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THE *HUBBLE SPACE TELESCOPE* SURVEY OF BL LACERTAE OBJECTS: GRAVITATIONAL LENS CANDIDATES AND OTHER UNUSUAL SOURCES

Riccardo Scarpa[1] and C. Megan Urry[1]
Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218; scarpa@stsci.edu, cmu@stsci.edu
Renato Falomo
Astronomical Observatory of Padova, Vicolo dell'Osservatorio 5, 35122 Padova, Italy; falomo@astrpd.pd.astro.it
Joseph E. Pesce
Eureka Scientific; pesce@astro.psu.edu
Rachel Webster and Matthew O'Dowd
Melbourne University Parkville, Victoria, Australia, 3052; rwebster@isis.ph.unimelb.edu.au, modowd@isis.ph.unimelb.edu.au
and
Aldo Treves
University of Insubria, Via Lucini 3, Como, Italy; treves@uni.mi.astro.it
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ABSTRACT

We present *Hubble Space Telescope* (*HST*) observations of seven unusual objects from the *HST* "snapshot survey" of BL Lacertae objects, of which four are gravitational lens candidates. In three cases a double point source is observed: 0033+595, with 1".58 separation, and 0502+675 and 1440+122, each with ∼0".3 separation. The last two also show one or more galaxies, which could be either host or lensing galaxies. If any are confirmed as lenses, these BL Lac objects are excellent candidates for measuring H_0 via gravitational time delay because of their characteristic rapid, high-amplitude variability. An additional advantage is that, like other blazars, they are likely superluminal radio sources, in which case the source plane is mapped out over a period of years, providing strong additional constraints on the lensing mass distribution. The fourth gravitational lens candidate is 1517+656, which is surrounded by three arclets forming an almost perfect ring of radius 2".4. If this is indeed an Einstein ring, it is most likely a background source gravitationally lensed by the BL Lac object host galaxy and possibly a surrounding group or cluster. In the extreme case that all four candidates are true lenses, the derived frequency of gravitational lensing in this BL Lac sample would be an order of magnitude higher than in comparable quasar samples. We also report on three other remarkable BL Lac objects: 0138−097, which is surrounded by a large number of close companion galaxies; 0806+524, whose host galaxy contains an uncommon arclike structure; and 1959+650, which is hosted by a gas-rich elliptical galaxy with a prominent dust lane of $\sim 5 \times 10^5\ M_\odot$.

Subject headings: BL Lacertae objects: general — galaxies: structure — gravitational lensing

1. INTRODUCTION

The *Hubble Space Telescope* (*HST*) "snapshot survey" of BL Lacertae objects[2] produced high-resolution images of ∼100 BL Lac objects from six complete samples spanning the redshift range $0.05 \lesssim z \lesssim 1.2$ (Falomo et al. 1998; Urry et al. 1999b; Scarpa et al. 1999). The main goal was to study the host galaxies and near environments and their evolution over cosmic time. In general, the BL Lac objects lie in luminous elliptical galaxies, often surrounded by groups or poor clusters, as has been found previously from ground-based surveys (Wurtz, Stocke, & Yee 1996; Pesce, Falomo, & Treves 1995). The excellent spatial resolution of the *HST* WFPC2 allowed for better determination of galaxy properties like morphology or core radius and, even in the relatively short snapshot exposures, allowed easy detection of host galaxies out to redshifts $z \sim 0.5$.

HST Wide Field Planetary Camera 2 (WFPC2) spatial resolution also revealed new and unusual morphologies in a handful of BL Lac objects. In this paper we report seven unusual cases: three BL Lac objects with double nuclei, a ring of three arcs surrounding a BL Lac, a BL Lac host galaxy with an isolated arc, a BL Lac with many close companions, and a host galaxy with a prominent dust lane. The double nuclei and the ring are new candidates for gravitational lensing. In § 2 we briefly reviews the observations and data analysis, which are described more fully elsewhere. In § 3 we discuss individual objects, and in § 4 we give our conclusions. Throughout the paper $H_0 = 50$ km s^{-1} Mpc^{-1} and $q_0 = 0$ are used.

2. OBSERVATIONS AND DATA ANALYSIS

2.1. *WFPC2 Data*

Observations and data analysis are described fully by Falomo et al. (1997b), Urry et al. (1999a), and Scarpa et al. (1999); they are only briefly reviewed here. All BL Lac objects were observed with the WFPC2 through the F702W filter. Targets were centered on the PC chip, which has pixels 0".046 wide. To obtain a final image well-exposed in both the inner, bright nucleus and in the outer regions where the host galaxy emission is still above the wings of the point-spread function (PSF), we made a series of increasingly longer exposures with total duration ranging from 300

[1] Also at Department of Astronomy, Padova University, Vicolo dell'Osservatorio 5, 35122 Padova, Italy.

[2] 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.

to 1000 s. The journal of the observations in Table 1 gives the coordinates (J2000), date of observation, total exposure time in seconds, and reported redshift of the target BL Lac objects.

After preliminary reduction carried out as part of the standard *HST* pipeline processing (flat-fielding, dark and bias subtraction, and flux calibration), we simultaneously combined images and removed cosmic rays using the IRAF task CRREJ. Fluxes were converted to *R*-band magnitudes following the prescription of Holtzman et al. (1995, their eq. [9] and Table 10). Finally, we modeled the PSF in two parts: the core using the Tiny Tim software (Krist 1995) and the wings (at $\gtrsim 2''$ radius) using the average of well-exposed stellar images (Urry et al. 1999a; Scarpa et al. 1999).

2.2. *NICMOS Data*

An *HST* Near-Infrared Camera Multiobject Spectrograph (NICMOS) observation of the BL Lac object 0502+675 was carried out as part of a related but separate survey of BL Lac objects. The observation was on 1998 May 5 through filter F160W, which is equivalent to the standard *H* band, with the NICMOS camera 2, which has a pixel size of 0.″075. Because of the lower resolution of *HST* in the infrared, this pixel size offers a sampling of the PSF as good as the PC camera in the *R* band. Three separate images were obtained and dithered among three positions in order to better estimate the contribution of the sky to the total signal. The data were first reduced and flux-calibrated in the standard *HST* pipeline, then the effect of the random bias (known as the "pedestal") was removed. Images were cleaned from cosmic rays and other defects, and a sky frame, obtained by median filtering the three frames, was subtracted. Each image was then resampled, increasing the sampling by a factor of 2 and finally recentered and combined.

3. RESULTS AND DISCUSSION OF INDIVIDUAL OBJECTS

3.1. *1ES 0033+595*

The *HST* image of this BL Lac object, an *Einstein* Slew Survey source (Perlman et al. 1996), shows two objects of similar brightness at the reported optical position, separated by 1.″58 (Fig. 1). Neither the VLA radio map nor the optical finding chart given by Perlman et al. (1996) indicate the source is double, nor would they, given their low spatial resolution.

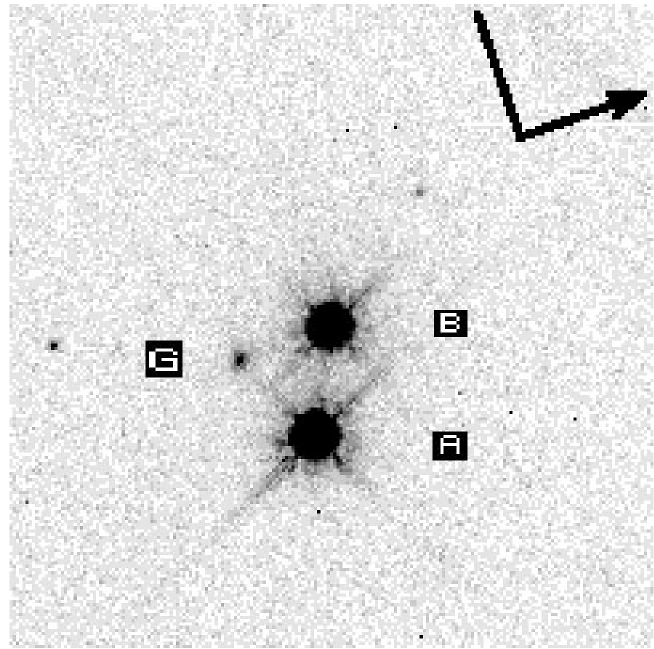

FIG. 1.—Central part of the *HST* WFPC2 F702W image of 0033+595 (PC camera). The proposed counterpart of this BL Lac object is resolved into two point sources, A and B, which have comparable brightness (A is slightly brighter than B in *R*, but the situation is reversed in *U*) and are separated by 1.″58. It is reasonably probable that we would find one such pair, simply by chance, in a set of 100 observations. A faint galaxy (G) is also detected just to the east of the two point sources. The arrow indicates north and is 1.″84 (40 pixels) long.

The two sources "A" and "B" have magnitudes $m_R = 17.95 \pm 0.05$ and 18.30 ± 0.05 mag, respectively. Object B is at position angle 63° with respect to A. Absolute coordinates for both components, derived using the *HST* astrometric solution, are given in Table 1. A faint, clearly resolved object ("G") is also detected south of the two brighter objects. Its radial profile is consistent with that of an elliptical galaxy of total integrated magnitude $m_R = 22.3 \pm 0.15$ mag. The galaxy is 1.″39 south of source B and 1.″43 southeast of source A. There is no reported redshift either for the BL Lac object or for galaxy G.

Both A and B appear to be unresolved, although evaluating their radial profiles is made difficult by the small

TABLE 1

JOURNAL OF THE OBSERVATIONS

Object	α (2000)	δ (2000)	Date	Exposure (s)	z[a]
0033+595A......	00 35 52.549	59 50 03.47	1996 Mar 3	1060	...
0033+595B......	00 35 52.734	59 50 04.18	...	...	...
0138−097........	01 41 25.76	−09 28 43.4	1996 Sep 28	840	0.733 (1)
0502+675........	05 07 56.25	67 37 24.4	1996 Mar 2	740	0.314 (2)
0806+524........	08 09 49.15	52 18 58.7	1996 Sep 11	610	0.136 (2)
1440+122........	14 42 48.35	12 00 40.5	1997 May 7	320	0.162? (3)
1517+656........	15 17 47.60	65 25 23.9	1997 Feb 1	614	>0.7 (4)
1959+650........	19 59 59.87	65 08 54.1	1997 Jan 9	302	0.048 (5)

NOTE.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

[a] References for redshifts are as follows: (1) Stocke & Rector 1997; (2) E. S. Perlmann 1998, private communication; (3) Schachter et al. 1993 (see text for more on this value); (4) Beckmann et al. 1997, private communication; (5) Perlmann et al. 1996.

separation. In order to extract the radial profile of each source, we first modeled and subtracted the companion. As a model, we used a Tiny Tim–generated PSF (Krist 1995), computed with a factor of 3 oversampling. The PSF was centered on the object with a precision of $\sim$0.05 pixels, then it was resampled and convolved with the PC camera kernel. The flux normalization was done by matching the source flux in an annulus with $2 < r < 5$ pixels (avoiding the central pixel, which could be saturated). The radial profiles of the two sources and the PSF are very similar, with only minor deviations that are well within the uncertainties (not reflected in the error bars) introduced by the closeness of the two sources (Fig. 2). The fact that both profiles are slightly above the PSF may be due simply to a defective subtraction of the nearby companion. Based on the similarity of the two source profiles and their consistency with the PSF model, we conclude that both A and B are unresolved.

Two pointlike images can be produced by a chance alignment of the BL Lac with a foreground star or with a foreground or background active galactic nucleus (AGN), because the nucleus is physically double, as is sometimes observed in quasars (Kochanek, Falco, & Muñoz 1997), or because of gravitational lensing of a background point source by a foreground mass. The easiest way to shed light on this issue is uniquely identifying one of the two sources with the radio counterpart. The precision of the coordinates of the only available VLA map is $\sim 1''$ (Perlman et al. 1996), and so at present it is not possible to discriminate which (if only one) of the two optical point sources is the radio source. Formally, the radio position agrees better with the *HST* coordinates for the eastern (B) source ($\Delta\alpha = 0''.0$ and $\Delta\delta = 0''.1$) than with the western source (A; $\Delta\alpha = 0''.2$ and $\Delta\delta = 0''.6$). Interestingly, the VLA radio map does show a slight elongation exactly along the line connecting the two optical images, suggesting there may be two barely resolved radio sources coincident with the two optical images.

Given the relatively large separation of the two sources and the low Galactic latitude of 0033+595, the probability of a chance alignment of the BL Lac with a foreground star is not small. We derive the stellar surface density toward 0033+595 directly from the *HST* image. There are 33 stars as bright as object B in the whole WFPC2 field of view ($\sim$20,550 arcsec^2). This gives a probability of $\sim$1% of having a star within a ring of radius 1''.58 from A, which, for a sample of 100 targets, means that we actually expect to find one case like this (note, however, that not all 100 observed BL Lac objects are at this low Galactic latitude).

That object A is possibly a foreground star is also indicated by the much bluer color of object B ($U-B = 0.4$ mag and -0.1 mag for A and B, respectively; R. Falomo & J. Kotilainen 1999, private communication). Based on radio coordinates and color, then, it seems quite possible that B is the true BL Lac and A is a star. If this is the case, then the radio map is centered on B, and the elongation is on the opposite side with respect to A and is not associated with it. In Figure 3 we show a finding chart for this object with source B marked as the most probable BL Lac.

However, the hypothesis of gravitational lensing cannot be excluded, since the different color could be due to differential internal absorption through the lens. To produce a $\Delta U-B$ of 0.5 mag, source A should be reddened by $A_V \sim 2$ mag more than B, corresponding to a moderate hydrogen column density of 3.3×10^{21} cm^{-2}.

The presence of significant absorption is consistent with the lack of a strong blue continuum observed in the only published spectrum of 0033+595 (Perlman et al. 1996). This spectrum was obtained with a 2''.5–wide slit that included both sources; it is featureless and intriguingly red for a BL Lac object. If A is a red star, strong absorption lines should be present in the spectrum, but they are not seen. Similarly, if it were an unrelated quasar, one might expect to see emission lines. The absence of such spectral features does not rule out these possibilities but makes them less likely, given

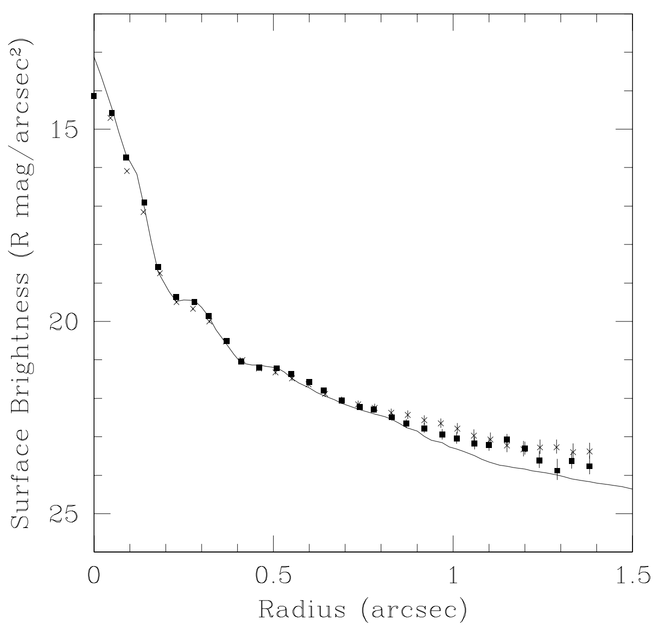

FIG. 2.—Radial profiles of 0033+595 A (*squares*) and B (*crosses*) and a PSF model including large-angle scattered light (*solid line*). The radial profile of B has been shifted by 0.2 mag to match that of A in order to better emphasize differences at large radii. Within the uncertainties, both appear unresolved.

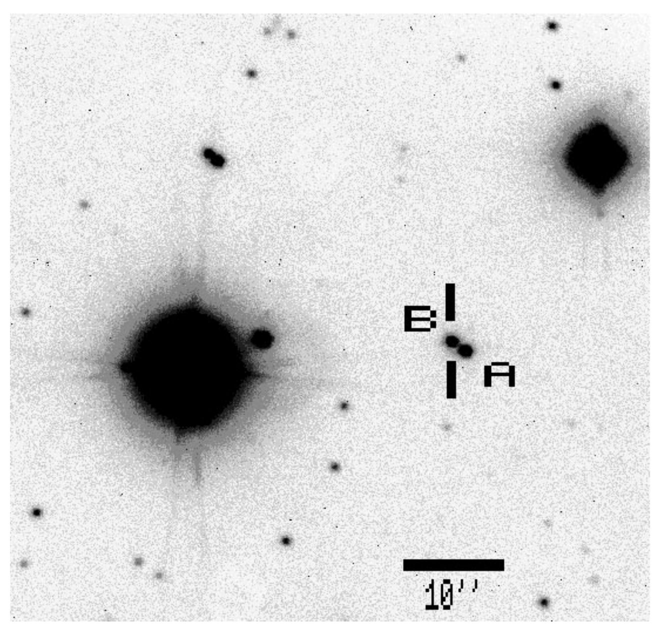

FIG. 3.—Finding chart for 0033+595. This image was obtained with the Canada-France-Hawaii Telescope in the *I* band. Object B is marked as the most probable identification of the BL Lac object. North is on top; east is on left.

the approximately equal brightness of the two point sources.

Spatially resolved spectra of each point source are crucial and, under good seeing conditions and with a properly oriented slit, should be easy to obtain from the ground. If the two point sources turn out to have identical spectra, the unusually red spectrum may be produced by internal absorption in an otherwise undetected, aligned lens.

3.2. *1ES 0502+675*

This *Einstein* Slew Survey source was identified as a BL Lac object on the basis of its featureless optical spectrum (Schachter et al. 1993). At *HST* resolution, 0502+675 is clearly double, with separation of only 0″.33 (Fig. 4).

A careful comparison of the two radial profiles (extracted as described for 0033+595) shows that the brighter object is more extended than the fainter one and differs significantly from the PSF profile (Fig. 5). We therefore fitted the radial profile of the brighter source with a PSF plus elliptical galaxy (de Vaucouleurs) model, convolved with the PSF. The best fit yields a point source of $m_R = 17.3 \pm 0.1$ mag and a surrounding galaxy of total magnitude $m_R = 18.9 \pm 0.1$ mag (integrated to infinity) and half-light radius $r_e = 0''.6 \pm 0''.07$. The addition of the galaxy is significant at the 99.99% confidence level according to an F-test. A disk galaxy cannot be ruled out, but given that BL Lac hosts and gravitational lenses are overwhelmingly elliptical galaxies, it is most likely to be this morphological type. Using these parameters we subtracted a two-dimensional model from the brightest object and reextracted the radial profile of the companion; it is consistent within the errors with the PSF profile (Fig. 5), and the derived magnitude of the point source is $m_R = 18.7 \pm 0.2$ mag.

Because of the small spatial separation, the likelihood that this close binary is the result of chance superposition is much less than in the case of 0033+595, even under the conservative assumption that the BL Lac is the brighter object, and the fainter object is an unrelated source. At high Galactic latitude there are 3×10^3 stars per square degree brighter than $m_R = 19.0$ mag (Bahcall & Soneira 1980) and a corresponding probability of $P \lesssim 7 \times 10^{-5}$ for a faint foreground star being as close as 0″.33 to the BL Lac object, or 7×10^{-3} for a sample of 100 objects. The probability for a chance alignment is therefore rather small.

A possible explanation for the presence of an object so close to the BL Lac is that it is a companion galaxy, frequently observed near BL Lac objects. However, even at *HST* resolution the alleged companion is unresolved, and the difference in luminosity between the two objects, $\Delta m_R = 1.4$ mag, is much less than the typical difference of several magnitudes between BL Lac objects and companion galaxies (Pesce et al. 1995; Falomo 1996), arguing against the suggestion that they are companion objects. The possibility of a double nucleus is somewhat more likely, because the two point sources have similar magnitudes, but in this case the galaxy is unlikely to be centered on one of the two, as observed.

Fortunately, as part of a related but separate snapshot survey of BL Lac objects carried out with the NICMOS camera 2, 0502+675 was reobserved in the H band. Both sources were clearly detected, as well as the galaxy surrounding them (Fig. 4). The two point sources have, within the errors, the same luminosity ratio in both bands; i.e., they have the same $R-H$ colors. For the brighter and fainter sources we measure $m_H = 15.4 \pm 0.1$ and 16.9 ± 0.2 mag, respectively. The corresponding optical-IR spectral index is $\alpha = -0.7$, typical for a BL Lac object.

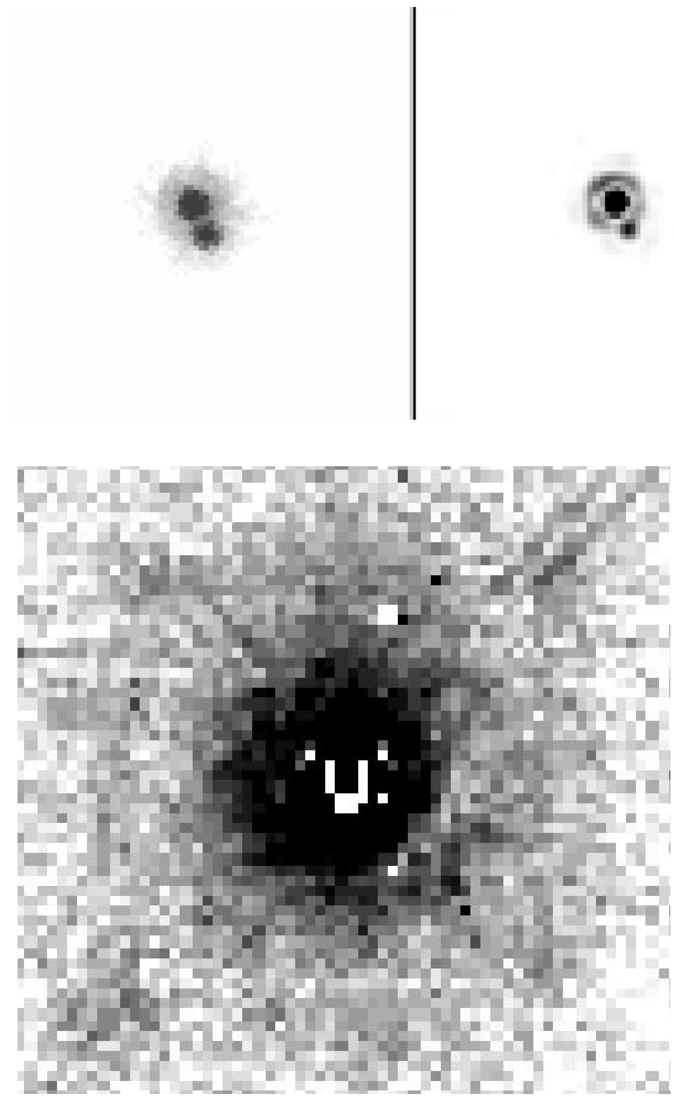

FIG. 4.—*HST* WFPC2 and NICMOS images of the BL Lac object 0502+675. *Top left*: Central part of the PC F702W image, showing two objects separated by 0″.33. Here the image is printed with a gray scale emphasizing the brightest structures so that the galaxy is not visible. The light surrounding the brighter source is due to the bright wings of the PSF. No other sources are detected within a radius of almost 10″. Figure orientation (north is roughly at the bottom) and scale can be derived from the position angle and separation of the fainter source with respect to the brighter (P.A. = 24° from north toward east and separation 0″.33). *Top right*: Central part of the NICMOS F160W image, with same linear scale and orientation as in the previous panel, at approximately the same intensity stretch. With this particular intensity stretch, all visible structures surrounding the brighter source (apart from the companion) are from the PSF. *Bottom*: Same NICMOS field as in the top right panel, but with the two point sources subtracted and intensity stretched to bring out the galaxy. The figure is 4″.3 on a side.

The best fit of the galaxy radial profile with a de Vaucouleurs model gives $m_H = 15.7 \pm 0.2$ mag and $r_e = 0''.5 \pm 0''.2$; the latter agrees very well with the value derived from the R-band image. Two-dimensional fitting of the outer galaxy isophotes is severely hampered by the presence of the two strong point sources, and so we were not able to determine whether the galaxy is actually centered on one of the two point sources or between them.

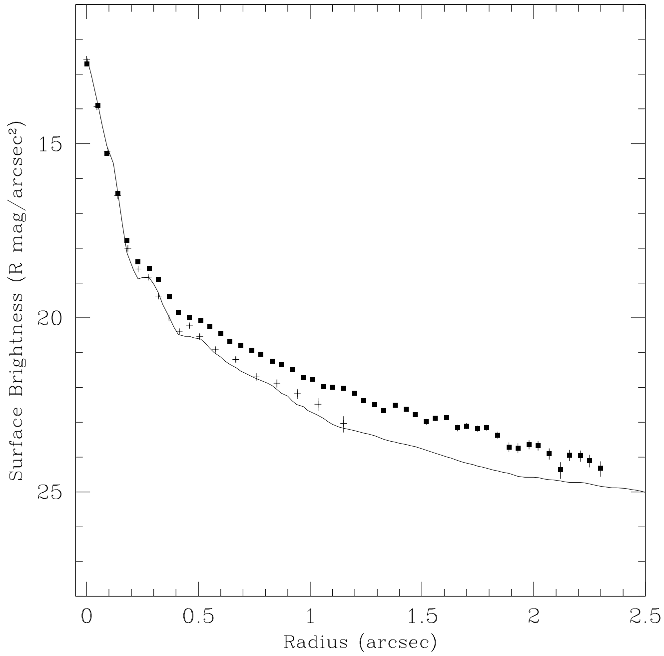

FIG. 5.—Comparison of the radial profiles of the brighter (A, *squares*) and fainter (B, *crosses*) point sources that comprise 0502+675. The solid line represents the *HST* PSF, which includes scattered light at large radii (see text for details). To better compare the two point sources, the radial profile of object B has been shifted up by 1.4 mag to match the few innermost pixels of the brightest source profile.

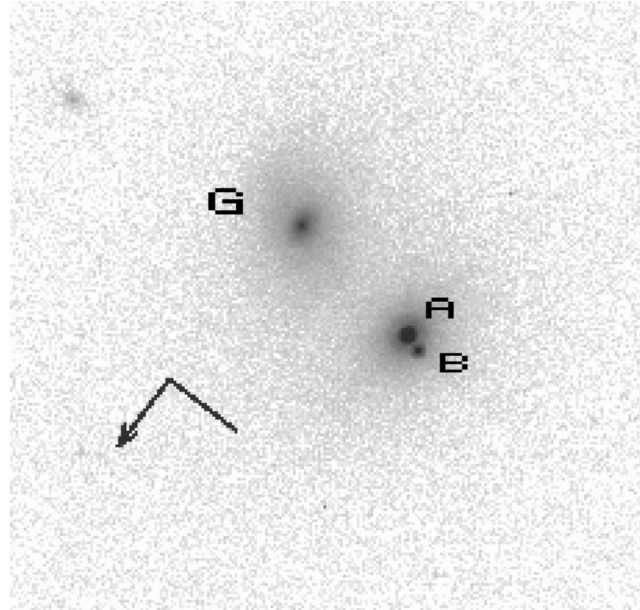

FIG. 6.—Complex field of the BL Lac object 1440+122 from the central part of the WFPC2 F702W PC image. The BL Lac object is an elliptical galaxy with a bright point source at its center (A), and there is a second point source (B) 0″.29 to the east. A second galaxy, of similar size and brightness, lies 2″.53 to the west; such luminous companions are not commonly found near BL Lac objects. The probability is low that the close pair A and B represents a chance superposition of two unrelated objects. The arrow points north and is 1″.38 (30 pixels) long.

Recently, a redshift of $z = 0.314$ has been reported, based on detection of Ca II H and K and Mg II absorption lines (E. S. Perlman 1998, private communication). At this redshift, the K-corrected absolute magnitude of the galaxy is $M_R = -23.2$ mag (including a K-correction of 0.4 mag in the R band, while in the H band the K-correction is negligible) and $M_H = -26.0$ mag. The corresponding color is $R-H = 2.8$ mag, to be compared with 2.9 mag expected for an early-type galaxy at that redshift (Kotilainen, Falomo, & Scarpa 1998 and references therein). However, the effective radius at that redshift (3.1 kpc) is relatively small for a galaxy of that absolute magnitude and is smaller than the average value for resolved host galaxies in the full survey of 100 BL Lac objects, $\sim$10 kpc (Urry et al. 1999b). Rather than being an unusually compact host, this galaxy could instead be a closer, intervening elliptical.

Given the wide separation in wavelength between the two *HST* observations, the similarity of the two point sources' spectra strongly favors the gravitational lensing hypothesis. To prove this is actually a lens requires spectroscopy with very high spatial resolution, which will be done in cycle 8 with the *HST* Space Telescope Imaging Spectrograph (STIS) long-slit (Proposal 8135, PI Scarpa). If the lensing scenario is confirmed, the observed galaxy is a good candidate for the lensing mass.

3.3. *1ES 1440+122*

This is another *Einstein* Slew Survey source, identified as a BL Lac object on the basis of a nearly featureless spectrum, with only a weak Ca II H and K break at $z = 0.162$ (Schachter et al. 1993). In the *HST* PC image (Fig. 6), 1440+122 is double, consisting of a large elliptical galaxy with a bright central point source (A) and a second point source just 0″.29 to the east (B). A second galaxy, without a central point source, lies 2″.53 to the west (G). The radio and optical positions reported for 1ES 1440+122 (Perlman et al. 1996) coincide most closely with A, which is most likely the BL Lac object, while G is either an unrelated galaxy or an unusually bright companion galaxy.

Since the identification spectrum was obtained through a large aperture, it likely included light from both A and G, meaning the reported redshift could refer to either object. The signal-to-noise ratio is also rather low, and all absolute quantities should be considered with caution.

We fitted object A with a model of an elliptical galaxy plus point source (Fig. 7), convolved with the PSF, and obtained best-fit values of the galaxy magnitude (integrated to infinity): $m_R = 16.70 \pm 0.05$ mag; half-light radius, $r_e = 3''.9 \pm 0''.25$; and point-source magnitude, $m_R = 16.9 \pm 0.1$ mag. For redshift $z = 0.162$, these correspond to an absolute magnitude $M_R = -23.6$ mag (including a K-correction of 0.2 mag), $r_e = 15$ kpc, and a point-source luminosity $M_R = -23.2$ mag. Similar results for the host galaxy were reported by Heidt et al. (1999).

The companion source B has a magnitude $m_R = 19.8$ mag and is located 0″.29 east of A at position angle 70°. Its radial profile is consistent with the PSF, but the closeness of the brighter source A makes it difficult to determine whether it is unresolved.

The nearby galaxy G (at position angle $\sim$260°) also has an elliptical morphology, with a total apparent magnitude $m_R = 17.56$ mag and $r_e = 2''.8$, which at $z = 0.162$ would correspond to $M_R = -22.7$ mag (including K-correction as for A) and $r_e = 10.6$ kpc. If the redshift is correct for both galaxies, they would be large, bright elliptical galaxies, similar to typical BL Lac host galaxies.

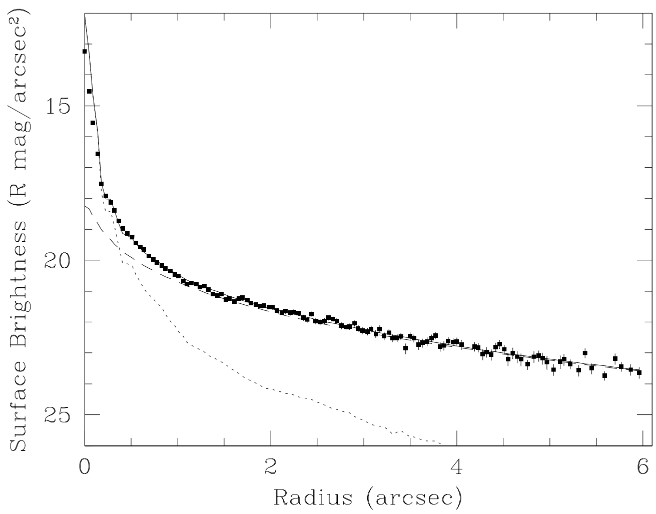

FIG. 7.—Radial profile of the BL Lac object 1440+122 (A in Fig. 6), described using a two-component model consisting of a de Vaucouleurs law (*dashed line*) plus a point source (*dotted line*). The sum of the two components (*solid line*) follows well the observed profile (*squares*) except within the first 0".1, where the PSF is undersampled.

A chance superposition of A and a foreground star (B) is possible and somewhat more likely ($P \sim 1\%$) than for 0502+675 because of the faintness of B but less likely than for 0033+595 because of the small angular separation of the two point sources. A double nucleus is highly unlikely given that the galaxy is centered on one of the point sources and they have very different magnitudes.

It remains possible that B and the point source in A are two images of a distant background blazar and that the galaxy in A is actually the foreground lensing galaxy. With such small splitting, the fact that the galaxy appears well centered on one of the two point sources (to within 0".05) is not unexpected.

Again, confirmation requires spatially resolved spectroscopy, which will also be done in cycle 8 with the *HST* STIS. We note that galaxy G will fortuitously fall within the STIS long slit.

If 1440+122 is not lensed and the point source and galaxy in A are physically associated (i.e., have the same redshift), this system is still very interesting. Specifically, if galaxy G is at the same redshift, it would be a relatively rare occurrence of two luminous companion galaxies so close together, only $\sim$10 kpc projected distance at $z = 0.162$. While BL Lac objects are often found in groups or poor clusters, most companions are much smaller and less luminous than the BL Lac host galaxy (e.g., Falomo 1996), suggesting the BL Lac object dominates the system. This is in contrast with what is observed for radio galaxies, which are more often found in such dumbbell systems (e.g., Fasano, Falomo, & Scarpa 1996 and references therein). Detection of more cases like this would strengthen the "unification" connection between BL Lac objects and radio galaxies.

It is worth noting that a dumbbell system like 1440+122 (or the one of 1415+529; Wurtz et al. 1996), when observed from the ground under normal seeing conditions, would be unresolved or only marginally resolved (especially if it were at larger redshift). In that case the central point source would also appear off-center with respect to the host. As an example, the BL Lac object MS 0205+315 was reported to have an off-center disk host (Wurtz et al. 1996) but, in better seeing, was found to have a normal elliptical host and a large companion galaxy (Falomo et al. 1997a).

3.4. *H1517+656*

The *HEAO* 1 A-3 BL Lac object 1517+656 (Elvis et al. 1992) is perhaps the most unusual object discussed here. At *HST* resolution the bright, unresolved BL Lac nucleus ($m_R = 16.2$ mag) is surrounded by three arcs describing an almost perfect ring of radius 2".4 (Fig. 8). The ring is off-center by $\sim$0".5 with respect to the BL Lac object but otherwise resembles an Einstein ring. Given the low signal-to-noise ratio in this image, it is also possible that the arclets describe two different rings centered on the BL Lac object, one traced by the two innermost arclets, another by the outermost one. The surface brightnesses of the arcs are approximately the same, $\mu_R \sim 22.4$ mag arcsec^{-2}, and they are resolved radially, having a width of $\sim$0".2. The two bright, resolved spots at position angles 126° and 260° have magnitudes $m_R = 23.6$ and 23.8 mag, respectively.

Because of the shortness of the exposure (320 s) the arcs, while clearly detected, are severely underexposed, and the signal-to-noise ratio is low. In a deeper image, the ring could well be filled in with fainter structures. Note that the narrowness of these arcs makes them very difficult to detect from the ground, where even in excellent seeing they would have surface brightness lower by $\sim$2–4 mag arcsec^{-2}, as well as greater contamination by scattered light from the BL Lac nucleus. (Our attempt to image the arcs using the much larger Canada-France-Hawaii Telescope was not successful, even with 10 times the exposure time.)

Mg II and Fe II absorption lines place a lower limit on the BL Lac redshift of $z > 0.7$ (V. Beckmann et al. 1997, private communication). The lack of an exact redshift adds uncer-

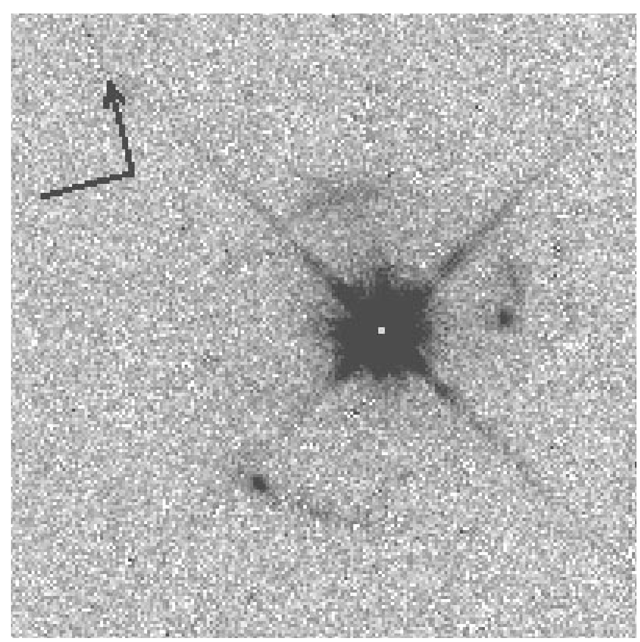

FIG. 8.—Part of the WFPC2 F720W PC image of the BL Lac object 1517+656, after smoothing with a Gaussian of $\sigma = 0.8$ pixels. Three narrow arclets surround the central point source, at position angles 2°, 145°, and 275°, describing an almost perfect ring. Two bright spots are also resolved, at position angles 126° and 260°. The arrow points north and is 1".38 (30 pixels) long.

tainty to the interpretation of the arcs. We discuss three scenarios:

1. The most likely option is that one or more background galaxies are gravitationally lensed to give the observed arclets. In this case the BL Lac object would necessarily be in the foreground; otherwise, if it were the central image of the lens, it would be heavily demagnified, and a second image should be observed outside the ring. If the BL Lac object is in the foreground, it is contributing to the lens (since the almost perfect alignment of more than two objects is highly unlikely). BL Lac objects are often associated with other galaxies, and these could account for the center of mass being offset from the BL Lac object and for the large diameter of the ring, 4″.8, which corresponds to a lens mass of a few times 10^{12} $M_\odot$ depending on source/lens redshifts and cosmology. These additional galaxies should be visible in a deeper *HST* image and may already have been seen in the two resolved spots.

In order to establish whether these arcs indeed constitute an Einstein ring, deeper images with $\sim$0″.1 resolution are required. Multicolor images would also constrain the redshift of the arcs, if indeed they represent stellar light. If confirmed, this would be the first discovery of a BL Lac object acting as a lens rather than being lensed itself.

2. The distant BL Lac object is located behind a foreground face-on spiral galaxy, possibly an Sc with a very small nucleus. Because of the short exposure time, we observe only the brightest regions of the spiral arms. The BL Lac object may be sufficiently offset from the galaxy nucleus so that it is not macroimaged, although it could still be microlensed by stars in the galaxy.

The primary argument against this picture is the high surface brightness of the arclike features. The central surface brightnesses of nearby spiral disks are roughly constant, $\mu_R = 20.5$ mag arcsec^{-2} (Freeman 1970; van der Kruit 1987, 1989), not much higher than the surface brightnesses of the observed arcs, which are well away from the putative galaxy center. Hence, even without the $(1+z)^4$ cosmological dimming, the ring is already much brighter than expected for a spiral galaxy. In addition, the spectrum of 1517+656 is not unusually red (V. Beckmann et al. 1997, private communication),in contrast to the one other BL Lac object thought to be located behind a spiral galaxy (1413+135; Carilli, Perlman, & Stocke 1992).

If this hypothetical galaxy were responsible for the detected Mg II and Fe II absorption lines at $z \sim 0.7$, its diameter would be $\gtrsim$45 kpc, unusually large for a spiral galaxy, though not impossible. (Of course, if the galaxy is closer, this consideration does not apply.) We conclude that this scenario is quite improbable.

3. The arcs are part of a galaxy associated with the BL Lac nucleus, either bright arms of a spiral galaxy or shells surrounding an elliptical galaxy. In the former case, 1517+656 would be the first BL Lac object for which spiral arms are unambiguously detected. (The possibility of spiral host galaxies in 2–3 other BL Lac objects remains extremely controversial; see the discussion in Urry & Padovani 1995 and Scarpa et al. 1999.) However, the arguments about size and surface brightness make this possibility doubtful.

If the arcs are elliptical shells, subject to $(1+z)^4$ cosmological dimming, the intrinsic surface brightness would be $\mu_R \lesssim 20$ mag arcsec^{-2}, at least several magnitudes brighter than usual (Forbes, Reitzel, & Williger 1995). Moreover, such shells always have surface brightnesses much fainter than the galaxy producing them (Malin & Carter 1983), and so we should clearly see the galaxy, whereas the BL Lac nucleus is unresolved.

Of these three possibilities, the first is the most plausible. To establish whether these arcs indeed constitute an Einstein ring requires deeper images with 0″.1 resolution.

3.5. *PKS 0138−097*

This BL Lac object from the 1 Jy sample (Stickel et al. 1991) is located in a rich environment, has a smooth IR-optical spectrum (Fricke et al. 1983), and is highly polarized (Impey & Tapia 1988). Weak emission lines from Mg II, [O II], and [Ne V] were recently detected at $z = 0.733$ (Stocke & Rector 1997), together with a previously known absorption system at $z = 0.501$ (Stickel, Fried, & Kuhr 1993). The BL Lac object appears bright and pointlike in our *HST* image (Fig. 9). To increase the signal-to-noise ratio and better investigate whether it is actually resolved, we extracted the azimuthally averaged radial profile, masking out nearby sources. The comparison of the radial profile of the BL Lac object with the PSF model shows a small but systematic departure beyond 1″ (Fig. 10), in excess of our estimated statistical uncertainties. However, after increasing the sky by 1 σ, the radial profile is fully consistent with the adopted PSF model, and we conservatively conclude that the source remains unresolved. At the 95% confidence level, the upper limit to the host magnitude is $m_R > 20.1$ mag or $M_R > -25.4$ mag at $z = 0.733$.

The environment near 0138−097 is rich, with at least four galaxies detected within a radius of 3″, corresponding to a projected distance of 10 kpc (Heidt et al. 1996, whose designation we adopt here). In our *HST* snapshot image

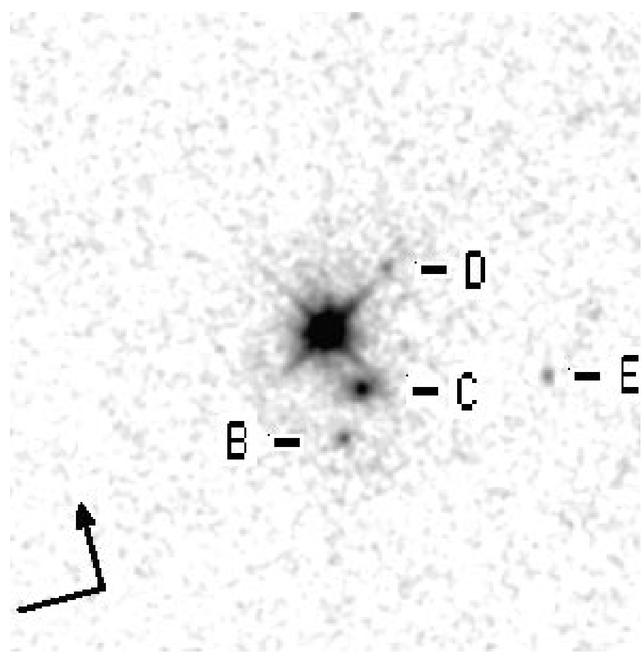

FIG. 9.—Part of the WFPC2 F702W PC image of the high-redshift BL Lac object 0138−097, after Gaussian smoothing with $\sigma = 2$ pixels. An unusual number of close companion galaxies can be seen clearly (B–D are named following Heidt et al. 1996). The arrow points north and is 1″.84 (40 pixels) long.

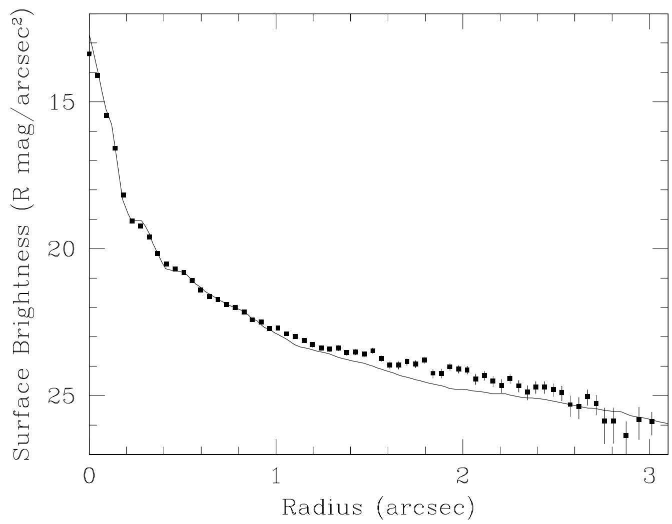

FIG. 10.—Average radial profile of 0138−097 (*squares*) compared with the PSF profile (*solid line*). There is some departure from the PSF, but we cannot claim the object is resolved (see text).

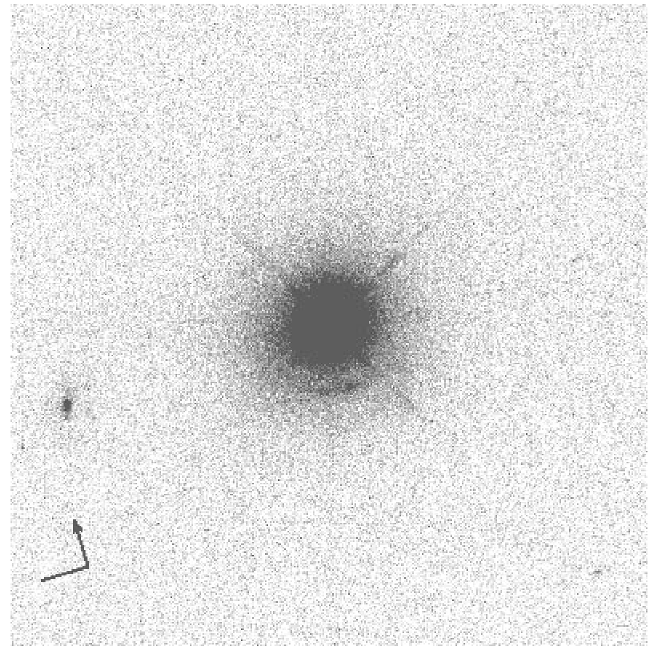

FIG. 11.—Part of the WFPC2 F702W PC image of the BL Lac object 0806+524, showing a well-resolved host galaxy surrounding a bright central point source. An unusual arclike structure is detected 1″.9 south of the nucleus, possibly a bright elliptical shell or the remnant of a previous gravitational interaction. The arrow points north and is 1″.38 (30 pixels) long.

(Fig. 9) three of the four are clearly visible, while object A is not detected, as expected given the short snapshot exposure time. The apparent *R* magnitudes, together with the distance from the BL Lac object, are given in Table 2 for each galaxy. Our measurements are generally in agreement with those of Heidt et al. (1996), apart from object "D," which we estimate is approximately 1 mag fainter, and object "E," for which they reported no data. Source "C" is clearly resolved, with a major axis at position angle ∼90°. The projected distance is only 14 kpc at $z = 0.733$, so there could well be gravitational interaction with the BL Lac object.

The presence of absorption systems and close companions led Heidt et al. (1996) to suggest that this BL Lac object may be affected by gravitational microlensing; galaxy C is a good candidate for producing the absorption line, given the small projected distance from the BL Lac object, and possibly for microlensing as well.

3.6. *1ES 0806+524*

This BL Lac object from the *Einstein* Slew Survey (Schachter et al. 1993) has a rather interesting morphology. In our WFPC2 F720W image (Fig. 11), the BL Lac nucleus is surrounded by a bright elliptical galaxy, as is typical of BL Lac objects at low redshift. Not typical at all is the large arclike structure 1″.93 south of the nucleus.

The radial profile of 0806+524 is well described by a point source plus a de Vaucouleurs host galaxy (the contribution of the arc to the azimuthally averaged light is negligible). The two components have comparable luminosity, with best-fit values $m_R = 16.3$ mag for the central point source and $m_R = 16.7$ mag and $r_e = 1''.7$ for the elliptical galaxy.

For this BL Lac object there is only a tentative redshift. The discovered optical spectrum was featureless (Schachter et al. 1993), as were two subsequent spectra of better quality (Bade, Fink, & Engels 1994; Perlman et al. 1996), but E. S. Perlman et al. (1998, private communication) have since obtained a new spectrum from which a redshift $z = 0.136$ was estimated from the Ca H and K absorption line. At this redshift, the absolute magnitude of the host galaxy would be $M_R = -23.25$ mag (including a *K*-correction of 0.2 mag), quite normal for a BL Lac host galaxy (Urry et al. 1999a; Wurtz et al. 1996; Falomo 1996).

The arc has radius of curvature of $\sim 2''$ and is roughly centered on the BL Lac nucleus, and its surface brightness is $\mu_R \sim 22.2$ mag arcsec^{-2}. Although the nature of the arc cannot be determined with only one image, a possible explanation is that it is a shell, not an uncommon feature in elliptical galaxies but uncommonly bright in this case (Malin & Carter 1983; Forbes et al. 1995). If so, it would be the first detection of such a shell in a BL Lac host galaxy. This idea is supported by the centering of the arc on the nucleus. The lack of a symmetric shell on the other side of the galaxy can be due to the faintness of the structure and/or to projection effects, especially if the detected arc lies in the foreground and the other in the background with respect to the galaxy. Alternatively, it could be the remnant of a past interaction, although there are no other signs of tidal disturbance, nor is the nucleus offset from the host galaxy.

TABLE 2

COMPANION OBJECTS NEAR 0138−097

Object	Separation (arcsec)	P.A.[a] (deg)	m_R
0138−097	...	...	17.48 ± 0.05
B	2.32	175	23.2 ± 0.3
C	1.45	198	22.1 ± 0.1
D	1.92	303	24.1 ± 0.4
E	4.87	244	24.6 ± 0.3

[a] Position angle from north toward east.

3.7. *1ES 1959+650*

This *Einstein* Slew Survey source was identified as a BL Lac object based on the high optical polarization and ratio of radio to X-ray emission (Schachter et al. 1993). The optical spectrum (Perlman et al. 1996) is dominated by the starlight from the host galaxy, which is well resolved in our *HST* image, with a radial profile well described by a de Vaucouleurs law plus a point source; a pure disk model is ruled out. Best-fit parameters are $m_R = 14.92 \pm 0.05$ mag and $r_e = 5\overset{''}{.}1 \pm 0\overset{''}{.}1$ for the galaxy and $m_R = 15.4 \pm 0.1$ mag for the point source. At redshift $z = 0.048$, this corresponds to $M_R = -22.5$ mag and $r_e = 6.6$ kpc for the galaxy and $M_R = -21.5$ mag for the nucleus. Heidt et al. (1999), fitting a PSF plus de Vaucouleur model, found similar values, $M_R(\text{host}) = 14.77$ mag and $r_e = 11$ kpc.

Some small deviations from the $r^{1/4}$ law are, however, evident, indicating a disturbed morphology. Indeed, after subtracting a scaled PSF from the image, a prominent dust lane is apparent along the major axis, $\sim 0\overset{''}{.}2$ north of the nucleus (Fig. 12).

With a single image, it is very difficult to calculate the mass of gas in the dust lane. We make a rough estimate assuming that the galaxy is intrinsically symmetric and that the difference in luminosity between opposite sides is entirely due to dust absorption. The dust extinction is then $A_R = 0.26$ mag in the R band or $A_V = 0.35$ mag in V, using the extinction curve of Cardelli, Clayton, & Mathis (1989). This can be converted to hydrogen column density via $E(B-V) = 3.1 A_V = \log N_{\rm H} - 21.83$ atoms cm^{-2} mag^{-1} (Shull & Van Steenberg 1985; Rieke & Lebofsky 1985). Given the observed dust surface area of $\sim 6 \times 10^{42}$ cm^2, the total gas mass is $\sim 5 \times 10^7$ $M_\odot$ with a dust mass of $\sim 5 \times 10^5$ $M_\odot$ for a gas-to-dust ratio of 100 (Bohlin, Savage, & Drake 1978). This figure is not unusual in normal elliptical galaxies (Wiklind, Combes, & Henkel 1995) but has not been reported previously in a BL Lac host, possibly because of the lower resolution of ground-based images, in which the dust lane could be washed out by scattered light from the nucleus and/or host galaxy.

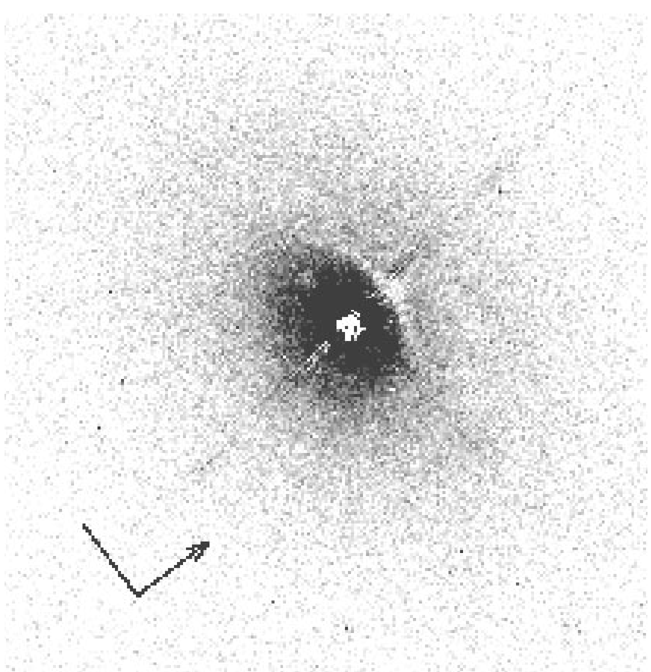

FIG. 12.—WFPC2 F720W image of 1959+650 after subtracting a scaled PSF. There is a large dust lane (pale arc) $0\overset{''}{.}8$ north of the nucleus, an unusual feature in BL Lac host galaxies. The straight structure inclined at $\sim 45°$ is a remnant spike from the PSF. The arrow points north and is $1\overset{''}{.}38$ (30 pixels) long.

4. DISCUSSION AND CONCLUSIONS

We have presented *HST* observations of seven unusual BL Lac objects from our *HST* snapshot survey (Urry et al. 1999b). Four are tentative candidates for gravitational lensing. These include three close doubles with one or more nearby galaxies that are plausible foreground lensing galaxies. For 0033+595, given the nonnegligible probability of a chance alignment with a foreground star and the clearly different colors of the two components, the possibility of a gravitational lens is not strong. Color and VLA coordinates suggest that the BL Lac is object B (Figs. 1 and 3). The case of 0502+675 is much stronger because the two images have similar luminosity ratios in both R and H bands, $\Delta m = 1.4 \pm 0.2$ and 1.5 ± 0.2 mag, respectively. The case of 1440+122 remains unclear because of the lack of an image in a second filter. The lensing scenario can be tested with spatially resolved spectroscopy; for the candidate with $1\overset{''}{.}6$ spacing this can be done from the ground, while for the other two, both of which have separations of $\sim 0\overset{''}{.}3$, *HST* or comparable resolution is required.

The fourth candidate for gravitational lensing is a partial ring of three arcs, possibly an Einstein ring, slightly offset from the unresolved BL Lac object. If this is a case of lensing, then the BL Lac object would be in the foreground, its host galaxy and (likely) surrounding cluster constituting the lensing mass, while the arcs would be images of one or more background galaxies. This is the opposite of the usual scenario, where the AGN is lensed by a foreground object. There are two resolved spots on the arcs themselves; if these were galaxies associated with a cluster around the BL Lac object (at $z > 0.7$), then their absolute magnitudes would be $M_R \lesssim -22.7$ mag (including a K-correction of 1.5 mag). This figure is not unreasonable for a galaxy but is ~ 1 mag brighter than an M^* galaxy, so it is possible that those structures are actually background object(s) magnified by the lens. Our WFPC2 image was not very deep, so additional galaxies within the ring and/or additional structure in the rings should easily be visible in a deeper *HST* image. (Because they are very thin, the rings would have very low surface brightnesses in typical ground-based seeing and so would be difficult to detect, and in any case they will remain unresolved, losing important lens-mapping information.) The alternative (nonlensing) explanations cannot be ruled out but seem somewhat less likely. Whatever the case, this BL Lac object remains unique.

The redshift distribution of BL Lac objects in our snapshot survey sample peaks below $z \sim 0.5$, although the redshifts of BL Lac objects are poorly known because of the weakness of detected features. About one-third have no measured redshift, and many measured values are either lower limits based on intervening absorption, as for 1517+656, or are based on features in the "host" galaxy. In at least some cases, like 1440+122, the reported redshift could refer to the lensing galaxy rather than the BL Lac object (Ostriker & Vietri 1985). Hence it is possible that the average redshift of our sample is somewhat bigger than $z \sim 0.5$. At such a small redshift, the probability of lensing is vanishingly small, so that if all lens candidates were confirmed, the incidence of lensing in this sample of 100 BL Lac objects would be much higher than in comparable surveys of quasars. For comparison, in samples of quasars with $1 \lesssim z \lesssim 2.5$, the incidence of strong lensing is roughly 1–2 in 1000 (Kochanek 1996), albeit at lower spatial resolution, and the expected number decreases rapidly with decreasing AGN redshift.

Considering only lens candidates with separation greater than 1″, we have only one (weak) case, 0033+595. The *HST* snapshot survey for lenses found $\lesssim 4$ lenses with such large separation in a sample of ∼500 bright quasars (Maoz et al. 1993). Allowing for the smaller size of our sample and a factor of ∼2 lower mean redshift, we would expect $\ll 0.4$ lenses in our BL Lac sample. Thus, for separations of ∼1″ or more, our survey may not be terribly out of line, especially considering the small number statistics.

Interestingly, Stocke & Rector (1997) reported an overdensity, by a factor of 4–5, in the number of Mg II absorption systems detected in the spectra of BL Lac objects relative to quasars and suggest this is the result of a magnification bias due to microlensing. The magnification bias for a particular sample depends on the steepness of the differential number counts. The high frequency of absorption lines and the large number of candidate lenses may both be due to a large magnification bias if the luminosity function of BL Lac objects is steep. Note that, out of the ∼300 BL Lac objects known, at least one is already a confirmed lens (0218+357, with separation 0″.34; Patnaik et al. 1992, 1993).

Time delays in gravitationally lensed, variable AGNs have been used to estimate the Hubble constant. For the three best cases, the ensuing errors on H_0 remain large simply because of uncertainties in the lens mass model: (1) 1115+080, for which $H_0 = 44 \pm 4$ or 65 ± 5 km s^{-1} Mpc^{-1} (Schechter et al. 1997; Impey et al. 1998); (2) 0957+561, for which the published value is $H_0 = 64 \pm 13$ km s^{-1} Mpc^{-1}, not including modeling uncertainties (Kundic et al. 1997); and (3) the BL Lac object 0218+357, for which a very short time delay, 12 ± 3 days, gives $H_0 \sim 60$ km s^{-1} Mpc^{-1} (Corbett et al. 1996). In the latter case, thanks to the large and rapid flux variability, combined with the small separation of the BL Lac images, only 80 days of observation were required to measure the time delay, to be compared with the almost 20 yr spent on 0957+561. Furthermore, the resolved milliarcsecond radio structure of 0218+257 greatly constrains the lens mass model. Since BL Lac objects are likely to be expanding superluminally, the source itself will map out the lensing plane in just a few years!

The uncertainties in measuring H_0 in individual lenses argues that new lenses are quite useful. Especially valuable are lensed BL Lac objects, in which the flux variability should be large and rapid (Ulrich, Maraschi, & Urry 1997), and the superluminal expansion of the radio source offers new and powerful constraints. Our close separation pairs, 0502+675 and 1440+122, if confirmed as gravitational lenses, will be especially powerful and convenient tools for estimating H_0. The time delay calculated using a simple isothermal mass model and a source redshift of $z \sim 1$ is ∼35 days. (More detailed models can be determined when the source and galaxy redshifts are known.) In this case, monitoring over a period of 4–6 months should be sufficient to estimate a useful value of H_0.

If instead these BL Lac pairs are shown to be true binaries, they will be the first such close-separation pairs of quasars, which can be used to study the role of tidal interactions in the AGN phenomena. At present, we do not have the data necessary to discriminate among these different hypotheses. To be confirmed as gravitational lenses, spectroscopic observations are required.

Among the other unusual sources presented in this work, 0806+524 shows an intriguing arclike structure 1″.9 from the nucleus, which may be the remnant of a past galaxy merger. The object 1959+650 is found to be hosted by a gas-rich galaxy, with a total dust mass of roughly 5×10^5 $M_\odot$. Large quantities of dust are quite often observed in elliptical galaxies, but perhaps because of the difficulty of observing them near a bright nucleus, they have not been reported for BL Lac hosts. The weakness of the emission lines in this class of AGN is sometimes attributed to a lack of gas surrounding the central power source (but see Scarpa & Falomo 1997), but the present observations of 1959+650 certainly argue against such an idea, demonstrating that at least 1 BL Lac resides in a gas-rich galaxy.

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