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Extensions around $z = 2$ QSOs

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ABSTRACT

Based on an *R*-band imaging survey of six high-redshift ($z \sim 2$) and high-luminosity ($M_B \lesssim -28$ mag) QSOs, we report the detection of extensions in two radio-quiet and one radio-loud QSO. The extensions are most likely due to the host galaxies of these QSOs, with luminosities of at least 3–7 per cent of the QSO luminosity. The most likely values for the luminosities of the host galaxies lie in the range 6–18 per cent of the QSO luminosities.

Key words: galaxies: active – galaxies: photometry – quasars: general.

1 INTRODUCTION

The study of high-redshift ($z \sim 2$) QSOs offers a unique opportunity to investigate conditions in the early Universe. In the currently favoured cold dark matter cosmogony, this epoch corresponds to the period when normal galaxies formed through hierarchical coalescence (Carlberg 1990), thereby giving rise to enormous concentrations of gas in the centres of the galaxies, which could feed a central black hole (Rees 1988) or provoke a massive starburst episode (Terlevich & Boyle 1993). As such, this picture is consistent with the observation that QSOs exhibit a peak in their activity at these redshifts (Schmidt, Schneider & Gunn 1991). Indeed, there has been much observational effort to obtain deep multicolour images of high-redshift radio galaxies and radio-loud QSOs, with spectacular results: enormous structures of up to 100 kpc aligned with the radio jet (Chambers, Miley & van Breugel 1987); luminosities and sizes of the parent galaxies larger than those of normal elliptical galaxies (Lehnert et al. 1992). However, radio-loud quasars are only a small fraction (< 5 per cent) of all QSOs, and many of the conclusions drawn from the studies of radio-loud objects might be unrepresentative of the conditions in the early Universe. It is, therefore, important to look into the properties of radio-quiet QSOs, as a better indicator of the general properties of galaxies at high redshifts. We present here deep images of a sample of six high-redshift, predominantly radio-quiet QSOs. Section 2 gives a summary of the observations, Section 3 explains the technique used to detect extensions around the QSOs, and Section 4 discusses the likelihood that the extensions are host galaxies.

2 OBSERVATIONS

Four radio-quiet and two radio-loud QSOs were observed during 1994 August 8/9 and 9/10 in the Harris *R* passband with the $f/11$ auxiliary port of the 4.2-m William Herschel Telescope (WHT) of the Observatorio de Roque de los Muchachos in La Palma. Luminous ($M_B \lesssim -28$ mag)[1] high-redshift ($1.8 \lesssim z \lesssim 2.2$) QSOs that lay close ($20 \lesssim \theta \lesssim 60$ arcsec) to stars of similar brightness were selected from the Véron-Cetty & Véron (1994) catalogue. The existence of a nearby star allowed us to determine an accurate point spread function (PSF) for each CCD frame. The observations were performed in excellent seeing (< 0.9 arcsec) under dusty and smoky non-photometric conditions.

We carried out the observations with a 1024^2 Tektronix CCD chip (TEK1), giving a spatial resolution of 0.105 arcsec pixel^{-1} over an unvignetted 1.8 arcmin diameter field. The configuration was chosen to provide an optimal sampling of the PSF, even in the best seeing conditions (≈ 0.5 arcsec). The chip was read out in QUICK mode, which yields a read noise of 4.3 e^- and a gain of 1.8 e^- ADU^{-1}.

Each QSO field was observed in a series of 600–900 s exposures to avoid saturation of the QSOs and PSF stars. Individual exposures were offset from one another by ~ 10 arcsec to prevent the repetition of any coherent signal (sources, cosmic rays, bad pixels) at a particular location on the chip. Table 1 summarizes the observations.

[1] $H_0 = 50$ km s^{-1} Mpc^{-1} and $q_0 = 0.5$ are used throughout this work.

Table 1. Summary of observations.

Name	B*	M_B*	z*	Radio-loud?*	Exposure time (seconds)	No. of frames	FWHM† (arcsec)
UM 281	17.4	−28.9	1.878	N	6600	11	0.7
1630.5+3749	18.3	−28.3	2.037	N	10500	15	0.6
PKS 2044–168	17.4	−29.1	1.943	Y	5400	9	0.9
PKS 2134+008	16.8	−29.6	1.936	Y	5850	7	0.6
Q 2230+0232	18.0	−28.7	2.150	N	5400	9	0.6
Q 2244−0105	18.0	−28.6	2.040	N	5400	9	0.7

* B, M_B, z and radio properties from Véron-Cetty & Véron (1994).
† Stellar FWHM measured on co-added frame.

3 DATA REDUCTION AND ANALYSIS

The data were reduced using the IRAF software package. For each separate QSO field, the images were first bias-subtracted and then flat-field-corrected using the sky flat-field derived from the median of all individual frames, after bright stars, galaxies and QSOs (and their surrounding regions) had been masked from the original data.

We then applied the PSF subtraction techniques provided by the IRAF package DAOPHOT to establish whether QSOs in this study exhibited any significant non-stellar extensions to their profiles. This procedure has already been successfully used to isolate intervening galaxies in the line of sight of QSOs (Steidel & Hamilton 1992). For each individual frame, we defined a two-dimensional PSF using the brightest of the closest stellar companions to the QSO. The PSF was defined over 30–40 pixel in radius. We then scaled the PSF to match the luminosity of the QSO and other nearby stars over the same region, and subtracted the scaled PSF from them. The remaining residuals in the non-PSF stars provided an accurate check of the validity of the subtraction process. We accepted the PSF subtraction if the residuals in the non-PSF stars accounted for less than 1σ of the Poisson noise expected from the subtraction technique, and showed no systematically repeatable pattern from frame to frame. The 1σ level was calculated by combining the Poisson noise from the different sources (sky subtraction, PSF fitting, QSO profile) in the PSF subtraction process. For one field, Q2230 + 0232, there was just one bright star near the QSO which was used to model the PSF. Although the residuals for the non-PSF stars are consistent with zero, the distance of these stars from the field centre (> 40 arcsec) results in a distinctive pattern in their residuals which repeats from frame to frame. For PKS 2044 − 168 there were two bright stars near the QSO, but neither star yielded a PSF that produced a non-zero residual when subtracted from the other, and therefore we cannot assess the significance of the residuals left in the QSO position.

For the remaining fields, the subtraction of non-PSF stars was successful. The subtracted frames were registered using the relative frame-to-frame X, Y shift derived from the positions of three bright stars in each original frame, and co-added to produce a final subtracted image. The same transformations were used to register and co-add the original frames to produce a final unsubtracted image.

The left-hand panels in Fig. 1 show the fields of the QSOs UM 281, 1630.5 + 3749, PKS 2134 + 008 and Q2244 − 0105. The right-hand panels in Fig. 1 show the same fields after subtracting the corresponding PSFs from both QSOs and stars. Fig. 2 shows, in more detail, 6 × 6 arcsec² sections of the residuals left in the positions of the QSOs and non-PSF stars. The residuals left in the positions of the stars are consistent with zero at a 1σ level (see above). Table 2 summarizes the significance of the residuals in the number of ADU. We have detected residuals in excess of 3σ in the following QSOs: 1630.5 + 3749 (4σ), PKS 2134 + 008 (3σ) and Q2244 − 0105 (3.7σ). All the residuals show a 'doughnut' shape with a well of negative counts in the centre. This indicates that there is a flatter component below the PSF in the centres of the QSOs, from which the nuclear (PSF) contribution has been over-subtracted. To estimate the true luminosities of these systems, we have subtracted smaller amounts of the PSF in order either (i) to produce zero counts in the centre of the residuals or (ii) to achieve a flat-topped profile with no depression in the centre. We regard these quantities as lower limits and best estimates, respectively, of the total luminosities of these extended components. In the lower limit case, the luminosities of the extensions comprise 3–7 per cent of the luminosities of the QSOs. In all cases, the FWHM of the flat-topped residual profiles are significantly larger than the FWHM of the stars in each field (see Tables 1 and 3). The estimates of the extended component luminosities derived from flat-topped profiles increase to 6–18 per cent of the luminosities of the QSOs. To obtain a crude zero-point (± 0.3 mag) for the images, we used the E magnitudes of the bright stars in the field provided by the APM Northern Sky Catalogue (Irwin, Maddox & McMahon 1994), which correspond to the R band (Evans 1989). Since we do not know the spectral energy distribution of the extensions, we have chosen not to correct for spectral slope or bandpass in these magnitudes, so that they correspond to magnitudes in a rest-frame band centred at ~ λ2300 Å. We list these magnitudes in Table 3.

To check the reliability of the luminosities obtained from the PSF subtraction technique, we tried to recover the luminosities of known faint compact (FWHM ~ 1–2 arcsec) galaxies in each CCD frame after we had 'added in' scaled versions of the stellar PSF, mimicking the contribution from the unresolved bright QSO nucleus. We found that subtractions that produced flat-topped residuals could recover the input luminosities of the galaxies within an error of less than 4 per cent, if the galaxies contributed more than 3 per cent to the total luminosity of the galaxy + PSF system. For galaxy contributions of ≲ 1 per cent, the input luminosities of the galaxies were poorly recovered, with errors of up to 30 per cent.

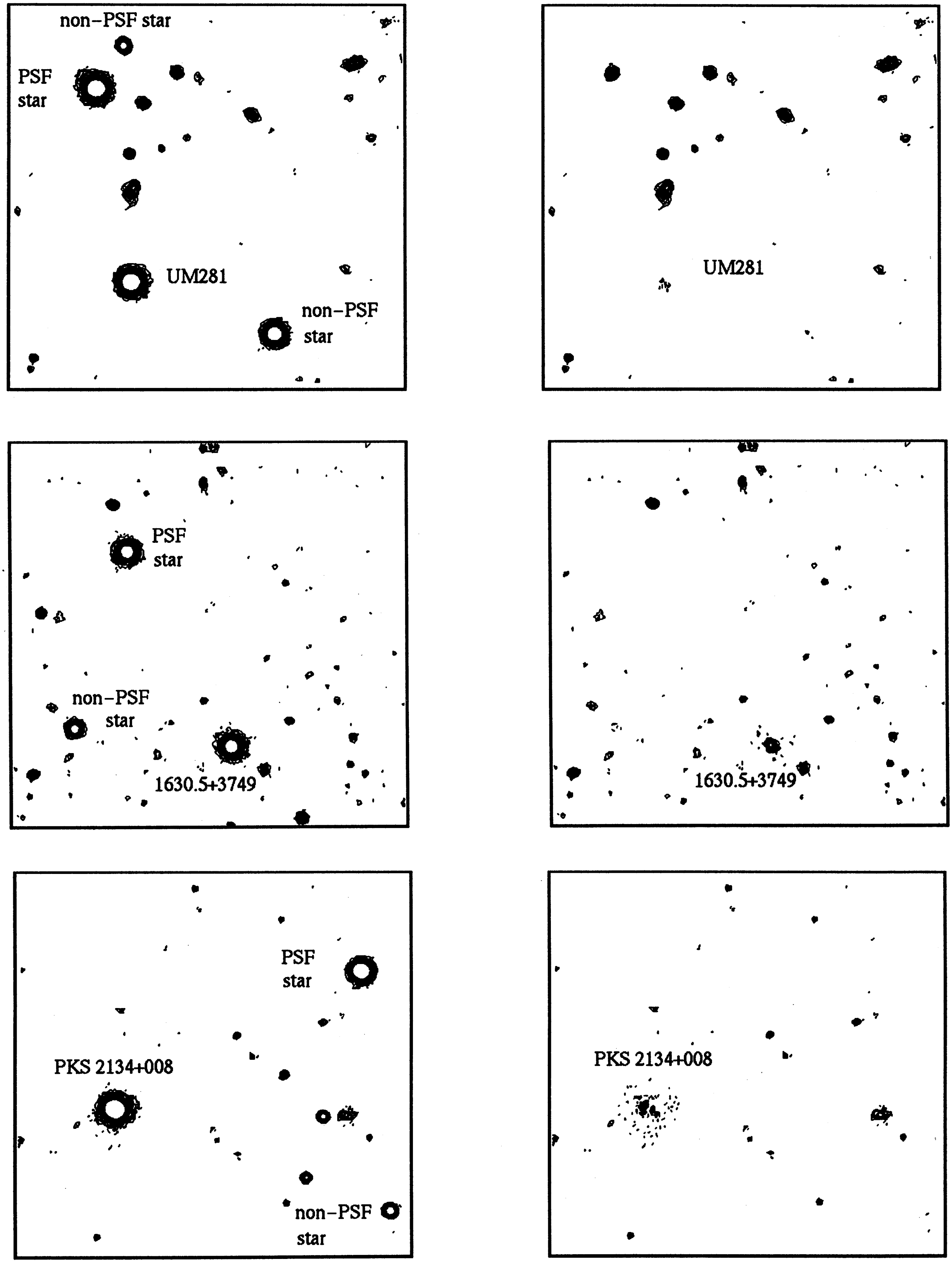

Figure 1. 50×50 arcsec^2 fields of the QSOs UM 281, 1630.5 + 3749, PKS 2134 + 008 and Q2244 − 0105. Left-hand panels show the fields before subtracting the PSF stars. Right-hand panels show the residuals left in the positions of the QSOs and stars, after a luminosity-scaled PSF has been subtracted. QSO residuals show a 'doughnut' profile, with negative counts in the centre. The minimum contour level has been set to be $\sim 2\sigma$ above the sky level. North is left, and east is down.

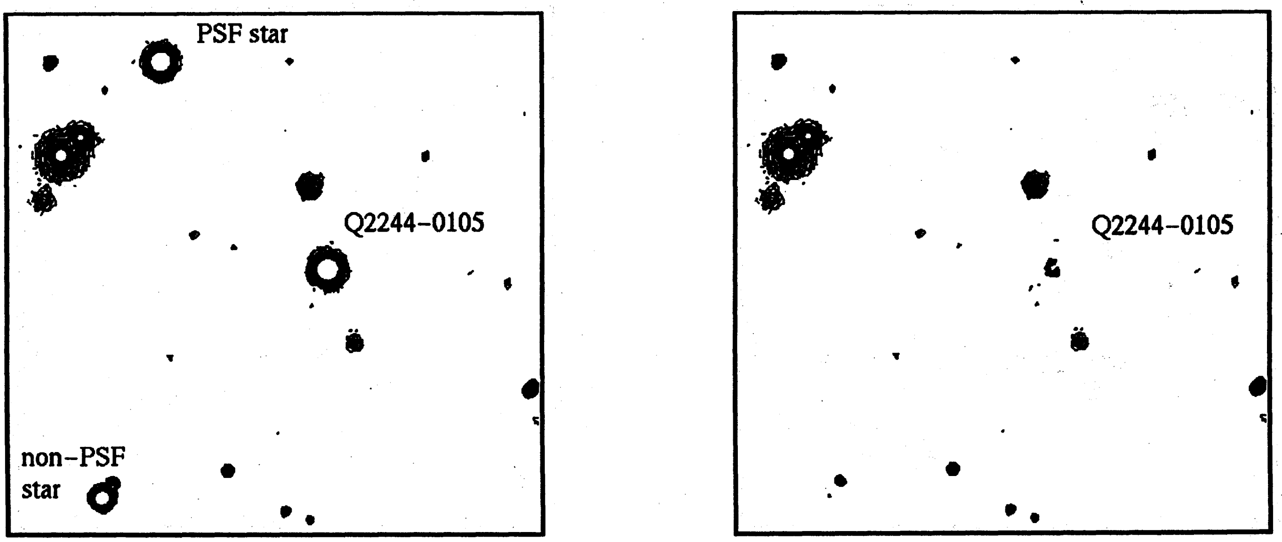

Figure 1 – *continued*

4 DISCUSSION

Out of a sample of one radio-loud and three radio-quiet QSOs with suitable PSF stars, we have been able to detect extensions in three cases. The best estimates for luminosities of these systems lie between 6 and 18 per cent of the total QSO luminosity. Host galaxies of radio-loud QSOs at $z \sim 2$ which comprise up to 20 per cent of the QSO R-band luminosity have already been detected by Lehnert et al. (1992) but, to date, no other detection has been made of hosts of high-redshift radio-quiet QSOs.

For radio-loud QSOs, the red colours of the extensions (Lehnert et al. 1992) favour a host galaxy origin of the light, rather than scattering by dust or electrons in the haloes of the QSOs. Although we lack colour information, the similarity between the nuclear-to-extended component luminosity ratio in radio-loud QSOs and that observed here leads us to believe that the extensions that we are detecting are also due to light from the host galaxy. Indeed, scattering models require the presence of a powerful transverse radio jet (Fabian 1989), which is unlikely to be present in either the radio-quiet QSOs or the core-dominated (Murphy, Browne & Perley 1993) radio-loud QSO around which we have detected extensions.

An alternative origin for the extensions could be extended nebular continuum, seen to be a major contribution in three powerful radio galaxies (Dickson et al. 1995). However, for nebular luminosities of $M_R \sim -26.5$ mag, as implied by these observations, the predicted narrow Hβ luminosity would be about 3×10^{44} erg s^{-1}, nearly half of the luminosity derived to be emitted by the broad component from the PSF light. Under these circumstances, the QSOs would exhibit prominent narrow lines with central peak intensities more than a factor of 3 greater than those of the broad lines. The spectra of these QSOs do not show such prominent narrow lines (Foltz et al. 1989; Osmer, Porter & Green 1994).

Galaxies as luminous as the extensions detected here have already been found in the imaging survey of radio-loud QSOs carried out by Lehnert et al. (1992). Four of the objects of their sample, with similar redshift to those in our sample, show 'fuzz' around the PSF of the nucleus. In the observed R frame, the absolute magnitude of this 'fuzz' ranges from -25.6 to -26.9 mag, as derived from the B and K colours that they report. Their galaxies are ~ 12 times more luminous than present-day giant ellipticals and ~ 2.5–3 mag brighter than the hosts of low-redshift QSOs. Our observations show that, if the extensions we have detected are indeed galaxies, extraordinarily massive and luminous galaxies are a characteristic not only of radio-loud objects, but of QSOs as an entire class.

Table 2. Significance of the 'doughnut' residuals: number of ADU.

Field	QSO	PSF star	non-PSF stars
UM 281	2123 ± 887	830 ± 890	740 ± 754
1630.5+3749	3932 ± 1003	491 ± 999	522 ± 831
PKS 2134+008	7940 ± 2539	−1491 ± 2207	1706 ± 1791
Q 2244−0105	4997 ± 1370	164 ± 1264	−324 ± 1071

Indeed, the radio-loud QSO studied in this sample does not exhibit a significantly larger or a more luminous extension than do radio-quiet QSOs. One of the radio-quiet QSOs exhibits no significant evidence for any extension. This is in contrast to the work of Lowenthal et al. (1995), who have established upper limits to the observed K luminosities of the host galaxies of a sample of high-redshift ($z \approx 2.5$) radio-quiet QSOs to be ~ 2 mag less luminous than those of radio-loud QSOs (Lehnert et al. 1992). A similar result is found in optical studies of low-redshift QSOs (see Smith et al. 1986), although this difference is not apparent in the near-infrared (Dunlop et al. 1993).

Clearly, our sample is too small to draw a firm conclusion, and further observations will be required to establish the differences between radio-loud and radio-quiet host galaxies

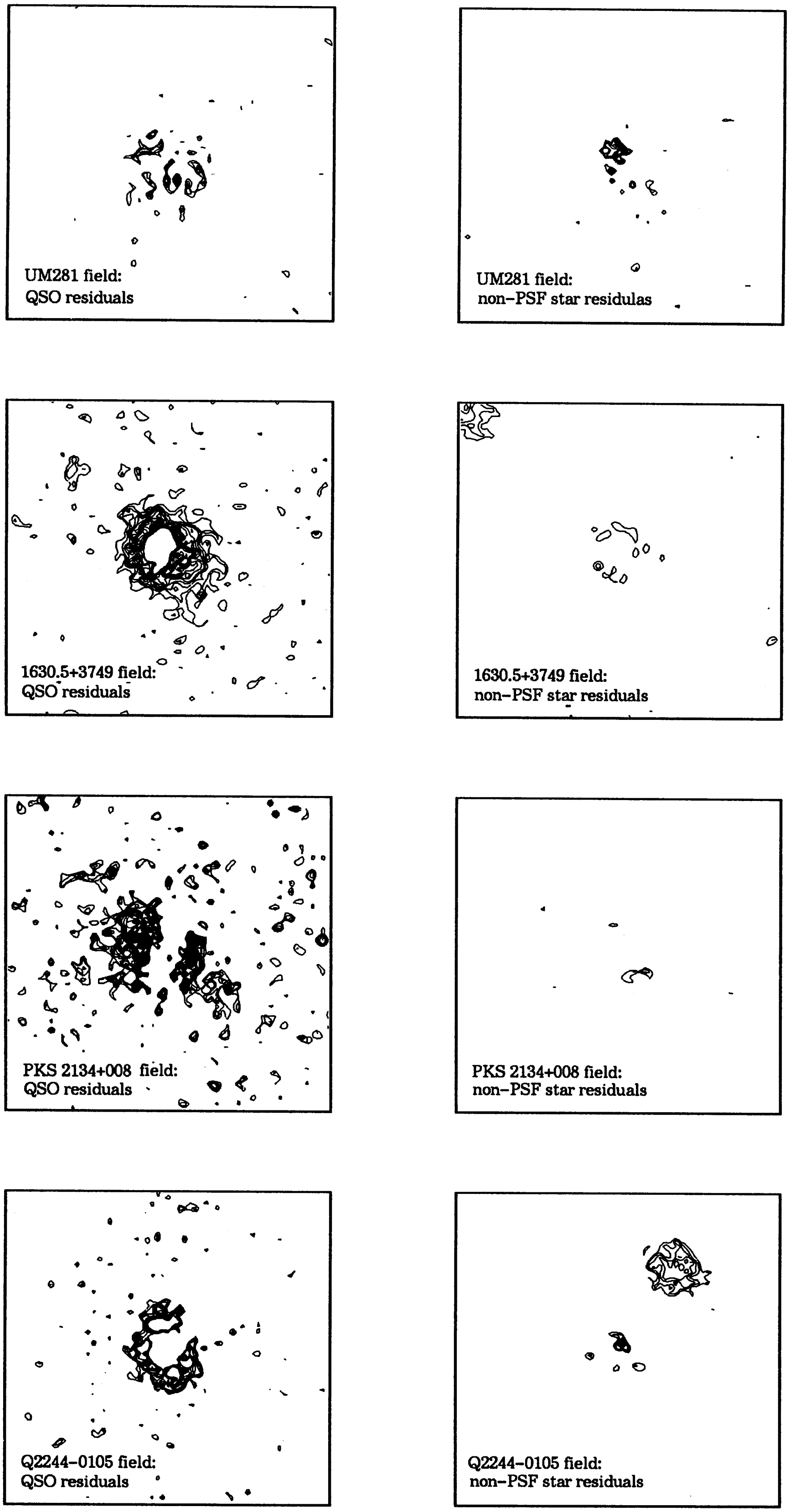

Figure 2. 6×6 arcsec^2 fields of the residuals of QSOs and non-PSF stars shown in Fig. 1. North is to the left and east is down. The centroids of the corresponding non-subtracted images lie in the centres of the plots. Note that the non-PSF star in the field of Q2244 − 0105 has a faint galaxy 1.7 arcsec to the south-west.

Table 3. Magnitudes of the QSOs and their extensions.

Name	M_R* (QSO)	M_R^1	R^1	ADU[1]	M_R^2	R^2	ADU[2]	FWHM[2] (arcsec)
1630.5+3749	−28.7	−24.8	21.7	15170 ± 1001	−25.9	20.9	32279 ± 998	1.05
PKS 2134+008	−30.1	−25.9	20.4	45509 ± 2536	−26.6	19.8	80597 ± 2534	0.80
Q 2244−0105	−29.0	−25.6	20.9	22595 ± 1368	−26.7	19.9	62975 ± 1365	0.84

*Total QSO M_R absolute magnitude, including extension.
[1] Properties for extension with zero counts in the centre after the PSF subtraction.
[2] Properties for extension with flat-topped profile after the PSF subtraction.

at high redshift. In particular, colour information will be vital, not only to establish conclusively that the extensions are due to the host galaxies, but also to provide some clues as to the evolutionary status of such systems.

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