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Very close pairs of quasi-stellar objects

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Abstract. It is pointed out that there are now known four very close pairs of QSOs with separations $<$ 5 arcsec and very different redshifts. Several estimates indicates that the probability that they are accidental con gurations are small; a conservative estimate of the probability to have four such pairs by random projection yields 3.5×10^{-3}. We conclude either that this is further evidence that QSOs have signi cant non-cosmological redshift components, or that the pairs must be explained by gravitational lensing.

Key words: quasi-stellar objects galaxies: redshifts { gravitational lensing

1. Introduction

If QSOs have redshifts entirely of cosmological origin and are randomly distributed in space, we shall expect to nd very few very close pairs with very different redshifts. The number depends on the surface density of QSOs, Γ, and the number of elds that have been examined (N), so that the number expected by accident n is given by

$$n = 2.42 \times 10^{-7} \Gamma \theta^2 N, \qquad (1)$$

where θ is measured in arc seconds and Γ is the number per square degree.

Thus when the rst QSO pair 1548+115A,B was discovered (Wampler et al. 1973), it was considered to be a strong argument in favor of non-cosmological QSO redshifts: its two components have separation of $4\overset{\prime\prime}{.}8$, and their redshifts are z_A = 0.44 and z_B = 1.90. The probability to nd such a close pair of QSOs among the $\sim$ 250 QSOs then identi ed was estimated to be about 1% if QSOs are distributed randomly on the sky.

In the following $\sim$ 20 years the number of QSOs with measured redshifts has increased to more than 7000 (cf Hewitt & Burbidge 1993). Also the gravitational lens phenomenon has been discovered and several close pairs with identical redshifts are known (see Keeton & Kochanek 1996 for a recent compilation of gravitationally lensed QSOs and candidate systems). Added to this are a number of double QSOs with nearly identical redshifts which are likely to be genuine QSO pairs and not lensed pairs since their spectra are not identically equal (cf Schneider 1994). These pairs are usually attributed to the spatial two-point correlation between QSOs.

Comparatively recently three more very close pairs with very different redshifts have been discovered. In Section 2 we describe and discuss them and look at the probability that they are accidental con gurations. In Section 3 we discuss all of the possible interpretations and implications of the results.

2. The observational data and probability calculations

Data on all four pairs of QSOs with very different redshifts are shown in Table 1.

(1) Burbidge et al. (1996), (2) Surdej et al. (1994), (3) Wampler et al. (1973).

AO 0235+164 A,B This system was originally classi ed as a BL Lac object with a second image often called a galaxy $2\overset{\prime\prime}{.}5$ away (Smith, Burbidge & Junkkarinen, 1977; Cohen et al. 1987). It has recently been shown that the two components are a QSO (A) and QSO or AGN (B) (Burbidge et al. 1996). QSO A has long been known to be rapidly varying at both radio and optical wavelengths, and A has two optical absorption-line redshifts at z = 0.524 and 0.852. The absorption at z = 0.524 is also found in the 21 cm line and was extensively studied by Wolfe, Davis & Briggs (1982). Several candidate galaxies are close to it, perhaps one even closer than object B (Stickel, Fried & Kühr 1988, Yanny et al. 1989). This object is a strong continuum radio source.

1009–025 A,B,C This system was discovered by Surdej et al. (1994). It has been entered in Table 1 as two pairs. In the spectra of 1009{025 A and B there are absorption redshifts at z = 0.87 and z = 1.62. This pair then suggests an interpretation as a gravitational lens. However, the pair 1009{025 A and C or for that matter the pairs 1009-025 B and C have

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Table 1. Very close pairs of QSOs

OBJECT	m_A	m_B	z_A	z_B	Separa-tions	Ref
0235+164A&B	14-19	19	0.94	0.52	2.″5	(1)
1009−025A&B	18.2	21.2	2.74	2.74	1.″55	(2)
1009−025A&C	18.2	19.3	2.74	1.62	4.″6	(2)
1148+055A&B	17.9	20.7	1.89	1.41	3.″9	(2)
1548+114A&B	18.1	18.8	0.44	1.90	4.″8	(3)

very different redshifts and the separation of A and C is only 4.″6.

1148+055 A,B This system was also discovered by Surdej et al. (1994).

1548+115 A,B As was previously mentioned this system was discovered by Wampler et al. (1973). It was one of a sample of 280 4C radio sources in the identi cation program of Hazard et al. (1973). There are a number of galaxies about 10″ from 1548+114 A which have redshifts $z \simeq 0.434$ (Stockton 1974), very close to the emission redshift of 1548+114 A. The spectrum of 1548+114 B contains absorption at redidenti ed on the POSS!); then the probability of nding four (or more) companions within 5″ of the primary QSOs is

$$p(\geq 4) = 3.5 \times 10^{-3} \; , \tag{2}$$

and the expected number of pairs is n = 0.61.

In the following section we consider ways of explaining the existence of these pairs.

3. Possible interpretations

There are in principle three possible explanations for these phenomena.

1. In the framework of standard cosmology an enhancement of the number of close pairs with discordant redshifts can be obtained if the two-point correlation function extends over distances corresponding to the redshift differences. However, the redshift differences in Table 1 are so large that none of the presently discussed cosmologies would predict any appreciable correlations in these cases.
2. The results taken at their face value indicate that signi cant parts of the redshifts have a non-cosmological origin (cf. for example Burbidge 1996) and the pairs are physically associated.
3. Back to the cosmological interpretation, it must be argued that a local enhancement of the QSO density in some part of the sky can be caused by gravitational lensing which affects the apparent magnitude of QSOs and can lead to the preferential inclusion of lensed QSOs into flux-limited samples.

Since (1) is clearly ruled out, we are left with (2) and (3). The authors of this paper have divergent views about the likelihood that (2) or (3) is the explanation. Much evidence for the existence of non-cosmological redshifts has been discussed elsewhere (Hoyle & Burbidge 1996; Burbidge 1996).

Thus we turn to (3) and discuss what can be said in favor of a gravitational lensing scenario.

4. A gravitational lens origin for close QSO pairs

Gravitational light deflection can not only lead to the occurrence of multiply imaged QSO and radio galaxies, but it also affects the apparent magnitude of sources when there is a matter concentration in or near the line-of-sight to them. An over-density of matter in the foreground of a source will magnify it. Depending on the steepness of the source counts, this magni cation can yield a dramatic biasing effect: Sources which without lensing would be too faint to be included in a flux-limited sample can be boosted above the flux threshold and thus be included in the sample. That is, magni ed sources are preferentially included in flux-limited samples. If the source counts are steep, then for every bright source there is a large number of faint sources, from which the magni ed sources can be drawn. Hence, this magni cation bias is strong for steep counts, and unimportant for flat counts (for a detailed discussion and references on the magni cation bias, see Sect. 12.5 of Schneider, Ehlers & Falco 1992).

It can be argued that at least two of the QSO pairs show strong evidence for lensing to be important. This is most obvious in the QSO 1009{025, where the QSO with the larger redshift is multiply imaged. In the spectra of the two QSO images, absorption lines are seen at redshift z_a = 0.87 and at z_a = 1.62 i.e., the redshift of the lower-redshift QSO (Hewett et al. 1994). While the available information about this lens system is not suf cient for constructing a detailed lens model, it is likely that the higher-z QSO is magni ed by at least 1 mag, as is typical for double images. In AO 0235+164, gravitational lensing has long been suspected, for example to account for the strong variability in the optical and the radio flux, which might nd an explanation in terms of microlensing. The long-known companion about 2″ to the south of AO 0235+164A, several candidate galaxies even closer to it (Stickel, Fried & Kühr 1988, Yanny et al. 1989), and the observed 21 cm line absorption (Wolfe, Davis & Briggs 1982) may be indications of potential lenses in this system; in fact, from the image of a galaxy only $\sim 0\farcs5$ away from the BL Lac (Stickel et al. 1988), one may ask why no multiple images are seen in this system (Narayan & Schneider 1990). Also, Iovino & Shaver (1986) have placed upper bounds on the mass of the foreground QSO in the system 1548+114 from the absence of a secondary image of the higher redshift QSO.

One can think of two variants of a lensing scenario: in the rst, the lenses are positioned at redshifts lower than both QSOs, i.e., both QSOs are magni ed, and in the second, the lens is physically associated with the foreground QSO and magnifying only the background QSO. From the preceding remarks about magni cation bias, the former scenario is considered unlikely: in three of the four pairs, the foreground QSO is at m = 19 or fainter, i.e., close to or beyond the break in the QSO number counts. At these magnitudes, the magni cation bias is very weak and can even lead to a decrease of the local number counts. Hence, in the rst scenario one would not expect to obtain an increased number of pairs from lensing. This conclusion may be slightly altered if the Hawkins & Veron (1995) counts are employed, as they do not show a clear turnover towards fainter sources; on the other hand, their bright-end slope is flatter than that assumed here, so that the overall ef cientcy of lensing would be reduced with the Hawkins & Veron counts.

Gravitational lensing as an explanation for an increased chance of nding pairs has been invoked by Gott & Gunn (1974) in the context of 1548+115. They picture the foreground QSO as the lens, modelled by a singular isothermal sphere (see also Iovino & Shaver 1986). However, in order to get an appreciable increase of pair probability, the mass associated with the foreground QSO must be quite large. Here we consider a somewhat different picture in which the foreground QSO is physically associated with a larger-scale mass overdensity which acts as the gravitational lens. Hence, the qualitative picture is similar to that empoyed in understanding the large angular scale associations of foreground galaxies with high-redshift QSOs (see, e.g., Bartelmann & Schneider 1994). There is one additional argu-

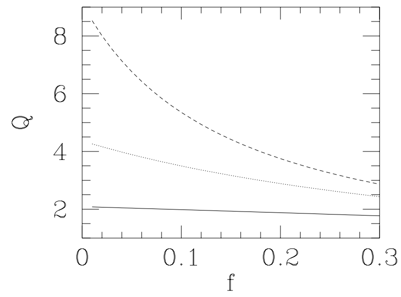

Fig. 1. The ratio Q of pairs of foreground-background QSOs in the lensing toy-model described in the text, relative to the case of no lensing present, as a function of the fraction of the sky f in which overdensities of matter leads to magnification of the background QSOs by a factor μ_+. The solid (dotted, dashed) curve corresponds to magnification of half a magnitude (one magnitude, 1.5 magnitudes), and it has been assumed that all foreground QSOs are situated in the overdense regions, $\nu_+ = 1/f$

ment in favour of such an interpretation: In two cases (0235+164 and 1548+115) there is evidence for an enhanced number density of galaxies surrounding the QSO which may indicate the existence of an associated (host) cluster. this evidence is supported through spectroscopic observations in the case of 0235+164.

A toy model should illustrate the possible effects of this scenario: Consider a 'foreground sky' and a 'background sky'; on the latter, the higher-redshift QSOs are randomly distributed, having unlensed source counts of the form $n(>S) \propto S^{-\alpha}$, with $\alpha \approx 2.6$ (e.g., Hartwick & Schade 1990). Suppose that a fraction f of the 'foreground sky' contains matter over-densities which magnify QSOs on the 'background sky' by a factor μ_+, whereas in the other directions, background sources are (de)magnified by a factor μ_-. Flux conservation (Schneider et al. 1992, Sect. 4.5.1) then requires that $\mu_- = \mu_+(1-f)/(\mu_+ - f)$. Futhermore, assume that QSOs in the 'foreground' are concentrated towards those directions in which over-densities of matter are present. That is, if n is the mean number density for foreground QSOs, let the number density in the magnifying fraction of the 'foreground sky' be $\nu_+ n$, whereas the number density in the rest of the sky is $\nu_- n = (1-\nu_+ f)/(1-f)$, with $\nu_+ \leq 1/f$. Using the preceding assumptions, one can then show that in a flux-limited sample of N background QSOs the expected number of foreground QSOs within an angle θ is

$$n_{12} = Q\pi\theta^2 N n \tag{3}$$

where the factor

$$Q = \frac{f\nu_+(\mu_+ - f)^{\alpha-1} + (1-f)^{\alpha-1}(1-\nu_+ f)}{f(\mu_+ - f)^{\alpha-1} + (1-f)^{\alpha}} \tag{4}$$

describes the ratio of expected pairs relative to the case that no lensing takes place. In Fig. 1, we have plotted Q as a function of f, for the maximum value of $\nu_+ = 1/f$, i.e. all QSOs in the foreground sky are assumed to lie in the over-dense regions.

As can be inferred from the figure, the increase in the expected number of pairs is quite substantial, even for low values of the magnification. For example, if the magnification in f = 10% of the sky is one magnitude ($\mu_+ = 10^{0.4}$), the expected number of pairs increases by a factor of about 3.5. Such an increase would suffice to increase the probability in Eq. (2) to about 18%, and hence the observed number of pairs would not pose an improbable statistical fluctuation. It should be clear that the toy model presented here is not realistic, but it illustrates the basic features of a more realistic lensing scenario. One of the problems encountered in making a realistic model is that the observed number density of QSOs flattens as we go to fainter magnitudes so that while $\alpha \simeq 2.6$ up to m_B = 19.5, it becomes $\alpha \leq 1$ for the range 19.5 to 21.5 (Hartwick and Schade 1990; but see Hawkins & Veron 1995). Another more basic problem is our lack of understanding the relation between matter overdensities and QSOs; if a 'biasing factor' were assumed for the QSOs, an analysis similar to that of Bartelmann (1995) could be employed.

To distinguish between a lensing scenario as discussed here and the one employed by Gott & Gunn (1974) one would have to investigate the number of pairs at larger separations. In the case that the QSO acts as a lens on its own, the number of pairs in excess of random would drop quickly beyond separations of a few arcseconds, whereas the other scenario implies lensing effects at larger separations. Unfortunately, no systematic search for (faint) QSOs in the vicinity of bright QSOs has been done, except for the lens surveys which restrict their search radius to a few arcseconds only. The involvement of radio QSOs may be seen as an additional hint for a lensing interpretation: if the foreground QSO is radio loud (as in 1548+115), one can argue from the fact that radio QSOs are supposed to be hosted in ellipticals which prefer a rich environment that the QSO is indeed located in an overdense region. If the background QSO is radio loud (as in 0235+164), the double magnification bias (Borgeest et al. 1991) increases the effective slope of the source counts, making lensing more effective.

5. Conclusion

We have shown that if the redshifts of the QSOs are of cosmological origin and gravitational lensing is not a factor, it is extremely improbable that the pairs could have these configurations by accident. If they are physically associated, and the lower emission redshift in each pair gives the true distance of the pair, then the intrinsic redshifts (z_i) of the higher redshift objects are: z_i = 0.27 for AO 0235+164; z_i = 0.43 for 1009{025; z_i = 0.19 for 1148+055, and z_i = 1.02 for 1548+115.

Two of us (GB and FH) consider that the existence of these pairs is further strong evidence in favor of the view that QSOs often have redshift components of intrinsic origin. One of us (PS) considers that while no realistic model has yet been constructed it may still be possible to interpret these phenomena in terms of gravitational lensing of QSOs with cosmological redshifts.

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