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. The luminosities and sizes of the hosts overlap with those of actively star-forming galaxies in the nearby Universe. Radial profiles over the outer resolved areas roughly follow de Vaucouleur or exponential disk laws. These properties give support to the host galaxy interpretation of the extended light around QSOs at high-redshift. 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.

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 [3], thereby giving rise to enormous concentrations of gas in the center of the galaxies, which could feed a central black hole [7] or provoke a massive starburst episode [12]. As such, this picture is consistent with the observation that the QSO population peaks at these redshifts [10].

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 [8]. However, radio-loud quasars are only a small fraction ($< 1\%$) of all QSOs, and many of the conclusions drawn from radio-loud objects

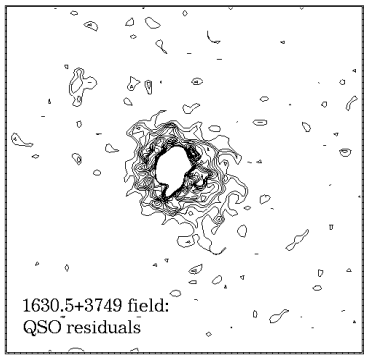

Figure 1: R-band residuals of the QSO 1630.5+3749 after PSF subtraction. QSO residuals show a 'doughnut' profile, with negative counts in the center. The minimum contour level has been set to be $\sim 2\sigma$ above the sky level. North is left, and East is down. The size of the frame is $6''$x$6''$.

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 [1][2] 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.

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

Table 1: Magnitudes of the QSOs and their extensions [1]

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 .

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.

A two-dimensional PSF subtraction similar to that performed in the optical images was also attempted in the infrared frames, with the only difference that individual frames were registered and co-added before performing the subtraction. The residuals left in the QSO positions were in all cases negligible.

Radial profile comparison of QSOs and PSF stars in the K-band images show that the differences between them are indeed minimal, and located in the outermost regions, where the

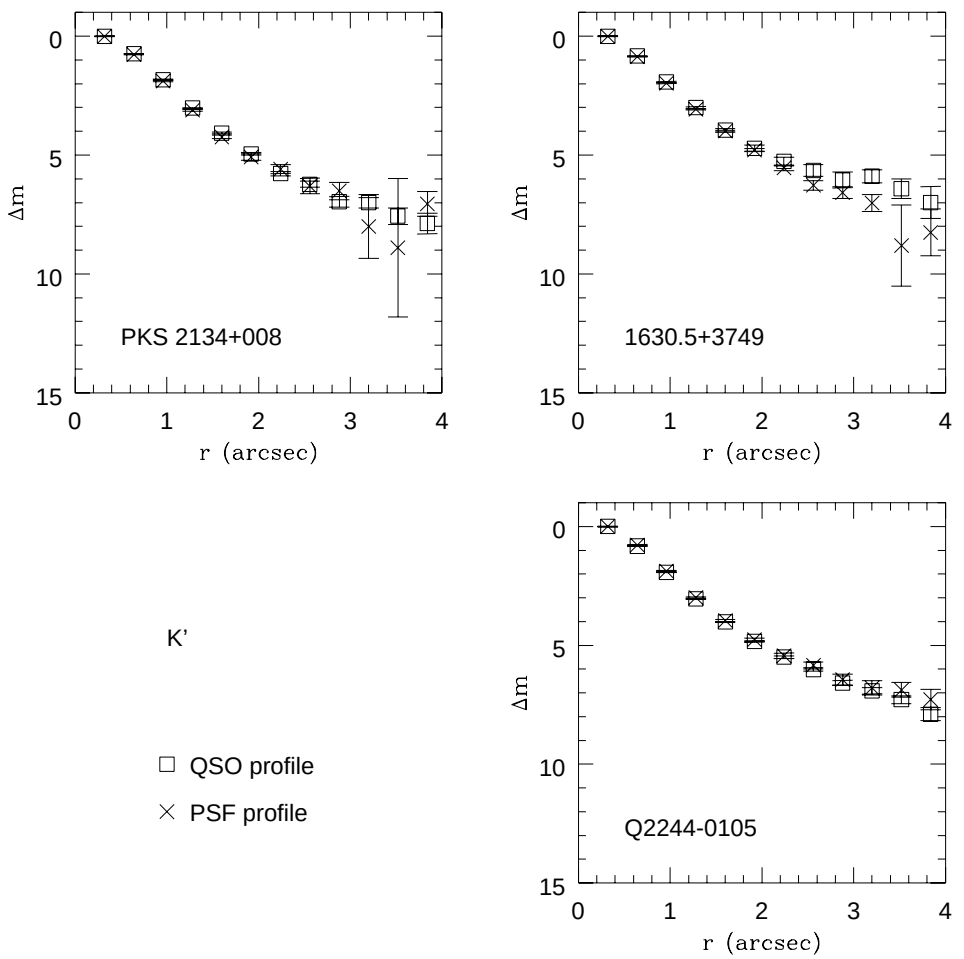

Figure 2: K'-band radial profiles of QSOs and stars in the field, normalized to their central flux.

sky subtraction is critical. Fig.2 shows the radial profiles normalized to the first computed ring at 0.32 arcsec for QSOs and stars. Only 1630.5+3749 has a marginal excess above the stellar profile at 2–4arcsec from the center. The excess doesn't disappear allowing for shifts in the overall sky level.

The colours of the QSOs 1630.5+3749 ($R-K = 2.5 \pm 0.12$ mag), PKS 2134+008 ($R-K = 2.1 \pm 0.10$) and Q 2244−0105 ($R-K \approx 3.4 \pm 0.3$) are within those measured in QSOs at these redshifts (1.4–2.6 mag). If we assume that the excess present in 1630.5+3749 is real, the surface brightness colour over the 2–3 arcsec region is $\mu_R - \mu_K = 3.3 \pm 0.5$ mag, redder by 0.8 mag than the observed colour of the QSO by a mild excess over the error bars. For the other two objects, 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.

The surface brightness limits for the K-band images are between 22.1 and 21.8 mag/arcsec^2 at 1σ in a pixel. The limits for 3σ detections of punctual objects in a seeing-disk area range between 20.8 and 21.1 mag. These limits are similar to those obtained in previous K band images of radio-quiet hosts at $z \approx 2$ which yielded non-detections [9].

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 [1] and no extensions in K-band, except for maybe one of them [2]. 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 a lobe-dominated radio-loud QSO sample previously observed [8], 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. Indeed, if the excess present in the K-band image of 1630.5+3749 is real, the colour of the host of this object does rule out the thin scattering case. Our colour limits for the excess light in the other two QSOs, include colours as blue as those of the QSOs themselves, and are therefore consistent with the colours expected from the optically thin scattering case but, also, with those of a young stellar population. They, however, exclude the colours of passively evolved bulge populations [4].

Most scattering models proposed to date require the presence of a powerful transverse radio-jet [6] 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 [5]. 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 [2].

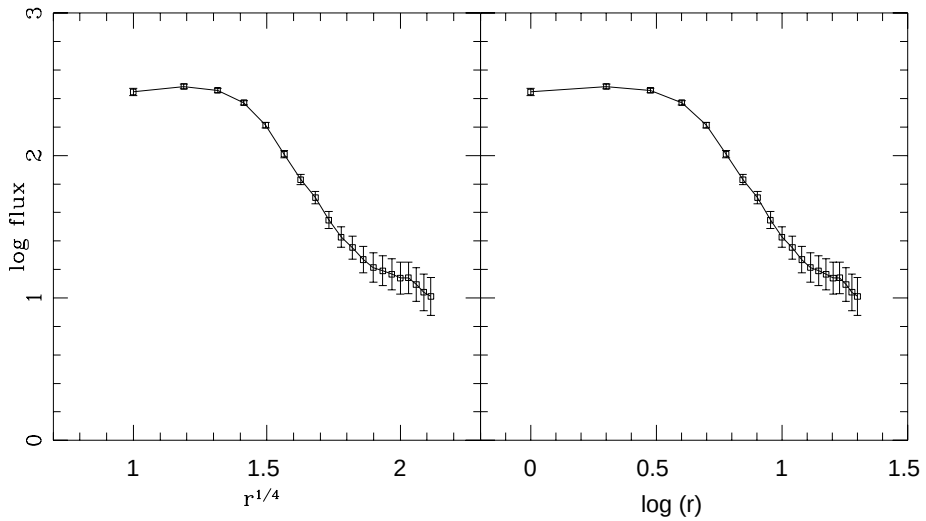

Figure 3: Radial profile of the R-band host of the QSO 1630.5+3749, in a log counts vs. $r^{1/4}$ and in a $\log(r)$ diagram. Elliptical profiles and disk-like profiles give linear relationships in the right-hand and left-hand pannel, respectively.

3.3 Host galaxies

In addition to the colours, 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 or disk-like profiles 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 numerical simulations. However, total luminosities and sizes are parameters which can be recovered well if the galaxy contribution exceeds 3% of the QSO+galaxy system.

b) The luminosities and radii of our hosts lie in the luminosity-radius relation of local young H II galaxies [11] (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 lobe-dominated radio-loud QSOs [8]. Four of the objects of that 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, 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.

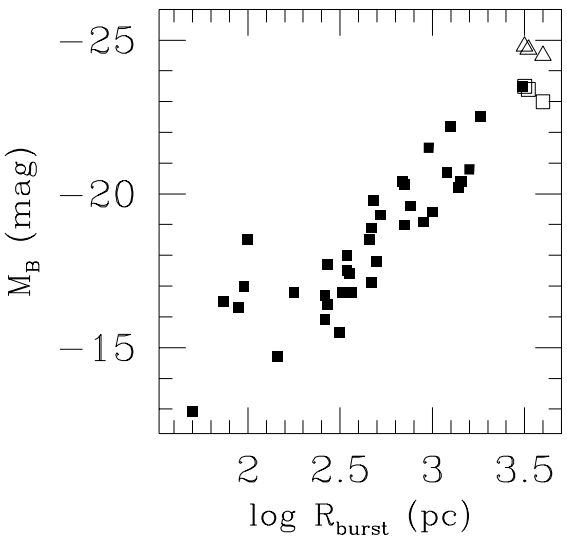

Figure 4: Luminosity–size relationship for nearby H II galaxies and QSOs hosts. H II galaxies are marked with filled squares. The three QSOs studied here lie in this relation if their SEDs are $f_\nu \propto \nu^0$ (open triangles) to $f_\nu \propto \nu^{0.5}$ (open squares). These SEDs are typical of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

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