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THE ENVIRONMENT OF H 0414+009: A BL LAC OBJECT ASSOCIATED WITH A CLUSTER OF GALAXIES[1]

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ABSTRACT

An analysis of galaxies in the field of the BL Lac object H 0414+009 is presented. Direct images indicate that the BL Lac lies in a moderately rich (Abell richness class 0) cluster of galaxies, of which the galaxy hosting H 0414+009 is the dominant member. It is shown that a number of surrounding galaxies share the same redshift as the host galaxy of H 0414+009. Such an environment is consistent with those in which FR-I radio galaxies, the proposed parent population of BL Lac objects, are often found.

1. INTRODUCTION

The environments of BL Lacertae objects (BL Lacs) have been poorly investigated with respect to those of quasars. Contrary to the case of quasars, the study of BL Lacs is complicated by the faintness of their spectral lines with respect to the continuum, hindering the derivation of redshifts and, thus, the proof of physical association with nearby galaxies.

In the past, a number of BL Lacs have been reported near clusters or groups of galaxies (e.g., Disney 1974; Fosbury & Disney 1976; Butcher *et al.* 1976; Craine *et al.* 1975). Early investigations generally failed to provide clear evidence of a physical association. Note, however, the case of 1400+162, for which the physical association of the BL Lac object with the nearest galaxy, in an adjacent small group, has been proven spectroscopically (Baldwin *et al.* 1977; Weistrop *et al.* 1983).

Recent findings of the possible association of BL Lacs with galaxies were reported for 1418+56 (Stickel *et al.* 1989), for H 1101−23 and 1426+428 (Remillard *et al.* 1989), and for PKS 2155−30 (Falomo *et al.* 1991). In the present work, we provide results obtained for the bright x-ray selected BL Lac object H 0414+009 (Ulmer *et al.* 1983). This is a moderately high redshift BL Lac (z =0.287; Halpern *et al.* 1991) hosted by a luminous (M_V ~ -23.5) elliptical galaxy (Falomo & Tanzi 1991). H 0414+009 is surrounded by many faint galaxies exhibiting a peculiar disposition (Falomo *et al.* 1991, hereafter referred to as FTT). The clustering of the galaxies around the object suggests that they form a loose group.

McHardy *et al.* (1992) recently studied the field in the radio, optical, and x-ray bands. Multicolor photometry was given for a large number of objects around the BL Lac and spectroscopy for some of the brightest sources. Moreover it was found that the radio morphology and emission of the host are typical of an FR-I radio galaxy.

We present multicolor photometry of the field and spectroscopy of a number of surrounding galaxies demonstrating that they indeed form a physical group associated with H 0414+009. The paper is organized as follows. In Sec. 2 we describe the observations and in Sec. 3 we report our results. A discussion of the results is given in Sec. 4.

2. OBSERVATIONS

Observations were obtained on 1991 February 17 and 18, using the 3.5 m New Technology Telescope (NTT) at the European Southern Observatory (ESO). Images and spectra were secured using the ESO Multi Mode Instrument (EMMI; Melnick *et al.* 1992)+CCD (TH 1024 $\times$1024 pixels; pixel size 19 μm). The CCD fields cover approximately 56 arcmin^2 at a scale of 0.44 arcsec pixel^{-1}. Conditions were photometric and seeing varied from 1.1 to 1.6 arcsec (FWHM). Observations of standard stars (Landolt 1983) were made to set the photometric zero point.

We obtained two to four short exposure (1–5 min) images in the filters V, R, and I (Cousins system), centered on H 0414+009. 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, and then combined to form an average frame for each filter.

The useful field of the images is 7.5$\times$7.5 arcmin^2 corresponding to 2.4$\times$2.4 Mpc^2 at z=0.287 (H_0=50 km s^{-1} Mpc^{-1}, q_0=0.5). In Fig. 1 we show the entire, averaged frame in R while Fig. 2 is the region centered on

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

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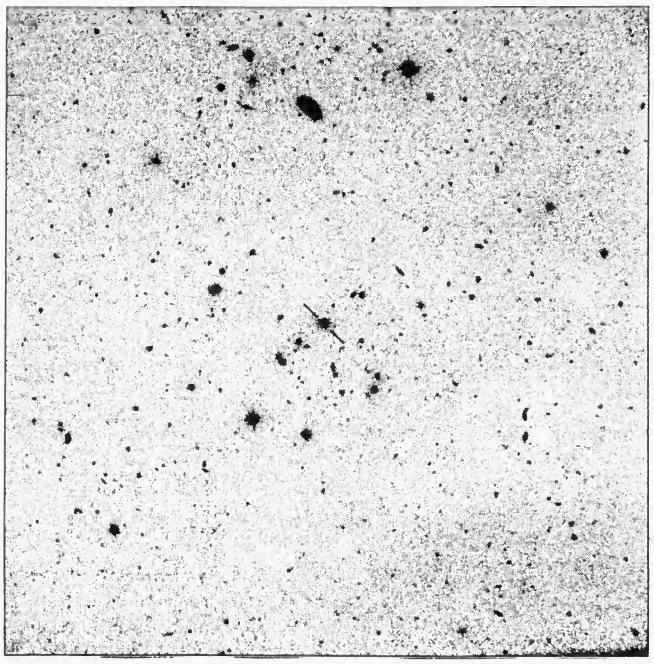

FIG. 1. The average R image of the 7.5×7.5 arcmin^2 field around H 0414+009. North is at the top and East is to the left.

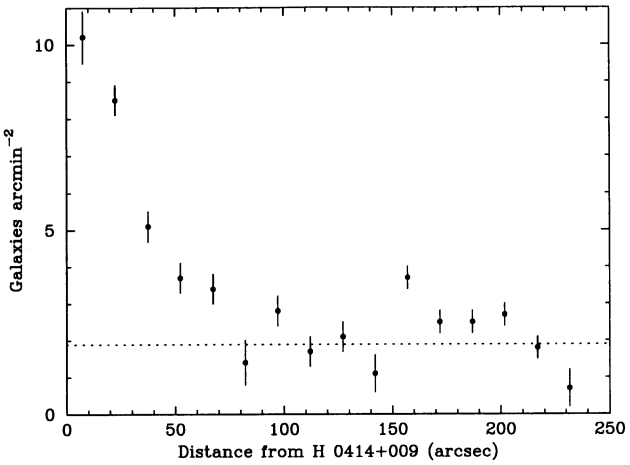

FIG. 3. Mean galaxy density for $R(<21.5)$ as a function of distance from H 0414+009. Bins are 15 arcsec and errors are $N^{-0.5}$, where N is the number of galaxies in each bin. Note the marked excess of galaxies within ~100 arcsec. The average background (dotted line) has a value of 1.9 ± 0.1 galaxies arcmin^{-2}.

H 0414+009. The galaxies are labeled as in FTT and McHardy *et al.* (1992).

Spectra of some of the galaxies in the field were obtained using EMMI with a grism of 300 gr mm^{-1} giving a dispersion of 246 Å mm^{-1} in the range 4000 to 8000 Å. A long slit (2 arcsec wide) was used at two position angles (126° and 121°) so as to obtain, in the same exposure, the spectra of galaxies A2, B2, BL Lac, and C1 and of the galaxies A1, B1, respectively (see Fig. 2). In the first position, two 30 min exposures were taken and the spectra summed, while a single 30 min exposure was made in the second position. One dimensional spectra were extracted using the APEXTRACT routine in IRAF. Due to slit size and positioning, the error of the spectrophotometry may be as large as a factor of 2.

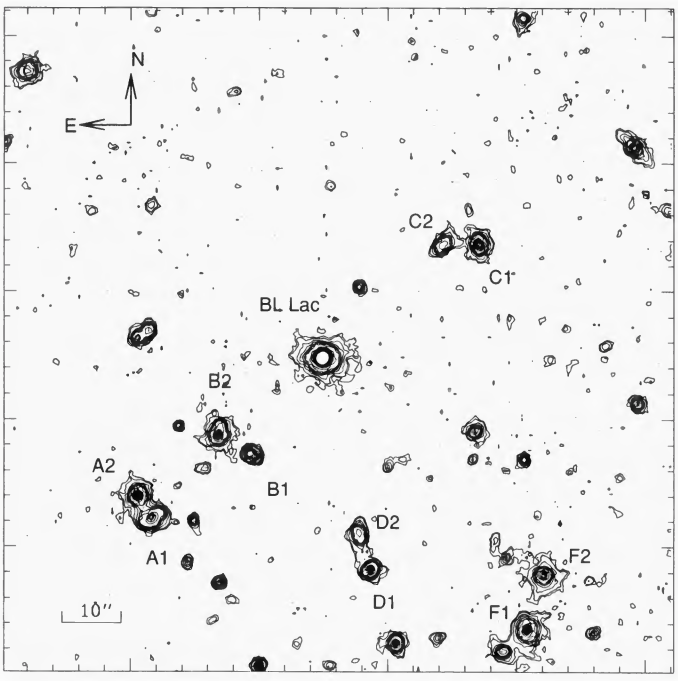

FIG. 2. Contour plot of the central part of the field around H 0414+009. Surrounding galaxies are labeled as in FTT (see text).

3. RESULTS

3.1 Imaging

A catalog of all objects in the average 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 determined from many stars in the field. Standard classification templates were used following Hintzen *et al.* (1991). We note that the total area encompassed by our frames (56 arcmin^2) is four times that previously studied by McHardy *et al.* (1992).

FOCAS "total" magnitudes have been used in this analysis. These are determined by increasing the detection isophote to $2\times$ the original detection area. This should include $\geqslant$90% of the total flux for a typical galaxy (see Hintzen *et al.* 1991 and references therein). Objects were detected and classified up to magnitude limits of $V=22.0$, $R=21.5$, and $I=21.0$. 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 objects classified as noise were visually inspected to be certain that they were real. We detected a total of 119 galaxies in R, 122 in I, and 61 in V for the magnitude limits listed above. In addition, we found 63 stars in R, 79 in I, and 62 in V. The matched R and I catalog contains 102 objects (50 V objects are matched) classified as a galaxy at least once. Of the 102 matched R and I objects, 95 have been classified as galaxies in both filters.

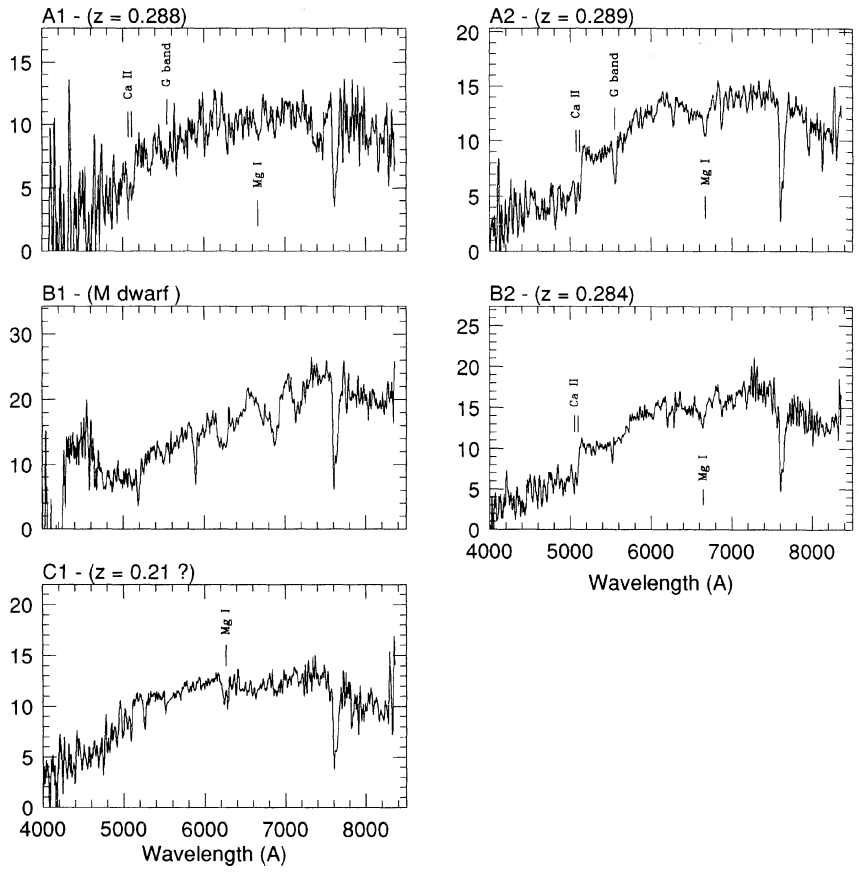

FIG. 4. Spectra of some objects in the field of H 0414+009. Flux is in units of 10^{-17} erg cm^{-2} s^{-1} Å^{-1}.

In Fig. 3 is plotted the galaxy density in filter R as a function of distance from the BL Lac. All 119 galaxies detected in R have been used. A clear excess of galaxies is apparent at distances less than $\sim$100 arcsec (corresponding to 0.5 Mpc). At larger distances, the distribution is relatively flat; presumably this corresponds to the general density of field galaxies. A similar result was obtained for filter I. While there may be some spurious galaxy classifications, the effects are expected to be small and, in any case, should make the observed excess less evident.

Formal background galaxy counts have been determined in the area beyond a circle of radius 100 arcsec (0.5 Mpc) centered on H 0414+009. Average background counts are 1.9 ± 0.1 galaxies arcmin^{-2} for $R(<21.5)$ and $I(<21.0)$. Our background counts compare very well with those of Hintzen *et al.* (1991) in the range $R=19.5$–21.5 and $I=18.5$–21.0. From the background counts we expect a total of 14.4 ± 3.8 galaxies for $R(<21.5)$ and $I(<21.0)$ within the inner 0.5 Mpc. Instead, we observe 29 and 32 galaxies, including the host galaxy of H 0414+009, in R and I, respectively. Assuming Poisson statistics, the probability that the central excess is due to background fluctuations is less than 1 percent.

3.2 Spectroscopy

Spectra have been obtained for five objects (A1, A2, B1, B2, C1), and are shown in Fig. 4. We detected clear absorption features (mainly Ca II, Mg I) in the spectra of galaxies A1, A2, and B2 which give redshifts of 0.288, 0.289, and 0.284, respectively, with typical errors of 0.001. The spectrum of object B1 reveals that it is a red M dwarf star. For galaxy C1 the spectrum is noisy and exhibits only one certain absorption feature at $\sim$6255 Å which, if identified with Mg I 5175 Å, yields a redshift of 0.21.

The redshifts of A1, A2, and B2 are very similar to the redshift of the giant elliptical hosting the BL Lac ($z=0.287$) thus confirming that they form a physical group. Moreover, the redshifts of galaxies A1 and A2 are identical within the errors, confirming that they form a physical pair.

McHardy *et al.* (1992) also obtained spectra for some of the galaxies in the field. However, we found some differences for the galaxies in common with their study (A2, B2, and C1). For galaxy B2 we obtain $z=0.284$ while they report $z=0.287$ and, for galaxy C1, we find $z=0.21$ while from their noisy spectrum they derive $z=0.289$. Our spectrum of object A2 clearly shows galaxian absorption fea-

tures at $z=0.289$ while the spectrum of McHardy *et al.* does not exhibit believable features.

4. DISCUSSION

Imaging and spectroscopy for the field of H 0414+009 have been presented. We find a statistically significant excess of galaxies near the BL Lac object. This result is substantiated by spectral analysis: four galaxies (including H 0414+009) have similar redshifts.

At least one of the pairs of galaxies mentioned by FTT (A1/A2) is a real binary system and may be interacting, since they are separated by only 24 kpc (and 300 km s^{-1}). There is, however, no evidence for such activity. The B1/B2 pair has been shown to be due to projection effects (B1 is, in fact, a foreground star). More spectroscopic work is required to prove the reality of the other pairs in the field. The present results substantially weaken the exotic possibility of gravitational focusing by a cosmic string considered by FTT.

In order to estimate the Abell richness class of the cluster we counted the number, $N_{0.5}$, of excess galaxies with $m \leqslant m_3+2$ (where m_3 is the third-ranked cluster galaxy, in our case object B2 with $m_R=19.23$), projected within a 0.5 Mpc radius of the cluster center, and used the empirical relation between $N_{0.5}$ and the number, N_R, of galaxies within the standard Abell radius (3 Mpc; Abell 1958) of the cluster center ($N_R=3.3N_{0.5}$; Bahcall 1981). We find $N_{0.5}=13$ and, thus, $N_R=43$ which translates into an Abell richness of class 0 (Bahcall 1988; Hill & Lilly 1991; Bahcall & Chokshi 1992). This is consistent with the finding of McHardy *et al.* (1992) who used a different, more uncertain method.

The study of clustering of galaxies around BL Lacs, besides its relevance for understanding the role of environment in triggering or fueling the active nucleus, is of importance for the assessment of the beaming model (e.g., Blandford & Rees 1978). Because cluster environments are independent of orientation effects, a comparison of the environments of BL Lacs and parent objects could constrain the hypothesis on the nature of the host galaxy.

FR-I galaxies have been proposed as the BL Lac parent population (Browne 1989; Ulrich 1989; Woltjer 1989). These galaxies are often found in groups or clusters of galaxies sometimes as rich as Abell richness class 1. (Prestage & Peacock 1988; Owen & Laing 1989; Hill & Lilly 1991). Both the environment and the properties of the host galaxy of H 0414+009 are consistent with this hypothesis. The present work provides the clearest example of a BL Lac object in a cluster of galaxies. Contrary to the early results of Weistrop *et al.* (1981), evidence is growing that BL Lacs are often found in groups and clusters. A recent study (Stickel *et al.* 1993) of images and spectroscopy for a sample of BL Lac objects indicate a number of cases (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. Moreover, evidence for an enhancement of galaxy density near BL Lacs of medium redshift has been presented by Fried *et al.* (1993).

The statistical significance of the occurrence of BL Lac objects in groups of galaxies, and a detailed comparison of the environment of BL Lac objects with that of other classes of AGN requires a rather broad observational program. The present work is part of larger, systematic survey of the environments of BL Lacs.

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