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Adaptive optics observations of LBQS 0108+0028: *K*-band detection of the host galaxy of a radio-quiet QSO at $z \approx 2$

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ABSTRACT

We report the *first* unambiguous detection of the host galaxy of a normal radio-quiet QSO at high redshift in the *K* band. The luminosity of the host comprises about 35 per cent of the total *K*-band luminosity. Assuming the average colour of QSOs at $z \approx 2$, the host would be about 5 to 6 mag brighter than an unevolved L_* galaxy placed at $z \approx 2$, and 3 to 4 mag brighter than a passively evolved L_* galaxy at the same redshift. The luminosity of the host galaxy of the QSO would thus overlap with the highest found in radio-loud QSOs and radio galaxies at the same redshift.

Key words: galaxies: active – galaxies: photometry – quasars: general – quasars: individual: LBQS 0108+0028 – infrared: galaxies.

1 INTRODUCTION

Recent evidence that the cosmological evolution of the density of star formation in the Universe (Madau et al. 1996) follows closely the QSO density evolution (Boyle & Terlevich 1998) emphasizes the need to study the kinds of galaxies that host active galactic nuclei in order to understand the link between star formation and nuclear activity, and potentially the role of nuclear activity in galaxy formation.

At the peak value of QSO density ($z \approx 2$ to 3), the few QSO host galaxies detected so far present rest-frame UV fluxes that reach up to 20 per cent of the total QSO luminosity, indicating star formation rates of about 200 $\mathrm{M}_\odot\,\mathrm{yr}^{-1}$ and above for both radio-loud (Lehnert et al. 1992) and radio-quiet samples (Aretxaga, Boyle & Terlevich 1995; Hutchings 1995). These values are almost an order of magnitude above those of field galaxies at similar redshifts selected through Lyman break techniques (Steidel et al. 1996; Lowenthal et al. 1997). The properties of these QSO hosts are not unprecedented, since they follow very closely the luminosity–size relation of nearby star-forming galaxies, overlapping with its high-luminosity end (Aretxaga, Terlevich & Boyle 1998). However, the UV fluxes only carry information about the high-mass end of the stellar populations in the galaxies, and say little about the bulk of the stellar mass which is better characterized by optical to near-infrared (NIR) observations.

Although a few hosts of extreme radio-loud QSOs at $z \approx 2$ have been detected in NIR bands (Lehnert et al. 1992; Carballo et al. 1998), attempts to image the hosts of normal radio-quiet QSOs at the same redshifts have been unsuccessful to date (Lowenthal et al. 1995; Aretxaga et al. 1998). Imaging radio-quiet systems, which constitute more than 95 per cent of all QSOs, is important in order to characterize the bulk of the population. The observed optical sizes of FWHM≈1 arcsec (Aretxaga et al. 1995) clearly demand a technique that offers the highest available angular resolution.

In this paper we focus our attention on the detection of the host of a normal radio-quiet $z \approx 2$ QSO with the adaptive optics system in operation at the ESO 3.6-m telescope in La Silla. Preliminary results on similar programmes to image the host galaxies of QSOs at $z \approx 0.5$ and 1.7 using adaptive optics have been presented at a recent conference devoted to quasar hosts (Bremer et al. 1997; Hutchings 1997).

2 DATA SET: ACQUISITION AND REDUCTION

We selected LBQS 0108+0028 at $\alpha(\mathrm{J2000}) = 01^{\mathrm{h}}10^{\mathrm{m}}38\overset{\mathrm{s}}{.}1$, $\delta(\mathrm{J2000}) = 00^\circ 44' 54''$, a $V = 18.3$ mag QSO at $z = 2.005$ which was discovered in the Large Bright Quasar Survey (Hewett, Foltz & Chaffee 1995), because it belongs to a narrow redshift–luminosity band ($1.8 \lesssim z \lesssim 2.2$, $M_B \lesssim -28$ mag for $H_0 = 50\,\mathrm{km\,s^{-1}Mpc^{-1}}$ and $q_0 = 0.5$) and it lies close in projection, $\theta = 21$ arcsec, to a bright star of magnitude $V = 12.0$ mag. The first selection criterion was imposed in order to explore the luminosity band that is predicted to contain the most luminous hosts by quasar formation theories (Terlevich & Boyle 1993; Haehnelt & Rees 1993), and it has indeed provided a high detection rate of extended fuzz (Aretxaga et al. 1995). The second condition was imposed in order to be able to correct the atmospheric turbulence with adaptive optics, using a nearby bright

Table 1. Summary of observations.

Object	α (J2000)	δ (J2000)	z	V(obj) (mag)	θ(obj - ★) (arcsec)	V(★) (mag)	t (s)
LBQS 0108+0028	1 10 38.1	0 44 54	2.005	18.3	21.0	12.0	10 800
star A	1 4 1.24	0 55 6.7	–	13.6	20.6	11.3	5400

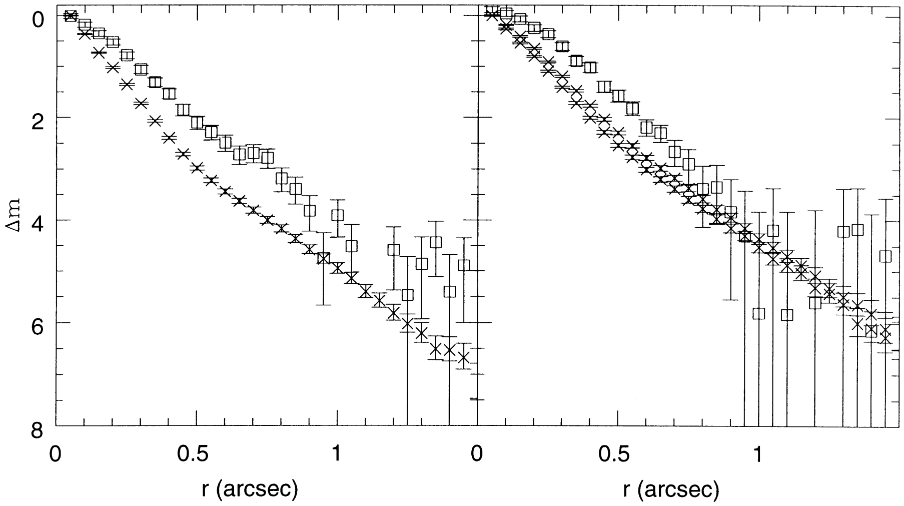

Figure 1. Radial profiles of two QSO coadded images of 20-min exposure (squares), compared with the stellar profiles (crosses) acquired before and after the QSO during the first night. Fluxes are normalized to their centroid values.

reference star on-axis, since QSOs at these redshift are too faint to allow for direct corrections on themselves. There is no radio detection of this QSO.

The observations were carried out in the K' band over 6 h spread through the nights of 1995 October 10, 11 and 12 at the ESO 3.6-m telescope in La Silla, with COME-ON+ (Rigaut et al. 1991; Rousset et al. 1994). We used Sharp II, the 256 × 256 Nicmos III array, in the general purpose 50 mas pixel^{-1} resolution mode, which gives a 12.8×12.8 arcsec^2 field of view.

In order to measure accurately a realistic point spread function (PSF) we observed every night a comparison double system that mimics the brightness of the reference star and its relative distance to the QSO. The comparison system comprises a star of magnitude $V = 13.6$ at $\alpha(\mathrm{J2000}) = 01^{\mathrm{h}}04^{\mathrm{m}}01\overset{\mathrm{s}}{.}24$, $\delta(\mathrm{J2000}) = 00^\circ55'00\overset{''}{.}6$, which we denote A, separated by $\theta = 20.6$ arcsec from a star B of magnitude $V = 11.3$ mag at $\alpha(\mathrm{J2000}) = 01^{\mathrm{h}}04^{\mathrm{m}}01\overset{\mathrm{s}}{.}24$, $\delta(\mathrm{J2000}) = 00^\circ55'06\overset{''}{.}7$ Star B was used as reference star to correct for atmospheric turbulence and star A was imaged to serve as a PSF calibrator star in the analysis of the QSO profile.

Coordinates, redshift, V-band brightnesses, distances from reference stars, brightnesses of reference stars, and total integration times are summarized in Table 1.

The observations were carried out in the following sequence: PSF star (5×30 s) in position 1 – PSF star (5×30 sec) in position 2 – QSO (10×60 sec) in position 1 – QSO (10×60 sec) in position 2 – PSF star (5×30 sec) in position 1 ... in a repeating cycle totaling 3 h of integration for the QSO and 45 min for the PSF star. Different frames were offset by approximately 6 arcsec (distance between positions 1 and 2) from one another in order to estimate the sky level from contiguous frames.

The seeing, as recorded by the differential image motion measurement, was 0.8 arcsec during the first night, being very stable (±0.03 arcsec), but variable on the second and third nights (0.8 to 1.8 arcsec).

The data were reduced with the image processing package ECLIPSE (Devillard 1997). The data were first sky-subtracted, using an average of contiguous frames with misplaced sources, and then flat-fielded with a gain-corrected sky flat frame. Bad pixels were identified in the gain map and substituted by linearly interpolated values from nearby pixels. The shift-and-add routines of ECLIPSE were then used to register individual frames and coadd them in imaging stacks of 10 min for QSO frames and 5 min for PSF calibrator star frames.

The final FWHMs of the coadded stacks of the PSF calibrator star were 0.3 to 0.4 arcsec during the first night; 0.3 to 0.9 arcsec during the second night; and 0.7 to 1.0 arcsec during the third night. The Strehl ratios attained (8 to 12 per cent for October 10, but below 5 per cent for October 11 and 12) were only acceptable during the first night. The second and third night image quality was poor, partly because of fast sky variations and partly because of fast bad seeing, which provoked a reduction of the isoplanatic patch to distances much smaller than those of our object to reference star systems.

The images were not flux-calibrated since we did not acquire calibration stars and there is no K-band measurement of this QSO in the literature.

3 PROFILE ANALYSIS

For each of the 10-min QSO images and 5-min PSF star images, we derived an azimuthally averaged radial profile using the STSDAS package in IRAF. We checked for variations across the chip (position 1 versus position 2) using the PSF profiles obtained during the first night, when the seeing was stable. We detected no variations within the error bars, and therefore coadded contiguous

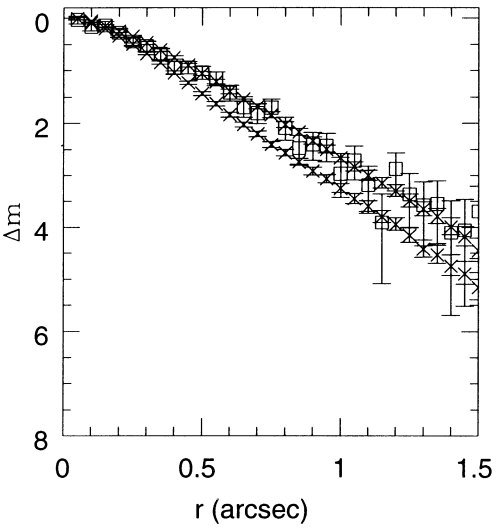

Figure 2. As Fig. 1, for the second night.

stacks of QSO and PSF star frames, into 20- and 10-min exposure images.

A comparison of the QSO profile and the PSF profile, normalized in order to reproduce the luminosity of the QSO at its centroid, are, however, different within the inner arcsecond. Fig. 1 represents two sets of QSO profiles versus the PSF star profiles obtained before and after each QSO observation. The recorded profiles were very stable throughout the night.

During the second and third nights the QSO profiles are typically indistinguishable from those of the PSF star and, when different, they are enclosed by the varying seeing profiles. Fig. 2 shows the comparison between QSO and PSF star for one of these cases. As stated in the previous section, during these nights the correction attained by COME-ON+ was poor owing to the poor seeing conditions, and there was little improvement in the spatial resolution of the images. The resulting stellar FWHM ≈1.0 arcsec implies that we should not expect to have resolved the extended structures at $r < 1.0$ arcsec that we detected during the first night, when the seeing was good and stable.

4 RESULTS

The QSO profile is more extended than that of the PSF star, with K' excesses of about 35 per cent of the total luminosity of the QSO. This is the first clear detection of the host of a distant radio-quiet QSO in the NIR. Previous attempts to detect them with direct imaging (Lowenthal et al. 1995; Aretxaga et al. 1998) resulted in non-detections at $z \approx 2$, with the exception of a marginal detection of a host at $r \approx 4$ arcsec (Aretxaga et al. 1998). The upper limits for the luminosities set by these studies were an order of magnitude above our detection. However, it is clear that this host would have gone undetected by these studies, since all the signal is localized in the inner 1 arcsec of the QSO profile while, typically, the previous studies were carried out with seeing values of FWHM between 0.9 and 1.3 arcsec (see also Fig. 2).

If we assume that this QSO has the average colour of QSOs at $z \approx 2$, $V - K \approx 2.2 \pm 0.6$ mag (Hewett, private communication), where the error bar indicates the total amplitude of colours, then the K-band magnitude of the extension will be about 17.2 ± 0.6 mag, overlapping with the K-band apparent magnitudes of radio-loud QSOs (Lehnert et al. 1992; Carballo et al. 1998) and radio galaxies (Lilly 1989) at the same redshift. Our K-band detection of the QSO host in this analysis demonstrates that there is at least one good example of a radio-quiet QSO host with an extremely luminous host galaxy at observed NIR wavelengths.

Since at $z \approx 2$ the observed K band corresponds approximately to the rest-frame R band, we can make an easy comparison of our host galaxy with local galaxies observed at optical wavelengths. A local L_* elliptical has a luminosity $M_R^* \approx -22.8$ mag, as derived from the local luminosity function of field galaxies (Efstathiou, Ellis & Peterson 1988). Thus the host of LBQS 0108+0028 is likely to be about 5 to 6 mag brighter than an unevolved L_* galaxy placed at $z \approx 2$. Taking into account the evolution that the stellar populations must have experienced between $z = 2$ and $z = 0$, an L_* galaxy at $z \approx 2$ would be about 2 mag brighter in the R band than nowadays if it had been passively evolving since formation (Charlot & Bruzual 1991). The host of LBQS 0108+0028 would thus be 3 to 4 mag brighter than a passively evolved L_* elliptical galaxy placed at $z \approx 2$. Even higher luminosities should be considered if the light that we are missing near the centre of the host is also taken into account.

The host of LBQS 0108+0028 would also be at least 5 mag brighter than the average radio-quiet host galaxies of nearby QSOs: $< M_V > \approx -21.6$ to -22.6 mag for QSOs at $< z > \approx 0.2$ (e.g. Smith et al. 1986; Hutchings, Janson & Neff 1989; Bahcall et al. 1997) which with a $V - R \approx 0.7$ mag colour for an Sb to E galaxy (Fukugita, Shimasaku & Ichiwava 1995) gives rest-frame luminosities of $M_R \approx -22.2$ to -23.2 mag. Nearby *IRAS*-selected QSOs can reside in very luminous galaxies of up to $L \sim 6L_*$ (Boyce et al. 1996).

As already noted by Lehnert and co-workers (1992) for their radio-loud sample, the density of luminous QSOs ($M_B \lesssim -28$ mag) at $z \approx 2$ like the one explored in this study is about 10 Gpc^{-3} (Boyle et al. 1991), and their hosts can be well accommodated at $z = 0$ by the tail of the luminosity function of field galaxies, an idea which has also been proposed by Terlevich & Boyle (1993) in their comparative study of the luminosity functions of QSOs and elliptical galaxies. Clearly, a bigger sample of hosts of radio-quiet QSOs should be detected in the K band before establishing an evolutionary link between these populations of galaxies.

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