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# QSO–Galaxy Correlations: Lensing or Dust?

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**Abstract:** We present evidence for an anti-correlation between faint QSOs and $B < 23$ galaxies. A sample of 192 QSOs in a 2.5 deg$^2$ area has been imaged using the Isaac Newton Telescope Wide-Field Camera. The cross-correlation signal is of a similar amplitude to the galaxy auto-correlation function at the limit of $B < 23$, but is negative in sign. As fainter galaxies are selected the negative correlation signal becomes less significant, until the signal is effectively zero at $B < 26$. We propose two alternate explanations for the observed effect. The first is gravitational lensing of the faint background QSOs, which have a flat number count slope. However, the lensing signal is significantly higher than expected in conventional models. The second possibility is that inter-galactic dust absorption is responsible. A reddening of only $E(B - V) \simeq 0.02$ is required to produce the observed correlation. The large 2dF and SDSS QSO surveys should allow a definitive solution to the question of QSO–galaxy correlations.

**Keywords:** gravitational lensing — galaxies: statistics — quasars: general — dust, extinction

## 1 Introduction

Many authors have found evidence of correlations between galaxies (or clusters of galaxies) and background QSOs (e.g. Tyson 1986; Fugmann 1988; Bartelmann & Schneider 1993; Rodrigues-Williams & Hogan 1994; Wu & Han 1995). A natural explanation is that these associations are due to gravitational lensing, which can provide either a positive or negative correlation between foreground lenses and a flux limited background population, depending on the form of the background number count faintward of the sample flux limit. For a number count of the form $N(<m) \propto 10^{\alpha m}$ a steep ($\alpha > 0.4$) slope causes a positive correlation, while a flat ($\alpha < 0.4$) slope causes a negative correlation. QSOs show both steep (at $B \lesssim 19.5$) and flat (at $B \gtrsim 19.5$) number count slopes. A problem with most QSO–galaxy correlation measurements is that the amplitude of the correlation (both positive and negative) is a factor of ~2–5 greater than expected from lensing in an $\Omega_0 = 1$ universe (e.g. Williams & Irwin 1998; Croom & Shanks 1999). An alternative is that patchy dust extinction in our own Galaxy could cause some of the observed positive correlation between QSOs and galaxies. However, negative correlations require inter-galactic dust associated with the foreground lenses, making a dust explanation appear rather contrived.

Here we use data from the Isaac Newton Telescope Wide-Field Camera (INTWFC) to cross-correlate galaxies with faint QSOs. A more in-depth discussion of this work will be given in Croom & Shanks (2001), which will also include further modelling of the cross-correlation results. The QSOs in this study were taken from a number of deep optical and X-ray surveys (Boyle, Jones & Shanks 1991; Almaini 1996; Crampton, Cowley & Hartwick 1989; Koo, Kron & Cudworth 1986; Boyle et al. 1990; McHardy et al. 1998), the main aim being to have a large number of QSOs within the field of view of the INTWFC. The redshift distribution of the QSOs is shown in Figure 1.

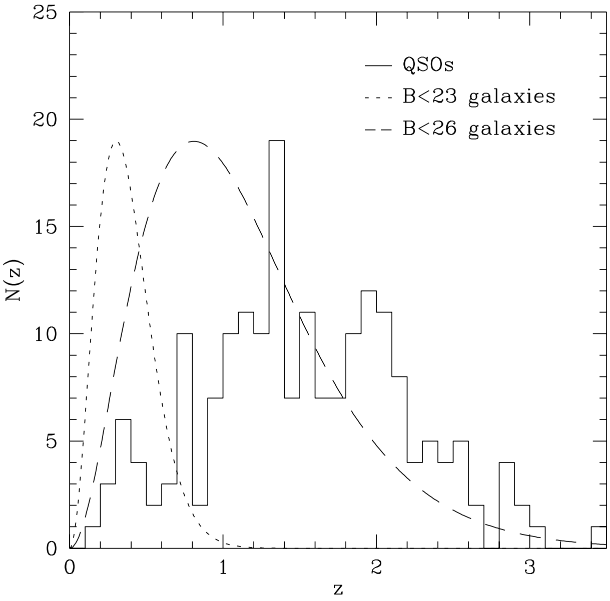

**Figure 1** The redshift distribution of QSOs used in our analysis (solid line), compared to model redshift distributions of galaxies with $B < 23$ mag (dotted line) and $B < 26$ mag (dashed line). The normalization of the Galaxy $N(z)$ distributions is arbitrary.

We observed a total area of 2.5 deg$^2$ in B–band with the INTWFC, containing a total of 192 QSOs. Galaxy catalogues were produced using SEXTRACTOR (Bertin & Arnouts 1996). Typical $5\sigma$ detection limits were equivalent to an isophotal magnitude of $B_{\rm ccd} = 27$–$27.5$. The total magnitude at which all objects are detected at $\geq 3\sigma$ is typically $B_{\rm ccd} = 25.5$–$26$, which forms our completeness limit.

## 2 Theoretical Expectation

For a QSO number count of the form $N(<m) \propto 10^{\alpha m}$, gravitational lensing causes a cross-correlation between

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galaxies and QSOs of the form $\omega_{\rm qg}(\theta) = b_{\rm g}(2.5\alpha - 1) \times \omega_{\mu\delta}(\theta)$ in the weak lensing regime. Note, we assume that the intrinsic number count slope is not significantly modified by the lensing, this is reasonable given the flat number count slope of the faint QSOs considered here (Hamana, Martel & Futamase 2000). $b_{\rm g}$ is the linear bias of the foreground galaxies and $\omega_{\mu\delta}(\theta)$ is the cross correlation function between the magnification, $\mu$, and the density contrast, $\delta$. Bartelmann (1995) has shown (see also Bartelmann & Schneider 1999) that $\omega_{\mu\delta}(\theta)$ is an integral over the mass power spectrum, $P(k)$, and the radial distributions of the QSOs and galaxies.

The observed galaxy auto-correlation function is $\omega_{gg} = b_g^2\omega_{\delta\delta}$. The mass correlation function, $\omega_{\delta\delta}$, is an integral over $P(k)$ and the radial distribution of galaxies (Limber 1953). When we take the ratio $\omega_{\mu\delta}/\omega_{\delta\delta}$ to first order the integrals over the $P(k)$ cancel such that the ratio is constant (to $\sim$1 − 2 per cent) as a function of $\theta$ on scales of interest. This makes it easy to compare QSO–galaxy cross-correlations to galaxy–galaxy auto-correlations via

$$\frac{\omega_{\rm qg}(\theta)}{\omega_{\rm gg}(\theta)} = \frac{(2.5\alpha - 1)}{b_{\rm g}}\frac{\omega_{\mu\delta}(\theta)}{\omega_{\delta\delta}(\theta)}. \qquad (1)$$

We assume a $\Gamma_{\rm eff} \simeq \Omega h = 0.25$ CDM power spectrum, allowing for non-linear effects using the empirical fits of Peacock & Dodds (1996). We also assume that $b_{\rm g}$ denotes the average linear bias of the population considered. We use the galaxy redshift distributions shown in Figure 1, which are analytic models of the form $N(z) \propto z^2 \exp[-(z/z_{\rm c})^\beta]$ (e.g. Baugh & Efstathiou 1993), with parameters $z_{\rm c}$ and $\beta$ chosen to match the redshift distributions found by Glazebrook et al. (1995) at $B < 23$ ($\beta \simeq 1.5$ and $z_{\rm c} \simeq 0.25$), and Fernández-Soto, Lanzetta & Yahil (1999) at $B < 26$ ($\beta \simeq 1.15$ and $z_{\rm c} \simeq 0.5$). We note that the exact form of the redshift distribution makes little difference to the expected lensing amplitude. The above redshift distribution for $B < 23$ gives $\omega_{\mu\delta}/\omega_{\delta\delta} \simeq 0.21$ and 0.09 for the EdS and $\Lambda$ cosmologies respectively. We use the Infante & Pritchet (1995) measurement of the auto-correlation function of $B < 23$ galaxies, $\omega_{\rm gg}(\theta) = (0.045 \pm 0.004)\,\theta^{-0.8}$ with $\theta$ in arcmins, to make our comparisons. We fit a −0.8 power law to the observed $\omega_{\rm qg}$ to determine the ratio $\omega_{\rm qg}/\omega_{\rm gg}$ and thus derive $(2.5\alpha - 1)/b_{\rm g}$ via Equation 1.

An alternative explanation for a cross-correlation signal is that dust associated with the foreground galaxies causes extinction in the QSOs, so that less are found nearby the galaxies. The extinction in the B–band is $A_{\rm B}$, with $A_{\rm B} = x(z)E(B - V)$, where $E(B - V)$ is the measured reddening, and $x(z) = A_\lambda/E(B - V)$ is a function of the redshift of the absorbing material. At $z = 0$, $x(0) = 4.0$ for absorption in the B–band. At higher redshift, the observed B–band is moved into the UV, so that for a given column of dust, the extinction will be greater. When integrating over the $n(z)$ distribution for $B < 23$ galaxies the mean value of $A_\lambda/E(B - V)$ for the observed $B$–band is 5.57. If $\alpha A_{\rm B} \ll 1$ then the cross-correlation due to inter-galactic dust is $\omega_{\rm qg}(\theta) \simeq -\alpha A_{\rm B} \ln(10)$, with $A_{\rm B}$ a function of $\theta$. The amount of dust required depends on the steepness of the QSO number counts slope.

## 3 QSO–Galaxy Cross-Correlations

The cross-correlation function between QSOs with $z > 1$ and galaxies with $B < 23$ is shown in Figure 2a (the samples were chosen for minimal redshift overlap). The dotted line is the amplitude of the integral constraint correction due to our normalisation of the density by the number of galaxies in the field. This is derived assuming

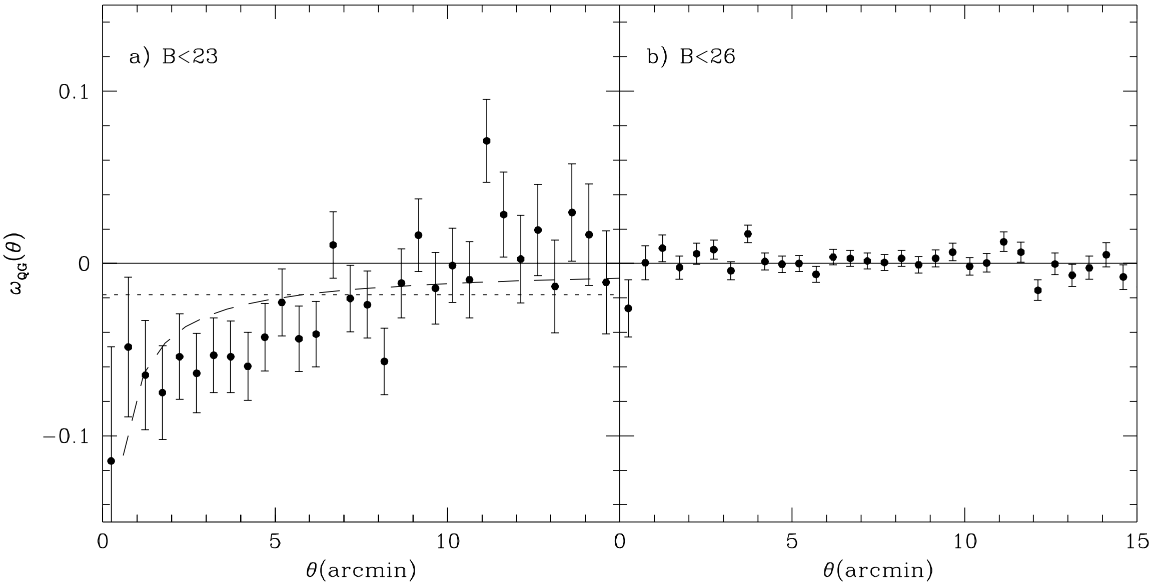

**Figure 2** Angular cross-correlation function between QSOs with $z \leq 1$ and galaxies limited to $B_{\rm ccd} < 23$ (a) and 26 (b). The data are are plotted after inclusion of the integral constraint. The dotted line indicates the amplitude of the integral constraint, which is too small to be visible in (b). The dashed line in (a) is the best fit −0.8 power law.

$\omega(\theta) = A\theta^{-0.8}$, from which we find the integral constraint to be $(6.5 \pm 0.1)A$. When fitting the data we therefore fit $\omega(\theta) = A(\theta^{-0.8} - 6.5)$. The best fit model has $A = 0.0028 \pm 0.0006$. Using Equation 1 this then implies that $(2.5\alpha - 1)/b_g = -7.8 \pm 0.7$ (EdS) or $-18.3 \pm 1.6$ ($\Lambda$). For realistic values of $\alpha$ ($\sim$0.2 for the QSO samples used) this implies a bias $b_g < 0.1$, an order of magnitude smaller than expected in standard models.

If we consider a dust interpretation, then we see that $A_B$ must be a function of $\theta$, but on scales $\sim$1–5$'$ we find $\omega_{qg}(\theta) \simeq -0.06$. This would imply $A_B \simeq 0.13$ ($\alpha = 0.2$), and therefore $E(B - V) \simeq 0.02$. This reddening is within the upper limit of $E(B - V) < 0.06$ (90%) found by Ferguson (1993) in clusters and groups. There appears to be a significant anti-correlation out to $\simeq 8'$, which corresponds to a physical scale of $\sim$1.2–1.3 $h^{-1}$ Mpc (depending on the cosmological model used) at the median redshift of the $B < 23$ galaxies, $z_{med} \simeq 0.25$. This is a scale typical of galaxy clusters, although currently there are no direct detections of intra-cluster dust distributed on these scales. However, there is tentative evidence of dust in the central parts of the Coma cluster (within $\sim$0.1 $h^{-1}$ Mpc) from ISO observations, with a reddening of $A_V \sim$0.01–0.26 mag inferred (Stickel et al. 1998).

At fainter flux limits ($B < 26$), we see that the anti-correlation disappears (see Figure 2b). First, this is good evidence that the $B < 23$ anti-correlation is not caused by any systematic errors in the galaxy catalogue. It appears that whatever the source of the anti-correlation with the brighter galaxies, it is compensated for by those fainter than $B = 23$. A randomly distributed population at $23 < B < 26$ is sufficient to remove the anti-correlation, due to the larger number of faint galaxies. As the redshift distribution of the $B < 26$ galaxies and the QSOs is likely to be similar (Figure 1), both the lensing and dust effects will be reduced. We will present detailed models describing this effect in Croom & Shanks (2001).

A much clearer conclusion will be available soon with large, homogeneous QSO surveys such as the 2dF QSO Redshift Survey (Croom et al. 2001) and the Sloan Digital Sky Survey (York et al. 2000) which will be analysed as a function of luminosity, as the break in the QSO number count is a good probe of the physics behind these correlations. These new large data sets will have sufficient numbers of QSOs to show whether the correlation changes sign as it goes past the break, as expected in lensing, or only changes in amplitude, as in a simple dust model.

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