ASSOCIATION OF DISTANT RADIO SOURCES AND FOREGROUND GALAXIES

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Abstract. A statistically significant (99.1%) excess of red galaxies from the APM Sky Catalogue is found around a sample of $z \sim 1$ 1Jy radio sources. The most plausible explanation for this result seems to be the magnification bias caused by the weak gravitational lensing of large scale structures at intermediate redshifts.

1. Introduction

The existence of statistically significant associations of foreground objects with high redshift AGNs, on scales ranging from a few arcseconds to $\sim 30'$, is a fact confirmed by several authors (Webster et al. 1988, Fugmann 1990, Hammer & Le Fèvre 1990, Thomas et al. 1995, Benítez et al. 1995, Seitz & Schneider 1995), and explained as a consequence of the magnification bias due to gravitational lensing by structures with sizes varying from galaxies to matter overdensities on scales at least as large as clusters of galaxies or even larger (Pei 1995, Bartelmann 1995). This effect is described by the expression $n_A(S) = n'_A(S/\mu)/\mu$, where $n_A(S)$ is the observed cumulative number density, μ is the magnification, and n'_A is the unlensed number density which is usually assumed to have the form $n'_A(S') \propto (S')^\alpha$, S' being the AGN flux in absence of magnification. Depending on the slope of the number counts of background sources, we may observe positive, insignificant or negative statistical associations of these foreground objects with background sources like distant AGNs (see Bartelmann 1995, Seitz & Schneider 1995). Radio-selected samples of high-redshift objects present a rather steep slope in their number counts-flux distribution and are thus

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very appropriate for trying to detect excesses of foreground objects due to the magnification bias.

Here we shall report the results of a study of the distribution of galaxies taken from the APM Sky Catalogue around a sample of AGNs from the 1Jy catalogue (Stickel et al. 1994). A full-length account of this investigation can be found in (Benítez & Martínez-González 1995).

2. The Data

The 1Jy catalogue of radio-sources is described in Stickel et al. (1994). It has been often and successfully used to prove the existence of correlations between several catalogues of foreground objects and distant AGNs (Fugmann 1990, Seitz & Schneider 1995, Bartelmann & Schneider 1994).

The APM Sky Catalogue, described in Irwin & McMahon (1992) and Irwin et al. (1994), contains all the objects found by an automatic detection algorithm on the scans of the O (equivalent to $U+B$) and E (corresponding to a narrow R) Palomar Sky Survey plates.

Our AGN sample amounts to 73 QSOs and radio galaxies from the 1Jy catalogue with $0.5 < z < 1.5$ and declination $\delta > 0$, and around which there are available $90' \times 90'$ APM fields with at least 2/3 of the total surface within one POSS plate.

We first considered the APM Sky Catalogue objects contained in these fields which are classified as galaxies and have $O < 19.5, E < 21$. Our chosen magnitude limits are 0.5 mag brighter than the limiting magnitudes on each band quoted by Irwin and collaborators. Number counts-magnitude plots show that they can be reasonably considered as completion limits in the sense that fainter than these limits the number counts-magnitude relation suddenly becomes steeper and spurious detections begin to dominate the number counts.

In order to exclude as many spurious galaxies as possible, we require our objects to be detected and classified as galaxies in both the red *and* blue bands. This discards $\approx 40 - 50\%$ of the objects at magnitudes below our completion limits. At brighter magnitudes ($E < 18$), most of them are objects classified as galaxies in one band and as stars or merged objects in the other. This is not surprising if we remember that the classification of the objects in the APM Sky Catalogue is an automated procedure and that the pixel resolution is rather low. At fainter magnitudes we are also losing many galaxies that due to their colors cannot be detected in both bands. Nevertheless, the procedure followed is necessary in order to obtain a sufficiently homogeneous sample.

The galaxy sample is thus finally formed by the $\approx 35,000$ APM Sky Catalogue objects contained in 73 fields which are classified as galaxies in *both* the *O and E* bands, $O < 19.5$, $E < 21$.

We performed two tests in order to check for the existence of systematic gradients over the fields. First, we divided each field into four $45' \times 45'$ boxes, added the number of galaxies found in each of these boxes over all the fields and compared among them. Second, we considered the number of objects within the central part of all the fields containing half of the total $5400'' \times 5400''$ surface (excluding a central $1000'' \times 1000''$ region which contains most of the excess) and compared it with the number of objects in the outer half. In both cases there is good agreement with a $\sqrt{N}$ Poissonian dispersion, what confirms the homogeneity of the fields on average.

3. Main results and discussion

We shall look for density enhancements on a certain scale l using the following method. The fields are divided into boxes of size l^2 and the density enhancement on each box is defined as

$$q_{ij} = \frac{\sum_f n_{ij}^f}{\sum_f \frac{s_{ij}^f N^f}{S^f}}$$

where n_{ij}^f and s_{ij}^f are respectively the number of galaxies and the useful surface in the box ij of the field f, N^f is the total number of galaxies in a field and S^f is its total useful surface area.

The statistical significance of the result is estimated through the empirical probability p, $p = N_{less}/N_{total}$, where N_{less} is the number of boxes (not including the central one) with a value of q less than or equal to that of the central box, and N_{total} is the total number of boxes in the field.

We have found that p is always similar or smaller than the value of the significance obtained using the empirical rms (which is a factor of $1.2 - 1.4$ times the one deduced from Poissonian statistics (Benítez et al. 1995)) and assuming a Gaussian distribution.

Table 1 lists the results for scales of $500''$ and $1000''$and different colors. The excess is not very prominent when we consider *all* the galaxies with $E < 19.5$ and $O < 21$, but if we select only the reddest galaxies with $O-E > 2$, the value of the density enhancement in the central box dramatically increases and reaches the highest value of all the $500'' \times 500''$ boxes in the field, $q = 1.298 \pm 0.114$ (rms error), corresponding to an empirical p of 99.1%.

This behavior agrees well with elementary considerations. Gravitational lens theory (Schneider et al. 1992) shows that background objects with redshift $z_s \approx 0.5 - 1.5$ are most efficiently magnified by foreground lenses with $z_l \approx 0.2 - 0.4$. Most types of M^* galaxies at these redshifts will have

TABLE 1. Data for the central box

$O-E$	500 arcsec		1000 arcsec	
all	1.109 ± 0.078,	91.4%	1.028 ± 0.041,	71.7%
>1	1.122 ± 0.082,	92.3%	1.039 ± 0.047,	83.9%
>2	1.298 ± 0.114,	99.1%	1.089 ± 0.059,	91.7%

colors $O - E \gtrsim 2$ ($H_0 = 50, \Lambda = 0, \Omega = 1$). M^* and k-corrections are taken from Driver et al. (1994), and we have used the relationship $O - E \approx 2(B-V)$ quoted in Irwin & McMahon (1992). Besides, at any given redshift, early type galaxies tend to concentrate toward cluster cores. Therefore, if we constrain the galaxies to have $O - E > 2$, we are selecting the ones in the deeper potential wells and at the redshifts most efficient for lensing. This increases the excess, which is otherwise diluted in projection among the objects not contributing so strongly to the lensing effect, and makes it more easily detectable. The scale at which the density enhancement is more significant, $500''$, corresponds to $\approx 2-3$ Mpc at redshifts of $z = 0.2 - 0.4$.

In order to show the dependence of the excess with the angular scale we plot the AGN-galaxy cross-correlation function

$$\omega_{AG}(\theta) = \frac{\sum_f N_G^f(\theta)}{\sum_f N_{exp}^f(\theta)} - 1$$

where $N_G^f(\theta)$ is the number of galaxies found in the annular bin θ of the field f and $N_{exp}^f(\theta)$ is its expectation value based on the number of objects on the whole field normalized to the useful surface of the bin, for the galaxies with $O < 21, E < 19.5$ and $O - E > 2$ (figure 1) as a function of the bin radius in arcsec. The error bars are Poissonian $\sqrt{N}$. The previous results can be confronted with the theoretical expectations of galaxy-QSO cross-correlations $\omega_{QG}(\theta)$ produced by weak and moderate gravitational lensing. Bartelmann (1995) has calculated the expected cross-correlation for samples of galaxies with different depths and AGN catalogues simulating the 1Jy, within a CDM cosmogony. The value of the parameter q on a scale of 500 $''$ in the case of no color constraint on the APM galaxies (see table1) agrees marginally with his results. In any case, as Bartelmann expected, the amplitude is not significantly different from zero due to the small number of AGNs considered and the rather bright magnitude limit of the APM galaxies, which shows how the detectability of the magnification bias is dramatically increased by a color cutoff in the galaxy sample.

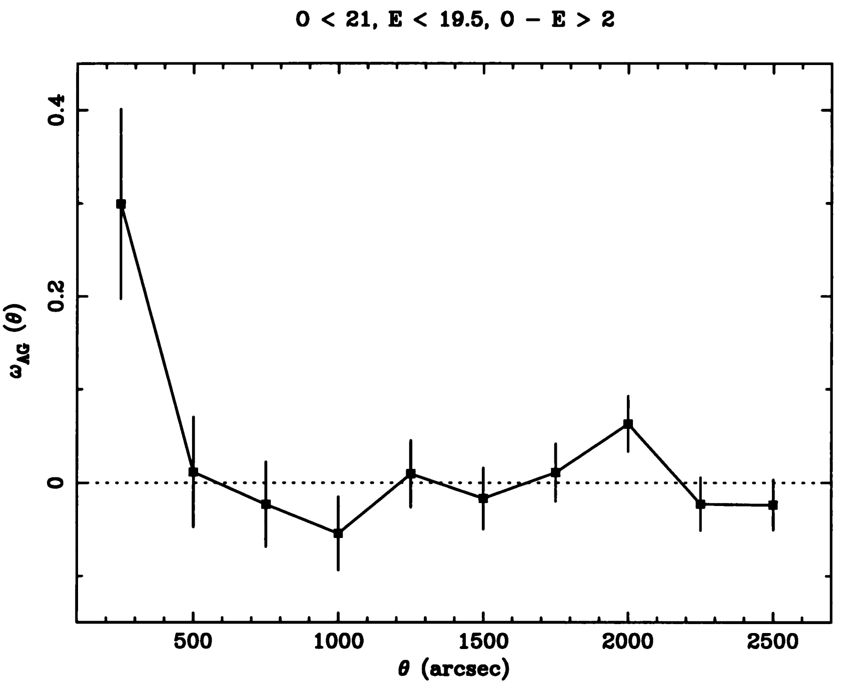

Figure 1. The cross-correlation function between 1Jy AGNs with $0.5 < z < 1.5$ and APM galaxies with $E < 19.5$, $O < 21$ and $O - E > 2$.

We have also tried to measure the effect of imposing a double flux limit by setting a cutoff on the optical magnitude of the AGNs. It seems that there is a tendency towards greater overdensities for AGNs with brighter optical magnitudes, but this constraint reduces the sample and lowers the statistical significance, which makes the results inconclusive. Larger samples are needed in order to better establish this effect.

The observed overdensity of foreground galaxies around high-redshift AGN seems to be a result gravitational lensing by large scale structure and is very difficult to reconcile with other proposed explanations such as obscuration by dust. The latter should produce the opposite effect: the objects forming the excess around high redshift AGNs would even tend to be bluer than the average, as they would be less reddened by dust.

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