

# The host galaxies of BL Lac objects in the near-infrared<sup>\*</sup>

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**Abstract.** We present the results of near-infrared H band (1.65  $\mu\text{m}$ ) imaging of 11 BL Lac objects with redshifts ranging from  $z = 0.05$  to 0.9. We are able to clearly detect the host galaxy in seven low redshift ( $z \leq 0.24$ ) BL Lacs, while the four unresolved BL Lacs have either high or unknown redshift. The galaxies hosting the low redshift BL Lacs are large (average bulge scale length  $R(e) = 8.8 \pm 9.9$  kpc) and luminous (average  $M(H) = -25.8 \pm 0.5$ ), i.e. slightly brighter than the typical galaxy luminosity  $L^*$  ( $M^*(H) = -25.0 \pm 0.2$ ), and of similar luminosity to or slightly fainter than brightest cluster galaxies ( $M(H) = -26.3 \pm 0.3$ ). The average optical/near-infrared colour and colour gradient of the BL Lac hosts ( $R-H = 2.2 \pm 0.5$ ;  $\Delta(R-H)/\Delta(\log r) = -0.09 \pm 0.04$ ) are consistent with the hosts being normal ellipticals, indicating that the nuclear activity has only a marginal effect on the star formation history and other properties of the hosts. The BL Lac hosts appear slightly less luminous than those of higher redshift flat spectrum radio quasars. The nucleus-to-galaxy luminosity ratio of the BL Lacs is similar to that of low redshift radio galaxies and consistent with what found in previous optical studies of BL Lacs. However, it is smaller than that found for flat spectrum radio quasars, suggesting there is a difference in the intrinsic brightness of the nuclear source or in the Doppler beaming factor between the two types of blazars.

**Key words:** BL Lacertae objects: general – galaxies: active – galaxies: nuclei – galaxies: photometry – infrared: galaxies

## 1. Introduction

BL Lac objects are active galactic nuclei (AGN) characterized by strong and rapidly variable continuum emission and polarization across the electromagnetic spectrum, strong compact flat spectrum radio emission and superluminal motion (see e.g. Kollgaard et al. 1992 for general references). They share many properties with flat spectrum radio quasars (FSRQ) and are often grouped together as blazars. The clearest difference between

them is that the latter have strong broad emission lines, while these are very weak or absent in BL Lacs.

Blazar properties are usually explained by the beaming model (Blandford & Rees 1978), where the observed emission is dominated by a synchrotron emitting relativistically boosted jet oriented close to our line-of-sight. This model is supported by the fact that almost all blazars are strong and rapidly variable  $\gamma$ -ray sources (e.g. von Montigny et al. 1995). The beaming model implies the existence of a more numerous parent population of intrinsically identical objects but with their jet oriented at larger angles to our line-of-sight. In the current unified models for radio-loud AGN (e.g. Urry & Padovani 1995), BL Lac objects are unified with low luminosity core-dominated (F-R I) radio galaxies (RG) seen nearly along the jet axis, while the high luminosity lobe-dominated (F-R II) RGs represent the parents of FSRQs (Padovani & Urry 1990; Urry, Padovani & Stickel 1991). However, for potential problems in this simple unification, see Urry & Padovani (1995). For a direct test of the unification model, we need to compare orientation-independent properties of BL Lac objects with those of the parents, e.g. extended radio emission, host galaxies and environments.

Considerable amount of optical imaging exists for relatively nearby ( $z \leq 0.5$ ) BL Lac hosts (e.g. Abraham, McHardy & Crawford 1991; Stickel, Fried & Kühr 1993; Falomo 1996; Wurtz et al. 1996; Falomo et al. 1997b; Jannuzi, Yanny & Impey 1997). The host galaxies of nearby BL Lacs have turned out to be predominantly giant ellipticals with similar magnitude to F-R I RGs, although there appear to be some cases of disk dominated host galaxies (e.g. McHardy et al. 1991; Abraham et al. 1991; Stocke, Wurtz & Perlman 1995, but see contradicting views by e.g. Romanishin 1992; Stickel et al. 1993; Falomo et al. 1997a). The extended radio power and optical environments of BL Lacs are also consistent with those of F-R I RGs, but suggest a contribution to the parent population from F-R II RGs (Kollgaard et al. 1992; Pesce, Falomo & Treves 1995; Wurtz et al. 1997).

Very little near-infrared (NIR) imaging exists on BL Lac objects. However, NIR wavelengths may offer some advantages. Optical emission from BL Lacs is often dominated by the nuclear source, while the luminosity of the massive old stellar population peaks in the NIR. This leads to a better contrast of the nebulosity with respect to the nuclear source at these wave-

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<sup>\*</sup> Based on observations collected at the European Southern Observatory, La Silla, Chile.

lengths. One also needs to apply much lower K-correction in the NIR than in the optical. In this paper we present NIR H-band ( $1.65 \mu\text{m}$ ) images of 11 BL Lac objects and compare the NIR host properties with those of RGs and FSRQs. The BL Lacs were observed during our project to study the host galaxies of a complete sample of FSRQs (Kotilainen, Falomo & Scarpa 1998; hereafter KFS98) and thus they do not satisfy any criteria of completeness. However, all the low redshift BL Lacs in this sample have previously been imaged in the optical by us. The same procedure of analysis was performed on the NIR and optical datasets, thus allowing us to investigate the R-H colour of the host galaxies in a homogeneous manner. Properties of the observed objects are given in Table 1. In Sect. 2, we briefly describe the observations, data reduction and the method of the analysis and refer the reader to a more thorough discussion given in KFS98. Our results are presented in Sect. 3 and conclusions in Sect. 4. Throughout this paper,  $H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}$  and  $q_0 = 0$  are used.

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

The observations were carried out at the 2.2m telescope of European Southern Observatory (ESO), La Silla, Chile, in August 1995 and January 1996, using the  $256 \times 256 \text{ px}$  IRAC2 NIR camera (Moorwood et al. 1992) with pixel scale  $0.27'' \text{ px}^{-1}$ , giving a field of view of  $69 \text{ arcsec}^2$ . Log of the observations is given in Table 1. The observations, data reduction and modeling of the luminosity profiles were performed following the procedure described in KFS98. Briefly, for nearby targets object frames were interspersed with sky frames. Distant targets, on the other hand, were always kept in the field by shifting them across the array. Individual exposures were coadded to achieve the final integration time (see Table 1).

Data reduction consisted of correction for bad pixels by interpolating across neighboring pixels, sky subtraction using a median averaged sky frame (for nearby sources) or a median averaged frame of all observations (for distant sources), flat-fielding, and combination of images of the same target. Standard stars from the list of Landolt (1992) were used for photometric calibration, for which we estimate an accuracy of  $\sim 0.1 \text{ mag}$ . K-correction was applied to the host galaxy magnitudes following the method of Neugebauer et al. (1985). The size of this correction is insignificant at low redshift in the H filter ( $m(H) = 0.01$  at  $z = 0.2$ ). No K-correction was applied to the nuclear component, assumed to have a power-law spectrum ( $f_\nu \propto \nu^{-\alpha}$ ) with  $\alpha \sim -1$ .

Azimuthally averaged radial luminosity profile was extracted for each object and stars in the frames down to surface brightness of  $\mu(H) = 22\text{--}23 \text{ mag arcsec}^{-2}$ . Only for few objects, bright stars were present in the field for straightforward PSF determination. For most sources, the core of the PSF was derived from faint field stars, while the wing was extrapolated using a suitable Moffat (1969) function obtained from fitting bright stars in other frames of similar seeing during the same night. We stress that this extrapolation does not affect the fit for

the low redshift, often host-dominated BL Lacs in our sample. The luminosity profiles were fitted into point source and galaxy components by an iterative least-squares fit to the observed profile. For low redshift objects, we attempted both elliptical (de Vaucouleurs law) and exponential disc models to represent the galaxy. However, consistently with results from optical images, in no case did the disc model give a better fit than the elliptical one for the observed sources. For higher redshift objects, data quality does not allow one to discriminate between the morphologies and for them the elliptical model was assumed. We estimate the uncertainty of the derived host galaxy magnitudes to be  $\sim \pm 0.3 \text{ mag}$ .

## 3. Results and discussion

In Fig. 1 we show the H band contour plots of all the BL Lacs, after smoothing the images with a Gaussian filter of  $\sigma = 1 \text{ px}$ . We are able to clearly detect the host galaxy in all the BL Lacs at low redshift ( $z \leq 0.24$ ). In the unresolved cases, the redshift is either high (PKS 1538+14;  $z = 0.605$ , PKS 0537-441;  $z = 0.896$ ) or unknown but probably high ( $z \geq 0.5$ ; PKS 0048-097 and  $z \geq 0.557$ ; PKS 0118-272). Therefore, these sources are still consistent with being hosted by giant ellipticals. On the other hand, if their redshifts are lower, they may reside in sub-luminous hosts, which could account for the failure to detect absorption lines in the spectra of the latter two BL Lacs. In Fig. 2, we show the radial luminosity profiles of each BL Lac object, together with the best-fit models overlaid. In the Appendix, we compare our NIR photometry with previous studies, and discuss in detail individual BL Lacs, including comparison with previous optical determinations of the host galaxies. The results derived from the profile fitting are summarized in Table 2, where column (1) and (2) give the name and redshift of the object; (3) the bulge scale-length in arcsec and kpc; (4) and (5) the apparent nuclear and host galaxy magnitude; (6) the nucleus/galaxy luminosity ratio; (7) and (8) the absolute nuclear and host galaxy magnitude; and (9) whether the image of object is resolved (R) or unresolved (U).

### 3.1. The near-infrared properties of the host galaxies

The host galaxies of all the low redshift resolved BL Lacs in this sample have previously been studied by us in the optical (Falomo 1996; Falomo & Kotilainen, in preparation). The observations presented here are, however, the first study of them in the NIR, and allow us to address for the first time the issue of the optical-NIR colour of the BL Lac host galaxies. The integrated colours of the host galaxies are given in Table 3, where column (1) gives the name of the BL Lac; (2) and (3) the absolute magnitude of the host galaxy in the H band (this work) and R band (literature value), respectively; (4) the reference for column (3); (5) the R-H colour of the host galaxy computed from columns (2) and (3); (6) the same as column (5), but computed from our colour profiles (see below); and (7) the R-H colour gradient of the host. For comparison, in Table 4 we give optical and optical-NIR colours of elliptical galaxies from literature

**Table 1.** Journal of observations.

Name	Other name	z	V	M(B)	Date	Exp. time (min)	FWHM (arcsec)
PKS 0048-097	OB-080	$\geq 0.5(?)$	16.3	-	21/8/95	40	1.0
PKS 0118-272	OC-230.4	$\geq 0.557$	15.9	$\leq -26.8$	18/8/95	37	1.0
PKS 0521-365		0.055	14.6	-22.3	13/1/96	21	1.2
PKS 0537-441		0.896	15.0	(-27.0)	13/1/96	36	1.1
PKS 0548-322		0.069	15.5	-22.0	13/1/96	28	1.0
PKS 1514-241	AP Lib	0.049	14.9	-21.7	19/8/95	15	0.9
PKS 1538+149	4C 14.60	0.605	17.8	-25.2	21/8/95	40	1.7
PKS 2005-489		0.071	14.4	-24.8	19/8/95	30	1.0
MS 2143.4+070		0.237	18.0	-22.8	18/8/95	40	0.9
PKS 2155-305		0.116	13.5	-25.9	19/8/95	22	1.0
PKS 2254+074	OY 091	0.190	16.4	-23.3	18/8/95	10	1.2

**Table 2.** Properties of the host galaxies.

Name	z	r(e)/R(e) arcsec/kpc	m(nuc)	m(g)	L(nuc)/L(gal)	M(nuc)	M(gal)	Note
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
PKS 0048-097	$\geq 0.5(?)$		13.7		$\geq 100$	$\leq -29.2$		U
PKS 0118-272	$\geq 0.557$		13.1		$\geq 100$	$\leq -30.1$		U
PKS 0521-365	0.055	2.55/3.8	12.0	12.4	1.70	-25.8	-25.2	R
PKS 0537-441	(0.896)		13.0		$\geq 100$	(-32.0)		U
PKS 0548-322	0.069	4.55/8.3	15.4	12.4	0.087	-23.0	-25.7	R
PKS 1514-241	0.048	2.50/3.3	13.3	12.2	0.43	-24.1	-25.1	R
PKS 1538+149	0.605		14.7		3.0	-28.7		U
PKS 2005-489	0.071	1.65/3.1	11.7	11.9	1.38	-26.6	-26.3	R
MS 2143.4+070	0.237	1.10/5.5	16.4	15.1	0.35	-24.7	-25.9	R
PKS 2155-305	0.116	1.75/5.0	11.0	12.4	4.00	-28.5	-26.9	R
PKS 2254+074	0.190	7.60:/32.5:	14.0:	14.9:	2.27:	-26.5:	-25.6:	R

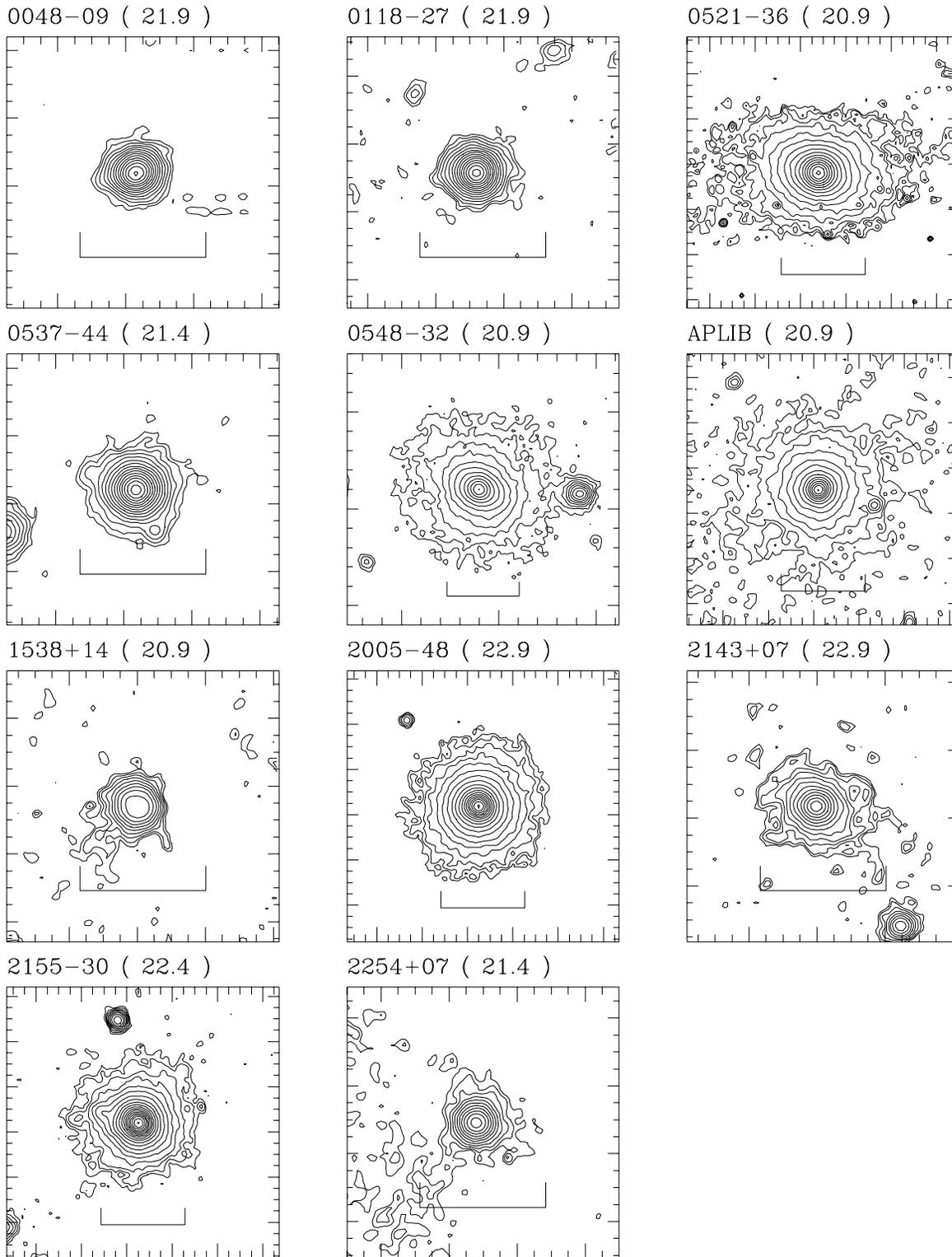
: uncertain values (see Appendix).

search. The average and median R-H host colours of our BL Lac sample,  $R-H = 2.2 \pm 0.5$  and  $R-H = 2.3$  are consistent with those found for local giant ellipticals ( $R-H = 2.5$ ; see Table 4), considering the large variations both within the sample and in the previous optical determinations of the host parameters. The average R-H colour also agrees well with recent evolutionary population synthesis models, which predict for low redshift, solar metallicity ellipticals  $R-H \sim 2.2$  (Poggianti 1997; age 15 Gyr) and  $R-H \sim 2.4$  (Fioc & Rocca-Volmerange 1997; age 13 Gyr).

We have next computed radial R-H colour profiles for six of the BL Lacs (Fig. 3). From these profiles we have computed the R-H colour gradients of the host galaxies as reported in Table 3, column (7). With the exception of PKS 2254+074 (see Appendix), all colour profiles show a modest colour gradient (average  $\Delta(R-H)/\Delta(\log r) = -0.09 \pm 0.04$ ) that makes the galaxies bluer in the outer regions. The sign and amplitude of the color gradient is similar to that exhibited by normal non-active ellipticals ( $\Delta(V-K)/\Delta(\log r) = -0.16 \pm 0.18$ ; Peletier, Valentijn & Jameson 1990; 12 ellipticals);  $\Delta(V-K)/\Delta(\log r) = -0.26 \pm 0.15$ ;

Schombert et al. 1993; 16); the R-H gradient tends to be smaller than that of V-K, probably due to the smaller wavelength baseline. Finally, we show in Fig. 4 the colour-magnitude diagram of the BL Lac host galaxies, compared with those of elliptical and S0 galaxies in the Virgo and Coma clusters (Bower, Lucey & Ellis 1992a,b). With the exceptions of PKS 0548-322 and PKS 2254+074 (see Appendix for details), the BL Lac hosts follow reasonably well the established relation for elliptical galaxies.

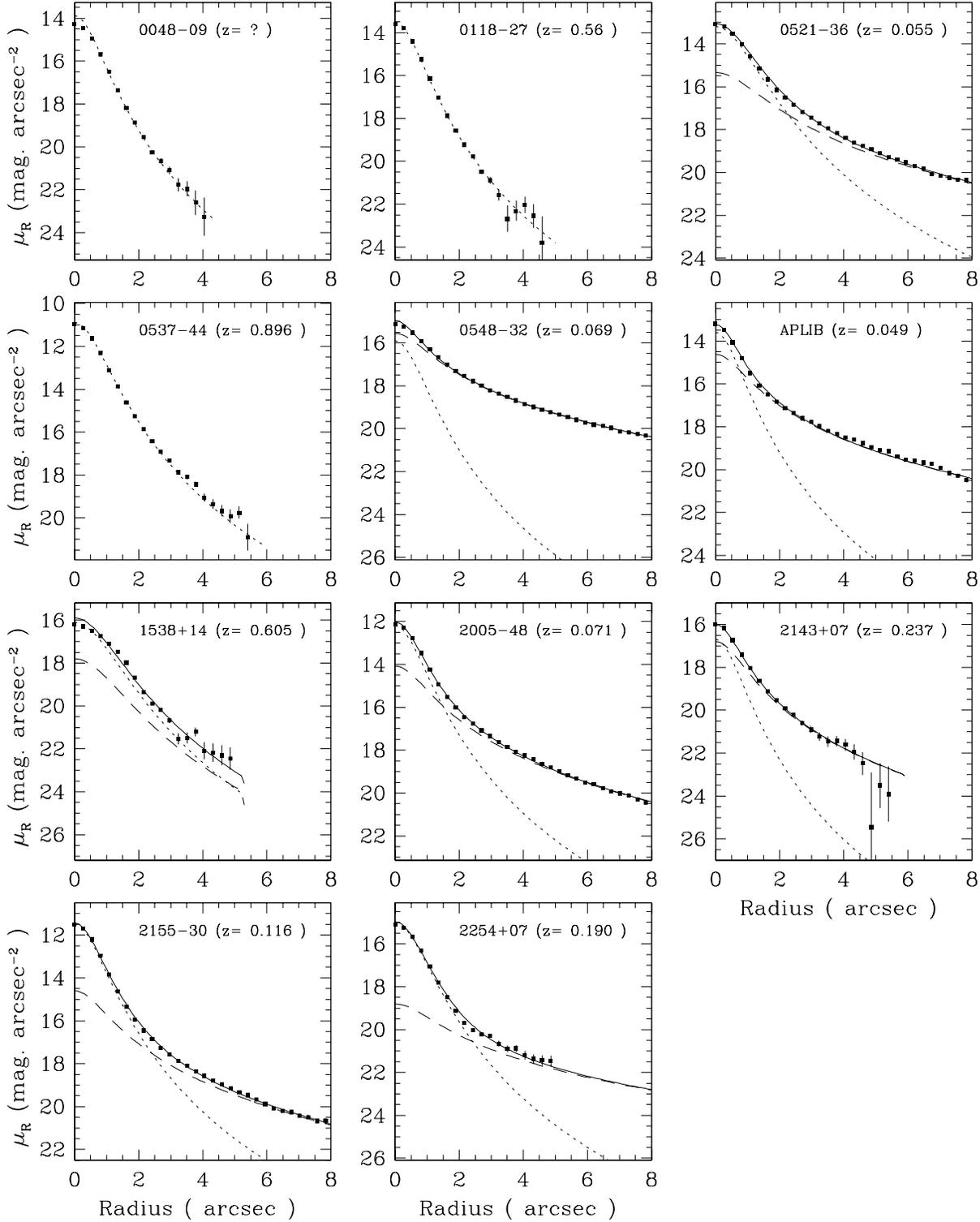
There is increasing evidence that the photometric properties of elliptical galaxies (at least of those in nearby clusters) can be explained in terms of a single burst of star formation at high redshift, followed by passive stellar evolution (e.g. Stanford, Eisenhardt & Dickinson 1998 and references therein). The similarity of the colours and colour gradients of BL Lac hosts to those of normal elliptical galaxies then indicates that the nuclear activity has only marginal effect, if any, on the overall properties of the host galaxy. For example, galaxy interactions and mergers, often invoked to explain the BL Lac phenomenon and AGN in general (e.g. Heckman 1990), do not seem to induce strong



**Fig. 1.** Gaussian smoothed contour plots of the sample objects in the H band. The scale of each image is indicated by a 10 arcsec bar. The surface brightness of the lowest contour is indicated in parenthesis. The contours are separated by 0.5 mag intervals. North is up and east to the left.

recent star formation in the BL Lac hosts. This is perhaps due to a very low gas density in the host and/or in the interacting

galaxy. Alternatively, it may be that the timescales of the star formation episodes and nuclear activity are different.



**Fig. 2.** Results of the profile fits for each galaxy. The solid points represent the observed profile, dotted line the PSF, dashed line the deconvolved model convolved with the proper PSF, and the solid line the fitted model profile.

Table 5 presents a comparison of the H-band absolute magnitudes of the BL Lac hosts with the average values of relevant samples of blazars and RGs from previous optical and NIR studies in the literature. 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 H band nuclear and k-corrected host galaxy absolute magnitude of the sample. All magnitudes were transformed into our adopted cosmology and

**Table 3.** Optical-NIR colours of the host galaxies.

Name (1)	M(H) (2)	M(R) (3)	Ref. (4)	R-H (5)	R-H (6)	$\Delta(R-H)/\Delta(\log r)$ (7)
PKS 0521-365	-25.4	-23.2	F94	2.2	2.3	-0.08
		-23.0	W96	2.4		
PKS 0548-322	-25.7	-24.2	F95	1.5	2.1	-0.06
		-23.2	W96	2.5		
PKS 1514-241	-25.1	-22.8	B87	2.3	2.1	-0.12
		-22.8	A91	2.3		
		-23.5	S93	1.6		
		-22.9	this work	2.2		
PKS 2005-489	-26.3	-24.2	S93	2.1	2.7	-0.15
		-23.7	F96	2.6		
MS 2143.4+070	-25.9	-23.4	W96	2.5	2.5	-0.04
PKS 2155-305	-26.8	-24.4	F96	2.4 <sup>a)</sup>		
PKS 2254+074	-25.6:	-24.1	S93	1.5:	1.8:	0.10:
		-23.9	F96	1.7:		
		-23.9	W96	1.7:		

<sup>a)</sup> Original observations obtained in the Gunn i filter by F91.

: uncertain values (see Appendix).

A91 = Abraham et al. (1991), B87 = Baxter, Disney & Phillipps (1997),

F94 = Falomo (1994), F95 = Falomo, Pesce & Treves (1995), F96 =

Falomo (1996), S93 = Stickel et al. (1993), W96 = Wurtz et al. (1996).

**Table 4.** Optical and optical-NIR colours of elliptical galaxies from literature.

Ref.	V-R	V-I	V-K	J-H	H-K	J-K
Gregg (1989)	0.58±0.11	1.23±0.22				
Carollo et al. (1997)		1.30±0.05				
Schombert et al. (1993)			3.29±0.09			0.87±0.04
Bressan, Chiosi & Tantalo (1996)			3.28±0.11			
Recillas-Cruz et al. (1990)				0.72±0.08	0.22±0.06	
Silva & Elston (1994)						0.90±0.02

into the H band. Based on the similarity of the BL Lac host galaxies to giant ellipticals (see discussion above), the transformation of published magnitudes to the H band was obtained assuming the following colours of giant ellipticals, computed from the literature values given in Table 4: V-H = 3.1, R-H = 2.5, I-H = 1.8, and H-K = 0.2. Finally, transformation from Gunn r filter (r-H = 2.8) was obtained from R-H = 2.5 (above) and r-R = 0.3, appropriate for low redshift ellipticals (Fukugita, Shimasaku & Ichikawa 1995).

In Fig. 5 (upper panel) we show the H-z (Hubble) diagram for the BL Lac hosts (this work), together with data for FS-RQs (KFS98) and F-R II RGs (Taylor et al. 1996), compared to the established relation for RGs (solid line; e.g. Lilly & Longair 1984; Lilly, Longair & Miller 1985; Eales et al. 1997), and the evolutionary model for elliptical galaxies derived from passive stellar evolution models (Bressan, Chiosi & Fagotto 1994, dashed line), normalized to the average redshift and magnitude

of the low redshift RGs from Taylor et al. 1996). The resolved BL Lac hosts lie quite well on the H-z relation. In Fig. 5 (lower panel) we show the H-z diagram for the mean values of various blazar and RG samples from the literature. These values consistently follow the H-z relationship (within the errors), with the average value for the BL Lacs derived in this work well matching the relationship.

In Fig. 6 (upper panel), we show the H-band host galaxy absolute magnitude vs. redshift for the BL Lacs (this work), FSRQs (KFS98) and RGs (Taylor et al. 1996). In Fig. 6 (lower panel), the same diagram is shown for the mean values of various blazar and RG samples. The average H-band absolute magnitude of the seven clearly resolved low redshift ( $z \leq 0.2$ ) BL Lac hosts is  $M(H) = -25.8 \pm 0.5$ , and the average and median bulge scalelength  $R(e) = 8.8 \pm 9.9$  kpc and 5.0 kpc. The host galaxies are therefore large (all have  $R(e) \geq 3$  kpc, the upper boundary of normal local ellipticals; Capaccioli, Caon & D'Onofrio

**Table 5.** Comparison of average host galaxy properties with other samples.

Sample <sup>a)</sup>	filter	N	$\langle z \rangle$	$\langle M_H(nuc) \rangle$	$\langle M_H(host) \rangle^b)$
(1)	(2)	(3)	(4)	(5)	(6)
BL this work	H	7	0.112±0.068	-25.7±1.7	-25.8±0.5
L* Mobasher et al. (1993)	K	136	0.077±0.030		-25.0±0.2
BCM Thuan & Puschell (1989)	H	84	0.074±0.026		-26.3±0.3
BCM Aragon-Salamanca et al. (1998)	K	25	0.449±0.266		-27.0±0.3
BL Falomo (1996)	R	11	0.143±0.082	-26.3±2.1	-26.0±0.6
BL Wurtz et al. (1996)	r	35	0.266±0.162	-24.5±2.3	-26.3±0.7
BL Falomo et al. (1997b), Jannuzi et al. (1997)	I	6	0.351±0.172	-26.0±0.8	-26.0±0.8
RG Fasano et al. (1996)	R	25	0.061±0.027		-26.6±0.6
RG low-z Zirbel (1996)	V	55	0.107±0.047		-25.8±0.6
RG F-R II high-z Zirbel (1996)	V	25	0.389±0.053		-25.9±0.4
RG F-R II Taylor et al. (1996)	K	12	0.214±0.049	-25.1±0.7	-26.1±0.8
FSRQ/R+M KFS98	H	9	0.671±0.157	-29.7±0.8	-26.7±1.2
FSRQ/R KFS98	H	4	0.673±0.141	-30.2±0.7	-27.8±0.3

<sup>a)</sup>: BL = BL Lac objects; L\* = typical field galaxies; BCM = brightest cluster members; RG = radio galaxies; FSRQ = flat spectrum radio quasars.

<sup>b)</sup>: Transformation to H band was done assuming the following galaxy colours: V-H = 3.1, r-H = 2.8, R-H = 2.5, I-H = 1.8, and H-K = 0.2 (for references, see text and Table 4).

1992) and slightly more luminous than an L\* galaxy ( $M(H) = -25.0 \pm 0.2$ ; Mobasher et al. 1993). Indeed, we find no BL Lac host fainter than L\*. As found in the optical by Wurtz et al. (1996), the BL Lac hosts have slightly, but not significantly lower luminosities in the NIR than nearby brightest cluster member galaxies (BCM;  $z = 0.07 \pm 0.03$ ;  $M(H) = -26.3 \pm 0.3$ ; Thuan & Puschell 1989). However, they appear significantly fainter than BCMs at higher redshift ( $z = 0.45 \pm 0.27$ ;  $M(H) = -27.0 \pm 0.3$ ; Aragon-Salamanca, Baugh & Kauffmann 1998).

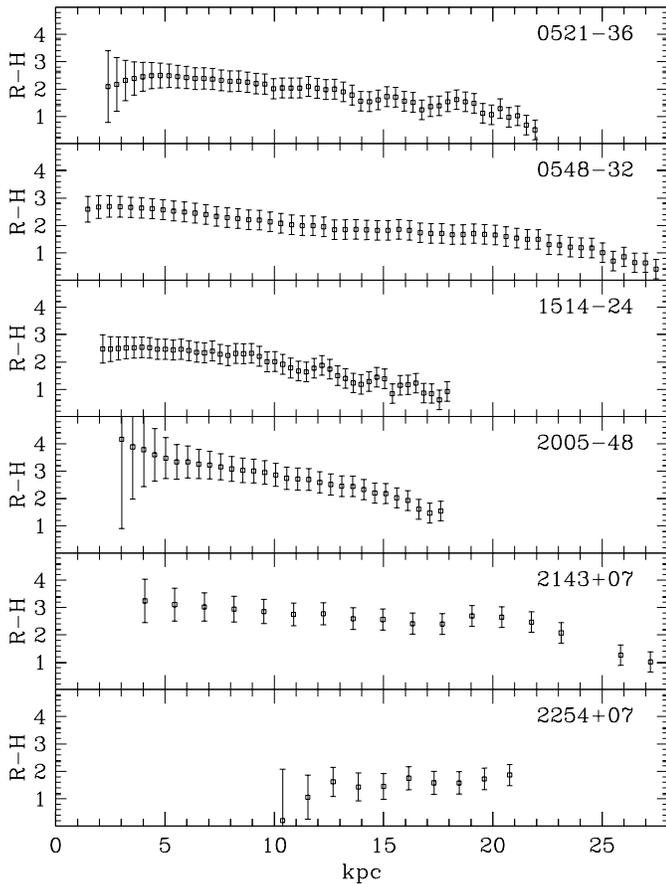
Although the number of objects in this study is small, it is interesting to compare the NIR absolute magnitudes of BL Lac hosts to those of available samples of BL Lacs, RGs and FSRQs from the literature. These samples span a moderately large range in redshift from  $z \sim 0.03$  up to  $z \sim 0.7$ . The average host galaxy magnitudes for the various samples are given in Table 5, and shown in Fig. 6. The BL Lacs in our study have host galaxies very similar in luminosity to those found by previous optical studies of BL Lacs if normal colors are assumed. Interestingly, there is good agreement between the BL Lac hosts in this study and the F-R II RGs of Taylor et al. (1996), the only RG sample studied in the NIR and thus almost free from colour term uncertainty. The lack of direct comparison sample of F-R I RGs, however, prevents us from discussing the issue of the parent population of BL Lac objects further.

Since BL Lacs share many properties (e.g. variability and polarization) with FSRQs, it is interesting to compare the host

properties of these two types of blazars. Recently, KFS98 found for clearly resolved FSRQ hosts at  $z \sim 0.7$   $M(H) = -27.8 \pm 0.3$ , while the value adding their marginally resolved hosts is  $M(H) = -26.7 \pm 1.2$  (Table 5). Because not all FSRQs were resolved, it is possible that the average host luminosity of FSRQs is even fainter. Moreover, given the large difference of redshift between the BL Lac and FSRQ samples, it is also possible that the  $\sim 0.5$  mag difference in host luminosity is due to cosmological evolution in the stellar population of an elliptical galaxy that makes it fade by  $\sim 0.8$  mag between  $z \sim 1$  and  $z \sim 0$  (e.g. models by Bressan et al. 1994). Indeed, there is increasing observational evidence for significant evolution in the colours and luminosity of early-type galaxies (e.g. Aragon-Salamanca et al. 1998 and references therein). The present data suggests that BL Lac hosts are less luminous than those of FSRQs but, given the limits described above, additional homogeneous observations of BL Lacs and FSRQs are needed to reach a firm conclusion.

### 3.2. The nuclear component

The average absolute magnitude of the fitted nuclear component for the clearly resolved BL Lacs is  $M(H) = -25.7 \pm 1.7$ . On the other hand, the FSRQs have much brighter nuclear component ( $M(H) = -29.7 \pm 0.8$ ; KFS98). This difference in the strength of the nuclear component is also more evident considering the nucleus/galaxy luminosity ratio  $L(nuc)/L(gal)$  in Table 2. None of

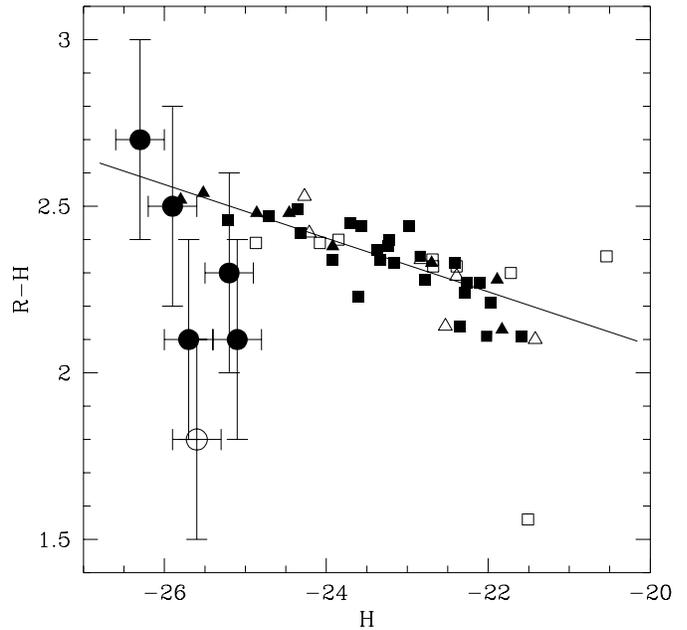


**Fig. 3.** The host galaxy R-H colour vs. radius for the resolved BL Lacs in the sample.

the low redshift BL Lacs (or the RGs from Taylor et al. 1996) have  $L(\text{nuc})/L(\text{gal}) \geq 10$ , whereas about half of the FSRQs are above this limit (KFS98). From Figs. 5 and 6 it is clear that the host galaxies of the various samples considered here are not dramatically different in intrinsic luminosity, especially if cosmological evolution is taken into account. Therefore, this difference suggests that FSRQs exhibit a nuclear component which is systematically brighter than that of the low redshift BL Lac objects, possibly due to either intrinsically higher luminosity or a larger Doppler beaming factor. While this result disagrees with the current unified models of AGN, further observations of larger and unbiased samples of BL Lacs and FSRQs are needed to elucidate this point.

#### 4. Conclusions

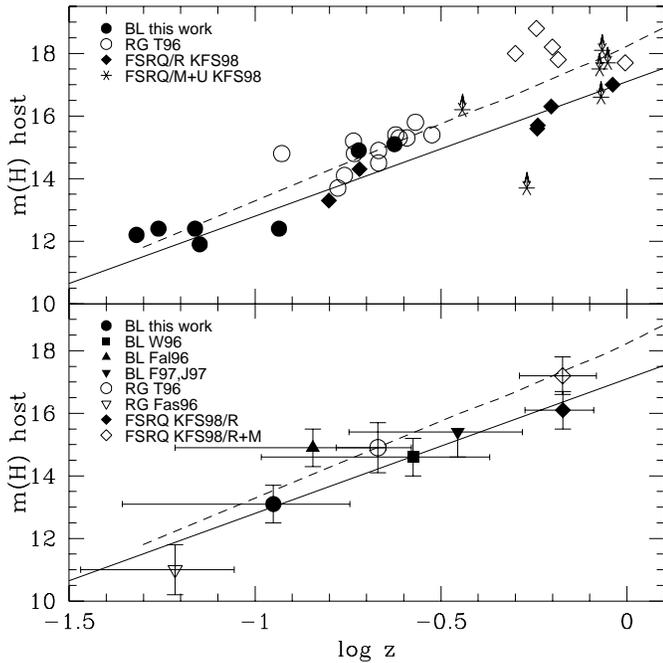
In this paper we have presented the results of a near-infrared imaging study of a sample of 11 BL Lac objects, for most of which the host galaxy is clearly resolved. Consistently with what is found in optical studies, we find that the host galaxies of low redshift BL Lacs are large (average bulge scale length  $R(e) = 8.8 \pm 9.9$  kpc) and luminous (average  $M(H) = -25.8 \pm 0.5$ ); they are more luminous than  $L^*$  galaxies (by  $\sim 1$  mag) but of similar luminosity to or slightly fainter than the brightest cluster



**Fig. 4.** The R-H vs. H colour-magnitude diagram for the BL Lac host galaxies (filled circles: Table 3, column 6) in this sample. The uncertain value for PKS 2254+074 (see Appendix) is indicated as an open circle. The other symbols indicate elliptical galaxies in the Virgo (filled triangles) and Coma (filled squares) clusters, and S0 galaxies in the Virgo (open triangles) and Coma (open squares) clusters (from Bower et al. 1992a,b). The solid line shows the best-fit regression line for Virgo and Coma clusters (Bower et al. 1992b). The V-K vs. V diagram of Bower et al. (1992b) has been transformed into R-H vs. H assuming  $V-R = 0.6$ ,  $H-K = 0.2$  (see text), and distance moduli for Virgo and Coma clusters  $m-M = 31.0$  and  $34.6$ , respectively (Bower et al. 1992b).

galaxies. Our NIR study was able for the first time to address the issue of the optical-NIR colour of BL Lac host galaxies. The average R-H colour and colour gradient of the BL Lac hosts are consistent with those of non-active early-type galaxies, suggesting that the nuclear activity does not have much effect on the star formation history of the host galaxies. The nucleus-to-galaxy ratio of BL Lacs is similar to that found in low redshift RGs and consistent with what found in previous optical studies of BL Lacs. However, it is smaller than that found for the higher redshift FSRQs (KFS98), suggesting there is a difference in the intrinsic brightness of the nuclear source or in the Doppler beaming factor between the two types of blazars. We finally encourage a systematic NIR multiwavelength study of a large, well defined sample of BL Lac objects and their immediate environments with the new generation large NIR arrays.

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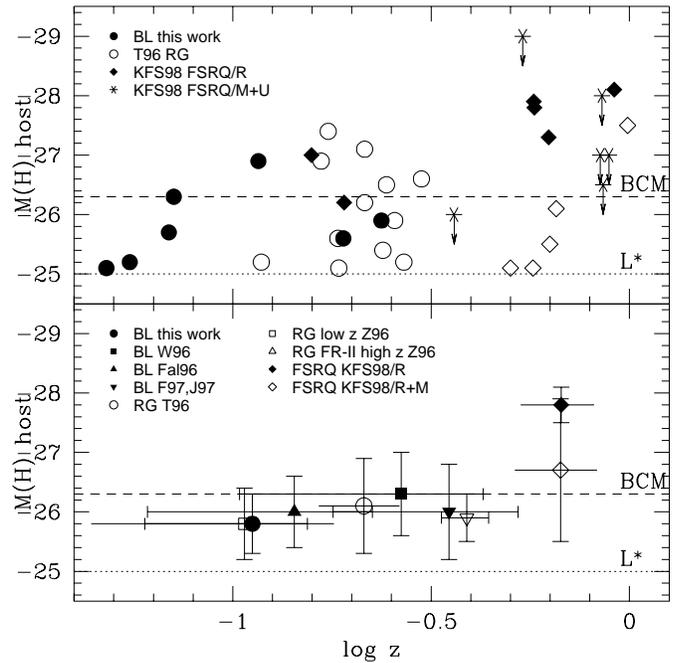


**Fig. 5.** **a** Plot of the apparent H magnitude of the host galaxies vs. redshift (“Hubble diagram”). The BL Lacs are marked as filled circles, the FSRQs from KFS98 (H band) as filled diamonds (resolved hosts) and asterisks (marginally resolved and unresolved hosts), and RGs from Taylor et al. (1996; K band) as open circles. The solid line is the K-z relation for RGs derived by Lilly et al. (1985) and Eales et al. 1997), converted to H magnitudes assuming H-K = 0.2, and the dashed line is the evolutionary model for elliptical galaxies derived from passive stellar evolution models (Bressan et al. 1994), normalized to the average redshift and magnitude of the low redshift RGs from Taylor et al. (1996). **b** As **a**, except we show the mean values of our sample in comparison with samples from literature. Symbols are as in **a**, except the open diamonds are a combined sample of the resolved and marginally resolved FSRQs. Additional samples based on optical imaging of BL Lacs from Wurtz et al. (1996), Falomo (1996), Falomo et al. (1997b) and Jannuzi et al. (1997) and of RGs from Fasano, Falomo & Scarpa (1996) are marked as indicated in the figure.

#### Appendix A: notes on individual objects and comparison with previous NIR photometry

**PKS 0048-097.** Our H-band photometry agrees well with previous studies (Table 6). High resolution optical imaging by Falomo (1996) revealed a faint ( $m(R) \sim 22.5$ ) companion object  $\sim 2.5''$  to the E of the BL Lac nucleus. The host galaxy of PKS 0048-097 remained unresolved by Falomo (1996), but assuming an elliptical host of  $M(R) = -23.5$ , he derived a lower limit to the redshift of  $z \geq 0.5$ . The host galaxy remains unresolved in the NIR. Some hint of the eastern companion object is visible in NIR.

**PKS 0118-272.** Our H-band magnitude is slightly fainter than that found in the literature (Table 6). The host galaxy remains unresolved in the optical (Falomo 1996), however, this is consistent with the presence of a luminous host ( $M(R) = -23.5$ ) at the proposed redshift of  $z \geq 0.559$ . The host galaxy remains unresolved in the NIR.



**Fig. 6.** **a** Plot of the absolute H band magnitude of the host galaxies vs. redshift. For symbols, see Fig. 5a. The dotted lines are the luminosities of  $L^*$  ( $M(H) \sim -25.0$ ; Mobasher, Sharples & Ellis 1993) and brightest cluster member galaxies (BCM;  $M(H) \sim -26.3$ ; Thuan & Puschell 1989). **b** As **a**, except for the mean values of various samples. For symbols, see Figs. 5a and **a**. Additional samples of RGs from Zirbel (1996) are marked as indicated in the figure.

**PKS 0521-365** is at redshift  $z = 0.055$ . Our H-band photometry agrees well with literature values (Table 6). The host galaxy has been imaged in the optical by Falomo (1994), who found best fit for a giant elliptical ( $M(R) = -23.2$  and  $R(e) = 9$  kpc) with a faint stellar disk, and by Wurtz et al. (1996), who fit the host with an elliptical galaxy having  $M(R) = -23.0$  and  $R(e) = 5.4$  kpc. These values are in good agreement with those found in this study ( $M(H) = -25.4$ ,  $R(e) = 5.8$  kpc).

**PKS 0537-441** is a high redshift BL Lac ( $z = 0.896$ ; Peterson et al. 1976). Our H-band magnitude agrees well with previous studies (Table 6). The existence and nature of extended emission around this BL Lac, and its relevance to gravitational lensing, has been debated in the literature (e.g. Stickel, Fried & Kühr 1988; Falomo, Melnick & Tanzi 1992). No nebulousity surrounding this high redshift BL Lac is detected in the NIR, in agreement with Falomo et al. (1992), who conclude that there is no evidence for a foreground lensing galaxy.

**PKS 0548-32** is the dominant member of a rich cluster of galaxies at redshift  $z = 0.069$  (Fosbury & Disney 1976). Our H-band photometry is slightly fainter than found in previous studies (Table 6). Falomo et al. (1995) fit the host galaxy with a giant elliptical ( $M(R) = -24.2$  and  $R(e) = 51$  kpc) and a faint stellar disk. Wurtz et al. (1996) found for the host galaxy an elliptical fit, with  $M(R) = -23.2$  and  $R(e) = 14$  kpc. The values derived by us in the NIR are  $M(H) = -25.7$ , and  $R(e) = 8.3$  kpc. Note that this BL Lac is surrounded by an extended halo, which was detected in the optical by Falomo et al. (1995), but not in the

**Table A1.** H-band photometry compared to previous literature photometry.

Name	H mag <sup>a)</sup>	H mag range	References
	(this work)	(literature)	
PKS 0048-097	13.64	12.78 - 14.86	M90, A82
PKS 0118-272	13.29	12.69 - 13.10	M90, B92
PKS 0521-365	11.75	10.80 - 12.64	A74, B86
PKS 0537-441	13.04	11.69 - 13.34	T86, B92
PKS 0548-322	13.39	12.81 - 13.13	G79, A82
PKS 1514-241	12.47	11.54 - 12.58	B92, B86
PKS 1538+14	14.57	14.23 - 14.67	B86, G93
PKS 2005-48	11.34	11.40	B92
MS 2143.4+07	15.25	14.60	G93
PKS 2155-305	10.93	10.70 - 11.06	B86, B92
PKS 2254+074	14.38	12.99 - 14.09	A82, M90

<sup>a)</sup> Aperture photometry in a 6'' diameter aperture.

A74 = Andrews, Glass & Hawarden (1974); A82 = Allen, Ward & Hyland (1982); B86 = Brindle et al. (1986); B92 = Bersanelli et al. (1992); G79 = Glass (1979); G93 = Gear (1993); M90 = Mead et al. (1990); T86 = Tanzi et al. (1986)

NIR. Therefore, the real colour of the host is redder than that derived from difference of total magnitudes in the two bands (see table 3).

**PKS 1514-241 = AP Lib** is at redshift  $z = 0.0486$  (Disney, Peterson & Rodgers 1974). Our H-band magnitude agrees reasonably well with literature photometry (Table 6). The elliptical host galaxy has been studied extensively in the optical. Baxter et al. (1987) obtained  $M(V) = -22.8$ , Abraham et al. (1991)  $M(R) = -22.8$  and  $R(e) = 7.5$  kpc, and Stickel et al. (1993) derived  $M(R) = -23.5$  and  $R(e) = 11.5$  kpc. Finally, we have analysed our unpublished optical images of this BL Lac, obtained at the ESO 2.2m telescope, and find  $M(R) = -22.9$  and  $R(e) = 4.3$  kpc. The host galaxy parameters derived by us in the NIR ( $M(H) = -25.1$ ,  $R(e) = 3.3$  kpc) are in reasonable agreement with those found in the previous studies.

**PKS 1538+149** is at redshift  $z = 0.605$  (Stickel et al. 1993). Our H-band photometry agrees well with those found in the literature (Table 6). Stickel et al. (1993) could not resolve the host galaxy, while Wurtz et al. (1996) found a marginal fit for the host, with  $M(R) = -24.2$  and  $R(e) = 12$  kpc. Falomo et al. (1997b) derived for the host from HST imaging  $M(I) = -25.2$ . The host galaxy remains unresolved in the NIR.

**PKS 2005-489** is at redshift  $z = 0.071$  (Falomo et al. 1987). Our H-band magnitude agrees well with previous studies (Table 6). Stickel et al. (1993) derived for the host galaxy  $M(R) = -24.2$  and  $R(e) = 5.2$  kpc, while Falomo (1996) found the host to be an elliptical with  $M(R) = -23.7$  and  $R(e) = 11$  kpc. The absolute magnitude derived by us in the NIR is:  $M(H) = -26.3$ .

**MS 2143.4+07** is at redshift  $z = 0.237$ . Our H-band photometry is slightly fainter than found in previous studies (Table 6). Wurtz et al. (1996) derived for the elliptical host galaxy  $M(R)$

$= -23.4$  and  $R(e) = 12$  kpc, while Jannuzi et al. (1997) derived from HST imaging  $M(I) = -24.0$  and  $R(e) = 9.0$  kpc. These values are in excellent agreement with those derived by us in the NIR ( $M(H) = -25.9$ ,  $R(e) = 5.4$  kpc).

**PKS 2155-305** is at redshift  $z = 0.116$  (Falomo, Pesce & Treves 1993) and it is one of the brightest and most studied BL Lacs and is often considered the prototype of X-ray selected BL Lacs. Our H-band magnitude is in good agreement with literature values (Table 6). For the host galaxy, Falomo et al. (1991) derived  $M(R) = -24.4$  and  $R(e) = 13$  kpc, while Wurtz et al. (1996) could not resolve the host, with  $M(R) \geq -23.1$ . The NIR properties of the host ( $M(H) = -26.8$ ,  $R(e) = 5.7$  kpc) are in good agreement with Falomo et al. (1991). The companion galaxy at 4.2'' E of PKS 2155-305, previously detected in the optical (Falomo et al. 1991), is clearly seen in the NIR image (see Fig. 1).

**PKS 2254+074** is at redshift  $z = 0.190$  (Stickel et al. 1993). We obtained only a short exposure of this source under poor sky conditions. We also note that the BL Lac was situated in a bad area of the array during the observations. Consequently, both the NIR photometry (slightly fainter than found in literature; Table 6), and the host properties are less accurate than for the other resolved BL Lacs. Optical determinations of the host galaxy have yielded  $M(R) = -24.1$  and  $R(e) = 14.5$  kpc (Stickel et al. 1993),  $M(R) = -23.9$  and  $R(e) = 15$  kpc (Falomo 1996),  $M(R) = -23.9$  and  $R(e) = 17$  kpc (Wurtz et al. 1996) and  $M(I) = -24.8$  and  $R(e) = 15$  kpc (Falomo et al. 1997b). The absolute magnitude derived by us in the NIR ( $M(H) = -25.5$ ) is  $\sim 1$  mag fainter than implied by the optical studies, assuming normal elliptical colours.

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