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OPTICAL IMAGING OF QSOs WITH 0.5 arcsec RESOLUTION

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ABSTRACT

We present optical imaging data on 28 low redshift QSOs with 0.5 arcsec resolution. The group includes a range of radio and IR luminosities. The high-resolution data reveal significant new morphological information on 16 objects, and yield good luminosity profiles on all of them. Most objects appear to have $R^{1/4}$ law or peculiar luminosity profiles. The QSOs are almost all found to be in merging or interacting galaxies, most of them with a smaller companion. The observed structural details appear to be similar to lower luminosity AGN at low redshift. There are a few unexplained features such as "jets" near the nucleus. Detailed descriptions are given of all objects. We also describe new high-resolution radio observations of a few of the QSOs.

1. INTRODUCTION

Optical imaging of low redshift QSOs over the past decade has revealed much about their host galaxies. Most QSOs of redshift 0.5 or less are clearly seen to be extended, and the best results have shown that the objects have peculiarities in morphology, color, size, and luminosity profile. The host galaxies of radio-loud QSOs and radio galaxies are more disturbed than the radio-quiet objects (Hutchings *et al.* 1989; Heckman *et al.* 1986). The radio-loud host galaxies resemble ellipticals while the radio-quiet ones resemble spirals, albeit disturbed and abnormally colored ones. It is widely held that the nuclear activity is connected with these peculiarities; if this is true then a detailed understanding of the host-galaxy properties should provide an essential key to understanding the extraordinary energetic events in the nuclei.

Optical imaging is overwhelmingly limited by the scattered light from the bright nucleus, whose flux is usually comparable with or in excess of that of the surrounding host galaxy. Since QSO host galaxies usually extend only a few arcsec, images with FWHM 1 arcsec or more have severe contamination by nuclear light. This results in unreliable luminosity profiles, and little information on the bright inner parts of the host galaxy. In addition, resolution of 1 arcsec or more is insufficient to see host-galaxy structures such as spiral arms, tidal tails, dust lanes, bars, etc. A trial observing run using a rapid guiding HR Camera on the CFHT to achieve 0.5 arcsec resolution (Hutchings & McClure 1990), revealed significant new detail and provided significantly improved luminosity profiles in all of the three objects observed. Here we present the results of a much larger study.

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2. SAMPLE SELECTION AND OBSERVATIONS

2.1 *Sample Selection*

This paper describes the results of an imaging program on a sample of 28 low z QSOs, with the HR Cam. The objects were largely selected (18 of 28) from those for which we already have deep FWHM$\sim$1 arcsec CFHT images (e.g., Hutchings *et al.* 1984a,b; Hutchings *et al.* 1988). (In the discussion below these are the references to "our" data.) The high spatial sampling (0.13 arcsec) of HR Cam forced us to choose between long integration times to reach the faintest levels, and consequently a small sample, or a larger sample where we obtained good signal only in the inner bright part of the host galaxy. We opted for the latter, but note that for objects of which we already have deep images at lower resolution, we have information on the overall size and large-scale features as well as the inner regions.

The sample was chosen to cover a range of optical luminosities and to include both radio-loud and radio-quiet objects over the $z\sim$0.1–0.5 range. Table 1 lists the QSOs and their principal properties. We have noted the discovery wavelength of each QSO, as this may relate to selection effects. Subsequent to discovery, many of them were detected at other wavelengths as well, and we note here the radio and IR luminosities. The absolute magnitudes are for the combined QSO and host galaxy, and do not contain any k corrections (which would be small for the nuclear light anyway at these redshifts). Some of the sources have extended radio luminosity which exceeds the core values listed here. The radio details can be found in Gower and Hutchings (1984) and Hutchings *et al.* (1988). We have already published separate discussions of HR Cam data on several QSOs of individual interest (Hutchings & McClure 1990; Hutchings & Neff 1991; Hutchings *et al.* 1992; Hutchings 1992). These are included in the table and form part of the sample for discussion.

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TABLE 1. Properties of observed QSOs.

Name	Discovery class[a]	z	m_v	6 cm core log (W/Hz)	60 μm log ($L_\odot$)	$-M_V$
1223+252	O	0.268	16	23.8		23.7
1226+023	R	0.158	12.9	28.7	12.1	25.5
1229+204	O	0.064	15.3			21.1
1302−102	R*	0.286	14.9	26.4		24.9
1334+246	IR	0.107	15		11.8	22.5
1351+640	O	0.088	14.8	23.6	11.1	22.3
1400+162	R*	0.24	16.4	25.4		23.0
1403+434	IR	0.32	16.5		12.3	23.6
1411+442	O	0.089	15.0		10.5	22.2
1444+407	O	0.267	16.0			22.3
1525+227	R*	0.253	16.4	24.9	11.2	23.2
1549+203	O	0.250	17.4			22.1
1553+113	O	0.36	15		<11.7	25.3
1613+658	O	0.129	15.2		11.5	22.7
1700+518	O	0.288	15.4	23.5	12.1	24.0
1803+676	O	0.136	15.8			22.2
1821+643	X	0.297	14.1	<23	12.4	25.8
2112+059	O	0.466	15.5		11.8	25.4
2121−176	IR	0.11	16.5			21.1
2130+099	O	0.061	14.6		10.6	21.7
2135−147	R	0.20	15.9	25.2		23.1
2141+175	R	0.213	15.5	25.6	11.1	23.7
2201+315	R	0.297	15.5	26.6	11.5	24.4
2214+134	O	0.066	14.6			21.8
2233+134	O	0.325	16.0			24.1
2251+113	R	0.323	15.8	24.0	12.6	24.3
2305+187	R	0.313	17.5	25.4		22.5
2344+184	X	0.138	15.9			22.1

Notes to TABLE 1

All luminosities are for $H_0=100$, $q_0=0.5$.
[a]O=Opt; R=Radio; IR=*IRAS*; X=x ray.
*VLBI data in this paper.

$\Sigma\ R-Q=16$; $\Sigma\ R-L=12$; Σ IR$=14$; Σ (R,IR)$-L=7$; Σ (R,IR)$-Q=9$.

2.2 Optical Observations

In almost all cases the QSO nucleus was used as the guide star, as in Hutchings & McClure (1990). This provides optimal guiding and also helps reduce the nuclear scattered light, as the guide pickoff removes 95% of the nuclear flux from the imaging detector. The guide hole is 0.75 arcsec in radius, and the transmitted 5% was sufficient to locate the nucleus and to measure its FWHM. Most of the QSOs were observed with both *V* and *I* filters, with integration times of 20 min each, using the SAIC CCD. Usually two frames were taken in *I* and one in *V*. The read noise was about 6*e*, but there was an ac pickup in the read electronics which added an oblique pattern of amplitude $\sim 6e$, which could not be modeled accurately and thus added a little more ($\sim 2e$) noise. The pixels were 0.13 arcsec on the sky, so that the field is about 2 arcmin. The measured FWHM for most of the images was close to 0.5 arcsec, with a small ellipticity (due to astigmatism). The QSOs were observed within 30° of the zenith, to reduce offsetting of the nucleus within the guide hole by atmospheric refraction and to minimize airmass (and hence seeing) effects. The camera was generally guiding in the range 15–100 Hz: the fainter objects required the slower rates, but we found no correlation between achieved FWHM and the guide rate. The telescope was operated at prime focus and with full (3.6 m) aperture. We did not use the "smart shutter" option, since a few experiments showed that in the seeing conditions of the run, it made no measurable difference.

Flat-field frames were taken on the twilight sky and a photometric sequence in M92 was observed for calibration. The disadvantage of guiding on the QSO is that we cannot obtain accurate photometry on the QSO nucleus. Because there is variable spillover from the nucleus this means that the host-galaxy magnitudes are also unreliable although the host colors away from the nucleus are measurable in some cases. The data were processed using DAO VISTA.

Figures 1 and 2 show the image morphology in grey scale and contour form, for selected objects. Figure 3 shows the luminosity profiles for others. These are referred to in detail in the discussions below. We note that we have chosen to display only those results which are useful in each of these formats, in the sense of illustrating the new results clearly.

2.3 Radio Observations

We also present new high-resolution ($<\sim 0.1$ arcsec) radio observations for a few objects in the sample. These

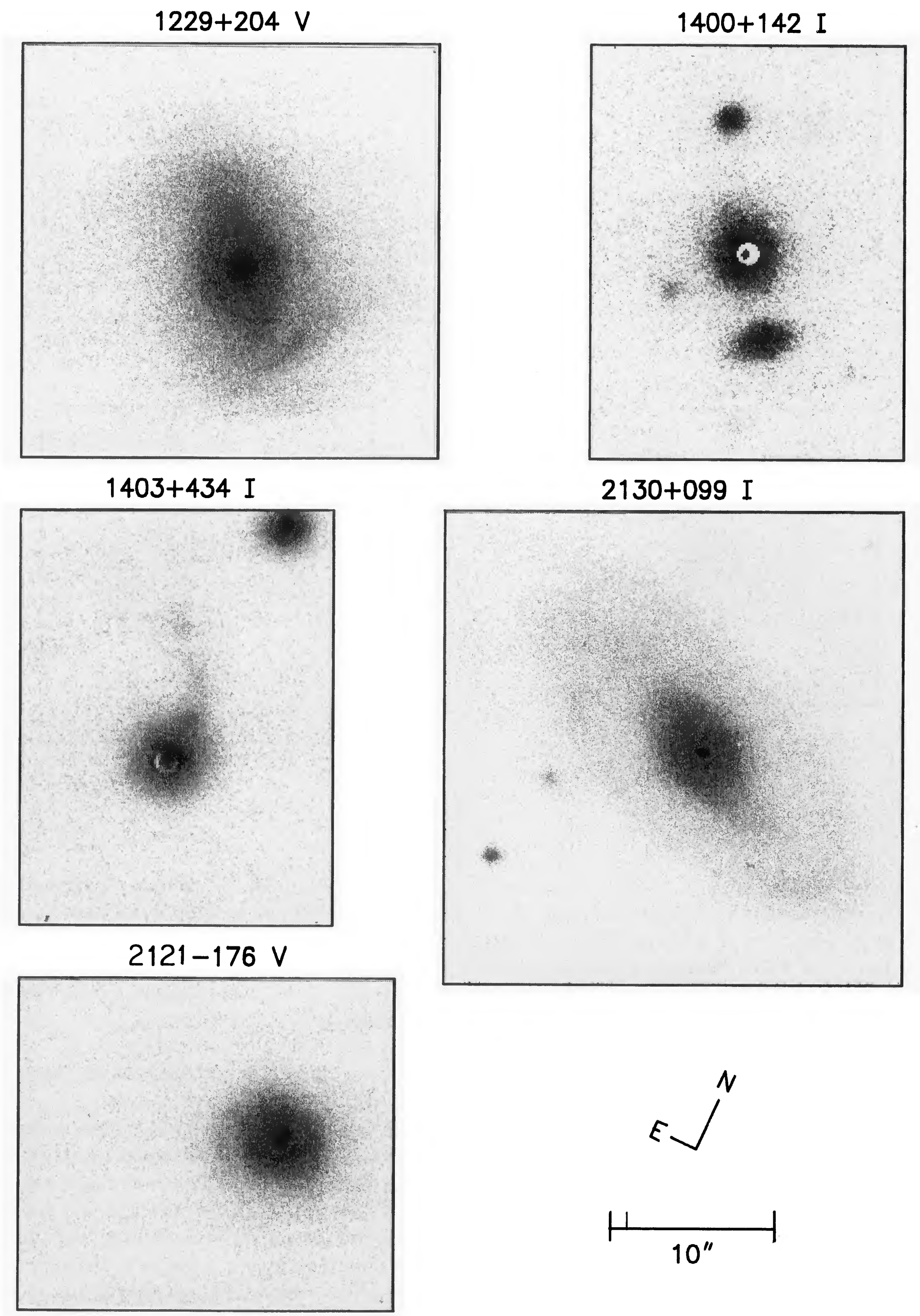

FIG. 1. Grey-scale images of sample objects. See text for details on individual objects. All scales and orientations are the same. The bar shows 10 and 1 arcsec scales. The 1.5 arcsec guide hole at the nucleus is visible in most objects. The 2201+315 image is the ratio of *I*- to *V*-band images.

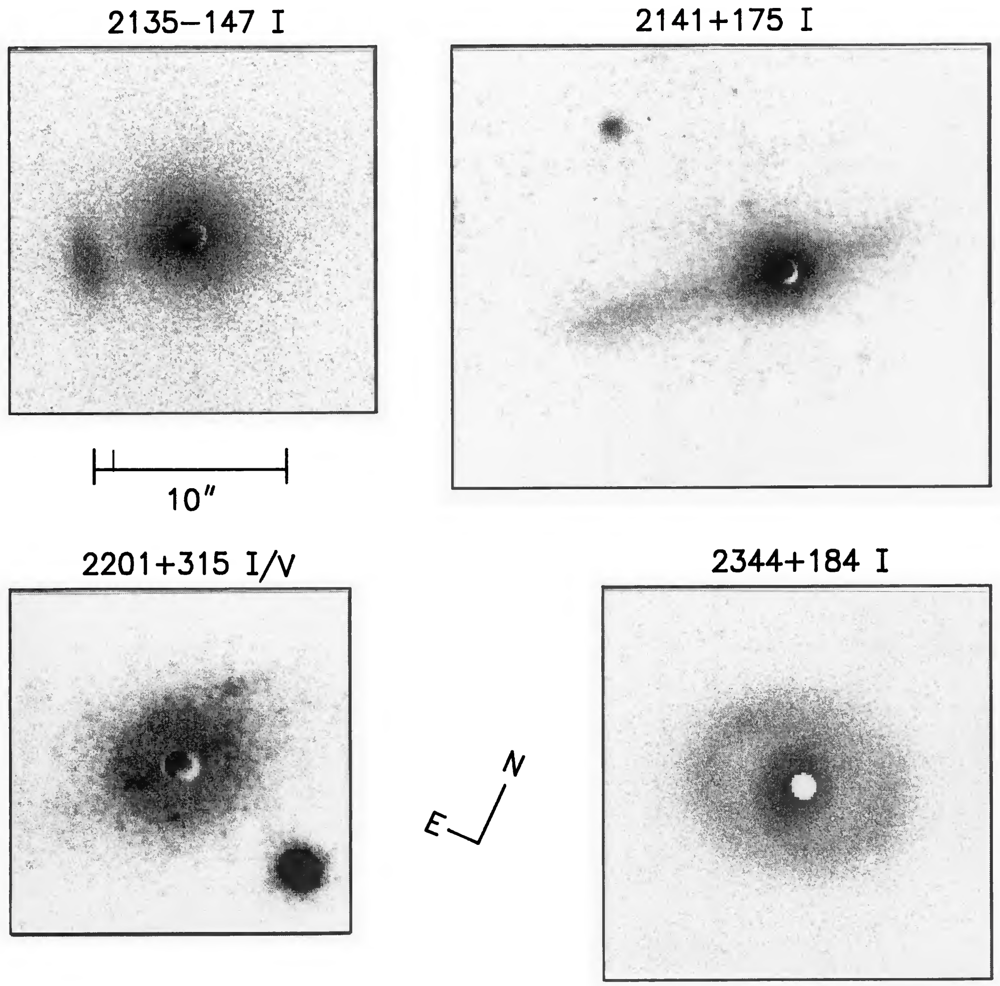

FIG. 1. (continued)

VLBI observations are noted with an asterisk (*) in Table 1, column 2. The observations were made at 21 cm (1417 MHz) for 4–8 hr per object on 13–17 June 1984, using four stations of the European VLBI Network (EVN). The 100 m antenna at Effelsberg, the 75 m dish at Jodrell Bank, and the 25 m telescope at Onsala operated with system temperatures of about 50, 55, and 40 K, respectively. The Westerbork Synthesis Radio Telescope (WSRT) was operated in the total-power mode (van Ardenne 1978) and was therefore equivalent to a single dish of diameter 92 m with a system temperature of about 60 K. Hydrogen-maser oscillations (at Effelsberg, WSRT, and Onsala) and a rubidium oscillator at Jodrell Bank were used as time and frequency standards. The rms noise in a 4 min coherent integration is about 5 mJy using the Effelsberg–WSRT–Jodrell Bank triangle and somewhat worse on the less sensitive baselines to Onsala. All stations observed with left circular polarization, using the standard MkII VLBI recording system (Clark 1973) and a bandwidth of 1.8 MHz.

Data correlation was carried out at NRAO in Charlottesville. Fringe fitting, calibration, and hybrid mapping were carried out using a combination of the NRAO AIPS package and the Caltech VLBI package. The data were calibrated against the sources DA193 (0552+398) and OQ208 (1402+286), assumed to be unresolved on the EVN baselines and to have flux densities of 1.63 and 0.83 Jy, respectively. This calibration is estimated to have an absolute accuracy of about 10%. Structures of size much larger than about 0.1 arcsec are not well sampled by these observations.

3. NOTES ON INDIVIDUAL OBJECTS

In this section we give an extended description of the results on each object. Detailed discussion of our previously published observations are not repeated here, although the references are given at the end of the section. We comment on the morphology, the luminosity profile and the color (when possible). In some cases, we also comment on the tidal interaction status; these remarks are based on comparison with an extensive grid of galaxy interaction and merger models which we have run using N-body simulations based on the Barnes–Hut tree code. In particular, we have tried to estimate the time evolutionary stage in the tidal event and the relative mass of the interacting body to the QSO host galaxy where it appears reasonable to do so. We summarize and discuss these estimates and their limitations at the beginning of Sec. 4.

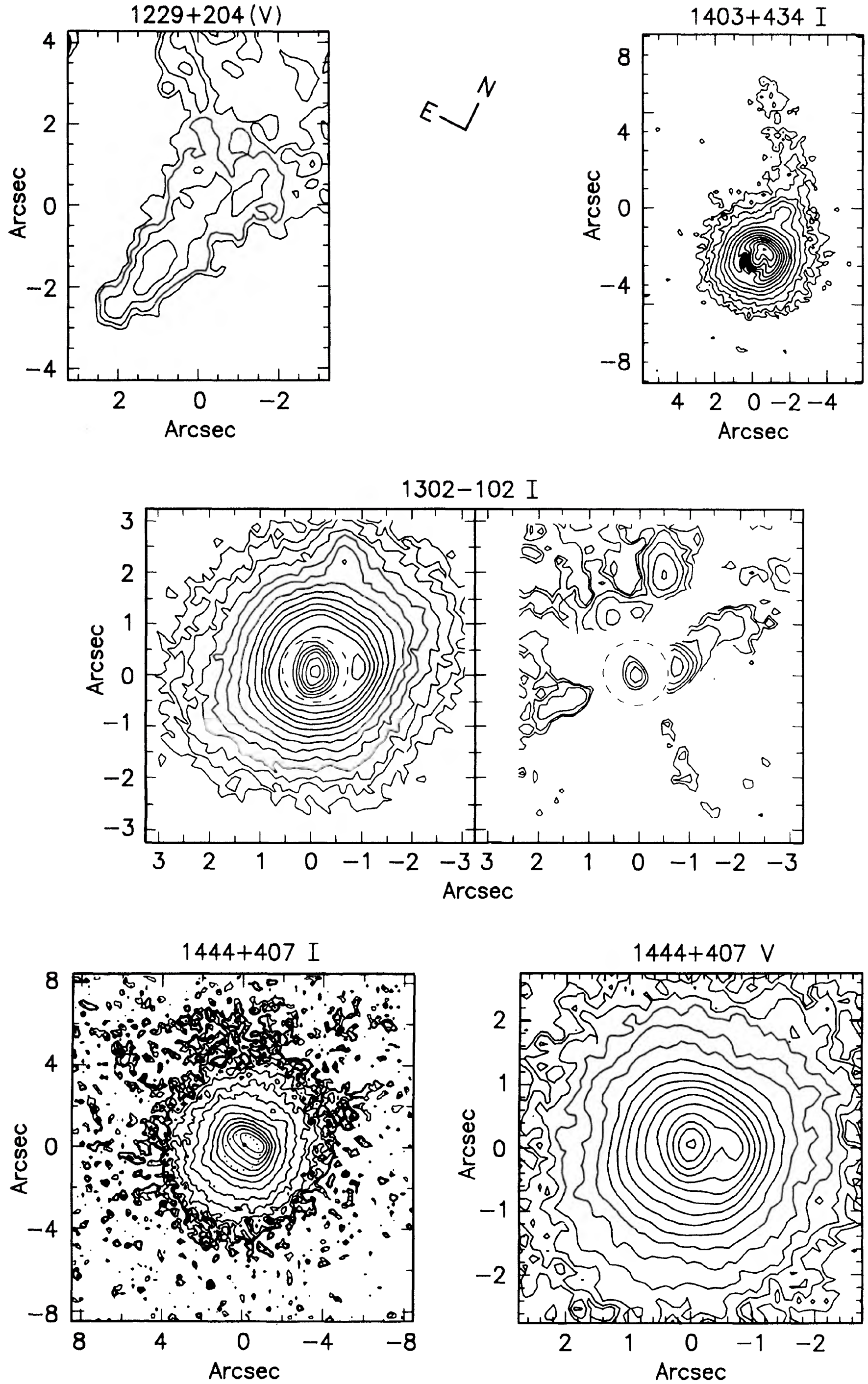

FIG. 2. Contours of selected sample objects. Levels are chosen to illustrate morphological features, but are generally a factor 1.5 apart. The images of 1229+204, 1302−102 (right), and 2135−147 have a smooth model of the host galaxy subtracted to show the residual features. The 1444+407 (left) image has the nucleus removed to show the off-center feature to the N. The 1.5 arcsec guide hole is obvious in most cases. See text for individual details.

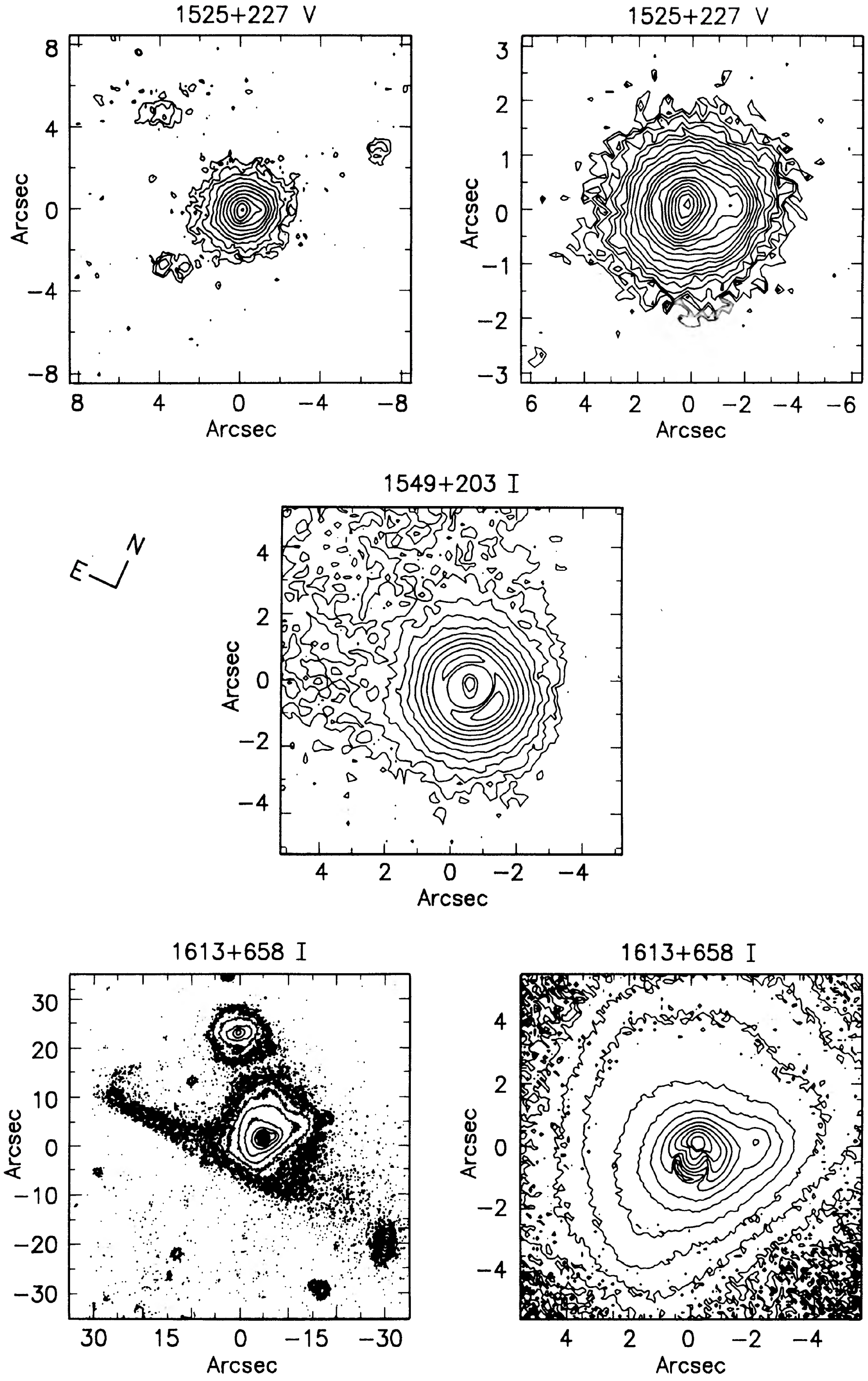

FIG. 2. (continued)

1229+204. This is a low redshift ($z=0.06$) object which has been known for some time to have a bar-like structure, with a luminous extension at the end of one side of the bar which is thought to be a small merging companion. In the new data (Fig. 1), we can see a spherical bulge component of the main galaxy and a weak concentric shell in the bar-free region to the W. The N arm of the bar is wider than the S, and we can see structure in the merging companion. The companion has no strong nucleus but is arrowhead shaped (Fig. 2), with two luminous concentrations near the tip of the point, and a long linear diverging tail. The outer isophotes from our earlier deep imaging show that the tail extends over some 10 arcsec, while the main galaxy has a diameter of ~ 20 arcsec. The color data

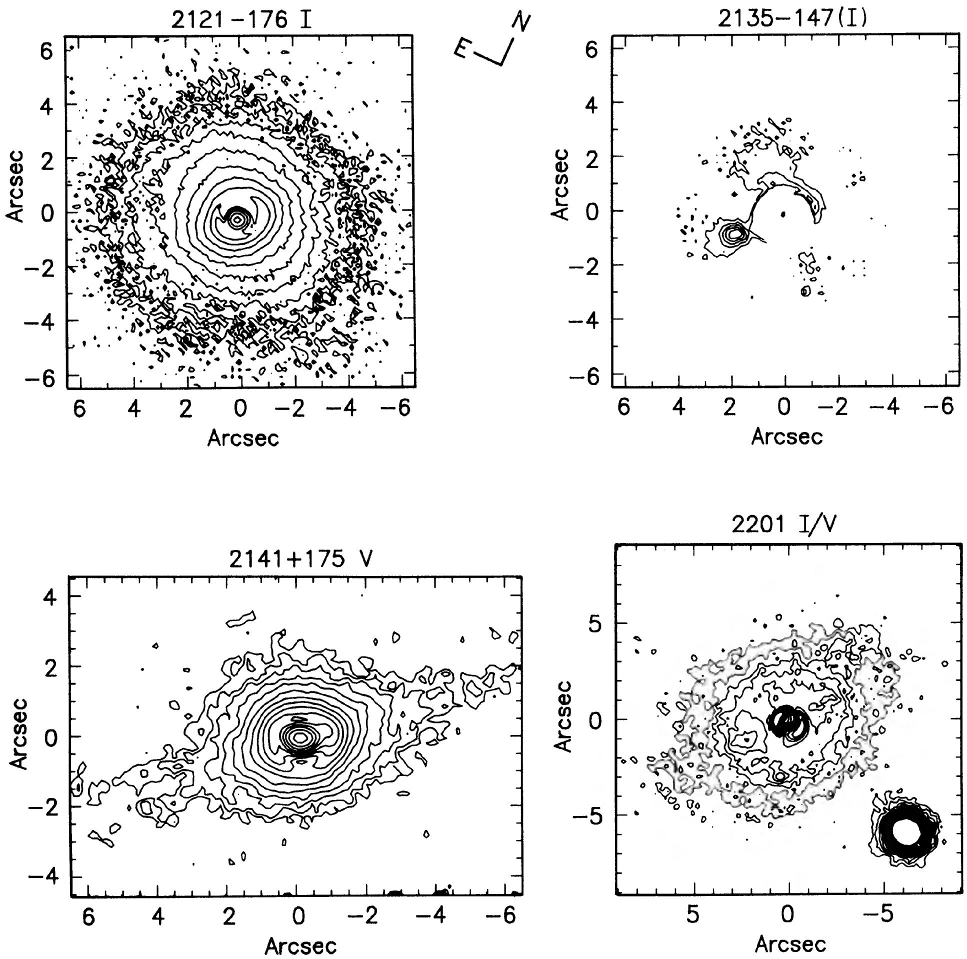

FIG. 2. (continued)

show that the companion is blue, and that the main galaxy is blue in the bulge, becoming redder with increasing distance from the nucleus. The ends of the main galaxy bar are red. The color of the companion is bluest where it is brightest. The shell is also bluer than its immediate surroundings in the main galaxy. The azimuthally averaged luminosity profile (Fig. 3) has an exponential region, with a steeper gradient in V than I, before falling off faster beyond the bar ends.

Overall, the object appears consistent with models where a barred spiral's (small irregular) companion is undergoing tidal disruption on a near-linear prograde trajectory. The companion appears to have a young stellar population, and may have active star formation in its bright knots; the bar asymmetry and the shell are indications that there is significant damage to the main galaxy too.

1302−102. This $z=0.29$ QSO had no resolved structure in our previous work, although the profile was more extended than that of a star. Veron-Cetty & Woltjer (1990) show an extension to the N. Our new optical data shows this feature (Fig. 2) 2 arcsec to the N, some 0.5 arcsec wide, and also a bright feature only 0.8 arcsec from the nucleus, to the W. These two features are elongated along the same line, and thus may be related, or even be parts of a single feature which is obscured or fainter in the middle. Figure 2 shows this in the model-subtracted image (besides the telescope diffraction spikes). In this object, the outer knot is redder than the main galaxy, and the inner feature is too close to the edge of the guiding hole to measure its color. The host galaxy has no other structure, being a smooth ellipse with a small eccentricity. The luminosity profiles are close to an $R^{1/4}$ law for the inner 3 arcsec radius, and there is an exponential halo outside this, which we can measure to a radius of 7 arcsec.

Gower & Hutchings (1984) found small (15 arcsec) two-sided radio structure to the NE and SE, with a 570 mJy core at 20 cm. The compact radio core is unresolved at 21 cm (this work) on a scale of 100×40 milliarcsec at 10° P.A., and contained 640 mJy flux in that size at the time of the observations. Thus, essentially all of the radio emission arises from a size of $\leqslant$300 pc. The optical and radio structures have no features in common: rather, the radio lobes are swept back from the inner optical knot. The bent morphology and extent (45 kpc) of the extended radio emission suggest that the radio source is moderately old and/or poorly confined.

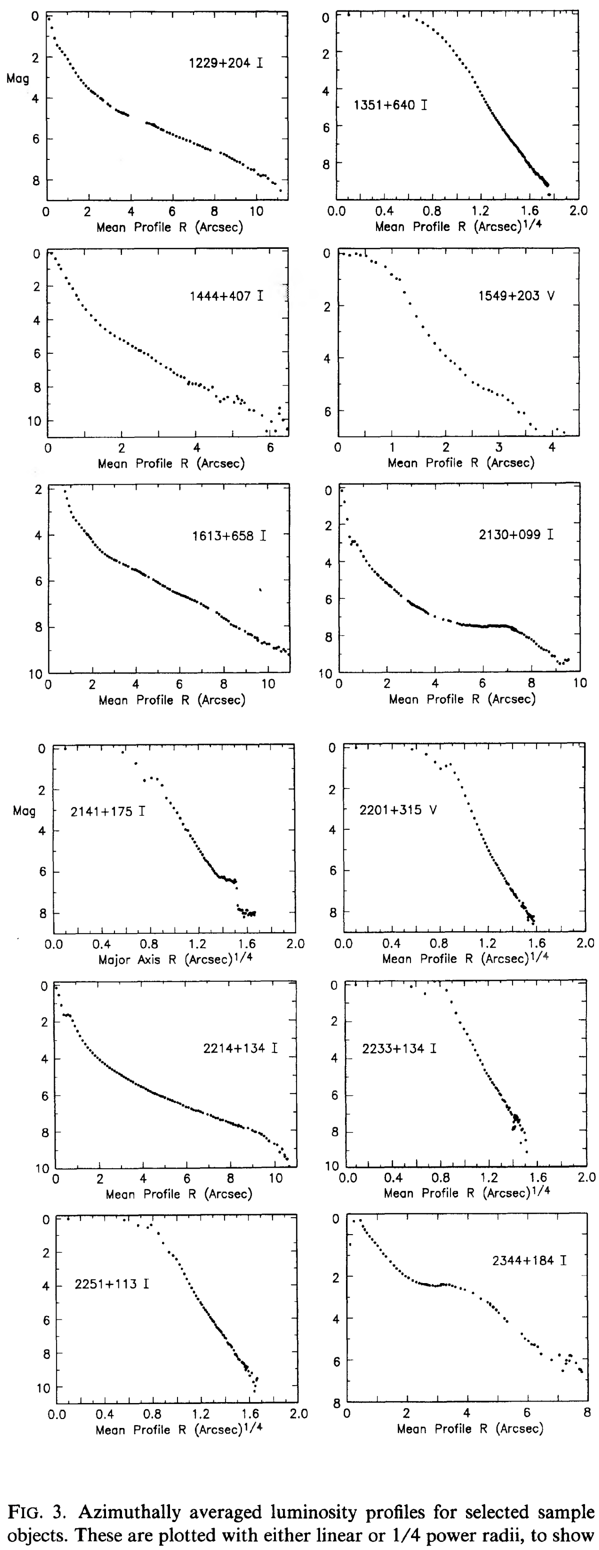

FIG. 3. Azimuthally averaged luminosity profiles for selected sample objects. These are plotted with either linear or 1/4 power radii, to show how they do or do not fit standard profile forms. The noise level may be judged by the scatter at large radii. The attenuation through the guide hole is evident at the smallest radii in most cases.

The hybrid luminosity profile is consistent with a mildly disturbed elliptical galaxy. The linear nature of the object nearest the nucleus suggests the trajectory of a small merging companion. We suggest that the companion may have been spiralling into the main galaxy for some time. The smoothness of the profile and presence of the small companion(s) suggest this rather than an old merger where a new elliptical has formed after merging with a massive companion. This is in agreement with the relatively undisturbed extended radio source.

1351+640. The QSO is a luminous *IRAS* source (Neugebauer *et al.* 1986). Previous optical observations (HCC) show this $z=0.09$ QSO to be resolved but with no obvious structure; the new data also show no structure. This is one of the six objects in the sample for which the HR Cam data do not reveal previously unknown structure. The host galaxy is detected to a radius of 10 arcsec, in which the galaxy is very round and smooth, with a well-centered nucleus. The luminosity profile is closer to an $R^{1/4}$ law than an exponential (Fig. 3), but neither is a good fit.

Gower & Hutchings (1984) report an unresolved radio source at the nucleus, while Neff & Hutchings (1992) find it to be marginally extended; this suggests that the radio source may be fairly young or extremely confined or both.

The luminosity profile may be considered to be consistent with a very old merger, where only excess light in the outermost isophotes provides traces of the event.

1400+162. This object has been classified as a BL Lac, but it has an absorption line redshift of 0.24, and apparently lies in a rich cluster of galaxies (e.g., Hutchings *et al.* 1984b). Previous results show the object to be the brightest member of a compact group of four galaxies, with several tens of other galaxies within a radius of 1 arcmin. The HR Cam data show that all the galaxies in the small group are smooth and elliptical (see Fig. 1). The QSO host galaxy is round and featureless, and has no luminous connection to any of its neighbors. There is a faint bulge of luminosity about 2–3 arcsec to the N, on the side away from the nearest companion, which is seen in the *I* but not the shorter-wavelength images; thus it might be a (tidal) bulge of old population stars. The galaxies all have similar colors, as does the QSO host, after allowance for the scattered nuclear light. It has no significant color gradient or structure. The HR Cam resolution does not reveal much that is new in this case. The luminosity profile is confused by the close neighbors, but does not appear to fit an $R^{1/4}$ law very well.

The radio structure in 1400+162 appears to be an extended double-jet source (Saikia *et al.* 1987); the jet-like structure appears to be continuous down to sizes of ~ 50 mas. The core source contains 102 mJy in 60×40 mas (16° P.A.), which is about 1/2 the 20 cm VLA core peak flux. This suggests that the radio source is middle aged but still undergoing active outflow of relativistic material.

1403+434. This is an *IRAS*-discovered object, at $z=0.32$. Low *et al.* (1988) note that it has a BAL spectrum, which makes it one of a handful of such objects at low redshift. We have not observed this object before. The image is typical of IR-bright QSOs in showing peculiar morphology: in this case the host galaxy is small, smooth, and round, but has a long curved knotty tail to the N (see Figs. 1 and 2). There is no other galaxy companion apparent.

The tail extends over 7 arcsec (20 kpc for $H=100$) and its brightest spot is closest to the QSO, 2.6 arcsec from the nucleus, and the tail bends at a nuclear distance of 4 arcsec, so that its inner part is directed toward (or away from) the nucleus. The width of the tail is approximately constant along its length at 1.5 arcsec. The bright part of the tail is redder than the QSO galaxy. The nucleus is centrally located in the host galaxy, and there is no other structure, or ellipticity. The luminosity profile is hybrid—fitting an $R^{1/4}$ law approximately over its 3 arcsec radius, and definitely not an exponential.

The object has the appearance of a medium-sized elliptical which is merging with a small galaxy which has already been tidally destroyed. As in other resolved BAL objects (e.g., 1444+424, 1700+518), we see no morphological clue to the BAL phenomenon.

1444+407. This is a $z=0.27$ PG QSO, which we have not observed previously. The host galaxy is generally smooth and round with no tails or companions. Our isophotes extend to a radius of 5 arcsec. However, the inner isophotes show some evidence of structure in the form of extra light near the nucleus toward the W (Fig. 2). The peak of the luminous feature is very close to the edge of the guiding hole and may be partly hidden. Figure 2 also shows a smooth reconstruction through the guide hole and excluding the nucleus. This suggests the feature is bar-like and centered 0.5 arcsec from the nucleus; but it must be regarded as only suggestive at this time. The peak that we see is some 0.8 arcsec from the nucleus. The edge of the guide hole makes color measures unreliable, but the area surrounding the knot or bar is bluer than the rest of the host galaxy. The host galaxy has no other structure, except for a small eccentricity in the outermost isophotes. The nucleus is well centered. The luminosity profile (Fig. 3) is neither $R^{1/4}$ or exponential.

This system appears to be a late stage of merging between two galaxies of considerably different mass.

1525+227. This radio QSO ($z=0.25$, Fig. 2) has three faint close companions, the nearest of which, 5 arcsec to the SE, coincides on the sky with the principal extended radio lobe (Gower & Hutchings 1984). This object is more compact and brighter than the other two companions. It has a fainter extension seen in our unpublished 1 arcsec resolution R-band deep image, which is resolved in the new data as a separate faint object. Our older data also show a faint broad luminous link between these objects and the main QSO galaxy. The deep image shows that there are about ten more faint galaxies in the surrounding 20 arcsec radius, so that the QSO probably lies in a cluster.

The deep R image shows the QSO galaxy extends to 5 arcsec radius, reaching the projected distances of all the close companions. The HR Cam data are good over a radius of 3 arcsec. The QSO host is smooth and circular with the exception of a bright spot 0.8 arcsec to the W of the nucleus (Fig. 2). This spot is at the edge of the guide hole so that its shape and color are not certain. The presence of this spot and the close companions also make it difficult to measure the overall luminosity profile. However, where the profile is clean, it appears to be hybrid. The host galaxy and the companions are similar in color (to within 0.2 in $V-I$). The close (double) companion is the bluest. The off-nuclear spot is several times more luminous than any of the companion galaxies, after subtracting the underlying host galaxy. Stockton & MacKenty (1987) note that the [O III] emission in this object is slightly extended to the NW, which is opposite to the direction of the resolved companions.

The extended radio structure is discussed by Gower & Hutchings (1984); it is a one-sided extended source. The radio core is unresolved on a scale of 50×40 milliarcsec (P.A. 20°) and contains 40 mJy flux in that size (this work). Therefore, all of the core radio emission (43 mJy with the VLA at both 6 and 20 cm) originates from a size of $\leqslant120$ pc. The modest size (5 arcsec or 12 kpc) of the extended radio emission suggest that the radio source is not very old or is confined or both.

Many aspects of this system suggest that it is in the very late stage of a merger, although the presence of several close companions suggests that it may also be in the early stages of another (newer) tidal interaction with the closest companion.

1549+203. This is a $z=0.25$ optically selected object, not previously imaged. The QSO lies in a smooth round galaxy, and there are several galaxies of similar brightness and size within 30 arcsec, which may constitute a small open group. There are no obvious interactions. The QSO lies in the scattered light of a nearby bright star, which makes the background uneven and higher than normal. The QSO image is measurable over a diameter of 5 arcsec, and has a small eccentricity (Fig. 2). The only structure seen is light which extends approximately N–S on either side from the nucleus guide hole. This is seen in both V and I, and may be a bar-like structure that extends through the nucleus. This extension is not parallel to the small astigmatism of the nuclear light, and appears to be real. The "bar" is redder than the rest of the galaxy. The outer isophotes are not elliptical in the normal behavior of a barred spiral galaxy, and the luminosity profile is not exponential (Fig. 3). The profile for a nearby galaxy of comparable brightness, which is quite elliptical, is fitted well with an $R^{1/4}$ law.

A bar-like structure is a common transient phenomenon in the later stages of simulations of galaxy mergers. Thus, 1549+203 appears to be an elliptical type host galaxy in the late stages of a merging event.

1553+113. This is a bright (15 m) BL Lac object at $z=0.36$; it has not been imaged previously by us. The data show a smooth round object with a well-centered nucleus. The field is devoid of probable companions, although the I-band data show two faint objects close to the QSO which look more like background galaxies than dwarf companions. No tidal effects are seen. The data have a slight pattern of guide errors which distort the inner isophotes somewhat. The same pattern is seen in the image of a nearby star. This makes the detection of color gradients in the host galaxy difficult, but it seems likely that any gradients present are small. The PSF is very close to that of the QSO, so that we have not detected any resolved structure, even with this seeing. The luminosity profiles are similar in V and I and are hybrid, i.e., neither exponential nor $R^{1/4}$.

1613+658. This is a PG QSO (also Mkn 876) of low (z=0.12) redshift and a luminous *IRAS* source. The object is a large disturbed galaxy with long tidal tails, and a barred spiral companion (Fig. 2). The tails extend over 50 arcsec (85 kpc) and the main host galaxy is 35 kpc across. The structure is very asymmetrical and complex, and there is a second "nucleus" or knot 1.6 arcsec to the W of the main one (Fig. 2). This knot is bluer than the surroundings, but otherwise there is no general color gradient with radius. The luminosity profile is peculiar (Fig. 3), but similar in V and I.

The galaxy resembles Mkn 231 (Hutchings & Neff 1987) and is probably a recent merger of two large galaxies. The companion galaxy, 23 arcsec to the N, does not seem to be tidally connected with the active galaxy.

1803+676. This is a low redshift (z=0.13) object that is surprisingly compact. The early CFHT deep image suggests a disturbed faint outer halo. The HR Cam data do not reach deep enough to see this halo, and the bright inner part of the QSO host is very small and smooth. The diameter with detectable signal is 6 arcsec in I (10 kpc). There is a companion galaxy 11 kpc away whose long axis (if at the same redshift) is 4 kpc; the companion looks like an inclined spiral with arms. We can see no structure in the QSO. The luminosity profile fits an $R^{1/4}$ law and there is no detectable color gradient. However, the image is dominated by the central PSF, even at this resolution. This appears to be a bright QSO in a fairly faint elliptical galaxy. (The luminosity and size would be more normal at $z\sim0.4$.)

Since the outer disturbed halo is the only detected structure, it may be a galaxy in the very late stages of absorbing a smaller companion.

2112+059. This is a PG QSO of redshift 0.47. Its appearance is very similar to 1803+676: small (6 arcsec diameter), round, and structureless. The QSO host has a companion galaxy about 16 arcsec away which is almost a twin, and fainter companions within 20 arcsec which appear to be a group of galaxies. The guiding was hampered by winds which elongated the images E–W. Since similar deviation from circularity is seen in the contours of the QSO and the companion galaxy, we assume that the noncircularity is mostly due to the guiding. However, the long-axis direction differs between the QSO and companion by about 10°, so that there may be weak evidence for a bar-like structure roughly E–W in the inner QSO. We also have a deep 1 arcsec resolution image which shows the outer isophotes to be irregular; unfortunately, this is somewhat confused by a bad CCD column. In this object therefore, we suspect that there is some inner bar-like structure or a near-nuclear knot, but we do not definitely detect such structure. The relatively large redshift may be at least some of the reason for the lack of detected structure in this QSO. Both QSO and companion become redder with increasing radius and both fit an $R^{1/4}$ law better than an exponential.

2121−176. This QSO was discovered as an IR source (Low *et al.* 1988). It is at low redshift, with z=0.11. The object is large and fuzzy, but with little fine detail. It is round, with an off-centered nucleus, and a spiral arm emerging in the E and fading to the S (Fig. 1). The inner isophotes rotate by nearly 90° (Fig. 2), as a face-on barred spiral. The luminosity falls off rapidly beyond the resolved arm and the luminosity profile is fit well by an $R^{1/4}$ law. The color becomes redder with increasing radius. The luminosity drop-off occurs at a radius of 6.5 arcsec (10 kpc); if anything lies beyond this radius, it is too faint for these observations to detect.

We suggest that this system may be a recent prograde merger whose tidal tails are still winding up, rather than a normal spiral.

2130+099. This object has been discussed as an inclined spiral by Hickson & Hutchings 1987, who found an extended Balmer emission-line region near the nucleus but no evidence for extensive star formation. They also noted that the luminosity profile is peculiar. Our new images clearly show the outer arms and the bulge (Fig. 1). The SW inner arm is also seen emerging from the bulge. The outer arms are bright and form a major bump in the luminosity profile (Fig. 3), which is not exponential. The host galaxy in this respect resembles a ring galaxy. The inner part of the profile fits quite well to an $R^{1/4}$ law. The color becomes redder with radius and in the bulge there appears to be a blue region extended normal to the long axis. There are no bright features near the nucleus. There are no bright companions, but there are several small galaxies in the close vicinity, which may be dwarf companions.

The object does not appear to be a normal spiral, but may be in a post-interaction/merger state.

2135−147. This is a radio-loud QSO at z=0.20. We have published earlier imaging data, and Hickson & Hutchings (1987) reported long-slit spectroscopy. Their main result was that there is extended [O III] emission that lies between the nucleus and the close luminous knot to the E. Stockton & MacKenty (1987), on the other hand, report that their [O III] image is slightly extended in the opposite direction. The QSO has a small galaxy companion some 5 arcsec to the E, and a closer smaller companion or knot along the same radius, 2 arcsec from the nucleus. The extended radio structure is large and two-sided, and is also extended along this direction (Gower & Hutchings 1984).

The new HR Cam data show that the host galaxy is round and smooth apart from the close knot, and that the 5 arcsec companion is elliptical and smooth (Fig. 1). The 5 arcsec companion is redder than the QSO host, as is the knot. The host galaxy is blue, becoming redder with increasing radius. Neither of the two main galaxies appears to have strong tidal distortion. The 5 arcsec companion however is slightly extended toward the QSO along its edge nearest to the QSO. The lower isophotes also show that there is a broad bridge of connecting luminosity between the galaxies.

Most of the new information relates to the close knot. It appears to be extended along the host-galaxy radius [seen in both the original (Fig. 1) and the model-subtracted contours in Fig. 2]. This is close to the direction of the telescope diffraction spikes, although the spikes cannot be seen in any of the other three directions. The shape of the knot is roughly triangular. The extended [O III] may arise from star formation or nuclear ionization in the leading edge of the tidally extended object. The luminosity profile is confused by the close companions, but does follow an $R^{1/4}$ law as far as can be seen.

The QSO host may be an elliptical in the process of merging with one or more of its small companions in a small group, in a process that may have taken a relatively long time. The shape and orientation of the close knot, if found to be real, suggest that it could be a small galaxy merging with the QSO host.

2141+175. This is a radio-loud QSO at $z=0.21$. Our earlier imaging showed the object to be elongated and asymmetrical, somewhat like an inclined disk, but with no resolved substructure. The extension was considerably less visible in B light. Other published images (Smith *et al.* 1986; Stockton & MacKenty 1987; Stockton & Farnham 1991) have shown the extensions to be more tail-like. The radio source is unresolved (Gower & Hutchings 1984).

The new data show well that the structure consists of a double "tail," which is longer on one side, and slightly curved (Fig. 1). The tails are much brighter in I than V light, and have sharp edges and ends, so that they appear to be tidal and consist of old red stars. Stockton & Farnham (1991) show spectroscopic data that indicate the tail(s) to be composed of stars. The tails extend 12.5 and 8 arcsec on either side of the nucleus, and appear continuous across the nucleus. The shorter side is brighter close in to the nucleus (Fig. 2). Along most of its length the longer tail has approximately constant surface brightness, although there is a gradual rise in brightness near the end. The tails are redder in the outer parts. It seems likely that they are a single tail viewed edge-on and projected across the nucleus.

The host galaxy itself is round and featureless, but the nucleus is displaced from the center by about 0.2 arcsec. The luminosity profile fits an $R^{1/4}$ law fairly well (Fig. 3). There is a small radial color gradient becoming redder with increasing radius, which may be a measure of the nuclear scattered light. There is a faint small galaxy 4 arcsec to the N, which is irregular and merges with the outer isophotes of the QSO host. There is also a brighter but still small galaxy 12 arcsec to the NE, which has a slightly irregular shape.

This object thus appears to be the result of a recent merger. The linear "tail" suggests that we are seeing the remains of a disk galaxy viewed close to its plane which has a projected size greater than the main population of stars (as suggested by Stockton & Farnham 1991).

2201+315. This is a radio-loud QSO at redshift 0.30. The radio structure is large (90 arcsec, 330 kpc) with two diffuse lobes, a bright core, and a weak jet toward the SW (Gower & Hutchings 1984; Neff & Brown 1984). Our earlier optical image showed a host galaxy with long axis perpendicular to the radio axis and two nearby unresolved objects.

In the new HR Cam data we see that the two companions are galaxies, the nearer and brighter of which has a bright nucleus. The outer parts of the QSO host are knotty, and the color ratio image (Figs. 1 and 2) shows that the whole host galaxy is filled with red knots and has a background that is bluer than the companion galaxies. This is unique in our present sample: if the knots are dust, they are not distributed in the usual configuration of lanes or concentrated to the galaxy center. The bright inner parts of the galaxy do not show any significant structure, and look like a smooth elliptical galaxy. The luminosity profiles are a poor fit to an $R^{1/4}$ law (Fig. 3), with extra light in the inner regions. The mean color becomes markedly redder with increasing radius.

We suggest that the system is an unusual post merger.

2214+134 (Mkn 304). This object is usually classified as a Sy 1 as it is easily seen to be nonstellar at its redshift of 0.07; its luminosity places it in the QSO class, with $M=-23$. We do not have other imaging data on the object. The galaxy is very smooth and round, with no irregular structure. Our data have good signal to a radius of 7.5 arcsec; further out the fainter signals fall off abruptly at a radius of 10 arcsec. The profile definitely does not fit an exponential or $R^{1/4}$ law (Fig. 3). The color becomes redder with radius, also in a very smooth and symmetrical way.

2233+134. This is an optically selected $z=0.33$ object, previously imaged by Smith *et al.* (1986). The QSO is resolved but small and round, with no resolved substructure. There are several (about ten) small faint galaxies in the field, the closest of which is 3.5 arcsec away, on the edge of the signal from the QSO host galaxy. The QSO host is by far the largest galaxy in the field. The QSO host is bluer than the faint galaxies, but has no detectable color structure. The luminosity profile is a reasonable fit to $R^{1/4}$ (Fig. 3), and not to an exponential. The QSO is not known to be a radio source.

It is possible that the nearby companion is tidally affected by the QSO host, since it is irregular. There is no other evidence of interactions.

2251+113. This is an IR-bright QSO at $z=0.32$, which is a radio source (Hutchings *et al.* 1988). It is also known to have extended [O III] structure (Stockton & MacKenty 1987). Hutchings & Crampton (1990) obtained off-nuclear spectra along three slits through the emission-line structure. The gas velocities appear to be irregular over several hundred km s^{-1}, and tens of kpc. We do not have previous direct imaging of this object.

The HR Cam data show a smooth round host galaxy covering some 10 arcsec. There is no central substructure, and a smooth color gradient becoming redder with increasing radius. In the I-band image, there is a faint resolved light at a radius of 3–4 arcsec at 1 o'clock and 8 o'clock. In the V band, only the 8 o'clock feature is seen. The latter feature coincides with the brightest [O III] knots, and the SE radio lobe. The 1 o'clock feature lies in the outer parts of the N extension of the line emission. The luminosity profile fits $R^{1/4}$ (Fig. 3).

In this relatively undisturbed host galaxy, we know that the faint outer features correspond to very irregular and disturbed gas. The smoothness of the optical profile and the large size of the radio structure suggest that any tidal

TABLE 2. Morphology and interaction status.

Name	Basic shape	Other	Profile[a]	Merger	Mass ratio
1223+252	Complex	Bar, knots	—	Med	2
1226+023	Irreg, ellip	Off-center, jet	R	Old	1
1229+204	Barred spiral	Blue disr galaxy	E	Early	High
1302−102	Smooth	Disr comp 0.8–2.0″	R+E	Med	High
1334+246	Spiral, large	Merged comp	(E)	Early	High
1351+640	Smooth, round	Halo	(R)	Very old	?
1400+162	Smooth, round	Faint red bulge	(R)	Old?	1
1403+434	Smooth, round	Knotty bent tail	(R)	Early	High
1411+442	Spiral, large	2 jets	E	Old?	2
1444+407	Smooth, ellip	Blue knot/bar 0.5″	H	Old	High
1525+227	Smooth, round	Knot 0.8″	H	Old, multi?	High
1549+203	Smooth, round	Small, bar±1″	H	Old, multi?	High
1553+113	Smooth, faint	—	(H)	?	—
1613+658	Complex	Double nuc 1.6″, tail	—	Med	1
1700+518	Irreg, ellip	Arc, jets	H	Med?	2
1803+676	Smooth, round	Small	R	Old	>2
1821+643	Smooth, round	Off-center, comps	(E)	Old?	1
2112+059	Smooth, ellip	Small, bar	(R)	Old	>2
2121−176	Face-on spiral	Sharp edge, bar	R	Med	2
2130+099	Incl spiral	Sharp edge, ring	(R)	Med	1
2135−147	Smooth, round	Knot 2.0″	R	Med, multi	High
2141+175	Round, off-center	Tails, irreg comp	R	Early	2
2201+315	Lumpy, ellip	Red knots	(R)	Old	1?
2214+134	Smooth, round	Edge brightened	(H)	Old	2
2233+134	Smooth, small	Small comp 3.5″	R	V old/wk	High
2251+113	Smooth, round	Faint comps 3.5″	R	Old	High
2305+187	Ellip, irreg	Merging comp, ridges	R	Old, multi?	>2
2344+184	Barred spiral	Uniform color	—	?	—

Notes to TABLE 2

[a]Profile codes: R=$R^{1/4}$; E=exponential; H=Hybrid. Parentheses indicate poor fit.

triggering of nuclear activity occurred a long time ago.

2344+184. This QSO is radio quiet, x-ray selected, at $z=0.14$. It was imaged by Malkan *et al.* (1984), who did not comment on any resolved structure. We do not have previous imaging data. The HR Cam data (Fig. 1) show that the QSO lies in a well-resolved barred spiral galaxy which is near to face-on, with an inclined disk companion 30 arcsec to the N. The color is quite uniform over the galaxy, becoming slightly redder with increasing radius. The SW arm is slightly more extended than the NE, but otherwise the galaxy is very symmetrical. There are no bright knots or dark areas. The luminosity profile (Fig. 3) has a large broad bump across the outer arms, and is not an exponential.

QSO's with HR Cam data published elsewhere: In addition to the QSOs described above, we have already published HR Cam data on the following: 1223+252, 1334+246, 1411+442 (Hutchings & McClure 1990); 1223+023 (3C273) (Hutchings & Neff 1991a); 1821+643 (Hutchings & Neff 1991b); 1700+518 (Hutchings *et al.* 1992); and 2305+187 (Hutchings *et al.* 1992).

4. DISCUSSION

We now assess what we have learned as a result of the resolution of HR Cam, compared with the earlier resolutions of 1 arcsec or more. We see morphological peculiarities in the majority of the QSOs observed. The evidence for tidal interaction in many earlier studies of QSO morphology has led to the widely discussed hypothesis that low redshift QSOs are triggered and fueled by such events (e.g., Hutchings *et al.* 1984a; Heckman *et al.* 1986; Stockton & MacKenty 1987). We feel that the higher-resolution data presented here adds substantially to both the amount and detail of circumstantial evidence supporting this general idea. Therefore, in the following discussion we have chosen to explore our results in terms of the tidal interaction scenario. In Table 2 we give a summary of the descriptions in the preceding section, including a rough assessment of the interaction/merging status of the host galaxies where it can be determined. We note that such information and comment in Table 2 is necessarily subjective, and is based on the above assumption of activity fueled through tidal interaction.

In the group of 28 objects, HR Cam has provided major new morphological information on 16 objects, and significantly improved upon the details of a further six. In the remaining six, we have not detected any significant new structure, but their smoothness is significant, and in almost all cases we are able to derive luminosity profiles that are well sampled and free of massive distortions by the nuclear scattered light. Thus, we stress that 0.5 arcsec resolution has led to a significant increase in information on QSOs, and we may expect that further resolution improvements will be equally rewarding.

4.1 Interaction Assessment

The last two columns of Table 2 describe the merger status as derived from comparison with *N*-body models. This grid of models is described separately elsewhere (Hutchings *et al.* 1992), but consists of simple star-only models in a variety of disk and elliptical configurations, with a wide range of initial velocities, spin orientations, and relative masses. They are consistent with other published models, and were generated in order to have a uniform set of models, which can be examined from any line of sight and with variable physical resolution. While there is an infinite number of variations, there are features common to types of interaction, such as prograde or retrograde encounters in disks, rapid and slow mergers, and similar or very different initial galaxy masses. It is from these general behavior patterns that we have estimated the interaction age and relative masses of the galaxies given in Table 2.

We have performed a similar assessment of interaction status in our study of *IRAS* galaxies (Hutchings & Neff 1991c), some of which are QSOs. In that connection, the QSO sample in this paper is notable for having galaxy interactions or mergers which are not very "new" and generally between galaxies of significantly different mass. We suggest therefore that the QSOs studied in this paper are all mergers rather than passing interactions; further these appear to be mergers in which a big galaxy captures and assimilates a smaller one. In the *IRAS* source paper (Hutchings & Neff 1991c) we also found that the QSOs appeared to be associated with "old and weak" interactions, while with most of the IR-bright objects appeared to be in early stages of interaction between two large galaxies. Thus QSO activity appears to be more often the delayed result of mergers between a large and a small galaxy.

In four cases we find the situation sufficiently complex to suggest that more than one event may have taken place. This reflects on the rich local environment of many low redshift QSOs, and further implies that such mergers should eventually deplete the QSO activation trigger.

4.2 Merger Status

If we assign numbers to the interaction age from 1 to 4 from early to very old, we find a mean value of 2.5 (± 0.8) for the whole group. The IR-loud, radio-loud, and radio-quiet subgroups do not differ significantly (or by more than 0.2) from this value. Similarly, assigning 4 as a "high"-mass ratio, we find a mean interaction mass ratio index of 2.6(± 1.3) for the group. None of the above subsets differs from this either.

In searching for possible correlations among the new results, we find a possible trend for more luminous QSOs to arise in older interactions. In our numbers this has only an 85% confidence level, and so needs confirmation. We note, however, the result in Hutchings & Neff (1991c) that suggests among *IRAS* source that QSO activity arises in "older" interactions.

4.3 Peculiar Morphologies

We find bar structures in 7 of the 16 radio-quiet objects. This compares with the 25% fraction of normal spirals which are barred. We also note that simulated mergers almost always create a small bar which lasts for some time after the initial merging event (long enough to be visible in old mergers). In fact the models predict that with better resolution we should be able to see these bars in most QSOs.

We find other peculiar structure in the inner regions of many QSOs. We count 13 objects in this category, aside from the bars already mentioned. These features may be second nuclei, tidally disrupted merging galaxies, starburst knots, dust, or nuclear "jets." These are all common in merging galaxies which have been studied in more detail at low redshift, and give us definite clues as to the recent history in the QSO hosts.

Our new data are not well suited to finding very faint tails because of the short exposures. Nevertheless, we have found a few brighter cases, and their details are significant in identifying the type of tidal even that has occurred. We also know from studies of nearby interacting galaxies that faint extended tidal plumes are commonly observed, as well as characteristic of models.

4.4 Luminosity Behavior

The luminosity profiles are quite superior to what is obtained with 1 arcsec resolution and sparser sampling, and we have been able to make a reasonable classification of most of them. We note that 14 of the sample fit best to an $R^{1/4}$ law while only 4 fit an exponential. We also note that a further seven are hybrid, and three are peculiar. Thus, the luminosity profile may be useful as an indicator of the merging status of the galaxy, since major mergers eventually mimic ellipticals, and most mergers (of mass ratios 4 or less) disturb the luminosity profile for considerable times. Thus, the general contention that QSO host-galaxy types can be classified by their luminosity profiles (e.g., Malkan 1984; Smith *et al.* 1986) is a good start but perhaps an oversimplification.

Our observations appear to support the contention that radio-loud objects are in general associated with ellipticals, but it is clear that the situation is not a simple one. All the radio-detected objects in this study have $R^{1/4}$ or hybrid luminosity profiles, and all the exponential profiles are radio-quiet.

As found in the larger samples of Hutchings & Neff (1990, 1991c), the optical luminosity is strongly correlated with the IR and radio. In this group, we find the optical-IR correlation at the 99.3% level, and the optical radio at the 95% level. However, the radio and IR do not correlate at all, but the sample here has only six objects. We find no biases or correlations with redshift.

5. SUMMARY

Overall, the new HR Cam results suggest that the majority of low *z* QSOs are tidally interacting objects. We have made rough estimates of the ages and types of tidal encounters for most of the objects observed. They are not spectacularly interacting galaxies, and mostly involve merging of small galaxies with large ones, rather than collisions between large galaxies. Luminosity profiles are significantly improved over previous observations. The luminosity profiles range from $R^{1/4}$ through hybrid to exponential, and the profile type appears to be a strong indicator of the merging status of the galaxy system. We find bright knots to the nucleus in several objects. We expect that further high-resolution work will strengthen these conclusions.

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REFERENCES

Clark, B. G. 1973, Proc. IEEE, 61, 1242
Gower, A. C., & Hutchings, J. B. 1984, AJ, 89, 1658
Heckman, T. M., *et al.* 1986, ApJ, 311, 526
Hickson, P., & Hutchings, J. B. 1987, ApJ, 312, 518
Hutchings, J. B., Crampton, D., & Campbell, B. 1984a, ApJ, 280, 41
Hutchings, J. B., *et al.* 1984b, ApJS, 55, 319
Hutchings, J. B., Johnson, I., & Pyke, R. 1988, ApJS, 66, 361
Hutchings, J. B., Janson, T., & Neff, S. G. 1989, ApJ, 342, 660
Hutchings, J. B., Price, R., & Gower, A. C. 1988, ApJ, 329, 122
Hutchings, J. B., & Crampton, D. 1990, AJ, 99, 37
Hutchings, J. B., & Neff, S. G. 1987, AJ, 93, 14
Hutchings, J. B., & Neff, S. G. 1990, AJ, 100, 1441
Hutchings, J. B., & Neff, S. G. 1991a, PASP, 103, 26
Hutchings, J. B., & Neff, S. G. 1991b, AJ, PASP
Hutchings, J. B., & Neff, S. G. 1991c, AJ, 101, 434
Hutchings, J. B., & McClure, R. D. 1990, PASP, 102, 48
Hutchings, J. B., Neff, S. G., & Gower, A. C. 1992, PASP, 104, 62
Hutchings, J. B., Crabtree, D., Neff, S. G., & Gower, A. C. 1992, PASP, 104, 66
Low, F. J., *et al.* 1988, ApJ, 327, L41
Malkan, M. 1984, ApJ, 287, 555
Malkan, M. A., Margon, B., & Chanan, G. A. 1984, ApJ, 280, 66
Neff, S. G., & Brown, R. L. 1984, AJ, 89, 195
Neff, S. G., & Hutchings, J. B. 1992, AJ (in press)
Neugebauer, G., *et al.* 1986, ApJ, 308, 815
Saikia, D. J., Salter, C. J., Neff, S. G., Gower, A. C., Sinha, R. P., & Swarup, G. 1987, MNRAS, 228, 203
Sanders, D. B., Soifer, B. T., Elias, J. H., Madore, B. F., Matthews, K., Neugebauer, G., & Scoville, N. 1988, ApJ, 325, 74
Smith, E., Heckman, T. M., Bothun, G. D., Romanishin, W., & Balick, B. 1986, ApJ, 306, 64
Stockton, A., & MacKenty, J. W. 1987, ApJ, 316, 584
Stockton, A., & Farnham, T. 1991, ApJ, 371, 525
van Ardenne, A. 1978, NFRA Note, No. 273
Veron-Cetty, M.-P., & Woltjer, L. 1990, A&A, 236, 69