IMAGING OF LOW REDSHIFT QSOs WITH WFPC2

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Abstract

Observations with the PC2 CCD of the Hubble Space Telescope are described of two bright QSOs of redshift ∼0.3. 1403+434 is IR-bright and radio-quiet, and 2201+315 is radio-loud with extended structure. Exposures were taken with the F702W and F555W filters. The images are deconvolved on their own and combined with 0.5 arcsec ground-based images. Both host galaxies have the form and luminosity of bright ellipticals, with nuclei of 1-2 times higher luminosity. 1403+434 is strongly interacting while 2201+315 may be in later stages of a merger, both with a smaller companion. Both host galaxies have compact knots and other small-scale peculiar features. Some general remarks are made based on the total program sample of 6 QSOs.

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1. INTRODUCTION

This paper extends the work described by Hutchings et al (1994) on imaging of selected low redshift QSOs with the corrected optics of the Hubble Space Telescope. We report results on the last two QSOs in the program, and discuss the total sample of six, of which 2 were observed before the HST optical correction. The QSOs were selected from the extensive sample for which we have CFHT imaging data, to cover a representative range of radio luminosity, optical luminosity, and morphology as seen from the ground-based data. Table 1 summarises the sample objects.

The new observations were made with the F702W filter (4 x 140sec) and F555W filter (500, 2 x 800, 1100 sec). The multiple reads allow easy removal of significant cosmic ray events, and the range of exposure times allows for correction for saturation effects at the QSO nuclei. The major problems in this work are the large dynamic range between the nucleus and the faint host galaxy, and the shape of the PSF itself. It is clear in retrospect that these difficulties need more careful attention in designing the observations: ideally the pointing should be dithered at a sub-pixel level to improve the sampling, and similar specific PSF observations should be taken with a star at the same detector location.

Nevertheless, the new data contain significant new information on the morphology and luminosity of bright knots and features in the host galaxies, and add to our understanding of the activation of QSO nuclei. In what follows, we use $H_0=100$, and $q_0=0.5$, although there is little sensitivity to $q_0$ at these redshifts.

2. 1403+434

This z=0.32 QSO was discovered as an IRAS source by Low et al (1989). These authors note that the spectrum shows a BAL Mg II line profile, and that it is radio-quiet. Hutchings and Neff (1992) report CFHT imaging with 0.5 arcsec resolution, which suggests that the QSO is the nucleus of a round and featureless galaxy which is in early interaction stages with a smaller companion on a plunging orbit.

The HST observations (Figure 1) support this conclusion. The tail consists of two
almost straight sections with a bend at a place of diffuse brighter flux (knot B). The head of the tail (knot A) is extended almost tangentially to the radius vector and there is no extra light closer in than this. The outer end of the tail is somewhat brighter and fairly sharply bounded normal to its length. It gets wider with increasing distance from the nucleus out to this point. Two other faint knots (E,F) are seen within or superposed on the opposite side of the host galaxy. They are seen as $\sim 3\sigma$ detections in both filters and are extended, although more compact than a typical galaxy. Thus, they might be compact knots in the host galaxy.

Restored images and PSF-subtracted images were made, using point spread functions derived from star images and from the program Tiny Tim (Krist 1993). The PSF in WFPC2 has structure which varies over the field because of variable shadowing in the optical path and small optical differences across the detectors. In addition, even the PC field is undersampled so that it is almost impossible to match the pixel placement of PSF with the observation. These conclusions were arrived at empirically, after many attempts at restoration and subtraction.

In the case of our QSOs, the PSF structure dominates the signal over some 0.5 arcsec diameter, so that within this area we cannot definitively isolate the host galaxy structure or luminosity profile. Image restoration does improve the resolution of structure outside this area, but in the outermost regions where the signal is weak, restoration tends to enhance noise features. In no case (Figure 1) were we able to completely remove the PSF structure, by restoration or by subtraction.

Thus, the host galaxy luminosity profile was measured from the raw HST image in which the main diffraction spikes are ignored or edited out, as well as the interacting galaxy light. The resulting profile does not fit an exponential, but does indicate a power law (see Figure 2) in the radius range out to $\sim 3$ arcsec. PSF subtraction was performed from the profiles in Figure 2, and also in flux-scaled images, and on both cases the result is close to a straight line that fits the outer part of the plots in Figure 2. This result is consistent with the CFHT luminosity profile in Hutchings and Neff (1992), which extends over larger
radii, and for which a similar conclusion was drawn. Thus, the host galaxy appears to be an elliptical with some minor disturbance by its smaller merging companion.

As in Hutchings et al (1994) and references therein, we have combined the CFHT and HST images with the Lucy-Hook algorithm, to enhance the resolution of the weak outer signal. Figure 1 illustrates the results. The results are somewhat limited by the large difference in resolution and signal between the datasets. Nevertheless, the process improves the information on much of the structure, especially in the faint outer part of the tail. The failure of any restoration to remove the PSF structure makes the restored images unreliable for luminosity profiles. However, the combined restored images show similar profiles to the raw data, but with significantly more scatter.

Table 2 shows the photometry from this object and the features identified in Figure 1. The nucleus is unusually red for a QSO, consistent with its high IR luminosity. If the reddening is by dust of a normal QSO nucleus, then there is $\sim 1.5$ mag of extinction in the observed R and $\sim 2$ mag in observed V. This makes the nucleus quite luminous and able to account for the observed IR luminosity by dust heating. The light of the host galaxy estimated as described above, corresponds to a luminous elliptical with $M_v = -22.3 \pm 0.5$, and fairly blue colour. We discuss later the reliability of this estimate.

The bright knot (A) at the head of the tail has a total luminosity of -18, while the whole tail is about 1 magnitude brighter. Thus, if this is a disrupted galaxy, it has a luminosity similar to the LMC. The length of the tail is about 7.5 arcsec, which is about 20Kpc at the QSO redshift. The core of the bright knot A at the head has $M_v \sim -16$, and is also apparently as red as the QSO nucleus. All other colours are intermediate between this and the host galaxy general colour: i.e. the knots and tail are redder than the main host galaxy mass.

The two faint knots (E,F) on the opposite side have the brightness of a 30 Dor type cluster, if they are associated with the QSO. They can just be detected in the CFHT images.

The most tantalising part of the image lies close to the nucleus. We have removed the
PSF by subtraction of a PSF image, and also by $180^\circ$ rotation and subtraction of the image from itself. This was done for both colours, and raw and deconvolved images. In every case, there is a residual arc of luminosity as shown in Figure 1(6), from about 2 o’clock to 5 o’clock about 1 arcsec from the nucleus. This arc might be a part of an elliptical ring that passes through the head A of the tail, with the local extension of A forming part of this ring. The brightness cannot be measured very accurately but it appears to be similar in colour to the main tail, and about 1 magnitude fainter.

If this structure is real, then it implies either a disturbance deep within the QSO host, or a double tail, with this second one superposed on the inner part of the QSO host galaxy.

3. 2201+315

This is a radio-loud QSO, also described in Hutchings and Neff (1991). The redshift and optical luminosity are both similar to 1403+434. However, the optical object has somewhat different morphology, and it is also a large double-lobed radio source (see e.g. Hutchings and Gower 1984). The CFHT images indicated an overall elliptical shape, extended normal to the radio axis, but with a radial colour gradient (redder with increasing distance), and some irregular knots within the host galaxy. It was hoped that the WFPC2 images would resolve some of the knots.

The WFPC2 images had the same exposures as in 1403+434, so that the F555W exposure is considerably deeper than the F702W. Both show weak signal with little structure in the host galaxy. However, the 3 principal features in the CFHT image are seen, and one more which is compact and faint. These are labelled A to D in Figure 3. We also note that the two bright nearby objects are unresolved and are presumably foreground stars. They have redder colours ($\sim1.2$ mag) than any of the QSO features except for the faint new knot A.

Feature A is clearly extended in both HST and CFHT images. Features B and C are very compact, but they are resolved. Feature D is so close to the nucleus that its boundaries and structure are not well defined, but it appears to be a large region which is
brighter than the corresponding area on the other side of the nucleus. Table 2 shows the measures made on these features, based on both raw and restored images.

Image restoration was done on the CFHT and WFPC2 data separately and combined, and confirm the reality of the features we discuss. Restoration tends to move signal into the nucleus in a way that may not be photometrically correct. The ratio of nuclear to host galaxy flux in the raw images is 0.4 from CFHT and 0.8 from the WFPC. Restoration increases these to 1.0 and 3.2 respectively, and 1.2 in the combined restoration with equal weight to each. A best estimate of 1.5 is adopted in Table 3. The total magnitudes are close to those quoted in Hewitt and Burbidge (1993) and Hutchings and Neff (1992), and the small differences are probably due to differing amounts of the extended host galaxy that were measured.

Figure 2 shows the luminosity profile from the edited raw HST image. As with 1403+434, the restored image is not reliable for this measurement. The inner 3 arcsec of 2201+315 clearly has a power law form and not an exponential, as in 1403+434. The slopes are very similar, with some extra light at ~1 arcsec radius, as also seen in the CFHT data by Hutchings and Neff (1992). The outer CFHT luminosity profile suggests some disturbance, presumably from a merging event older than in 1403+434, which triggered the radio source growth.

The CFHT image shows that there are many faint small galaxies in the field, which may be a more distant cluster. Their distribution, size, and brightness are such that it is possible that feature A is one of them. However, A is brighter, bigger, and bluer than most of them. Also, even in the CFHT image, feature C appears more compact than these galaxies. Thus, it seems reasonable to treat the features in Table 2 as associated with the QSO.

The region D is the brightest but it may reflect an off-centred nucleus or central dust feature rather than a separate luminous entity. Its flux is thus very uncertain and the region has no clear boundaries. The elongated feature A is better defined and is the bluest part of the QSO environment, and bluer than the nucleus. Region C is very compact and
bright. Its size is \(\sim 4\) pixels which corresponds to 500 pc. It is conceivably the nucleus of a merging galaxy, as in 1403+434, but there is no sign of a contiguous tail. The feature B is also compact, but larger, and very red.

Thus, we find that there are small regions and compact knots of different colours, as suspected by Hutchings and Neff. Feature D may be related to the overall shape of the galaxy, but otherwise none of the features is related to any other, or to the overall galaxy, or to the radio structure, which emerges perpendicular to the long axis of the galaxy.

4. DISCUSSION

The PC2 images are able to resolve compact features in the inner parts of the QSO host galaxies. These are details of tidal tails, compact sites of star-formation, or kpc-scale structure in the host galaxies. None of the observed features is normal spiral structure, and in the sample of 6 in Table 1, only 1229+204 shows any kind of symmetrical structure - in that case a bar. In all 6 QSOs we see compact blue knots which are consistent with being clusters of several thousand young hot stars, perhaps like 30 Dor in the LMC.

The objects were selected on the basis of known structure seen in the pre-existing CFHT images, and so may be biased towards bright and peculiar host galaxies. However, all objects appear to be in the middle to late stages of merging with a smaller (M33 or LMC-size) companion. The luminosity profiles are not simple and not characteristic of an archetypical spiral or elliptical, which is also consistent with the modelled effects of merging. This is consistent with the discussion by Hutchings and Neff (1992) based on 0.5 arcsec imaging of a larger and unbiased sample.

The other WFPC2 radio-loud QSO in this program, 2141+175, has a featureless host galaxy, with an excess of light on one side of the nucleus, similar to region D seen here in 2201+315. 2141+175 has one faint compact knot in the host galaxy, which is blue. 2141+175 has large tidal tails, not seen in 2201+315. 2141+175 is an unresolved radio source while 2201+315 is very large. Thus, 2201+315 is likely to be an older source, in which there are no longer major visible traces of a merger that triggered it. The two QSOs
observed with the aberrated HST (Table 1) are also radio-loud, and we cannot see the same detail. However, they do contain knots of luminosity that are not symmetrical or spiral in overall morphology.

Of the four good HST host galaxy luminosity profiles, only one shows an exponential shape. The one that runs counter to ‘convention’ is the (currently) radio-quiet IR-loud 1403+434. This is apparently an elliptical in fairly early stages of merging, and with significant dust. Either of these circumstances may have suppressed formation of a central radio source: Neff and Hutchings (1992) discuss this phenomenon in a sample of IR-loud sources.

We note that in a similar imaging program of bright low redshift QSOs, Bahcall, Kirhakos, and Schneider (1994) report that all four of their QSOs have low luminosity host galaxies. We have CFHT data on one of these (0953+414) and also find in that object a faint host galaxy, in agreement with their estimates. In previous ground-based work (e.g. Hutchings, Janson and Neff 1989), we have found a range of nuclear to host luminosity ratio of about 100.

We have have two comments on this topic. First, in the cases where there is overlap, the results from the CFHT programs are not inconsistent with those from HST. This is encouraging, considering that the ground-based data reach to significantly lower flux levels, in the outer parts of the host galaxies, and also that the ground-based data have considerably less host galaxy information close to the nucleus. Evidently, the corrections made for these effects result in similar values for the host galaxy luminosity.

The second comment refers to empirical PSF-subtraction in the HST data. In neither our nor the Bahcall et al subtractions is the PSF structure eliminated, so that there is a significant uncertainty in the best normalisation to use. (Note that data from the WFC detectors are less well sampled by more than a factor 2.) The results shown by Bahcall et al consistently show negative flux in the diffraction spikes. In our subtractions, we regard this as overcorrected, so that they may be underestimating the host galaxy signal as a result. Also, the faint signal in the HST images can lead to underestimate of the host
Both our PSF-subtracted and our deconvolved images indicate host galaxies which are luminous, as shown in Tables 2 and 3, and consistent with our ground-based results. However, the complex PSF and weak signal make estimation of the host galaxy flux and profile unreliable. The scaling of the PSF is quite arbitrary and there is no definitive criterion to follow. We do not regard the HST values for host galaxy flux as superior to ground-based.

Thus, the results of Bahcall et al (1994) and those in this program appear to represent different extremes in this regard, and possibly neither may be used for general conclusions on host galaxy luminosities. It is not generally true that QSO host galaxies are of low luminosity.

It is clear that significant progress in QSO imaging with HST requires attention to several things: observation of a PSF at the same position as the QSO, with good signal; a large accumulated exposure (in short sections to eliminate saturation and cosmic rays), sub-pixel dithering; and deep ground-based images of the best possible resolution (0.5 arcsec or better).
Captions to Figures

1. 1403+434 images. 1,2 are CFHT raw and restored images in I band. 4 is HST F555W raw image. 5 is combined CFHT + HST restored image, with components marked (see Table 2). 3 and 6 are restored and PSF-subtracted HST images on a larger scale. In panel 6 the shape of the nucleus A can be seen, and the possible ring of extra flux on the opposite side of the nucleus.

2. Azimuthally averaged luminosity profiles for the two QSOs from F555W images, and the model PSF. The innermost (saturated) pixels are not used, and the relative levels are estimated from image subtraction. The actual scatter of points from the PSF-subtracted image of 1403+434 is shown with an arbitrary displacement. The PSF-subtracted profiles follow the lines defined by the QSO profiles at radii larger than \( \sim 0.5 \) arcsec. The two host galaxies have significant flux and similar profiles.

3. 2201+315 images. 1,2 are CFHT raw and restored images. 4,5 are HST raw images from F555W and F702W. Knots A, B, C and the diffuse region D are marked (see Table 3). 3 is the combined CFHT + HST restored image. 6 is the PSF-subtracted image, with the saturated central pixels masked out. The extended flux around feature B can be seen.
References.
Bahcall J.N., Kirkahos S., Schneider D.P. 1994, ApJ, 435, L11
Hewitt A., Burbidge G., 1993, ApJS, 87, 451
Hutchings J.B., Morris S.C., Gower A.C., Lister M.L. 1994, PASP, 106, 642
Hutchings J.B., Holtzman J., Sparkes W.B., Morris S.C., Hanisch R.J., Mo J., 1994, ApJ, 429, L1
Hutchings J.B., Crabtree D., Neff S.G., Gower A.C. 1992, PASP, 104, 66
Hutchings J.B., and Neff S.G. 1992, AJ, 104, 1
Krist J., 1994, in ASP Conf Ser 52, Astronomical Data Analysis Software and Systems II, ed R.J.Hanisch, R.J.V.Brisssenden, and J.Barnes (San Francisco: ASP).
Low F.J., Cutri R.M., Kleinman S.G., and Huchra J.P. 1989, ApJ, 340, L1
Neff S.G., and Hutchings J.B. 1992, AJ, 103, 1746.