r_w and of p_w. If we analyze separately these 8 "non VC" HJ quasars we see that they have $r_w = 0.97132$ and $p_w = 6.72\%$, i.e. they are strongly *anticorrelated* with foreground galaxies at the 93.28% level. However, if we look at the other seven HJ faint objects which have similar optical and radio fluxes ($B_J > 18.6$, $S_{2.7} < 0.8$) but were included in the VC catalog, they have $< r_w >= 1.03805$ and $p_w = 93.43\%$, that is, an excess much stronger than that detected for the full HJ sample. If we put together these 15 faint quasars, we get $r_w = 0.99953$, that is, practically no correlation whatsoever, positive or negative. Since magnitudes, radio-fluxes, absolute luminosities, redshifts and galactic latitudes are very similar for both faint "minisamples", the only remaining difference seems to be their inclusion in the '96 version of the Veron-Cetty & Veron catalog, something which only depends on the date when the quasars were identified. That happened in 1983 for the 7 VC quasars, whereas the "non-VC" redshifts were first published in Drinkwater et al. (1997). If we compare the values of r_w of the 8 "non-VC" objects with the rest of quasars (86) from the HJ sample, a Kolmogorov-Smirnov test shows that their r_w distributions are incompatible at the 99.31% level. This is rather puzzling, and barring a statistical fluke, the only remaining possibility seems to be something which might be called "identification bias": apparently the first radio sources to be spectroscopically identified in a catalog tend to be those in regions of higher galaxy density. It is possible that due to the positional uncertainty of the radio identifications, there was a tendency to start the identification of a radio catalog with those fields which have more "candidates" close to the radio position. Although in our case the samples are small, the differences among them are so significant that one must conclude that any results about quasar-galaxy associations obtained with incomplete catalogs should be considered with great caution.

The results of BMG97 are a good example: if we look at the 86 quasars in the HJ sample considered in that paper (where the 8 "non-VC" objects were not included) one obtains $r_w = 1.01554$ and $p_w = 99.14\%$. The total HJ sample gives $r_w = 1.01178$ and $p_w = 97.33\%$, as we see from Table 1. Although the galaxy excess does not disappear when we use the complete sample, the values of r_w and p_w drop ap-

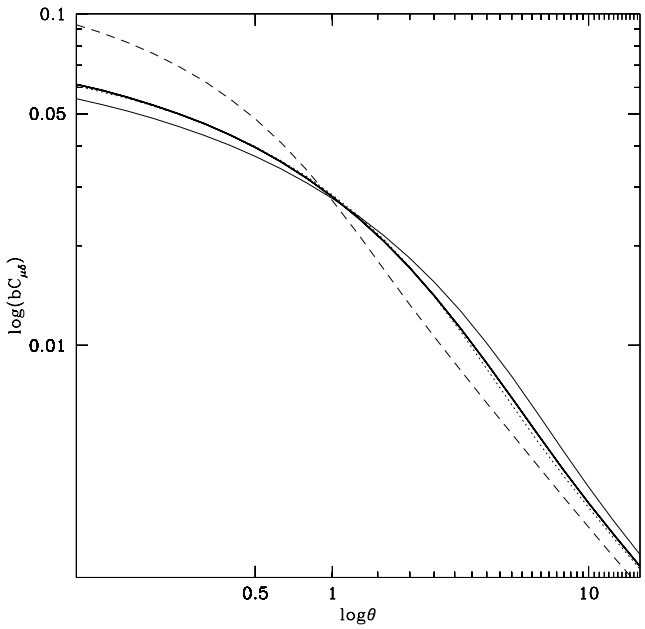

Figure 5. The product $bC_{\mu\delta}$ for several omega values, $\Omega_m = 0.1$(dashed), 0.4 (dotted) ,1 (solid thin line). The thick line is $< bC_{\mu\delta} >$.

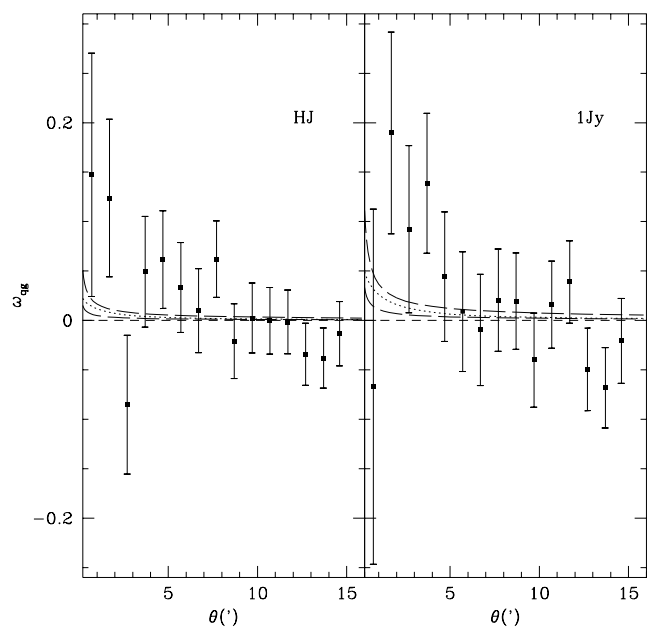

Figure 6. Quasar-galaxy correlation for the HJ (to the left) and 1Jy (to the right) samples. The error bars are poissonian and the bin width is approximately $1'$. The dotted line corresponds to $(\alpha_e - 1) < bC_\mu\delta >$ (see sec.4.1). The two dashed lines correspond to the estimation of w_{qg} of Sec. 4.2 with $\Omega/b = 0.3$ (lower) and $\Omega/b = 1$ (upper). We can see that in both cases the observed correlation is much larger than the expected one.

preciably. If this happens with a sample which was almost (86/94 = 91%) complete, results as those of Tyson (1986) , Hintzen et al. (1991), or Burbidge et al. (1990), which use QSO samples extracted from incomplete compilations as those of Hewitt & Burbidge (1980) and the Veron-Cetty & Veron (1984) catalogs, may be seriously biased, explaining the extremely strong amplitudes of w_{qg} found by these authors.

Therefore, it seems clear that valid samples for quasar-galaxy correlation measurements should be complete or randomly extracted (e.g., depending on the celestial coordinates) from complete catalogs, as the 1Jy and HJ. Note that the 1Jy has the highest value of r_w for the samples in Table 1, i.e. it is the most strongly correlated, in qualitative agreement with the magnification bias effect, although p_w is not very high due to the smaller size of the sample, which increases the statistical uncertainty.

4 COMPARISON WITH THEORY

To compare with theory, we shall assume that the biasing factor $b = \delta_g/\delta_m$ is approximately constant within the relevant angular range. Two estimates of w_{qg} will be considered, that of Sanz, Martinez-Gonzalez & Benítez (1997), which takes into account the nonlinear evolution of the power spectrum using the ansatz of Peacock & Dodds (1996), and the more recent estimation of Benítez & Sanz (1999).

4.1 Power spectrum-based estimate

In Sanz, Martínez-González & Benítez (1997) we showed that the the value of $C_{\mu\delta}$ in Eq. (1) practically does not change if, instead of using the real galaxy and quasar distributions for the calculations, it was assumed that all the galaxies and quasars were respectively placed at redshifts z_b and z_f. Our calculations are normalized to the cluster abundance (Viana & Liddle 1996) $\sigma_8 = 0.6\Omega^{-0.34+0.28\Omega-0.13\Omega^2}$

For consistency we have to normalize the large-scale biasing factor as $b = \sigma_8^{-1}$. As we saw above, $\omega_{qg} \propto bC_{\mu\delta}$, so this product contains all the information relevant to the dependence of ω_{qg} on Ω. The variation of b and of the amplitude of $C_{\mu\delta}$ with Ω somehow cancel and the product $bC_{\mu\delta}$ depends weakly on Ω, as it is shown in Fig 5, where we plot $bC_{\mu\delta}$ calculated using delta-functions for the galaxy and quasar distributions with $z_g = 0.15, z_q = 1.4$. We see that there are two different regimes for w_{qg}, one at small scales $\theta \leq 1'$ and the other at larger scales, $\theta > 2'$.

The dependence of w_{qg} on Ω at small scales can be approximated as

$$w_{qg} \approx A_s(\Omega) \log\theta + B_s$$

This fit is valid for the angular scales $0.1' < \theta < 1'$. $A_s(\Omega) = -0.029\Omega^{0.37\log\Omega}$ and B_s (which is equal to the value of w_{qg} at $1'$) is practically a constant, $B_s = 0.029 \pm 0.02$. A_s quickly drops as Ω grows, although the amplitude of the variation is relatively small, $A_s = 2.34$ at $\Omega = 0.1$ and $A_s = 1$ for a flat universe. At larger scales, $\theta >> 1'$, w_{qg} is reasonably well approximated by a law of the form

$$w_{qg} \approx A_l\theta^{-1}$$

The amplitude A_l also weakly depends on Ω, with $A_l =$

$0.029\Omega^{0.2}$, but unlike the situation on small scales, it grows with the value of Ω.

Since the variation of w_{qg} with Ω is small, the observations will only be compared with the product $(\alpha_e - 1) < bC_{\mu\delta} >$, where $< bC_{\mu\delta} >= \int_0^1 d\Omega bC_{\mu\delta}(\Omega)$. This comparison is shown in Fig 6a, where we plot w_{qg} as measured from the HJ and 1Jy samples. It is clear that the observed correlation is much stronger than the model prediction.

To estimate this mismatch we perform a maximum likelihood fit to the data of the form

$$w_{qg} = A(\alpha_e - 1) < bC_{\mu\delta} > \quad (8)$$

and leave A as a free parameter. We found that for the HJ sample $A = 12.7 \pm 6.5$, where the error limits enclose a 68% confidence interval, and $A > 1$ at the 98.40% level. The 1Jy sample also displays a much stronger correlation than expected: $A = 10.2 \pm 4.5$, and $A > 1$ at the 99.08% level. These results are not appreciably changed by varying $bC_{\mu\delta}(\Omega)$ within the range $0.1 < \Omega < 1$.

4.2 Model independent estimate

Benítez & Sanz (1999) propose a model-free estimation of w_{qg}, summarized in Eq. (2). We can only apply it approximately, since it assumes that the foreground and background galaxies are localized in 'thin' slices, with the angular cosmological distance practically constant. This is not strictly the case here, but a rough estimate can be found as $w_{qg} \propto w_{gg}$ and $A_{qg} \approx A_{gg}Q(z_f, z_b)\Delta z_f(\alpha - 1)\frac{\Omega}{b}$, where for z_b and z_f we will take the median values of the QSO ($z_b = 1.4$) and galaxy populations ($z_f = 0.15$) respectively. Also for the galaxies $\Delta z_f \approx 0.2$, $A_{gg} \approx 0.44$. Since the proportionality factor is $Q(0.15, 1.4) \approx 0.45$ (Benítez & Sanz 1999), and we expect to measure a correlation amplitude of $\frac{A_{qg}}{\alpha-1} \approx 0.04\frac{\Omega}{b}$. A maximum likelihood fit to the data using a function of the form $w_{qg} \propto A\theta^{-\gamma}$, taking a fixed $\gamma = 0.688$ and leaving A as a free parameter, yields $\frac{A_{HJ}}{\alpha_{HJ}-1} = 0.39 \pm 0.20$ and $\frac{A_{1Jy}}{\alpha_{1Jy}-1} = 0.31 \pm 0.14$, again much higher than expected. Given the redshifts of the background and foreground populations, including a cosmological constant Λ would not change significantly the results.

5 DISCUSSION

Although the observed results seem to qualitatively agree with the lensing hypothesis (for instance, the amplitude of w_{qg} divided by $\alpha_e - 1$ is almost constant for both the 1Jy and the HJ catalogs), they cannot be quantitatively reconciled with it. For instance, from the results of the above paragraph and the estimate of Benítez & Sanz (1999) one would need $\frac{\Omega}{b} \sim 10$. There seems to be plenty of evidence for $\Omega \simeq 1/3$ (see e.g. Bahcall et al. 1999), and therefore the above ratio would imply absurdly low values of the biasing parameter b. In spite of some hints of 'antibiasing' in low Ω LSS simulations (Jenkins et al. 1998), most measurements point at values of $b \approx 1$ for the APM galaxies (e.g. Frieman & Gaztañaga 1999), although on scales several times larger than the ones considered here ($R < 1.5h^{-1}$ Mpc at $z < 0.15$).

It seems difficult to believe that the weak lensing theory is wrong by an order of magnitude. For instance, the calculation by Williams (1999) taking into account second-order effects only changes in $\approx 10\%$ the first-order results. Are there other possible explanations for these high values of the QSO-galaxy correlation?

One option often considered is absorption by Galactic dust (Norman & Williams 1999). It is easy to see that this effect would lead to a positive correlation between galaxies and high-z quasars: Let's suppose that $\delta\tau(\theta)$ represents a (small) fluctuation of the galactic extinction in the sky. The induced fluctuations in the galaxy and quasar number density, δn_g and δn_q respectively would be $\delta n_q \approx -\alpha_q\delta\tau$ and $\delta n_g \approx -\alpha_g\delta\tau$, where α_q and α_g are the slopes of the optical number counts magnitude distributions of quasars and galaxies. Therefore,

$$w_{qg}^{\tau} =< \delta n_q \delta n_g >\approx \alpha_q\alpha_g C_{\tau\tau} \quad (9)$$

where $C_{\tau\tau}$ is the dust-dust correlation function in e.g. Schlegel, Finkbeiner, & Davis (1998). Although the quasar-galaxy correlation w_{qg}^{τ} also increases with the value of the slope α_q, there are significant differences with the correlation generated by the magnification bias effect: w_{qg}^{τ} is always positive, even for values of α_q smaller than 1. This could allow to distinguish between the contribution of each effect to the total correlation. The best observational results on $C_{\tau\tau}$ available so far, those of Finkbeiner, Schlegel & Davis (1998) do not resolve adequately the angular scales on which w_{qg} is measured in this paper. A tentative extrapolation of the $C_{\tau\tau}$ presented in the above mentioned paper is too flat to explain the measured correlations. Future measurements of $C_{\tau\tau}$ on small scales will serve to establish the contribution of w_{gg}^{τ} to the total, observed w_{gg}.

It is also interesting to explore the contribution to w_{qg} on relatively large scales, $> 1'$, from strong lensing effects. Let's suppose that a fraction f_S of the quasars in a sample is strongly lensed (not necessarily multiply imaged) by individual foreground galaxies. These galaxies, which will be very close to the quasar positions, are correlated with other galaxies, following a correlation function w_{gg}. If the typical quasar-lens distance is considerably smaller that the galaxy-galaxy correlation scale, this would indirectly cause a "strong-lensing" quasar–galaxy correlation $w_{qg}^S \sim f_S w_{gg}$. Since the "weak lensing" correlation estimated above is $w_{qg}^W \approx 0.02 - 0.04 w_{gg}$, relatively small values of f_S could generate a correlation w_{qg}^S of comparable amplitude. A quick inspection of the Digital Sky Survey images around the quasars in the HJ sample reveals several cases of very close, $\theta <$ few arcsec 'associations' in a sample of ~ 100 quasars. Unfortunately, and due to the poor quality of these images (some of the 'associated' objects may be stars or defects), it is difficult to give an exact value of f_S for this sample. However, if an appreciable fraction of these objects are galaxies, this effect would contribute significantly to the total amplitude of w_{qg}. Obviously this point merits a more detailed consideration with improved observations.

Last but not least, another possibility is that the observed correlation w_{qg} is affected by unforeseen systematic effects, or due to a statistical fluke. This sounds very unlikely given the variety of quasar and galaxy catalogs considered in w_{qg} studies (Benítez 1997). But it should not be forgotten that many of the positive results reported in the

literature are based on bright, radio–loud quasars, and they are so scarce in the sky that overlaps among the samples are unavoidable.

As in most scientific controversies, the solution will eventually come from more and better data: ongoing surveys as the Sloan Digital Sky Survey (Gunn & Weinberg 1995) or the 2dF (Folkes et al. 1999) will provide huge QSO and galaxy catalogs, from which it will be possible to select complete samples well suited to measure w_{qg}.

6 CONCLUSIONS

Gravitational lensing predicts an enhancement of the density of background QSOs around foreground galaxies. We measure this QSO—galaxy correlation w_{qg} for two *complete* samples of radio-loud quasars, the southern 1Jy and Half-Jansky samples. The existence of a positive correlation between distant $z \sim 1$ quasars and $z \approx 0.15$ galaxies is confirmed at a $p = 99.0\%$ significance level ($> 99.9\%$ if previous measurements on the northern hemisphere are included). A comparison with the results obtained for incomplete quasar catalogs (e.g. the Veron-Cetty and Veron compilation) suggests the existence of an 'identification bias', which spuriously increases the estimated amplitude of w_{qg} for incomplete samples. This effect could explain most of the very strong quasar–galaxy statistical associations found in the literature. Nevertheless, the value of w_{qg} that we measure in our complete catalogs is still considerably higher than the predictions from weak gravitational lensing theory. Including the effects of strong lensing could help to explain this discrepancy.

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REFERENCES

Bahcall, N. A., Ostriker, J. P., Perlmutter, S. & Steinhardt, P. J. 1999, Science, 284, 1481
Bartelmann, M. 1995, A&A, 298, 661
Bartelmann, M. & Schneider, P. 1993a, A&A, 268, 1
Bartelmann, M. & Schneider, P. 1993b, A&A, 271, 421
Bartelmann, M., & Schneider, P. 1994, A&A, 284, 1
Bartsch, A., Schneider, P. & Bartelmann, M., 1997, A&A, 319, 375
Benítez, N. 1997, PhD. thesis, Universidad de Cantabria
Benítez, N., & Martínez-González, 1995, (BMG95) ApJLett, 339, 53
Benítez, N., & Martínez-González, 1997, (BMG97) ApJ, 477, 27
Benítez, N., Martínez-González, E., González-Serrano, J.I., & Cayón L. 1995, AJ, 109, 935
Benítez, N., Martínez-González, E. & Martín-Mirones, J. M. 1997, A&A, 321, L1
Benítez, N. & Sanz, J. L. 1999, ApJLett, 525, L1
Borgeest, U., von Linde, J., Refsdal, S. 1991, A&A, 251, L35
Boyle, B.J., Fong, R. & Shanks, T. 1988, MNRAS, 231, 897
Burbidge, G., Hewitt, A., Narlikar, J. V. & Gupta, P. D. 1990, ApJS, 74, 675
Canizares, C. R. 1981, Nature, 291, 620
Crampton, D. , Cowley, A. P. & Hartwick, F. D. A. 1989, ApJ, 345, 59
Croom, S. M. & Shanks, T. 1999, MNRAS, 307, L17
Dolag, K. & Bartelmann, M. 1997, MNRAS, 291, 446
Drinkwater, M. J., Webster, R. L., Thomas, P. A. & Millar, E. 1992, Proceedings of the Astronomical Society of Australia, 10, 8
Drinkwater, M. J., et al. 1997, MNRAS, 284, 85
Ferreras, I. , Benítez, N. & Martínez-González, E. 1997, AJ, 114, 1728
Finkbeiner, D. P., Schlegel, D. J. & Davis, M. 1998, Berlin Springer Verlag Lecture Notes in Physics, v.506, 506, 367
Folkes, S. , et al. 1999, MNRAS, 308, 459
Frieman, J. A. & Gaztañaga, E. 1999, ApJLett, 521, L83
Fugmann, W. 1988, A&A, 204, 73
Fugmann, W. 1990, A&A, 240, 11
Gunn, J. E., & Weinberg, D. H. 1995, in Wide-Field Spectroscopy and the Distant Universe, ed. S. J. Maddox & A. Aragón-Salamanca (Singapore: World Scientific)
Hammer, F. & Le Fevre, O. 1990, ApJ, 357, 38
Hartwick, F.D.A & Schade, D. 1990, ARAA, 28, 437
Hawkins, M. R. S. & Veron, P. 1995, MNRAS, 275, 1102
Hewett, P.C., Foltz, C.B.& Chafee, F.H., 1995, AJ, 109, 1498
Hewitt, A. & Burbidge, G. 1980, ApJS, 43, 57
Hintzen, P., Romanishin, W., & Valdés, F., 1991, ApJ, 371, 49
Jenkins, A., et al. 1998, ApJ, 499, 20
Keeton, C. R., Kochanek, C. S. & Falco, E. E. 1998, ApJ, 509, 561
Maddox, S. J., Efstathiou, G., Sutherland, W. J. & Loveday, J. 1990, MNRAS, 242, 43P
Maoz, D., 1995, ApJ, 455, 115
Narayan, R. 1989, ApJLett, 339, L53
Norman, D. J. & Impey, C. D. 1999, AJ, 118, 613
Norman, D.J. & Williams, L.L.R. 1999, astro-ph/9908177
Peacock, J. A. 1982, MNRAS, 199, 987
Peacock, J. A. & Dodds, S. J. 1996, MNRAS, 280, L19
Rodrigues-Williams, L. L. & Hogan, C. J. 1994, AJ, 107, 451
Romani, R. W. & Maoz, D. 1992, ApJ, 386, 36
Sanz, J. L., Martínez-González, E. & Benítez, N. 1997, MNRAS, 291, 418
Schlegel, D. J., Finkbeiner, D. P. & Davis, M. 1998, ApJ, 500, 525
Schneider, P., Ehlers, J., & Falco, E.E. 1992, Gravitational Lenses (Heidelberg: Springer)
Seitz, S. & Schneider, P. 1995, A&A, 302, 9
Smith, R.J., Boyle, B.J.& Maddox, S.J., preprint astro-ph/9506093
Stickel, M., Meisenheimer, K., & Kühr, H. 1994, A&AS, 105, 211
Stickel, M., Rieke, M.J., Rieke, G.H. & Kühr, H. 1996, A&A, 306, 49
Thomas, P.A., Webster, R.L., & Drinkwater, M.J. 1994, MNRAS, 273, 1069
Tyson, J.A., 1986, AJ, 92, 691
Webster, R.L., Hewett, P.C., Harding, M.E., & Wegner, G.A. 1988, Nature, 336, 358
Williams, L. L. R. & Irwin, M. 1998, MNRAS, 298, 378
Williams, L.L.R. 1999, submitted to ApJ, astro-ph/9908318
Wright, A. & Otrupcek, R.E. PKSCAT90: Radio Source Catalogue and Sky Atlas (Australia Telescope National Facility, Epping, NSW, 1990)
Veron-Cetty, M. -P. & Veron, P. 1984, ESO Scientific Report, Garching: European Southern Observatory (ESO), 1984,
Veron-Cetty, M.P. & Veron, P., 1996, European Southern Observatory Scientific Report, 17, 1
Viana, P. T. P. and Liddle, A. R. 1996, MNRAS, 281, 323
Yentis, D.J, Cruddace, R.G., Gursky, H., Stuart, B.V., Wallin, J.F., Mac-Gillivray, H.T. & Thompson, E.B., 1992, Digi-

tised Optical Sky Surveys, Ed. H.T. Mac-Gillivray and E.B. Thompson, Kluwer,Dordrecht, 67