1992PASAu..10....8D

# Associations between Galaxies and Bright Quasars[1]

**M. J. Drinkwater**, *Anglo-Australian Observatory, Coonabarabran, NSW 2357*

**R. L. Webster**, *School of Physics, University of Melbourne, Parkville, Vic 3052*

**P. A. Thomas**, *MAPS, University of Sussex, Brighton BN1 9QH, UK*

**D. Millar**, *Department of Astronomy, University of Toronto, Toronto, Ont M5S 1A1, Canada*

**Abstract:** The results of a new imaging survey of 68 bright ($m_V < 18$) high redshift ($z > 0.7$) quasars are presented. The distribution of celestial distances between the quasars and the nearest galaxy neighbours shows an excess at small separations ($<$ 15 arcseconds) significant at the 99.96% level. The redshifts of these galaxies are not known, so two interpretations are possible. If the galaxies are in groups physically associated with the quasars then they must be significantly brighter ($>$ 3 magnitudes) than normal $M_*$ galaxies at the present epoch. Alternatively, this may be the result of a bias caused by gravitational amplification of background quasars by compact lenses in the halos of the nearest neighbour (foreground) galaxies. Of the present sample, 25% of the quasars have extra galaxies. If this is caused by a gravitational lensing bias, then, allowing for incompleteness, the results imply that as many as 60% of bright quasars may be gravitationally lensed.

## 1. Introduction

One of the proposed explanations for recent detections of quasar galaxy associations involves gravitational lensing (see Canizares 1981). Although the theory and results of gravitational lensing have been the subject of many excellent reviews (see Canizares 1987, Blandford 1990 and references therein), it is useful here to review some of the results relevant to quasar-galaxy associations.

The classical multiple imaging caused by lensing (e.g., the double quasar; Walsh, Carswell and Weymann 1979) is not the only gravitational effect we can detect. When multiple imaging occurs, it produces image splittings of the order

$$\theta_{sep} \approx 10^{-6}(M_{lens}/M_\odot)^{0.5} \text{ arcseconds,}$$

for the idealised case of a point lens of mass $M_{lens}$ half-way between the source and the observer (see Canizares 1987). This gives detectable splittings of a few arcseconds when the lens is a galaxy, but if the lens is a star, the splitting will be of the order $10^{-6}$ arcseconds. The term 'microlensing' refers to this effect. This splitting typically cannot be resolved at optical wavelengths, but it will cause amplification of the source due to the imaging that has taken place. The amplification of a background quasar image by stars in an intervening galaxy has been detected by Irwin *et al.* (1989). Relatively few instances of multiple images are known (some ten cases among 5000 known quasars), but unresolved effects, such as microlensing, may be much more widespread. This is referred to as 'statistical' gravitational lensing.

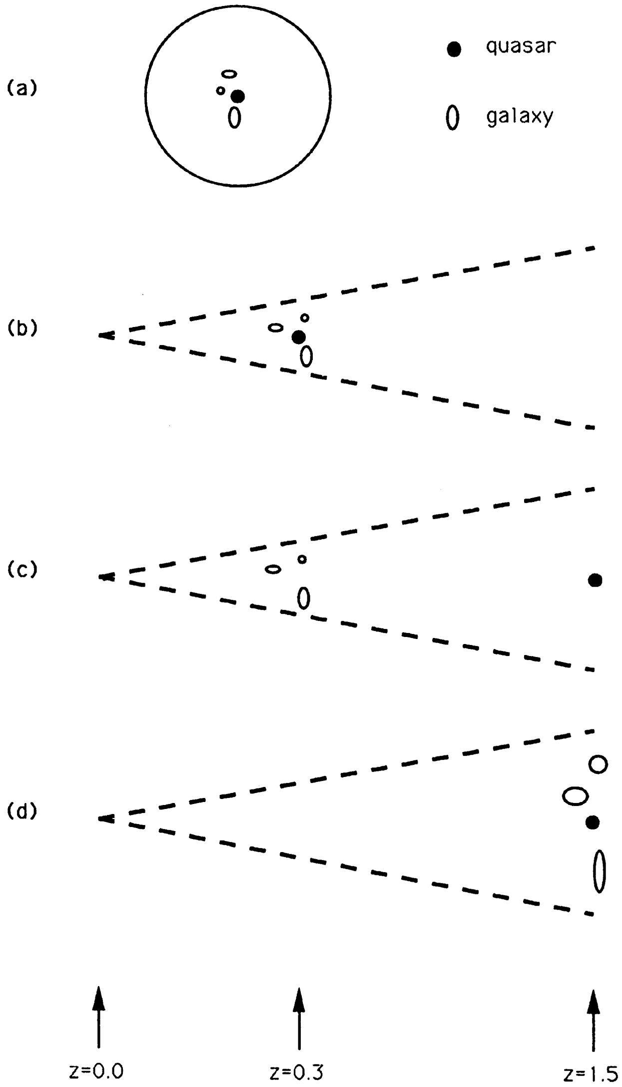

Figure 1 — Schematic illustration of quasar-galaxy associations. The observed effect is an excess of galaxies close to the line-of-sight to a quasar (a). Not knowing the galaxy redshifts, different interpretations of the physical arrangement of these objects are possible depending on the quasar redshift. For a low-redshift quasar we are probably detecting galaxies physically associated with the quasar (b). For a high-redshift quasar these are either foreground galaxies (c) or galaxies at the same redshift as the quasar (d).

Recent observations of quasar-galaxy associations may provide evidence for statistical gravitational lensing. The term 'quasar-galaxy association' is explained graphically in Figure 1. An example of the detected result is given in Figure 1(a); along the line-of-sight to a quasar, within some nominal radius (say 15 arcseconds) we see more galaxies than in a direction chosen at random. Not knowing the redshifts of these galaxies, we cannot be sure of the physical interpretation of this observation. If the quasar is at low-redshift (*e.g.*, $z < 0.5$) then it is fairly likely that we are detecting galaxies at the quasar redshift as shown in Figure 1(b). Several cases of this are discussed in the literature where the galaxy redshifts have confirmed that the galaxies lie in clusters associated with the quasar (e.g., Yee and Green 1987; Smith and Heckman 1990; Ellingson, Green and Yee 1991). We do not discuss associations with low-redshift quasars in the present paper.

---

[1] Based on observations made at Observatoire du Mont Mégantic, Université Laval, Québec, Canada.

The situation for high-redshift ($z \gtrsim 0.7$) quasars is much less clear. Associations have been detected by recent observations, but the cause has not been established. If the galaxies are at lower redshifts than the quasars, as in Figure 1(c), there is evidence that these are biased lines-of-sight. The way in which microlensing might cause apparent associations was discussed by Canizares (1981) who suggested that it could arise if the galaxies were preferentially amplifying any background quasars. If anything behind a galaxy is amplified then there is a higher probability of including these objects in any flux-limited sample of quasars. Hence the positions of quasars in the sample are correlated with the positions of the foreground galaxies. Alternatively, the galaxies may be in groups at the quasar redshift, as in Figure 1(d). If this is the case, the galaxies must be much brighter than at the present epoch in order to have been detected at such a high redshift.

Fugmann (1988, 1989) has obtained CCD $r$ images of 12 radio-selected quasars. These all have redshifts $z > 1.7$ and galaxies are detected to a magnitude limit of $r \lesssim 21.5$. In this sample an excess of galaxies was detected at the 97.5% confidence level, the result being interpreted as due to a gravitational lensing bias. A much larger sample is presented by Webster *et al.* (1988) with an automated photographic survey of 296 quasars with magnitudes $B_J < 18.7$. The quasars were selected independently of their morphology, so there is no bias against including quasars with very close companions because they do not appear stellar. There were 11 quasar-galaxy associations detected within separations of 6 arcseconds, compared to $2.6 \pm 1.6$ expected: a significance of 99.99%. Redshifts of 8 of the galaxies have since been obtained: these are all $z < 0.43$, much less than the quasar redshifts (Webster, private communication), supporting the interpretation that the effect is due to statistical gravitational lensing.

Tyson (1986) and Hintzen, Romanishin and Valdes (1991) have imaged 23 and 16 quasars respectively with CCDs. Both samples have redshifts $1.0 \lesssim z \lesssim 1.5$, and both display a significant excess of galaxies close to the quasars. The authors interpret this as the detection of galaxies at the quasar redshift. However, with galaxy magnitude limits of $R \lesssim 21,23$ respectively, this implies that the galaxies are intrinsically very bright if they are at redshifts $z > 1.0$. The authors invoke a strong evolution in luminosity (2 to 3 magnitudes brighter than at the present epoch) to explain this.

In the present paper the results of CCD imaging of a large new sample of bright, high-redshift quasars are presented. The use of bright quasars is particularly interesting, as, under the lensing hypothesis the effect should be strongest in bright magnitude-limited samples (Canizares 1981). The samples of Tyson (1986) and Hintzen, Romanishin and Valdes (1991) use fainter quasars ($17 \lesssim m_V \lesssim 20$) than in our sample ($16 \lesssim m_V \lesssim 18$).

## 2. Data

### (a) Quasar sample

The quasars were originally observed as part of a study of absorption-line systems and are selected from the compilations of Weymann *et al.* (1979), Young, Sargent and Boksenberg (1982), Foltz *et al.* (1986), Tytler *et al.* (1987), and Sargent, Steidel and Boksenberg, (1988). These lists were compiled according to quasar position and magnitude, so there should be no bias with respect to the presence of nearby galaxies. For the present project a subset of these quasars was observed according to the following criteria: 1. coordinates suitable for observing at Mont Mégantic (latitude +45.46°) 2. published finding charts available, 3. the quasar redshift $0.7 < z < 2.5$ where the lower limit is to reduce the chance of detecting galaxies at the same redshift as the quasar and the upper limit was chosen for the absorption-line study to avoid confusion between any low-redshift MgII absorption lines and the Lyman-α forest in the quasar spectrum. A further 15 quasars were included that had been observed as part of a project (Millar 1991) to image quasars from the Kiso survey (Wegner and Swanson 1990). The total sample consists of 68 quasars with $16 \lesssim m_V \lesssim 18$.

Of the 53 quasars not taken from the Kiso survey, 29 were initially discovered as radio-sources according to Hewitt and Burbidge (1987) and a further five have detectable radio emission. Thus although the primary selection criterion of this sample was bright optical (apparent) magnitude, a large fraction of the quasars are radio sources. We hope to compare the properties of radio-quiet and radio-loud samples in a future paper.

### (b) Observations

Broad band R CCD images of the quasars were obtained using the 1.6m telescope at the Observatoire Astronomique du Mont Mégantic. A 320 by 512 pixel RCA CCD was used having a scale of 0.48 arcseconds per pixel giving a field of 2.6 by 4.1 arcminutes. The observations were made during a total of 5 observing sessions from June 1989 to April 1991. The limiting magnitude varies significantly between images because of large variations in the seeing (a full-width-at-half-maximum of 1.4 to 2.9 arcseconds as measured in the final combined images).

### (c) Reduction

The CCD images were reduced and calibrated in a standard way using the IRAF[1] image analysis software. Catalogues of the images in each field were then generated as follows.

First the mean point-spread-function (PSF) in each image was fitted and subtracted from the quasar in order to reveal any close faint companions obscured by the seeing disk. The PSF fitting and removal was done using the IRAF package DAOPHOT. The results for stellar images other than the quasar were checked in each case to ensure that no artificial structure was introduced by the process. At this stage a control star was chosen from the photometry list as having the magnitude closest to that of the quasar, whilst lying at least 15 arcseconds from the quasar and the edges of the image. The DAOPHOT procedure procedure revealed eight new close companions in the sample, notably a galaxy with magnitude $R = 22.3$ only 1.″3 from QSO1209+107 (previously observed with the 4m CFH Telescope by Arnaud *et al.* 1988).

The images were then analysed using the FOCAS package in IRAF (Valdes 1982) to automatically detect and classify images. A catalogue of objects was first determined, using relatively conservative detection limits: each image having

---

[1] IRAF is distributed by the National Optical Astronomy Observatories, which is operated by the Association of Universities for Research in Astronomy, Inc. under cooperative agreement with the National Science Foundation.

greater than 16 pixels $3\sigma_{sky}$ above the background. The images were then classified using a simple criterion based on the concentration of the image compared to the shape of the mean PSF. Star-galaxy classification algorithms become much less efficient at faint magnitudes, so although fainter images could be detected, it was unclear that any algorithm could successfully sort out the stars from the galaxies. Merged images were identified, and each catalogue was carefully checked by eye for spurious image detections. Images which were saturated or on the boundary of the frame were not included in the final catalogue.

## 3. Analysis

### *(a) Nearest neighbour statistics*

The image catalogues were analysed by finding the distances to the closest galaxy and the closest star to each quasar. This was also repeated around the control stars. The nearest neighbour statistic has the advantage that the effect of any galaxy clustering is not important because only one point is used. The probability distribution for the distance $r$ to the nearest neighbour is given by

$$P(r \le r_0) = 1 - e^{-\pi r_0^2 \sigma},$$

where $\sigma$ is the surface density of objects. However the surface density of objects varies from field to field so we cannot compare distributions of $r$ in different fields. This problem is avoided by using a normalised distance $s$ given by $s = \sqrt{\pi \sigma}\, r$ (so $s$ is the ratio of $r$ to the mean separation of objects). The probability distribution of $s$ is then

$$P(S \le s_0) = 1 - e^{-s_0^2},$$

which is independent of the surface density, and thus constant from field to field.

### *(b) Results*

The normalised nearest neighbour distributions for the 68 quasar fields are plotted in Figure 2 along with the Poisson distribution. In Figure 2(a) the distributions of stars and galaxies about the control stars are given. These do not differ significantly from the random values. Although it does vary from field to field, the mean separation of galaxy neighbours corresponding to $s = 1$ is about 30 arcseconds, and for star neighbours it is about 20 arcseconds. Figure 2(b) shows the distributions of star and galaxy neighbours around the quasars. Here there is a strong excess of galaxy neighbours at small separations. The distribution of stars around the quasars is not statistically different from random at small separations. The significances of the excesses have been calculated using the Kolmogorov-Smirnov (KS) test and are given in Table 1. The galaxy excess is significant at the 99.96% confidence level. There is also a small excess in the number of close star neighbours but this is only significant at the 92% confidence level (1.3 $\sigma$). Furthermore, we would expect a small excess because some of the fainter galaxies will be misclassified as stars.

Table 1 — Nearest neighbour statistics for quasars

| Neighbour | $D_{max}\sqrt{n}$ | $s_{max}$ | KS significance |
|---|---|---|---|
| Galaxies | 2.12 | 0.47 | 99.96% |
| Stars | 1.28 | 1.01 | 92.00% |

Notes: $D_{max}$ is the maximal difference between the observed cumulative distribution and the Poisson distribution, $n = 68$ is the sample size, $s_{max}$ is the value of $s$ at which $D_{max}$ occurs and KS significance is the probability that the observed distribution deviates from Poisson as measured by the Kolmogorov-Smirnov test.

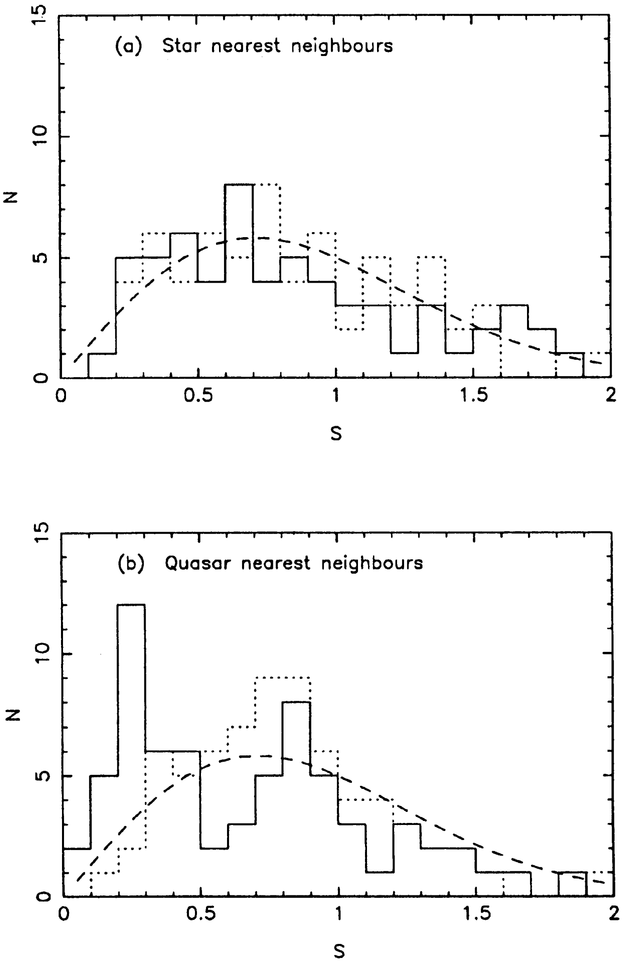

Figure 2 — Nearest neighbour distributions of (a) control stars and (b) quasars. In each the solid histogram refers to galaxy neighbours, the dotted histogram to star neighbours and the dashed curve gives the Poisson prediction for a random distribution.

### *(c) Discussion*

The results presented here confirm previous studies which show that there is an excess of galaxies close to the lines-of-sight to high-redshift quasars. The quasars in this sample have a brighter magnitude limit than the previous samples.

Some previous detections of the galaxy excess were interpreted as physical associations of quasars with unusually bright galaxies. This brightening of up to 3 magnitudes was explained by invoking strong luminosity evolution of galaxies within $150h^{-1}$Mpc of the quasars (Tyson 1986). Thus $M_*$ galaxies would brighten to $M_V \sim -24$ at redshifts of $z = 1.5$. There is no evidence for this in the complete survey of faint field galaxies by Colless *et al.* (1990), but it is conceivable that the galaxy luminosity function changes this close to quasars. In the present sample we detect fainter galaxies and the quasars reach higher redshifts, so even stronger luminosity evolution would be required. If our nearest neighbour galaxies were at the quasar redshift they would have absolute magnitudes as bright as $M_V = -23.5$ to $-27$ making them more like AGN than normal galaxies.

If the nearest neighbour galaxies are at the quasar redshifts, then there should be some relation between their apparent magnitude and the quasar redshift. Our data show no variation in the galaxy magnitudes as a function of the quasar redshift. Similarly, Webster and Hewett (1990) find no such variation in the data of Hintzen, Romanishin and Valdes (1991). This could only occur if the luminosity evolution in the quasar neighbourhoods exactly cancelled the fading in apparent magnitude caused by cosmological and K-correction factors over the redshift range $0.7 < z < 2.3$.

Furthermore, redshifts are available in the literature for four of the close galaxies we found (Bergeron and Boissé 1991) and these are all significantly lower than those of the quasars.

The alternative interpretation is that the galaxies are at low redshifts and that the excessive number of close associations is due to a gravitational lensing bias. Irwin *et al.* (1989) show that gravitational lensing can amplify sources without producing observable multiple images, and this interpretation has the advantage of not invoking large amounts of luminosity evolution. However it is essential that the redshifts of the nearest neighbour galaxies be obtained to decide between the two interpretations and properly model the effect.

Schneider (1991 preprint; see also Narayan 1989) has shown that, in the case of the Webster *et al.* (1988) detection, amplification by microlensing is not strong enough to cause the observed effect when modelled with the currently accepted quasar luminosity function. However, if a large fraction of bright quasars have been lensed, then this distorts the observed luminosity function; the true luminosity function would be steeper and the models could then explain the observed degree of associations. In view of that it is interesting to note that in the present sample (25 ± 6)% of the quasars have a closely associated galaxy, in excess of random. Unless there has been some luminosity evolution, we are unlikely to detect galaxies over more than at most one third of the path-length to each quasar. Therefore it is not unreasonable to consider the possibility that the true overdensity is even higher than we detected and that at least 60% of bright quasars are amplified by lensing. Thus the possibility that the observed quasar luminosity function is distorted (steepened) at the bright end should be seriously considered (Webster 1991).

## 4. Conclusion

In this paper we have presented a new CCD imaging survey of bright quasars which we have searched for galaxies in the quasar fields. The distribution of celestial distances between each of the quasars and the nearest galaxy neighbour shows a significant excess at small separations. Quasar-galaxy associations of varying degrees have been found in other samples based on CCD imaging, but here a brighter quasar sample is used which would make the effect — if any — due to gravitational amplification of the quasars more pronounced. Furthermore, the sample is larger than previous ones, giving our results a greater statistical significance. We have also introduced a new statistic: the normalised nearest-neighbour test which is a powerful means of detecting associations and at the same time is relatively unbiased by the effects of galaxy clustering.

The interpretation of these observations is still not certain and will depend on the redshifts of the nearest neighbour galaxies when they can be measured. If the galaxies are in groups physically associated with the quasars then they must be unusually bright compared to normal $M_*$ galaxies at the present epoch. The alternative explanation in terms of an amplification bias due to microlensing by compact objects in the halos of the galaxies is more natural in that it does not invoke the dramatic brightening of the galaxies, but is dependent on the galaxy redshifts for confirmation.

The present sample may suffer from morphological bias in the selection of the quasars (which would most likely reduced the measured effect), so we have started a new survey imaging a large number of radio quasars from the Parkes catalogue of Otrupcek and Wright (1990).

## Acknowledgements

We thank M. Neeser for assistance with the observations. Mont Megantic Observatory is supported by grants from NSERC (Canada) and FCAR (Quebec). RLW acknowledges support from NSERC, and MJD thanks MESS (Quebec Government) for travel funds.

Arnaud, J., Hammer, F., Jones, J. and Le Fèvre, O., 1988, *Astr. Astrophys.*, **206**, L5.

Bergeron, J. and Boisse, P., 1991, *Astr. Astrophys.*, **243**, 344.

Blandford, R. D., 1990, Qrt. J. R. astr. Soc., **31**, 305.

Colless, M., Ellis, R. S., Taylor, K. and Hook, R. N., 1990, *Mon. Not. R. Astr. Soc.*, **244**, 408.

Canizares, C. R., 1981, *Nature*, **291**, 620.

Canizares, C. R., 1987, in *IAU Symp. No. 124* 'Observational Cosmology', eds. A. Hewitt *et al.* p.729.

Ellingson, E., Green, R. F. and Yee, H. K. C., 1991, *Astrophys. J.*, in press.

Foltz, C. B., Weymann, R. J., Peterson, B. M., Sun, L., Malkan, M. A. and Chaffee, F. H., 1986, *Astrophys. J.*, **307**, 504.

Fugmann, W., 1988, *Astr. Astrophys.*, **204**, 73.

Fugmann, W., 1989, *Astr. Astrophys.*, **222**, 45.

Hewitt, A. and Burbidge, G., 1987, *Astrophys. J. Suppl.*, **63**, 1.

Hintzen, P., Romanishin, W. and Valdes, F., 1991, *Astrophys. J.*, **366**, 7.

Irwin, M. J., Webster, R. L., Hewett, P. C., Corrigan, R. T. and Jedrzejewski, R. I., 1989. *Astron. J.*, **98**, 1989.

Millar, D., 1991, PhD thesis, University of Toronto.

Narayan, R., 1989, *Astrophys. J.*, **339**, L53.

Otrupcek, R. E. and Wright, A. E., 1990, Proc. Astron. Soc. Aust., **9**, 170.

Sargent, W. L. W., Steidel, C. C. and Boksenberg, A., 1988, *Astrophys. J.*, **334**, 22.

Smith, E. P. and Heckman, T. M., 1990, *Astrophys. J.*, **348**, 38.

Tyson, J. A., 1986, *Astron. J.*, **92**, 691.

Tytler, D., Boksenberg, A., Sargent, W. L. W., Young, P. J. and Kunth, D., 1987, *Astrophys. J. Suppl.*, **64**, 667.

Valdes, F., 1982, *FOCAS User's Manual*, (Tucson: KPNO).

Walsh, D., Carswell, R. F. and Weymann, R. J., 1979, *Nature*, **279**, 381.

Webster, R. L., Hewett, P. C., Harding, M. E. and Wegner, G. A., 1988, *Nature*, **336**, 358.

Webster, R. L. and Hewett, P. C., 1990, in *Gravitational Lensing*, eds. Mellier *et al.* p.73.

Webster, R. L., 1991, to appear in the proceedings of the Quasar Workshop, held in Victoria, British Columbia, June 1991 (*Publ. Astr. Soc. Pacif.*, conf. series).

Wegner, G. and Swanson, S. R., 1990, *Astron. J.*, **99**, 330.

Weymann, R. J., Williams, R. E., Peterson, B. M. and Turnsheck, D. A., 1979, *Astrophys. J.*, **234**, 33.

Yee, H. K. C. and Green, R. F., 1987, *Astrophys. J.*, **319**, 28.

Young, P., Sargent, W. L. W. and Boksenberg, A., 1982, *Astrophys. J. Suppl.*, **48**, 455.