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THE ENVIRONMENT OF THE BL LACERTAE OBJECT PKS 2155−304[1]

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ABSTRACT

We report on direct imaging and spectroscopy of the field around the BL Lac object PKS 2155−304. An analysis of the richness of galaxies in the field shows that the source is located in a poor cluster of galaxies. Spectra of three galaxies indicate that they are at redshift $z \sim 0.116$, and the spectrum of the nebulosity surrounding the BL Lac object, yielding $z = 0.116$, shows that the BL Lac object belongs to the cluster. The galaxy environment of BL Lac objects, together with those of F-R I radio sources, the proposed parent objects in the beaming hypothesis, is briefly discussed.

Subject headings: BL Lacertae objects: individual (PKS 2155−304) — galaxies: clustering

1. INTRODUCTION

The study of the environment of active galactic nuclei (AGNs) is of interest because it may be a way to address fundamental issues such as their very origin (e.g, Rees 1993). In particular, the study of the environment might provide a useful tool for probing the unified model of AGNs (e.g., Antonucci 1993). In the case of BL Lac objects one can place constraints on the hypothesis that they are the beamed population of F-R I type radio galaxies, since, in this case, the environments of the two classes should be similar.

Until recently, unlike those of quasars, the environments of BL Lac objects have been poorly studied. Early works (Craine, Tapia, & Tarenghi 1975; Butcher et al. 1976) reported a number of possible associations of groups of galaxies with BL Lac objects, but only in the case of 1400+162 was the physical association demonstrated (Weistrop et al. 1983). Later studies (Stickel, Fried, & Kühr 1993) indicated a number of objects (e.g., 1418+546, 1652+398, 1807+698, 2005−489 and 2254+074) with one to three galaxies in the field at the same redshift as the BL Lac object. Moreover, some statistical evidence for an enhancement of galaxy density around BL Lac objects of medium redshift was presented by Fried, Stickel, & Kühr (1993). A detailed study of the field around H 0414+009 shows that the object is found in a cluster of Abell richness 0 (McHardy et al. 1992; Falomo, Pesce, & Treves 1993), giving the first example of a BL Lac object in a relatively rich environment.

In this *Letter*, we present a study of the environment of the bright ($m_V = 13$), X-ray selected BL Lac object PKS 2155−304. A first image of the field surrounding the object was published by Griffiths et al. (1979) who noted an asymmetric nebulosity, with a wider extension to the east, around the source. A spectrum centered on this extension was obtained by Bowyer et al. (1984) who found stellar absorption features yielding a redshift $z = 0.117$. High-resolution imaging by Falomo, Melnick, & Tanzi (1990) showed that the eastern extension is due to a faint ($m_R = 20$) galaxy $\sim 4''$ from the center of the object. In the following, this object will be referred to as G1. Falomo et al. (1991) demonstrated that the redshift reported by Bowyer et al. pertains to this companion galaxy, and found that the galaxy (G2) $\sim 25''$ to the southeast is at $z = 0.116$. Moreover, detailed surface photometry of the nebulosity showed the host galaxy has $M_V \sim -22.5$ and an effective radius $r_e = 4''.5$, and is likely a giant elliptical at a redshift $z \sim 0.1$.

In the following, we report and discuss imaging and spectroscopy of galaxies in the field of PKS 2155−304 which allow a detailed study of the galaxy environment. Spectroscopy of the nebulosity surrounding the BL Lac object enables us to determine its redshift.

2. OBSERVATIONS

Observations were obtained in 1992 July 31 and August 1, using the 3.5 m New Technology Telescope (NTT) at the European Southern Observatory (ESO). Images and spectra were acquired using the ESO Multi-Mode Instrument (EMMI; Melnick, Dekker, & D'Odorico 1992) + CCD (TH 1024 × 1024 pixels; pixel size 19 μm). The CCD fields cover approximately 56 arcmin^2 at a scale of $0''.44$ pixel^{-1}. Conditions were photometric but seeing was poor ($\sim 1''.8$ FWHM). Observations of standard stars (Landolt 1983) were used to set the photometric zero point.

We obtained one to two short-exposure (2–3 minutes) images in V, R, and I (Cousins system) filters, centered on PKS 2155−304. 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. Two images in R were combined to form an average frame.

The useful field of the images is 7.5 × 7.5 arcmin^2 corresponding to 1.25 × 1.25 Mpc^2 at $z = 0.116$ (see below). We assume $H_0 = 50$ km s^{-1} Mpc^{-1} and $q_0 = 0.5$ throughout this letter. In Figure 1 we show the central portion of the averaged R frame with the galaxies labeled as in Falomo et al. (1991).

In addition to direct images, we obtained long slit spectra of the nebulosity of PKS 2155−304 and one bright galaxy in the field, employing a grism of 300 gr mm^{-1} giving a dispersion of

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

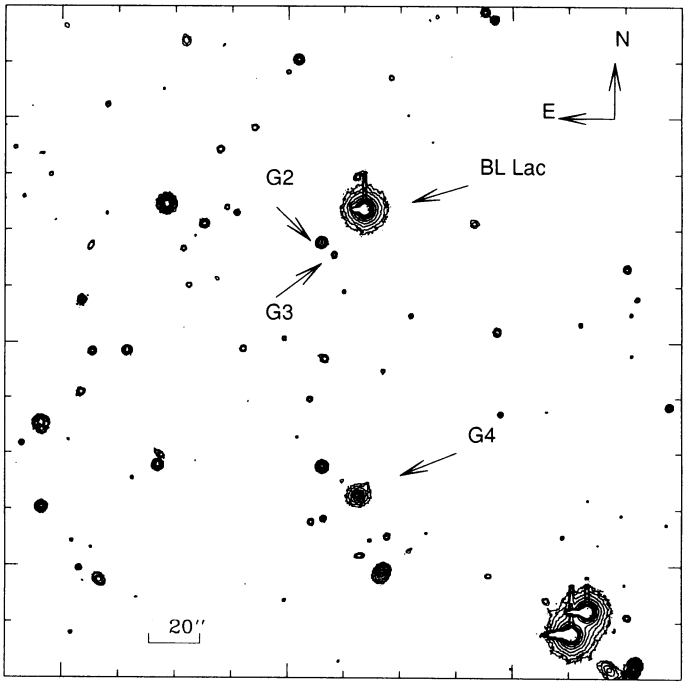

FIG. 1.—Contour plot of the average R image of the field centered on PKS 2155−304. North is at the top and east is to the left. The figure covers the 3.7×3.7 arcmin^2 central portion of the CCD frame. The galaxy referred to as G1 in the text (see also FTT) does not appear in this figure due to the resolution of the image.

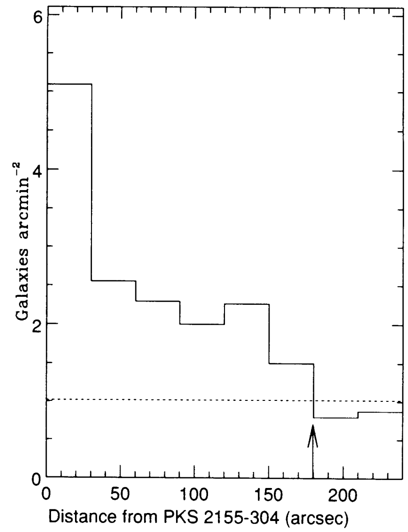

FIG. 2.—Density distribution of galaxies surrounding PKS 2155−304, showing the excess of objects around the BL Lac source. The arrow indicates the radius of 0.5 Mpc at $z = 0.116$ and the dotted line is the average background determined for objects beyond 150″ from PKS 2155−304. The slight excess at ∼130″ is due to the group around galaxy G4 (see text).

246 Å mm^{-1} in the range 4000 to 8000 Å. Spectra were wavelength calibrated using an HeAr lamp. Flux calibration was provided by observations of the standard star Feige 110 (Stone 1977). On July 31 a 2″ wide slit was centered on the galaxy 113″ south of PKS 2155−304 (G4; see Fig. 1) and at PA = 357° such as to include the nebulosity of PKS 2155−304, 3″ west from the center of the BL Lac object. Two successive 40 minute exposures were obtained and then summed. On August 1 a 30 minute exposure with a 2″ slit centered on a region 3″ west (PA = 0°) of the BL Lac nucleus was also obtained.

3. RESULTS

3.1. *Field Galaxy Density*

In order to analyze the galaxy environment around PKS 2155−304 a catalog of all objects in the frames 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 (PSF) 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 $V = 21.5$, $R = 21.5$, and $I = 20.5$, which were determined from the peaks of the differential number-count distribution. Above these magnitudes it becomes difficult to distinguish galaxies from stars with the automatic detection algorithm of FOCAS. Three FOCAS catalogs (for filters V, R, and I) were produced and all dubious objects were visually inspected to ascertain their nature. We detected a total of 91 galaxies in R, 65 in I, and 41 in V for the magnitude limits listed above. PKS 2155−304 was classified as a saturated star in all images, while G1 was not detected due to the resolution of the images. However, in the following analysis we include both the host galaxy of PKS 2155−304 and galaxy G1. In addition to the galaxies, we found 88 stars in R, 78 in I, and 62 in V.

Figure 2 shows the galaxy density in filter R as a function of distance from the BL Lac object. The distribution exhibits an enhancement of galaxy density near the source and presumably drops to the background density of field galaxies beyond ∼150″ from the center. A similar result was obtained for filters I and V. We also note that the small enhancement of galaxy density at ∼130″ corresponds to the galaxies surrounding G4 (the second brightest galaxy in the field; see below).

Assuming all galaxies at distances greater than 150″ are field galaxies we obtain formal background galaxy counts of 1.02 ± 0.18 galaxies arcmin^{-2} for $R < 21.5$. This is lower than the average counts (1.8) found by Metcalfe et al. (1991) in 14 independent fields. However, such a difference is not atypical when different individual fields are compared (see, e.g., Jones et al. 1991; Metcalfe et al. 1991). Thus, from our background counts we expect a total of 20 ± 5 galaxies within the central 150″ (0.4 Mpc). Instead, we observe 46 galaxies. Assuming Poisson statistics, the probability that the central excess is due to background fluctuations is much less than 1%.

We note that our background counts may be lower than average due to the small area employed. However, a significant excess of galaxies around PKS 2155−304 is still found using background counts from Metcalfe et al. (1991). We believe that for a study of this sort, the *local* densities should be used, as average counts may hide excesses above a low, local background.

An alternative method to evaluate the clustering of galaxies is to compute the amplitude of the two-point correlation function (cf. Peebles 1980). Following Hartwick & Schade (1990), we calculated the normalized correlation amplitude A_{gBL}/A_{gg} for the field within 0.5 Mpc of PKS 2155−304 and found $A_{gBL}/A_{gg} = 12.5 \pm 3.3$ The result is comparable to the values obtained for low-redshift quasars by Yee & Green (1984, 1987) and for radio galaxies by Yates, Miller, & Peacock (1989).

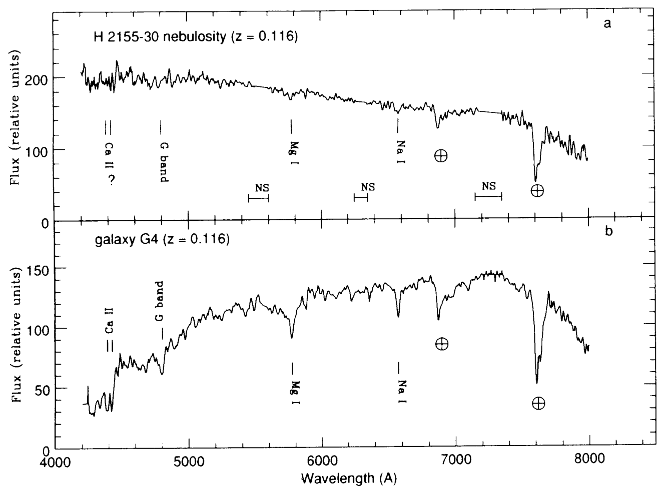

FIG. 3.—(*a*) Averaged spectrum of the host galaxy of PKS 2155−304. The absorption features labeled correspond to a redshift $z = 0.116 \pm 0.002$. Strong night-sky emission lines have been removed and their locations are marked with "NS." (*b*) Spectrum of the galaxy G4. This is an elliptical galaxy at $z = 0.116 \pm 0.002$. For both spectra, flux is in relative units.

3.2. *Spectroscopy of the Nebulosity*

As described above, we acquired three spectra of the nebulosity ($\sim 3''$ west of the nucleus). Although the slit was centered far from the nucleus, the contribution from the wing of the PSF of the central source is still the dominant component. The individual spectra exhibit the characteristic continuum of power-law shape. To increase the S/N we combined the three spectra using the average, weighted by the exposure time. The combined spectrum (Fig. 3*a*) shows some weak absorption features and we checked that these were not spurious artefacts due to poor sky subtraction. The regions of the spectrum heavily contaminated by the presence of intense night-sky emission lines were removed in the analysis. Apart from the telluric oxygen absorption bands, the strongest absorption features are at $\lambda\lambda$ 4795, 5773 6575 Å and we identify them with, respectively, the *G* band, Mg I λ5175 Å and Na I λ5892 Å at a redshift $z = 0.116 \pm 0.002$. We verified, a posteriori, the consistency of these absorption features in the individual spectra and found reasonable agreement. Therefore we conclude that the host galaxy of PKS 2155−304 is at $z = 0.116$.

3.3. *The Galaxy G4*

The second brightest galaxy (G4) in our field is the $m_V \sim 18$ elliptical galaxy at $\sim 113''$ south of the BL Lac object (see Fig. 1). The average of the two spectra obtained (Fig. 3*b*) very clearly shows absorption features of Ca II H and K, the *G* band, Mg I λ5175 Å and Na I λ5892 Å at redshift $z = 0.116 \pm 0.002$. The object is highly extended and surrounded by numerous faint galaxies (see Fig. 4). Moreover, we detected an emission feature $\sim 4''.5$ (PA $\sim 320°$) from the center of G4. This could be either a jetlike structure associated with, or a faint galaxy superposed onto the image of, G4.

We performed surface photometry in the *R* band on the galaxy using the Numerical Mapping Package (Barbon, Benacchio, & Capaccioli 1976). Isophotes down to $\mu_R = 25$ mag arcsec^{-2} were computed and then fitted by ellipses to study the radial profile. We found the profile is well described by a $r^{1/4}$ de Vaucouleurs law with $r_e = 3''$ and ellipticity $e = 0.15$ (PA = 310°). The total magnitude (a la de Vaucouleurs) is $m_R(\text{tot}) = 16.5$, while the magnitude computed integrating the flux within limits of detectability is $m_R = 17.0$, and the absolute magnitude of G4 is $M_V = -21.4$.

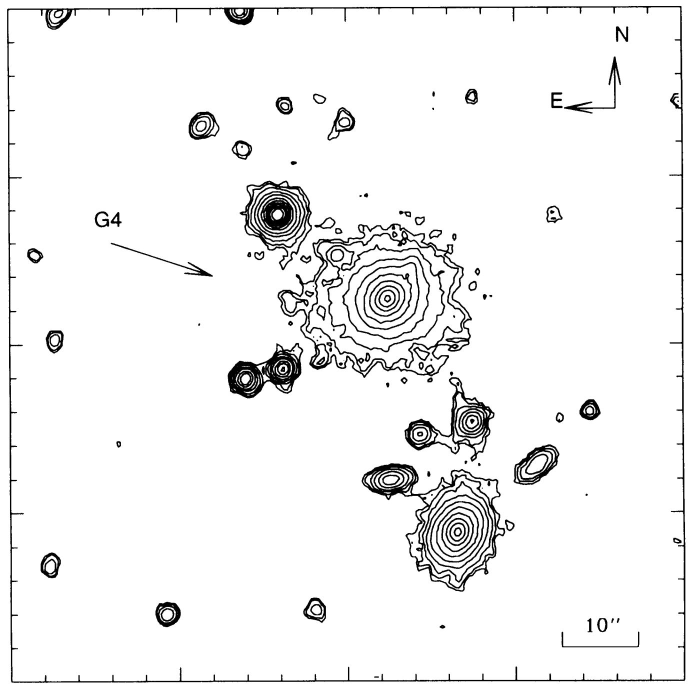

FIG. 4.—Contour plot of the region around the galaxy G4. Note the numerous faint galaxies surrounding this elliptical. The large galaxy to the southeast is the third brightest galaxy in the field.

Therefore, G4 belongs to the cluster and lies at ~ 300 kpc from PKS 2155−304. Although fainter and smaller than the BL Lac host galaxy it is probably a giant elliptical at the center of a small subcluster. While such binary clusters are not unusual, this seems the first example involving a BL Lac object.

4. DISCUSSION

Our imaging and spectroscopic observations of the field around PKS 2155−304, together with results presented in Falomo et al. (1991), show that the source belongs to a poor cluster of galaxies. Four of the galaxies in the field (the BL Lac host, G1, G2, and G4) are at the same redshift and thus form a physical group.

We were able to detect absorption features in the average spectrum of the nebulosity at $z = 0.116$. This value is close to that reported by Bowyer et al. (1984) ($z = 0.117$) although the latter referred to the companion galaxy G1. Our determination of the redshift does not change the interpretation of the 600 eV absorption feature discovered by Canizares & Kruper (1984) and further discussed by Bowyer et al. (1984) and Krolik et al. (1985).

Our observations of PKS 2155−304 allow us to comment on the UV absorption features discovered with *IUE* (Maraschi et al. 1988), and studied in greater detail with the *HST* (Allen et al. 1993). The most prominent features are at $\lambda\lambda$1281, 1284 and λ1344 and if interpreted as Lyα absorption yield $z_{\text{abs}} = 0.056$ and $z_{\text{abs}} = 0.104$. These values represent lower limits on the redshift of the BL Lac object and are fully consistent with $z = 0.116$ of the host galaxy. The images do not show any reasonable galaxies near PKS 2155−304 to which these absorption features could be attributed. Therefore we believe it is unlikely that these absorption lines are produced by material in the halo of a normal foreground galaxy. Instead, the most reasonable interpretation is that they are due to intervening low z Lyα absorption systems.

In order to estimate the Abell richness class of the cluster, we have counted the number, $N_{0.5}$, of excess galaxies with $m \leq m_3 + 2$ (m_3 is the third-ranked cluster galaxy; in our case $m_R = 17.43$), projected within a 0.5 Mpc radius of the cluster center. Using the empirical relation between $N_{0.5}$ and the number, N_R, of galaxies within a standard Abell radius (3 Mpc; Abell 1958) of the cluster center ($N_R = 3.3N_{0.5}$; Bahcall 1981), we find $N_{0.5} = 3$ and, thus, $N_R = 10$. This corresponds to a cluster of galaxies poorer than an Abell richness class of 0 ($\langle N_{0.5} \rangle = 12$; Bahcall 1988; Hill & Lilly 1991; Bahcall & Chokshi 1992). We note, however, that this value of $N_{0.5}$ may represent a lower limit to the richness, since the galaxy m_3 may be foreground. If we use the next faintest galaxy (the fourth brightest galaxy in the field) as m_3, we find $N_{0.5} = 8$ and $N_R = 26$. Also in this case the cluster is found to be poorer than Abell richness class 0.

Based on a large sample of radio galaxies, Hill & Lilly (1991) found the richness parameter, $N_{0.5}$, of F-R I galaxies in a range from 0 to 15, thus consistent with that found for PKS 2155−304. In the case of the X-ray BL Lac object H 0414+009 Falomo et al. 1993 found $N_{0.5} = 13$ corresponding to a cluster of Abell richness class 0–1. Fried et al. (1993) have presented statistical evidence for an enhancement of galaxy density around BL Lac objects of medium redshift, corresponding to clusters of richness class 0 and 1. For low to medium redshift BL Lac objects these findings lend support to the hypothesis that they are F-R I radio galaxies with the jet closely aligned to the observer's line of sight. The situation is less clear for higher redshift objects. Fried et al. (1993) found no increase in galaxy surface density toward the BL Lac object, but at their magnitude completeness limit most of the highest redshift galaxies may not be detectable.

In order to reach firm conclusions on the comparison of the environmental properties of BL Lac objects and F-R I galaxies, a larger, statistical sample for both classes is needed. Comparisons of the environments of low- and high-redshift BL Lac objects, besides the intrinsic value for the beaming hypothesis, may contribute to the diatribe on the existence of two different classes of BL Lac objects (e.g., Antonucci 1993).

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