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The luminous host galaxies of high redshift BL Lac objects*

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Abstract. We present the first near-infrared *K*s-band (2.1 μm) imaging study of a sizeable sample of 13 high redshift ($0.6 < z < 1.3$) BL Lac objects in order to characterize the properties of their host galaxies. We are able to clearly detect the surrounding nebulosity in eight objects, and marginally in three others. In all the well resolved objects, we find that the host galaxy is well represented by a de Vaucouleurs $r^{1/4}$ surface brightness law. In only two cases the object remains unresolved. These new observations represent in most cases the first detection of the host galaxy and taken together with previous optical studies of $z > 0.5$ BL Lacs substantially increase the number of detected hosts (from ∼20 to ∼30). This dataset allows us to explore the evolution of BL Lac hosts from $z \sim 1$ to the present epoch.

We find that the host galaxies of high redshift BL Lacs are large (average bulge scale length $\langle R(\mathrm{e})\rangle \sim 7$ kpc) and similar to those hosting low redshift BL Lacs, indicating that there is no evolution in the host galaxy size. On the other hand, these host galaxies are very luminous (average $\langle M(K)\rangle = -27.9 \pm 0.7$). They are ∼3 mag brighter than the typical galaxy luminosity L^*, and ∼1–1.5 mag more luminous than brightest cluster galaxies at low redshift. They are also ∼1 mag brighter than radio galaxies at low redshift and they appear to deviate from the $K - z$ relationship of radio galaxies. On the other hand, these high luminosities agree with the few optical studies of high redshift BL Lacs and are similar to those of flat spectrum radio quasars studied by us in the near-infrared.

The nuclear luminosity and the nucleus-galaxy luminosity ratio of the high redshift BL Lacs are much larger than those found for low redshift BL Lacs and similar to those observed in flat spectrum radio quasars at similar redshift. This mainly reflects the selection effects in the surveys and may be due to either an higher intrinsic nuclear luminosity, or due to enanched luminosity because of strong beaming. Contrary to what is observed in low redshift BL Lacs, the luminosities of the host galaxy and of the nucleus appear fairly well correlated, as expected from the black hole mass – bulge luminosity relationship found in nearby spheroids, if the nuclear emission works at the same regime. Our observations indicate that high redshift BL Lacs radiate with a wide range of power with respect to their Eddington luminosity, and this power is intermediate between the low level observed in nearby BL Lacs and the higher level occurring in luminous radio-loud quasars.

The comparison with BL Lac host galaxies at lower redshift suggests that there is a ∼2 mag brightening of the hosts. We argue that the large luminosity of the hosts is due to a strong selection effect in the surveys of BL Lacs that makes observable only the most luminous sources at $z > 0.5$ and produces a correlation between the nuclear and the host luminosity that emerges at high redshift. However, this may also suggest a strong luminosity evolution which is inconsistent with a simple passive evolution of the stars in the host galaxies, and requires a contribution from recent star formation episodes that takes place at $z > 0.5$.

Key words. BL Lacertae objects: general – galaxies: active – galaxies: elliptical and lenticular, cD – galaxies: nuclei – galaxies: photometry – infrared: galaxies

1. Introduction

Models for the formation of galaxies based on hierarchical merging of galaxies (e.g. Franceschini et al. 1999; Kauffmann & Hähnelt 2000; Di Matteo et al. 2003) predict a close link between the cosmological formation and evolution of massive spheroids and the processes that fuel their central black holes (BH). This connection is strongly supported by the virtually ubiquitous detection of supermassive BHs in the centers of nearby inactive elliptical and bulge-dominated spiral galaxies (e.g. Magorrian et al. 1998; van der Marel 1999), and the strong correlation between the BH mass and the luminosity (mass) and kinematics (velocity dispersion) of the host galaxy (e.g. Magorrian et al. 1998; Gebhardt et al. 2000; Ferrarese & Merritt 2000; McLure & Dunlop 2002; Marconi & Hunt 2003). More circumstantial evidence is provided by the census of local BH masses being comparable to the BH mass integrated over the Hubble time using the quasar luminosity function

* Appendix is only available in electronic form at
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(Yu & Tremaine 2002), and by the similarity of the strong cosmological evolution of the AGN population (e.g. Dunlop & Peacock 1990; Warren et al. 1994) to the evolution of the star formation history of the universe (e.g. Madau et al. 1998; Franceschini et al. 1999). It is thus plausible that galaxy bulge formation simultaneously triggers star formation and accretion onto the BH. If the nuclear activity is a common transient phenomenon during the lifetime of all giant galaxies (Cavaliere & Padovani 1989), with one or several phases of nuclear activity with recurrent accretion episodes, understanding the luminosity evolution of AGN host galaxies is fundamental to study the link between AGN activity and galaxy formation and evolution (e.g. Franceschini et al. 1999).

Detailed imaging studies of nearby AGN have shown that the host galaxies of low redshift ($z < 0.5$) powerful radio-loud AGN (radio-loud quasars [RLQ] and FR II radio galaxies [RG]) are luminous large elliptical galaxies (e.g. Dunlop et al. 2003; Falomo et al. 2003; Pagani et al. 2003) that have the same structural and photometric properties (e.g. the same Kormendy relation) and appear to follow the same BH mass – host luminosity relation as that found for inactive nearby galaxies (McLure & Dunlop 2002). At higher redshift ($z > 1$), the host galaxies are more luminous but still follow a similar Kormendy relation and are consistent with having formed at very high redshift ($z \geq 2$) followed by passive stellar evolution of their host galaxies (e.g. McLure & Dunlop 2000; Kukula et al. 2001; Zirm et al. 2003; Falomo et al. 2004). Passive evolution is also supported by the few available spectroscopic studies of low redshift quasar hosts and RGs (e.g. Nolan et al. 2001), indicating that they are dominated by an old evolved stellar population. This behaviour is different from brightest cluster galaxies (BCG; Aragon-Salamanca et al. 1998) and normal inactive elliptical galaxies (e.g. Stanford et al. 1998; Bell et al. 2004), which exhibit flat luminosity evolution from $z \sim 1$. However, it has for long been suggested that the maximum AGN power increases with the host mass (e.g. Smith et al. 1986; O'Dowd et al. 2002; Dunlop et al. 2003), resulting in apparent evolution in flux-limited samples. Furthermore, the amount of scattered nuclear light and the level of extended line emission from ionized gas around the nucleus increases with the AGN power. This may contaminate the measurement of the host galaxy emission and, if not taken into account, may lead to an erroneous evaluation of the host luminosity and its trend with redshift.

Less is known about the evolution of the host galaxies of low luminosity radio-loud AGN (FR I RGs and BL Lac objects). In agreement with luminous radio-loud AGN, low redshift FR I RGs are large luminous ellipticals which follow the same Fundamental Plane defined by the properties of inactive ellipticals (Govoni et al. 2000; Bettoni et al. 2003). FR I RGs are, however, difficult to detect at $z > 0.2$ (Magliocchetti et al. 2002) where the evolutionary effects start to become important. The only reasonable possibility to study the host galaxies of low luminosity radio-loud AGN over a wide redshift range is therefore afforded by BL Lac objects, which together with flat spectrum radio quasars (FSRQ) form the AGN subclass of blazars. However, unlike BL Lacs which have weak or absent optical line emission (e.g. Scarpa & Falomo 1997), FSRQs have strong emission lines of similar intensity to "normal" steep spectrum radio quasars (SSRQ).

In the current unified models of AGN (Urry & Padovani 1995), the parent population of FSRQs are the high luminosity lobe-dominated FR II RGs, whereas BL Lacs are low luminosity core-dominated FR I RGs whose apparent luminosity is dominated by a relativistically beamed synchrotron jet seen aligned close to our line-of-sight. BL Lacs are, therefore, intrinsically low power AGN, with much lower accretion rates than in RLQs (O'Dowd et al. 2002) which, due to the beaming, can be detected in significant numbers to high redshift. The nuclei of the BL Lacs are on average fainter than those of quasars, which makes the determination of their host properties much easier.

Optical imaging studies (e.g. Falomo 1996; Wurtz et al. 1996; Falomo & Kotilainen 1999; Scarpa et al. 2000a; Urry et al. 2000; Pursimo et al. 2002; Nilsson et al. 2003) and, more recently, near-infrared (NIR) imaging studies (Kotilainen et al. 1998b (KFS98); Scarpa et al. 2000b (S00); Cheung et al. 2003 (C03); Kotilainen & Falomo 2004 (KF04)) have shown that virtually all nearby ($z < 0.5$) BL Lacs are hosted by luminous, mostly unperturbed giant elliptical galaxies located in poor environments and following the Kormendy relation for inactive ellipticals. Their estimated BH masses (Barth et al. 2003; Falomo et al. 2002; Falomo et al. 2003; Woo et al. 2004) are in the range found for quasars, and their host galaxies follow the Fundamental Plane of normal ellipticals. The host galaxies and the environments of BL Lacs are therefore similar to those of FR I RGs. Possible contribution to the parent population from higher luminosity FR II RGs is, however, not excluded (e.g. Falomo & Kotilainen 1999; Cassaro et al. 1999).

At higher redshift ($z > 0.5$), BL Lac hosts have been very little investigated, because of the increasing difficulty of both resolving them and the rapid cosmological $(1 + z)^4$ dimming (i.e. by ~3 mag from $z = 0$ to $z = 1$) of the host galaxy surface brightness. Until now, only ~20 high redshift ($z > 0.5$) BL Lac host galaxies have been resolved, and all of them in the optical (including nine resolved BL Lacs in the *I*-band study of Heidt et al. 2004 (H04) and five in the *R*-band HST study of O'Dowd & Urry 2004 (OU04)). This lack of available data has hampered until now a reliable study of the evolution of the host galaxies.

In order to better investigate the evolution of the host galaxies of BL Lacs, we have thus collected deep NIR *K*s-band (2.1 μm) images of BL Lac hosts at high redshift. At variance with previous studies, the choice of a NIR wavelength allows us to explore the host galaxies in rest-frame wavelength 0.9–1.3 μm, where the host galaxies are dominated by the massive old stellar population, the brightness contrast between the nucleus and the host galaxy is significantly lower than that at shorter wavelengths, the K-correction is relatively small and the contributions from nuclear scattered light and extended line emission are insignificant. Due to their extreme properties (especially the absence or weakness of emission lines), currently there exist relatively few (only ~35) BL Lacs with a confirmed redshift $z > 0.5$. The observed BL Lacs were selected from among these, with the only additional observability constraint of dec > –20°. We plan in the near future to extend this sample

Table 1. The sample and journal of observations[a].

Name (1)	z (2)	V (3)	Date (4)	T(exp) min (5)	*FWHM* arcsec (6)
PKS 0138-097	0.733	18.0	19+20/07/2002	65	0.65
PKS 0235+164	0.940	15.5	08/08/2003	60	0.85
B2 1308+326	0.997	19.0	18+19/07/2002	57	0.80
RXJ 14226+5801	0.638	19.0	19/07/2002	37	0.75
1ES 1517+656	0.702:	15.5	19+20/07/2002	30	0.60
1ES 1533+535	0.890:	17.6	20/07/2002	51	0.60
PKS 1538+149	0.605	17.2	08+09/08/2003	60	0.60
S4 1749+701	0.770	16.5	19/07/2002	60	0.70
S5 1803+784	0.684	16.4	08+09/08/2003	60	0.65
S4 1823+568	0.664	18.4	07/08/2003	46	0.80
PKS 2032+107	0.601	18.6	20/07/2002	48	0.55
PKS 2131-021	1.285	19.0	08+16/08/2003	78	1.05
PKS 2207+020	0.976	19.0	09+16/08/2003	45	0.80

[a] Column (1) gives the name of the object; (2) the redshift; (3) V-band apparent magnitude; (4) the dates of observation; (5) total exposure time; and (6) seeing *FWHM*.

as the number of BL Lacs with known redshift at $z > 0.5$ is expected to increase (e.g. Sbarufatti et al. 2005).

This work presents the first NIR study of 13 high redshift BL Lac host galaxies. The new NIR data are combined with previous optical studies of BL Lacs (H04, OU04) at $z > 0.5$, in order to probe the cosmological evolution of the BL Lac host properties from $z \sim 1$ to $z = 0$ from comparison with the hosts of lower redshift BL Lacs, previously studied in the NIR (KF04 and references therein); to compare the properties of the BL Lac hosts with those of other blazars (FSRQs) and "normal" SSRQs in the same redshift range (Kotilainen et al. 1998a; Kotilainen & Falomo 2000); to study the role of the host galaxy in different types of radio-loud AGN and to investigate the relationship between nuclear and host luminosity in BL Lacs. The properties of the observed objects are given in Table 1. In Sect. 2, we describe the observations, data reduction and the method of analysis used to characterize the host properties. Results and discussion are presented in Sect. 3 and the main conclusions drawn in Sect. 4. Throughout this paper, to facilitate comparison with literature studies, $H_0 = 50$ km s^{-1} Mpc^{-1} and $q_0 = 0$ are used.

2. Observations, data reduction and modeling of the luminosity profiles

The observations were carried out at the 2.5 m Nordic Optical Telescope (NOT) in July 2002 (visitor mode) and August 2003 (service mode), using the 1024 × 1024 px NOTCam NIR camera with pixel scale 0.235″ px^{-1}, giving a field of view of ∼4 × 4 arcmin^2. The Ks-band (2.1 μm), corresponding to ∼0.9–1.3 μm rest-frame, i.e. the minimum in the nucleus/host luminosity ratio, was used for all the observations. The seeing during the observations was generally very good, ranging from 0.″55 to 1.″05 arcsec *FWHM* (average and median 0.″7 *FWHM*). A journal of the observations is given in Table 1. For all these distant targets, the images were acquired keeping the target in the field by dithering it across the array in a random grid with typical offsets of ∼20 arcsec and acquiring several short (60 s) exposures at each position. Individual exposures were then coadded to achieve the final integration time (Table 1).

Data reduction was performed using the NOAO Image Reduction and Analysis Facility (IRAF[1]). Bad pixels were identified via a mask made from the ratio of two sky flats with different illumination level, and were substituted by interpolating the signal across neighboring pixels. For each science image sky subtraction was obtained using a median averaged frame of all the other temporally close frames in a grid of eight exposures, after scaling it to match the median intensity level of individual science frames. Flat-fielding was made using normalized median averaged twilight sky frames with different illumination level, and images of the same target were aligned and combined using field stars as reference points to obtain the final reduced co-added image.

Observations of standard stars taken from Hunt et al. (1998) were obtained throughout the nights in order to provide photometric calibration which resulted in accuracy ∼0.1 mag from the comparison of all observed standard stars. K-correction was applied to the host galaxy magnitudes following the method of Neugebauer et al. (1985). The size of this correction is significant at high redshift in the K-band ($m(K) = -0.68$ and $m(K) = -0.59$ at $z = 0.5$ and $z = 1.0$, respectively). No K-correction was applied to the nuclear component, assumed to have a power-law spectrum ($f_\nu \propto \nu^{-\alpha}$) with $\alpha \sim -1$. Interstellar extinction corrections were computed using R-band extinction coefficient from Urry et al. (2000) and $A_K/A_R = 0.150$ (Cardelli et al. 1989).

[1] IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

Table 2. Previous NIR photometry of high redshift BL Lacs[a].

Name (1)	K mag this work (2)	K mag range literature (3)	Refs. (4)
PKS 0138-097	12.8	12.7–14.3	A82 M90
PKS 0235+164	12.8	8.8–14.3	A82 F99 G85 G86 G93 H84 I82 I84 M90 O78
B2 1308+326	12.5	10.6–15.0	F99 G85 G86 G93 H84 I82 I84 O78
PKS 1538+149	13.6	13.2–14.6	A82 F99 G93 I82
S5 1803+784	12.1	12.4	F99
S4 1823+568	12.8	13.0–13.1	G93
PKS 2131-021	14.2	14.2–14.9	A82 G93
PKS 2207+020	14.9	15.4	A82

[a] Column (1) gives the name of the object; (2) the K-band magnitude in this work; (3) the range of K-band magnitudes in literature; (4) references for literature values: A82 = Allen et al. (1982); F99 = Fan & Lin (1999); G85 = Gear et al. (1985); G86 = Gear et al. (1986); G93 = Gear (1993); H84 = Holmes et al. (1984); I82 = Impey et al. (1982); I84 = Impey et al. (1984); M90 = Mead et al. (1990); O78 = O'Dell et al. (1978).

For eight sources we found published NIR photometry in the literature (Table 2). Our K-band photometry agrees generally well with the previous studies, considering their intrinsic flux variability. In five cases, our new NIR photometry is within the literature range, while for three sources, our photometry is slightly brighter than in the literature.

In order to characterize the properties of the host galaxies, azimuthally averaged one-dimensional radial luminosity profiles were extracted for each BL Lac object and for field stars in the frames out to surface brightness $\mu(\mathrm{K}) \sim 23$ mag arcsec^{-2}, depending on exposure time and observing conditions. All regions affected by nearby companions were masked out from the profiles. In most cases, there were several field stars available, and the core and the wing of the PSF were derived from faint and bright field stars, respectively. When available, the profiles of several faint stars were combined to represent the PSF wing. Comparison of the final PSF and the profiles of individual stars in the frames, as well as comparison between the PSFs for each target, indicates that this procedure resulted in a good and stable representation of the true PSF. The only exception was the field of 1ES 1533+535, where only a few faint stars were available. In this case, the PSF core was estimated from these stars, whereas the PSF wing was derived from the fields of PKS 0138-097 and PKS 2032+107 that were observed during the same night and with similar seeing and airmass conditions.

The luminosity profiles were decomposed into a point source (modeled by a PSF) and galaxy components (convolved with the PSF) by an iterative least-squares fit to the observed profile. There are three free parameters in the fit: the PSF normalization, the host galaxy normalization, and the effective radius of the host galaxy. We attempted both elliptical (de Vaucouleurs $r^{1/4}$ law) and exponential r^{-1} disc models to represent the host galaxy. The host galaxy was deemed to be resolved if the best PSF + host galaxy fit resulted in a significantly lower reduced χ^2 value than the PSF-only fit. Consistent with the results from previous work in the field but for objects at lower redshift (see references above), in no case did the disc model give a significantly better fit than the elliptical one. In the following, therefore, we consider only the results from the fit with the elliptical model.

The uncertainty of the derived host galaxy magnitudes depends mainly on the nucleus/host luminosity ratio. The uncertainty of the host magnitude for each object has been evaluated from the variation of the two relevant parameters (μ_{o} and r_{e}) from their best-fit value within the χ^2 map and assuming a $\Delta\chi^2 = 2.7$ (e.g. Avni 1976). These uncertainties are given in Table 3, Col. 12. The estimated uncertainty in the host galaxy luminosity ranges from $\sim\pm0.2$ mag to $\sim\pm0.6$ mag, with the three marginally resolved hosts having the largest uncertainty. The average value for the sample is $\sim\pm0.3$ mag.

3. Results

In Fig. 1 we show the K-band contour plots of all the observed BL Lacs. We are able to clearly detect the host galaxy in eight BL Lacs, and marginally in three others (PKS 0138-097, B2 1308+326 and PKS 2032+107). The host remains unresolved in only two cases contaminated by overlapping or nearby sources, PKS 0235+164 and PKS 2207+020 (see Appendix). This high detection rate is most likely due to a combination of filter choice (rest-frame $\sim 1\ \mu$m, targeting the dominant stellar population in the galaxies), relatively long integration times, and subarcsec seeing conditions. In Fig. 2, we show the K-band azimuthally averaged radial luminosity profiles of each BL Lac object, together with the best-fit PSF + elliptical host models overlaid. In the Appendix, we discuss in detail the results for individual BL Lacs, including comparison with previous optical characterization of the host galaxy properties. The results derived from the best-fit model parameters (PSF + elliptical host galaxy) of the profile fitting are summarized in Table 3. To establish upper limits to the undetected hosts, we have assumed that the size of the host galaxy in the two unresolved BL Lacs corresponds to the average value of the sample ($R(\mathrm{e}) = 7$ kpc). We gradually increased the luminosity of the host in the fit (by increasing its surface brightness) until it becomes detectable by our observation within the associated errors. The upper limit to the host galaxy magnitude was then

Table 3. Properties of the host galaxies[a].

(1)	z (2)	A(K)[b] mag (3)	K-corr mag (4)	m_K(n) (5)	m_K(g) (6)	μ_e[c] (7)	r_e arcsec (8)	R_e kpc (9)	M_K(n)[d] (10)	M_K(g)[e] (11)	± (12)	N/G (13)	Note (14)
PKS 0138-097	0.733	0.02	–0.66	13.25	16.17	17.58	0.41	3.9	–30.77	–27.21	0.43	26.5	M
PKS 0235+164	0.940	0.02	–0.61	12.97	>13.95				–31.55	>–30.16		>3.6	U
B2 1308+326	0.997	0.01	–0.59	12.95	15.49	18.18	0.72	7.8	–31.82	–28.69	0.39	17.9	M
RXJ 14226+5801	0.638	0.01	–0.67	15.61	16.20	18.83	0.70	6.4	–27.92	–26.66	0.31	3.2	R
1ES 1517+656	0.702	0.02	–0.67	13.79	14.96	18.12	0.90	8.6	–30.01	–28.17	0.31	5.4	R
1ES 1533+535	0.890	0.01	–0.62	16.67	16.78	17.93	0.48	5.0	–28.07	–27.35	0.20	1.9	R
PKS 1538+149	0.605	0.04	–0.67	14.28	15.31	19.93	1.75	15.6	–29.13	–27.43	0.40	4.8	R
S4 1749+701	0.770	0.09	–0.66	13.70	15.42	16.83	0.40	4.0	–30.42	–28.04	0.34	9.0	R
S5 1803+784	0.684	0.04	–0.67	12.61	14.14	17.03	0.79	7.4	–31.14	–28.93	0.20	7.7	R
S4 1823+568	0.664	0.04	–0.67	13.41	14.68	16.58	0.50	4.6	–30.25	–28.31	0.21	6.0	R
PKS 2032+107	0.601	0.04	–0.67	12.35	15.50	18.28	0.75	6.6	–31.05	–27.23	0.59	33.7	M
PKS 2131-021	1.285	0.04	–0.53	14.70	16.52	17.93	0.40	4.7	–30.85	–28.51	0.29	8.6	R
PKS 2207+020	0.976	0.04	–0.60	15.20	>17.03				–29.31	>–27.19		>7.0	U

[a] Columns (1) and (2) give the name and redshift of the object; (3) the interstellar extinction correction; (4) the K-correction for first-ranked elliptical galaxies from Neugebauer et al. (1985), interpolated to the redshifts of the BL Lacs; (5) and (6) the apparent nuclear and host galaxy magnitude; (7) the surface brightness μ(e); (8) and (9) the bulge scalelength in arcsec and kpc; (10) and (11) the absolute nuclear and host galaxy magnitude; (12) the ± error estimate of the derived host galaxy luminosity (see text for details); (13) the nucleus/host galaxy luminosity ratio; and (14) R = resolved; M = marginally resolved; U = unresolved.
[b] The interstellar extinction corrections were computed using R-band extinction coefficient from Urry et al. (2000) and A_K/A_R = 0.150 (Cardelli et al. 1989).
[c] Corrected for Galactic extinction, K-correction and cosmological dimming.
[d] Corrected for extinction only. The BL Lac nuclei are assumed to have flat power law spectra and therefore have negligible K-correction.
[e] Corrected for extinction and K-correction.

derived by integrating the profile of the model host galaxy. The derived upper limits to the host luminosities are M(K) = –30.2 for PKS 0235+164 and M(K) = –27.2 for PKS 2207+020. The faint upper limit for PKS 2207+020 indicates that the host must belong to the faintest among the sample.

3.1. Luminosity of the host galaxies

It is now well established that RGs exhibit a smooth apparent magnitude vs. redshift ($K-z$) Hubble relation with relatively small scatter out to at least $z \sim 3$ (e.g. Lilly & Longair 1984; Eales et al. 1997; Jarvis et al. 2001), consistent with a coeval, passively evolving galaxy population that formed at $z \geq 4$. In Fig. 3, we show the K-band Hubble diagram for AGN hosts, namely high redshift BL Lac hosts (this work), low redshift BL Lac hosts (KFS98, S00, C03 and KF04), FSRQ hosts (Kotilainen et al. 1998a), and RLQ hosts (Falomo et al. 2004), compared to the most recent relation obtained for RGs (solid line; Willott et al. 2003). Note that the majority of the low redshift BL Lacs lie on or above the established RG relation, i.e. toward fainter magnitude by ~0.5 mag on the average. On the other hand, the high redshift BL Lac hosts and the firmly detected FSRQ hosts tend to be displaced in the opposite direction, i.e. toward brighter magnitude, suggesting that at around $z \sim 0.5$ there is an increase in the host brightness with respect to the Hubble diagram defined by the RGs. Interestingly, this increase is not followed by the hosts of more powerful radio-loud AGN (Falomo et al. 2004), which are in good agreement with the Hubble diagram.

In Fig. 4, we show the K-band host galaxy absolute magnitude vs. redshift for the BL Lacs (this work, KFS98, S00, C03, KF04, OU04 and H04), FSRQs (Kotilainen et al. 1998a), RLQs (Falomo et al. 2004) and RGs (Willott et al. 2003). The average K-band absolute magnitude of the high redshift ($z \geq 0.5$) BL Lac hosts in this study is $\langle M(K)\rangle = -27.9 \pm 0.7$. This is ~2.5 mag more luminous than the characteristic magnitude for nearby non-active ellipticals (an L^* galaxy with $\langle M(K)\rangle = -25.2 \pm 0.3$; Mobasher et al. 1993), and is encompassed within M^*-1 and M^*-3. The BL Lac hosts are, therefore, preferentially selected from the high-luminosity tail of the galaxy luminosity function.

It is interesting to compare the K-band absolute magnitude distribution for our BL Lac hosts to those of other relevant samples of BL Lacs, FSRQs and RGs from previous NIR studies (see references above). These samples span a moderately large range in redshift from $z \sim 0.03$ up to $z \sim 1$. The average host galaxy magnitudes for the various samples are given in Table 4. All published magnitudes were transformed into our adopted cosmology (note that OU04 use H_0 = 70 km s^{-1} Mpc^{-1}, Ω_M = 0.3 and Ω_λ = 0.7) and into the K-band, and based on the similarity of the BL Lac host galaxies to giant ellipticals, assuming the average rest-frame colour of giant ellipticals, $R-K$ = 2.7, $I-K$ = 2.0 (Kotilainen et al. 1998a) and $H-K$ = 0.22 (Recillas-Cruz et al. 1990).

The hosts of high redshift BL Lacs appear also to be more luminous in the NIR than nearby BCGs ($\langle M(K)\rangle = -26.5 \pm 0.3$; Thuan & Puschell 1989) but only slightly more luminous than BCGs at higher redshift ($z \sim 0.4$; $\langle M(K)\rangle = -27.2 \pm 0.3$;

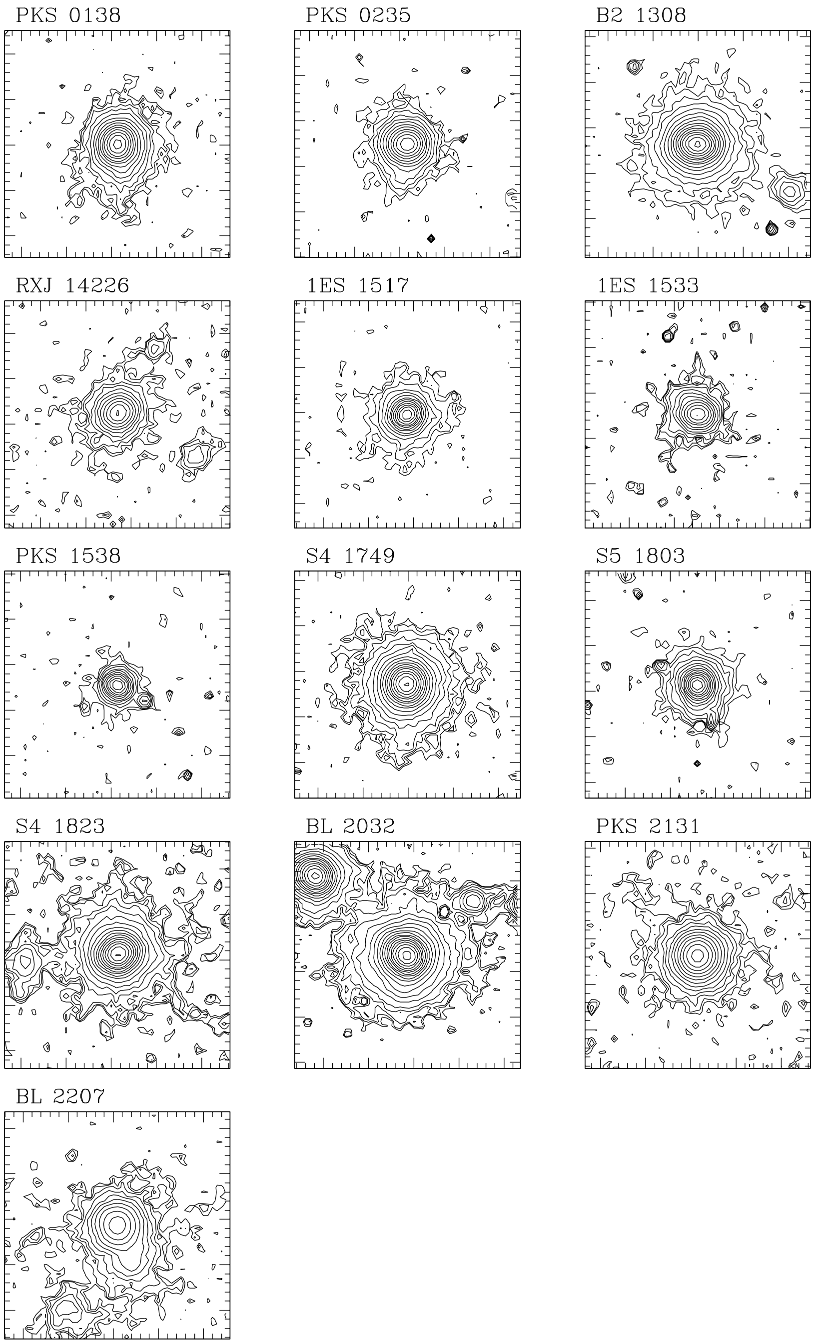

Fig. 1. Contour plots of the BL Lac objects (*center*) in the *K*-band. The distance between major tick marks is 10 px (2.″35). Successive isophotes are separated by 0.5 mag intervals. North is up and east to the left.

Aragon-Salamanca et al. 1998), with many of the BL Lac hosts falling into the BCG range. They are also brighter than RGs at $0.5 < z < 1$ ($\langle M(K)\rangle = -26.8 \pm 0.5$; Willott et al. 2003), but consistent with RGs at $z > 1$ ($\langle M(K)\rangle = -27.4 \pm 0.7$; Willott et al. 2003). The BL Lacs in our study also have host galaxies significantly brighter than those found by previous NIR studies of lower redshift ($z \sim 0.15$) BL Lacs ($\langle M(K)\rangle = -26.1 \pm 0.6$; KF04).

On the other hand, the high redshift BL Lac hosts are in good agreement with the previous optical studies of high redshift BL Lacs ($\langle M(I)\rangle = -25.2 \pm 0.8$; corresponding to $\langle M(K)\rangle = -27.2 \pm 0.8$ (H04) and $\langle M(R)\rangle = -25.0 \pm 0.9$; corresponding to $\langle M(K)\rangle = -27.7 \pm 0.9$ (OU04)). As noted above, we have assumed normal elliptical galaxy colours in converting the optical magnitudes into the *K*-band, but this appears reasonable, as the small amount of available data indicates that the host galaxy colour of high redshift BL Lacs is on average similar to that of normal ellipticals (see Appendix). BL Lacs share many properties (e.g. variability and polarization) with FSRQs and it is therefore also interesting to compare the host properties of the two types of blazars. The average host magnitude of the high redshift BL Lac hosts is closely similar to the value found for resolved FSRQ hosts at $0.5 < z < 1.0$ ($\langle M(K)\rangle = -28.0 \pm 0.3$; Kotilainen et al. 1998a).

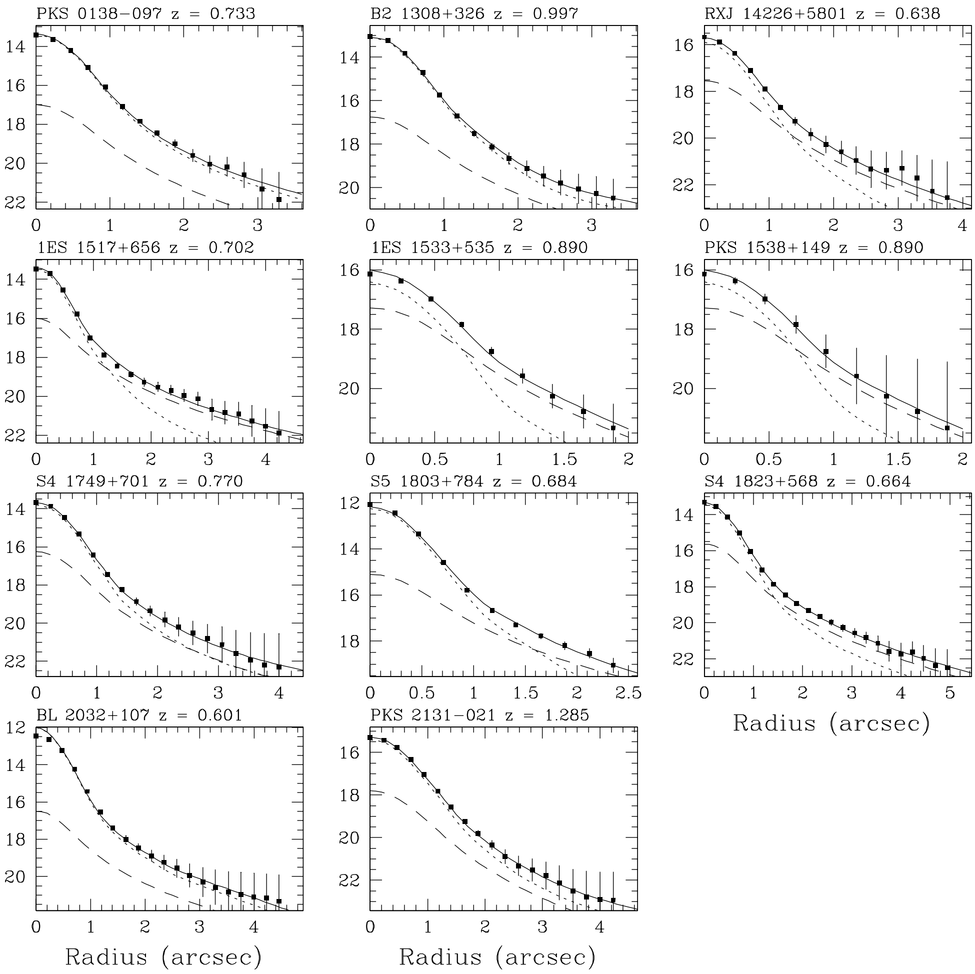

Fig. 2. The observed K-band azimuthally averaged radial surface brightness profile (solid points with error bars) for each BL Lac object, overlaid with the scaled PSF model (dotted line), the de Vaucouleurs $r^{1/4}$ model convolved with the PSF (long-dashed line), and the fitted PSF + host galaxy model profile (solid line). The y-axis is in mag arcsec^{-2}.

3.2. Evolution and selection effects

The main result derived from the above comparison is that high redshift BL Lac and FSRQ host galaxies are very luminous, much brighter than those seen at low redshift. They appear also more luminous than what is predicted by models of passive stellar evolution from a high redshift formation epoch (Fig. 4) or by models of a non-evolving population. The ~2 mag difference between the high redshift BL Lac (and FSRQ) hosts and the low redshift hosts could be either due to a significant host luminosity evolution with redshift, or assuming that the nuclear and the host luminosity are correlated, due to selection effects because of the relatively bright completeness level of flux limited surveys of BL Lacs.

In order to investigate the role of the possible selection effects, we have analyzed the properties of the various BL Lac samples in the luminosity-redshift plane. Figure 5 compares the distribution of the high and low redshift BL Lacs in the luminosity-redshift plane at radio (5 GHz), optical (V-band and 5500 Å) and X-ray (1 keV) frequencies. The nuclei of high redshift BL Lacs (this work) are much more luminous at all wavelengths from radio to X-rays than the nuclei of low redshift BL Lacs (the best overlap of the distributions is in X-rays). The well known flux limit effect with high redshift surveys implies a dependence of the luminosity on distance. A similar situation is found for quasars (e.g. Falomo et al. 2004). However, in the case of BL Lacs, this effect appears to be more significant than in the case of quasars. This comparison indicates that it is not possible to directly compare the properties of objects belonging to the same population at different redshift (which could then be different because of evolution). On the contrary, comparison of BL Lac objects at significantly different redshifts implies having to study objects belonging to different regions of the BL Lac luminosity function.

Because of the shape of the luminosity funcion of BL Lacs, and of the flux limits in the surveys, the large majority of the objects at high redshift remain undetected and only the most luminous objects are observable. Indeed, at $z \geq 0.7$ only a few very luminous objects belonging to the BL Lac class have been discovered. Therefore, to make an unbiased comparison of the host properties at different redshifts, one should choose samples that have matched nuclear luminosity. However, this is in practice not possible because in the available BL Lac samples

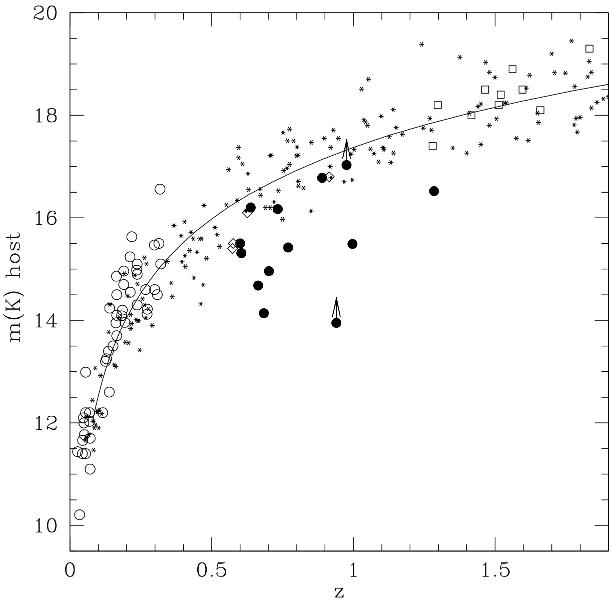

Fig. 3. Plot of the apparent K-band magnitude of the host galaxies vs. redshift (Hubble diagram). The high redshift BL Lacs from this work are marked as filled circles, low redshift BL Lcs as open circles (Kotilainen et al. 1998a; Scarpa et al. 2000b; Cheung et al. 2003; Kotilainen & Falomo 2004), FSRQ hosts as open diamonds (Kotilainen et al. 1998b) and high redshift quasar hosts as open squares (Falomo et al. 2004). The solid line is the $K - z$ relation for RGs derived by Willott et al. (2003). These RGs are shown as asterisks. Filter conversion assumes $H - K = 0.2$.

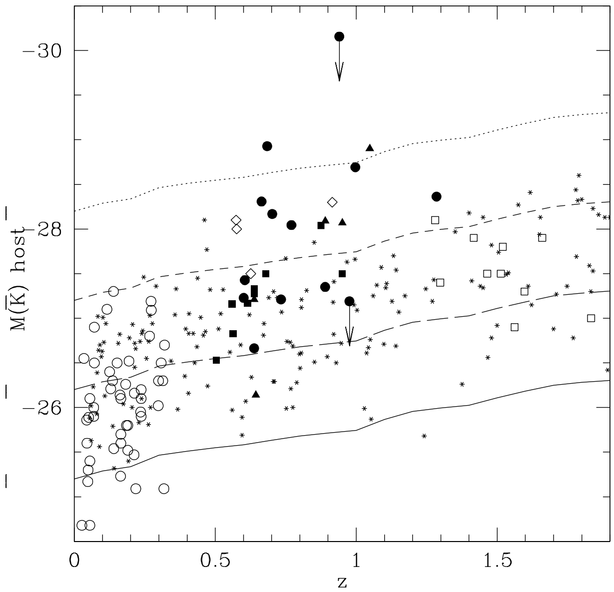

Fig. 4. Plot of the absolute K-band magnitude of the host galaxies vs. redshift. For symbols, see Fig. 3. Additional symbols indicate optical studies of high redshift BL Lacs (filled squares; Heidt et al. 2004, and filled triangles; O'Dowd & Urry 2004). Filter conversions assume $R-K = 2.7$; $I-K = 2.0$ and $H-K = 0.2$. The solid, long-dashed, short-dashed and dotted lines are the luminosities of L^* ($M(K) \sim -25.2$ at low redshift; Mobasher et al. 1993), L^*-1, L^*-2 and L^*-3 galaxies, respectively, following the passive evolution model of Bressan et al. (1998).

there is very little overlap in the nuclear luminosity distributions (Fig. 5) for objects below and above $z \sim 0.5$.

In spite of the strong selection effect described above, the comparison of the host properties for objects at different redshift could be unbiased unless there is a significant correlation between the nuclear and the host luminosity. In the case of low redshift (low power) BL Lacs (see next section), the host galaxy luminosity is unrelated to the nuclear luminosity. If this were the case also for high redshift BL Lacs, then the brightening of their hosts should be due to strong luminosity evolution of similarly massive galaxies. However, for our sample (and the other available small samples) of high redshift BL Lacs there seems to be a significant correlation between the nuclear and the host luminosity. Therefore, the alternative view that this correlation, combined with the selection effect, causes the most luminous BL Lacs (with the most massive BHs) to be preferentially found in the (very rare) most luminous (massive) galaxies remains valid. Consequently, the difference in nuclear luminosity may fully account for the observed difference in host luminosity, and no strong luminosity evolution would be required.

3.3. The size of the host galaxies

The average effective radius of the 11 resolved high redshift ($z \geq 0.5$) BL Lac hosts presented in this study is $\langle R_e \rangle = 6.8 \pm 3.2$ kpc. This is in fair agreement with the typical value of intermediate redshift FSRQs (Kotilainen et al. 1998a; $\langle R(e) \rangle = 11.6 \pm 7.6$ kpc). Our value also agrees with that found for the high redshift BL Lacs studied by H04 ($\langle R(e) \rangle = 10.6 \pm 7.3$ kpc), but contrast with the significantly larger value reported by OU04 ($\langle R(e) \rangle = 32 \pm 17$ kpc) for five BL Lac hosts. OU04 suggested that their large scale lengths indicate that some of the host galaxies may have substantial disk components as well as bulges, but this is not corroborated by ground-based studies with a larger field-of-view (this work; H04).

The host galaxy sizes of high redshift BL Lac hosts are similar to those of lower redshift objects studied in the NIR, $\langle R(e) \rangle = 7.2 \pm 3.6$ kpc (KF04 and references therein). This indicates that at least up to $z \sim 1$ there is no significant change in the global structure of the hosts, in agreement with what is found for RLQs and FR II RGs (e.g. McLure & Dunlop 2000; Kukula et al. 2001; Falomo et al. 2004). Our measurements of the scale length of BL Lacs extends to higher redshift the finding that the average size of the BL Lac hosts is a factor ~2–4 smaller than that of low redshift RGs studied in the optical by Govoni et al. (2000; $\langle R(e) \rangle = 16 \pm 10$ kpc) and in the NIR by Taylor et al. (1996; $\langle R(e) \rangle = 26 \pm 16$ kpc), and for $z \sim 0.5$ RGs ($\langle R(e) \rangle = 19 \pm 8$ kpc; McLure et al. 2004).

3.4. Surface brightness – effective radius (Kormendy) relation

Normal early-type galaxies and spiral bulges define a continuous tight relation between the effective radius, r_e, and the surface brightness at that radius, μ_e (the Kormendy relation; Kormendy 1977; Kormendy & Djorgovski 1989). This is indeed a 2D projection of the 3D Fundamental Plane linking the

Table 4. Comparison of average host galaxy properties with other samples[a].

Sample (1)	Filter (2)	N (3)	$\langle z \rangle$ (4)	$\langle M_K(\mathrm{nuc})\rangle$ (5)	$<M_K(\mathrm{host})$ (6)
BL (this work)	K	12	0.795 ± 0.197	–30.1 ± 1.2	–27.9 ± 0.7
BL H04	I	9	0.669 ± 0.140		–27.2 ± 0.8
BL OU04	R	5	0.843 ± 0.156		–27.7 ± 0.9
BL KF04	H	23	0.155 ± 0.091	–24.5 ± 1.6	–26.0 ± 0.7
BL C03	K	8	0.186 ± 0.088	–25.6 ± 0.8	–26.0 ± 0.4
BL S00	H	9	0.206 ± 0.074	–25.0 ± 1.6	–26.4 ± 0.4
BL KFS98	H	7	0.112 ± 0.068	–25.7 ± 1.7	–26.0 ± 0.5
BL all low redshift	H/K	42	0.164 ± 0.084	–25.0 ± 1.5	–26.1 ± 0.6
L^* Mobasher et al. (1993)	K	136	0.077 ± 0.030		–25.2 ± 0.2
BCG Thuan & Puschell (1989)	H	84	0.074 ± 0.026		–26.5 ± 0.3
BCG Aragon-Salamanca et al. (1998)	K	25	0.449 ± 0.266		–27.2 ± 0.3
RG F–R II Taylor et al. (1996)	K	12	0.214 ± 0.049	–25.1 ± 0.7	–26.3 ± 0.8
RG Willott et al. (2003) $z < 0.3$	K	42	0.170 ± 0.075		–26.2 ± 0.7
RG Willott et al. (2003) $0.5 < z < 1$	K	45	0.749 ± 0.132		–26.8 ± 0.5
RG Willott et al. (2003) $1 < z < 2$	K	63	1.480 ± 0.306		–27.4 ± 0.7
FSRQ/R+M Kotilainen et al. (1998b)	H	9	0.671 ± 0.157	–29.7 ± 0.8	–26.9 ± 1.2
FSRQ/R Kotilainen et al. (1998b)	H	4	0.673 ± 0.141	–30.2 ± 0.7	–28.0 ± 0.3
SSRQ/R+M Kotilainen & Falomo (2000)	H	16	0.690 ± 0.088	–28.3 ± 1.3	–27.2 ± 1.2
SSRQ/R Kotilainen & Falomo (2000)	H	10	0.683 ± 0.077	–28.2 ± 1.2	–27.4 ± 1.1
RLQ Falomo et al. (2004)	H/K	10	1.514 ± 0.157	–30.9 ± 0.8	–27.5 ± 0.4

[a] Column (1) gives the sample; (2) the filter; (3) the number of objects in the sample; (4) the average redshift of the sample; and (5) and (6) the average K-band nuclear and host galaxy absolute magnitude of the sample.

above parameters to the velocity dispersion σ. This relation is well established for early-type galaxies and spiral bulges in nearby clusters (e.g. Jörgensen et al. 1996) and is closely related to the morphological and dynamical structure of galaxies, and to their formation processes.

We combined our $\mu_e - r_e$ data with previous data from KFS98, S00, C03 and KF04 to construct the Kormendy relation for the largest available sample of BL Lac host galaxies studied in the NIR (Fig. 6). The surface brightnesses of the hosts have been corrected for galactic extinction and cosmological dimming ($10 \times \log(1+z)$). The H-band data from KFS98, S00 and KF04 were converted to the K-band assuming $H - K = 0.22$ (Recillas-Cruz et al. 1990). We have also included a correction for passive evolution of a single age stellar population with formation redshift $z = 2$ in the K-band, adapted from van Dokkum & Franx (2001). The size of this correction is ~0.45 mag at $z = 0.5$, increasing to ~0.9 mag at $z = 1$. Even after these corrections, only a few of the high redshift BL Lac hosts are readily in agreement with respect to the relations for low redshift BL Lacs (KF04) and for normal elliptical galaxies (Pahre et al. 1995). Most of the high redshift BL Lac sources are offset from these relations towards brighter surface brightness by ~1.5 mag on average, This is in agreement with the detected difference of their integrated luminosity.

The unavoidable conclusion is that at $z > 0.5$ the hosts of high redshift BL Lacs are structurally similar (they have the same size) as lower redshift BL Lac hosts and normal early-type galaxies but they have much higher surface brightness. This can be interpreted in terms of the passive evolution of the stellar populations, if they are dominated by an old stellar population with a small fraction of the mass involved in a more recent secondary star formation episode. Note that similar offsets have been found for high redshift ($0.8 < z < 1.9$) 3CR RGs (Zirm et al. 2003) and for $z \sim 0.5$ field early-type galaxies (Treu et al. 2001), in the sense that, for a given effective radius, the high redshift galaxies are brighter than expected from the local relation.

3.5. Nuclear and host properties

The absolute magnitude of the nuclear component of the high redshift BL Lacs ranges from $M(K) \sim -28$ to $M(K) \sim -32$, with average $\langle M(K)\rangle = -30.1 \pm 1.2$. This is ~5 mag brighter than the average value of the nuclear luminosity of low redshift BL Lacs (KF04 and references therein). This ~ factor 100 of

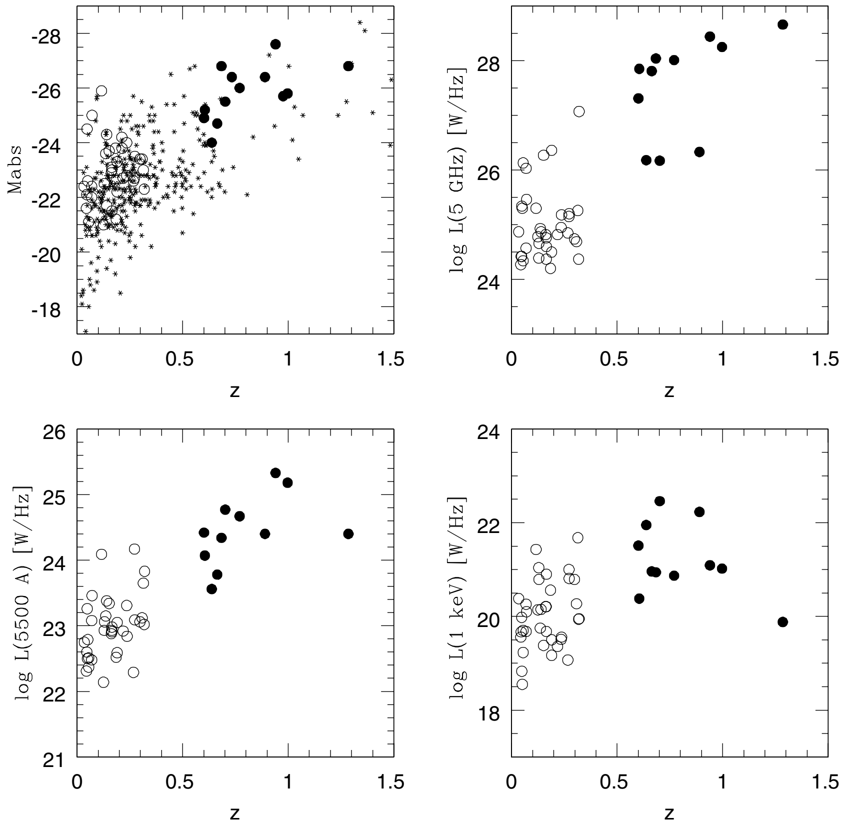

Fig. 5. Comparison of high and low redshift BL Lacs (filled and open circles, respectively) at various wavelengths. *Top left*: *V*-band absolute magnitude. *Top right*: the 5 GHz radio power. *Bottom left*: the 5500 Å monochromatic luminosity. *Bottom right*: the 1 keV luminosity. The first panel uses data from Veron-Cetty & Veron (2003), and the others from Donato et al. (2001).

difference is the consequence of the selection effect that prevents the detection of faint BL Lac objects with increasing redshift. On the other hand the nuclear luminosity of the high redshift BL Lacs is very similar to that of high redshift resolved FSRQs (ranging from $M(K) \sim -29$ to $\sim$–32, with average $\langle M(K)\rangle = -29.7\pm0.8$; Kotilainen et al. 1998a), suggesting that these objects are prefentially chosen from the most luminous tail of the luminosity function.

The difference in the strength of the nuclear component at low and high redshift is also evident considering the nucleus/galaxy luminosity ratio L(nuc)/L(gal) in Table 3. None of the low redshift BL Lacs have $L(\mathrm{nuc})/L(\mathrm{gal}) \geq 3$ (KF04), whereas all FSRQs (Kotilainen et al. 1998a) and all but one of the high redshift BL Lacs are above this limit. The high nuclear luminosity observed in the high redshift sources may be either due to their systematically higher intrinsic nuclear luminosity, or to the fact that we are preferentially selecting (because of the luminosity bias effect) those objects which are more strongly beamed. Although both effects may play a role, the former is likely the dominant one since the beaming distribution is independent of the redshift. This is consistent with the fact that the high redshift host galaxies are more luminous than those at low redshift.

In Fig. 7, we show the relation between the K-band luminosities of the nucleus and the host galaxy for the BL Lacs, FSRQs and high redshift quasars. While the host luminosity of high redshift BL Lacs is distributed over a range of only ~2.5 mag (~4 mag adding low redshift BL Lacs), the nuclear luminosities span over ~4 mag (~10 mag adding low redshift BL Lacs). While the majority of the low redshift ($z < 0.5$) BL Lac objects are homogeneously distributed in the M(nuc) – M(host) plane, the high redshift BL Lacs clearly tend to occupy the region of the more luminous host galaxies and nuclei. Moreover, they exhibit a reasonable correlation between the host and nuclear luminosities, similarly to the resolved FSRQs (Kotilainen et al. 1998a). No such correlation is found for low redshift (lower nuclear luminosity) BL Lacs.

Before discussing the implications of such a relationship, note that some selection effects may induce a spurious correlation between the nuclear and host galaxy luminosity. In particular, two effects may combine to depopulate the M(nuc) – M(host) plane in opposite regions. Firstly, low luminosity host galaxies are very difficult to detect under luminous nuclei. In our sample, however, this should not play a significant role because the selection criteria of BL Lacs are only based on the nuclear properties, and the objects are not biased with respect to their host properties. Indeed, only two host galaxies in our sample remained unresolved. Secondly, low luminosity AGN are difficult to detect against luminous hosts. This incompleteness may certainly be present at high redshift, but this effect is likely to be small because high luminosity galaxies are very rare.

The observed relationship between the host and nuclear luminosity, therefore, appears genuine and supports the

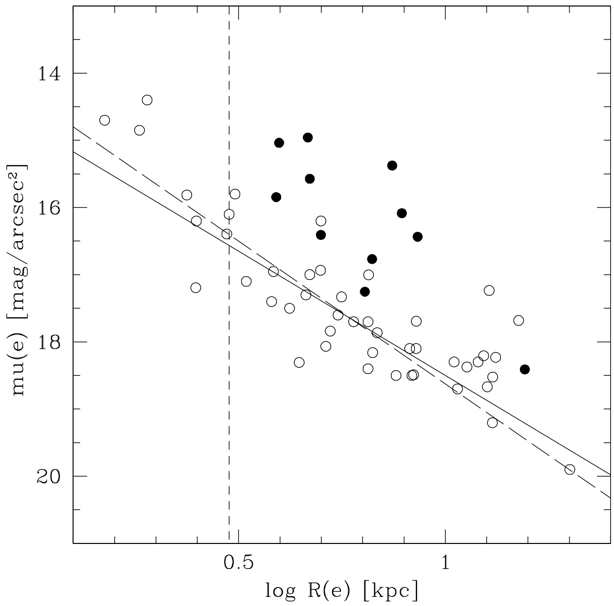

Fig. 6. The K-band $\mu_e - r_e$ Kormendy relation for the BL Lac host galaxies. Conversion from H- to K-band was made assuming $H - K$ = 0.22 colour, typical of normal ellipticals (Recillas-Cruz et al. 1990). Passive evolution of a single age stellar population with formation redshift $z = 2$ in the K-band was adapted from van Dokkum & Franx (2001). For symbols, see Fig. 3. The solid and long-dashed lines are linear least-square best-fit relations for low redshift BL Lacs (KF04) and normal inactive ellipticals (Pahre et al. 1995), respectively. The short-dashed vertical line is the dividing line between normal and giant ellipticals at R(e) = 3 kpc (Capaccioli et al. 1992).

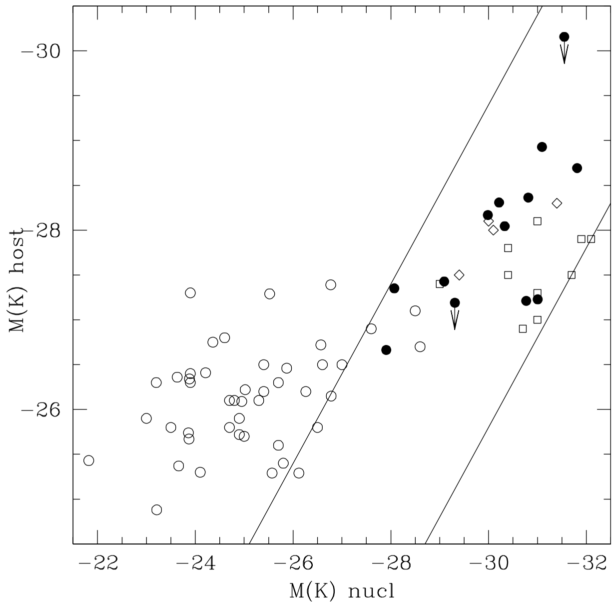

Fig. 7. Plot of the K-band nuclear vs. host luminosity. For symbols, see Fig. 3. The solid lines represent loci of constant ratio between host and nuclear emission. These can be translated into Eddington ratios assuming that the central black hole mass – galaxy luminosity correlation holds at high redshifts and that the observed nuclear power is proportional to the bolometric emission. The two solid lines encompass a spread of 1.5 dex in the nucleus/host luminosity ratio.

longstanding idea (e.g. McLeod & Rieke 1994) that the onset of the correlation occurs only after a certain threshold in the host galaxy luminosity. The widely accepted interpretation is that for a given host luminosity, the central BH mass is given by the BH mass – bulge mass correlation, and that at the highest luminosities (highest BH masses) AGN may accrete near their Eddington limit, triggering the onset of the BH – host correlation (see also e.g. Lacy et al. 2000; Sanchez et al. 2004). Such a correlation appears to follow the trend of a roughly constant ratio between the host galaxy luminosity (mass) and the nuclear emission. The relatively large (∼1.5 dex) scatter would then mainly reflect differences in the accretion rates.

Assuming that the bolometric luminosity scales as the K-band luminosity, and that the host galaxy luminosity is proportional to the BH mass (as seems to be the case for nearby inactive galaxies and low redshift AGN; e.g. Marconi & Hunt 2003; McLure & Dunlop 2002), the nucleus/galaxy luminosity ratio should be proportional to the Eddington factor $\xi = L/L_E$, where $L_E = 1.25 \times 10^{38} \times (M_{BH}/M_\odot)$. The average K-band nucleus-to-host luminosity ratio of the high redshift BL Lacs is $\langle \log(M_{nuc}/M_{host}\rangle = 0.90 \pm 0.36$. This is about a factor of 10 larger than that found for the objects at low redshift ($\langle \log(M_{nuc}/M_{host}\rangle \sim 0$; Falomo & Kotilainen 1999; Urry et al. 2000; KF04) but still smaller than the ratio found for high redshift RLQs ($\langle \log(M_{nuc}/M_{host}\rangle = 1.36 \pm 0.33$; Falomo et al. 2004). These differences are consistent with the idea that BL Lacs are intrinsically low power AGN, with much lower accretion rates than those in RLQs (as found at low redshift by e.g. O'Dowd et al. 2002). The luminous high redshift BL Lacs appear thus, in this context, intermediate power AGN between the lower power BL Lacs (which dominate the population at low redshift) and the higher power RLQs.

4. Summary and conclusions

We have presented the first near-infrared imaging study of a sizeable sample of BL Lac objects at $z > 0.5$. In 11/13 cases, we are able to resolve the objects and to characterize the properties of their host galaxies. We find that at $z \sim 0.8$ BL Lac host galaxies are very luminous (average $\langle M(K)\rangle = -27.9 \pm 0.7$), ∼3 mag brighter than L^* galaxies. The BL Lac hosts have similar luminosity to the hosts of high redshift FSRQs, consistent with the idea that they form a common class of AGN (blazars). The high redshift BL Lac hosts are large (average bulge scale length $\langle R(e)\rangle = 6.8 \pm 3.2$ kpc) and of similar size to their low redshift counterparts, indicating that there is no evolution in the host galaxy size.

At variance with the behaviour for low redshift BL Lacs, we find a correlation between the luminosity of the host galaxy and that of the nucleus in the high redshift BL Lacs. This can occur at a fixed fraction of the Eddington luminosity, as the result of a more massive BH is interpreted as an increase of emitted power, as expected from the BH mass – bulge luminosity correlation found in nearby spheroidals. High redshift BL Lacs appear to radiate with a wide range of power with respect to their Eddington luminosity, and this power is intermediate between the low level observed in nearby BL Lacs and the higher level occurring in luminous radio-loud quasars.

The main finding of this work is that the host luminosity is ~2 mag brighter than that of lower redshift BL Lacs. This substantial increase in luminosity can be due to a combination of a strong selection effect in the surveys of BL Lacs that makes observable only the most luminous sources at $z > 0.5$ and produces a correlation between the nuclear and the host luminosity that emerges at high redshift. Alternatively, since this difference in host luminosity is inconsistent with a simple passive evolution of the host galaxies, to interpret this difference one should invoke a non-negligible contribution from recent star formation episodes that took place at $z > 0.5$.

Detailed spectroscopic studies and colour information of these host galaxies would clearly help to elucidate this issue. On the other hand, future deeper surveys of BL Lacs could provide data to probe the full population of BL Lacs up to $z \sim 1$ and thus significantly reduce the selection effects.

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References

Abraham, R. C., Crawford, C. S., Merrifield, M. R., Hutchings, J. B., & McHardy, I. M. 1993, ApJ, 415, 101
Allen, D. A., Ward, M. J., & Hyland, A. R. 1982, MNRAS, 199, 969
Aragon-Salamanca, A., Baugh, C. M., & Kauffmann, G. 1998, MNRAS, 297, 427
Avni, Y. 1976, ApJ, 210, 642
Barth, A. J., Ho, L. C., & Sargent, W. L. W. 2003, ApJ, 583, 134
Bell, E. F., Wolf, C., Meisenheimer, K., et al. 2004, ApJ, 608, 752
Bettoni, D., Falomo, R., Fasano, G., & Govoni, F. 2003, A&A, 399, 869
Bressan, A., Granato, G. L., & Silva, L. 1998, A&A, 332, 135
Capaccioli, M., Caon, N., & D'Onofrio, M. 1992, MNRAS, 259 323
Cardelli, J. A., Clayton, G. C., & Mathis, J. S. 1989, ApJ, 345, 245
Cassaro, P., Stanghellini, C., Bondi, M., et al. 1999, A&AS, 139, 601
Cavaliere, A., & Padovani, P. 1989, ApJ, 340, L5
Cheung, C. C., Urry, C. M., Scarpa, R., & Giavalisco, M. 2003, ApJ, 599, 155
Di Matteo, T., Croft, R. A. C., Springel, V., & Hernquist, L. 2003, ApJ, 593, 56
Donato, D., Ghisellini, G., Tagliaferri, G., & Fossati, G. 2001, A&A, 375, 739
Dunlop, J. S., & Peacock, J. A. 1990, MNRAS, 247, 19
Dunlop, J. S., McLure, R. J., Kukula, M. J., et al. 2003, MNRAS, 340, 1095
Eales, S., Rawlings, S., Law-Green, D., Cotter, G., & Lacy, M. 1997, MNRAS, 291, 593
Falomo, R. 1996, MNRAS, 283, 241
Falomo, R., & Kotilainen, J. K. 1999, A&A, 352, 85
Falomo, R., & Ulrich, M.-H. 2000, A&A, 357, 91
Falomo, R., Kotilainen, J. K., & Treves, A. 2002, ApJ, 569, L35
Falomo, R., Kotilainen, J. K., Carangelo, N., & Treves, A. 2003, ApJ, 595, 624
Falomo, R., Kotilainen, J. K., Pagani, C., Scarpa, R., & Treves, A. 2004, ApJ, 604, 495
Fan, J. H., & Lin, R. G. 1999, ApJS, 121, 131
Ferrarese, L., & Merritt, D. 2000, ApJ, 539, L9
Franceschini, A., Hasinger, G., Miyaji, T., & Malquori, D. 1999, MNRAS, 310, L5
Gear, W. K., Robson, E. I., Brown, L. M. J., et al. 1985, ApJ, 291, 511
Gear, W. K., Brown, L. M. J., Robson, E. I., et al. 1986, ApJ, 304, 295
Gear, W. K. 1993, MNRAS, 264, 919
Gebhardt, K., Bender, R., Bower, G., et al. 2000, ApJ, 539, L13
Govoni, F., Falomo, R., Fasano, G., & Scarpa, R. 2000, A&A, 353, 507
Heidt, J., Nilsson, K., Pursimo, T., Takalo, L. O., & Sillanpää, A. 1996, A&A, 312, L13
Heidt, J., Tröller, M., Nilsson, K., et al. 2004, A&A, 418, 813 (H04)
Holmes, P. A., Brand, P. W. J. L., Impey, C. D., & Williams, P. M. 1984, MNRAS, 210, 961
Hunt, L. K., Mannucci, F., Testi, L., et al. 1998, AJ, 115, 2594
Impey, C. D., Brand, P. W. J. L., Wolstencroft, R. D., & Williams, P. M. 1982, MNRAS, 200, 19
Impey, C. D., Brand, P. W. J. L., Wolstencroft, R. D., & Williams, P. M. 1984, MNRAS, 209, 245
Jarvis, M. J., Rawlings, S., Eales, S., et al. 2001, MNRAS, 326, 1585
Jörgensen, I., Franx, M., & Kjaergaard, P. 1996, MNRAS, 280, 167
Kauffmann, G., & Hähnelt, M. 2000, MNRAS, 311, 576
Kormendy, J. 1977, ApJ, 218, 333
Kormendy, J., & Djorgovski, S. 1989, ARA&A, 27, 235
Kotilainen, J. K., Falomo, R., & Scarpa, R. 1998a, A&A, 332, 503
Kotilainen, J. K., Falomo, R., & Scarpa, R. 1998b, A&A, 336, 479 (KFS98)
Kotilainen, J. K., & Falomo, R. 2000, A&A, 364, 70
Kotilainen, J. K., & Falomo, R. 2004, A&A, 424, 107
Kukula, M. J., Dunlop, J. S., McLure, R. J., et al. 2001, MNRAS, 326, 1533
Lacy, M., Bunker, A. J., & Ridgway, S. E. 2000, AJ, 120, 68
Lilly, S. J., & Longair, M. S. 1984, MNRAS, 211, 833
Madau, P., Pozzetti, L., & Dickinson, M. 1998, ApJ, 498, 106
Magliocchetti, M., Celotti, A., & Danese, L. 2002, MNRAS, 329, 377
Magorrian, J., Tremaine, S., Richstone, D., et al. 1998, AJ, 115, 2285
Marconi, A., & Hunt, L. K. 2003, ApJ, 589, L21
McLeod, K. K., & Rieke, G. H. 1994, ApJ, 431, 137
McLure, R. J., & Dunlop, J. S. 2000, MNRAS, 317, 249
McLure, R. J., & Dunlop, J. S. 2002, MNRAS, 331, 795
McLure, R. J., Willott, C. J., Jarvis, M. J., et al. 2004, MNRAS, 351, 347
Mead, A. R. G., Ballard, K. R., Brand, P. W. J. L., et al. 1990, A&AS, 83, 183
Mobasher, B., Sharples, R. M., & Ellis, R. S. 1993, MNRAS, 263, 560
Neugebauer, G., Matthews, K., Soifer, B. T., & Elias, J. H. 1985, ApJ, 298, 275
Nilsson, K., Charles, P. A., Pursimo, T., et al. 1996, A&A, 314, 754
Nilsson, K., Pursimo, T., Heidt, J., et al. 2003, A&A, 400, 95
Nolan, L. A., Dunlop, J. S., Kukula, M. J., et al. 2001, MNRAS, 323, 308
O'Dell, S. L., Puschell, J. J., Stein, W. A., & Warner, J. W. 1978, ApJS, 38, 267
O'Dowd, M., Urry, C. M., & Scarpa, R. 2002, ApJ, 580, 96
O'Dowd, M., & Urry, C. M. 2004, ApJ, in press [arXiv:astro-ph/0411099], (OU04)

Pagani, C., Falomo, R., & Treves, A. 2003, ApJ, 596, 830
Pahre, M. A., Djorgovski, S. G., & de Carvalho, R. R. 1995, ApJ, 453, L17
Pursimo, T., Nilsson, K., Takalo, L. O., et al. 2002, A&A, 381, 810
Recillas-Cruz, E., Carrasco, L., Serrano, A., & Cruz-Gonzalez, I. 1990, A&A, 229, 64
Sanchez, S. F., Jahnke, K., Wisotzki, L., et al. 2004, ApJ, 614, 586
Sbarufatti, B., Treves, A., Falomo, R., et al. 2005, AJ, 129, 559
Scarpa, R., & Falomo, R. 1997, A&A, 325, 109
Scarpa, R., Urry, C. M., Falomo, R., et al. 1999, ApJ, 521, 134
Scarpa, R., Urry, C. M., Falomo, R., Pesce, J. E., & Treves, A. 2000a, ApJ, 532, 740
Scarpa, R., Urry, C. M., Padovani, P., Calzetti, D., & O'Dowd, M. 2000b, ApJ, 544, 258 (S00)
Smith, E. P., Heckman, T. M., Bothun, G. D., Romanishin, W., & Balick, B. 1986, ApJ, 306, 64
Stanford, S. A., Eisenhardt, P. R., & Dickinson, M. 1998, ApJ, 492, 461
Stickel, M., Fried, J. W., & Kühr, H. 1988, A&A, 198, L13
Stickel, M., Fried, J. W., & Kühr, H. 1993, A&AS, 98, 393
Taylor, G. L., Dunlop, J. S., Hughes, D. H., & Robson, E. I. 1996, MNRAS, 283, 930
Thuan, T. X., & Puschell, J. J. 1989, ApJ, 346, 34
Treu, T., Stiavelli, M., Bertin, G., Casertano, S., & Moller, P. 2001, MNRAS, 326, 237
Urry, C. M., & Padovani, P. 1995, PASP, 107, 803
Urry, C. M., Falomo, R., Scarpa, R., et al. 1999, ApJ, 512, 88
Urry, C. M., Scarpa, R., O'Dowd, M., et al. 2000, ApJ, 532, 816
van der Marel, R. 1999, AJ, 117, 744
van Dokkum, P. G., & Franx, M. 2001, ApJ, 553, 90
Veron-Cetty, M. P., & Veron, P. 2003, A&A, 412, 399
Warren, S. J., Hewett, P. C., & Osmer, P. S. 1994, ApJ, 421, 412
Watson, D., Smith, N., Hanlon, L., et al. 2000, A&A, 364, 43
Willott, C. J., Rawlings, S., Jarvis, M. J., & Blundell, K. M. 2003, MNRAS, 339, 173
Woo, J.-H., Urry, C. M., Lira, P., van der Marel, R. P., & Maza, J. 2004, ApJ, 617, 903
Wurtz, R., Stocke, J. T., & Yee, H. K. C. 1996, ApJS, 103, 109
Yu, Q., & Tremaine, S. 2002, MNRAS, 335, 965
Zirm, A.W., Dickinson, M., & Dey, A. 2003, ApJ, 585, 90

Online Material

Appendix A: Notes on the host galaxies of individual objects

PKS 0138-097: This BL Lac object at $z = 0.733$ has a smooth IR-optical spectrum and is highly polarized. Until now, the host galaxy has remained unresolved in the optical (e.g. Stickel et al. 1993; Heidt et al. 1996; Scarpa et al. 1999, 2000a; Pursimo et al. 2002; OU04) and in the NIR (C03). Although Scarpa et al. (1999, 2000a) noted a small systematic departure from the PSF profile at $r > 1$ arcsec, they concluded that the excess light was due to nearby galaxies, with an upper limit to the host magnitude of $m(\mathrm{R}) > 20.1 (M(R) > -25.4)$. This source was marginally resolved by OU04 but was considered unresolved ($m(R, \mathrm{host}) > 19.6$) because the fit was not better than the fit with the PSF only. The environment near PKS 0138-097 is rich, with at least four galaxies within 3 arcsec radius (projected distance of 30 kpc; Heidt et al. 1996). They could be responsible for the intervening absorption system at $z = 0.501$ (Stickel et al. 1993; Falomo & Ulrich 2000). The closest of these galaxies (source C in Heidt et al. 1996) is at a distance of 1.45 arcsec (projected distance of 14 kpc), indicating gravitational interaction with the BL Lac object. The presence of absorption systems and close companions led Heidt et al. (1996) to suggest that this BL Lac object may be affected by gravitational microlensing. In the NIR, we fit only the profile of the northern part of the source (free of intervening galaxies), and the source was found to be marginally resolved, with $R(\mathrm{e}) = 3.9$ kpc and $M(K, \mathrm{host}) = -27.2$.

PKS 0235+164: This BL Lac object at $z = 0.940$ is well known to be in a complex environment and with close companions that in part are responsible for the intervening systems at $z = 0.852$ and $z = 0.524$ (e.g. Falomo 1996; Nilsson et al. 1996, and references therein). Claims of detection of a surrounding nebulosity were proposed by Stickel et al. (1988) and by Abraham et al. (1993) but were not confirmed by later optical studies (Falomo 1996; Nilsson et al. 1996). The object was also not resolved by HST (Scarpa et al. 2000a). Because of the presence of the close companions, the extraction of a reliable radial profile is very difficult. Instead of masking the regions contaminated by companions, we preferred in this case to fit only the part of the image around the target that is free of intervening galaxies, and the source was found to be unresolved in the NIR. Therefore, PKS 0235+164 has been left out of all discussion of the host galaxies.

B2 1308+326: This object at $z = 0.997$ has variable emission line strengths (Stickel et al. 1993; Scarpa & Falomo 1997), high bolometric luminosity and a high Doppler boost factor (Watson et al. 2000), and it may be classified as a composite quasar/BL Lac object. It has a number of faint companion galaxies, the closest at ∼5 arcsec (55 kpc) to SW. Nilsson et al. (2003) obtained a deep R-band exposure (6000 s) under good seeing conditions (0.9 arcsec), yet no sign of the host galaxy was seen ($m(R, \mathrm{host}) > 20.6$). Urry et al. (1999) found the object also unresolved in their deep HST exposure ($m(I, \mathrm{host}) > 20.1$). This source was marginally resolved by OU04 but was considered unresolved ($m(R, \mathrm{host}) > 20.1$) because the fit was not better than the fit with the PSF only. Due to its high redshift, this object has been suggested as a case of microlensing by stars in a foreground galaxy.

RXJ 14226+5801: The host galaxy of this BL Lac object at $z = 0.638$ was not resolved in the HST survey (Scarpa et al. 2000a; $m(R, \mathrm{host}) > 21.7$). However, it was resolved in the groundbased I-band imaging by H04 ($r(\mathrm{e}) = 2.3$ arcsec; $R(\mathrm{e}) = 21$ kpc; $m(I) = 18.9$; $M(I) = -25.3$). The host was also well resolved by OU04, with $R(\mathrm{e}) = 24$ kpc and $M(R, \mathrm{host}) = -24.5$. We detect the host galaxy in the K-band with $r(\mathrm{e}) = 0.7$ arcsec ($R(\mathrm{e}) = 6.4$ kpc), i.e. smaller extent than in the optical, and with $m(K, \mathrm{host}) = 16.2$ ($M(K, \mathrm{host}) = -26.7$). The integrated colours of the host galaxy are thus $R - K = 2.2$ and $I - K = 1.4$, slightly bluer than for normal ellipticals ($R - K = 2.7$; $I - K = 2.0$). There are two companion galaxies at ∼4 arcsec (36 kpc) to the NW and SW.

1ES 1517+656: This BL Lac at $z = 0.702$, although being a high frequency peaked BL Lac, is one of the most luminous BL Lac objects in the X-ray, optical and radio range. It remained unresolved in the groundbased R-band imaging by Nilsson et al. (2003), and by Falomo & Kotilainen (1999). It was also unresolved in the HST snapshot survey (Scarpa et al. 1999, 2000a), with an upper limit $m(\mathrm{host}) > 19.9$, corresponding to $M(\mathrm{host}) > -25.2$. This BL Lac shows an unusual morphology with three non-homogeneous arclets describing an almost perfect Einstein ring surrounding the nucleus at 2.4 arcsec (23 kpc) distance (Scarpa et al. 1999), suggestive of gravitational lensing of one or more background galaxies by a foreground galaxy. Deeper images (Falomo & Kotilainen 1999) show that there are many other faint sources in the close environment. They found no signature of a massive foreground galaxy, therefore weakening the lens hypothesis. In this work, the host galaxy is detected in the NIR, with $R(\mathrm{e}) = 8.6$ kpc and $M(K, \mathrm{host}) = -28.2$.

1ES 1533+535: The radial profile of this BL Lac at $z = 0.890$ showed some deviations from the PSF model at large radii in the HST survey (Scarpa et al. 2000a), but the source was considered unresolved ($m(R, \mathrm{host}) > 19.7$). The host galaxy was well resolved by OU04, with $r(\mathrm{e}) = 3\farcs4$ ($R(\mathrm{e}) = 36$ kpc) and $M(R, \mathrm{host}) = -25.4$. In the K-band, we detect the host galaxy with $m(K) = 16.5 (M(K) = -27.3)$ and $r(\mathrm{e}) = 0.4$ arcsec ($R(\mathrm{e}) = 4.2$ kpc). The colour of the host galaxy is thus $R - K = 1.9$, bluer than in normal ellipticals.

PKS 1538+149: PKS 1538+149 is at $z = 0.605$. The host was only barely resolved in the HST snapshot survey by Scarpa et al. (2000a; $m(R) = 20.2$; $M(R) = -24.6$; $r(\mathrm{e}) = 2\farcs5$; $R(\mathrm{e}) = 22$ kpc). However, in deeper HST observations, this object was well resolved (Urry et al. 1999; $m(I) = 19.0$; $M(R) = -25.1$; $r(\mathrm{e}) = 2\farcs4$; $R(\mathrm{e}) = 21$ kpc). Nilsson et al. (2003) detected the host with $m(R) = 19.9 (M(R) = -24.8)$ and $r(\mathrm{e}) = 3\farcs0$ ($R(\mathrm{e}) = 27$ kpc). The host galaxy remained unresolved in our previous NIR imaging (Kotilainen et al. 1998a), obtained in poor seeing ($FWHM \sim 1\farcs7$). In this work, we resolve the host in the NIR and derive for it $R(\mathrm{e}) = 15.6$ kpc and $M(K, \mathrm{host}) = -27.4$. The NIR host scalelength is the largest for the high redshift BL Lac sample, although smaller than the optical scalelength. The host galaxy colour is $R - K \sim 2.7$, in agreement with normal ellipticals. There are several faint galaxies within 50 kpc of the BL Lac (Urry et al. 1999), consistent with L^* galaxies at the redshift of the BL Lac object.

S4 1749+701: This BL Lac object at $z = 0.770$ remained unresolved with HST (Scarpa et al. 2000a; $M(R) > -27.1$) and in deeper ground-based R-band imaging (Nilsson et al. 2003; $m(R, \mathrm{host}) > 18.7$; $M(R) > -26.1$). We detected the host galaxy in the K-band with $m(K) = 15.4 (M(K) = -28.0)$.

S5 1803+784: This object ($z = 0.684$) remained unresolved in the studies by Stickel et al. (1993), Scarpa et al. (2000a) and Pursimo et al. (2002). For example, Pursimo et al. (2002) derived an upper limit to the host luminosity of $M(R) > -27.2$. We detected the host galaxy in the K-band with $R(\mathrm{e}) = 7.4$ kpc and $M(K) = -28.9$).

S4 1823+568: This BL Lac at $z = 0.664$ was resolved by Nilsson et al. (2003), with $m(R) = 20.0 (M(R) = -25.2)$ and $r(\mathrm{e}) = 2\farcs5$ ($R(\mathrm{e}) = 23$ kpc). It was also resolved with the HST by Scarpa et al. 2000a ($m(R) = 20.2$; $M(R) = -25.1$; $r(\mathrm{e}) = 0\farcs6$; $R(\mathrm{e}) = 5.6$ kpc) and by Urry et al. 1999 ($m(I) = 18.8$; $M(I) = -25.6$; $r(\mathrm{e}) = 1\farcs1$; $R(\mathrm{e}) = 9.3$ kpc). We detected the host galaxy in the K-band with $R(\mathrm{e}) = 4.6$ kpc and $M(K) = -28.3$). This corresponds to a host colour of $R - K \sim 3.2$, redder than in normal ellipticals. There are several faint galaxies in the field, especially a nonstellar object 5 arcsec (46 kpc) east of the source. This object is highly distorted with asymmetric faint emission elongated toward the south, and it may have suffered strong tidal interaction with the host galaxy.

PKS 2032+107: To our knowledge, no previous imaging data exist for this BL Lac object at $z = 0.601$. In this work, the host galaxy is detected in the NIR, with $R(\mathrm{e}) = 6.6$ kpc and $M(K, \mathrm{host}) = -27.2$.

PKS 2131-021: This is the highest redshift BL Lac object in the sample ($z = 1.285$). It has a faint companion galaxy ~4 arcsec (47 kpc) to NE. The host galaxy remained unresolved in the optical studies by Scarpa et al. (2000a; $M(R) > -27.0$), H04 ($M(I) > -28.3$), and Pursimo et al. (2002) ($M(R) > -27.8$). Despite the mediocre seeing ($FWHM \sim 1\farcs0$), we detected the host galaxy in the K-band with $R(\mathrm{e}) = 4.7$ kpc and $M(K) = -28.5$).

PKS 2207+020: To our knowledge, no previous imaging data exist for this BL Lac object at $z = 0.976$. In the close environment, there are two companion galaxies, at $5\farcs1$ (55 kpc) SE and at $2\farcs0$ (22 kpc) S–SW. The isophotes of the latter companion superimposed on the target result in a cometary appearance. The radial profile of the target was derived avoiding these nearby sources, and was found to be unresolved. Therefore, PKS 2207+020 has been left out of all discussion of the host galaxies.