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Host galaxy and close environment of BL Lacertae objects

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ABSTRACT

High-resolution *R*-band images for 16 BL Lacertae (BL Lac) objects are reported. The data allow us to study the properties of the host galaxies and the close environment with sub-arcsec resolution. We are able to detect the surrounding nebulosity for 11 sources, while four remain unresolved. One case (0235 + 164) is complex and it is considered in detail. We discuss the average properties of host galaxies, including a number of objects previously investigated with the same instrumentation and analysis procedure. It is found that in all studied cases, the host galaxies are elliptical or bulge-dominated systems. Although for some objects the presence of a disc galaxy cannot be ruled out, there are no convincing justifications for preferring disc rather than elliptical models. The average absolute magnitude of host galaxies is $M_R = -23.5$ ($H_0 = 50$ km s^{-1} kpc^{-1} and $q_0 = 0$).

For six objects we have detected companions, which are often resolved and are located at a projected distance from the BL Lac object of about 10–40 kpc. This gives support to the idea that interactions may be important to the BL Lac phenomenon, and is consistent with the finding that many BL Lacs are located in groups of galaxies.

Key words: BL Lacertae objects: general – galaxies: general.

1 INTRODUCTION

BL Lacertae (BL Lac) objects are under current investigation at many frequencies because their extreme properties of non-thermal emission, polarization and strong and rapid flux variability make them challenging to understand. The recent discovery that some of them are strong emitters at γ frequencies lends additional support (see for example von Montigny et al. 1995 and references therein) to the basic current idea that BL Lac objects are sources which have plasma moving at relativistic speeds (i.e. jets) closely aligned with the line of sight of the observer.

This scenario clearly implies that there are objects intrinsically identical to BL Lacs that have a jet (or jets) pointing away from the observer's line of sight. It was proposed (e.g. Urry & Padovani 1995 and references therein) that radio galaxies of Fanaroff–Riley (FR) type I morphology may represent the parent population of BL Lacs. Some support to this hypothesis was given based on a comparison of statistical counts and taking into account the effects of the beaming on the luminosity function.

A direct test of this hypothesis is to compare the observed properties, not modified by beaming, of BL Lacs with those of their parents. Both host galaxies and galaxy environment properties are basically independent of orientation effects. While a search of the nebulosities surrounding BL Lacs was undertaken soon after the discovery of BL Lacs, the properties of the galaxies hosting BL Lacs have only recently been investigated in any detail (Abraham, McHardy & Crawford 1991; Stickel, Fried & Kühr 1993; Wurtz, Stocke & Yee 1996). From past studies it is recognized that host galaxies are elliptical or bulge-dominated systems of absolute magnitude comparable with that of giant ellipticals. Some examples of BL Lac objects in a disc-dominated galaxy have been proposed (1415 + 255: Halpern et al. 1986; 1413 + 135: McHardy et al. 1991; 1418 + 54: Abraham et al. 1991). In other cases (1415 + 255: Romanishin 1992; 1418 + 54: Stickel et al. 1993) the disc hypothesis was disproved or a different interpretation (lensing) was given (1413 + 135: Stocke et al. 1992; 1418 + 54: Stickel, Fried & Kühr 1090; 0205.7 + 3509: Stocke, Wurtz & Perlman 1995). Preliminary investigations of the close environments have suggested that asymmetries and/or distortion of the surrounding nebulosity may be a rather frequent phenomenon (Falomo, Melnik & Tanzi 1990). Moreover, some objects

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exhibit close companions which in some cases have turned out to be galaxies interacting with the host galaxy (Falomo, Pesce & Treves 1995). This is consistent with the finding that BL Lacs are preferentially located in poor groups of galaxies (Fried, Stickel & Kühr 1993; Smith et al. 1995; Pesce, Falomo & Treves 1994, 1995).

The presence of a strong nuclear source and the lack of a known redshift combine to hinder the determination of the properties of the host galaxies of BL Lacs. To mitigate the effects due to the bright point source (see e.g. Abraham, Crawford & McHardy 1995), observations with the highest possible resolution are needed. The use of *Hubble Space Telescope* (*HST*) data would thus clearly assist in this study. Some observations of this kind have been already obtained and others are planned.

In this paper we present high-resolution ($\lesssim$1 arcsec) images of a sample of 16 BL Lac objects, and derive the properties of the immediate environment. Together with four other sources (0521 − 365, 0548 − 322, 2155 − 305, and 2356 − 31) already studied, we are able to discuss the nebulosities around 14 objects using a homogeneous analysis.

The objects are not drawn from a complete sample but represent different examples of BL Lac objects with various characteristics: radio versus X-ray selection, absence or weakness of emission lines, variability and pure featureless spectrum (no known redshift) sources. For some of these latter sources, no previous investigations are available and their images are first presented here. For the objects of unknown redshift, the study of the nebulosity yields a lower limit of the distance assuming their hosts are similar to those of other BL Lacs.

The main aim of this paper is to study the properties of the immediate environment of BL Lcas, and in particular to derive the host properties using mainly sub-arcsec images and adopting a homogeneous analysis. Throughout the paper, $H_0=50$ km s^{-1} kpc^{-1} and $q_0=0$ is adopted.

The outline of the paper is as follows. In Section 2 we describe the observations and the data analysis. Results of the surface photometry and modelling of the brightness profile are given in Section 3, together with a description of the close environment. The whole sample of objects is then discussed in Section 4, and their average properties are compared with other samples of BL Lacs as well as of radio galaxies.

2 OBSERVATIONS AND DATA ANALYSIS

Observations were obtained using the 3.5-m New Technology Telescope (BNTT) at the European Southern Observatory (ESO), operated either at the local site (La Silla) or via remote control at the ESO headquarters in Garching, Germany. Images were acquired during several observing runs from 1992 to 1994, using the direct imaging system SUperb Seeing Imager (SUSI) (Melnick, Dekker & D'Odorico 1992) which is installed at one of the Nasmyth foci of the NTT. All images were acquired using an *R*-band filter (Cousins system) and a CCD (TK 1024) with 24-μm pixel size corresponding to 0.13 arcsec on the sky. Conditions were photometric and seeing was very good, and in most cases the FWHM was < 1 arcsec. Observations of standard stars (Landolt 1983) were used to set the photometric zero-point. We obtained most of the images, centred on the BL Lac object, with typical exposure times from 2 to 20 min. For many targets, we secured one short and one long exposure in order to better study the host galaxy and its immediate environment.

The images were processed in the standard way (bias-subtracted, trimmed, flat-fielded, and cleaned of cosmic rays) using the Image Reduction and Analysis Facility (IRAF) procedures. A complete journal of the observations is given in Table 1.

In order to enhance low-contrast features very close to the bright nucleus, we have deconvolved the central portion of the frames centred on the BL Lac using the Lucy–Richardson algorithm, with a number of iterations ranging from 5 to 25. Because this procedure might produce artefacts, we have retained as real all the features that are also visible in the original frames. The region around the BL Lac object is reproduced in Fig. 1 (opposite p. 242) for selected targets.

2.1 Point spread function

The point spread function (PSF) was derived independently for each observed frame, averaging many stars detected in

Table 1. Journal of observations.

IAU Name	z	Date	m_{sky}	Exp.	seeing
0048-097	...	92 Aug 1	20.5	300	0.95
	...	94 Jan 7	20.7	120	0.75
		94 Jan 7	20.7	1200	0.80
0109+224	...	92 Aug 1	21.1	300	1.30
0118−272	>0.56	92 Aug 1	19.6	660	0.90
		93 Mar 12	19.6	6x120	0.90
0235+164	0.94	94 Jan 7	20.3	120	0.87
		94 Jan 7	20.6	1200	0.85
0301−243	(0.26?)	92 Jul 31	21.6	2x600	0.75
0323+022	0.147	94 Jan 7	20.6	120	0.70
		94 Jan 7	20.6	1200	0.70
0414+009	0.287	94 Jan 7	21.0	120	0.62
		94 Jan 7	21.0	1200	0.65
0422+004	(0.2?)	94 Jan 7	20.6	120	0.72
		94 Jan 7	20.6	1200	0.62
0754+100	(0.3?)	94 Jan 5	20.8	120	0.65
		94 Jan 5	20.8	1200	0.73
0823−223	>0.910	94 Jan 5	20.0	120	0.65
		94 Jan 5	20.0	1200	0.72
0829+046	0.18	94 Jan 5	20.7	120	0.75
		94 Jan 5	20.7	1200	0.80
1034−293	0.312	94 Jan 5	20.3	120	0.62
		94 Jan 5	20.3	1200	0.68
2005−489	0.071	92 Aug 1	21.3	180	1.00
2201+044	0.028	92 Aug 1	20.9	120	1.10
2254+074	0.19	92 Aug 1	20.7	420	0.97
2335+031	0.27	92 Aug 1	20.0	360	0.85

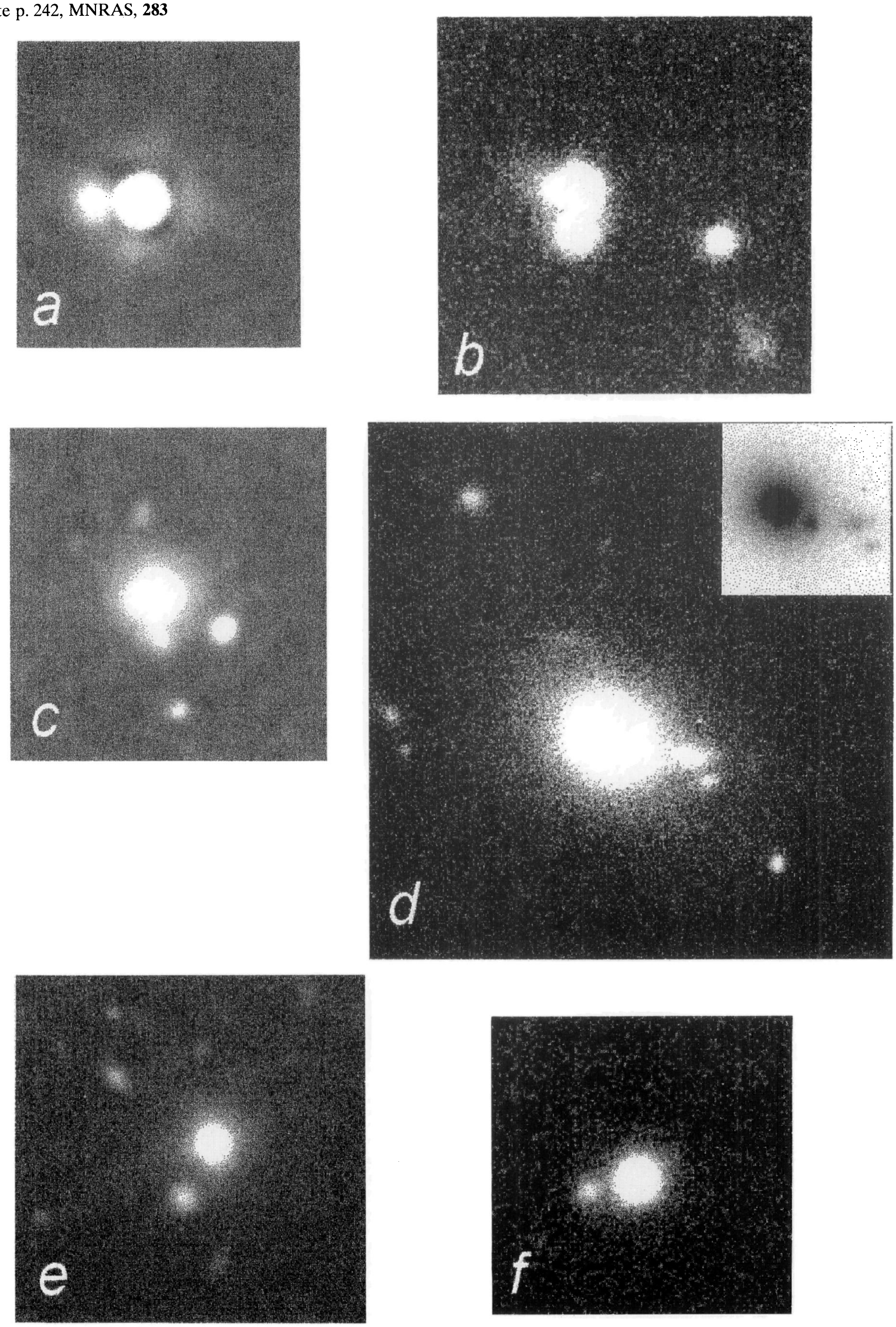

Figure 1. Central portion of the *R*-band NTT images for selected BL Lacs showing close companions and/or peculiar features. (a) 0048 − 097: deconvolved image (14 × 14 arcsec^2) with the eastern resolved companion; (b) 0235 + 164: central portion (17 × 17 arcsec^2) of the original frame showing the southern companion and the eastern elongation; (c) 0301 − 243: deconvolved image (27 × 27 arcsec^2) showing companions and a jet-like feature; (d) 0323 + 022: (34 × 24 arcsec^2) distorted nebulosity together with extended south-west companions; in the inset the closer, more compact companion is well visible; (e) 0829 + 046: (22 × 22 arcsec^2) extended companions around the BL Lac source; (f) 2335 + 031: (16 × 16 arcsec^2) the BL Lac object and its close resolved companion to the east; (g) 0414 + 004: the luminous host galaxy together with the galaxies in the associated cluster (field 85 × 85 arcsec^2). For all images, north is up and east to the left.

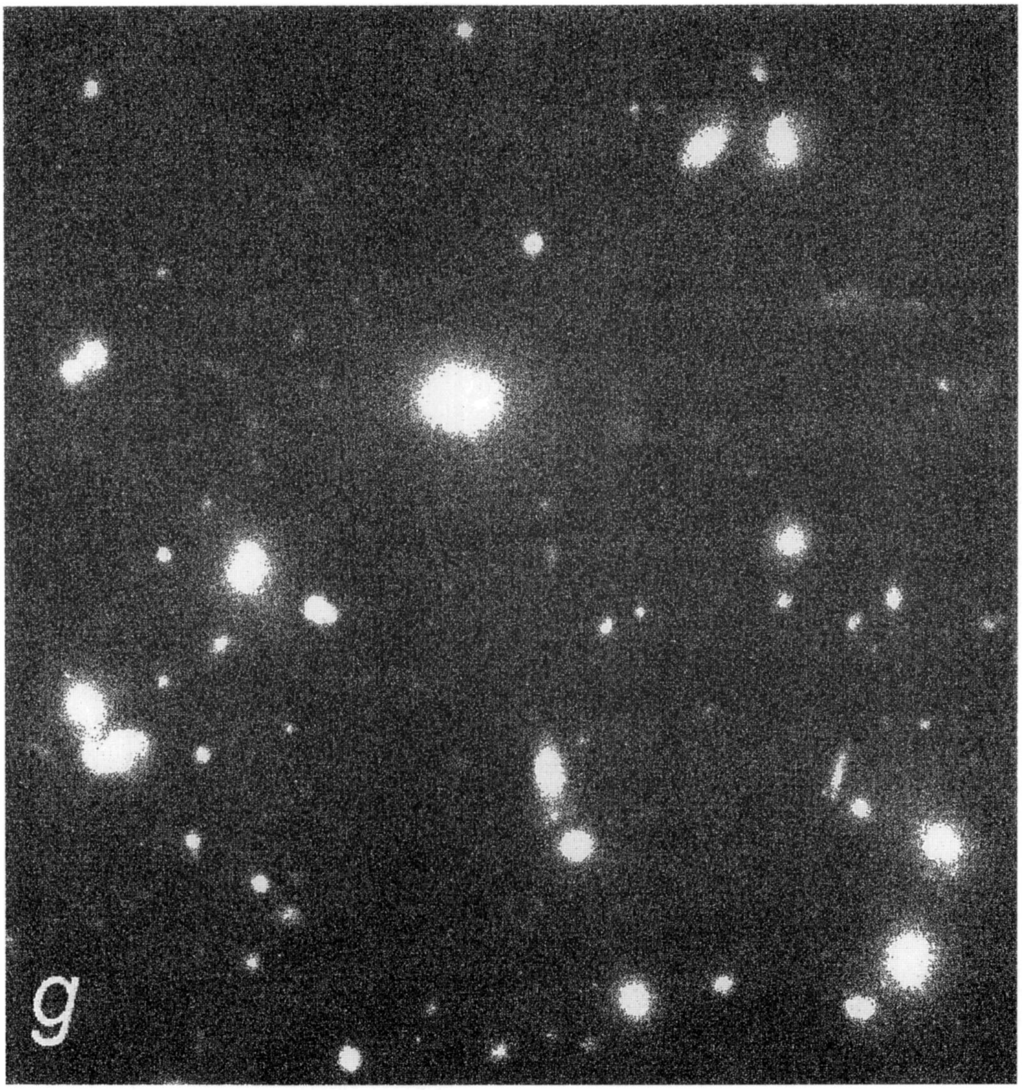

Figure 1 – *continued*

the frame. When bright (saturated) and faint (unsaturated) stars were available, we combined them in order to properly determine the core and the wings of the PSF. This is particularly important for the marginally resolved objects, because the reliability of the derived host properties depends on assumptions of the PSF shape. The combination of stars of different magnitudes permits us, in fact, to greatly increase the dynamical range of the PSF.

If sufficiently bright stars are not present in the same frame, we use those of other frames obtained during the same observing run and with similar seeing conditions. This ensures that the wings of the PSF, which are essentially dependent on the instrument rather than on the seeing conditions, are adequately modelled. We believe that the extrapolation to large radii of the PSF, derived from a single unsaturated star, may lead to an underestimate of the contribution of the nebulosity around bright point-like sources. Moreover, for moderately high-redshift objects, where the apparent size of the observable host galaxy is of the order of a few arcsecs, the use of a PSF with underestimated (or unreliable) wings may lead to an incorrect evaluation of the host morphology derived from the luminosity profile.

2.2 Surface photometry

We have performed a surface photometry analysis of all objects imaged using an interactive numerical mapping package (Astronomical Image Analysis Package – AIAP: Fasano 1990). This package allowed us to derive photometrical and structural parameters of host galaxies. First we modelled the sky background using a first- or second-order two-dimensional polynomial, and subtracted it from the original (reduced) frames. We then computed isophotes down to the surface brightness magnitude $\mu_R \sim 26$ mag arcsec^{-2}.

All the regions around the target that were contaminated by companion objects and/or by small defects were properly masked using an interactive procedure. Each masked isophote was fitted by an ellipse, using an interactive χ^2 algorithm with $K\sigma$ rejection. The parameters of each ellipse were free, except for the centre which would optionally be fixed to the position of the previous isophote. Beside the coordinates of the centres (X_0 and Y_0), we derived the semi-major axes (a), the ellipticities ($\varepsilon = 1 - b/a$ where b is the semiminor axis), the position angles (θ) and the coefficients of the Fourier analysis of the residuals (see e.g. Nieto et al. 1992). Errors in the surface photometry were computed according to Fasano & Bonoli (1990), by taking into account the sky level uncertainty.

The surface brightness profile was analysed with respect to a generalized radius [$r = (1-\varepsilon)^{1/2}$]. We fit the observed profile with a model consisting of a point source (described by a PSF) plus a galaxy described by either a de Vaucouleurs law or an exponential disc convolved with the proper PSF.

Because the surface photometry analysis cannot determine the brightness profile in the region within ~ 1 arcsec from the nucleus, we have also obtained the brightness profile of the inner region ($\lesssim 3$ arcsec) from the azimuthally averaged fluxes. The matching of these two profiles (one obtained from results of the isophotal analysis and the other from the simple averaged radial profile) in the common region (at radii around 2–3 arcsec) was always excellent, so in the following we consider this combined profile. In the few cases where the BL Lac nucleus was saturated in the long exposure image, the azimuthally averaged profile was derived from the short exposure image. This procedure permits us to improve the dynamical range of the image and is practically error-free when the level of saturation is low. We found that, in the common region, the agreement of the brightness profiles derived from saturated and non-saturated objects was always excellent.

For the sources with unknown redshift and with no detected nebulosity, we determined a lower limit of the redshift by assuming that a host galaxy, of average absolute magnitude (see below), was present but not detectable by the observation. This was obtained by adding a simulated galaxy (at various redshifts) to the image of the object and evaluating the redshift at which the nebulosity would become detectable.

3 RESULTS FOR INDIVIDUAL OBJECTS

0048 − 097 This is a well-studied BL Lac object (see e.g. Falomo et al. 1988 and references therein) belonging to the 1-Jy radio sample. No spectral features have been reported in the optical spectra (Stickel et al. 1993; Falomo, Scarpa & Bersanelli 1994) and the redshift remains unknown.

We obtained several images of this object, most of them with subarcsec resolution. The best images of 1994 January show clearly the presence of a faint ($m_R = 22.5$) close companion about 2.5 arcsec east of the BL Lac nucleus. This feature is also visible on previous images and was first suggested in our preliminary study of a number of BL Lacs (Falomo et al. 1990). This companion was not detected by Stickel et al. (1993) but this may be the result of their substantially lower resolution (1.3 as opposed to 0.8 arcsec). The companion object appears resolved (see Fig. 1) and might be associated with the BL Lac source.

The BL Lac object is unresolved and its radial brightness profile perfectly matches that of the PSF (see Fig. 2). Assuming the host galaxy to be an elliptical of $M_R = -23.5$, we set a lower limit to the redshift of $z2 > 0.5$.

0109 + 224 We have only one 5-min image for this object, observed with 1.3-arcsec seeing. The object is unresolved and has an apparent magnitude of $m_R = 16.8$. Its brightness profile is identical to that derived for the PSF (see Fig. 2). Although the resolution of this image is not very good, we set a limit to the redshift of 0.4 if the BL Lac is hosted in a galaxy of $M_R = -23.5$. There are a number of galaxies located north-east of the BL Lac object (see Fig. 3). The closest is one with $m_R \approx 21.3$, ~ 8 arcsec from the BL Lac source.

0118 − 272 This is a relatively bright BL Lac source that shows a power-law spectrum in the UV to near-IR region (see e.g. Pian et al. 1994). The optical spectrum is featureless apart from a narrow absorption doublet identified as Mg II 2800 and yielding a lower limit to the redshift of $z = 0.559$ (Falomo 1991).

We secured images of this target at two epochs (see Table 1). In one case, several short (2 min) exposure frames were obtained from the 'service operation' mode available on the NTT. These images were then co-added to obtain one single average frame. Our images show that this source is not resolved even at sub-arcsec resolution. The radial brightness profile is well-matched by the estimated PSF down to the faintest surface brightness (see Fig. 2). The observation is still consistent with the presence of a luminous host ($M_R = -23.5$) at $z \gtrsim 0.6$.

There are several faint galaxies in the neighbourhood of the BL Lac object. Within a circle of 30 arcsec radius (corresponding to ~ 250 kpc at $z = 0.56$), we find ~ 15 galaxies with magnitudes in the range of 20.5 to 21.5. The closest galaxy ($m_R = 21.1$) lies at 8 arcsec (PA ~ 40). These galaxies are likely to form a foreground small cluster at $z = 0.56$.

0235 + 164 A0 0235 + 164 is a very intriguing object. Its optical spectrum is quasi-featureless and exhibits one intervening absorption system at $z = 0.524$ and a much weaker system at $z = 0.89$, while weak emission lines are observed at $z = 0.94$ (Cohen et al. 1987). Optical imaging clearly shows the complexity of the field around A0 0235 + 164. A faint ($m_R = 20.5$) compact companion is located at 2 arcsec south, the spectrum of which shows emission features at $z = 0.524$ [the same as the intervening system (Smith, Burbidge & Junkkarinen 1977)]. In addition, an extended nebulosity, elongated to the east up to ~ 2 arcsec, was reported by Stickel et al. (1988) and by Yanni, York & Gallagher (1989). Different interpretations of this eastern image elongation have, however, been proposed. Stickel et al. interpret this elongation as the result of a foreground disc galaxy slightly displaced from the centre of the BL Lac nucleus. Yanni et al. ascribed the elongation to an extended emission feature located ~ 1.5 arcsec east of the nucleus. More recent observations by Abraham et al. (1993) yield support to the presence of a luminous foreground galaxy (an elliptical was assumed) and tried to reconcile the observations by Stickel et al. and Yanni et al., suggesting the presence of both features observed (extended galaxy with low surface brightness and the compact structure at 1.5 arcsec east). These observations led Stickel et al. to propose that 0235 + 164 is a gravitational lensing candidate BL Lac object.

Our observations, obtained during a low state of the source, have resolution significantly better than that of the images obtained by Stickel et al., and comparable to that of Abraham et al. (see Figs 1 and 3).

A resolved emission structure ($m_R \approx 22.4$) is present at ~ 1.7 arcsec east of the BL Lac nucleus and extends for about 1.5 arcsec towards PA ~ 45. This feature is very similar to, but slightly brighter than, that located 10 arcsec at PA = 238 (labelled as B in Fig. 3). This emission structure is the major feature responsible for the eastern elongation of the image of A0 0235 + 164. No clear evidence of an extended emission superposed on to the BL Lac is apparent from this image. Moreover, we do not see any signatures of emission knots or structures close to the western side of the BL Lacs like those reported by Abraham et al. (1993).

In order to study the brightness profile of the BL Lac source, we have excluded all the regions that are affected by the presence of the southern and eastern companions. Since this field is rather complex, we masked different regions in order to understand their effects on the resulting parameters. From this analysis we obtained a radial profile as well as the centre and ellipticity of each ellipse. No systematic off-centring of ellipses was found with amplitude larger than 0.1 arcsec. As an alternative approach, we computed an average brightness profile directly from the observed data using only the region defined by $270° < \mathrm{PA} < 360°$ with respect to the nucleus of the BL Lac object. We obtained the radial intensity distribution from the centre (which is rather well-defined) of the BL Lac image up to a distance of 5 arcsec, where only the sky signal is recorded, averaging many single radial profiles in that region. This is quite a safe procedure, because this region appears uncontaminated by other objects in the field and it is directly derived from the observations. The comparison of the profiles obtained with the two different procedures are in good agreement, so we assume it to be the radial brightness profile of the object (see Fig. 2).

The BL Lac profile (see Fig. 2) is in perfect agreement with that of the PSF up to ~ 1.2 arcsec, and then a small excess is apparent. This excess is, however, still compatible with the PSF if a 1 per cent systematic error is assumed for the sky level. On this basis it might be regarded as a possible hint for the presence of either an extended structure around the object (cf. Stickel et al. 1988; Abraham et al. 1993) or a very close, diffuse companion object on the western side. In the first hypothesis we find that the surrounding nebulosity (modelled by an elliptical galaxy) would have a total magnitude $m_R \approx 21.5$ and effective radius $r_e \sim 1.2$ arcsec. This yields a fainter and smaller object than that reported by Stickel et al. 1988 and Abraham et al. 1993.

0301 – 243 Our image of this BL Lac object clearly shows an extended nebulosity with complex morphology and close companions (see Figs 1 and 3). The redshift for this source, however, remains unknown. The immediate region around the object is rich with faint galaxies and there is a marked enhancement of galaxy density within ~ 60 arcsec from the BL Lac object. Spectra of two galaxies angularly close to 0301 – 243 indicate they are at $z = 0.263$, suggesting that a cluster of galaxies of Abell richness class 0 might be associated with the BL Lac source at this redshift (Pesce et al. 1995).

There are many faint resolved companions superposed on to the nebulosity surrounding this BL Lac. After masking these companions, we performed the surface photometry analysis. The external isophotes have ellipticity $\varepsilon = 0.3$. The radial profile is adequately represented by a point source plus the elliptical model (see Fig. 2 and Table 2), while the fit with an exponential disc is less acceptable. The companions have magnitudes in the rang $m_R \sim 21.5$ to 22.5 and could be modest galaxies ($M_R = -19$ to -20) at $z \sim 0.26$.

0323 + 022 This is a highly variable X-ray source (Doxey et al. 1983) that is identified with a BL Lac object (Margon & Jacoby 1984; Feigelson et al. 1986) at redshift 0.147 (Filippenko et al. 1986).

Previous optical images have reported an extended asymmetric nebulosity, the properties of which are consistent with that of an $M_V \approx -22.5$ elliptical. Our high-resolution image shows that the reported asymmetry of the nebulosity is due (at least in part) to close resolved companion objects (see Figs 1, 3). The closest object (A: $d = 2.4$ arcsec, PA = 330°) is unresolved and it could be a chance superposition with a galactic star, although it is still plausible that it represents the nucleus of a merging galaxy. Spectroscopy of this close companion would clarify this point. The other bright knots (see Fig. 1) could be the remnants of interacting galaxies. At the faintest observed levels of surface brightness ($\mu \sim 25$ mag arcsec^{-2}), the isophotes appear elon-

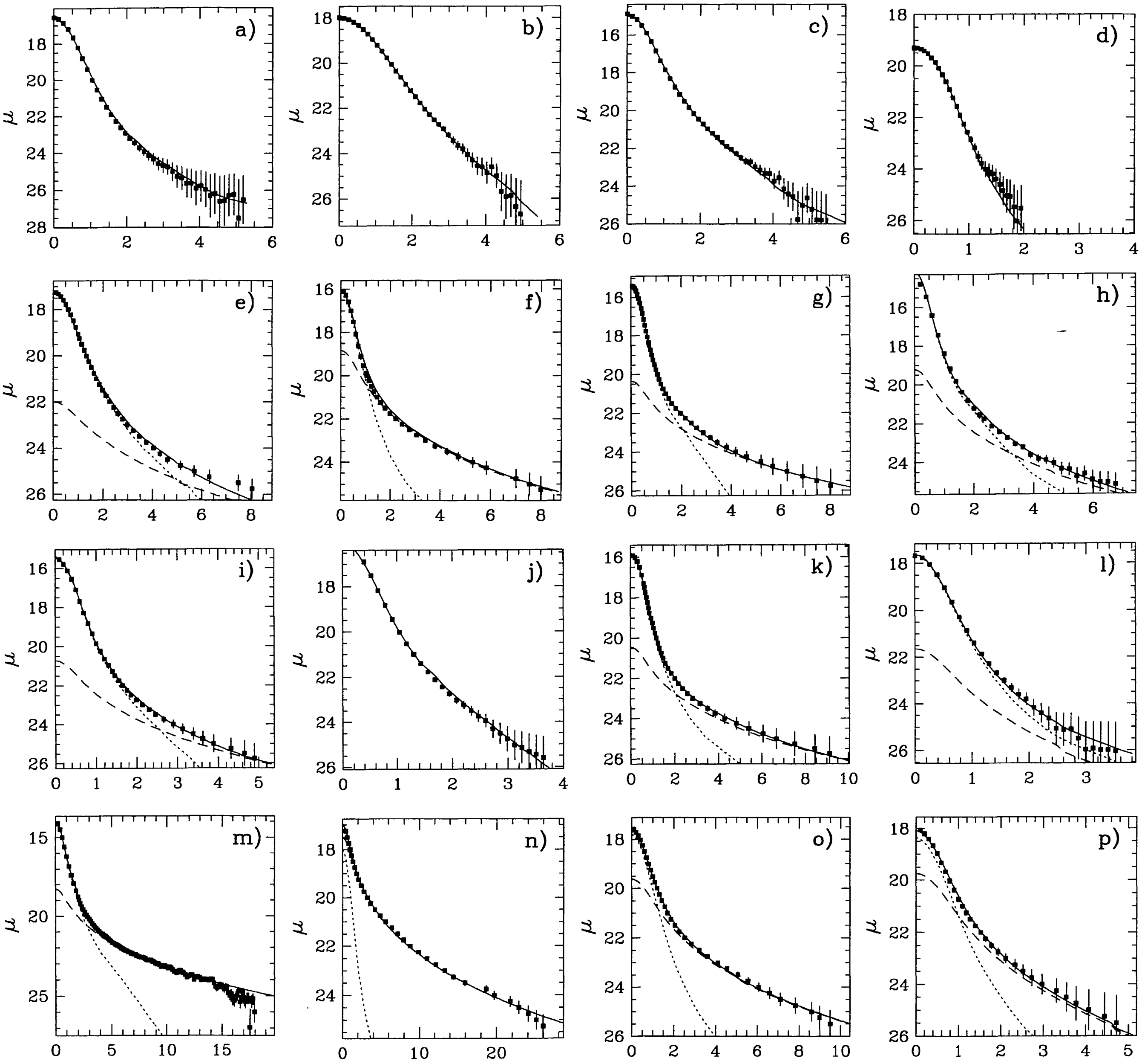

Figure 2. Radial surface brightness profiles of observed BL Lacs in the R band. Observed profiles (filled squares) ar shown, as derived by surface photometry analysis (see text), compared with the fitted model (solid line). The point source is modelled by a scaled PSF (dotted line), while the host galaxy (dashed line) is given by a convolved $r^{1/4}$ law. Where the dotted line is not visible it is superposed on to the solid line. (a) 0048 − 097; (b) 0109 + 224; (c) 0118 − 272; (d) 0235 + 164; (e) 0301 − 243; (f) 0323 + 022; (g) 0414 + 009; (h) 0422 + 004; (i) 0754 + 100; (j) 0823 − 223; (k) 0829 + 046; (l) 1034 − 293; (m) 2005 − 489; (n) 2201 + 004; (o) 2254 + 074; (p) 2335 + 031.

gated towards the south-west companion (labelled as D in Fig. 3).

It is noticeable that the bright galaxy ~1 arcmin east of H 0323 + 022 (projected distance ~200 kpc) is at $z = 0.16$ and might have interacted with the BL Lac host. After proper masking of the regions contaminated by companions, we have performed the surface photometry analysis of the host galaxy as described above. The nucleus is centred within 0.1 arcsec on the galaxy isophotes. The maximum ellipticity is $\varepsilon = 0.2$, with a slight tendency to increase towards faintest surface brightness. The radial profile may be represented by a point source plus an elliptical galaxy with $M_R(\text{tot}) = -23.1$ and $R_e = 8$ kpc. A disc model, on the other hand, gives an unacceptable fit.

0414 + 009 This is a moderately distant ($z = 0.287$) object that is found in a cluster of galaxies of Abell richness class 0 (McHardy et al. 1992; Falomo, Pesce & Treves 1993, hereafter FPT93). The host galaxy is a luminous elliptical that is the dominant member of the associated cluster (Falomo & Tanzi 1991; McHardy et al. 1992). The new images presented here essentially confirm the previous findings, and, thanks to the better resolution (seeing ~0.65 arcsec), it is possible to obtain more reliable values for host parameters. The luminosity profile (see Fig. 2) can be well fitted by an

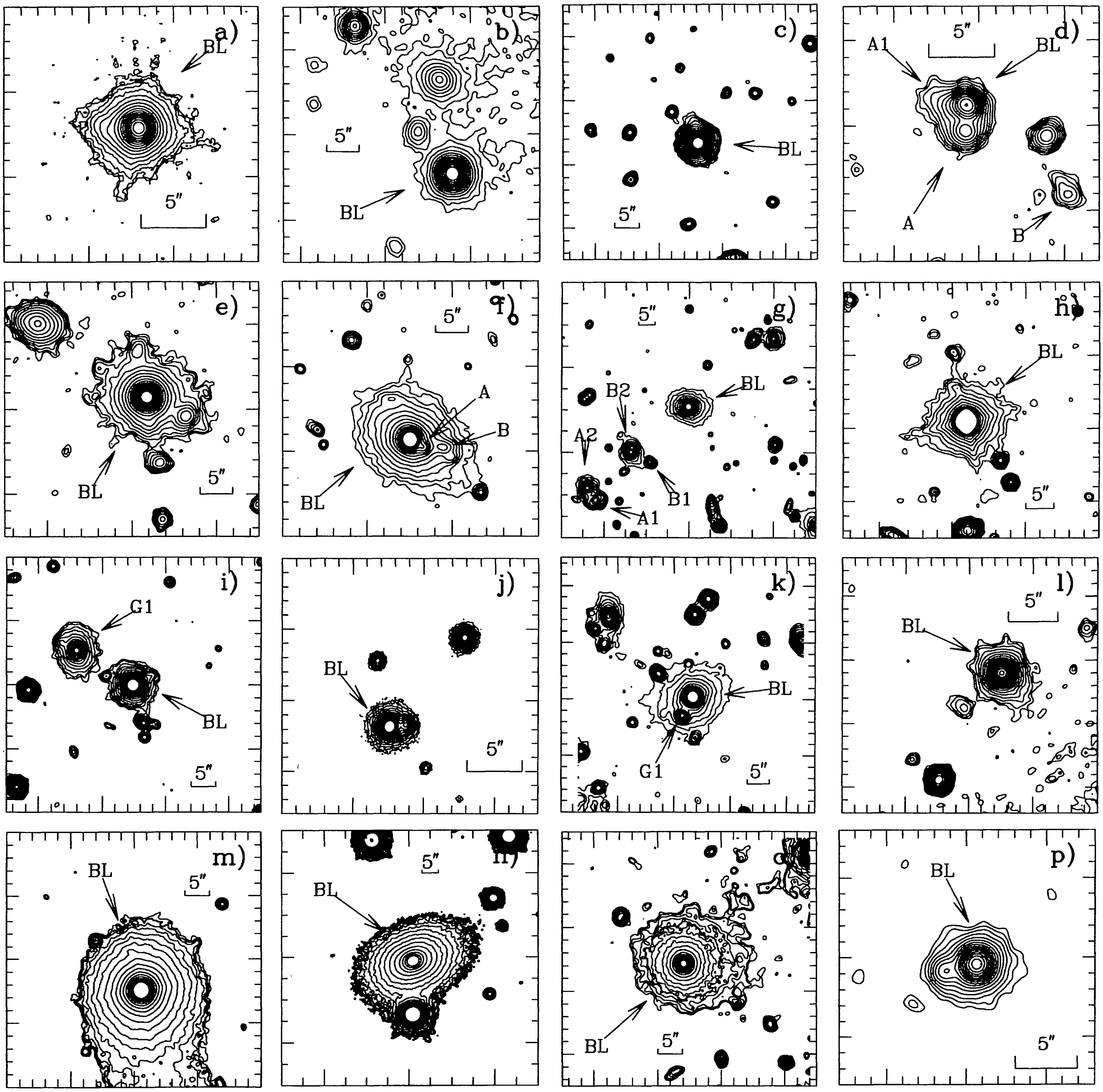

Figure 3. Contour plots in the R band of the region around the BL Lac objects. The images have been slightly smoothed in order to emphasize the faintest isophotes. The spacing between isophotes is 0.5 mag while faintest shown levels are typically $\mu_R = 25.5$ mag arcsec^{-2}. North is up and east to the left. (a) 0048 – 097; (b) 0109 + 224; (c) 0118 – 272; (d) 0235 + 164; (e) 0301 – 243; (f) 0323 + 022; (g) 0414 + 009; (h) 0422 + 004; (i) 0754 + 100; (j) 0823 – 233; (k) 0829 + 046; (l) 1034 – 293; (m) 2005 – 489; (n) 2201 + 004; (o) 2254 + 074; (p) 2335 + 031.

elliptical model (plus point source) with effective radius of 5 arcsec (29 kpc at $z = 0.287$). This effective radius is substantially larger than that reported previously (about 1 arcsec). The discrepancy is mainly due to the reliability of points close to the nucleus (around ~2 arcsec) that allow us to better constrain the model. With worse seeing, only the farthest (and faintest) part of the profile has a significant fraction of the light from the host galaxy. In the latter case, the net effect would be to underestimate the effective radius. In spite of a large difference of effective radius, the total magnitude is consistent with previous findings (cf. also Abraham et al. 1995).

The excellent resolution of these images permits us to clarify a number of points about the associated group of galaxies. For a number of galaxies in this field, spectroscopy was obtained that confirmed that the galaxies form a physical group, with the galaxy hosting H0414 + 004 being the dominant member (FPT93). The object labelled B1 by FPT93 is composed of a star (late spectral type) and a fainter galaxy ~1 arcsec to the south-west. Also, the galaxy

Table 2. Properties of surrounding nebulosity.

Object	resolved	H/BL[a]	Ell-Model (m_{tot})	(r_e'')	C[b]	CL[c]
0048−097	unresolved	0	...	...	Y	...
0109+224	unresolved	0	...	...	...	...
0118−272	unresolved	0	...	...	...	Y
0235+164	complex	...	(21.5)	(1.2)	Y	...
0301−243	resolved	0.13	18.6	5.2	Y	Y
0323+022	resolved	0.73	16.9	2.3	Y	...
0414+009	resolved	0.22	17.7	5	...	Y
0422+004	resolved	0.06	17.9	2.0	...	...
0754+100	resolved	0.07	18.9	2.3	...	...
0823−223	unresolved	0	...	...	Y	...
0829+046	resolved	0.22	17.6	4.8	Y	Y
1034−293	resolved	0.1	20.4	1	...	...
2005−489	resolved	0.28	14.8	6	...	Y
2201+044	resolved	20.3	13.9	6.3	...	...
2254+074	resolved	1.63	16.8	3.5	...	...
2335+031	resolved	0.90	18.4	0.9	Y	...

[a]Host to BL Lac total flux ratio
[b]Presence of close companions
[c]Associated group/cluster of galaxies

B2 is actually an elliptical and has a fainter companion galaxy at 1 arcsec to the north. Galaxies C1 and C2 have early spiral and irregular barred Magellanic-like morphology, respectively. Finally, the galaxy pair A1 and A2 is composed of an elliptical (A2) and a late barred spiral (A1). The presence of the bar in A1, together with a faint emission which appears to connect these two galaxies (that have the same redshift), supports the interaction hypothesis.

0422 + 044 There is no spectroscopic redshift for this source, but Abraham et al. (1991) were able to resolve the object and, assuming an elliptical morphology, they estimated a redshift of ~0.3.

Our image was very good (seeing of 0.6 arcsec) and the object was clearly resolved. The radial brightness profile (see Fig. 2) was fit with both elliptical and disc models, and although the elliptical one is slightly better, the disc model cannot be ruled out. If the redshift is 0.2 (0.3) the host galaxy would have $M_R = -22.9$ (-24). The two faint objects at 9.4 and 13.5 arcsec (PA ~ 310) are unresolved and are probably projected stars, while the $m_R \approx 20$ southern object ($d = 19.5$ arcsec; PA = 270) is a spiral galaxy possibly associated with the host of BL Lac (cf. Pesce et al. 1995).

0754 + 100 Our high-resolution images show this source clearly resolved but, due to the relatively bright nucleus, both elliptical and disc models can fit the data. Abraham et al. (1991) were also able to resolve this source, but no host parameters are given. There is only a tentative redshift ($z = 0.66$, Persic & Salucci 1986) for this object. If the elliptical model is assumed at this redshift, the host would be extremely luminous ($M_R \sim -25$), while for the disc model a less extreme (but still very bright) value is found. This leads us to consider this redshift rather unlikely. On the other hand, we note that the galaxy G1 (13 arcsec north-east of the BL Lac object) is at $z = 0.27$ (Pesce et al. 1995), and if associated with 0754 + 10 would be at a projected distance of ~70 kpc. At a redshift of 0.3 the host galaxy would have a much more reasonable absolute magnitude ($M_R = -23.1$).

0823 − 223 This is a low galactic latitude ($b \approx 9°$) source whose optical spectrum shows an absorption system of Mg II 2800 Å at $z = 0.910$ (Falomo 1990). At this redshift, the host galaxy is expected to be completely hidden by the light of the BL Lac nucleus, even with sub-arcsec resolution. High-resolution imaging may, however, be useful to detect the object responsible for the intervening absorption and/or to search for possible foreground galaxies superposed on to the BL Lac image. The source is in fact highly luminous ($M_V < -29$) and it is therefore a candidate for gravitational lensing.

There is a compact companion located at 1.5 arcsec west of the BL Lac that was found to be a galactic star (cf. Veron-Cetty & Veron 1993). The other two closest objects (5 and 6 arcsec, respectively, from 0823 − 22) appear unresolved and are also most likely galactic stars. The radial luminosity profile is well matched by that of a scaled PSF, so there is no indication of a superposed nebulosity (at least down to $\mu_R = 25.5$ mag arcsec^{-2}).

0829 + 046 We secured two good images of this object ($z = 0.18$, Falomo 1991) that clearly show it is surrounded by an extended nebulosity up to 10 arcsec from the nucleus. The external isophotes have $\varepsilon \approx 0.15$ and PA = 130. There are a number of galaxies superposed on to the nebulosity. The closest and brightest one (G1 at ~5 arcsec, PA = 190) is apparently another low-luminosity AGN not associated with 0829 + 04. After masking all companion objects (see Fig. 3), we studied the brightness profile and found that it was very well fitted by an $r^{1/4}$ law plus a point source (see Fig. 2). Although the elliptical model gives a better representation than the disc model, the latter cannot be ruled out from the present data. Also, Abraham et al. (1991) were able to resolve this source and found that both elliptical and disc models can adequately fit their data. We derive an absolute magnitude $M_{tot}(R) = -23.1$ that is more than 1 mag fainter than was found by Abraham et al. (1991) after accounting for the different redshift used and the isophotal-to-total magnitude correction.

1034 − 293 This source is reported in the list of BL Lacs by Hewitt & Burbidge (1987). The optical spectrum shows narrow and broad emission features at $z = 0.312$. Because of the strength of the emission lines, and Hα in particular (equivalent width ~50 Å), 1034 − 293 is probably a highly polarized quasar rather than a BL Lac object. Although the image quality is excellent (seeing < 0.7 arcsec), this object is only marginally resolved. Fitting the profile with an elliptical model yields an apparent magnitude of $m_R = 20.4$. This translates to a rather faint ($M_R \sim -21.8$) absolute magnitude. Because of the uncertain classification of this source we have not included it in the following analysis.

2005 − 489 We secured two images of this source under

1 arcsec seeing. Unfortunately, in both images there is a smear of scattered light, due to a bright nearby star, superposed onto the BL Lac image. Because this affects the analysis mainly at the faintest flux levels, we have restricted the surface photometry to relatively bright levels. This is a low redshift ($z = 0.071$) object and its nebulosity is quite evident (although the nucleus is very bright). The host galaxy is rather round ($\varepsilon \lesssim 0.05$) and the luminosity profile is well described by the elliptical model plus point source. The derived absolute magnitude ($M_R = -23.7$) is slightly fainter than that ($M_R = -24.2$) derived by Stickel et al. (1993).

2201 + 04 This source is a very low redshift ($z = 0.028$) BL Lac object which also exhibits a weak narrow and broad emission lines (e.g. Falomo et al. 1987). The galaxy is well detected with just a short exposure image. The isophotes have almost constant ellipticity $\varepsilon \approx 0.2$ and show a modest twisting (ΔPA ~ 20) from PA = 100 to 120. The radial profile is quite well represented by the elliptical model from the faintest observed levels to a few arcsec from the nucleus, where an excess is present that we attribute to a modest point source (see Fig. 3).

2254 + 074 We obtained three subsequent images of this source with seeing of 1 arcsec and then stacked them in an average frame. The nebulosity is well visible and looks rather round ($\varepsilon < 0.1$). The galaxy extends up to ~10 arcsec at surface brightness $\mu_R \sim 26$ mag arcsec^{-2}. The radial profile is well fitted by an elliptical model plus point source, yielding a galaxy of absolute magnitude $M_R = -23.9$. A disc model plus point source also gives a satisfactory fit of the radial profile, although it is not better than the elliptical one. In addition, our analysis of the Fourier coefficients does not show any significant excess due to the discy isophotes, thus favouring the elliptical model. The host galaxy of this source has been also studied by Stickel et al. (1993) who find very similar parameters for the host galaxy. These authors also took spectra of two galaxies close to the BL Lac object, finding one at the same redshift as 254 + 07. A fainter value ($\Delta m \sim 0.5$) of absolute magnitude is reported by Wurtz et al. (1996).

2335 + 031 There is a companion object at 2.5 arcsec east of the BL Lac nucleus clearly visible in our images. This was already noted by Craine, Tapia & Tarenghi (1976) using photographic plates. Our sub-arcsec images are able to resolve this companion object. The projected distance from the nucleus of the BL Lac is only 13 kpc and could be interacting with the BL Lac host galaxy, as suggested by the presence of emission lines at $z = 0.27$ in the spectrum of 2335 + 031 (Veron-Cetty & Veron 1993). The luminosity profile of the host galaxy, after proper masking of the companion, can be well fitted by a point source plus elliptical galaxy model. The derived parameters are similar to those reported by Romanishin 1987 (although we measured a brighter host by 0.5 mag) on the basis of a considerable lower resolution image. Abraham et al. 1991 could also resolve this source but were unable to constrain any model for the host galaxy. We tried to fit the observed brightness profile using a disc model instead of the elliptical one and found a good representation of the profile, therefore both models remain valid from the present analysis. In the latter case the magnitude of the host galaxy would, however, be 0.5 mag fainter. After subtracting a model for the BL Lac object (point source plus galaxy), we studied the luminosity profile of the companion galaxy and found that it may be well represented by an elliptical galaxy of $M_R \sim -20.8$ (assuming $z = 0.27$).

4 DISCUSSION

4.1 Properties of host galaxies

Table 2 summarizes our results. For the resolved objects we give the total apparent magnitude and effective radius of the elliptical galaxy model. In addition, the ratio of the flux from the galaxy to that of the nuclear point souce is reported. For 11 out of 16 objects, we have been able to resolve the nebulosity around BL Lac objects. For all the resolved objects the properties of the host galaxies are consistent with an elliptical galaxy model, and although in some cases an underlying disc galaxy cannot be excluded, we found no cases in which the disc model gives a significantly better representation of the data than does the elliptical galaxy model. In Table 3 we report the main parameters of the host galaxies after correction for galactic extinction and k-correction. For the resolved objects with no spectroscopic redshift, we have adopted a likely value enclosed within parentheses. This is based on the apparent magnitude of the nebulosity and/or on the redshift of close companion galaxies. In Table 2, we have also added parameters for some other host galaxies that we have investigated using the same procedures. the average absolute magnitude for the 14 sources in Table 3 is $\langle M_R \rangle = -23.5 \pm 0.6$. Excluding 0422 + 00 and 0754 + 10 (that have only a rough estimate of their redshift) we get essentially the same result.

Our average absolute magnitude is similar to that ($\langle M_R \rangle = -23.8$; 7 objects) given by Stickel et al. (1993), but fainter than that ($\langle M_R \rangle = -24.3 \pm 0.4$, assuming $V-R = 0.9$ and including corrections for the different adopted cosmol-

Table 3. Host galaxies.

IAU name	z	$M_R(tot)$	Re(Kpc)	Refs.
0301−243	(0.26?)	(-22.9)	(28)	1
0323+022	0.147	-23.1	8	1
0414+009	0.287	-24.3	5	1
0422+004	(0.2?)	(-23.3)	(8)	1
0521−365	0.055	-23.2	9	3
0548−322	0.067	-24.2	51	2
0754+100	(0.3?)	(-23.1)	(14)	1
0829+046	0.18	-22.7	20	1
2005−489	0.071	-23.7	11	1
2155−305	0.116	-24.4	13	4[a]
2201+044	0.028	-22.5	5	1
2254+074	0.19	-23.9	15	1
2335+031	0.27	-23.3	5	1
2356−309	0.165	-23.1	13 3	5

[a]Derived from photometry in the Gunn i filter.
References: Falomo 1991; Falomo et al. 1991; Falomo 1994; Falomo et al. 1995; this paper.

ogy and isophotal-to-total magnitude conversion) reported by Abraham et al. (1991) for 6 objects. In a large recent study of BL Lac hosts with $0.03 < z < 0.64$, Wurtz et al. (1996) found the average absolute magnitude to be $\langle M_R \rangle = -24.0 \pm 0.7$ (after conversion from Gunn r to R magnitudes assuming an intrinsic colour $r-R=0.6$). However, since some luminosity evolution may be present (cf. Wurtz et al. 1996), if only the sources with $z < 0.2$ are considered the average absolute magnitude becomes $\langle M_R \rangle = -23.7 \pm 0.6$, which is in good agreement with our findings.

The average absolute magnitude ($\langle M_R \rangle = -23.5$) of BL Lac hosts is about 0.5 mag fainter than the average found for FR type I radio galaxies reported by Owen & Laing (1989), when allowance is made for the different cosmology adopted and conversion from isophotal-to-total magnitude is done. This difference is maintained even using total magnitudes derived from a different sample of FR type I radio galaxies, and using the same procedure adopted here (see Fasano, Falomo & Scarpa 1996).

On the basis of this kind of comparison it was noted (Wurtz et al. 1996) that the luminosities of BL Lac hosts are more similar to those of FR type II radio galaxies than of FR type I. The difference in host luminosity between FR type I and FR type II is small, and both classes cover a similar range of absolute magnitudes (cf. Owen & Laing 1989). The two classes are clearly much more differentiated in the radio power. Moreover, the difference in absolute magnitude may be less pronounced when using different samples (see Fasano et al. 1996). The lack of highly luminous host galaxies among BL Lacs has been also related to the finding that BL Lacs avoid the richest environments. However, in this context it is worth noting that some examples of luminous ($<M_R> \lesssim -24$) BL Lac host galaxies (see 0548 − 322, 0414 + 009 and 2155 − 305) exist at low redshift, and they are also in moderately rich environments (Abell class 2 to 0).

In the 4–5 cases in which the object appears unresolved, either the redshift is unknown or it is at $z \gtrsim 0.5$. Therefore, for these sources our observations are still compatible with their being hosted in giant ellipticals. In all cases that we have observed, we found the BL Lac nucleus to be well centred on the surrounding nebulosity within an accuracy of 0.1 to 0.3 arcsec. Although some individual cases of BL Lac/blazar objects behind a foreground galaxy may exist, the undetected off-centring of the nebulosity, in our sample as well as in other samples, argues that the microlensing hypothesis (Ostriker & Vietri 1985) is not an explanation for the class properties.

4.2 The immediate environment

From the 16 images presented here, we have detected close companion objects in several cases. In five sources (0048 − 097, 0301 − 243, 0323 + 022, 0829 + 046, 335 + 031) we found one or more faint companion objects (see Fig. 1) within angular distance < 5 arcsec. In some other cases a companion galaxy is apparent at larger angular distance (e.g. 0118 − 272, 0109 + 22, 0754 + 10, 0414 + 00). Other additional examples of close companions were reported elsewhere (2155 − 305: Falomo et al. 1991; 0548 − 322: Falomo et al. 1995).

In most cases the companions are resolved, and are five or more magnitudes fainter than the BL Lac object. While we know that for some of these cases the companion galaxies are at the same redshift as the BL Lac source, for the other objects (in particular for those with unknown redshift) there is no spectroscopic proof of physical association with the BL Lac object. It is worth noting, however, that because close companions seems to occur rather frequently around BL Lacs it is unlikely that they are, in general, chance alignments. At the typical redshift of observed sources, the companion objects have a projected distance to the BL Lac nucleus corresponding to 10–40 kpc. This is consistent with the hypothesis that the companions are associated with the BL Lac source and may either be interacting with it or be the leftover of a merging event. The few well-studied cases of BL Lacs with associated companions (Falomo et al. 1991, 1995) give additional support to this hypothesis.

Since the sample of objects presented here is not complete in any way, the statistical relevance of companions for BL Lacs is still difficult to assess. We note also that from imaging studies performed with ground instruments, even on a more large and complete sample, some companions might be not detected because of the low resolution of observations and the large difference of magnitude with respect to the bright BL Lac nucleus. A quick survey made with *Hubble Space Telescope* imagers would give more suitable data, in terms of both the statistical relevance and the capability of detecting signatures of interactions with the host galaxies.

Recent studies of quasar environments conducted with *HST* (cf. Bahcall, Kirhakos & Schneider 1995; Disney et al. 1995) have shown that very similar companions are often found within a few arcsec from the observed QSOs. The projected linear distance between companion and QSO is very similar to that found in the case of BL Lacs. Also, the luminosities of BL Lac companions, assuming they are at the same redshift as the BL Lac source, appear comparable to those found for QSO companions. It is therefore reasonable to believe that we are looking at the same kind of phenomenon in different types of AGNs. The presence of close companions has long been believed to be associated with fuelling and possibly triggering the activity in the nucleus of a galaxy. As in the case of QSOs, a systematic, combined imaging and spectroscopy study of these features, possibly performed on a complete sample, should be carried out in order to assess the importance of these 'ancillary' features in the activity phenomenon.

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