HST Planetary Camera images of quasar host galaxies

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Accepted 1998 March 2. Received 1998 March 2; in original form 1997 September 9

ABSTRACT

We present Hubble Space Telescope (HST) images of seven low-redshift quasars (six taken with the Planetary Camera, one with the Wide Field Camera). These complete the sample of 14 quasars observed by the Faint Object Camera Investigation Definition Team (FOC IDT). Following subtraction of the quasar nuclear light, host galaxies can be seen in all seven cases. A combination of the optical morphology and luminosity profiles of the residual host galaxies and the results of 2D cross-correlation model fitting implies that five of the objects have elliptical host galaxies and two have disc host galaxies. The luminosities vary from slightly fainter than $L^*$ to about 1.3 mag brighter than $L^*$.

We discuss the properties of the complete sample of 14 quasars. Nine of the objects appear to have elliptical host galaxies (all six of the radio-loud quasars in the sample as well as three radio-quiet quasars). Two further radio-quiet quasars appear to lie in disc galaxies. The other three objects (radio-quiet, ultraluminous infrared quasars) all lie in violently interacting systems. The sample as a whole has an average luminosity about 0.8 mag brighter than $L^*$, although the radio-loud objects have hosts on average 0.7 mag brighter than the radio-quiet objects.

We compare our results with those from HST imaging of quasars by other authors. Taken together, our observations are in broad agreement with those of Bahcall et al. Radio-loud quasars appear to lie in luminous elliptical galaxies whereas radio-quiet quasars are found to lie in either elliptical or spiral hosts. Host galaxy luminosities (of radio-quiet and radio-loud quasars) are much brighter than would be expected if they followed a Schechter luminosity function.

Key words: galaxies: active – galaxies: interactions – galaxies: nuclei – quasars: general.

1 INTRODUCTION

The imaging of quasar host galaxies at high resolution was one of the principal scientific goals of the Hubble Space Telescope (HST). The subject has a long and distinguished history from the ground. Some representative papers are: Kristian (1973); Wyckoff, Wehinger & Gehren (1981); Tyson, Baum & Kreidl (1982); Hutchings et al. (1982); Gehren et al. (1984); Heckman et al. (1984); Malkan, Margon & Chanan (1984); Boroson, Persson & Oke (1985); Smith et al. (1986); Stockton & Mackenty (1987); Yee (1987); Hutchings, Janson & Neff (1989); Romanishin & Hintzen (1989); Veron-Cetty & Woltjer (1990); Hutchings & Neff (1992); Dunlop et al. (1993); McLeod & Rieke (1994a,b) and Taylor et al. (1996). The analysis of ground-based data is difficult because atmospheric seeing smears the light from the bright central source over the light from the inner regions of the host galaxy. The far superior resolution of the HST lessens this problem to a considerable degree.

Several groups have now reported the results of the imaging of low-redshift quasars with the HST (Bahcall, Kirhakos & Schneider 1994, 1995a,b, 1996; Bahcall et al. 1997; Hutchings et al. 1994; Hutchings & Morris 1995; Disney et al. 1995; Boyce et al. 1996). These results have clearly illustrated the large improvement which the HST enables in the study of the quasar host problem. The results so far have produced no single coherent class of objects which are the hosts of quasars. For example, Bahcall and co-workers from their WFC imaging of a sample of 20 quasars found examples of quasars in diverse environments including ellipticals (with luminosity from $L^*$ to that of brightest cluster members), normal spirals, and complex systems of gravitationally interacting components.
In this present work we conclude our description of a sample of quasars observed with the PC of the HST by the Faint Object Camera Investigation Definition Team (FOC IDT). The sample was chosen to include a range of quasar types (radio-loud, radio-quiet, X-ray loud, luminous IR sources) and to have low redshift (z < 0.5), the intention being to study a group of nearby quasars of a variety of types at the highest HST resolution. The final observed sample consists of 14 objects. 11 of these were chosen from table 1 of the catalogue of Veron-Cetty & Veron (1993) and are unambiguously quasars within the definition used by Veron-Cetty & Veron (i.e. M_V < -23, H_0 = 50 km s^{-1} Mpc^{-1}, q_0 = 0.5). The other three were chosen from the lists of Low et al. (1988, 1989) who selected very luminous IRAS sources (i.e.L_{IR} > 10^{12} L_\odot) which are also optical quasars based on the breadth of their emission lines and their appearance on the POSS. Two of these objects are included in table 1 of Veron-Cetty & Veron. The third (IRAS 13218+0552) is slightly too faint and is listed by Veron-Cetty & Veron as a Seyfert Type I.

The first four objects observed (PHL 1093, MS 22152–0347, PKS 1302–102 and PKS 2128–123) were presented in Disney et al. (1995). All four quasars appear to have luminous elliptical host galaxies. All four also show circumstantial evidence for interaction in that all have at least one very close companion object. In Boyce et al. (1996) we presented the results for the three luminous IRAS quasars included in the sample (IRAS 40505–2958, IRAS 07598+6508 and IRAS 13218+0552). All three quasars appear embedded in spectacular interactions among two or more luminous galaxies, probably spirals. We discussed the evolutionary connection, if any, between these three objects and the far more numerous ultraluminous IR galaxies. We argued that these three objects are probably young and therefore do not fit a scenario in which quasars emerge only in the later stages of an interaction when most of the dust has been blown away. It may be that we are simply viewing them from a fortuitous angle allowing a clear view into the cores.

In this paper we present the results from the now completed observations of the remaining seven quasars in the FOC IDT sample. In section 2 we describe the observations and data reduction. In section 3 we present the results as a set of grey-scale images and luminosity profiles. In section 4 we consider the results derived for the whole FOC IDT quasar sample and compare these to those derived by other workers. In section 5 we summarize our conclusions. We assume H_0 = 75 km s^{-1} Mpc^{-1}, q_0 = 0 throughout this paper.

### 2 OBSERVATIONS AND DATA REDUCTION

Six of the seven quasars presented here were observed between 1994 and 1996 with the Wide Field/Planetary Camera-2 (Trauger et al. 1994) in Planetary Camera (PC) mode. The seventh (PG 0043+039) was observed with the WFPC-2 in Wide Field (WF) mode. All observations were taken through the F702W filter, which is similar to the i-bandpass but is slightly redder; the mean wavelength and FWHM of the F702W response are 6997 and 1481 Å respectively. This camera-filter combination was chosen because of its high relative sensitivity to galaxy light and because it has sufficient resolution and dynamic range to reduce saturation in the areas close to the quasar nucleus. All of the objects were observed for a total exposure time of 1800 s. In the case of PG 1216+069 this consisted of 3 × 600 s exposures. For the remaining objects four exposures were taken: two of 600 s and one each of 400 and 200 s. Table 1 presents a journal of the observations.

The PC has a field of 800×800 CCD pixels of size 0.046 arcsec pixel^{-1}. The image scale of the WF detectors is 0.0966 arcsec pixel^{-1}. We report the measured F702W magnitudes on the HST photometric scale established by Holtzman et al. (1995b). For further information about the WFPC2, see Burrows et al. (1996), Trauger et al. (1994) and Holtzman et al. (1995a,b).

Initial data processing was performed at Space Telescope Science Institute (STSCI) with the standard HST pipeline software. Subsequent reductions were done on Starlink, making use of STSDAS software packages supplied by the STSCI. After bias-subtraction, flat-fielding and calibration the individual frames were median combined (to remove cosmic-ray events) to yield the ‘raw images’.

### 3 RESULTS

#### 3.1 Images after subtraction of a stellar PSF

In Fig. 1 we present grey-scale images of the seven quasars after the removal of a best-fitting PSF. For the six quasars observed with the PC this PSF was derived from a co-added 10 × 200 s exposure of a standard star. In the case of PG 0043+039 a model PSF generated using the TINY TIM software (Krist 1993) was used. The scaling factor in all cases was chosen so that, after subtraction, the residual ‘galaxy’ image continued to increase monotonically to the smallest radius at which the image was not saturated on the shortest exposure. The diffraction spikes were also excluded from the fitting procedure since these are known to vary considerably across the PC frame. Although fairly crude, experiments show that this technique yields a probable error in the scaling factor of no more than ±20 per cent. This limit is set by the condition that the scaling factor must not be so big that significant numbers of pixels in the residual image assume negative values and that the scaling factor must not be so small that parts of structure of the PSF can clearly be seen on the residual image.

In Fig. 1 the inner few pixels in each image (where there was significant saturation) have been replaced by null values as have the pixels in the regions of the diffraction spikes. All of the images (even the 200-s exposure) suffer from saturation in the inner few pixels. However, none of the images is saturated beyond a radius of 5 pixels in the shortest exposure and most do not suffer saturation outside the central 3 pixels. The replacement of these pixels with null values was necessary in order to determine the scaling factor for the subtraction of the PSF. However, it also means that all the data displayed in each frame have had the PSF removed with reasonable accuracy.

<table>
<thead>
<tr>
<th>Object</th>
<th>Type</th>
<th>V</th>
<th>z</th>
<th>Camera</th>
<th>Exposure Time (sec)</th>
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<td>PG 1358+04</td>
<td>RQ</td>
<td>16.3</td>
<td>0.427</td>
<td>PC</td>
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<td>0.385</td>
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<td>0.398</td>
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<td>0.371</td>
<td>PC</td>
<td>1×200, 2×400, 2×600</td>
</tr>
<tr>
<td>PKS 0312-77</td>
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<td>0.223</td>
<td>PC</td>
<td>1×200, 2×400, 2×600</td>
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<tr>
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<td>0.096</td>
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<td>PG 1216+069</td>
<td>RQ</td>
<td>15.7</td>
<td>0.334</td>
<td>PC</td>
<td>3×600</td>
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</table>
This subtraction technique enables us to study the morphology of the underlying host galaxies in a model independent way. A residual underlying host galaxy can be seen in all seven objects. In the cases of MS 07546+3928, PKS 0312–77 and 3C 351 the underlying host galaxies are sufficiently bright and extended to enable luminosity profiles to be derived. These are presented in Fig. 2. Luminosity profiles are shown both as a plot of log(intensity) versus semimajor-axis and as log(intensity) versus (semimajor-axis)$.4$. The profiles were produced by fitting isophotal ellipses to the residual galaxy images using the ISOPHOTE package in STSDAS. Pixels contaminated by saturation, diffraction spikes or an obvious companion were ignored in this process. The error bars represent $\pm 1$ standard deviation of the mean intensity within each isophotal ellipse. The profiles are plotted out to the point where the signal-to-noise ratio in each annulus falls to a value of $\approx 4$.

The luminosity profiles from the residual images for 3C 351 and PKS 0312–77 are well fitted by a de Vaucouleurs $r^{1/4}$-law model, suggesting that both galaxies are ellipticals. The more complex luminosity profile of MS 07546+3928 is discussed below.

Although a host galaxy can be clearly seen in the case of PG 1216+069, the light from it is severely contaminated by scattered light from a nearby bright star, making the determination of a meaningful luminosity profile impossible. The residual light seen in PKS 0202–77, PG 1358+04 and PG 0043+039 is much fainter than in the other four cases. It is not possible to derive meaningful luminosity profiles from such low signal-to-noise ratio data since they only have a signal-to-noise ratio of greater than 3 at very small radii (i.e. close to the nucleus). None the less, the non-quasar nature of this light is confirmed by the cross-correlation model fitting (Section 3.2 below).

3.2 Determination of galaxy parameters using 2D cross-correlation

The PSF-subtraction procedure used to create the images in Fig. 1 and the luminosity profiles of Fig. 2 enables the host galaxies to be studied in a model-independent way. In order to determine accurate (model-dependent) parameters for quasar and host galaxy we again employed the 2D cross-correlation technique used in Paper I. Details of this method can be found in Phillipps & Boyce (1992) and Boyce, Phillipps & Davies (1993).

Two-dimensional (2D) galaxy and PSF model templates were cross-correlated with the data to determine optimal values of quasar flux, and host galaxy flux, exponential scalelength or effective radius, axial ratio and position angle. As in Paper I we used a model PSF created using the TINY TIM software (Krist 1993). Two sets of galaxy templates were used: one set representing idealized elliptical galaxies with de Vaucouleurs $r^{1/4}$-law (GdV) profiles; the other set representing idealized disc galaxies with exponential profiles. Hence for each object we obtained a best-fitting exponential disc model and a best-fitting de Vaucouleurs $r^{1/4}$-law model.

Each of these best-fitting galaxy models has an associated best-fitting value for quasar flux. Our software also calculates the $\chi^2$ residuals for each best-fitting model and, hence, enables us to determine which of the best-fitting models (i.e. disc or de Vaucouleurs) produces the better fit for each object. We excluded from the fitting process all pixels affected by saturation or contamination by an obvious companion. We also excluded the diffraction spikes from the process for the reasons discussed above.

The 2D cross-correlation technique produces very accurate results even in very low signal-to-noise ratio data. Simulations suggest that, in the type of data considered here, there will be systematic errors of $<10$ per cent in the derived quasar and host galaxy luminosities. However, this error limit is meaningful only if the underlying galaxies really do have such idealized luminosity profiles. As can be seen from Fig. 2, clearly these idealized profiles do not exactly match reality in every case (most notably in the case of MS 07546+3928). In interpreting the results of the cross-correlation model fitting, this fact should be born in mind. None the less, the 2D cross-correlation technique generally produces an accurate determination of the quasar luminosity even when the nature of the host galaxy is rather uncertain (see Boyce et al. 1993).

Numerical results of the cross-correlation process are presented in Table 2. Column 1 lists the target name. Columns 2, 3 and 4 list the results for the best-fitting de Vaucouleurs model (apparent $F702W$ quasar magnitude, apparent $F702W$ host galaxy magnitude and half-light radius). Columns 5, 6 and 7 list the results for the best-fitting exponential disc model (apparent $F702W$ quasar magnitude, apparent $F702W$ host galaxy magnitude and exponential scale-length). Column 8 denotes which of the models produces the better fit (i.e. has the minimum value of $\chi^2$).

Table 3 presents a summary of the main derived results for the seven quasars presented here and also for the rest of those in FOC IDT sample. Column 1 lists the object name. Column 2 lists whether the object is radio-loud or radio-quiet (based upon the criteria of Kellerman et al. 1994). Column 3 lists the object’s redshift. Columns 4 and 5 list the absolute $F702W$ magnitudes of the quasar and the host galaxy respectively. For the seven quasars presented here and the four quasars presented in Disney et al. (1995) (PHL 1093, MS 22152–0347, PKS 1302–102 and PKS 2128–123), $M_{F702W}(F702W)$ and $M_{F702W}(F702W)$ were found using the 2D cross-correlation technique. The quoted values are those obtained from the best-fitting model. In the case of the three IRAS quasars presented in Boyce et al. (1996) it was clearly unrealistic to attempt to fit simple model profiles to the residual light. The values given for $M_{F702W}(F702W)$ in these cases were derived by summing the residual light left around the quasars after the subtraction of a model PSF using the method used to produce Fig. 1. Some of the central pixels suffered from saturation and were given null values. Hence the values for $M_{F702W}(F702W)$ are lower limits in these cases. No attempt was made in any case to correct for dust extinction internal to the system. Hence all derived absolute magnitudes are lower limits. Column 6 lists the effective radius (for the GdV fits) or scalelength (for the exponential disc fits) of the host galaxy and column 7 lists the derived axial ratio. Column 8 denotes whether the best-fitting model, the derived parameters of which are listed, was a de Vaucouleurs $r^{1/4}$-law or an exponential disc type. Column 9 lists a value of $M_{F702W}(V)$ for each host galaxy. The values for $M_{F702W}(V)$ were obtained by transferring the derived $M_{F702W}(F702W)$ magnitudes to $V$ by applying the $k-$corrections calculated by Fukugita, Shimashuku & Ichikawa (1995). For this purpose we assumed that each galaxy had the morphology assigned to it in Table 3. We assumed that the IRAS galaxies are S0s.

Published values of $L^*$ differ by up to 1 mag (see e.g. Lin et al. 1996). In order to have a point of comparison, in this paper we nominally adopt the value derived by Lin et al. (1996). This corresponds to $M_{V}(L^*)=-20.0$ in the cosmology adopted here. The uncertainties in this value should be borne in mind.

3.3 Comments on individual objects

3C 351 The radio structure of this radio-loud quasar has been studied by many authors, e.g. Kellerman et al. (1994) who reported it to have an unresolved core (to resolution 0.5 arcsec) coincident
with the optical quasar in the middle of a double lobe structure having PA = 35° and total extent =55 arcsec. Hutchings & Neff (1990) presented the results of optical CCD imaging of the object. They found no evidence for interaction. The PC data presented in Fig. 1 reveal a host galaxy with a luminosity profile well-fitted by an $r^{1/4}$ law. The cross-correlation model fitting confirms the $r^{1/4}$-law nature of the luminosity profile. The derived $M_{\text{Host}}(V) = -21.2$ is about 1 mag brighter than $L^*$. The host galaxy has an axial ratio =0.65 (i.e. E3) and PA = 60°. There is a close companion at a separation of 3.3 arcsec (28 kpc). There is no sign of any ongoing gravitational interaction.

**PKS 0312–77** Veron-Cetty & Woltjer (1990) performed $i$-band imaging of this radio-loud quasar. They fitted a spheroidal model to the residual light left after subtracting a PSF and determined an $m_i = -17.6$ ($M_i = -22.4$ in the cosmology adopted here) and scalelength 12 kpc for the host galaxy. The PC data presented in Fig. 2 reveal an elliptical host galaxy with a luminosity profile well-fitted by an $r^{1/4}$-law model. The cross-correlation model fitting confirms that the galaxy is better fitted by a de Vaucouleurs model than an exponential disc. The host galaxy has an axial ratio = 0.70 (i.e. E3) and PA = 130°. The derived values of $M_{\text{Host}}(F702W) = -22.3$ and scalelength = 17.7 kpc compare reasonably with those derived by Veron-Cetty & Woltjer. The derived $M_{\text{Host}}(V) = -21.2$ is about one mag brighter than $L^*$. An apparent companion is seen at a projected separation of 4.7 arcsec (23 kpc). There is no sign of ongoing gravitational interaction.

**MS 07546+3928** This radio-quiet quasar is also an IRAS galaxy (IRAS 07546+3928). There are no reports of previous optical imaging. Vigotti et al. (1989) mapped the source at 1.46 GHz with the VLA (15 arcsec resolution). They detected a single resolved source of flux 35 mJy and size = 40 arcsec. The PC data presented here reveal a host galaxy that appears to have a bright nucleus surrounded by a large ring-type structure. The nuclear source in this case was very bright and it is possible that much of the light in the central part of the PSF-subtracted image is residual light from the nuclear point source. Outside $r = 50$ pixel there are hints of spiral structure in the PSF-subtracted image. The luminosity profile (Fig. 2) also clearly shows two components to the residual light distribution. The inner part of the profile could be explained as the residual of the nuclear point source. Outside $r = 50$ pixel the profile follows an exponential pattern. We suggest that outside this radius the host galaxy

Figure 1. Planetary Camera images of the seven QSOs following subtraction of a scaled PSF as described in the text. North (arrow) and east are denoted. The scale bar represents 1 arcsec.
is dominating the residual light distribution and tentatively propose that this host is some kind of disc galaxy. During the cross-correlation model fitting we excluded the pixels inside $r = 50$. The cross-correlation technique confirmed that, outside this radius, the galaxy is better fitted by an exponential disc model than an de Vaucouleurs $r^{1/4}$-law model. The derived $M_{\text{Host}}(V) = -19.9$ is slightly fainter than $L^*$. There is an apparent companion at a projected separation of 9.5 arcsec (19 kpc).

**PG 1216+069** This radio-quiet object was imaged by Hutchings, Crampton & Campbell (1984) who described it as having a halo. Kellerman et. al. (1994) presented 5-GHz D and A-configuration VLA maps of the source. These show an unresolved core coincident with the optical quasar plus a second elongated component stretching from the core with a PA=25°. The total size of the radio source is 0.85 arcsec. The PC image of this object is severely contaminated by scattered light from a nearby bright star. None the less, we managed to obtained a reasonable fit to the data using the cross-correlation technique by only fitting to the pixels to the south of the image (away from the scattered light). The image is better fit by a GdV model than an exponential disc. The best-fitting model gives a derived $M_{\text{Host}}(V) = -20.9$, about 1 mag brighter than $L^*$. There are two close apparent companion objects, one at a projected separation of 1.8 arcsec (13.6 kpc), the other at 2.7 arcsec (20.4 kpc).

**PG 1358+04** Fabian & Usher (1996) did not resolve any under-lying galaxy in this radio-quiet quasar although they noted that the quasar image was not completely spherical. This object has not been detected as a radio source. This (along with PKS 0202–76) is one of the two faintest host galaxies in the sample. Outside $r = 10$ pixels it is hard to detect this image on the plot shown in Fig. 1. None the less, binning up the data does reveal that there is a low intensity host out to $r = 54$ pixels (2.48 arcsec). The cross-correlation fitting procedure confirms this. The best-fitting model has a GdV profile and produce a derived $M_{\text{Host}}(V) = -20.1$, roughly $L^*$. There are no detectable apparent companions within a projected separation of 30 kpc.

**PKS 0202–76** Veron-Cetty & Woltjer (1990) performed i-band imaging of this radio-loud quasar. They determined an $m_i = 19.5$ ($M_i = -21.9$ in the cosmology adopted here) for the host by fitting a spheroidal model to the residual light left after subtracting a PSF. As in the case of PKS 1358+04 it is necessary to bin up the data to reveal a low intensity host galaxy out to $r = 40$ pixel (1.84 arcsec). The best-fitting model derived by the cross-correlation technique

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**Figure 1 – continued**

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has a GdV profile and a derived $M_{\text{host}}(V) = -19.8$, slightly fainter than $L^*$. The derived $M_{\text{host}}(F702W) = -21.3$ compares reasonably with the results of Veron-Cetty & Woltjer's model fitting. There are no detectable apparent companions within a projected separation of 30 kpc.

**PG 0043+039** This radio-quiet object was observed in the $i$-band by Veron-Cetty & Woltjer (1990). They determined an $m_i = 18.8$ ($M_i = -22.5$) for the host by fitting a disc model to the residual light left after subtracting a PSF. The best-fitting spheroidal model gave $m_i = 18.0$ ($M_i = -23.3$). Kellerman et al. (1994) presented a 5-GHz D-configuration VLA map, which revealed the object to have a unresolved core coincident with the optical quasar plus a second elongated component with PA=170°. The total extent of the radio source is about 15 arcsec. Although a residual host galaxy is clearly seen in the PSF-subtracted image, it is very faint outside $r = 10$ pixel. This, coupled with the larger pixel size in this WF image, make it impossible to determine a meaningful luminosity profile. The cross-correlation technique, however, produces a better fit for a disc model. This best-fitting disc produces a derived $M_V = -20.1$, close to $L^*$. The derived $M_{\text{host}}(F702W) = -21.6$ for the best-fitting disc model is about 1 mag fainter than that derived by Veron-Cetty & Woltjer. The object appears to lie within a rich cluster although there are no apparent close companions within a projected separation of 30 kpc.

### 4 DISCUSSION

In this section we discuss the properties not just of the seven quasars presented in Section 3 but also of the rest of the quasars in the FOC IDT sample. We then compare these results with other published results of quasar host galaxy analysis using HST data.

#### 4.1 Host morphologies

Of the 14 objects in the sample, the morphologies of the three IRAS quasars considered in Boyce et al. (1996) are difficult to determine owing to the highly disturbed nature of these systems. All three are clearly in current ongoing gravitational interaction. In Boyce et al. (1996) we suggested that the host galaxies in these three cases were probably spirals since there appear to be no giant ellipticals in their environment.

Of the other 11 quasars, the host galaxies of six (PHL 1093, PKS 2128–123, PKS 1302–102, MS 22152–0347, PKS 0312–77 and 3C 351) appear to be ellipticals, based upon their observed morphology and derived luminosity profiles. The cross-correlation

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**Figure 2.** Luminosity profiles of the host galaxies of 3C 351, PKS 0312–77 and MS 07546+3928 after subtraction of a scaled PSF.
model-fitting technique lends further weight to this classification, in all cases giving a better fit with a GdV model than an exponential disc. The luminosity profile of one object (MS 07546+3928) is closer to an exponential form than a GdV profile. This is confirmed by the cross-correlation model-fitting process.

Although residual host galaxies can be seen in the PSF-subtracted images of PKS 0202–76, PG 1358+04 and PG 0043+039, it was not possible to determine morphology either from the images or by deriving luminosity profiles (see above). In the first three cases, the cross-correlation process produces a better fit using a GdV profile model than an exponential disc model. However, in the case of PG 0043+039, the cross-correlation process favours a disc model.

All six of the radio-loud quasars in our sample have elliptical host galaxies (including PKS 0202–76). Of the eight radio-quiet quasars in our sample, two (MS 07546+3028 and PG 0043+039) appear to lie in disc galaxies: three have elliptical hosts (MS 22152–0347, PG 1216+069 and PG 1358+04) and three have a detected host of uncertain morphology (IRAS 04505-0347, PG 1216+069 and PG 1358+04) but are clearly undergoing violent interaction.

4.2 Host luminosities

The derived values of $M_{\text{host}}(V)$ for our sample (listed in Table 3) range from about 1 mag below $L^*$ (in the case of IRAS 13218+0552) to 1.3 mag brighter than $L^*$ (in the cases of PHL 1093 and PKS 1302–77). If we exclude the three IRAS galaxies (for which only lower limits to the luminosity were obtained) then for the sample as a whole:

$$<M(V)_{RQ+RL}> = -20.8 \pm 0.5 \text{ mag.}$$

This is about 0.8 mag brighter than $L^*$. Hence, our results are not consistent with the galaxies having a Schechter luminosity function. The average absolute luminosity for a field galaxy in a Schechter luminosity function is about 1.8 mag fainter than $L^*$, i.e. about $-18.2$ in the cosmology adopted here. On average our galaxies are about 2.6 mag more luminous than typical field galaxies (assuming a Schechter luminosity function). Even if the value of $M(L^*)$ were revised upwards by one mag, the quasar host galaxies would still be drawn from the bright end of the luminosity distribution.

There is a marked difference between the luminosities of the radio-quiet and radio-loud objects. For the radio-quiet objects (again excluding the three IRAS objects)

$$<M(V)_{RQ}> = -20.4 \pm 0.5 \text{ mag.}$$

For the radio-loud objects

$$<M(V)_{RL}> = -21.1 \pm 0.4 \text{ mag.}$$

The mean luminosity of each sample is separated by more than 3σ (of the error in the mean) from the mean luminosity of the other sample. The average redshifts of the two samples are 0.30 (radio-quiet) and 0.34 (radio-loud). Hence, this effect cannot easily be explained by the radio-loud objects having a larger redshift, especially since the radio-loud objects with the brightest hosts (PHL 1093 and PKS 1302–102) have redshifts lower than the mean. Taken separately, both samples are still too bright to be consistent with being derived from a Schechter luminosity function.

4.3 Companions

A notable result of Disney et al. (1995) was that all four of the quasars studied had close apparent companions within 2 arcsec of the nucleus. This gave weight to the idea that some form of

Table 2. Derived results from 2D cross-correlation model fitting to the the seven quasars presented here.

<table>
<thead>
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<th>Objects</th>
<th>Type</th>
<th>redshift</th>
<th>$M_{\text{host}}(F702W)$</th>
<th>$M_{\text{quasar}}(F702W)$</th>
<th>$r$(kpc)</th>
<th>axial ratio</th>
<th>$\chi^2$</th>
<th>$M_{\text{host}}(V)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>PG 1358+04</td>
<td>RQ</td>
<td>0.427</td>
<td>-24.4</td>
<td>-21.8</td>
<td>4.2 kpc</td>
<td>0.75</td>
<td>GdV</td>
<td>-20.1</td>
</tr>
<tr>
<td>PKS 0202–76</td>
<td>RL</td>
<td>0.389</td>
<td>-23.4</td>
<td>-21.3</td>
<td>4.9 kpc</td>
<td>0.80</td>
<td>GdV</td>
<td>-19.8</td>
</tr>
<tr>
<td>PG 0043+039</td>
<td>RQ</td>
<td>0.385</td>
<td>-24.0</td>
<td>-21.6</td>
<td>10.7 kpc</td>
<td>0.95</td>
<td>Disc</td>
<td>-20.1</td>
</tr>
<tr>
<td>PHL 1093</td>
<td>RL</td>
<td>0.258</td>
<td>-22.0</td>
<td>-22.5</td>
<td>16.0 kpc</td>
<td>0.90</td>
<td>GdV</td>
<td>-21.3</td>
</tr>
<tr>
<td>MS 22152–0347</td>
<td>RQ</td>
<td>0.241</td>
<td>-21.6</td>
<td>-21.9</td>
<td>3.6 kpc</td>
<td>0.80</td>
<td>GdV</td>
<td>-20.7</td>
</tr>
<tr>
<td>PKS 1302–102</td>
<td>RL</td>
<td>0.286</td>
<td>-24.6</td>
<td>-22.6</td>
<td>7.0 kpc</td>
<td>0.85</td>
<td>GdV</td>
<td>-21.3</td>
</tr>
<tr>
<td>PKS 2128–123</td>
<td>RL</td>
<td>0.501</td>
<td>-25.7</td>
<td>-22.8</td>
<td>24.9 kpc</td>
<td>0.90</td>
<td>GdV</td>
<td>-21.0</td>
</tr>
<tr>
<td>MS 07546+3928</td>
<td>RQ</td>
<td>0.096</td>
<td>-21.3</td>
<td>-20.9</td>
<td>4.1 kpc</td>
<td>0.90</td>
<td>Disc</td>
<td>-19.9</td>
</tr>
<tr>
<td>PG 1216+069</td>
<td>RQ</td>
<td>0.334</td>
<td>-24.3</td>
<td>-22.3</td>
<td>6.3 kpc</td>
<td>0.95</td>
<td>GdV</td>
<td>-20.9</td>
</tr>
<tr>
<td>IRAS 04505–2958</td>
<td>RQ</td>
<td>0.286</td>
<td>-22.6</td>
<td>-22.0</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>IRAS 07598+6508</td>
<td>RQ</td>
<td>0.148</td>
<td>-21.9</td>
<td>-21.2</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>IRAS 13218+0552</td>
<td>RQ</td>
<td>0.201</td>
<td>-18.2</td>
<td>-19.9</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

Table 3. Derived results for the whole FOC IDT sample of quasars.

<table>
<thead>
<tr>
<th>Object</th>
<th>Type</th>
<th>redshift</th>
<th>$M_{\text{host}}(F702W)$</th>
<th>$M_{\text{quasar}}(F702W)$</th>
<th>$r$(kpc)</th>
<th>axial ratio</th>
<th>$\chi^2$</th>
<th>$M_{\text{host}}(V)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>3C 351</td>
<td>RL</td>
<td>0.371</td>
<td>-29.5</td>
<td>-28.3</td>
<td>4.1 kpc</td>
<td>0.85</td>
<td>GdV</td>
<td>-20.0</td>
</tr>
<tr>
<td>PKS 0312–77</td>
<td>RQ</td>
<td>0.371</td>
<td>-29.5</td>
<td>-28.3</td>
<td>4.1 kpc</td>
<td>0.85</td>
<td>GdV</td>
<td>-20.0</td>
</tr>
<tr>
<td>MS 07546+3928</td>
<td>RQ</td>
<td>0.096</td>
<td>-21.3</td>
<td>-20.9</td>
<td>4.1 kpc</td>
<td>0.90</td>
<td>Disc</td>
<td>-19.9</td>
</tr>
<tr>
<td>PG 1216+069</td>
<td>RQ</td>
<td>0.334</td>
<td>-24.3</td>
<td>-22.3</td>
<td>6.3 kpc</td>
<td>0.95</td>
<td>GdV</td>
<td>-20.9</td>
</tr>
<tr>
<td>IRAS 04505–2958</td>
<td>RQ</td>
<td>0.286</td>
<td>-22.6</td>
<td>-22.0</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>IRAS 07598+6508</td>
<td>RQ</td>
<td>0.148</td>
<td>-21.9</td>
<td>-21.2</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>IRAS 13218+0552</td>
<td>RQ</td>
<td>0.201</td>
<td>-18.2</td>
<td>-19.9</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

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interaction event had led to the turning on of the quasar. Further weight was added to this idea by the observations of six quasars (three by Boyce et al. 1996, and three by Bahcall et al. 1997) in ongoing gravitational interactions. Bahcall et al. described these objects as being ‘caught in the act.’ Five of these objects are radio-quiet quasars (0316–346, PG 1012+008, IRAS 13218+0552, 04505–2958 and 07598+6508) and one is radio-loud (PKS 2349–014).

In Table 4 we summarize the properties of the companion objects for each quasar in the FOC IDT sample (excluding the three IRAS quasars from Boyce et al. 1996). Column 1 lists the quasar name. Column 2 lists the number of apparent companions within 30 kpc. Column 3 lists the apparent separation in arcsec of the companions. Column 4 lists the projected separation in kpc of the companions. Column 5 lists the apparent F702W magnitude of each companion (the contribution of the host galaxy and nuclear source were subtracted from the companion by interpolating from each companion (the contribution of the host galaxy and nuclear continuum with \( M(F702W) \)). Column 6 lists the absolute F702W magnitude of the companions (assuming they lie at the distance of the quasar). If the companions do lie at the same distance as the quasars then they are all much fainter than \( L^* \). The companions of MS 07546+3928 and MS 22152–0347 must be very faint dwarfs.

We find three cases (PG 1358+04, PKS 0202–76 and PG 0043+039) in which there is no evidence of interaction and no close apparent companion detected. It should be noted that (apart from PKS 2128–123), these three objects have the highest redshifts in the sample. Simulations suggest that a companion fainter than \( M(F702W) = -16.0 \). The companions of MS 07546+3928 and MS 22152–0347 must be very faint dwarfs.

<table>
<thead>
<tr>
<th>Object</th>
<th>Companions</th>
<th>Separation (&quot;)</th>
<th>Separation (kpc)</th>
<th>( m_{\text{Comp}}(F702W) )</th>
<th>( M_{\text{Comp}}(F702W) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>PG 1358+04</td>
<td>0</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>PKS 0202–76</td>
<td>0</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>PG 0043+039</td>
<td>0</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>PHL 1093</td>
<td>1</td>
<td>1.3&quot;</td>
<td>6 kpc</td>
<td>21.1</td>
<td>–19.2</td>
</tr>
<tr>
<td>MS 22152–0347</td>
<td>1</td>
<td>1.6&quot;</td>
<td>8 kpc</td>
<td>23.7</td>
<td>–16.5</td>
</tr>
<tr>
<td>PKS 1302–102</td>
<td>2</td>
<td>1.1&quot;, 2.3&quot;</td>
<td>7, 15 kpc</td>
<td>21.3, 22.0</td>
<td>–19.3, –18.5</td>
</tr>
<tr>
<td>PKS 2128–123</td>
<td>1</td>
<td>1.9&quot;</td>
<td>25 kpc</td>
<td>23.9</td>
<td>–18.5</td>
</tr>
<tr>
<td>3C 351</td>
<td>1</td>
<td>3.3&quot;</td>
<td>28 kpc</td>
<td>23.9</td>
<td>–17.3</td>
</tr>
<tr>
<td>PKS 0312–77</td>
<td>1</td>
<td>4.7&quot;</td>
<td>23 kpc</td>
<td>20.8</td>
<td>–19.2</td>
</tr>
<tr>
<td>MS 07546+3928</td>
<td>1</td>
<td>9.5&quot;</td>
<td>19 kpc</td>
<td>21.8</td>
<td>–16.2</td>
</tr>
<tr>
<td>PG 1216+069</td>
<td>2</td>
<td>1.8&quot;, 2.7&quot;</td>
<td>13.6, 20.4 kpc</td>
<td>23.2, 23.0</td>
<td>–17.8, –18.0</td>
</tr>
</tbody>
</table>

4.4 Comparison with other HST quasar imaging

Bahcall et al. (1997) included 14 radio-quiet quasars in their sample of 20 bright quasars. They found seven to lie in elliptical hosts, three to lie in spiral hosts, two to be involved in complex systems of gravitational interaction and two that were too faint to be detected. In comparison, of our eight radio-quiet objects, three appear to be in elliptical hosts, two in disc galaxies and three in systems undergoing gravitational interaction. Our work has added a further three radio-quiet quasars with elliptical hosts to the seven detected by Bahcall et al. (1997). This further undermines the idea (prevalent before the advent of HST) that radio-quiet quasars lay exclusively in spiral galaxies.

Bahcall et al. found that five of the six radio-loud quasars in their sample lie in elliptical galaxies. The sixth (PKS 2349–014) lies in a complex interacting system. From the two samples, this is the only radio-loud object seen in current interaction. All six of the radio-loud objects in our sample appear to have elliptical hosts. The radio-loud elliptical hosts from the Bahcall et al. sample are systematically much brighter than would be expected if they followed a Schechter luminosity function. Our work further confirms the finding that radio-loud quasars appear to lie preferentially in luminous galaxies.

The average absolute magnitudes of the radio-quiet and radio-loud quasars from Bahcall’s sample (adapted to the cosmology adopted here) are

\[
M(V)_{\text{ROI}} = -20.0 \pm 0.6 \text{ mag}
\]

and

\[
M(V)_{\text{RL}} = -21.0 \pm 0.6 \text{ mag}.
\]

These compare reasonably with the values derived from our sample. A common feature of the two samples (Bahcall’s and ours) is that the hosts of the radio-loud quasars are systematically brighter than those of the radio-quiet quasars (by 1.0 mag in the Bahcall et al. sample and by 0.7 mag in our sample). In neither sample can this effect be explained by the radio-loud sample having higher redshifts.

Bahcall et al. (1997) found that 14 of the quasars in their sample of 20 had at least one close apparent companion [i.e. one closer than 33 kpc to the centre-of-light of the quasar and brighter than \( M(606W) = -15.8 \)]. Fisher et al. (1996) calculated that the probability of the observed counts (of close companions) being a Poisson realization of the background is extremely small \((P = 8 \times 10^{-9})\). We found eight of our sample of 14 quasars to have a close companion object within 30 kpc (but to a brighter absolute magnitude limit). Clearly the probability of the observed number of apparent companions in our sample being a chance realization of the background is similarly small.

Hooper, Impey & Foltz (1997) presented the results of PC imaging of a sample of quasars in the redshift range \( 0.4 < z < 0.5 \). They found host galaxy magnitudes similar to or brighter than \( L^* \), consistent with the results of Bahcall et al. and our work. However, they found no difference in host galaxy luminosity.
between radio-loud and radio-quiet quasars, assuming that they are all of the same galaxy type. If we had made this assumption with our data (i.e. assume that PG 0043+039 and MS 07546+3928 are ellipticals) then we derive an average $M(V)_{RQ} = -20.8 \pm 0.5$ mag, 0.3 mag less than that of the radio-loud objects. Hooper et al. also found many host galaxies with small axial ratios ($<0.5$). They suggested that these may indicate inclined disc systems or, alternatively, that the elongated appearance may be as a result of bars or other distinctive morphological features which are visible while the bulk of the underlying lower surface brightness features are not. We found no objects with an axial ratio $<0.65$.

5 CONCLUSIONS

Taken together our observations and those of Bahcall et al. are in broad agreement. They illustrate the ability of HST to study the host galaxies of quasars and their environs with vastly improved resolution compared to previous work. However, the results have not, as yet, led to a single coherent pattern of quasar behaviour. This may emerge later as larger number of quasars are observed. The results have revealed a strong tendency for radio-loud quasars to reside in luminous elliptical galaxies whereas radio-quiet quasars are found to lie in either elliptical or spiral hosts. The host galaxy luminosities are systematically much brighter than if they followed a Schechter luminosity function. Six examples have been found where the quasar lies in the middle of a strong ongoing gravitational interaction between two or more galaxies. In 19 other cases close companion objects are detected suggesting a recent gravitational interaction. However, there are eight cases where no such circumstantial evidence for an interaction or merger can be found although the detection limits are such that companions as bright as those detected around some of the nearer objects would not be seen in these cases. In common with Bahcall et al., we can find no evidence in our data for the quasar affecting the host galaxy in which it lies. Some pre-HST theoretical analysis (e.g. Falle, Perry & Dyson 1981; Weymann et al. 1982; Begelman 1985) had suggested that the nuclear sources may have dramatic effects on their environments via the radiation or hot winds that the quasar emits.

A further result from our work is that the WFPC images reveal far more morphological information for the host galaxies of the lower redshift quasars. For example, although the images of the three objects with the highest redshifts (PG 1358+04, PKS 0202–76 and PKS 2128–123) reveal residual light following subtraction of the quasar light, no morphological information can be derived (other than a determination of whether the luminosity profile is best fitted by an $r^{1/4}$ law or an exponential profile). A comparison with the images of the four lowest redshift objects in our sample (MS 07546+3928, IRAS 07598+6508, IRAS 13218+0552 and PKS 0312-77) shows clearly that the quality of the morphological information that can be derived from WFPC imaging of quasars falls dramatically beyond $z = 0.3$. A comparison of our results and those of Bahcall and his co-workers with those of Hooper et al. (1997) (whose sample was in the redshift range $0.4 \leq z \leq 0.5$) further emphasizes this point. Although Hooper et al.’s images show residual galaxy light, few morphological features can be seen and it
is not possible to determine whether the galaxy luminosity profile is best fitted by an \( r^{1/4} \) law or an exponential profile.

We suggest that future HST imaging studies of quasar host galaxies would achieve the best scientific return by concentrating initially on low-redshift objects. In Fig. 3 we plot the distribution in the redshift/absolute magnitude plane of the lower redshift (\( z \leq 1 \)) quasars in the Veron-Cetty & Veron catalogue (1996). We have highlighted a small group of quasars that lie much closer to us than their co-peers with the same absolute luminosity and, therefore, the same or similar physics. We label this group of objects the ‘Neighbourhood Sample’. This ‘Neighbourhood Sample’ contains examples of all the main ‘types’ of quasar: 11 are radio-loud, four are radio-quiet, one is a luminous IRAS source and one is a 4U X-ray identification. Because it contains the closest quasars at each absolute luminosity, it offers the best hope of studying QSO hosts of a particular \( M_{\text{abs}} \) with the highest physical resolution.

We may expect further improvements in the quality of quasar data from the NICMOS camera (Axon et al. 1996) with its coronographic facility and its ability to perform non-destructive read-outs at very short time intervals. This latter feature is vital for studying the bright inner regions close to the nucleus where existing WFPC-2 data suffer from saturation. It will enable much better subtraction of the light from the nuclear source.

ACKNOWLEDGMENTS

This paper is based on observations made with the NASA/ESA Hubble Space Telescope, obtained at the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS 5-26555. PJB acknowledges financial support from PPARC.

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