The hosts of $z = 2$ QSOs

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Abstract. We present results of the hosts of four high-redshift ($z \approx 2$) and high luminosity ($M_B \lesssim -28$ mag) QSOs, three radio-quiet one radio-loud, imaged in R and K bands. The extensions to the nuclear unresolved source are most likely due to the hosts galaxies of these QSOs, with luminosities at rest-frame 2300Å of at least $3-7$ per cent of the QSO luminosity, and most likely around $6-18$ per cent of the QSO luminosity. Our observations show that, if the extensions we have detected are indeed galaxies, extraordinary big and luminous host galaxies are not only a characteristic of radio-loud objects, but of QSOs as an entire class.

1 Introduction

The study of high redshift ($z \approx 2$) 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 center of the galaxies, which could feed a central black hole (Haehnelt & Rees 1993) or provoke a massive starburst episode (Terlevich & Boyle 1993). As such, this picture is consistent with the observation that the QSO population peaks at these redshifts (Schmidt et al. 1991).

Searches for galaxies hosting high-redshift QSOs were first carried out in radio-loud objects, with spectacular results: luminosities several magnitudes brighter than the most luminous galaxies in the nearby Universe were observed (Lehnert et al. 1992). However, radio-loud quasars are only a small fraction ($< 1\%$) of all QSOs, and many of the conclusions drawn from 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 they may be better indicators of the general properties of galaxies at high redshifts. We present here deep multicolor images of one high-redshift radio-loud and three high-redshift radio-quiet QSOs.

2 Data analysis

The four QSOs were observed in the Harris R passband with the auxiliary port of the 4.2m William Herschel Telescope (WHT) at the Observatorio de Roque

de los Muchachos in La Palma, and in K band with the Cassegrain focus of the 3.5m at the Observatorio de Calar Alto in Almería. The QSOs were selected so as to have bright stars in the field ($20 \lesssim \theta \lesssim 50$ arcsec), which enabled us to define the point spread function (PSF) of each observation accurately (see Aretxaga et al. 1995,1997 for a detailed description of data and analysis).

For each QSO field, we defined a 2-dimensional PSF using the brightest of the closest stellar companion to the QSO. 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. We have detected R-band residuals in excess of 3σ in the following QSOs: 1630.5+3749 (4σ), PKS 2134+008 (3σ) and Q 2244−0105 (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. As an example, Fig.1 shows the R-band residuals for the radio-quiet QSOs 1630.5+3749, after subtracting a luminosity-scaled PSF.

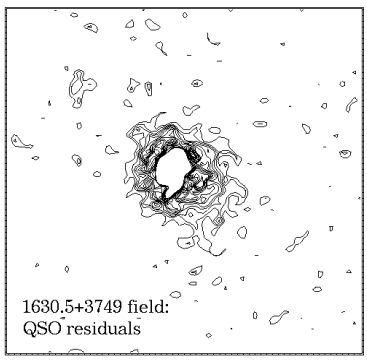

Fig. 1. R-band residuals of the QSO 1630.5+3749 after PSF subtraction (Aretxaga et al. 1995). The size of the frame is $6''$x$6''$.

To estimate the true luminosity of these systems, we subtracted smaller amounts of the PSF in order either a) to produce zero counts in the center of the residuals or b) to achieve a flat-top profile with no depression in the center. We regard these quantities as lower limits (3–7% of the QSO luminosity) and best estimates (6–18% of the QSO luminosity), respectively, of the total luminosity of these extended components (Table 1). In all cases, the FWHM of the flat-top residual profiles are significantly larger than the FWHM of the stars

in each field: 1″.05 vs. 0″.7 for 1630.5+3749, 0″.8 vs. 0″.7 for PKS 2134+008 and 0″.84 vs. 0″.7 for Q 2244−0105.

The K-band images of the same hosts show no significant extensions to the stellar profiles (see Fig.2), over a 1σ limiting magnitude $\mu_K \approx 23$ mag/arcsec^2 (Aretxaga et al. 1997). These limits are consistent with previous non-detections of $z \approx 2$ radio-quiet hosts in K band (Lowenthal et al. 1995). If there are no colour gradients, from the $r \sim 2 - 3''$ non-detection limits, the colours of the hosts are $R - K \lesssim 3.3$ mag.

Table 1. Magnitudes of the QSOs and their extensions (Aretxaga et al. 1995)

Name	M_R^* (QSO)	M_R^1	R^1	M_R^2	R^2	FWHM^2 (arcsec)
1630.5+3749	−28.7	−24.8	21.7	−25.9	20.9	1.05
PKS 2134+008	−30.1	−25.9	20.4	−26.6	19.8	0.80
Q 2244−0105	−29.0	−25.6	20.9	−26.7	19.9	0.84

* Total QSO M_R absolute magnitude, including host ($H_0 = 50$ Km s^{-1} Mpc^{-1}, $q_0 = 0.5$).

[1] Properties for hosts with zero counts in the center after the PSF subtraction.

[2] Properties for hosts with flat-topped profile after the PSF subtraction .

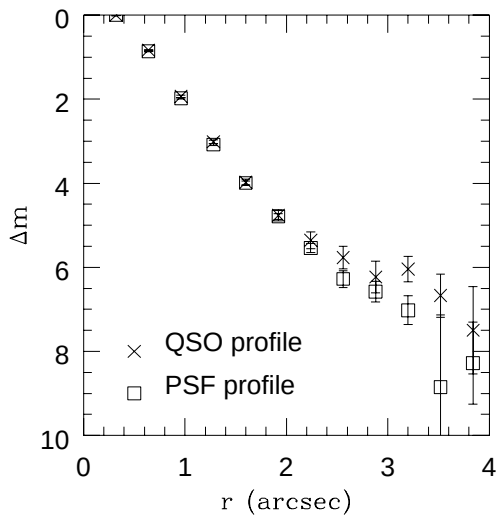

Fig. 2. Comparison between the QSO (1630.5+3749) radial profile and the PSF stellar radial profile in K-band, where crosses indicate QSO and squares stellar profiles

3 Discussion: the origin of the 'fuzz'

From a sample of one radio-loud and three radio-quiet QSOs with suitable PSF stars, we have detected R-band extensions in three cases (Aretxaga et al. 1995) and no extensions in K-band (Aretxaga et al. 1997). The best estimates for R-band (2300Å rest-frame) luminosities of these systems lie between 6–18% of the total QSO luminosity.

3.1 Scattering

For the lobe-dominated radio-loud QSO sample of Lehnert et al. (1992), the red colours of the hosts favour a host galaxy origin of the excess light, rather than scattering by dust or electrons in the halo of the QSOs. Our colour limits for the excess light, $R-K \lesssim 3.3$ mag, include colours as blue as those of the QSOs themselves ($R-K \approx 2.3$ mag), and are therefore consistent with the colours expected from the optically thin scattering case and, also, with those of a young stellar population. They, however, exclude the colours of passively evolved bulge populations (eg. Bressan et al. 1993).

However, most scattering models proposed to date require the presence of a powerful transverse radio-jet (e.g. Fabian 1989) which is unlikely to be present in either the radio-quiet QSOs, or the core-dominated radio-loud QSO around which we have detected extensions.

3.2 Nebular continuum

An alternative origin for the hosts could be extended nebular continuum, seen to be a major contribution to the UV continuum in three powerful radio galaxies (Dikson et al. 1995). However, if our hosts are due to nebular luminosities of $M_R \sim -26.5$ mag, the predicted narrow Hβ luminosities would be about 3×10^{44} erg s^{-1}. From the PSF light we derive that the luminosity of the broad component is about double that. If this is so, the QSOs would exhibit prominent narrow lines with central peak intensities of more than 3 times those of the broad lines. The spectra of our QSOs do not show such prominent narrow lines .

3.3 Host galaxies

There is some circumstantial evidence that the extensions we have detected are most probably the galaxies which host these QSOs:

a) The radial profile of the R-band hosts, derived from the flat-top solutions, falls approximately as an $r^{1/4}$-law for radii $r \gtrsim 0.6$ arcsec (Fig. 3). Profiles derived for radii smaller than the FWHM of the observations are usually unreliably recovered by flat-top subtractions, as confirmed by our the numerical simulations of galaxy+PSF. However, total luminosities and sizes are parameters which can be recovered well if the galaxy contribution exceeds 3% of the QSO+galaxy system.

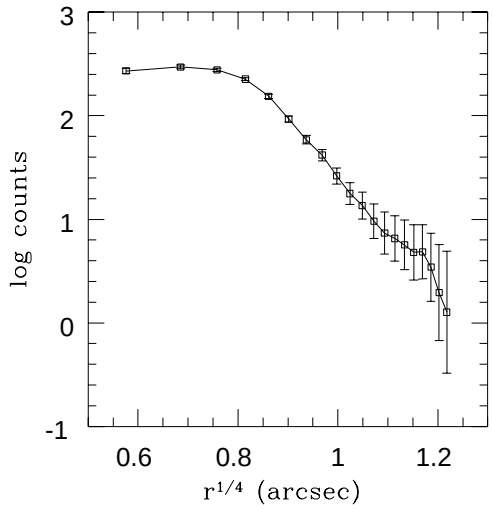

Fig. 3. Radial profile of the R-band host of the QSO 1630.5+3749, in a log counts vs. $r^{1/4}$ diagram: an $r^{1/4}$ profile would appear as a straight line.

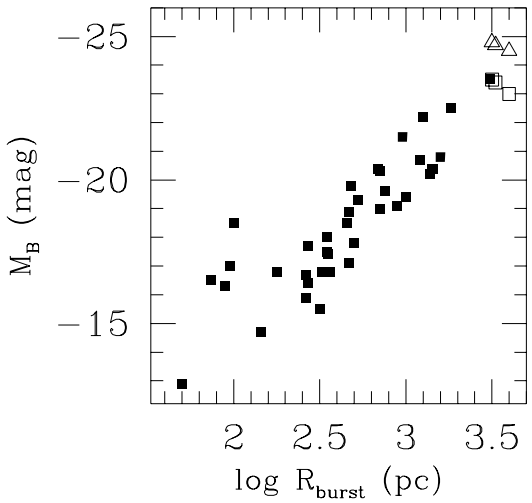

Fig. 4. Luminosity–size relationship for nearby H II galaxies (Telles 1995). H II galaxies are marked with filled squares. The three QSOs studied here lie in this relation if their SEDs are $f_\nu \propto \nu^0$ (open triangles) to $f_\nu \propto \nu^{0.5}$ (open squares). These SEDs are typical of young H II galaxies

b) The luminosities and radii of our hosts lie in the luminosity-radius relation of local young H II galaxies (Fig.4). We converted the UV luminosities of the hosts (observed R-band) to rest-frame B-band using the spectral energy distribution (SED) of local H II galaxies ($f_\nu \propto \nu^\alpha$, with $0 \lesssim \alpha \lesssim 0.5$). This is equivalent to converting the B-band luminosities of the H II galaxies to rest-frame 2300 Å and then comparing the UV luminosity-radius relationship of H II galaxies with that of the hosts. Notice that there is at least one H II galaxy which is as big and luminous as our hosts. At $z \approx 2$, an unevolved $L_\star$ galaxy with SED typical of an H II galaxy would appear to be about 3 mag fainter than the hosts we have detected. The star formation rates involved would be of the order of a few hundreds of solar masses per year.

Galaxies as luminous as the extensions detected here have already been found in the imaging survey of lobe-dominated radio-loud QSOs carried out by Lehnert et al. (1992). Four of the objects of their sample, with similar redshifts 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 they report, which compares to the -25.9 to -26.7 mag we found in our study of two radio-quiet and one core-dominated radio-loud QSO. Our observations show that, if the hosts we have detected are indeed galaxies, young massive and luminous galaxies are not only a characteristic of radio-loud QSOs, but of QSOs as an entire class. Indeed, the only radio-loud QSO studied in this sample does not exhibit a significantly larger or a more luminous extension than those of radio-quiet QSOs. One of the radio-quiet QSOs exhibits no significant evidence for any extension in any band.

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