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HST IMAGING OF QUASI-STELLAR OBJECTS WITH WFPC2

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ABSTRACT

Early images were taken with the optically corrected WFPC2 camera of the *Hubble Space Telescope* of the low-redshift QSOs 1229+204 and 2141+175, which are radio-quiet and radio-loud, respectively. We discuss image restoration on the data. The objects were chosen on the basis of structure seen with 0.″5 resolution with the CFHT high-resolution camera (HRCAM). 1229+204 was known to be a barred spiral with an asymmetrical extra blue feature: this is now resolved into a ring of knots which are probably young stellar populations in the tidal debris of a small gas-rich companion. There are also shell-like structures along the bar. 2141+175 has a faint smooth curved tidal arm without knots which extends on both sides of a compact elliptical-shaped central galaxy. There is also a short jetlike feature emerging from the nucleus. We discuss the properties and implications of these morphological details.

Subject headings: quasars: individual (1229+204, 2141+175)

1. INTRODUCTION AND DATA

Among the first observations taken with the newly installed WFPC2 camera in the *HST*, were of two low-redshift QSOs which were known to have subarcsecond structure from ground-based images (Hutchings & Neff 1992: HN). They were chosen to test the resolution and dynamic range near to a bright object, of the corrected *HST*; the uncorrected Point Spread Function was so large as to obscure almost all such structure (e.g., Hutchings et al. 1994). The observations, taken on 1993 December 29 and 31, consisted of five 140 s integrations with each of the F606W and F702W filters, which correspond roughly to *V* and *R* bandpasses. A second set of 1229+204 observations was taken on 1994 January 13. The QSOs were observed with the PC detector, with 800 × 800 0.″046 pixel^{-1}. Telescope tracking was nominal during all observations, and the WFPC2 focus and alignment settings were determined from early alignment data. Subsequent data and analysis have shown that these settings were very close to optimum.

The images were processed using standard procedures. The data were flat-fielded using predicted flats from the WFPC2 Thermal Vacuum test and a model of the *HST* vignetting pattern; these flats should be good to several percent. The individual frames were median combined, which eliminated all visible cosmic-ray signals, and left only a few "hot" pixels. The two sets of 1229+204 observations had a roll angle difference of ~6.°5, which was determined by measurements on the images for rotation and alignment before co-adding.

The exposure levels were short, and only the brightest parts of the QSO host galaxies were easily measurable. The images are shown in Figure 1 (Plate L1). Compared with the somewhat deeper, but less well-resolved CFHT images (HN), the gain in resolution is immediately evident, and the details are of considerable interest. We performed image restoration on the WFPC2 images, and also used the Lucy-Hook method of combining the CFHT and WFPC2 images.

The image restorations are difficult owing to the need for a PSF model of very high dynamic range. Despite the fact that the QSO exposures are short, the QSO image is saturated in its central few pixels. This leads to two related problems: (1) it is not possible to extract an empirical PSF from another data frame—if the exposure is short enough to avoid saturation of the core, the S/N ratio in the wings will be inadequate for use as a PSF in the QSO restorations; and (2) the saturated pixels must be masked in the image to be restored so that the saturated data values are not taken as true measures of the intensity. An empirical PSF could be obtained by combining images taken with a range of exposure times, but this was not done for these observations. Thus, a model PSF was computed using the Tiny TIM PSF modeling software (Krist 1993) and an approximation for the WFPC2 CCD scattering function (Krist, private communication). It is clear that better PSFs are required for optimum future work.

Restorations of 1229+204 were done using the Richardson-Lucy algorithm as implemented in the STSDAS software package (e.g., Stobie, Hanish, & White 1994). Only a small number of iterations (30 accelerated) could be run before the underlying galaxy image began to have an unacceptably grainy appearance. Nevertheless, there were some gains from the process, and we note these below.

The co-addition algorithm of Lucy & Hook (1991) was used to combine the WFPC2 and HRCAM observations. In the case of the HRCAM, PSFs were derived by fitting two-dimensional Gaussian functions to star images, which were available because the HRCAM field of view is considerably greater than that of the PC. Because of the existence of an attenuation region in the HRCAM images (guiding on the QSO nucleus), as well as the problems with PC saturation mentioned earlier, the results close to the QSO nuclei must be considered inaccurate. Otherwise, the combined images show details not visible in the originals, which are robust to the nuclear signal uncertainties.

The photometric results we quote are consistent to less than 5% between the raw and restored images, and use is made of both in the descriptions below. We describe the results for the two QSOs individually in the following sections.

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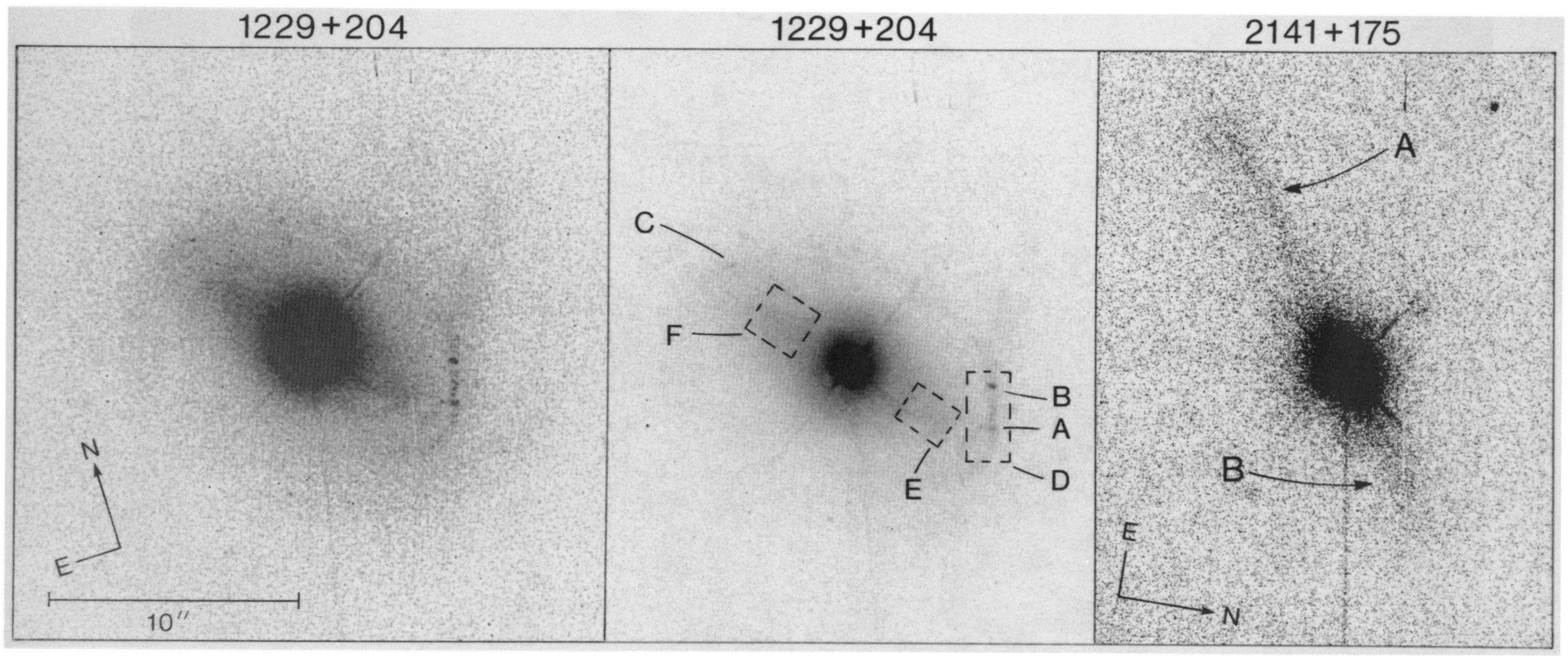

FIG. 1.—Images of QSOs. The two panels of 1229 + 204 are the combined CFHT-HRCam and WFPC2 image (left), and the F0606W and WFPC2 image (center). The 2141 + 175 image is the F702W WFPC2 data. Features referred to in the text and Table 1 are labeled.

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2. 1229+204

The immediate impression from the WFPC2 image is that this looks like a barred spiral with a ringlike structure. Previous deeper imaging by HN suggested that this object is a barred spiral with a tidally damaged gas-rich companion. The WFPC2 images add substantial detail to this picture and are consistent with this conclusion; the strong asymmetry of the galaxy makes us believe in the existence of a companion rather than spiral structure in the host galaxy. The general signal level is weak beyond ~8″ from the nucleus, but the string of bright knots which surround all of one side of the object, is evident in both parts of Figure 1. In Table 1 we show the measured flux from the principal features identified in Figure 1; we have transformed the magnitudes and colors using preliminary flight calibration data (Holtzman, WFPC2 Status Report) and the calibrations of Harris et al. (1991). K-corrections to the colors are smaller than the uncertainties in the numbers, and are not applied. At the redshift of 0.064, $H_0 = 100$ and $q_0 = 0.5$, 1″ is ~1 kpc.

The smallest knots are resolved with FWHM of ~2 pixels. The measured knots and the overall region of bright knots (D) are all bluer than the nucleus. The overall host galaxy color outside the nucleus is also bluer than the nucleus, but the brightest regions along the inner bars, E and F, are redder than the nucleus, with one side (E) apparently redder than the other. By comparison with the other QSO, and from the absolute color, the nucleus may be reddened by ~0.2 mag in $V-R$. This would correspond to ~0.5 mag of extinction.

The restored images do not differ in significant detail from the raw image. The nuclear light to a radius of 0″.4 is unaltered at the 5% level, and no new features are seen close in. The knots in the outer structures are better resolved in the restored images and are shown in Figure 2.

The smallest knots in the string near A and B are similar in brightness to C. These have absolute magnitude near −12 and blue colors: they may be regions of predominantly early-type stars, and indeed would correspond to the light of ~50 O stars. Thus, they are not proto–globular clusters. The absolute magnitude and color of the host galaxy is typical of a large spiral.

TABLE 1

WFPC2 Magnitudes for QSO Components

Object	F606 mag	F702 mag	$V-R$[a]	M_v[b]
1229+204				
Whole QSO	14.6	14.2	0.5	−21.6
Nucleus	16.0	15.5	0.6	−20.2
Host galaxy	15.0	14.6	0.5	−21.2
A	23.1	22.8	0.4	−13.1
B	22.6	22.3	0.4	−13.6
C	24.5	24.3	0.3	−11.7
D	21.5	21.3	0.3	−14.9
E	22.8	22.0	0.9	−14.1
F	22.1	21.5	0.7	−14.1
2141+175				
Whole QSO	15.8	15.4	0.5	−23.2
Nucleus	16.2	15.8	0.5	−22.8
Host galaxy	17.2	16.7	0.6	−21.8
Tail A	20.2	19.4	0.9	−19.8
Tail B	20.8	20.2	0.7	−18.2
"Jet"	24	23	1	−15

[a] Corrected to ground system band values; no K-correction.
[b] For $H_0 = 100$ and $q_0 = 0.5$.

Fig. 2.—The brightest knots in region D in the outer 1229+204 image from the F606W image, restored with WFPC2 PSF. Orientation is the same as Fig. 1.

These data separate the nucleus from the host galaxy better than any previous observations, and it is interesting to note that the nucleus is a magnitude fainter than the host galaxy: this is not a highly luminous nucleus, even with an extinction correction of 0.5 mag.

The light profile is well defined over the innermost ~2″, and Figure 3 shows how there is a nearly exponential profile in this range. The raw and restored images had the same result, which gave a scale length of 0″.44, or ~0.5 kpc. The CFHT results of HN show an outer disk with scale length of 2″, and the bend between the regions can be seen in their plot. Thus, we have mapped the profile of the *bulge* region around the nucleus. The nuclear PSF does not affect the data beyond ~0″.5.

There is shell-like structure along the bars, which we believe to be unique in observation or models. It appears in both filters, and in the combined CFHT + WFPC2 image. This may be some tidal resonance effect and may be worth modeling attempts with *N*-body codes. Both the individual and CFHT + WFPC2 combined images show a strong divergence of the main tidal feature above the brightest knots, as illustrated by HN, and seen in Figure 1. There are no knots in the outer arm of this feature, and this presumably is another tidal feature associated with the merging galaxy.

3. 2141+175

This QSO is also bright, an unresolved radio source (OX 169), and is described in HN. The redshift is 0.213 and the scale ~2.5 kpc arcsec^{-1}. It was known to have faint linear optical structure extending asymmetrically from a featureless host

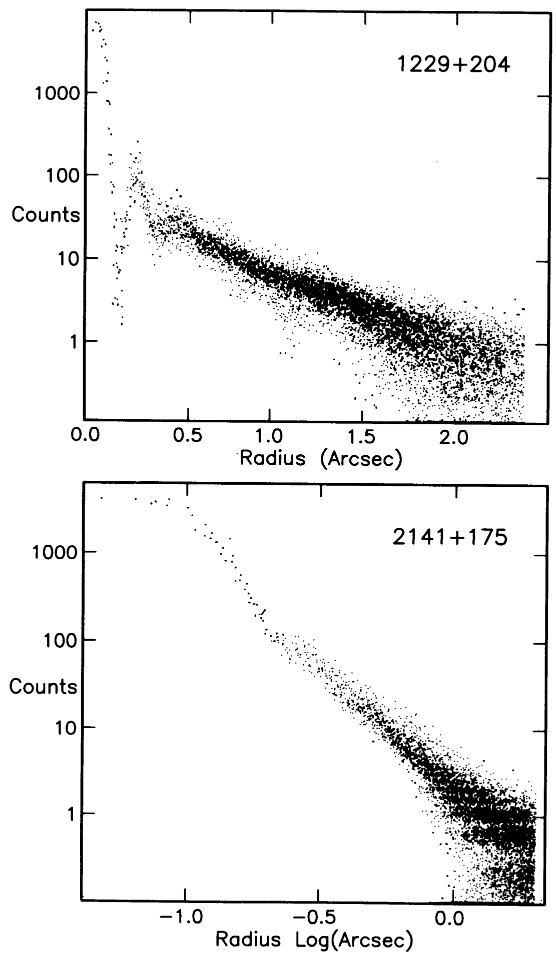

FIG. 3.—Inner luminosity profiles from WFPC2 images as labeled. Note the exponential part of 1229+204 (*top*) and the power-law part of 2141+175 (*bottom*). Neither host galaxy maintains a single profile type over its whole extent.

galaxy (HN; Stockton & Farnham 1991). HN suggested that it is an elliptical and edge-on spiral in collision.

The WFPC2 images (Fig. 1) do not reveal any knotty structure, such as seen in 1229+204. The D complex in 1229+204 would be detectable in 2141+175 in spite of the higher redshift. The linear extensions are very faint, but are smooth and red, and the longer arm is smoothly curved and brighter at the end. This all implies quite strongly that the feature is not an edge-on disk, but a curved tidal tail of old stars. This is an interesting contrast to 1229+204. The presence of the tidal tail and the compact radio source suggest that the nucleus has only recently become activated.

HN find the outer luminosity profile to fit a de Vaucouleur law between 0."7 and 2."4 radius. The WFPC2 profile (Fig. 3) shows that this extends inward to ~0."3 radius. The profile does not fit an exponential. The feature at 0."3 may be in part due to the diffraction rings of the PSF, especially as they affect the diffraction spikes from the mirror supports. Our image restoration does not entirely remove the diffraction spikes, but does reduce them, and enhances the diffraction rings. We thus cannot trace the $r^{1/4}$ slope closer than a radius of 0."3.

The nuclear color is a little bluer than in 1229+204, and the host galaxy a little redder (Table 1). The tidal tails are red, comparable with the inner bar of 1229+204. The nuclear absolute magnitude is brighter than the host galaxy by 1 mag. The host galaxy itself has the luminosity of a fairly bright elliptical, while the flux from the tails correspond to a fainter galaxy, comparable with M33 (although the original galaxy may have been significantly brighter than this). The tails extend some 30 and 17 kpc from the nucleus.

The inner part of the host galaxy has a feature which is not symmetrical, as the obvious PSF structure is. It is shown in Figure 4. We performed image restoration on both images and this feature does not disappear or fade as the rest of the PSF structure. It is also seen in the combined CFHT + WFPC2 restorations. Thus we treat it as a real feature. It resembles an expanding cone or jet centered on the nucleus, and its fluxes (in Table 1) were estimated by summing the signal in boxes around it, and subtracting the sky level measured at similar distances from the nucleus in other directions.

Since this "jet" appears in both filters, it is presumably a continuum feature rather than line emission. The [O III] λ5007 line would lie in the center of the F606W filter; no strong line lies in the F702W filter but the feature is brighter. It is seen over a length of at least 16 pixels, which corresponds to ~1.8 kpc in the host galaxy.

The extended tails are characteristic of a merged disk system, but there is no sign of the disk itself, or of star-formation from gas anywhere. Thus, the nature of the precollision galaxy is unclear. The host galaxy light is extended in the general direction of the tails (see Fig. 4), but at a small angle (~20°) to the tail. Since the tail is seen on both sides of the host galaxy, this is probably a distortion of the main host galaxy, presumably as a result of the tidal event. In the F606W filter, there is a faint extended knot in this region, which has a magni-

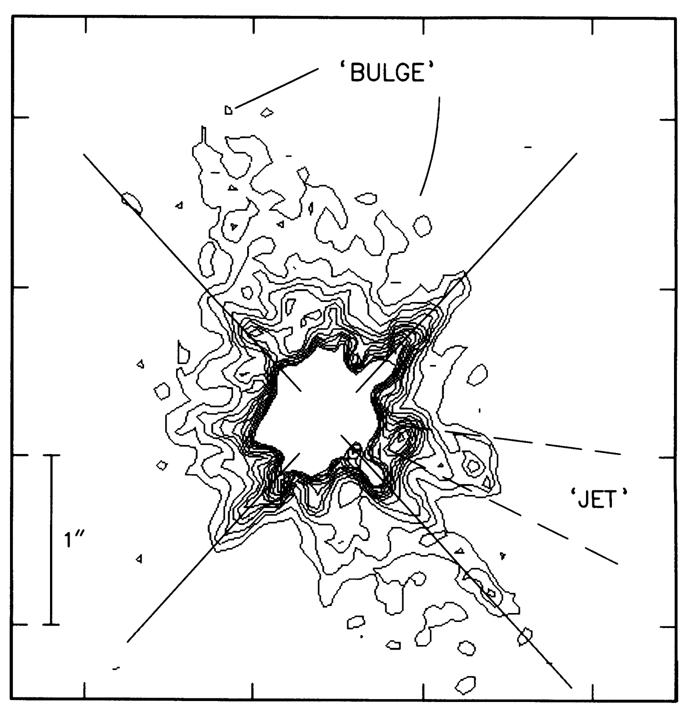

FIG. 4.—2141+175 inner jet and host galaxy from restored F702W image. The main diagonal features marked are instrument diffraction spikes. The other labeled features are seen in the raw images and different restorations. The extended host galaxy light is at ~20° to the direction of the long tidal tail. Orientation is the same as Fig. 1.

tude of ~25. It is not seen in F702W. It is possible that this is an ionized cloud of [O III]: if it is real, it is intrinsically slightly more luminous than the individual knots in 1229+204.

3. DISCUSSION

The new images have added substantially to our detailed knowledge of two QSOs. Although they were chosen to be of different type, both appear to be in host galaxies which have recently merged with a less massive companion. We would like to understand what the essential differences are between the two situations and whether they are relevant to the type of nuclear activity.

At the most trivial level, the spiral-like nature of 1229+204 and the elliptical-like nature of 2141+75 are consistent with long-standing assumptions about radio-loud and radio-quiet host galaxies. However, much of the observed morphology and star formation is a result of the recent tidal events, and both objects are peculiar. 1229+204 resembles a stage in the sequence of a disk merging with a dwarf companion by Mihos & Hernquist (1994). 2141+175 might be the later stages of an event with at least one disk, as indicated by the long tail(s). There is clearly much active star formation in 1229+204 in the asymmetrical outer ring. The main galaxy bar may be original or formed by the interaction: its lack of young stars or near-nuclear activity argues for the former. The lack of star formation in 2141+175 suggests that its premerger galaxies were not gas rich. The central radio source and nuclear "jet" may also be a result of this lack of gas.

It is noteworthy that the data resolve knots of hot stars which correspond to less than 100 stars, and reveal features and the luminosity profile as close as 0"2 from the nucleus. We are able to revise the ratio of nuclear to galaxy luminosity from measured values of 2.2 and 14 (from 0"9 images of Hutchings, Crampton, & Campbell 1984), to 0.4 and 2.5, for 1229+204, and 2141+175, respectively. It is premature to draw wide conclusions on the basis of these two objects. However, it is clear that there is sufficient detail in the corrected *HST* images to allow the morphological analysis of a large sample of QSOs.

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