

Faint galaxies around quasars at $z = 1$ and gravitational lensing of distant objects

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Abstract. Very deep imaging data of three optically luminous radio-loud quasars with redshifts between $z = 0.9$ and $z = 1.36$ are presented. The data are complete for galaxies down to $R = 26$. There is no evidence for excess numbers of galaxies around the quasars; foreground galaxy clusters are excluded by the data as well as clusters with richness classes greater than 1 associated with the quasars. We find clear evidence for gravitational lensing for two quasars. It is further shown that due to the high surface density of galaxies all distant ($z > 1$) objects are moderately affected by gravitational lensing; the amplification factors are estimated to be in the range 1.1 – 1.5.

Key words: quasars: general – gravitational lensing – galaxies: halos

1. Introduction

Galaxies around low redshift ($z = 0.3 - 0.6$) quasars have been studied extensively by various authors (Gehren et al. 1984, Green and Yee 1988, Hintzen et al. 1991, Ellingson, Yee and Green 1991, Fried 1991); there is general agreement that low redshift radio-loud quasars are found in moderately rich galaxy clusters with richness classes 0 – 1. Radio-quiet QSOs are usually found in less dense environments. Green and Yee (1988) and Fried (1991) have found evidence for an evolution of the environment between redshift $z = 0.3$ and $z = 0.6$ in the sense that the qso-galaxy covariance amplitude is larger at $z = 0.6$.

At redshifts $z \approx 1$ associations between different types of AGN and galaxies have been sought by Tyson 1986, Hintzen, Romanishin and Valdes 1991, Fried, Stickel and Kühr 1993, Hutchings, Crampton and Persram 1993, Hutchings, Crampton and Johnson 1995, Boyle and Couch 1993, and Benitez et al. 1995. These works are based on imaging data with limiting magnitudes around 23.^{mag}. Since a galaxy with $M^* = -21$ appears as faint as $m = 24.35$ at redshift $z = 1$ (choosing $H_0 = 75 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $q_0 = 0.5$ and applying an R-band K-correction of 2 mag according to Metcalfe et al. (1991)) this implies that galaxies associated with QSOs at $z \geq 1$ can be detected in

such data only if they are overluminous by 1 – 3 mag. Furthermore, only the brightest members of possible associated clusters can be detected. The results of these studies are discrepant, there are claims both for and against excess numbers of galaxies (a detailed discussion is given below). Since redshifts of these galaxies are not available, the excess numbers of galaxies are interpreted either as true physical association of these galaxies with the QSOs or as foreground galaxies acting as gravitational lenses.

In this paper we present data on the fields around 3 quasars. The quasars were selected from the catalogue of Veron & Veron (1993); they are all radio-loud and have redshifts $z = 0.901$ (PKS 2216-03), $z = 1.066$ (PKS 2356+196) and $z = 1.36$ (OT 566). The data are complete for galaxies to $R = 26$ and thus allow detection of galaxies at the redshifts of the quasars down to $M^* + 2$. The data were originally taken to search for a possible galaxy excess around the quasars; this is discussed in Sect. 3.1. It was also found that the data have implications for gravitational lensing (Sect. 3.2). In Sect. 3.3 it is shown that the size of the absorber in the line of sight to PKS 2216-03 may have been severely overestimated.

2. Observations and data reduction

The direct images presented here were obtained at the prime focus of the 3.5 m telescope on Calar Alto, Spain. All observations were made in the R-filter band. A CCD with 640x1024 pixels of $15 \mu\text{m}$ was used as detector. The long exposure times which are necessary to reach faint light levels were broken into many shorter exposures of 500 sec each, with the telescope moved between the exposures by several steps of $4''$ each in right ascension and/or declination; flatfields for each night were constructed from an unregistered median of the individual frames. The frames were debiased, flatfielded and then registered. To correct cosmic ray events, the median and sigma for each pixel were calculated for 6-8 registered frames; those pixels which deviated more than $\approx 3 \sigma$ from the smoothed median were replaced by the median. This procedure removes cosmic ray events very effectively even in the flanks of stellar images. These cosmic ray free frames were then summed to construct the final

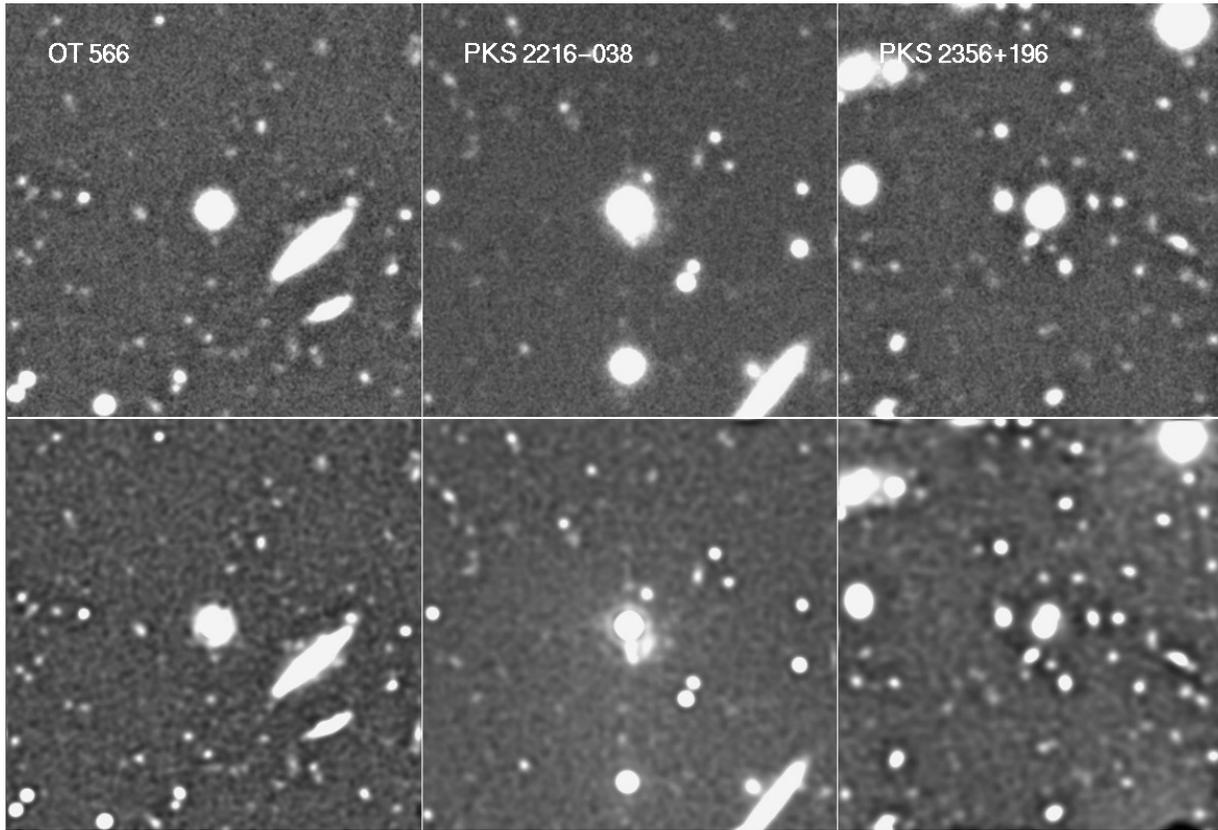


Fig. 1. Fields around three quasars. The quasars are in the field centers; the fields are $64''$ square. The upper panels show the original, the lower panels the deconvolved data. North is to the top, east to the left.

Table 1. Counted/expected numbers of galaxies from background with $R = 18 - 23$ and $R = 23 - 26$ within the given radii from the quasars.

quasar	R = 18 - 23			R = 23 - 26		
	100 kpc	250 kpc	500 kpc	100 kpc	250 kpc	500 kpc
OT 566	1/1.3	8/8.3	33/33.1	14/11.1	73/69.3	256/277.1
PKS 2216-038	3/1.1	8/6.6	29/26.4	10/13.1	77/81.7	337/327.0
PKS 2356+196	3/1.9	18/12.2	49/48.7	5/14.8	81/92.6	333/370.4

coadded images. It should be emphasized that the median is used only for constructing a flatfield and for correction of cosmic events, since Steidel and Hamilton (1993) have shown that the median operation changes the true intensity distribution of objects close to the sky level. The total integration times are between 13.5 ksec and 26.0 ksec; the 1σ surface brightness limits are between $\mu_R = 29.6 \text{ mag}/\square''$ and $\mu_R = 30.1 \text{ mag}/\square''$. The central parts of the three fields are shown in Fig. 1.

Since the weather was not photometric during the whole observing run, frames of the three objects obtained during photometric conditions were calibrated with observations of standard stars, and these calibrations were used to scale the final coadded images. Photometric errors due to atmospheric instabilities should be less than 0.1 mag. The seeing was acceptable throughout the whole observing run; the coadded images have PSFs with FWHM $1.1 - 1.2''$.

The detection of objects and separation into stars, galaxies and image defects was done using the FOCAS software (Valdes 1982). The completeness limit can easily be determined from differential number counts (Fig. 2). These number counts are *not* corrected for incompleteness due to diminishing detection probability of the objects near the faint end and thus demonstrate clearly that the data are complete for galaxies down to 26^{th} magnitude. The data are well fitted by a linear relation $\log N(m) = \text{slope} \cdot R + \text{constant}$. The slope and constant are 0.31 ± 0.01 and -2.91 ± 0.31 for OT566, 0.36 ± 0.08 and -4.28 ± 0.18 for PKS2216-038, and 0.29 ± 0.01 and -2.40 ± 0.23 for PKS2356-196 in very good agreement with other determinations reaching $R \geq 26$ (Tyson 1988, Steidel and Hamilton 1993, Metcalfe et al. 1995, Smail et al. 1995).

Table 2. Ratio of expected number of galaxies within given radii for galaxy clusters of given richness class to 1σ Poisson fluctuations in the background for the two subsamples with $R = 18 - 23$ and $R = 23 - 26$

$R = 18 - 23$					$R = 23 - 26$					
richness class					richness class					
r[kpc]	back	0	1	2	3	back	0	1	2	3
100	1.43 ± 1.2	0.7	1	1.7	2.6	13 ± 3.6	2.1	2.9	5	7.9
250	9 ± 3	1	1.7	2.7	5.5	81 ± 9	3	5	16.3	16.7
500	36 ± 6	1.1	1.8	2.9	4.6	325 ± 18	3.3	5.5	8.8	13.8

3. Results

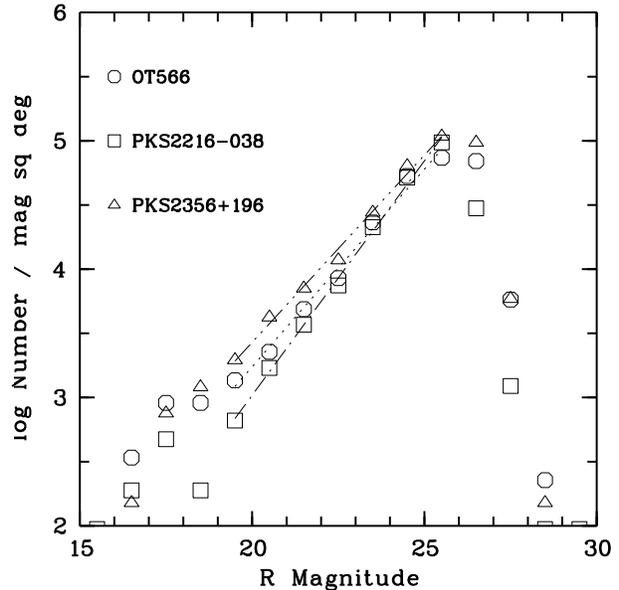
3.1. Excess of galaxies around the quasars?

A possible excess of galaxies around the quasars is most easily detected on plots of galaxy surface density (galaxies per square degree) as a function of projected distance from the quasars. Foreground clusters of galaxies should show up in the $R = 18 - 23$ subsample, whereas clusters of galaxies associated with the quasars should show up in the $R = 23 - 26$ subsample because the apparent magnitudes would be in this range (see introduction). From Fig. 3 it is evident that the galaxy surface density is constant, i.e. there is no evidence for a galaxy excess in either field. In Table 1, the number of galaxies counted within various radii from the quasars is compared to the number expected from background. Since there is no radial gradient in the data, the background has been taken as the mean over each individual field. However, while Fig. 3 and Table 1 suggest that there is no galaxy excess in any of the 3 fields, statistical fluctuations in the background could exceed the number of galaxies expected for poor clusters. Table 2 lists the ratio of expected numbers of galaxies within certain radii for Abell clusters of richness classes 0 - 3 and the 1σ Poisson fluctuations in the background counts. The number of galaxies expected within a given radius was integrated for a King profile with core radius $r_c = 250h_{50}^{-1}$ kpc (Bahcall 1975) and the total numbers of cluster members were taken as the mean of the population numbers for each richness class given by Abell 1958. All counts were taken as the mean of the 3 fields. Table 2 shows that foreground clusters can be excluded on a 3σ level, clusters associated with the quasars only for richness classes greater than 1.

3.1.1. Comparison with other work

The quasars studied here are all radio-loud and optically luminous, the mean absolute visual magnitude for our small sample being $\langle M_V \rangle = -25.9$. Samples with similar properties have been studied by Tyson (1986) and Hintzen, Romanishin and Valdes (1991).

Tyson (1986) found a significant excess of bright galaxies with $m < 21$ within $30''$ of the quasars, which he believed to be due to enhanced luminosity evolution of galaxies near the quasars. However his data are not easily comparable to other work since they were measured in white light and the galaxy excess was detected only after considerable correction for decreased detection probability of galaxies close to a bright point

**Fig. 2.** Differential galaxy number counts in the fields of the quasars. The straight lines show the fits to the data in the range $R = 18 - 26$

source. Hintzen, Romanishin and Valdes (1991) could not confirm Tyson's results, but found an excess of fainter galaxies ($R < 23$) closer to the quasars ($< 15''$). They found 33.8 galaxies within $15''$ from the 16 quasars in their sample, compared to 19.3 galaxies expected from background counts which were determined in the outer regions of the fields. This excess is significant on the 3σ level using Poisson statistics. However, the fluctuations in galaxy counts are larger than given by Poisson statistics by about a factor of 2 in fields of few arcmin size (Metcalf et al. 1991, Tyson 1990). Thus the significance of the galaxy excess may be overestimated. Hintzen, Romanishin and Valdes (1991), too, interpreted the excess as being due to luminosity evolution by few magnitudes of the galaxies near the quasars.

If the unified scheme for AGNs is correct, then BL Lac objects owe their special properties to aspect angle; therefore they should be found in environments similar to those of radio galaxies and quasars. Fried, Stickel and Kühr (1993) analysed the environments of 1 Jy radio selected BL Lac objects. For redshifts $z \leq 0.6$ the environments are similar to those of radio-loud quasars, i.e. clusters of richness class 0 - 1 with denser environment at $z = 0.6$. The subsample with $\langle z \rangle = 1$ con-

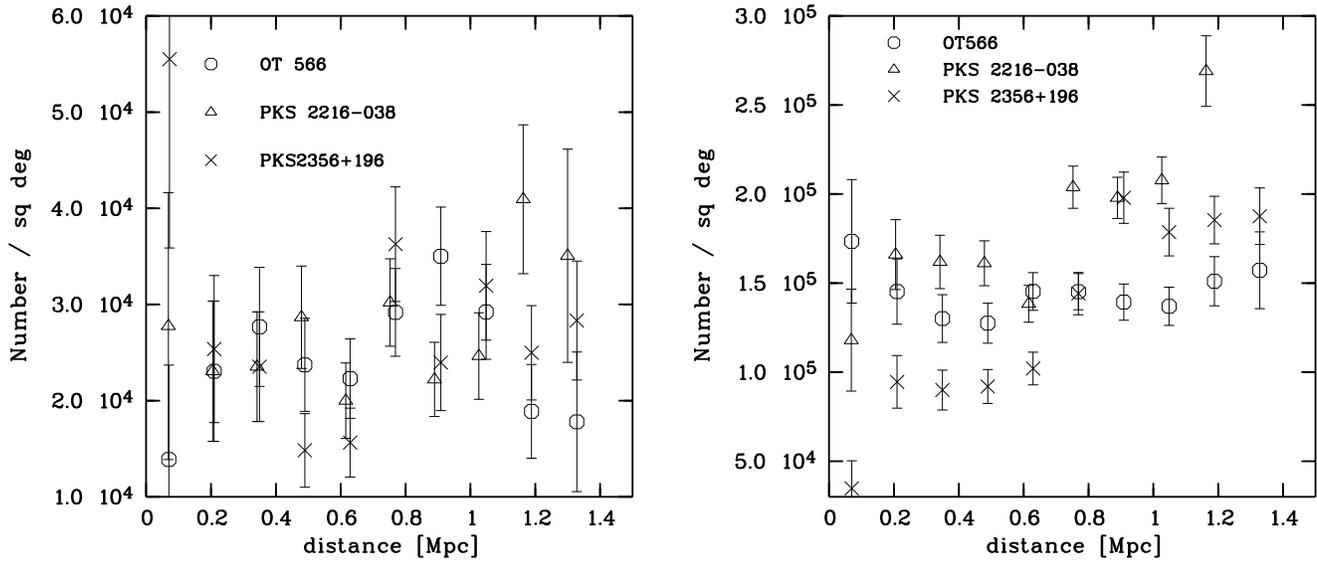


Fig. 3. Galaxy surface densities (galaxies per square degree) as a function of projected radial distance from the quasars. At $z = 1$, 100 kpc correspond to $\approx 18''$. The left panel contains galaxies with $R = 18 - 23$, the right panel galaxies with $R = 23 - 26$. The error bars are computed from Poisson statistics (1σ)

Table 3. Photometry and positions of galaxies closest to the line of sight to PKS2216-038 and PKS2356+196

	distance "	pos. angle degree	R mag
PKS 2216-038	5.6	330	21.9
	4.2	185	21.5
	4.1	220	21.7
PKS 2356+196	2.1	340	20.6
	5.0	162	21.6
	6.0	192	23.7
	7.6	278	21.9

sisted of 5 luminous ($\langle M_V \rangle = -25.4$) objects; no clustering was found, but there was evidence for gravitational lensing for 2 objects.

The sample of Hutchings, Crampton and Persram (1993) and Hutchings, Crampton and Johnson (1995) contains 14 QSOs which are optically fainter with $\langle M_V \rangle = -24.4$. The authors report an excess of galaxies over the background in 100 arcsec (568 kpc) subfields near the QSOs on the $2.5 - 3\sigma$ level; they interpret their data as evidence that QSOs are located in compact groups of starbursting galaxies. Three of the objects are radio-loud; the authors found no significant difference between radio-quiet and radio-loud objects.

A sample of 27 slightly fainter ($\langle M_R \rangle = -23.4$) radio-quiet QSOs has been analysed by Boyle and Couch (1993); there was no significant excess of galaxies with $R \leq 23.0$ around the QSOs.

At fainter optical magnitudes, Benitez et al. (1995) found an excess of bright ($19.5 < R < 22$) galaxies around 5 radio galaxies at the 99.4% confidence level. Since this excess was

not present for fainter ($22 < R < 23.5$) galaxies, the authors concluded that the galaxy excess is due to foreground objects and thus related to gravitational lensing.

This compilation shows that there is currently no consensus about an excess of galaxies around quasars. One might suspect that part of the discrepancies between the different studies might be due to luminosity effects both in the optical and radio regimes. However, as our compilation shows, the results are contradictory even when similar samples are compared. Our data are deeper by about 3 mag than the cited studies, but in the 3 cases studied here we find no evidence for a galaxy excess. There is also no consensus about the interpretation of a galaxy excess; since the redshifts of the galaxies around the quasars are not known, any detected excess can be interpreted either as true physical association or lensing of foreground objects.

3.2. Two lens candidates

Two of the three quasar images (PKS 2216-038 and PKS 2356+196) are definitely non-stellar (see Fig. 1). The MIDAS implementation of the Lucy-Richardson deconvolution algorithm was used to reveal the underlying structure. Images of stars, which had neighboring objects removed by interpolation, were used as PSFs. Already after very few iterations the deconvolution shows that the images of faint galaxies are superposed onto the images of the quasars PKS 2216-038 and PKS 2356+196; the final result of the deconvolution is virtually independent of the number of iterations. Table 3 lists the relevant data for the galaxies next to the quasars.

These galaxies appear very similar to the ones seen in the fields of the quasars. From redshift surveys it is known that galaxies with $B \approx 24$ have median redshift $z = 0.46$ (Glazebrook et al. 1995). Therefore it appears reasonable to assume

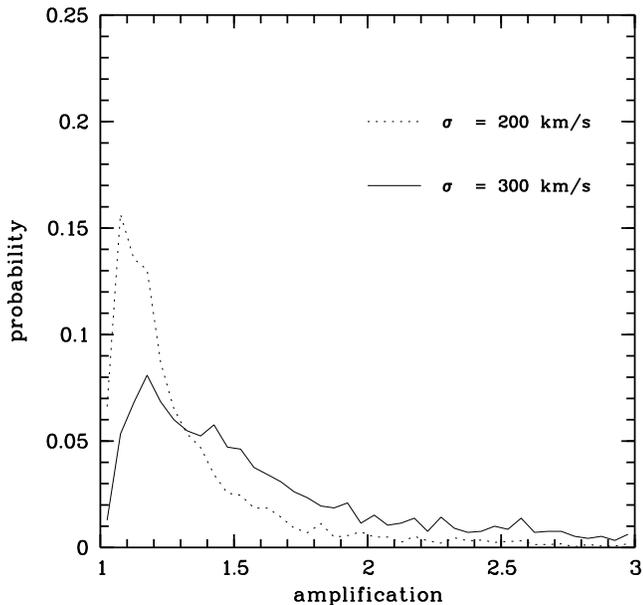


Fig. 4. Probability distribution of the amplification factors of random background ($z = 1$) objects by the galaxies in the field of OT566.

that the galaxies close to lines of sight to the quasars, too, are at $z \approx 0.5$; if so they are foreground to the quasars and amplify the light from the quasars by gravitational lensing.

Since redshifts and velocity dispersions of these galaxies are unknown, only crude estimates of the amount of lensing can be made: assuming $z_{lens} = 0.5$ and velocity dispersions for the lenses $\sigma_l = 200 \text{ km s}^{-1}$ and $\sigma_l = 300 \text{ km s}^{-1}$, the formula given by Turner, Ostriker and Gott (1984) gives amplification factors 1.2 and 2, respectively. The required masses are a few $10^{11} M_\odot$ and for a typical magnitude $R = 21.5$ (see Table 2) one obtains an absolute magnitude $M_R = -21$ using the chosen cosmology and a K-dimming and evolution correction of 1 mag according to Metcalfe et al. (1991). Therefore, these possible lenses would have masses and absolute magnitudes like typical bright galaxies.

It should be noted that PKS 2216-038 is included in the complete 1 Jy sample of radio sources; since its radio flux at 6cm wavelength is 1.5 Jy, this object may have entered the sample because it is lensed. Further evidence for lensing in this object has been given by Bartelmann, Schneider and Hasinger (1994); they have found a correlation between X-ray emission from foreground galaxy clusters and high-redshift radio-loud quasars from the 1 Jy-sample. PKS2216-038 is among the objects which show the highest correlation.

3.3. Lensing of distant objects

The integral surface density of galaxies $R \leq 26$ is $1.93 \cdot 10^5 / \square^\circ$ (mean of the three fields); this results in a projected mean distance between galaxies of only $8.2''$. Thus it is evident that many lines of sight to background (i.e. $z \geq 1$) objects pass close enough by a galaxy that they are affected by lensing.

Fig.4 shows the probability distribution of the amplification factor for the field of OT566 (the other fields give practically identical results). This was computed by putting random points into the field, and then calculating the distance to the nearest neighbor and the resulting amplification with the formula given by Turner, Ostriker and Gott (1984) for velocity dispersions of 200 km s^{-1} and 300 km s^{-1} , which correspond to mean galaxy masses of $8.1 \cdot 10^{11} M_\odot$ and $1.8 \cdot 10^{12} M_\odot$, respectively. These masses are in good agreement with recent dynamical mass estimates for nearby galaxies (Zaritsky and White 1994) and for faint galaxies within the magnitude range $20 \leq r \leq 23$ (Brainerd, Blandford and Smail, preprint). The redshifts of the lenses were distributed randomly between 0 and 1, and for the source we have taken $z_{source} = 1.2$. The assumed redshifts affect the result only weakly over a very wide range of redshifts. The diagram shows that the bulk of amplification factors relative to an 'empty' line of sight is between 1.1 and 1.5, the effect of lensing thus is moderate. From the width of the distribution of the amplification factors it is also obvious that lensing imposes a scatter on the observed luminosity function of distant objects. It must be emphasized that the assumptions on the velocity dispersions of the galaxies made for these estimations affect the amplification factor only quantitatively; the qualitative conclusion, that distant objects must be lensed by foreground galaxies, is based purely on the observed galaxy surface density. We are therefore *forced* to conclude that distant ($z \geq 1$) objects are lensed by foreground galaxies. On theoretical grounds this was anticipated by Press and Gunn (1973), who had concluded that all distant objects in a $\Omega = 1$ cosmology are lensed.

It is interesting to estimate the effects of microlensing. The optical depth $\tau_{\mu l}$ to microlensing is equal to the ratio of the surface density of the microlensing matter to the critical mass density $\Sigma_{crit} = \frac{c^2}{4\pi G D}$ where $D = \frac{D_l D_s}{D}$ and all symbols have their usual meaning. Σ_{crit} can be calculated from the chosen cosmology and the assumed redshifts $z_{source} = 1$ and $z_{lens} = 0.5$. The surface mass density of the lensing matter can be estimated for elliptical galaxies from $\Sigma_e = (M/L) I_e$ where the subscript e denotes the effective radius. Since $I_{tot} = 22.4 I_e r_e^2$ we obtain $\Sigma_e = \frac{M_{tot}}{22.4 r_e^2}$. Taking $M = 10^{12} M_\odot$ and $r_e = 5 \text{ kpc}$ gives $\tau_e = 1/2.5 (M/10^{12} M_\odot) (r_e/5 \text{ kpc})^{-2}$. For the random points which were put into the galaxy field of OT566 (see above), the mean distance to the nearest neighbor is about $4''$ or 18.6 kpc ; scaling $\tau_{\mu l}$ according to the $r^{1/4}$ -law gives a mean optical depth to gravitational microlensing of $\tau = 0.016$. This is well below unity, showing that microlensing by galaxies with $R \leq 26$ is not very important. An optical depth $\tau_{\mu l} \approx 1$ would require a galaxy surface density about 15 times the one measured to $R \leq 26$. Now, the differential galaxy number counts rise continuously to $R = 26$ with an increase in galaxy surface density by about a factor 2.3 per mag. The counts of Smail et al. (1995) show that this continues to $R = 27.5$ with no indication of a declining slope. If the counts would rise continuously to $R = 29 - 30$, then the nearest neighbor distance $\approx 5 \text{ kpc}$ and thereby $\tau_{\mu l} \approx 1$. Evidence that all distant objects are indeed microlensed has been given by Hawkins (1993); he measured

the lightcurves of many QSOs and found that the origin of variability of high-redshift QSOs ($z \geq 1$) is not intrinsic to the QSOs, but rather caused by microlensing. Since Hawkins and Veron (1993) had previously shown that virtually *all* QSOs are variable to some extent, these results present strong evidence that all distant objects are actually microlensed.

3.4. Galaxy halos

Accidentally the quasar PKS 2216-038 was also included in the sample of Le Brun et al. (1993) who were searching for galaxies close to quasars with MgII $\lambda\lambda 2798$ absorption lines in their spectra. Le Brun et al. (1993) report a possible detection of this absorption line at a redshift $z_{abs} = 0.202$ and identified a galaxy 34 arcsec away from the quasar as absorber; this galaxy would have a large halo of $102h_{75}^{-1}$ kpc radius. However, as Fig. 1 shows there are several galaxies within few arcsecs to the line of sight to the quasar. These galaxies have apparent magnitudes around $R = 21.5$; at the absorption line redshift their absolute magnitudes would be $M = -18.6$ (neglecting K-correction and evolution, but both effects are small at such low redshifts). York et al. (1986) have shown that even low-luminosity galaxies such as the Magellanic Clouds can cause absorption lines in the spectra of distant objects. Therefore, the galaxies few arcsec from the quasar can well be the true absorbers; if so, the size of the halo of the absorbing galaxy given by LeBrun et al. (1993) may be severely overestimated. Due to the high surface density of faint galaxies, cases like PKS 2216-038 may not be exceptional and may at least in some cases lead to severe overestimation of the sizes of galaxy halos.

4. Summary

We have presented very deep direct images of the fields of three quasars with redshifts between $z = 0.9$ and $z = 1.36$.

Counts of galaxies which are complete down to $R = 26$ give no evidence for a galaxy excess around the quasars in any of the three fields. We find no evidence for foreground clusters; associated galaxy clusters with richness classes larger than 1 are excluded.

Two of the quasars have faint galaxies within few arcsec to their line of sight; since these galaxies are almost certainly foreground, the quasars are lensed with amplification factors probably between 1.2 and 2.

The high surface density of galaxies leads to the conclusion that virtually all distant $z \geq 1$ objects are affected by gravitational lensing. The bulk of amplification factors relative to an 'empty' beam are estimated to be in the range 1.1 to 1.5.

The quasar PKS 2216-038 may also have an MgII absorption line at $z = 0.2$ in its spectrum; if one of the galaxies detected in our image is the true absorber, then only a moderately sized halo of 10 kpc radius is required in contrast to claims of a huge 102 kpc halo.

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