HUBBLE SPACE TELESCOPE IMAGING OF THE HOST GALAXIES OF THREE X-RAY-SELECTED BL LACERTAE OBJECTS

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Received 1997 May 22; accepted 1997 July 23

ABSTRACT

Hubble Space Telescope (HST) WFPC-2 I-band (F814W) images of three X-ray-selected BL Lacertae objects (MS 1221.8 + 2452, MS 1407.9 + 5954, and MS 2143.4 + 0704) reveal that each of these BL Lac objects is well centered in an extended nebula that is consistent in brightness and morphology with light from an elliptical galaxy at their previously reported redshifts. Each of the detected host galaxies have radial surface-brightness profiles that are well fitted by a de Vaucouleurs law with effective radii of between 3 and 12 kpc (H_0 = 50 km s^{-1} Mpc^{-1}, q_0 = 0). The absolute magnitudes of the host galaxies fall in the range of luminosities determined for other BL Lacertae object host galaxies, -24.7 < M_I < -23.5. In addition to allowing the measurement of the host galaxy magnitudes and radial surface brightness profiles, the HST images allow a search for substructure in the host galaxies and for the presence of close companion galaxies at spatial resolutions not yet achievable from the ground. While no evidence was found for any "bars" or spiral arms, "boxy" isophotes are present in the host galaxy of at least one of the three objects observed as part of this study (MS 2143.4 + 0704). The apparent magnitudes and image properties of the companions of the BL Lac objects are cataloged as part of this work. The three BL Lac objects appear to occur in diverse environments, from relative isolation (MS 1221.8 + 2452) to, possibly, a rich group of galaxies (MS 1407.9 + 5954).

Subject headings: BL Lacertae objects: individual (MS 1221.8 + 2452, MS 1407.9 + 5954, MS 2143.4 + 0704) — galaxies: active — galaxies: photometry

1. INTRODUCTION

The spectral energy distributions of cataloged BL Lacertae objects are dominated from radio to ultraviolet wavelengths by the variable and polarized emission of compact synchrotron sources (see, e.g., Impey & Neugebauer 1988; Wagner & Witzel 1995). The synchrotron emission is believed to be generated in "jets" of relativistic material viewed nearly along the jet axes (Blandford & Rees 1978). The Doppler boosting of the emission to large apparent luminosities results in very bright point sources at optical and IR wavelengths and greatly complicates efforts to observe the nearby environments of BL Lac objects.

Observations of the surrounding nebulosities (or host galaxies) and companions of BL Lacertae objects are of particular interest because they provide direct tests of proposed schemes to unify BL Lac objects and other classes of active galactic nuclei (AGNs) or radio galaxies (e.g., Farnaroff-Riley I radio galaxies; Urry & Padovani 1995) and allow the investigation of the role of the nearby environment in generating and maintaining the observed properties of BL Lacertae objects. Despite the difficulties caused by the bright point sources of BL Lac objects, studies of the host galaxies of BL Lac objects have been successfully undertaken from the ground for over 20 years (Oke & Gunn 1974; Thuan, Oke, & Gunn 1975; Ulrich et al. 1975; Miller, French, & Hawley 1978; and many others including Ulrich 1989; Abraham, Crawford, & McHardy 1991; Pesce, Falomo, & Treves 1994, 1995; Wurtz, Stocke, & Yee 1996, hereafter WSY; Wurtz et al. 1997; Falomo 1996, and references therein). While we will review some of these past results in § 3.2, the main result of the past work can be generalized as follows: whenever the host galaxies of BL Lac objects have been well observed, they have proven to be elliptical galaxies.

Despite the impressive past results, the majority of well-observed host galaxies are at low redshift (z < 0.6) or are hosts of BL Lac objects that do not have large ratios of observed nuclear brightness to surrounding nebulosity. Studies of BL Lac objects using the high spatial resolution obtainable with the Hubble Space Telescope (HST) have been made, now allowing measurement of the properties of each host galaxy closer to the nucleus (a factor of 2 to 10 times closer than ground-based imaging, depending on the quality of the ground-based imaging) and detection of close companions (Falomo et al. 1997; Yanny, Jannuzi, & Impey 1997).

Unfortunately, the number of BL Lac objects that have been well imaged with HST is small and much lower than the significant number of luminous quasars that have been observed (see, e.g., Disney et al. 1995; McLeod & Rieke 1995; Bahcall et al. 1997, and references therein; Hooper, Impey, & Foltz 1997). Efforts to obtain a significant sample

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1 Based on observations 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 NAS5-26555.
of HST-imaged BL Lac objects are in progress by two groups of researchers, a team led by C. M. Urry and our team. We coordinated target selection and filter and detector choices in an attempt to provide, in the end, as large and homogeneous a data set as possible. The planetary camera of the WFPC-2 was chosen as the instrument to use because of its large dynamic range and pixel scale. The F814W filter is used in these BL Lac host observations to allow comparison with ground-based I-band Kron-Cousins (IKC) fluxes and to maximize the contrast of the host galaxy (expected to be red in color) over the nonthermal point source.

First results from the Urry team on the imaging of three radio-selected BL Lac objects are presented by Falomo et al. (1997). Two of these objects were found to be in luminous elliptical hosts, while no underlying host was detected for the third. We have previously reported results of our imaging of the radio-selected BL Lac object OJ 287 (Yanny et al. 1997), which might have an offcenter host galaxy or a bright model field star to show the PSF. All three of the BL Lac objects used for the host galaxy and host + PSF subtraction were simply averaged together, weighted by exposure time and with cosmic-ray rejection (Yanny et al. 1994).

For each of the three BL Lac object images, a background sky level was subtracted from each image and elliptical isophotes were fitted to the combined image of each object using the ellipse-fitting routines of IRAF/STSDAS. This allowed us to determine that the unresolved point-source components of each BL Lac object are extremely well centered in the surrounding nebulosity. Comparison of image centroids of the residual light in the point-source function subtracted images shows that the limits on offsets between the total light (point source plus nebulosity) and the underlying nebulosities alone are Δr < 0.01 for MS 1221.8 + 2452, Δr < 0.03 for MS 1407.9 + 5954, and Δr < 0.01 for MS 2143.4 + 0704. These results are consistent with the BL Lac objects being perfectly centered in each of these cases.

We constructed azimuthally averaged semimajor axis radial profiles for each object and these are shown in Figure 1. To aid comparison of the profiles in Figure 1, we have normalized the central intensity of the unsaturated point sources at a radius of zero. There is abundant excess extended light for each of the BL Lac objects when compared to the reference point-spread function (PSF) profile seen in Figure 1. The radii to which the radial profiles are plotted in Figure 1 were determined by the point where the signal in the averaged surface brightness becomes comparable with instrumental read noise in the PC detector.

In Figures 2, 3, and 4 (Plates 3, 4, and 5), we show for each of the BL Lac objects the combined WFPC-2 image. In each figure, the target object is in the approximate center. Objects with measured fluxes are labeled, and the aperture magnitudes and extents (resolved or point source) are listed in Tables 1, 2, and 3. A large aperture of 150 pixels (6′′9) is used for the host galaxy and host + PSF measurements.

2. OBSERVATIONS

2.1. Sample Definition

We selected the three objects discussed in this paper for observation with HST because they are all X-ray-selected BL Lac objects in the complete flux-limited Einstein Extended Medium Sensitivity Survey (EMSS) sample of BL Lac objects (Morris et al. 1991). While not evident from the study of individual objects, some differences in the typical properties of BL Lac objects selected at different wavelength bands (e.g., X-ray and radio) have been noted, particularly in the degree of variability in the total and polarized optical flux and the polarization position angle (for examples of further discussion, see Stocke et al. 1985; WSY; Jannuzi 1990; and Jannuzi, Smith, & Elston 1993, 1994). Ultimately, if a larger database of observations can be compiled, we hope to be able to compare the more isotropic properties of various BL Lac object subsamples (host galaxy properties, group and cluster environments, etc.). Some such comparisons have been made by WSY from their Canada-France-Hawaii Telescope (CFHT) imaging survey of 50 objects. Finding charts and coordinates for the three fields whose images are presented in this paper can be found in Smith, Jannuzi, & Elston (1991).

2.2. WFPC-2 Imaging

Our observations consisted of multiple long and short exposures with the WFPC-2 on the HST using the F814W filter. For references on the WFPC-2 instrument, see, e.g., Holtzman et al. (1995). For MS 1221.8 + 2452, three 500 s and two 200 s exposures were obtained on 1996 January 13 UT. For MS 1407.9 + 5954, four 900 s and three 160 s exposures were taken on 1995 October 22 UT, and for MS 2143.4 + 0704, two 1100 s and five 350 s exposures were recorded on 1995 September 8 UT. The short exposures were designed to ensure that at least some images of each BL Lac object were obtained without saturated cores. In practice, none of the three variable BL Lac nuclei were bright enough when imaged to saturate the detector during even the longest exposures we obtained. Therefore all exposures of an object were simply averaged together, weighted by exposure time and with cosmic-ray rejection (Yanny et al. 1994).

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quoted in the tables. Apertures with smaller radii of 6–20 pixels were used for measuring fainter objects in the field. The fields were well flattened, and although a small change in the DC sky level affects the integrated surface brightness and derived scale radius significantly, the aperture magnitudes are stable to much better than 0.1 mag over a large range of aperture radii.

Instrumental F814W magnitudes were converted to the Kron–Cousins I passband using the formulas of Whitmore (1996; and B. Whitmore 1996, private communication). No reddening correction was applied. Uncertainties for the separate measurements of the host galaxies and the point-source brightnesses are approximately 0.1 mag owing to systematics in the PSF subtraction. The uncertainty in the measurement of the combined host + PSF brightness of each object is much smaller. The 5σ limit on detection for faint point-source objects is approximately $I = 24.5$ in each of the three fields. As in Figure 1, it is clear in these images that the unresolved point-source components of each BL Lac object are surrounded by resolved nebulosities.

### TABLE 1

| Object ID          | Δ R.A. (arcsec) | Δ Decl. (arcsec) | $I_K$ (mag) | FWHM (arcsec) |
|--------------------|-----------------|------------------|-------------|---------------|
| MS 1221.8 + 2452   | 0.00            | 0.00             | 16.94       | ext           |
| Host               | 0.00            | 0.00             | 17.41       | 0.68          |
| Point Source       | 0.00            | 0.00             | 18.06       | 0.14          |
| A                  | −8.12           | −12.41           | 21.24       | 0.14          |
| B                  | −10.52          | 9.10             | 21.41       | 0.14          |
| C                  | 13.60           | −2.54            | 22.27       | ext           |

- The label “ext” indicates the object is significantly extended, while “pt” indicates a point source.
- For the host galaxy (Host), FWHM is replaced by the elliptical scale radius $r_e$.

### TABLE 2

| Object ID          | Δ R.A. (arcsec) | Δ Decl. (arcsec) | $I_K$ (mag) | FWHM (arcsec) |
|--------------------|-----------------|------------------|-------------|---------------|
| MS 1407.9 + 5954   | 0.00            | −0.01            | 17.96       | ext           |
| Host               | −0.00           | 0.16             | 18.93       | pt            |
| Point Source       | 0.29            | −0.02            | 18.60       | 0.11          |
| A                  | −8.30           | −9.02            | 17.81       | ext           |
| B                  | −7.40           | −5.74            | 20.68       | 0.11          |
| C                  | 0.18            | −11.15           | 20.99       | 0.09          |
| D                  | 10.58           | −10.98           | 18.60       | 0.11          |
| E                  | 5.22            | 2.91             | 21.18       | 0.12          |
| F                  | −12.78          | 0.99             | 21.69       | 0.17          |
| G                  | 11.21           | −7.83            | 21.51       | 0.09          |
| H                  | −14.19          | 6.31             | 22.69       | 0.11          |
| J                  | −20.91          | −3.37            | 22.13       | 0.1           |
| K                  | −22.39          | 0.84             | 21.47       | ext           |
| L                  | 8.45            | 9.52             | 22.78       | 0.27          |
| M                  | 9.91            | 6.93             | 23.69       | 0.11          |
| N                  | 16.00           | 1.78             | 23.35       | 0.15          |
| O                  | 2.95            | −16.39           | 23.52       | 0.09          |
| P                  | −6.93           | −1.94            | 24.30       | 0.09          |
| Q                  | 3.21            | −5.32            | 24.39       | 0.34          |
| R                  | −5.16           | 2.65             | 24.91       | ext           |
| S                  | −10.46          | 4.60             | 23.85       | 0.17          |
| T                  | 3.02            | 5.33             | 24.70       | 0.13          |
|                   | 5.44            | −13.39           | 24.99       | ext           |

- The label “ext” indicates the object is significantly extended, while “pt” indicates a point source.
- For the host galaxy (Host), FWHM is replaced by the elliptical scale radius $r_e$.

### TABLE 3

| Object ID          | Δ R.A. (arcsec) | Δ Decl. (arcsec) | $I_K$ (mag) | FWHM (arcsec) |
|--------------------|-----------------|------------------|-------------|---------------|
| MS 2143.4 + 0704   | 0.00            | −0.00            | 16.88       | ext           |
| Host               | 0.00            | −0.01            | 17.13       | 1.79          |
| Point Source       | 0.00            | −0.01            | 18.58       | pt            |
| A                  | −6.79           | −9.87            | 18.88       | 0.02          |
| B                  | −15.87          | −3.29            | 20.10       | 0.02          |
| C                  | −15.92          | 9.48             | 22.09       | ext           |
| D                  | −1.31           | 0.99             | 23.60       | 0.18          |
| E                  | −2.38           | 6.34             | 23.14       | 0.09          |
| F                  | −3.97           | 1.64             | 23.37       | 0.03          |
| G                  | −12.95          | 13.56            | 23.33       | 0.09          |
| H                  | −13.67          | 9.21             | 24.19       | 0.05          |
| I                  | −5.28           | 14.66            | 23.71       | ext           |
| J                  | 1.35            | 6.17             | 24.57       | pt            |
| K                  | −0.62           | 3.28             | 25.63       | ext           |
| L                  | −0.47           | −2.56            | 24.97       | ext           |
| M                  | −18.75          | 13.62            | 24.48       | ext           |
| N                  | 4.72            | −11.56           | 23.65       | ext           |
| O                  | 2.40            | −7.75            | 24.87       | ext           |

- The label “ext” indicates the object is significantly extended, while “pt” indicates a point source.
- For the host galaxy (Host), FWHM is replaced by the elliptical scale radius $r_e$.

An appropriately scaled model of the WFPC-2 instrumental PSF was subtracted from each BL Lac + underlying host (Yanny et al. 1997). Determining the appropriate scaling for the PSF is difficult for these well-centered objects, and there remains some uncertainty in the subtraction. Our normalizations were obtained by examining both the one-dimensional radial profiles and the two-dimensional residuals for a variety of PSF scalings. Figures 5, 6, and 7 show averaged semimajor axis plots of the profiles of the PSF + host galaxy, the host galaxy alone, and the scaled PSF alone for the three objects we studied for this

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**FIG. 5.** — Elliptical isophote fits to the image of MS 1221.8 + 2452. The solid line shows the radial profile (elliptical semimajor axis) of the sky-subtracted data. The dashed line is an HST stellar point-spread function scaled to match the point-source component of the BL Lac object image. The asterisks mark the underlying host galaxy light once the scaled point source has been centered and subtracted from the image. The filled circles represent the best least-chi-squared fit for a de Vaucouleurs profile to the host galaxy light for radii between 0.15 and 1.5. The open circles represent the best-fit exponential disk profile to the host galaxy light. The small error ticks at 1.6 and 2.1 show read noise-induced errors in the surface brightness measurements.
paper. Note that in each case, a de Vaucouleurs profile is a much better fit at small radii than an exponential disk (which would be expected if the host objects were spiral galaxies), and the extent to which a de Vaucouleurs profile is a better fit highlights the effectiveness of the resolving power of HST over ground-based observations. We use this evidence in §3 as part of the support for identifying all three host galaxies as elliptical galaxies.

As a check on the accuracy of the model PSF (Krist 1996; J. Krist 1996, private communication) that we used for subtracting the contribution of the unresolved point source to the image of each BL Lac object, several stellar objects in the field were also fit and subtracted. We note that their radial profiles agree well with that of the model PSF out to the radius at which their signal to noise ratio becomes low. To demonstrate the extent to which the host galaxy (the underlying nebulosity) is present in all three cases, we present in Figure 8 (Plate 6) an image of a field star in the MS 1407.9 + 5954 field from which a model PSF has been subtracted. The BL Lac object in Figure 8 has also had a scaled PSF subtracted from its image. The residual only contains the underlying nebulosity and should be compared to the image in Figure 3. The inset in Figure 8 shows MS 1221.8 + 2452 after a PSF of twice the correctly scaled PSF has been subtracted in order to show that a misscaled PSF subtraction when extended light is present does not remove light far from the core. The residual ring is clear evidence for an underlying host. No stellar object, such as star D in Figure 8, shows a similar residual.

In Figure 9 we show contour maps, each $4.6 \times 4.6$, centered on the three BL Lac objects with the same orientations as shown in Figures 2-4. The upper panels show the BL Lac + host galaxies before subtraction of the scaled PSF, and the lower panels show the residual underlying hosts after scaled PSFs have been subtracted. The contours are geometrically spaced by factors of two in flux density, except for the outer three contours, which are linearly spaced in flux density. We note that the contours for MS 2143.4 + 0704 appear boxy, further supporting its interpretation as a large elliptical host.

### 2.3. Notes on Individual Objects

In this section we present additional details about our measurements of the host galaxies of MS 1221.8 + 2452, MS 1407.9 + 5954, and MS 2143.4 + 0704 and compare our measured host galaxy properties to some of the existing observations of each object. We also make additional notes specific to the individual object fields. Observed quantities for field objects are listed in Tables 1-3. Physical properties of the host galaxies were calculated assuming $H_0 = 50$ km s$^{-1}$ Mpc$^{-1}$ and $q_0 = 0$ and are summarized in Table 4.

MS 1221.8 + 2452 ($z = 0.218$) has a circular (ellipticity $1 - b/a = 0.03 \pm 0.03$) host galaxy that is well fitted by a de Vaucouleurs profile with a scale length of 0.68 (3.2 kpc) and $I_{KC} = 17.41$. We measure $I_{KC}$ surface brightness (SB) at one scale length of $\mu = 20.0$ mag arcsec$^{-2}$. For the unresolved point-source component of the BL Lac object we measured $I_{KC} = 18.06$. This object was successfully resolved by WSY during their CFHT imaging survey of BL Lac objects. They observed MS 1221.8 + 2452 to contain a point source with Gunn $r > 21.2$. They determined the host galaxy had a brightness in the Gunn $r$ passband of $r = 18.65$ with a surface brightness at one scale length of Gunn $r \mu = 20.82$ mag arcsec$^{-2}$. WSY measured a scale length of 0.6 (2.6 kpc).

MS 1407.9 + 5954 ($z = 0.495$) was previously reported by WSY to have an elliptical host galaxy containing a point-source BL Lac object. We measure a host with an ellipticity of $1 - b/a = 0.16 \pm 0.03$ at P.A. 17°, a de Vaucouleurs scale length of 1.52 (12.2 kpc), and $I_{KC} = 18.53$. The SB(I) at one $r_e$ is $\mu = 22.3$ mag arcsec$^{-2}$. For the BL Lac object itself, we measure $I_{KC} = 18.93$. WSY determined a host galaxy brightness in the Gunn $r$ passband of $r = 19.37$, with a surface brightness at 1 scale length of Gunn $r \mu = 23.4$ mag arcsec$^{-2}$ and a scale length of 1.4 (10 kpc). At the time WSY observed it, the central point source had Gunn $r > 20.1$.

MS 2143.4 + 0704 ($z = 0.237$) has a host galaxy with an ellipticity $1 - b/a = 0.20 \pm 0.02$ at P.A. 64°, a de Vaucouleurs scale length of 1.79 (9.0 kpc) and $I_{KC} = 17.13$. The SB(I) at $r_e$ is $\mu = 21.3$ mag arcsec$^{-2}$. For the point source, we measure $I_{KC} = 18.58$. Object L near the BL Lac object is very elongated and is a candidate for a lensed arc. This BL Lac object also has close companions D, F, and K within a few arcsec. WSY quote Gunn $r = 17.89$ for the large host object, with an SB of $\mu = 22.95$ at one scale radius of 2.4 (12 kpc). The point source had a brightness of Gunn $r = 22.2$ (WSY).

Given the different passbands and the variability of the BL Lac objects, our measurements for the brightnesses and

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**Fig. 6.**—Same as Fig. 5, but for MS 1407.9 + 5954

**Fig. 7.**—Same as Fig. 5, but for MS 2143.4 + 0704
scale lengths of the host objects agree well with ground-based measurements. Our uncertainties for the brightnesses of the host galaxies are estimated to be 0.1 mag (10%), dominated by systematics in the subtraction of the point sources. To derive quantitative surface brightnesses and effective radius ($r_e$) measurements, elliptical isophotes were fitted to the image of each host galaxy; our tabulated results correspond to the values along the semimajor axis. Any deviation from a de Vaucouleurs profile in the underlying host galaxy (such as the boxy isophotes seen in MS 2143.4 + 0704) will result in a magnitude reconstructed from the surface brightness and scale radius that systematically differs from the fixed-aperture magnitude measured for that object. Estimated uncertainties on these quantities are 0.2 mag on the surface brightnesses and 10% on the scale radii.

The WFPC-2 on HST provides some of the most accurate measurements to date of the nebulosity surrounding BL Lac sources because of the high dynamic range and

| Name       | $I$ (mag) | Redshift | K-Correction | $m - M$ (mag) | $M_I^a$ (mag) | $M_K^a$ (mag) | $M_R^a$ (mag) | $r_e^2$ (kpc) |
|------------|-----------|----------|--------------|---------------|--------------|--------------|--------------|--------------|
| 1823 + 568 | 18.3      | 0.664    | 0.54         | 43.72         | -26.0        | -25.3        | -24.7        | 6.5          |
| 2254 + 074 | 15.9      | 0.19     | 0.11         | 40.49         | -24.7        | -24.0        | -23.4        | 15.0         |
| MS 1221.8 + 2452 | 17.41 | 0.218    | 0.13         | 40.81         | -23.5        | -22.8        | -22.2        | 3.2          |
| MS 1407.9 + 5954 | 18.53 | 0.495    | 0.37         | 42.84         | -24.7        | -24.0        | -23.4        | 12.2         |
| MS 2143.4 + 0704 | 17.13 | 0.237    | 0.14         | 41.01         | -24.0        | -23.3        | -22.7        | 9.0          |
| OJ 287     | 18.3      | 0.306    | 0.19         | 41.65         | -23.5        | -22.8        | -22.2        | ...          |

$^a$ $H_0 = 50$ km s$^{-1}$ Mpc$^{-1}$ and $q_0 = 0$, $M_I = I - (m - M) - K$-correction.
$^b$ $V-I = 1.3$ and $V-R = 0.6$ are assumed, as in Falomo et al. 1997.
$^c$ Radio-selected BL Lac host data from Falomo et al. 1997.
$^d$ OJ 287 BL Lac host data from Yanny et al. 1997.
spatial resolution provided in PC images. These properties allow the separation of PSFs from extended light at radii as small as \( \sim 0.2 \).

3. DISCUSSION

3.1. Host Galaxies Are Luminous Elliptical Galaxies

Our HST WFPC-2 observations of three X-ray-selected BL Lac objects confirm previous observations of these objects (see, e.g., WSY) that indicated that these BL Lac objects are located in luminous elliptical host galaxies. The evidence supporting this conclusion includes the following:

1. The unresolved point-source component of each BL Lac object is extremely well centered in the surrounding nebula or host galaxy light (see § 2.2), consistent with the point source being physically associated with or "in" the nebula rather than being a background source lensed by a foreground galaxy. In this latter scenario, some decentering would be expected (see WSY for discussion and references therein).

2. The available morphological evidence for each of the host galaxies strongly supports the classification of these objects as elliptical galaxies. Both the one-dimensional (de Vaucouleurs profile fitting) and two-dimensional appearances of the host galaxies (see Figs. 2–4 and 9) are more consistent with elliptical galaxies than spirals. The least-squares fits to the residual light after subtraction of scaled point sources show much better fits by de Vaucouleurs profiles than by exponential disk profiles (see Figs. 5–7). The evidence is for boxy isophotes in one of the host galaxies, a characteristic shared by many elliptical galaxies, while there are no signs in any of the host galaxies of "bars," spiral arms, or other substructures that might be expected in a spiral host galaxy. The observed ellipticities and scale radii are also consistent with the properties of elliptical galaxies.

3. The detected host galaxies are luminous. In Table 4 we list the observed and derived absolute magnitudes for the three X-ray–selected BL Lac objects in this paper as well as the two radio-selected BL Lac objects imaged with HST by Falomo et al. (1997) and the radio and X-ray–selected BL Lac object OJ 287 imaged by Yanny et al. (1997). A K-correction has been applied to each absolute magnitude based on the cataloged redshift of the BL Lac object; our assumed cosmology, and the typical rest-frame colors of ellipticals assumed by Falomo et al. (1997) when they made similar calculations to derive the absolute magnitudes of their detected host galaxies (\( V - I = 1.3, B - V = 0.96, \) and \( V - R = 0.61 \)). No correction for the effects of spectral evolution have been made (as was done by WSY). If we were to include the effects of evolution in order to derive what the absolute magnitudes of these host galaxies would be if they were evolved to the current epoch, then this might result in a change of from 0.2 mag (for objects at \( z \approx 0.2 \)) to 0.6 mag (for objects at \( z \approx 0.5 \)) in the absolute magnitudes of the objects (see Poggianti 1997 for examples of the size of the evolutionary corrections required for a given observed band and assumed intrinsic spectral energy distribution). While assuming normal elliptical colors for these host galaxies is probably not unreasonable, we have only obtained F814W passband images with HST. By comparison with the ground-based measurements of WSY, we find that the \( r - I_{BC} \) colors of the three objects are 1.2, 0.8, and 0.8 mag respectively. The derived host-galaxy absolute magnitudes (i.e., \( -23.4 < M_V < -22.2 \)) are within the range of observed luminosities of the brightest cluster galaxies (BCGs), although perhaps not as bright as the brightest of the BCGs (the more luminous BCGs have \( M_V \approx -23.6 \); Hoessel & Schneider 1985; Postman \\& Lauer 1995; for distribution of BCG luminosities, see WSY; Hoessel, Gunn, \\& Thuan 1980). If spectral evolution is significant, as seems likely, then since the comparison sample of BCGs are typically at redshifts of 0.15, a significant evolution correction would only have to be applied to the results for MS 1407.9 + 5954. Before comparing the absolute magnitude of this object’s host galaxy to the distribution of BCGs absolute magnitudes, we should make fainter the absolute magnitude of MS 1407.9 + 5954 by 0.4 to 0.6 mag. As a result, MS 1407.9 + 5954 would be fainter than the brightest BCGs, but it would still be quite a luminous elliptical.

3.2. Comparison with Other AGN Host Galaxies

One of the main goals of studying the properties of the host galaxies of BL Lac objects is to allow a comparison between the observed properties of the hosts of BL Lac objects and the host galaxies of other AGNs and candidate parent populations (i.e., comparison with the observed properties of the host galaxies and environments of Farnarof-Riley I and II radio galaxies; see, e.g., Zirbel 1995a, 1996b, 1997). The largest optical survey of BL Lac host galaxy properties, ground- or space-based, is the survey of made by WSY. They imaged 50 BL Lac objects with the CFHT and resolved a host galaxy in over 90% of the objects. Based on radial profile fits to their images, they classified at least 70% (possibly as high as 90%) of the detected host galaxies as ellipticals, with no more than 12% showing exponential disk- or spiral-type hosts.

Despite our small sample size and the resulting inability to draw new conclusions for the entire class of BL Lac objects, we can place the objects we observed in context by comparing the absolute magnitudes of the hosts of the objects we observed to other well-known BL Lac or quasar host galaxies. For example, when our XSBLs are compared to a sample of radio-selected BL Lac objects (RSBLs) studied by Falomo et al. (1997) at comparable redshift, the XBL host galaxies are found to be about 1 mag fainter than those of BL Lac objects selected by their radio emission, although they are still quite luminous.

We can also compare our BL Lac host galaxies to those observed in the larger sample of luminous low-redshift quasars that have been observed with the WFPC-2, as the nuclear luminosity-generating mechanisms may (or may not) be similar. Bahcall et al. (1997) have surveyed the hosts of 20 quasi-stellar objects (QSOs) with HST resolution at redshifts ~0.2. The host galaxies of radio-quiet QSOs are ellipticals in more than 60% of the cases and have \( M_V = -22.2 \pm 0.6 \) on average, about the same magnitude as those seen here for XBL hosts at \( z = 0.2 \) (see Table 4).

3.3. Companion Objects

The field of the WFPC-2 PC CCD is 36” × 36”. At redshift \( z = 0.2 \), the radius of the field corresponds to \( r < 90 \) kpc. All objects within this radius of the three BL Lac objects that are the focus of this paper were noted in the figures and in Tables 1, 2, and 3. Since the redshifts of these objects are not known, one cannot tell for certain which objects are true companions to the BL Lac objects; however, objects within a projected distance of a few arcsec of the BL Lac objects and brighter than about \( I < 24 \) are likely to be physically associated with them. We note that,
based on the Hubble Deep Field galaxy counts (Williams et al. 1996), the number of galaxies expected with \( I_{614} < 23.5 \) in a circular patch of radius 17" is \( \approx 4 \).

The field of MS 1221.8+2452 has only three objects in the field other than the BL Lac + host, and none are within 10". This appears to be an isolated BL Lac object.

In contrast, the field of MS 1407.9+5954 is relatively rich, with 20 objects in the field, all but two of them non-stellar. MS 1407.9+5954 may be in a relatively rich group or cluster (see also Wurtz et al. 1993).

The field of MS 2143.4+0704 is intermediate between the other two in the number of objects in the field, with 12 nonstellar objects. It has, however, several very close neighbors that are likely to be physically associated with it. Objects D and F are especially likely to be associated with the BL Lac object. Object L is of interest because its elongation and alignment are reminiscent of gravitationally lensed objects seen in the field of massive clusters. A redshift of object L and further analysis are needed. We note that HST has provided images of similarly elongated objects that have proven to be spiral galaxies.

Our three randomly selected XSBLs show differing field environments. This demonstrates clearly, if not unexpectedly, that a sample of three objects is not large enough to draw any conclusions about the role that environment may play in BL Lac phenomena. The richness of the environments of larger samples of BL Lac objects has been quantitatively studied using ground-based imaging data (see, e.g., Wurtz et al. 1997, including data on the three objects studied in this paper), but such studies still lack spectroscopic confirmation of the association of the BL Lac objects with the apparent companion objects. Spectroscopic follow-up would be valuable not only to confirm group membership but also to determine velocity dispersions for the groups.

4. SUMMARY

We have presented HST WFPC-2 I-band (F814W) images of three X-ray-selected BL Lac objects, measured the properties of the BL Lac host galaxies, and cataloged the companion objects in the fields of these BL Lac objects. From these data we have determined the following:

1. The host galaxies of the X-ray-selected BL Lac objects MS 1221.8+2452, MS 1407.9+5954, and MS 2143.4+0704 are luminous elliptical galaxies with absolute luminosities in the range \(-24.7 < M_r < -23.5\). These host galaxies appear typical of the BL Lac host galaxies that have been previously observed.

2. The three XSBLs observed in our program have a wide range in apparent numbers of companion objects, but without spectra or color information to allow a more accurate determination of which objects are true companions of each BL Lac object, we are not able to investigate further whether or not the larger scale environments of these three objects are disparate or are we able to compare their environments to those of BL Lac objects studied by others (see, e.g., Wurtz et al. 1997).

3. The BL Lac hosts near \( z = 0.2 \) have absolute magnitudes comparable to those of radio-quiet QSO hosts seen by Bahcall et al. (1997). There is a suggestion that XSBL host galaxies might be fainter than RSBL hosts, but this needs to be tested with high-quality imaging of larger and more well-defined samples.

The small sample of six objects that have been well imaged by HST (the objects discussed in this paper; the two objects with detected host galaxies in Falomo et al. 1997; and OJ 287, in Yanny 1997) is not large enough to draw strong conclusions about all BL Lac objects or about differences in subgroups. Fortunately, additional objects are being imaged and the total sample size will certainly grow. HST imaging offers the potential of undertaking studies of higher redshift objects that can be integrated into the larger data sets of images of low-redshift BL Lac objects.

We acknowledge useful discussions with A. Dey, R. Falomo, T. Lauer, S. Kent, R. Scarpa, and J. Stocke. We acknowledge support from NASA grant GO-5992.02-94A. B. Y. acknowledges support from the Fermi National Accelerator Laboratory. B. T. J. acknowledges support from the National Optical Astronomy Observatories, operated by the Associated Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

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Fig. 2.—Image obtained with the WFPC-2 of the MS 1221.8+2452 field. The BL Lac object and its host are in the center of the image. No subtraction has been performed. Measurements for labeled objects are listed in Table 1.

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Fig. 3.—Image obtained with the WFPC-2 of the MS 1407.9 + 5954 field. The BL Lac object and its host are in the center of the image. No subtraction has been performed. Measurements for labeled objects are listed in Table 2. Note the rich field.

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FIG. 4.—Image obtained with the WFPC-2 of the MS 2143.4+0704 field. The BL Lac object and its host are in the center of the image. No PSF subtraction has been performed. Measurements for labeled objects are listed in Table 3. Note the close companions D and L. L is very elongated. The apparent "ejecta" from the SE of the object is a diffraction spike produced by the central point source.

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Fig. 8.—Results of subtracting a scaled PSF from several objects in our images. In the main image, the Galactic field star labeled D has had a PSF scaled and subtracted from it. Note the complete lack of any diffuse emission beyond the core of the residual. This is the expected result for all point-source objects. In contrast, after subtraction of a scaled PSF from MS 1407.9 + 5954 (shown in the center of the image), there is considerable residual extended emission from the elliptical host galaxy. In the inset, a PSF of twice the fitted value was intentionally oversubtracted from MS 1221.8 + 2452 to show the extended emission in contrast to the lack of emission surrounding the field star D in the main field.

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