QSO HOST GALAXIES AT Z=2.3

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Abstract

Images are discussed of 6 QSOs at z=2.3, one QSO-like IRAS source at z=2.3, and one QSO at z=1.1, taken with resolution 0.6 to 0.9 arcsec. 5 of the QSOs are radio-quiet. All QSOs except one are just resolved, while the IRAS source has definite structure. In some cases, part of the QSO fuzz appears to be a close companion rather than a concentric host galaxy. The luminosities implied for the hosts or companions are typical of bright galaxies with young hot star populations. Radio-quiet QSOs appear to have host galaxies less luminous by ~ 2 magnitudes, than radio-loud QSOs.

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1. Introduction

Host galaxies of QSOs of all types have been resolved at redshifts up to ~0.5 (e.g. Hutchings and Neff 1992). At redshifts 0.5 to 0.9, host galaxies of radio-loud QSOs are resolvable with good signal and image quality (<0.7 arcsec: see Hutchings 1992). At high redshifts (≥2), only those of very high radio luminosity have been resolved (Lehnert et al 1992). Lowenthal et al (1995) report marginal K-band detection of radio-quiet host galaxies at z~1 but no detection at z=2.5. In addition to the host galaxies themselves, radio-loud QSOs often have extended emission-line gas, sometimes of large size and luminosity, and often associated with the extended radio structure (Heckman et al 1991). It thus appears that at higher redshifts, radio-loud QSOs are hosted by exceptionally luminous galaxies, while the majority of (radio-quiet or lower radio-luminosity) QSO host galaxies have been too faint to detect. The results reported in this paper resolve for the first time, the host galaxies of high redshift radio-quiet QSOs.

The observations are already reported by Hutchings, Crampton and Johnson (1995) and Hutchings (1995), in discussions of the environments of these objects. The data were obtained using the High Resolution Camera of the CFHT. This covers a field of ~2 arcmin with 0.11 arcsec pixels, and rapid tip-tilt guiding. Exposures were 600 sec in R-band for all objects and also in I band for the z=1.1 object. These correspond to rest wavelengths of 2100A at z=2.3 and 3300A and 3800A at z=1.1. The image FWHM was in the range 0.6 to 0.9 arcsec, which is significantly worse than the 0.4 arcsec obtainable in the best conditions. The image width at 1% of peak (see below) is ~3 arcsec. The detector was a Loral CCD with ~6e read noise, and gain 1.9 e/ADC unit.

2. Data reductions

The observing conditions were photometric with variable seeing, and variable sky brightness due to moonlight. Photometric standard fields were observed on each of the two nights of observation, in April 1993. In each standard field about 10 stars were used to generate the calibration curve: resulting magnitudes for the QSOs are estimated to

be accurate to ± 0.1 mag. The point spread function (PSF) differed significantly between exposures, but not across any individual image. Rapid guiding was done on a bright star within ~ 1 arcmin in all fields. In each image there was one or more bright star and several faint stars (comparable with the QSO) to use to generate PSFs for each image. PSF stars were chosen to be free of close galaxy companions, cosmic rays, and detector flaws. In a few instances, cosmic ray signals of a few pixels near to the PSF stars or the QSO were edited out and replaced by values close to the local mean. The processed image sky signal is flat to well below 1% over the small fields of interest (20 arcsec or less).

The QSO images were not saturated and were measured using IRAF aperture photometry. Some of the bright PSF stars were saturated in their centres and these pixels were not used. The Images of the QSOs and the PSF stars were fit using the 'ellipse' task of STSDAS, which also estimates RMS errors for each value. The PSF peaks were derived from the fainter stars and the outer parts using the bright stars. In all cases there was excellent agreement between PSF profiles in the same image. Figure 1 shows some PSFs and the scatter among the individual stars used.

Figure 2 shows the QSO profiles fitted with PSF profiles which are matched at the peak signal. The principal uncertainty in the process is the sky level to subtract, since we are measuring the profiles down to signal levels within one or two counts of the sky, which had a typical value of 150. The sky photon noise is the principal noise source. The sky level was measured by image statistics near the stars, and by the 'rimexam' task in IRAF; in all cases values were tried over a range of 5 about the best value, to check the sensitivity of the results. In most cases, the correct sky value was clearly indicated by the profile signal stabilizing around zero far from the object, where there are no other objects seen in the image. In no case was the apparent resolution of the QSO dependent on the sky level chosen within this range.

In all cases except one, the QSO profile is broader than the PSF at radii above the 1 -2 arcsec range. Beyond about 5 arcsec, the signal level is too low to measure, except where there are obvious faint galaxies near the QSO. While a number of individual profile

points lie within their error bars of the PSF profile, there are many that lie systematically 1 - 2 σ above the PSF, and none that lie more than 1 σ below. Thus, the cumulative result is that the QSO images are generally extended with faint signal.

Considering the faintness of the signal and the short range of radius over which it is detected, no attempt was made at measuring the shape of the PSF-subtracted profile. The integrated extended light was measured and is given in Table 1. The 1σ uncertainty in the ratio of nuclear to resolved flux is a factor 1.5, or about 0.5 in host galaxy magnitude, at host galaxy magnitudes <22. For the fainter ones the uncertainty rises to ∼twice this factor.

3. Individual objects

0820+296. This radio-loud QSO has several companions nearby (see Hutchings 1995) and they show up in the profile beyond 4 arcsec. The extended light within this radius appears to be azimuthally spread.

10214+4724. This IRAS source with QSO-luminosity has been resolved before (e.g. Soifer et al 1992). The object has an elliptical inner shape and a curved tail emerging from the long side of the ellipse. Figure 3 shows contours from the CFHT image.

The central resolved elliptical host has half the luminosity of the unresolved nucleus, and the arc has comparable luminosity to the host. The arc extends more than 4 arcsec in this image (20 Kpc at high redshift). Soifer et al suggest that the arc is a separate and possibly disconnected galaxy as its peak flux lies well away from the central source. The image in Figure 3 shows that the arc does extend to within 1 arcsec of the nucleus, and thus seems very likely to be connected with the source - probably an tidally extended companion in the process of merging.

Broadhurst and Lehar (1995) have modelled this object as a seyfert galaxy lensed by an elliptical galaxy at z∼1. In the present observations only the central 'nuclear' object is seen in B and NB (rest Lyα) images taken at the same time. This may further test the lensing model.

1232+134. This QSO has faint resolved fuzz visible below 23.8 mag/arcsec^2. Some guiding jitter affected the central pixels, equally in QSO and PSF.

1246+005. This is the only QSO that shows no resolved luminosity. The 1σ upper limit for undetected luminosity is 1/50 of the QSO flux, as given in Table 1.

1338+277. This is the most clearly resolved QSO image, and appears fuzzy on the screen. The QSO is also the faintest of the sample. There is a faint compact knot as well, that lies 1.2 arcsec N of the nucleus.

1632+391. This is the only QSO at lower redshift, and is radio-loud. It has centrally distributed resolved light. There is a large nearby galaxy (see Hutchings, Crampton and Johnson 1995) that was edited out of the image or azimuthally ignored in the measurements.

1641+395. The resolved luminosity lies principally to one side and probably includes a very close companion galaxy. The QSO lies in a very compact group of faint galaxies (Hutchings 1995).

1641+410. This QSO also lies in a compact group of companions (Hutchings 1995). Some ($\sim$60%) of the resolved light may come from a non-centred faint companion.

4. Discussion

The results indicate that we have just resolved the host galaxies of the sample of high redshift QSOs observed with the HR Camera. Table 1 shows the measured quantities from the PSF subtraction. Since the limiting isophote level and the seeing and guiding are different for each image, the results probably depend on these quantities. A plot of limiting isophote against nuclear to resolved flux suggests that higher ratios can be detected with fainter isophotes, as expected. We might also expect the resolved host flux to depend on the nuclear fux, but this does not show up in a plot. Thus, we probably see a real spread in host galaxy luminosities.

It is interesting to note that the host galaxies of the radio-loud QSO 0820+296 and the IR source are the brightest. The other radio-loud QSO is at z = 1.1, and at z = 2.3

would be at the limit of resolution with these data. 10214+4724 is also a radio source: all 3 radio-loud objects in the sample have fluxes of 0.4 to 0.5 Jy at 5 GHz, which corresponds to the fairly high luminosities of (log) 26.5 - 27.5 W/Hz. However, they are an order of magnitude less luminous than typical high redshift 3C sources.

In Table 1 the absolute magnitudes are given for the unresolved and resolved flux, for H_0=100, q_0=0.5. No k-correction is applied to any of these values. The rest wavelength of the observations at the QSO is 2100A (3300A for 1632+391), so the k-correction depends greatly on the stellar population. If the galaxies have present-epoch populations, the k-corrections must be 6 or more magnitudes, making the host galaxies extraordinarily luminous. If they consist of type B0 stars, they are 2 magnitudes *less* luminous, and if they consist of A0 stars, they are 0.5 magnitudes more luminous. Thus, the detected host galaxies have the luminosity of normal bright galaxies if they have a young population of stars. This seems a plausible scenario, and implies that the QSOs live in new galaxies or extreme starbursting galaxies at this redshift. This is consistent with the results on the companion galaxies discussed by Hutchings et al (1995).

Lehnert, Heckman, Chambers, and Miley (1992) found resolved light about 2 magnitudes brighter than these radio-quiet QSOs, in a sample of radio-loud QSOs. Hutchings, Ellingson, and Ozard (1992) also resolved a radio-loud QSO at z=2 with a similarly luminous host galaxy. Two of the 3 radio-loud objects in this sample, have host galaxy magnitudes comparable with theirs. Thus, it appears that radio-quiet host galaxies are considerably less luminous than radio-loud ones - at this rest wavelength. This result is consistent with the lack of detection of radio-quiet host galaxies with lower optical resolution than the present sample. Clearly, better results and colour measurements should be possible with deep exposures in excellent seeing conditions.

References

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Captions

1. Examples of comparison of PSFs for stars in a single image. Different symbols distinguish the stars. The dashed line indicates the mean PSF used. The scales and individual error bars can be compared directly from Figure 2.

2. Azimuthally averaged profiles of QSOs and PSFs from program images. PSFs are matched at the profile peak, and have error bars less than the plot symbols in the ranges shown. Magnitude scales are referred to the limiting magnitude values in Table 1.

3. Contours of R image of 10214+4724. Levels are a factor $\sim$1.5 apart. Note that the arc extends to near the nucleus, and the inner extension perpendicular to the arc.

Table 1. Measured and derived quantities

QSO	FWHM (")	m_R (mag)	limit (m/"^{2})	N/F ($\pm$factor)	m_{gal}	M_{nuc}^1	$M_{gal}^{1,2}$
0820+296[R]	0.6	18.5	26.8	23 (1.5)	21.9	-26.9	-23.5
10214+4724[R]	0.7	20.2	25.2	1.9 (1.5)	21.5	-24.7	-23.9,-23.9
1232+134	0.9	17.4	26.7	150 (2.0)	22.8	-28.0	-22.6
1246+005	0.7	17.7	25.8	(>50)	>21.9	-27.7	(>-23.5)
1338+277	0.8	20.7	27.7	4 (2.0)	22.4	-24.5	-23.0
1632+391[3,R]	0.7	17.7	25.5	35 (1.5)	21.6	-25.4	-21.5
1641+395	0.9	18.6	26.5	50 (2.5)	23.6	-26.8	-21.8,-22.3
1641+410	0.9	20.1	26.1	15 (2.5)	23.6	-25.3	-21.8,-21.8

Notes to Table 1

[1] No k-correction. For B0 star k = -2.0m; for A0 star k = 0.5m.

[2] Estimates for companion galaxies where separated: not included in N/F value. Uncertainties are tied to the N/F uncertainty factors quoted.

[3] z = 1.1; all others z=2.3.

R = radio-loud source