Astron. Astrophys. 341, 683–692 (1999)

ASTRONOMY
AND
ASTROPHYSICS

High-resolution imaging of Einstein Slew Survey BL Lacertae objects*

J. Heidt[1], K. Nilsson[2], A. Sillanpää[2], L.O. Takalo[2], and T. Pursimo[2]

[1] Landessternwarte Heidelberg, Königstuhl, D-69117 Heidelberg, Germany
[2] Tuorla Observatory, FIN-21500 Piikkiö, Finland

Received 2 June 1998 / Accepted 29 October 1998

Abstract. High-resolution images of 7 newly identified BL Lac objects (among them one BL Lac candidate) at z ≤ 0.2 from the Einstein Slew Survey are presented for the first time. In all cases we were able to resolve the host galaxy. Our 2−dimensional analysis of the host galaxies shows that all these BL Lac objects are embedded in elliptical galaxies with an average $M_R = -23.1$ and r_e = 10 kpc. One BL Lac might have both a bulge and an underlying disk. These results are similar to those obtained for the hosts of other BL Lac objects.

We searched in our BL Lac objects for host galaxies, whose surface brightness distribution does not follow a pure de Vaucouleurs law and determined the statistical significance with numerical simulations. In two BL Lac objects (1ES 1255+244 and 1ES 1959+650) significant deviations were found.

The environments of the BL Lac objects are highly interesting. In at least two (perhaps three) cases we found evidence for interaction. All BL Lac objects (except one) have at least 2 companions, some of which are bright, within a projected distance of 60 kpc from the BL Lac. In two cases we found 5 companions within 50 kpc. This implies that gravitational interaction is potentially important to the BL Lac phenomenon at least in these sources.

Key words: methods: data analysis – galaxies: active – galaxies: BL Lacertae objects: general – galaxies: elliptical and lenticular, cD – galaxies: interactions

1. Introduction

BL Lac objects, characterized by strong variability from the radio up to the gamma regime, variable polarization in the radio and optical domain as well as weak or absent emission lines in their spectra, are the most enigmatic active galactic nuclei (AGN). Due to their extreme properties it is nowadays believed that their energy output is dominated by Doppler−boosted synchrotron radiation arising from a relativistic jet, which is seen in a very small inclination angle (Urry & Padovani 1995). As a consequence observing their host galaxies and close environment is a challenge for observers, since the light of the relativistic jet in many cases overwhelms the light from the host galaxy.

However, such studies are very important. By comparing isotropic properties of the individual subclasses of radio−loud AGN, the "Unified Scheme" can be tested. For example, one would expect to find similar host galaxies for BL Lac objects and their putative parents, the low−luminosity Fanaroff−Riley I radio galaxies. Comparing the properties of BL Lac host galaxies with "normal" (inactive) galaxies may give clues as to why some galaxies harbor an AGN and (perhaps) others not. Finally, they are one key to search for indications that the BL Lac phenomenon is related to merging/interaction processes of galaxies (feeding the monster) as seems to be the case for quasars (e.g. Hutchings & Neff 1992, Bahcall et al. 1995).

In recent years much effort has gone into studies of the host galaxies of BL Lac objects using ground−based telescopes, leading to a rapidly increasing number of resolved host galaxies up to redshifts of ~ 0.7. Most of them (perhaps all) are hosted by luminous elliptical galaxies ($M_R \sim -23.5$; e.g. Ulrich 1989, Abraham et al. 1991; Stickel et al. 1993; Falomo 1996; Wurtz et al. 1996). Observations with the HST, providing superior resolution, gave essentially the same results (Falomo et al. 1997, Jannuzi et al. 1997).

The immediate environment has so far not been studied in detail. Falomo et al. (1990) and Falomo (1996) noted the high frequency of close ($<$ 40 kpc), mostly faint ($M_R < -20$ if at the same redshift) companions among $\sim$ 20 observed BL Lac objects. For some BL Lac objects, it could be shown that their (bright) companions are either at a similar redshift or that they are physically associated (e.g. Stickel et al. 1993; Pesce et al. 1994, 1995). Finally there are a few cases, where signs of interaction and physical association have been observed through imaging and spectroscopy (e.g. Falomo et al. 1995).

In this paper we report the first high-resolution images of 7 newly identified BL Lac objects (among them one BL Lac candidate) taken from the Einstein Slew Survey sample (Perlman et al. 1996; hereafter P96). Their X−ray to radio flux ratios log f_x/f_r are > -11, which defines them as high−energy cutoff BL Lac objects (HBL, Giommi & Padovani 1994, Padovani & Giommi 1995). Due to their low redshifts ($z \leq 0.2$) we were

Send offprint requests to: J. Heidt (jheidt@lsw.uni-heidelberg.de)

* Based on observations made with the Nordic Optical Telescope, operated on the island of La Palma, jointly by Denmark, Finland, Iceland, Norway, and Sweden, in the Spanish Observatorio del Roque de los Muchachos of the Institute de Astrofisica de Canarias.

Table 1. Journal of the observations.

Object	z	Exp. [s]	FWHM [″]	kpc/1″
1ES 1255+244	0.141	900	0.67	3.41
1ES 1440+122	0.162	1200	0.65	3.81
1ES 1745+504	(0.45)	1800	1.11	(7.71)
1ES 1853+671	0.212	720	0.88	4.69
1ES 1959+650	0.048	990	0.67	1.32
1ES 2037+521	(0.05)	1500	0.97	(1.37)
1ES 2326+174	0.213	960	0.79	4.71

able to carry out a fully 2−dimensional analysis of their host galaxies. This allowed us not only to study the morphology of the host galaxies in detail, but also to investigate their close ($<$ 50 kpc) environment.

This paper is organized as follows. In Sect. 2 the observations and data reduction are summarized followed by a description of the data analysis in Sect. 3. In Sect. 4 we give a short overview of the results and describe than each object individually. The properties of the hosts as well as the environment are discussed in Sect. 5. Finally, we summarize in Sect. 6. Throughout the paper $\mathrm{H_0} = 50\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ and $\mathrm{q_0} = 0$ is assumed.

2. Observations and data reduction

The observations were carried out with the Nordic Optical Telescope on the nights July 8/9, 10/11 and 12/13 1996. A 1k CCD (scale 0.176″/pixel) and a R filter was used throughout. For most of the time we enjoyed excellent seeing conditions ranging from 0.65″ up to 1.1″ FWHM. The exposure times varied between 120s and 1800s depending on the brightness of the objects and the requirement not to saturate the BL Lac. The nights were photometric, standard stars from Landolt (1983) were frequently observed during each night to set the zero point.

The data were reduced (debiased, flatfielded using twilight flatfields), cleaned of cosmics, aligned and coadded. Dark current was proven to be negligible. A journal of the observations along with the targets, their redshift, the total integration time, the measured FWHM and the conversion from angular to linear scale is given in Table 1. The redshifts are from P96. For 1ES 1745+504 and 1ES 2037+521 (the former being a BL Lac candidate) no redshift is known yet. Based on the results of our analysis we assumed z = 0.45 and 0.05, respectively (see Sect. 4.1). The resulting redshift−dependent parameters are given in parentheses.

3. Data analysis

In order to model the BL Lac objects and their hosts we applied a fully 2−dimensional fitting procedure developed at Tuorla Observatory to the images. After masking close companions, faint features and projected stars we fitted 6 different models (three galaxy models with and without a nuclear point source) to the observed light distribution. The surface brightness I(r) of the galaxy at a distance r from its center was obtained from

$$\mathrm{I(r)} = \mathrm{I_e dex}\left\{-\mathbf{b}_\beta\left[\left(\frac{\mathrm{r}}{\mathrm{r_e}}\right)^\beta - 1\right]\right\} \qquad (1)$$

where $\mathrm{r_e}$ is the effective (half−light) radius of the galaxy, β is a shape parameter and b_β is a β−dependent constant (Caon et al. 1993). For our galaxy models we chose β = 0.25 (de Vaucouleurs profile), β = 1.0 (exponential disk) or left β as a free parameter. All galaxy models were convolved with the observed PSF. The nuclear point source was modeled with a scaled PSF, obtained by averaging several well exposed stars on the same frame as the BL Lac. We carefully checked for any PSF variations across the frames, but did not find any, except in the central regions ($\leq$ 2 pixel).

Our models had 6 to 10 free parameters depending on the model: the (x,y) center and magnitude of the core and the (x,y) center, magnitude, effective radius, ellipticity, position angle and optionally the β−parameter of the galaxy. The parameters were adjusted using an iterative Levenberg−Marquardt loop to find the minimum χ^2 between the model and the observed image.

The analysis of 1ES 1440+122 was very difficult due to the presence of a bright, close (projected distance $\sim$ 2.5″) companion. To overcome this, we used an iterative fitting procedure by fitting one of the two components first, subtracting it from the image, fitting the second, subtracting it from the original image, fitting the first etc. The iterations were stopped and final parameters adopted when the fitted models ceased to improve significantly.

Finally, the models for the BL Lac core and their hosts as well as for the bright companion of 1ES 1440+122 were subtracted from the images and aperture photometry performed of non−stellar objects (presumably galaxies) within a radius of 100 kpc from the BL Lac. Absolute magnitudes of the hosts were calculated using K−corrections adopted from Bruzual (1983), the galactic extinction was estimated from Burstein & Heiles (1982). For the absolute photometry of the companions we used the (estimated) redshift of the BL Lac.

4. Results

Although the presence of close companions (some of which are bright), stars or faint associated features made the analysis difficult for most of the sources, in every case a de Vaucouleurs model for the host galaxy gave a much better fit to the data than an exponential disk model. Leaving β as free parameter improved our fits as compared to the fits with β = 0.25 only marginally, with the exception of 1ES 1959+650 and 1ES 1255+244 and perhaps 1ES 2037+521. For 1ES 1959+650 we carried out further modeling, which will be described in detail in Sect. 4.1. We also estimated the significance of a deviation of β from 0.25 by numerical simulations, these are described in Sect. 5.1. In what follows, we will refer to the results of our fits with β = 0.25.

Table 2. Properties of the host galaxies of our BL Lac objects.

(1) Object	(2) m_{core}	(3) m_{host}	(4) F	(5) r_e [“]	(6) r_e [kpc]	(7) ϵ	(8) PA	(9) M_{host}	(10) β	(11) Δm_{core}	(12) Δm_{host}
1ES 1255+244	17.9	16.7	0.75	2.1	7.2	0.10	5	−23.2	0.18	0.15	−0.16
1ES 1440+122	17.6	17.2	0.59	2.3	8.8	0.18	170	−23.0	0.21	0.03	−0.09
1ES 1745+504	20.5	19.8	0.66	1.1	(8.5)	0.17	165	(−23.2)	0.28	−0.04	0.06
1ES 1853+671	19.2	18.1	0.73	2.0	9.4	0.12	155	−22.9	0.32	−0.08	0.10
1ES 1959+650	15.2	14.8	0.59	9.5	12.5	0.21	95	−23.0	0.41	−0.05	0.28
1ES 2037+521	19.3	15.9	0.96	9.0	(12.3)	0.19	120	(−23.2)	0.20	0.25	−0.20
1ES 2326+174	18.3	17.5	0.68	1.8	8.5	0.17	95	−23.4	0.17	0.17	−0.18

The results of our modeling are summarized in Table 2. Column 1 gives the object name, in columns 2 and 3 the magnitudes for the core and the host as derived from the model and in column 4 the host to total flux ratios F are presented. In columns 5 and 6 the half−light radii along the major axes in arcsec and kpc are shown, followed by the ellipticity in column 7 and the position angle PA (counted counterclockwise from north) in column 8. In column 9 the calculated absolute magnitudes are given. Finally, we display in columns 10−12 the results with β as free parameter and the resulting changes of the core and host magnitudes as compared to the fits with β = 0.25. As in Table 1, we assumed z = 0.45 for 1ES 1745+504 and z = 0.05 for 1ES 2037+521. Their redshift−dependent parameters are given in parenthesis.

In Figs. 1a−f and 2b−d we show the central region around each BL Lac before and after the subtraction of our model (host with β = 0.25+core except 1ES 1959+650, where the core and both the bulge and disk was subtracted). Although the residuals close to the center of the fitted objects sometimes look strong, they are in all cases fairly small compared to the total signal ($< 5\%$).

4.1. Results for individual objects

1ES 1255+244: The redshift of this source is z = 0.141 (P96). Our fitting procedure gives M_R = − 23.2 with r_e = 7.2 kpc and small ellipticity (ϵ = 0.1). The model fit is excellent as can be seen in Fig. 1a.

There are 2 brighter galaxies within 15″ from the BL Lac (A and B in Fig. 1a), with m_R = 20.4 and 20.6, respectively. Thus they would be fainter than $M_R = -20$, if at z = 0.141. The closest companion (A) is at a projected distance of 26 kpc. A relatively bright (m_R = 17.9) disk−type edge−on galaxy can be seen 23″ (80 kpc) to the north (C), which would have M_R = −22 at z = 0.141. Superimposed are a number of faint galaxies (e.g. to the west of the BL Lac).

1ES 1440+122: This is the most intriguing BL Lac object of our small sample. Its redshift is z = 0.162 (Schachter et al. 1993). The most remarkable feature is a very close, luminous companion 2.5″ (projected distance 9.5 kpc) to the west (Fig. 2b). As described in Sect. 3.2 we used an iterative fitting procedure to derive the parameters for the host galaxy of the BL Lac and for the close companion. The host galaxy is of typical brightness (M_R = −23.0), size (r_e = 8.8 kpc) and moderate ellipticity (ϵ = 0.18). The decentering (core vs. host centroids for the BL Lac) is negligible ($\sim 0.02''$). The companion is best fit by an early−type galaxy of similar brightness (M_R = −23.2) and size (r_e = 8.4 kpc), but of higher ellipticity ($\epsilon = 0.3$).

The residuals after the subtraction of our model for the BL Lac and companion are complex (Figs. 2c, d). Very close to the center of both fitted objects there are doughnut−like residuals, which are larger for the companion than for the BL Lac. Roughly along the major axis of the companion (north−south) there is additional diffuse emission left on both sides in the outer part of the galaxy. On top of the diffuse emission in the north is a low surface brightness feature $\sim$ 5″ from the center of the companion (already visible on the original frame). This feature could be a projected faint galaxy (B in Fig. 2d), although we can not rule out that it is part of the BL Lac or the bright companion. Whereas the residuals close to the center of both objects are artifacts due to the fitting procedure, the outer residuals for the companion − in spite of feature B − may be intrinsic to the source.

In order to test this, we carried out an isophotal analysis of the companion (after subtraction of our model for the BL Lac core + host) by fitting ellipses to the images according to the method outlined by Bender & Möllenhoff (1988). This method provides the azimuthally averaged surface brightness, ellipticity, position angle, the centers of the ellipses as well as the Fourier coefficients as a function of the semi−major radius *a* and semi−minor radius *b*. Our isophotal analysis of the companion shows clear indications of an isophote twist. Whereas ϵ grows from 0.2 at r = 2″ to 0.45 at 4.5″ and beyond, PA decreases from $\sim 30^{\circ}$ at 2″ to $\sim 10^{\circ}$ at 4.5″.

If we assume that the BL Lac and the companion are at the same redshift, our observations and the isophotal analysis suggests that we observe an interacting pair of very bright elliptical galaxies, one of which hosts an active nucleus. We note that the redshift of 1ES 1440+122 could be contaminated by its close companion. Therefore to verify our scenario redshifts of both galaxies are required.

The environment of 1ES 1440+122 is very interesting. The BL Lac is surrounded by $\sim$ 20 galaxies ($m_R \sim 20-22$), suggesting that 1ES 1440+122 is located in a group or small cluster of galaxies. Most of the galaxies are within 200 kpc of the BL Lac (Fig. 2a). We note that 5 galaxies (including the bright companion) are found within 8″ (30 kpc, A−E in Figs. 2c, d).

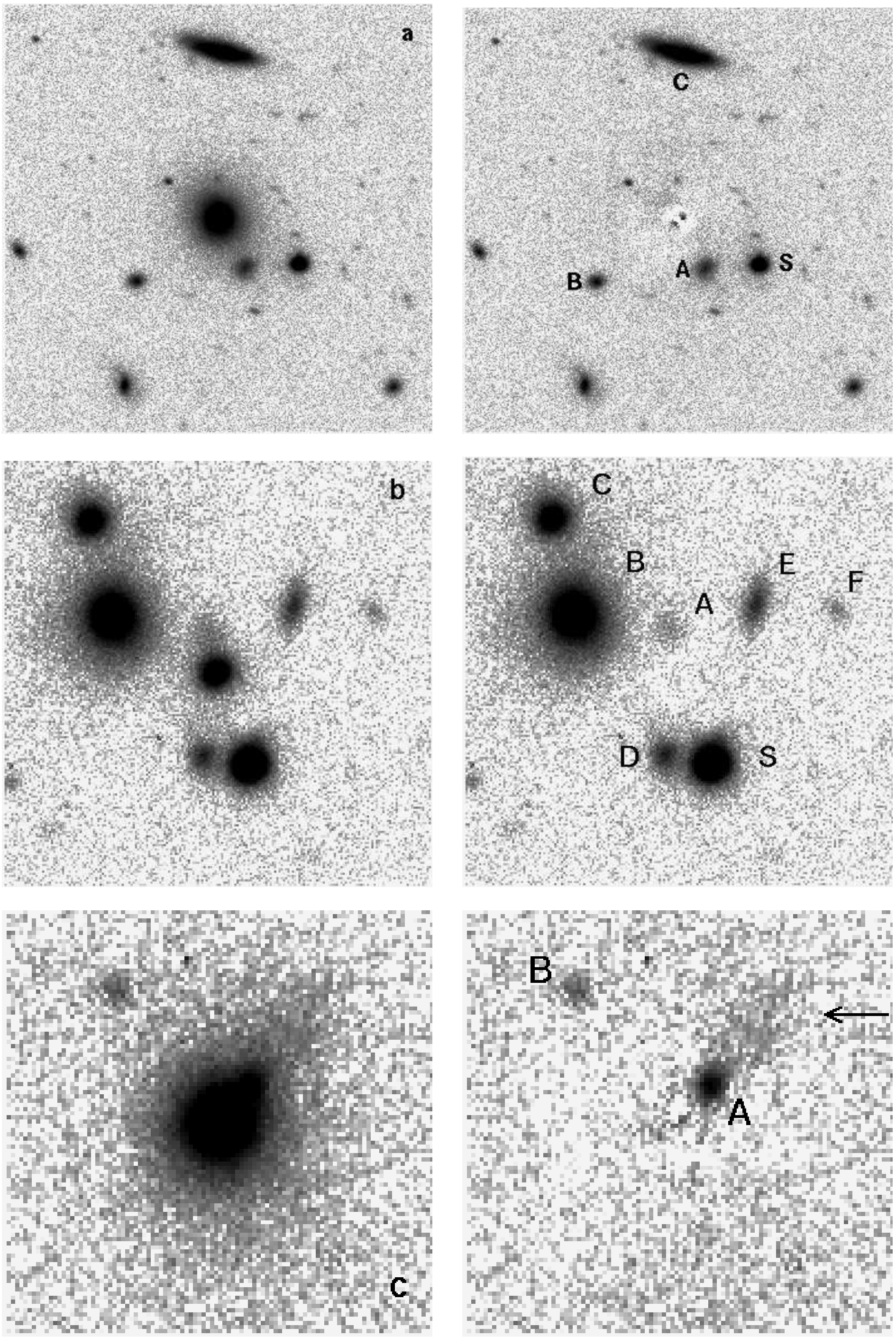

Fig. 1a–f. Images of the BL Lac objects observed. The left panel shows the central part of the original frames, the right panel the central part of the frames after subtraction of the BL Lac (convolved de Vaucouleurs model galaxy and scaled PSF, except 1ES 1959+650, where the model galaxy consists of a bulge and a disk). Galaxies discussed in the text are labeled, stars are labeled with "S". North is up, east to the left. The grey scale is logarithmic in order to enhance low surface brightness features. **a** 1ES 1255+244, $60'' \times 60''$ (200×200 kpc), **b** 1ES 1745+504, $34'' \times 34''$ (150×150 kpc), **c** 1ES 1853+671, $18'' \times 18''$ (85×85 kpc),

1ES 1745+504: This source is the BL Lac candidate from our Slew Survey subset. Its classification is still uncertain and no redshift is available (Perlman, priv. communication). Although our image of this source was taken under the worst seeing conditions (FWHM $\sim 1.1''$), the host galaxy is clearly resolved. Moreover, there is a faint feature towards the north (A in Fig. 1b). After proper masking this feature, the host can be fitted very well by an early−type galaxy with $\mathrm{m_R}$ = 19.8 and $\mathrm{r_e}$ = $1.1''$ (Fig. 1b).

Under the assumption that the host of 1ES 1745+504 has similar properties as the hosts of other BL Lac objects, we can try to estimate a redshift for 1ES 1745+504. The average $\mathrm{M_R}$ of the hosts of our BL Lac objects with firm redshift is −23.1 and the average $\mathrm{r_e}$ is 9.3 kpc (see Table 2). If we adjust the redshift of 1ES 1745+504 such that we derive similar values, a good guess would be z = 0.45. In that case we would derive $\mathrm{M_R}$ = − 23.2 and $\mathrm{r_e}$ = 8.5 kpc (including K−correction and galactic extinction). For z = 0.4 $\mathrm{M_R}$ would be −22.9, $\mathrm{r_e}$ = 7.9 kpc and for z = 0.5 $\mathrm{M_R}$ would be −23.6 and $\mathrm{r_e}$ = 9 kpc. We will use z = 0.45 hereafter.

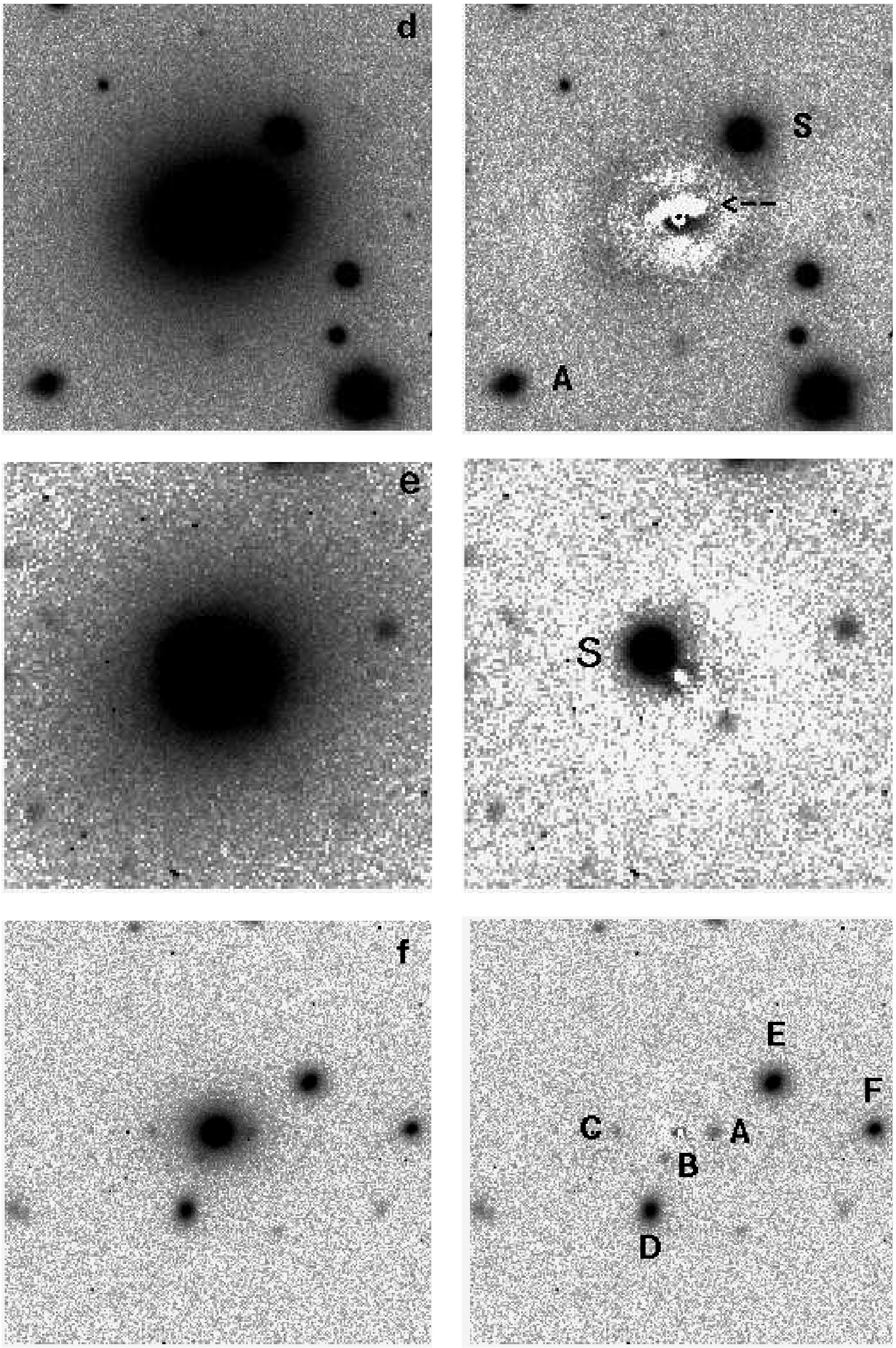

Fig. 1a–f. (continued) **d** 1ES 1959+650, 42″×42″ (55×55 kpc), **e** 1ES 2037+521, 24″×24″ (33×33 kpc), **f** 1ES 2326+174, 44″×44″ (200×200 kpc).

After subtraction of our model from the image, the feature to the north appears to be resolved, round and well separated from the BL Lac. Therefore, we consider it rather to be a galaxy than a tidal tail or a merger remnant possibly associated with the BL Lac. The integrated magnitude of this system is $\mathrm{m_R} \sim$ 23 at a projected distance of 3.5″.

Within 15″(110 kpc at z = 0.45) of the BL Lac 5 more companion galaxies are present (B−F in Fig. 1b), ranging in brightness from $\mathrm{m_R}$ = 17.9 up to 21.1. This suggests that they may form together with the BL Lac a small group.

1ES 1853+673: In view of the short integration time as opposed to its redshift (z = 0.212, P96) we secured a good image of this source, which shows interesting features. The host galaxy is clearly resolved, and again, a close, resolved companion 2″ to the northwest (9.4 kpc at z = 0.212) can be seen. Moreover, there is a low surface−brightness feature associated with the companion which extends $\sim$ 7″ to the northwest (the companion is labeled A and the feature indicated with an arrow in Fig. 1c). The optical appearance is striking and suggestive of a tidal tail resulting either from an interaction between both galaxies or a

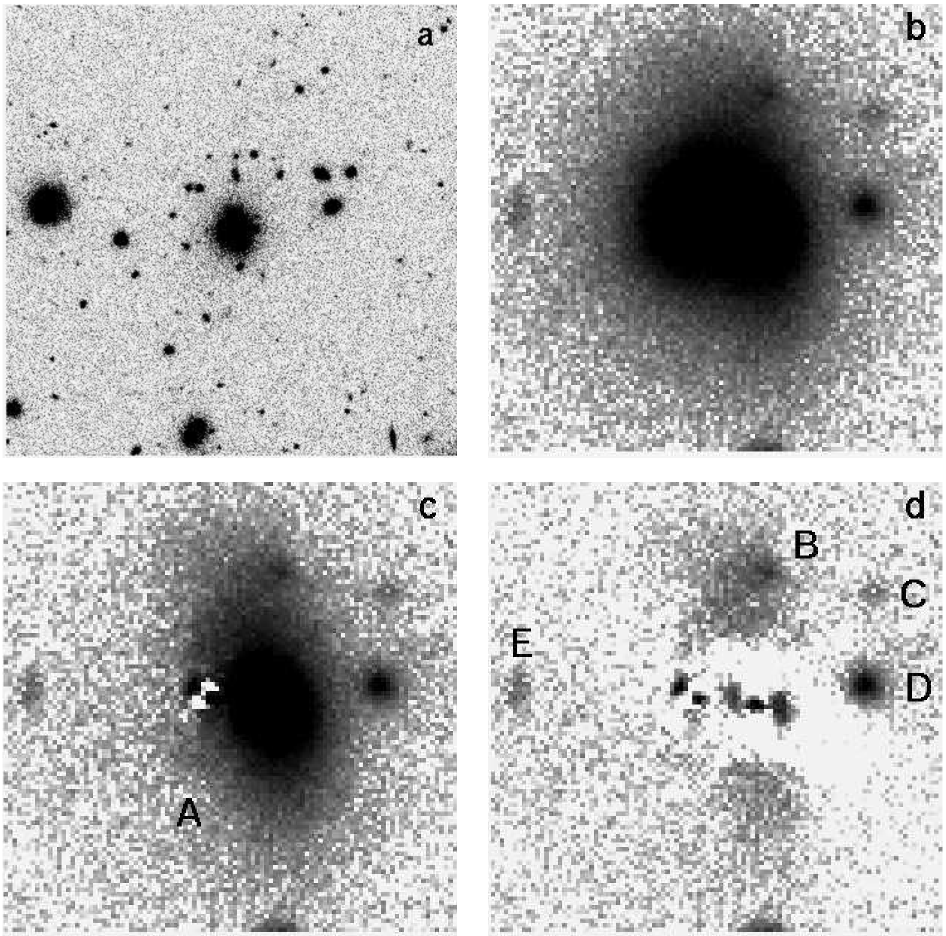

Fig. 2a–d. **a** Large scale environment of 1ES 1440+122 in order to show the galaxy enhancement close to the BL Lac. Field is $126'' \times 126''$ (430×430 kpc). **b** Central $18'' \times 18''$ (69×69 kpc). The BL Lac is the left object of the pair of galaxies. **c** Same as **b** with the model for the BL Lac (core + host) subtracted to show the close companion. **d** Same as **b** with the model for the BL Lac and the close companion subtracted. North is up, east to the left. The grey scale is logarithmic except a), where a linear scale was used.

merging process, where material was stripped off the companion.

After we had properly masked the companion and the "tidal tail" we were able to make a very good fit to the system. The host galaxy is very round ($\epsilon = 0.12$) with M_R = -22.9 and r_e = 9.4 kpc. Photometry of the companion gives $m_R \sim 21.8$, which would imply M_R = -19.2 at z = 0.212. Still the "tidal tail" is present, but due to its low surface brightness, we did not attempt to estimate a magnitude of that feature.

There is only one more galaxy within $11''$ (50 kpc) of the BL Lac (B, m_R = 23.1).

1ES 1959+650: This is the closest BL Lac of our targets (z = 0.048, P96, Schachter et al. 1993). We secured a very good image under excellent seeing conditions ($0.67''$ FWHM). The modeling of the host was slightly difficult due to a presence of a bright star $10''$ to the northwest.

None of our 6 different models fitted to the image gave satisfactorily results. Alternatively, we fitted a 3 component model consisting of a core, a disk and a bulge (with ϵ free and PA equal for disk and bulge). In all cases, we had residuals close to the core as well as in the outer parts of the host galaxy left.

A careful inspection of our image of 1ES 1959+650 before and after the subtraction of our models showed always a highly interesting feature (a hint of this feature is already visible on the original frame). Approximately $1''$ to the north of the center of 1ES 1959+650 there is an absorption feature roughly oriented along the major$-$axis of the host galaxy in E$-$W direction, suggestive of a dust lane (indicated in Fig. 1d with an arrow). If this could be confirmed, we would have found the first BL Lac hosted by a dust$-$lane elliptical galaxy with an underlying disk!

We masked the absorption feature and repeated the fitting procedure as described above. The fit with a de Vaucouleurs model gave m_R = 14.77 with r_e = 11.3 kpc and small ellipticity (ϵ = 0.20). However, best fits are obtained with either the model with core and β = 0.41 or with core and bulge and disk. For the latter we obtained m_R = 15.2 for the core, m_R = 15.0 and r_e = $10.2''$ (13.5 kpc) for the bulge and m_R = 16.7 and r_e = $4.8''$ (6.3 kpc) for the disk. The ellipticities are 0.01 for the bulge and 0.47 for the disk implying an inclination of $\sim 58°$. The disk$-$to$-$bulge ratio is $\sim$ 0.22 and M_R of the whole galaxy (disk and bulge) = -23.0.

Although we masked the absorption feature carefully, the residuals close to the center and in the outer parts of the host galaxy are still strong as compared to the other sources modeled. For the former we checked the quality of our PSF by subtracting a scaled version of it from different stars on different locations on the CCD frame and found always a very good match, except the inner 2 pixels. The residuals close to the center could still be a remnant of imperfect masking.

For the residuals in the outer part of the host galaxy, the absorption feature can not be the reason alone. In fact, our isophotal analysis (absorption feature masked) shows that in 1ES 1959+650 an isophote twist is occurring. The PA changes from $\sim 95^\circ$ at r = 3″ up to 140° at r = 15″ and ϵ changes from 0.2 to 0.

Basically, two scenarios could be responsible for our residuals and the observed change of PA and ϵ. Either the disk and bulge have not only different ellipticities, but also different PA, or the whole galaxy (β = 0.41) or at least the bulge (in the 3 component fit) is triaxial (Benacchio & Galletta, 1980).

Isophote twists can also be produced by interaction between galaxies (Madejsky, 1990). There are only three brighter galaxies on the full frame 24″, 37″ and 55″ to the southeast, south and northeast, respectively (31, 49 and 73 kpc at z = 0.048 with $\mathrm{m_R}$ = 20.0, 18.4 and 20.1, the closest labeled A in Fig. 1d). Since none of them shows signs of interaction with 1ES 1959+650, we consider this scenario as unlikely.

1ES 2037+521: This source was listed as BL Lac candidate in P96. Meanwhile it is confirmed as BL Lac spectroscopically, but still no redshift is known (Perlman, priv. communication). Due to its low galactic latitude (b $\approx 7^\circ$), the image is crowded with stars. The host galaxy is well resolved, but unfortunately a bright star 1.9″ northeast of the center of 1ES 2037+521 made the analysis difficult.

In spite of the difficulty with the bright, closeby star (which we subtracted before fitting) our model fits very well the observed light distribution (Fig. 1e). The host has $\mathrm{m_R}$ = 15.9 and $\mathrm{r_e}$ = 9.0″, the core is $\sim$ 3.5 mag fainter ($\mathrm{m_R}$ = 19.3). Thus the light of the host galaxy dominates almost entirely the system ($\sim$ 96% from the total flux of 1ES 2037+521 came from the host during our observations).

In order to estimate the redshift of 1ES 2037+521, we adopt a similar strategy as in the case of 1ES 1745+504. We adjust the redshift in such a way that the resulting redshift dependent parameters for the host are similar to those for our BL Lac objects with firm redshift. Here, however, is an additional difficulty due to the low galactic latitude of the object, which made the assumption of the galactic absorption very uncertain. Based on Burstein & Heiles (1982) we assume A(R) = 1.65 mag. The error may be as large as 0.3 mag.

Therefore a good guess for the redshift of 1ES 2037+521 would be z = 0.05. We would derive $\mathrm{M_R} = -23.2$ and $\mathrm{r_e}$ = 12.3 kpc (for z = 0.1 $\mathrm{M_R}$ would be -24.8 and $\mathrm{r_e}$ = 23 kpc, which would make the host of 1ES 2037+521 among the brightest and largest known).

Similarly to BL Lac itself, which is also a low galactic latitude source, there are only a few galaxies with $\mathrm{m_R} = 20-22$ on the full frame. No obvious companions within 30″ are present.

1ES 2326+174: This is the object with the highest redshift in our sample (z = 0.213, P96). Superimposed onto the outer parts of the host there are three faint galaxies ($\mathrm{m_R} \approx 22.5-23.5$) 3.4″, 3.1″ and 6.6″ to the west, south and east, respectively (16.0, 14.1 and 31.2 kpc if at z = 0.213, A−C in Fig. 1f).

The host can be well fitted by a de Vaucouleurs law with $\mathrm{M_R} = -23.4$ and $\mathrm{r_e}$ = 8.5 kpc. After subtracting the model for the BL Lac, the three close companions are well visible, with no obvious sign of interaction. Within 20″ ($\approx$ 100 kpc at z = 0.213) of the BL Lac there are three brighter galaxies ($\mathrm{m_R}$ = 19.5−20.5, D−F in Fig. 1f) which may together with the BL Lac form a small group.

5. Discussion

5.1. Properties of the host galaxies

Since we were able to carry out the observations of our sources under good, partly excellent seeing conditions and since most (perhaps all) of our sources are at redshifts ≤ 0.2, we were able resolve the host galaxies in all cases. This allowed us to apply a 2−dimensional fitting procedure to the images. In all cases, except one (1ES 1959+650), the host galaxy can best be modeled by a shape parameter β close to the canonical de Vaucouleurs value. In none of the cases did a disk−type host galaxy give an acceptable fit.

The results are well in the range found for other BL Lac objects by various groups. Falomo (1996) found for his BL Lac objects with z $<$ 0.2 a $\langle\ \mathrm{M_R}\ \rangle = -23.4 \pm 0.7$, while Wurtz et al. (1996) found $\langle\ \mathrm{M_R}\ \rangle = -23.7 \pm 0.6$ for z $<$ 0.2 BL Lac objects. We determined $\langle\ \mathrm{M_R}\ \rangle = -23.1 \pm 0.2$ for the 5 BL Lac objects with firm redshift which is in excellent agreement. For the half−light radii we derived $\langle\ \mathrm{r_e}\ \rangle = 9.3 \pm 2$ kpc, which is similar to most z $<$ 0.2 BL Lac objects observed by Wurtz et al. (1996), Falomo (1996) and Abraham et al. (1991) but not as large as 51 kpc determined for PKS 0548−322 (Falomo et al. 1995).

We found ellipticities ($\langle\epsilon\rangle = 0.16 \pm 0.05$) which are similar to those obtained from ground (Falomo 1996; Abraham et al. 1991) and with HST (Falomo et al. 1997; Jannuzi et al. 1997). The offsets between the core and host centroids are small (<0.1″). In all cases the light from the host galaxy dominates the system from 59% in 1ES 1440+122 and 1ES 1959+650 up to 96% in 1ES 2037+521. This is typical for HBL (see e.g. Wurtz et al. 1996).

The residuals after subtraction of our model (core + convolved host) are in all cases fairly small ($<$ 5% of the total light), except for 1ES 1959+650. These 6 sources have β close to 0.25, which shows that in these cases a de Vaucouleurs law is a good representation of the light distribution from the host galaxy.

One might ask, however, if the deviations from a pure de Vaucouleurs law observed here are significant or simply due to noise or systematic effects. An apparent deviation could be caused by at least 1) systematic errors in the fitting program, 2) photon and readout noise in the images, 3) incorrect background subtraction or 4) incorrect PSF. We have performed simulations to study the effect of 1) - 3) to the fitted β values. The effects of PSF errors are not accounted for in our simulations, but we expect these effects to be small given the relatively small residuals in the model subtracted images. A simulation including also the

PSF effects would be very useful provided that they could be included in a realistic way.

Thus we created $\sim$ 100 simulated images for each object taking the parameters for the core and host galaxy from our de Vaucouleurs fits. The host galaxy obeyed strictly the de Vaucouleurs profile in each simulated image. The images were convolved with the PSF, and photon noise, readout noise and a constant drawn from a Gaussian distribution with zero mean were added. The constant represents the error in the sky subtraction and its standard deviation was determined for each object from the sky measurement. Each simulated image was then fit with 10 free parameters, i.e. by letting β to be a free parameter. Masking of images was identical to the actual fits.

The first remark from the simulations is that in all 7 objects most of the uncertainty in β (and $m_{\rm core}$, $m_{\rm host}$ and $r_{\rm e}$ as well) comes from the uncertainty in the sky level; photon and readout noise have less effect on β in the S/N conditions present in our images. Also, the fitted values were scattered symmetrically around their true values showing that no bias is introduced by the fitting program. The sensitivity to assumed sky level emphasizes the importance of accurate sky subtraction if one wants to obtain correct host galaxy parameters.

Secondly, the final β values in the simulated images cluster around β = 0.25 with a standard deviation that varies from object to object. The distributions of β are nearly Gaussian, so we calculated the standard deviation σ_β and 99% (3 σ_β) confidence intervals for each object. In two objects, 1ES 1255+244 (β = 0.18, σ_β = 0.02) and 1ES 1959+650 (β = 0.41, σ_β = 0.01) the fitted β lies outside the 99% confidence interval. In 1ES 2037+521 (β = 0.20, σ_β = 0.02) the fitted β lies inside the 99% but outside the 95% interval. Thus we have evidence of β significantly different from 0.25 in two objects and marginal evidence in one object. Because we have not included the PSF errors in our simulations, the confidence intervals we calculate have to be regarded as lower limits. Thus 1ES 2037+521 might move inside the 95% limits after including the PSF errors, whereas the results for 1ES1255+244 and especially 1ES 1959+650 are more secure in this respect.

The results of our simulations may shed new light on the morphology of BL Lac host galaxies, although the amount of data is small. Most previous studies used either pure de Vaucouleurs or disk-type fits to determine their nature. In their 2−dimensional analysis of BL Lac host galaxies from the 1 Jy sample Stickel et al. (1993) left β as a free parameter, but did not convolve the galaxy models. It is nevertheless remarkable that according to their result the host galaxy of BL Lac itself can best be fitted by β = 0.66 in the R-band. With the current availability of large telescopes offering excellent seeing conditions and sufficient resolution in combination with a dedicated 2−dimensional analysis, we can now determine the fraction of BL Lac objects, whose host galaxies do not follow a pure de Vaucouleurs law. The data obtained during the HST Snap survey on BL Lac objects are perfectly suited for this kind of work.

Given the large residuals after subtraction of our model (convolved de Vaucouleurs + core) and the results from our numerical simulations, 1ES 1959+650 seems to be hosted by the most peculiar galaxy among the BL Lac objects we observed. Both a fit with β = 0.41 and a fit with a bulge and a disk for the host galaxy gave best results. At present we can not distinguish which of our models represents the true nature of the morphology of the host galaxy of 1ES 1959+650. Caon et al. (1993) found in their study of a sample of elliptical and S0 galaxies a wide range of β, with basically no difference between both galaxy types, whereas Capaccioli et al. (1992) noted that most early−type galaxies have disks.

So far, only one BL Lac object has been found to be hosted by an elliptical galaxy with a disk (PKS 0548−322; Falomo et al. 1995), but in this case the disk was very small.

There are also claims that a few BL Lac objects might be hosted by a disk−type galaxy (Abraham et al. 1992, Wurtz et al. 1997), some of them are discussed controversary (e.g. PKS 1413+135, Wurtz et al. 1997 and references therein).

In 1ES 1959+650 we found also an indication for a dust−lane, which would be the first ever seen in any BL Lac host. This is not unusual for elliptical or disk−type galaxies. Möllenhoff et al. (1992) found 21 out of 26 dust−lane elliptical galaxies to be radio emitters, 6 out of their 7 objects with unresolved radio structure are major−axis dust−lane elliptical galaxies. Since 1ES 1959+650 appeared unresolved at 6cm (P96) our findings would be consistent with their results. Unfortunately, this indication of a dust lane is based on measurements in one passband only. Multicolour images (e.g. in B band, where the dust lane should show up clearly and in the NIR, where the dust lane should not show up at all) are needed to verify the presence of a dust lane.

5.2. Environment

5.2.1. Evidence for interaction

So far only a couple of BL Lac objects have been reported to show clear evidence of interaction with other galaxies. In both, Ap Lib and 3C 371, a companion galaxy at projected distances of 110 and 83 kpc, respectively, have been found. Whereas the former was characterized by asymmetric isophotes elongated towards the companion, the latter shows a tidal tail connecting both galaxies (Arp 1970; Stickel et al. 1993; Nilsson et al. 1997). Spectroscopy by Stickel et al. (1993) and Pesce et al. (1994) found the companion galaxies at the same redshift as the BL Lac thus confirming their physical association.

Striking evidence for interaction has been found in PKS 0548−322 (Falomo et al. 1995). A relatively bright companion galaxy separated by 25 kpc from the BL Lac was detected, with signs of interaction present via extended low surface brightness emission. Unfortunately, no redshift for this galaxy is known yet.

A similar object to PKS 0548−322 is 1E 1415.6+2557. Halpern et al. (1986) noted a close, bright companion separated by 5″ (26 kpc in our cosmology) from the BL Lac. No redshift of the companion is known. Even more close, a jet-like feature 3″ (15 kpc) from the BL Lac was detected by Romanishin (1992), who interpreted this feature as an optical jet. This is still under debate, e.g. Gladders et al. (1997) interpreted this feature rather as an inclined spiral in projection against the BL Lac or a nearby companion galaxy.

In two (perhaps three) of our BL Lac objects we found evidence for interaction. 1ES 1440+122 has a close early−type companion (projected distance $\sim 2.5''$) with a brightness differing only by 0.2mag from that of the BL Lac host. If both objects would be at the same redshift, their cores would be separated by $\sim$ 9.5 kpc only! We found strong support for the interactions hypothesis by our isophotal analysis, which shows a clear isophote twist in the companion along with strongly varying ellipticity. The relatively undisturbed appearance of both galaxies suggests that they are currently approaching rather than having already undergone a close encounter.

The other source showing evidence of interaction was 1ES 1853+671. Similarly to 1ES 1440+122 we found a close companion (projected distance $\sim 2''$ = 9.4 kpc at z = 0.212), but $\sim$ 3.7 mag fainter than the host of 1ES 1853+671. In this case, however, there is a faint extension from the companion extending $\sim 7''$ to the opposite side of the BL Lac. This feature is very similar to tidal tails in interacting galaxies and a similar scenario is suggested here. Contrary to 1ES 1440+122, the optical appearance suggests, that the objects already had one close encounter, during which material was stripped off the companion. This system is similar to PKS 0548−322 and its close companion, but in the latter case the projected distance is 25 kpc.

Another source, which might be influenced by interaction is 1ES 1745+504, although the evidence is weak. This source has a faint feature to the north. After the subtraction of the model for the BL Lac, this feature seems to be quite round and (perhaps) separated. Thus we believe that this is rather a galaxy well separated from the BL Lac than an interacting system.

In summary, although this is just now tentative, our results imply that tidal interactions are potentially important to the BL Lac phenomenon at least in some sources. 1ES 1440+122 and 1ES 1853+671 may represent the extremes of this phenomenon (approaching, but already very close galaxies for the former and undergone interaction for the latter). Clearly, this issue has to be tested by very deep high-resolution imaging using HST and by spectroscopy from ground using large telescopes.

5.2.2. Close companions

Already Falomo et al. (1990) noted close ($<5''$), faint ($>$ 21mag) emission features around a couple of BL Lac objects. Since then a few studies related to this subject have been carried through both, imaging and spectroscopy (e.g. Stickel et al. 1993; Pesce et al. 1994, 1995; Falomo et al. 1995; Falomo 1996; Jannuzi et al. 1997). Whereas the imaging data allowed one to identify close companions for almost all of the objects, their physical association could only be confirmed for some of them. This is mainly due to their faintness as compared to the BL Lac and their close separation, which makes it hard to measure their redshifts even with large telescopes.

In all of our BL Lac objects − except 1ES 2037+521 − we found at least 2 companions within a projected distance of $\sim$ 60 kpc. Most companions were found around 1ES 1440+122 and 1ES 1745+504 (5 within 30 kpc and 6 within 60 kpc, respectively). 1ES 2326+174 has 6 companions within 100 kpc, three of them within 30 kpc projected distance. They span a wide range of brightnesses, between $\mathrm{m_R}$ = 17 and 23.5. Whereas some of the companions are most likely projected along the line of sight to the BL Lac (e.g. in 1ES 1745+504), and the faintest ones background galaxies, most of them could well be at the same redshift as the BL Lac, or at least members of the putative cluster surrounding the BL Lac.

These observations (and those reported in Sect. 5.2.1) point to the fact that interaction might be related to the BL Lac phenomenon as seems to be the case for QSOs (e.g. Hutchings & Neff 1992; Bahcall et al. 1995; Miller 1998). That this is generally the case, has not yet been convincingly demonstrated. One possible test would be a study of a well defined, low redshift sample of BL Lac objects, FR I radio galaxies (the assumed parent population of BL Lac objects) *and* a control sample of “normal” galaxies. The samples must well be matched in redshift and luminosity space. Since both, imaging and spectroscopy is needed for such a program (imaging for the number and luminosity distribution of the companions, spectroscopy to check their physical association), this would be a project requiring a lot of telescope time on (very) large telescopes. And even when it could be shown that the samples of active galaxies have e.g. on average more frequent and brighter companions at the same redshift as the control sample of “normal” galaxies, its not clear if every possible bias is taken into account. For example, the proper selection of the control sample is very difficult, because it should be chosen in such a way that it is not only well matched in redshift and luminosity distribution with the samples of active galaxies, but should also have the same mix of large−scale surroundings (cluster environments).

6. Summary

We have presented the first images of 7 newly detected BL Lac objects (among them one BL Lac candidate) from the Einstein Slew Survey. Since they are at low redshift and thanks to our excellent resolution, we could resolve their hosts in all cases. This allowed us to analyze the host galaxies, to study their properties by a 2−dimensional decomposition method and to investigate their environment.

The properties of the host galaxies are very similar to those derived for other BL Lac objects. They are luminous $\mathrm{M_R} \sim -23.1$ and large $\mathrm{r_e} \sim 10$ kpc elliptical galaxies. The host of 1ES 1959+650 is complex and may be either an elliptical galaxy with β = 0.41 or an elliptical (β = 0.25) galaxy with an underlying disk. Based on the average properties of the BL Lac hosts with firm redshift, we estimated a redshift of 0.45 for the BL Lac candidate 1ES 1745+504 and a redshift of 0.05 for 1ES 2037+521.

We searched for deviations of a pure de Vaucouleurs law ($\beta \neq 0.25$) in the host galaxies of our BL Lac objects and determined their statistical significance with numerical simulations. In two objects (1ES 1255+244, 1ES 1959+650) we found significant deviations. This may shed new light on the properties of the host galaxies of BL Lac objects, but due to the small number observations an analysis of a large sample of BL Lac objects is required.

The environments of the BL Lac objects are highly interesting. We found in at least two (perhaps three) cases evidence for interaction (1ES 1440+122, 1ES 1853+671 and perhaps 1ES 1745+504). In all except one cases we found at least 2 companions within a projected distance of 60 kpc around the BL Lac. In two cases we found at least 5 within 50 kpc (1ES 1440+122, 1ES 1745+504). This may show that interaction is potentially important to BL Lac phenomenon at least in these sources.

Acknowledgements. We thank the anonymous referee for his prompt and constructive comments. Thanks to E. Perlman for an update of the current status of the Einstein Slew Survey sample of BL Lac objects. We benefited from stimulating discussions on the morphology as well as the modeling of elliptical galaxies with J. Fried, C. Möllenhoff and C. Scorza de Appl. This work was supported by the DFG (Sonderforschungsbereich 328) and the Finnish Academy of Sciences. TP acknowledges support from the Wihuri Foundation.

References

Abraham R.G., McHardy I.M., Crawford C.S., 1991, MNRAS 252, 482
Arp H., 1970, ApJ 5, L75
Bahcall J.N., Kirhakos S., Schneider D.P., 1995, ApJ 450, 486
Benacchio L., Galletta G., 1980, MNRAS 193, 885
Bender R., Möllenhoff C., 1987, A&A 177, 71
Bruzual G., 1983, Rev. Mex. Astron. Astrofis. 8, 63
Burstein D., Heiles C., 1982, AJ 87, 1165
Caon N., Capaccioli M., D'Onofrio M., 1993, MNRAS 265, 1013
Cappacioli M., Caon N., D'Onofrio M., 1992, MNRAS 259, 323
Falomo R., 1996, MNRAS 283, 241
Falomo R., Melnick J., Tanzi, E.G., 1990, Nat 345, 692
Falomo R., Pesce J.E., Treves A., 1993, AJ 105, 2031
Falomo R., Pesce J.E., Treves A., 1995, ApJ 438, L9
Falomo R., Urry C.M., Pesce J.E., et al., 1997, ApJ 476, 113
Giommi P., Padovani P., 1994, MNRAS 268, L51
Gladders M.D., Abraham R.G., McHardy I.M., et al., 1997, MNRAS 284, 27
Halpern J.P., Impey C.D., Bothun G.D., et al., 1986, ApJ 302, 711
Hutchings J.B., Neff S.G., 1992, AJ 103, 1746
Jannuzi B.T., Yanny B., Impey C.D., 1997, ApJ 491, 146
Landolt A.U., 1983, AJ 88, 439
Madejsky R., 1990, Ph.D. Thesis, University of Heidelberg
McHardy I.M., Luppino G.A., George I.M., Abraham R.G., Cooke B.A., 1992, MNRAS 256, 655
Miller J., 1998, The hosts and environments of QSOs. In: Kidger M., de Diego J.A. (eds.) Proc. Blazars, Black Holes and Jets. in press
Möllenhoff C., Hummel E., Bender R., 1992, A&A 255, 35
Nilsson, K., Heidt, J., Pursimo, T., et al., 1997, ApJ 484, L107
Padovani P., Giommi P., 1995, ApJ 444, 567
Perlman E.S., Stocke J.T., Schachter J.F., et al., 1996, ApJS 104, 251
Pesce J.E., Falomo R., Treves A., 1994, AJ 107, 494
Pesce J.E., Falomo R., Treves A., 1995, AJ 110, 1554
Romanishin W., 1992, ApJ 401, L65
Schachter J.F., Stocke J.T., Perlman E.S., et al., 1993, ApJ 412, 541
Stickel M., Fried, J.W., Kühr H., 1993, A&AS 98, 393
Stocke T.J., Liebert J., Schmidt G., et al., 1985, ApJ 298, 619
Ulrich M.−H., 1989, The host galaxy of BL Lac objects. In: Maraschi L., Maccacaro T., Ulrich M.−H. (eds.) Proc. BL Lac Objects. Lecture Notes in Physics 334, Springer, p. 45
Urry C.M., Padovani P., 1995, PASP 107, 803
Wurtz R., Stocke, J.T., Yee H.K.C., 1996, ApJS 103, 109
Wurtz R., Stocke, J.T., Ellingson E., Yee H.K.C., 1997, ApJ 480, 547