The colours of $z \approx 2$ QSO host galaxies

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Abstract. Three high-redshift ($z \approx 2$) and high luminosity ($M_B \lesssim -28$ mag for $H_0 = 50$Km s^{-1} Mpc^{-1}, $q_0 = 0.5$) QSOs, two radio-quiet one radio-loud, were imaged in R, I and K bands. The luminosities, colours and sizes of the hosts overlap with those of actively star-forming galaxies in the local Universe. These properties give support to the young host galaxy interpretation of the extended light around QSOs at high-redshift. The rest-frame UV and UV-optical colours are inconsistent with the hypothesis of a scattered halo of light from the active nucleus by a simple optically-thin scattering process produced by dust or hot electrons. If the UV light is indeed stellar, star formation rates of hundreds of solar masses per year are implied, an order of magnitude larger than in field galaxies at similar redshifts and above. This might indicate that the QSO phenomenon is preferentially accompanied by enhanced galactic activity at high-redshift.

1. Introduction

Several attempts to find the early counterparts of big spheroids in large areas of the sky at high redshifts have been conducted but to date just a handful of candidates have been found [10]. Where are these bright objects hiding? In galaxy formation models based on the hierarchical merging of dark matter halos the majority of large spheroids are formed at lower redshifts, so that the present-day large systems were previously broken-up into small fainter pieces of a yet not completely assembled whole [8]. There is also a good possibility that some large spheroids may have gone undetected as the host galaxies of bright QSOs. Two pieces of observational evidence support this hypothesis. First, a significant number of nearby bright QSOs are associated with luminous ellipticals [3]. Secondly, many of the properties of high-z QSOs are consistent with their association with the cores of early luminous spheroids. Among them, the high metal content of the Broad Line Region of high-z QSOs [6]; the detection of large masses of dust in $z \approx 4$ QSOs [7]; and the correspondence of the observed luminosity function of QSOs and ellipticals [11], do suggest that QSO activity might be occurring in the central regions of young massive ellipticals.

All these points are reinforced by the recent discovery that about 5 to 20% of the luminosity of both radio-loud and radio-quiet QSOs at $z \approx 2$ arises from extended structures of FWHM$\approx 1 - 2$ arcsec [1,2,9]. Unraveling the nature of the extensions around QSOs at these redshifts is of major importance since they could be revealing the hidden signature of the elusive early large spheroid population.

In this contribution we focus our attention on the multicolour properties of the hosts of three $z \approx 2$ QSOs, in an attempt to characterize the emission mechanism.

2. Data analysis

The three QSOs, two radio-quiet 1630.5+3749 and Q 2244−0105, one radio-loud PKS 2134+008, were observed in the Harris R and I passbands 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 (Spain). 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 PSF using the brightest of the closest stellar companion to the QSO. We then subtracted a scaled version 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. We have detected R and I-band residuals revealing hosts in the three QSOs. In all cases, the FWHM of the flat-top residual profiles ($0''.8$ to $1''.1$) are significantly larger than the FWHM of the stars in each field (typically 0.7") – see in Figure 1 the residuals left in our best detection case, 1630.5+3749.

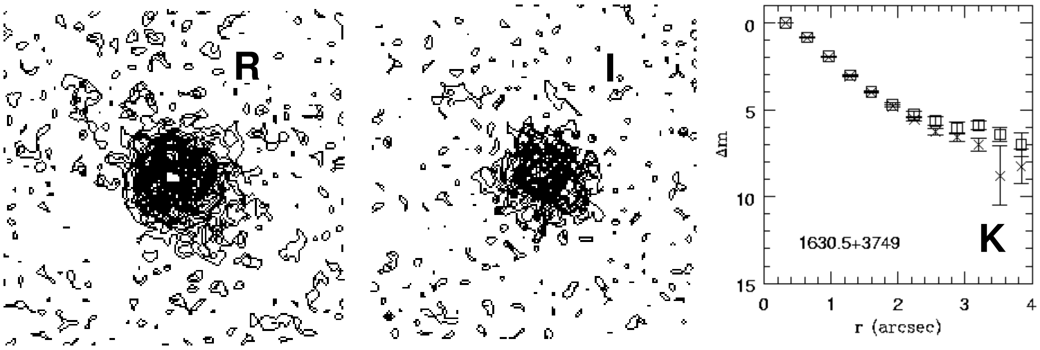

Figure 1: Countour plots of R and I-band residuals after performing a PSF subtraction that leaves zero counts in the center; and K-band radial profiles of QSO (squares) and star (crosses), normalized to their central flux.

3. The nature of the hosts

The hosts we have detected have luminosities that contribute between 5 and 12% of the luminosity of the QSOs (nucleus+extension) both in R and I-bands

(λ2300 Å and λ2800 Å rest-frame). If the excess over the stellar K-profile of 1630.5+3749 at $r \approx 3''$ is real, the K-band (λ7600 Å rest-frame) luminosity of the host as derived from the measured colours would also contribute to the total K-band QSO luminosity about 5%. Our measurements indicate large and luminous extended systems ($D_{eff} \approx 4$ Kpc, $R \approx 21$ to 22 mag). We will consider two alternative explanations for their nature: scattered light from the active nucleus and stellar light.

3.1. Scattering

Large structures detected in high-redshift radio-galaxies have been attributed to light scattered from the active nucleus by a powerful transverse radio-jet. Indeed, recent spectro-polarimetry of two $z \approx 1$ radio-galaxies that exhibit 'alignment effects' (optical structures oriented in the direction of the radio-jet) indicates that around 80% of the total UV continuum emission at rest-frame λ2800 Å is non-stellar scattered light [5]. Since radio-galaxies and radio-loud QSOs could be identical objects viewed from different angles, an important amount of scattered light may be present around radio-loud nuclei.

The host of the core-dominated radio-loud QSO studied in this paper, PKS 2134+008, has an $R-I$ colour that is 0.52 mag redder than the nucleus. This argues against the simple optically-thin scattering case, which would yield colours as blue as or bluer than the nucleus itself. The $R-K$ limits for this host ($\lesssim$ 3.3 mag) are not deep enough to probe the optically-thin scattering case value. Note that four lobe-dominated radio-loud QSOs at $z \approx 2-2.5$ [9] have hosts with $B-K$ colours redder than the nuclei. However the $B-K$ (or $R-K$) analysis discriminates poorly the origin of the light below the λ4000 Å break, since scattered light would contribute predominantly in B-band (rest frame λ1400 Å) and stellar light would contribute predominantly in K-band (rest-frame λ7300 Å).

The host of our radio-quiet QSO 1630.5+3749, exhibits the same general properties, with colours 0.25 and 0.8 mag redder than the nucleus in $R-I$ and $R-K$, respectively. These colours are inconsistent with the optically-thin scattering case as an explanation for the UV hosts of our QSOs. An optically-thick medium should be invoked in order to produce colours redder than those of the scattered source, but then the geometry of the scatterers should not be symmetrical since we still see the blue colours of the nucleus itself. This could be an alternative mechanism for the origin of the extended light in our sample, although there is no evidence in general for asymmetric scattering in radio-quiet QSOs.

3.2. Stellar light

Stellar light remains still the most plausible interpretation for the extended light we have detected. The colours, sizes, luminosities and radial profiles are indeed in agreement with those expected from young stellar populations:

a) The *colours* of the hosts, $R-K \approx 3.3$ mag for 1630.5+3749 and $R-K \lesssim 3.3$ for PKS 2134+008 and Q 2244$-$0105, are not consistent with the colours predicted from a simple passively evolved stellar population, usually assumed to be characteristic of elliptical galaxies. A passively-evolved stellar population for a $z \sim 2$ elliptical galaxy has colours $R-K \approx 5.5$ mag and slightly bluer for a mild amount of activity [4]. Younger populations are necessary in order to account for the blue colours observed in our hosts. As an example, typical nearby H II galaxies set at $z = 2$ would have colours as blue as $R - K \sim 1 - 1.7$, as derived from their characteristic flat spectral energy distributions (SED): $f_\nu \propto \nu^\alpha$, with $0 \lesssim \alpha \lesssim 0.5$.

b) and c) The *luminosities and radii* of our hosts lie along the luminosity–radius relationship of the local young H II galaxies [2]. And there is at least one local H II galaxy that is as big and luminous as our hosts.

d) The *radial profiles* of the R and I-band hosts, derived from the flat-top solutions, fall approximately as $r^{1/4}$-laws or exponential profiles for radii $r \gtrsim 0.6$ arcsec [2]. Profiles derived for radii smaller than the FWHM of the observations are usually unreliably recovered by flat-top subtractions, as shown by our numerical simulations of galaxy+PSF.

Therefore, the hosts of $z \approx 2$ high-luminosity radio-quiet and radio-loud QSOs are large and luminous, rivaling the most luminous nearby star forming galaxies. Colours, sizes, luminosities and radial profiles are compatible with the interpretation of the extended light as a young galaxy. If all the UV luminosity is coming from a stellar population, the implied star formation rates (in the continuous star formation case) are SFR$\gtrsim 100 - 200$ M$_\odot$/yr on scales of $D_{eff} \approx$ 4 Kpc. These values are about an order of magnitude higher than those derived for field galaxies at similar redshifts found by Lyman Break searches in the Hubble Deep Field. At $z \approx 2$, an unevolved $L_\star$ galaxy with SED typical of a star-forming galaxy would appear to be about 3 mag fainter than the hosts we have detected. The density of high-luminosity QSOs ($M_B \lesssim -28$ mag) at redshifts between $1 \lesssim z \lesssim 3$ is about 10 Gpc^{-3}. This means that the density of large luminous galaxies like the ones considered here should be about 8 Gpc^{-3} at $1 < z < 3$, taking into account the non-detection cases of extensions [1] and the relative under-abundance of radio-loud QSOs, which form less than 10% of the QSO population.

Acknowledgements: This work was supported in part by the 'Formation and Evolution of Galaxies' network set up by the European Commission under contract ERB FMRX-CT96-086 of its TMR programme.

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