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HOST GALAXY AND ENVIRONMENT OF THE BL LACERTAE OBJECT PKS 0548−322: OBSERVATIONS WITH SUBARCSECOND RESOLUTION[1]

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ABSTRACT

We report on direct, subarcsecond resolution imaging of the nebulosity and spectroscopy of galaxies in the field of the BL Lacertae object PKS 0548−322. Surface photometry of the nebulosity is used to derive the properties of the host galaxy ($M_V = -23.4$), which exhibits signs of interaction with a close companion galaxy at ∼25 kpc. The radial brightness profile of the nebulosity is well fitted by the contribution of a bulge ($r^{1/4}$) plus a point source and a small internal disk. An analysis of the galaxies in the field shows that the source is located in a rich cluster of galaxies. Spectra of five galaxies in the field indicate that they are at the same redshift as the BL Lac object, thus supporting the imaging result of a surrounding cluster associated with the BL Lac. This cluster is most likely Abell S0549.

Subject headings: BL Lacertae objects: individual (PKS 0548−322) — galaxies: clustering

1. INTRODUCTION

The study of the environment of BL Lac objects is of importance for testing hypotheses regarding the nature of the host galaxy. In particular, the host galaxies of BL Lacs and their proposed parents (the Fanaroff-Riley Type I radio galaxies) should have similar environments. The environment may also be important for understanding absorption features which seem to appear rather frequently in the soft X-ray emission of BL Lacs (e.g., Canizares & Kruper 1984; Madejski et al. 1991, 1995). Such features could be related to jets in, or cooling flows on to, the BL Lac host galaxy, or to an intracluster medium.

With this perspective we have undertaken a systematic study of BL Lac host galaxies and of their clustering properties. For results on objects studied so far we refer to Falomo, Pesce, & Treves (1993a, b), Pesce, Falomo, & Treves (1994), and references therein. For studies by other groups on this topic we refer the reader to, e.g., McHardy et al. (1992); Smith, O'Dea, & Baum (1993); Stickel, Fried, & Kühr (1993), and Wurtz et al. (1993).

Here we present the results of a study of the host galaxy and field of PKS 0548−322 (H 0548−322), a bright ($m_v = 15.5$) and nearby BL Lac object. It is, per se, a rather interesting case since it was one of the first BL Lacs for which an association with a group of galaxies (at $z \sim 0.04$) was proposed (Disney 1974). The alledged association of the cluster of galaxies with the BL Lac object was, however, ruled out by the measurement of the redshift ($z = 0.069$) of PKS 0548−322 (Fosbury & Disney 1976). Kinman (1978) noted the presence of nearby galaxies and suggested they are close enough to be interacting.

PKS 0548−322 exhibits one of the clearest examples of soft X-ray absorption features, as confirmed by recent *ASCA* observations (Tashiro et al. 1994). It is the only BL Lac known to be a head-tail radio source (Antonucci & Ulvestad 1984).

2. OBSERVATIONS

Observations were obtained on 1994 January 5–6 using the 3.5 m New Technology Telescope (NTT) at the European Southern Observatory (ESO), operated via remote control from the ESO headquarters in Garching (Germany). Images and spectra were acquired using the ESO Multi Mode Instrument (EMMI; Melnick, Dekker, & D'Odorico 1992) + CCD (1660 × 1450 useful pixels; pixel size 15 μm). The useable field covers ∼9.7 × 8.5 arcmin^2 at a scale of 0".347 pixel^{-1}, corresponding to 1.0 × 0.9 Mpc^2 at $z = 0.069$. We assume $H_0 = 50$ km s^{-1} Mpc^{-1} and $q_0 = 0.5$ throughout this *Letter*. Conditions were photometric and seeing was very good (<1" FWHM). Observations of standard stars (Landolt 1983) were used to set the photometric zero point.

We obtained two images (2 and 20 minute exposures) in the *R*-band (Cousins system) filter, centered on the BL Lac object. These were processed in the standard way (bias subtracted, trimmed, flat fielded, and cleaned of cosmic rays) using the Image Reduction and Analysis Facility (IRAF) procedures.

In addition to direct images, we obtained long-slit spectra of six galaxies in the field (G1–G6; see Fig. 1 [Pl. L1]) employing a grism of 300 gr mm^{-1} giving a dispersion of 246 Å mm^{-1} in the range 4000–8000 Å. We used a long slit (2" wide) at various position angles so as to obtain the spectrum of two to three

[1] Based on observations collected at the European Southern Observatory, La Silla, Chile.

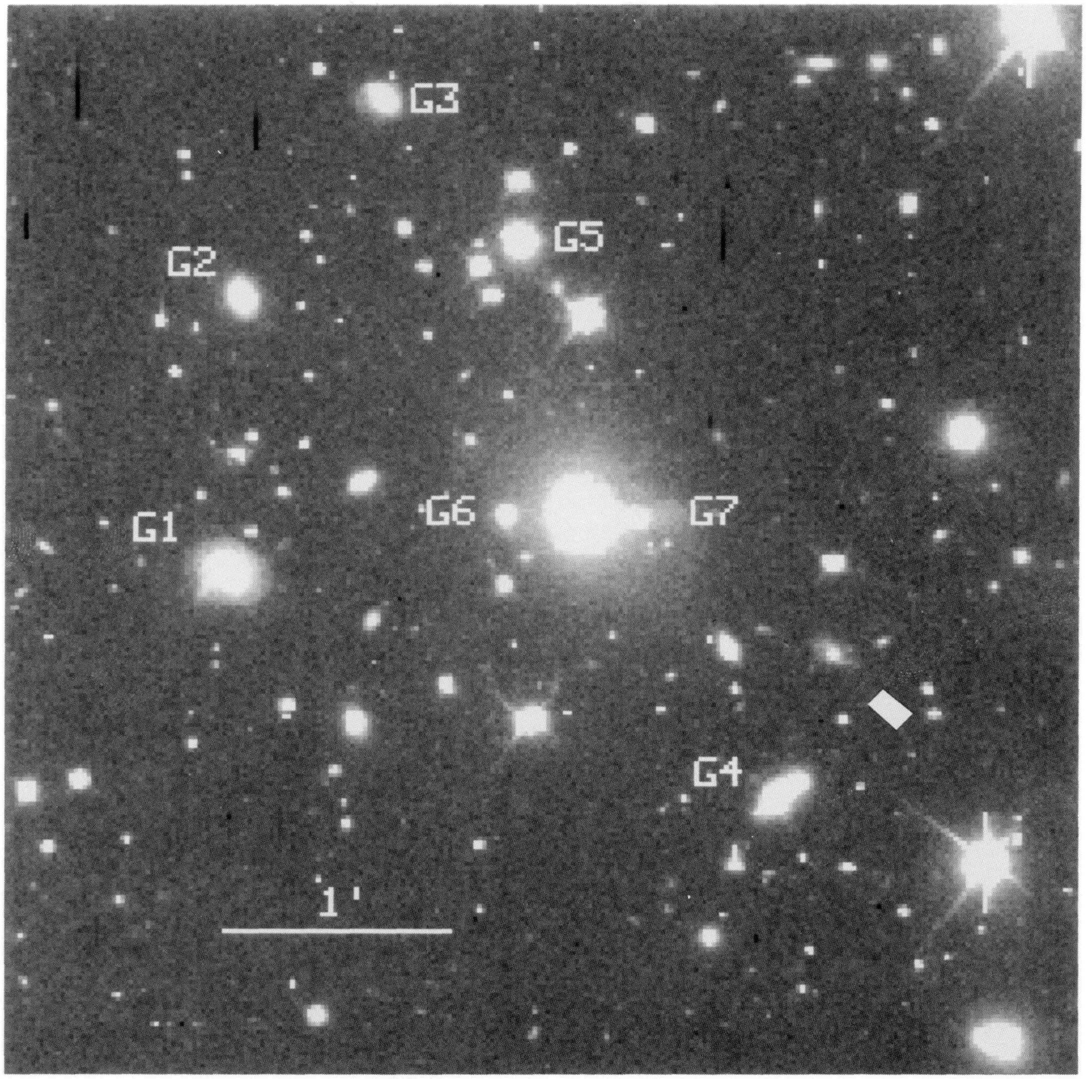

FIG. 1.—The 2 minute *R*-band image of the field centered on PKS 0548−322. North is at the top, and east is to the left. The image covers the central 5 × 5 arcmin^2 portion of the CCD frame.

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galaxies simultaneously. Spectra were wavelength calibrated using an HeAr lamp. Relative flux calibration was derived from observations of the standard star Feige 110 (Stone 1977).

Because the seeing conditions were particularly good we also obtained three images of PKS 0548−322 using the Superb Seeing Imager (SUSI; Melnick et al. 1992) which is installed at one of the Nasmyth foci of the NTT. These images were acquired using an R-band filter and a CCD (TK 1024) with 24 μm pixel size corresponding to 0″.13 on the sky. We obtained two frames (2 and 20 minutes) on January 5 with 0″.7 seeing and one 20 minute exposure on January 6 with 0″.5 seeing. The images were processed in a way similar to those obtained with EMMI.

3. RESULTS

3.1. *Host Galaxy*

We used the high-resolution images obtained with SUSI to study the properties of the host galaxy. In Figure 2 (Plate L2) we show the central part of the SUSI image obtained with 0″.5 resolution. The image clearly shows the extended nebulosity together with two companion galaxies (G6 and G7) at, respectively, 21″.2 and 14″.2 (38 and 25 kpc) from the BL Lac nucleus. Galaxy G7 exhibits clear signs of interaction with the host galaxy of PKS 0548−322 via the presence of extended, low surface brightness emission located $\sim 8''$ to the West.

We performed surface photometry in the R-band on the galaxy using the Numerical Mapping Package (Barbon, Benacchio, & Capaccioli 1976). A second-order two-dimensional polynomial was used to fit the sky [μ_R(sky) = 20.9] and then subtracted from the frame. We computed isophotes down to $\mu_R = 25$ mag arcsec^{-2} (see Fig. 3) and then fitted them by an ellipse with free parameters. The companion galaxies and the other regions affected by fainter objects were excluded from the fit. The nebulosity extends out to 40″ (at $\mu_R - 25$) from the center of the object and appears to be centered on the BL Lac nucleus to within 0″.1. The isophotes exhibit an increasing ellipticity [$\epsilon = (1 - b/a)$, where a and b are the semimajor and semiminor axes, respectively] up to $\epsilon \sim 0.3$ between $r = 1''$ and $r = 6''$ with position angle P.A. = 60°. At larger distances the ellipticity is $\lesssim 0.1$ but tends to increase again at $r \gtrsim 23''$.

To study the brightness profile we consider the surface brightness μ_R as a function of the generalized radius r_{eq} [$r_{eq} = a(1 - \varepsilon)^{1/2}$)] (see Fig. 4). The radial profile was modeled by a de Vaucouleurs ($r^{1/4}$) law (convolved with the point spread function [PSF]) plus the contribution of the point source in the nucleus. The PSF was computed as in Falomo et al. (1991) using stars of different magnitudes in the same frame to account for the core and wing components of the PSF.

We found the profile is well described by the $r^{1/4}$ de Vaucouleurs law with $r_e = 28''$ plus a point source over the whole range, but not around $r_{eq} = 1''.5$ where an excess of emission is present with respect to the model. To account for this excess we add a faint disk component to the inner part of the galaxy. The best decomposition of the profile is thus obtained with a small exponential disk of characteristic radius $r_D = 0''.6$ and magnitude 17.1. The observed magnitude of the galaxy, including the bulge and a small disk, integrated down to $\mu_R = 25$ mag arcsec^{-2} is $m_R = 14.2$, while the point source in the nucleus has a magnitude $m_R = 16.8$.

3.2. *Environment*

In order to analyze the galaxy environment around the BL Lac, a catalog of all objects in each of the frames (2 and 20 minute exposures) obtained with EMMI was produced using the Faint Object Classification and Analysis System software (FOCAS; Jarvis & Tyson 1981). Classification of objects as galaxies, stars, or noise is based on a comparison of their shape with the point-spread function determined from many stars in the field. Standard classification templates were used following Hintzen, Romanishin, & Valdes (1991). Objects were detected and classified up to magnitude limits of $m_R \sim 21.5$ for the short exposure and $m_R \sim 23$ for the longer one.

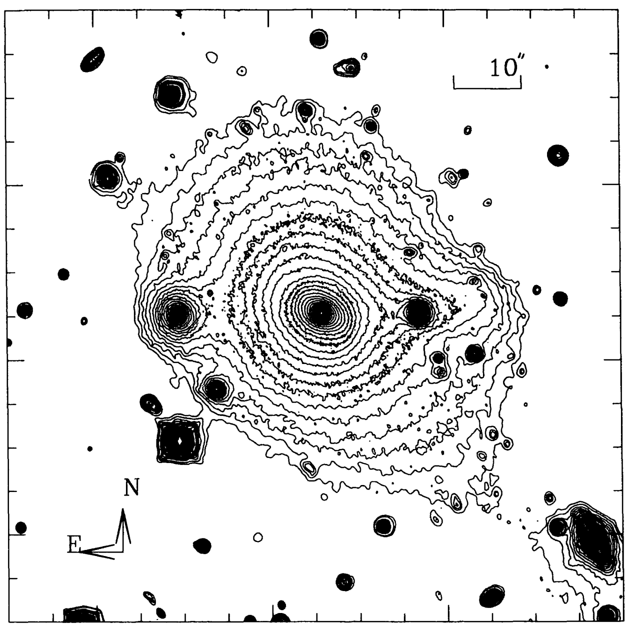

FIG. 3.—A contour plot of the region around the host galaxy of PKS 0548−322. The lowest isophote level is $\mu_R = 24.5$ mag arcsec^{-2} and spacing between isophotes is 0.4 mag arcsec^{-2}. North is at the top, and east is to the left in this image obtained with SUSI. The figure covers 1.5 × 1.5 arcmin^2.

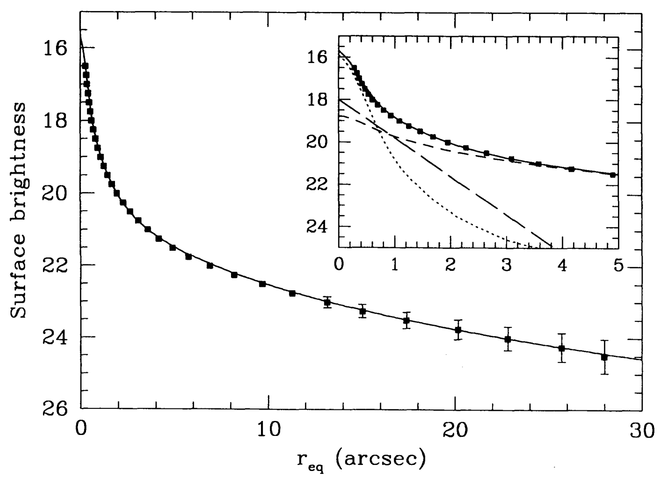

FIG. 4.—The surface brightness profile of PKS 0548−322 in the R-band filter (*filled squares*). The inset shows the inner region of the galaxy. The solid line is the sum of a PSF (*dotted line*) plus an elliptical $r^{1/4}$ law (*short-dashed line*) with $r_e = 28''$ and an exponential disk with $r_d = 0''.6$ (*long-dashed line*).

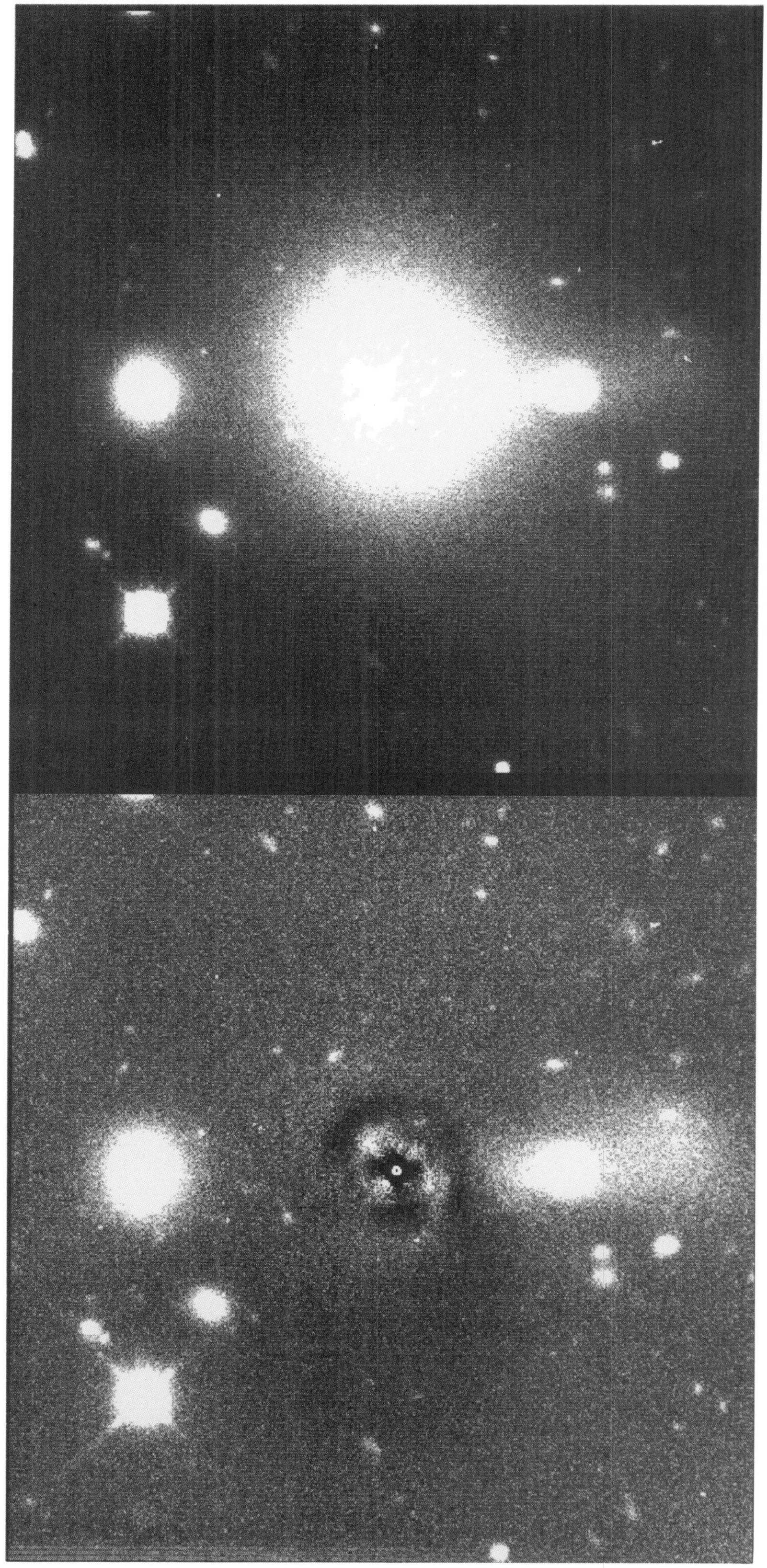

FIG. 2.—The host galaxy of the BL Lac object PKS 0548−322 (*top panel*), with the companion galaxies G6 and G7 (*left and right*; *see text*). North is at the top, and east is to the left. The companion galaxies, together with the low surface brightness emission west of galaxy G7, are clearly visible after subtraction of a model including the host galaxy and the BL Lac nucleus (*lower panel*). The dark "spiral-shaped" feature around the nucleus is an artifact due to the subtraction of the model.

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The two catalogs were combined in order to increase the dynamic range of detected objects, resulting in a total of 653 objects (478 galaxies and 175 stars) down to a magnitude limit $m_R = 23$. We used the objects identified as galaxies in the catalog to study their distribution around the BL Lac. Because the BL Lac is at low redshift ($z = 0.069$) we consider only galaxies brighter than $m_R = 21$, corresponding to objects of absolute magnitude $M_R = -17$.

The distribution of galaxy density as a function of the distance from the BL Lac exhibits an enhancement near the object and within 0.5 Mpc of PKS 0548−322 we find 124 galaxies with $m_R \leq 21$. Using the average galaxy counts determined from 14 independent fields (1.2 galaxies arcmin^2; cf. Metcalfe et al. 1991), we expect 79 ± 9 in the same area.

In order to estimate the Abell richness class of the cluster we counted the number, $N_{0.5}$, of galaxies above the background with $m \leq m_3 + 2$ (m_3 is the third-ranked cluster galaxy), projected within a 0.5 Mpc radius of the cluster center (Bahcall 1981). For the field around PKS 0548−322, $m_3 = 16.56$ (galaxy G1) and $N_{0.5} = 29$ (34 total galaxies and 5 background). This implies a cluster of Abell richness class 2 (Bahcall 1981).

Spectroscopy of a number of galaxies (G1–G6 in Fig. 1) around PKS 0548−322 clearly indicates that most of them are at a redshift very close to that of the BL Lac object ($z = 0.067$–0.072), giving direct proof of the physical association of the cluster of galaxies. The redshifts and characteristics of these galaxies are given in Table 1. Galaxies G1, G2, G5, and G6 exhibit spectral features (Ca II H and K, the G band, Mg I λ5175, Na I λ5892) typical of early-type galaxies. In the spectrum of galaxy G4 we found strong emission lines typical of AGNs, but with weak [O III] λ5007, strong Balmer emission lines, and particularly strong and broad features at ∼4900 and 5600 Å (Fe II blend emission at 4500–4680 Å and at ∼5100–5500 Å). Galaxy G4 thus probably belongs to the class of extreme Fe II emitting AGN (cf. Lípari, Terlevich, & Macchetto 1993). Our image shows that this galaxy is elongated (ellipticity = 0.6; P.A. = 130°) and appears to be interacting with a companion galaxy ($m_R = 18.2$) 7″.5 to the northwest. Galaxy G1 exhibits faint spiral arm structures and weak jetlike emission at ∼8″ from its nucleus (P.A. = 130°). The nature of this emission is not clear. For galaxy G3 we found, surprisingly, a redshift compatible with zero although the object clearly appears to be a galaxy with $m_R = 16.1$ and ellipticity 0.5. Moreover, the spectrum has the form of an F-type star. Thus, while it is not obvious from our images, the spectrum is probably that of a foreground star superposed on the nucleus of galaxy G3.

TABLE 1

GALAXIES IN THE FIELD OF PKS 0548−322

GALAXY	Δα (arcsec)[a]	Δδ (arcsec)[a]	PROJECTED DISTANCES (kpc)[a]	m_R	z
G1[b]......	+95″.0	−14.7	172	16.6	0.072 ± 0.001
G2.......	+91.9	+59.1	195	16.9	0.068 ± 0.001
G3.......	+54.3	+112.8	224	16.1	0.000 ± 0.001[c]
G4[d]......	−50.9	−76.1	164	17.3	0.072 ± 0.001
G5.......	+17.5	+74.4	137	16.7	0.068 ± 0.002
G6.......	+21.2	+0.3	38	18.2	0.067 ± 0.002
G7[e]......	−14.2	−0.7	25	18.3	...

[a] From PKS 0548−322.
[b] Galaxy has a jet/companion?
[c] Superposed foreground star?
[d] Interacting?
[e] Interacting with PKS 0548−322.

4. DISCUSSION

Our imaging and spectroscopic observations of the field around PKS 0548−322, show that the source belongs to a rich cluster of galaxies (Abell richness class 2) at $z \sim 0.07$. This is one of the richest clusters so far reported around a BL Lac object (see Pesce et al. 1994 and references therein). We note that all the galaxies observed spectroscopically (almost all the bright galaxies in our images) are within about 200 kpc of the BL Lac.

Because the galaxy density at 0.5 Mpc from the BL Lac is consistent with the average background, we do not believe the foreground group of galaxies, which is at lower redshift ($z \sim 0.04$; Disney 1974) and appears poor, contaminates our alue of $N_{0.5}$. Furthermore, the Southern Abell cluster, Abell S0549, is centered almost exactly on PKS 0548−322 (Abell, Corwin, & Olowin 1989). While the reported redshift of this cluster is derived from the foreground galaxies observed by Disney (1974), Robertson & Roach (1990) use the empirical distance-magnitude relation of Abell, Corwin, & Olowin and calculate a redshift of 0.078. Within the errors of the method used, the redshift is consistent with what we determine for the cluster around PKS 0548−322, which is, thus, most likely Abell S0549. If so, this is the first time a BL Lac has been found to be associated with an Abell cluster.

The galaxy hosting the BL Lac object is very luminous and extended, and has a pair of companions. The proximity of galaxies to BL Lac hosts seems to be rather common (see Falomo et al. 1991; Pesce et al. 1994), but the data are not extensive enough to make a firm statistical statement. For PKS 0548−322, one of the nearby galaxies is obviously in tidal interaction with the BL Lac host, as indicated by the low-surface brightness, extended emission clearly seen in Figure 2 (see, e.g., Malin & Carter 1983; Dupraz & Combes 1986). This is the first clear case of interaction between a BL Lac and a companion, while such interactions seem to occur frequently in Seyfert and other active galaxies (e.g., Heckman et al. 1986). One might wonder if tidal interactions may be connected, at least indirectly, to the BL Lac phenomena.

The absolute magnitude of the host galaxy, assuming $A_R = 0.1$ and a K correction of 0.06, is $M_R = -24.2$, corresponding to $M_V = -23.4$ if $V - R = 0.8$ is adopted. This value is significantly different than that ($M_V = -22.1$) derived from the CCD photometry of Weistrop, Smith, & Reitsema (1979) but similar to that ($M_V = -23.6$) estimated by Kinman (1978). The difference is likely attributable to differences of resolution and deepness of the images. The analysis of Weistrop et al. in fact does not extend much further than 10″ from the nucleus and thus underestimates both the magnitude and the effective radius of the host galaxy. Compared with other galaxies hosting BL Lac objects (see, e.g., Ulrich 1989; Abraham, McHardy, & Crawford 1991) the host of PKS 0548−322 appears on the bright side of the absolute magnitude distribution. The high luminosity and large effective radius are typical of cD galaxies (Sandage 1976; Hoessel, Gunn, & Thuan 1980).

We have also shown that the inner part of the brightness profile exhibits an excess of light that we interpret as due to a small disk imbedded in the spheroid of the galaxy. This is also supported by the increasing ellipticity of isophotes in the central part (see Fig. 3). The presence of a faint stellar disk in elliptical galaxies is not uncommon when high quality data are considered (see, e.g., Scorza 1992).

The large mass of the host galaxy and its presence at the center of a rich cluster make it a reasonable candidate for a cooling flow (although one was not detected in the data). Soft X-ray absorption and features observed in this object (Madejski et al. 1991; Tashiro et al. 1994) may be ubiquitous in the X-ray spectra of BL Lacs (Madejski et al. 1991) and may signal the presence of cooling flows or other types of intervening material such as an intracluster medium (e.g., White et al. 1991). The "head-tail" nature of the radio source is probably due to interactions with the nearby galaxies, as well as a dense intracluster medium.

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