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CCD PHOTOMETRY OF THE BL LACERTAE OBJECT 1400+162 AND THE ASSOCIATED GROUP OF GALAXIES

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ABSTRACT

Surface photometry of the BL Lacertae object 1400+162 and an apparently associated group of galaxies has been obtained using a CCD camera. Observations were made in V, broad bandpasses centered on 0.75 μm and 1.0 μm and with no filter. The colors of all but two of the galaxies suggest they are ellipticals, with the colors of the remaining two considerably bluer. Analysis using a method described by Schechter and Press suggests the group is a small one. The group may be similar to the one associated with the quasar 3C 273. The spectral index of the BL Lac object is $\alpha = 1.49 \pm 0.21$. This value allows, but does not require, the presence of an underlying elliptical galaxy. The radio-optical (α_{ro}) and optical–X-ray (α_{ox}) indices for 1400+162 are similar to values found for quasars.

Subject headings: BL Lacertae objects — galaxies: clusters of — quasars

I. INTRODUCTION

There are relatively few BL Lacertae objects in the same line-of-sight as clusters or small groups of galaxies. Among those that are, 3C 66 A (Butcher *et al.* 1976), PKS 0548−322 (Disney 1974), OY 091, PKS 2335+03, 4C 14.60 (Craine, Tapia, and Tarenghi 1975), and 1400+162, only for the latter object has an apparent association been confirmed by redshift measurements (Baldwin *et al.* 1977). PKS 0548−322 has been shown to have a redshift significantly different from that of the superposed galaxies (Fosbury and Disney 1976). Stockton (1980) has discussed the association of galaxies and low redshift quasars, in particular 3C 273. Investigation of the characteristics of the galaxies associated with 1400+162 will enable us to compare them with the characteristics of the galaxies associated with the low redshift quasars and may shed some light on the relationship between quasars and BL Lac objects. Study of the associated objects may elucidate the environment in which BL Lacs occur, and the role of that environment in the development of the BL Lac object. The relationship between BL Lac objects and galaxy evolution may also be explored further.

The BL Lac object 1400+162 (4C 16.39, OQ 100) is strongly polarized (Angel and Stockman 1980), has a normal radio spectrum ($\alpha \sim 0.7$ where $F \sim \nu^{-\alpha}$), a compact radio core (Baldwin *et al.* 1977) and has been detected in X-rays (Maccagni and Tarenghi 1981). It is superposed on a small group of galaxies (Hazard and Murdoch 1977). Baldwin *et al.* (1977), find a redshift $z = 0.244$ from one emission line in the BL Lac object. This value agrees with the redshift of the apparently nearest galaxy in the associated group and has been confirmed by Miller, French, and Hawley (1978). (Stockton 1978 has pointed out that the chances of a quasar and nearby galaxies having the same redshift coincidentally is very small.) 1400+162 is one of the few BL Lac objects which shows a classical double radio source, implying that we are not looking directly down a relativistic jet in this BL Lac object, unless the orientation of the jet has changed recently. The extended radio structure may also serve as a probe of the intergalactic medium in the group (Hintzen and Owen 1981). To further investigate the nature of 1400+162 and the associated galaxies, we report here the results of surface photometry for the group of objects. The observations and data reduction techniques are discussed in § II. The results for the galaxies and 1400+162 itself are discussed in §§ III and IV, respectively. Our conclusions are summarized in § V.

II. OBSERVATIONS

The observations were obtained 1979 May 4 using a charge-coupled device (CCD) camera mounted at the

TABLE 1
PHOTOMETRY FOR 1400+162 AND ASSOCIATED OBJECTS

Object	V (mag)	0.75 μm (mag)	1.0 μm (mag)	Effective Aperture	M_V (mag)
1400+162 ...	16.99±0.10(2)	16.33±0.10	15.88±0.12	12″	−24.2
A	20.73±0.13(2)	18.65±0.13	...	10	−21.0
B	19.68±0.10(2)	19.44±0.12	19.59±0.41	9	−21.4 (−22.1)
C	21.01±0.20	18.89±0.20	...	10	−20.8
D	19.99±0.11(2)	19.45±0.18	19.55±0.20	7	−21.1 (−21.9)
E	21.06±0.24	19.96±0.20	...	7	−20.8
F	21.61±0.19(2)	19.89±0.17	...	9	−20.2
G	21.84±0.24	20.78±0.13	...	6	−20.2
H	21.34±0.16	...	...	9	−20.5
I	20.37±0.10(2)	19.04±0.16	19.05±0.15	7	−21.5

Cassegrain focus of the 2.3 m telescope at the University of Arizona's Kitt Peak observing station. The detector was a Texas Instruments CCD array with a 500×500 pixel format. Broad-band direct imaging of the field was obtained with no filter, and through three filters, centered at 0.53 μm (V), 0.75 μm, and 1.0 μm. The integration times were 2 minutes with no filter, 2 minutes and 20 minutes in V, and 20 minutes and 30 minutes for 0.75 μm and 1.0 μm, respectively. Each frame was corrected for dark count and variations in pixel sensitivity. At the 2.3 m telescope, the scale in the focal plane is 9″.76 mm^{-1} with the f/9 cage. Each image covers an area of approximately 73″×73″ on the sky.

The observations used to calibrate the photometry have been described previously (Weistrop *et al.* 1981). The apparent magnitude of each object was determined by summing the counts in all pixels within a given radius, r, of the center of the object, and subtracting as sky background the sum of the counts in an annulus extending from r to $r+n$, where n was chosen so that the area of the annulus is equal to the area included in the object. If such a calculation is made for a series of values of r, the magnitude converges when the entire object is included within r, and the uncertainty can be estimated from the variations around the average value to which the magnitude has converged.

The photometry for 1400+162 and the associated galaxies is given in Table 1. The identification of the objects may be determined from the finding chart (Fig. 1) and Table 2, which gives the coordinates of the galaxies relative to the BL Lac object. The errors cited in Table 1 include the uncertainty in the magnitude calibration as well as that originating in the measurements. Those objects for which magnitudes were obtained from both the 2 minute and 20 minute V images are indicated in Table 1 by a "2" after the V magnitude, which is a weighted average of the two results. Photometry for the remaining objects was obtained from the 20 minute V image only. Only the relatively bright objects were detected at 1.0 μm, due to the declining sensitivity of the CCD at this wavelength. Object H was not detected at 0.75 μm or 1.0 μm but is included because it appeared on the unfiltered frame as well as the V frame.

III. THE GROUP OF GALAXIES

The method described by Burstein and Heiles (1978) was used to estimate the reddening due to our Galaxy, $E_{(B-V)}=0.0$ mag. This result is not surprising since the field is at galactic latitude $b=+70°$. Interstellar reddening and absorption are assumed to be negligible throughout the analysis. In Figure 2 the broad-band spectral distributions of the galaxies are compared to the known distribution for a giant elliptical galaxy. The distributions for all galaxies except B and D are consistent with this interpretation. The distributions for B and D are apparently bluer than would be expected from an elliptical galaxy and could be explained by late-type galaxy distributions (Fig. 3). For the eight objects, other than the BL Lac, for which colors are available, the average color is $(m_V - m_{0.75}) = 1.3 \pm 0.7$ mag. The color of the elliptical galaxy used for comparison is $(m_V - m_{0.75}) \sim 1.2$ mag. Objects B and D may represent the blue end of the color distribution, just as A and C represent the red end, although a χ^2 test indicates the probability that all eight objects have the same color is very much less than 0.001. (If the errors have been significantly underestimated, the results of the χ^2 test may be invalid.) The 1.0 μm observations are consistent with B and D being late-type galaxies (Fig. 3). The presence of emission lines in the galaxy spectra, e.g., $H\gamma$, λ4570 Fe II, may contribute to the apparently blue color. With the information available it is impossible to determine whether B and D have emission lines or to definitely distinguish among various morphologies. Observations are planned to determine whether B and D are late-type galaxies and to search for emission lines in the spectra. The 1.0 μm observation of galaxy I (0.8 μm in the rest frame of the system) is fainter than expected for an elliptical galaxy (Fig. 2). This object is very close

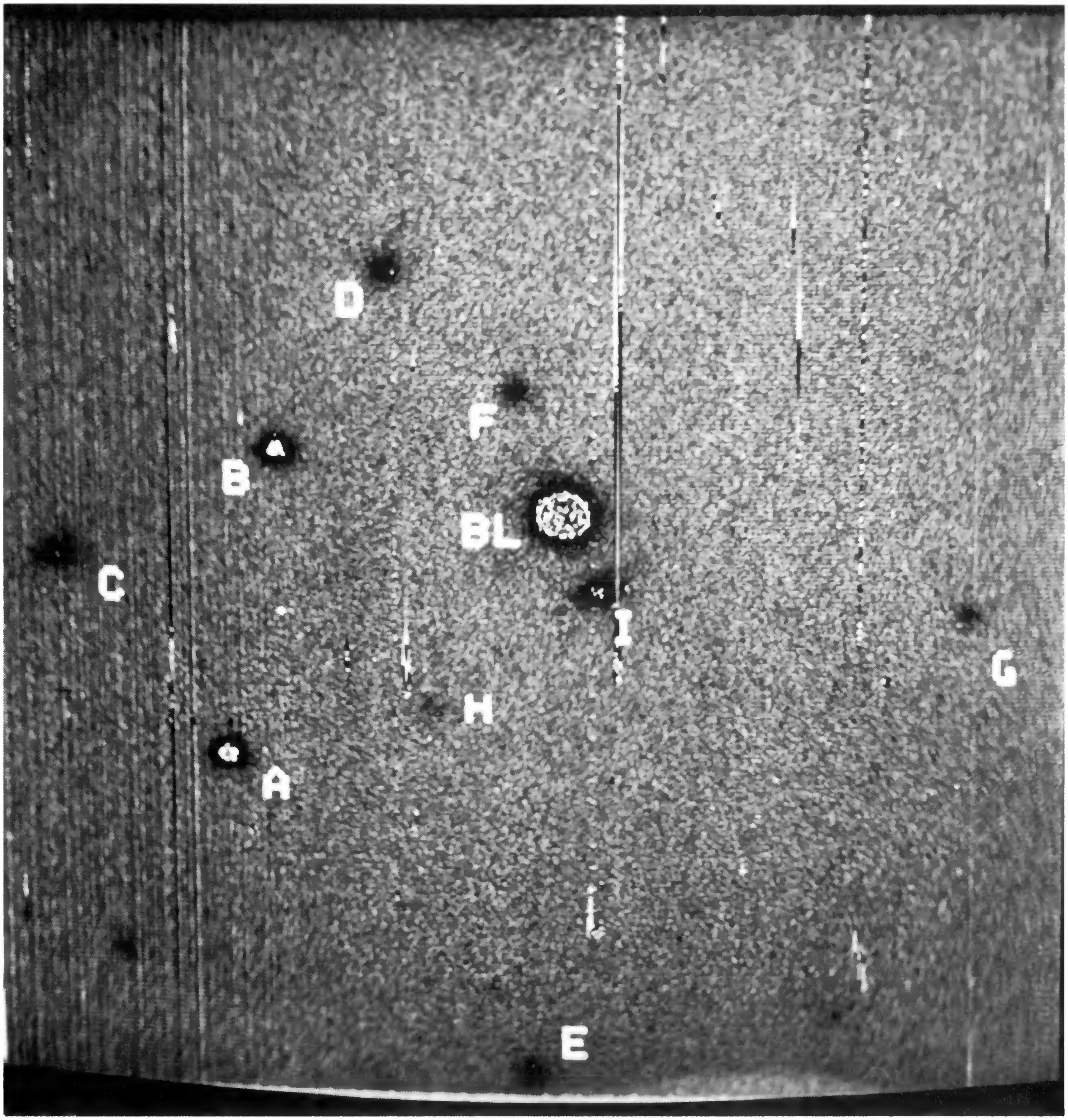

FIG. 1.—Finding chart for the 1400+162 field. North is at the top and east at the left. The BL Lac object is indicated by BL. The image is a negative, with bright pixels at the center of some objects due to bit clipping in the display system. The vertical columns are artifacts of the CCD chip.

to the BL Lac, which could affect measurement of the magnitudes.

Thus far we have assumed that all objects in the field except 1400+162 are galaxies; however, this may not be correct. In a 1.5 arcmin^2 field at galactic latitude $+70°$, two stars are expected down to $V = 22$ mag, with one between $V = 20$ and 22 mag, the magnitude range of most of the program objects (Bahcall and Soneira 1980). It therefore seems likely that at least one of the objects in the field is not a galaxy. It is impossible to use the profiles of the objects to identify possible stars since there is no known star in the field, so the point spread

TABLE 2

COORDINATES OF ASSOCIATED OBJECTS RELATIVE TO 1400+162

Object	Δ(R.A.)	Δ(decl.)
A	+1^s.50	−16″.5
B	+1.26	+4.3
C	+2.27	−2.8
D	+0.77	+16.4
E	+0.14	−37.9·
F	+0.19	+8.2
G	−1.93	−6.7
H	+0.59	−13.3
I	−0.17	−5.2

function cannot be measured, and the signal-to-noise ratios are low for all objects except 1400+162. The spectral energy distributions are consistent with the objects being either galaxies or stars. This uncertainty is considered further below.

To estimate the absolute visual magnitudes of the galaxies, corrections for effective aperture size and the K-dimming are applied. The aperture correction is necessary to determine the absolute magnitudes to a standard diameter, since the effective aperture through which each object is measured (Table 1) is determined by the signal-to-noise ratio in the outer parts of the image. The aperture corrections are calculated assuming a redshift $z = 0.244$ and the relationship given by Sandage (1972), modified for an assumed value $q_0 = +0.1$. These corrections are for giant elliptical galaxies. We are unable to estimate the aperture correction for late-type galaxies and do not apply one. If B and D are giant ellipticals, the aperture corrections are about -0.2 to -0.3 mag.

A K-correction of $K_V = 0.55$ mag is adopted for the elliptical galaxies, assuming $z = 0.244$ (Pence 1976; Coleman, Wu, and Weedman 1980; Whitford 1975). For late spiral and irregular galaxies, the K-corrections are much less than the uncertainty in the data (Pence 1976; Coleman, Wu, and Weedman 1980) and we assume $K_V = 0.00$ mag for objects B and D if they are late-type galaxies. The absolute magnitudes calculated for the galaxies are shown in Table 1. Values for B and D assuming they are ellipticals are given in parentheses. Within the uncertainty of the data, the luminosity distribution for the 1400+162 group is consistent with that for either clusters or small groups of galaxies, independent of whether B and D are early or late-type galaxies (Fig. 4). It would be useful to obtain longer integrations on the field to reduce the uncertainty in the magnitudes and to search for fainter members of the group. At least two or three additional objects may be present in the field, but since they were marginally detected on only one frame in our observations, they were not included in the analysis.

The method of Schechter and Press (1976, hereafter SP) has been employed to estimate the richness of the group of galaxies and the group redshift. (We note a misprint in eq. [8a] of SP, where the last term should be

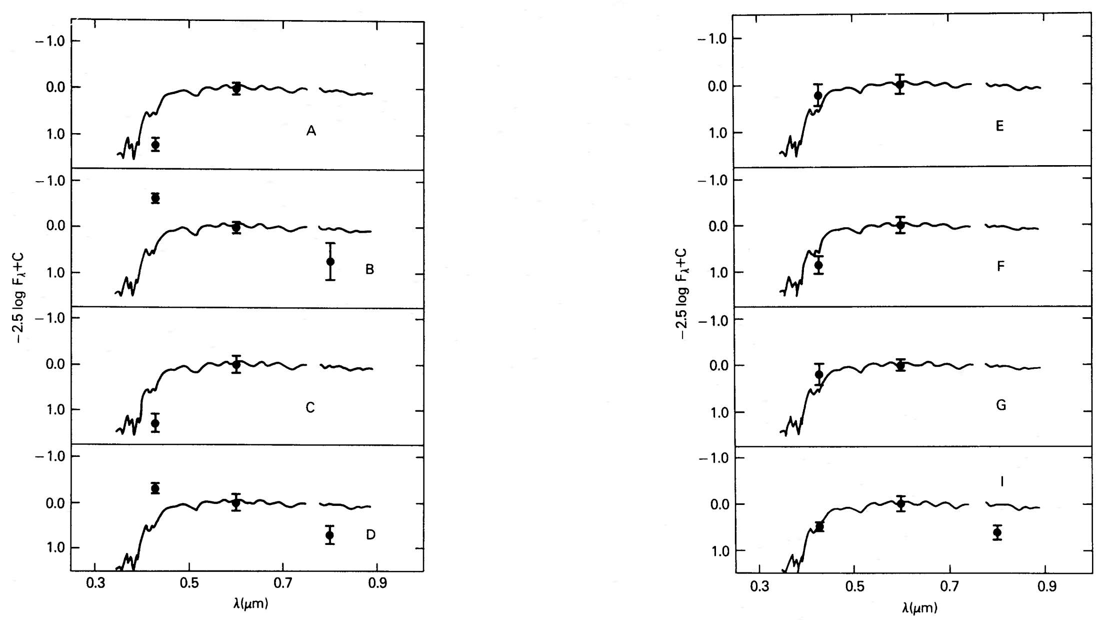

FIG. 2.—Comparison of broad-band spectral energy distributions of group members (*filled circles*) with the distribution for a giant elliptical galaxy (*solid line*; Whitford 1971). The distributions are normalized to 0.00 mag at 0.60 μm. Two-sigma error bars are shown.

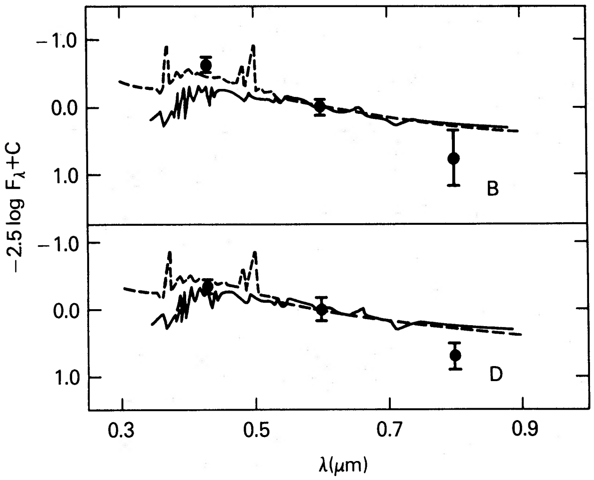

FIG. 3.—Comparison of broad-band spectral energy distributions of objects B and D (*filled circles*) with distributions of late-type galaxies. Turnrose's data (1976) for the late spiral galaxy NGC 1073 (*solid line*) and Coleman, Wu, and Weedman's results (1980) for an Im galaxy (*dashed line*) are shown. All data have been normalized to 0.00 mag at wavelength 0.60 μm. The error bars indicated have a total length 2 σ.

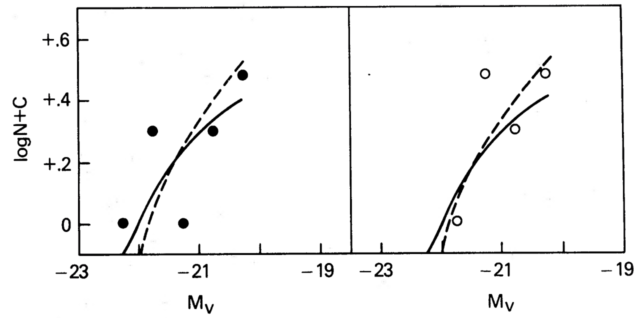

FIG. 4.—Comparison of the relative number of galaxies (N) as a function of luminosity for small groups (*solid line*; Turner and Gott 1976) and clusters (*dashed line*; Schechter 1976) with the luminosity distribution of the 1400+162 group. The data for the 1400+162 group are shown assuming all members are elliptical galaxies (*filled circles*) or objects B and D are late-type galaxies (*open circles*). The data from Turner and Gott 1976 and Schechter 1976 have been transformed to the visual magnitude system.

$N(\alpha+1)/\lambda^{*2}$ not $N(\alpha+1)/\lambda^*$. P. Schechter [1981, private communication] has checked this and confirms that the results in SP, Table 1 are correct.) We adopt SP's value of $M_V^* = -21.9$ mag for the characteristic absolute magnitude. The results for several cases are given in Table 3. The first three columns indicate the assumptions: column (1), the number of galaxies in the group; column (2), whether objects B and D are early- (E) or late- (L) type galaxies; and column (3), the value of the redshift, if it is assumed and not derived. Columns (4)–(7) give the derived redshift and its uncertainty, and the derived richness, n^*, and its uncertainty. The richness is proportional to the cluster luminosity with values for rich clusters in the range 20–115 (Schechter 1976). The results include the effect of the K-correction. The results assuming all the objects in the group are galaxies and B and D are late-type galaxies are shown in the first line. The derived redshift is larger than that measured for galaxy I by Baldwin *et al.* (1977), although the difference may be not significant. If B and D are elliptical galaxies, the redshift derived is in good agreement with that obtained from the spectra. The value of n^* suggests a small group. If a redshift of $z = 0.244$ is assumed, the richness criterion also suggests the group is a small one.

Statistically one or two objects in the field are expected to be stars (see previous discussion). There may also be foreground and/or background galaxies along the line of sight. To determine the effect of non–group members on the redshift and richness estimates, these were recalculated omitting in turn each single object and all pairs of objects. The resulting redshifts (Table 3, rows 3–6) are not significantly different from the values

TABLE 3

RICHNESS AND REDSHIFT ESTIMATES FOR THE GROUP

ASSUMPTIONS			RESULTS			
No. of Galaxies (1)	B, D Type (2)	z (3)	z (4)	Δz (5)	n^* (6)	Δn^* (7)
9	L	...	0.35	(+0.10, −0.08)	18	(+26, −10)
9	E	...	0.27	(+0.10, −0.07)	7	(+6, −4)
8	L	...	0.33–0.40	(+0.11, −0.08)	13–62	(+151, −8)
7	L	...	0.32–0.48	(+0.11, −0.09)	9–309	(+1665, −5)
8	E	...	0.26–0.31	(+0.10, −0.07)	5–9	(+10, −4)
7	E	...	0.25–0.36	(+0.11, −0.09)	4–15	(+28, −2)
10	L	...	0.26	(+0.09, −0.07)	6	(+6, −3)
10	E	...	0.23	(+0.09, −0.06)	5	(+4, −2)
10, 9, 8, 7	L, E	0.244	...	...	4–6	(+7, −2)

assuming all objects in the field are group members. The extreme values occur when either the faintest objects or galaxy I and one of the faintest objects are deleted. Since galaxy I has the same redshift as the BL Lac object, the latter case is unlikely. The redshifts estimated agree with the spectroscopic value within the uncertainties of the method whether B and D are assumed to be early- or late-type galaxies. The calculations suggest the group is a small one, if B and D are early-type galaxies or the redshift is constrained. These results may be compared to Stockton's finding (1980) that low-redshift radio quasars are often associated with small groups of galaxies, but are rarely found in rich clusters of galaxies. Sources of uncertainty in the estimated redshifts and richness criteria include the possible existence of other, undetected galaxies in the group, the limited accuracy of the SP method for sparse groups, and the possibility that some of the galaxies could be members of a more distant group.

Several BL Lac objects have underlying giant elliptical galaxies (Weistrop, Smith, and Reitsema 1979; Weistrop *et al.* 1981 and references therein). We recalculate the redshift and richness criteria assuming an elliptical galaxy with $M_V = -22.5$ mag underlying 1400+162 (Table 3, rows 7–9). At a redshift of 0.244 such a galaxy would have an observed diameter similar to that of the seeing disk of the BL Lac object and would not be readily distinguishable from the superposed point source, especially since there is no known point source in the field for comparison. The redshifts are in excellent agreement with the spectrographically determined redshift. The corresponding richness criteria again indicate a small group of galaxies.

We have compared the location of the galaxies in the 1400+162 group with Hintzen and Owen's high-resolution radio map of 1400+162 (1981). The position of the radio emission overlaps only galaxy I, the nearby galaxy southwest of the BL Lac object. Since that galaxy is closer to 1400+162 than the edge of the general extent of the radio emission, and is not located near a local emission peak, the coincidence in position is probably not significant.

We compare the galaxies apparently associated with 1400+162 with a small group associated with 3C 273. Down to a limiting magnitude of $m_B \sim 21.5$, there are four galaxies within 5′ of 3C 273 for which the redshifts are essentially the same as that of the QSO (Stockton 1980). The field we observed is considerably smaller than the area Stockton would have investigated for a QSO at $z = 0.244$. However, our faintest objects are about 1 mag fainter than Stockton's limiting magnitude, for $(B - V) = 1.0$ mag. There are nine possibly associated objects in our field, with one object having a redshift confirming the association. The absolute magnitudes of the four brightest objects in the 1400+162 group are similar to those for the 3C 273 group. The galaxies in the 3C 273 group are close to the QSO (within 2′.5), as are those in the 1400+162 group. Spectroscopy of the objects in the 1400+162 group is planned to determine whether they are all associated with the BL Lac object.

IV. 1400+162

The photometry for 1400+162 is given in Table 1. Miller, French, and Hawley (1978) find $V = 17.7$ mag, fainter than our result. O'Dell *et al.* (1978) report V magnitudes of 17.37 ± 0.14 mag and 17.08 ± 0.10 mag for 1976 June and 1977 June, respectively. (These observations were also reported by Baldwin *et al.* 1977.) Our results are in good agreement with those for 1977 June. Variability in this object would not be surprising, since it is strongly polarized (4%–14%) and there seems to be a strong correlation between polarization and variability in the optical flux for BL Lac objects (Angel and Stockman 1980). For $q_0 = +0.1$, the absolute magnitude is $M_V = -24.2$ mag, within the range previously found for the nonthermal component of BL Lac objects (Miller, French, and Hawley 1978). Over our observed spectral range of 0.53–1.0 μm, the spectral index is 1.49 ± 0.21, in good agreement with values determined previously (Nordsieck 1976; Miller, French, and Hawley 1978; O'Dell *et al.* 1978). The spectral index is consistent with the presence of an underlying galaxy.

The radio data for 1400+162 can be broken into two components, a relatively flat spectrum compact source which coincides with the optical point source, and a steep spectrum, distorted, extended source some 20″ (130 kpc) across (Baldwin *et al.* 1977; Hintzen and Owen 1981). The core source is very compact, $\leq 0''.001$ from the data of Weiler and Johnston (1980), after correcting the visibility for the true flux density of the core source. Owen, Spangler, and Cotton (1980) have observed this source simultaneously at several frequencies. The X-ray flux (Maccagni and Tarenghi 1981) is too weak to determine the spectral index of the X-ray emission. To compare the results for 1400+162 with those for quasars, we calculate the radio-optical spectral index (α_{ro}) and optical-X-ray spectral index (α_{ox}) (Zamorani *et al.* 1981). In this calculation only we assume $q_0 = 0$, the value Zamorani *et al.* use. We use the X-ray luminosity given by Maccagni and Tarenghi (1981) to calculate the emitted X-ray luminosity at 2 keV, the visual magnitude in Table 1 to calculate the luminosity at 2500 Å (emitted wavelength), and the flux at 5 GHz (Weiler and Johnston 1980) to calculate the emitted radio luminosity. The total flux at 5 GHz is used (Zamorani *et al.* 1981), even though it probably includes emission from extended as well as compact sources. If the X-ray spectral index is assumed to be $\alpha_x = 0.5$ as for the quasars, then $\alpha_{ox} = 1.3$. However, there is a wide range of X-ray spectral indices for BL Lac objects (Maccacaro and

Gioia preprint), so $\alpha_x = 0.5$ may not be appropriate. If we assume $\alpha_x = 2.0$, then $\alpha_{ox} = 1.5$ for 1400+162, not significantly different. We find $\alpha_{ro} = 0.6$. If the results for 1400+162 are plotted on the α_{ox}-α_{ro} diagram (Fig. 4, Zamorani *et al.*), the data are located well within the area defined by the quasar data, regardless of whether the value of α_{ox} for $\alpha_x = 0.5$ or $\alpha_x = 2.0$ is used. To the extent that one can draw conclusions from limited data, this result is consistent with the idea that the emission mechanisms for BL Lac objects and quasars are similar. Using the optical spectral index $\alpha = 1.49$ and the optical–X-ray index, the data for 1400+162 are also consistent with the behavior of quasars in the α_{ox}-$\alpha_{\rm VRI}$ diagram (Sitko *et al.* 1982). Sitko *et al.* suggest that, for quasars, the X-rays are not a simple extension of the visual-infrared spectrum. However, among the BL Lac objects for which X-ray spectral information is available, there are objects where the X-ray emission is an extrapolation of the optical emission and other objects where it is not (Kondo *et al.* 1981; Weistrop, Smith, and Reitsema 1979; Weistrop *et al.* 1981). More sensitive X-ray data with better spectral resolution are needed to determine the relationship between the radio, optical and X-ray data of 1400+162 and its implications for the mechanism of energy production.

Stockton (1982) and Hutchings, Campbell, and Crampton (1982) have suggested that in nearby quasars, the quasar activity may be induced by interaction with a galaxy. The projected linear distance between 1400+162 and galaxy I is 29 kpc ($H_0 = 50$ km s^{-1} Mpc^{-1}), about twice the largest projected distances for the objects discussed by Stockton (1982) and Hutchings, Campbell, and Crampton (1982). (We note that the projected distance between 0351+026 and its companion should be 7 kpc for $H_0 = 100$ km s^{-1} Mpc^{-1}, not 13 kpc as reported in Hutchings, Campbell, and Crampton 1982.) Unlike the companions discussed by these authors, galaxy I does not appear to be an unusual object. The observations do not show evidence of any interaction between the BL Lac object and galaxy I; although, if there is a galaxy underlying the BL Lac object and if the projected distance between the objects is close to the actual distance, the outer parts of the galaxies are probably passing through each other.

V. SUMMARY

Photometry of the BL Lac object 1400+162 and several apparently associated galaxies is reported. The colors for all but two of the galaxies are consistent with their being ellipticals. The colors of the remaining two are bluer than would be expected for early-type galaxies. Calculations using the method described in SP suggest the galaxies are members of a small group. This is consistent with a previous suggestion that the BL Lac phenomenon may avoid a cluster environment (Weistrop *et al.* 1981). The redshifts estimated for the group using the SP method are consistent with the spectroscopic value observed for one galaxy. The group may be similar to the small group of galaxies associated with 3C 273.

The spectral index of the BL Lac object in the wavelength region 0.5–1.0 μm is $\alpha = 1.49 \pm 0.21$. Such a steep spectral index is consistent with, but does not require, the presence of an underlying galaxy. The absolute magnitude, $M_V = -24.2$ mag, is consistent with absolute magnitudes determined for other BL Lac objects. The radio-optical and optical–X-ray spectral indices for 1400+162 are similar to those found for quasars, suggesting a common emission mechanism.

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