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A SEARCH FOR FAINT HIGHLY POLARIZED OBJECTS

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ABSTRACT

We have conducted a photographic search for faint highly polarized objects, to 20th magnitude. Our observations show no evidence of a large population of radio-quiet BL Lacertae objects, counterparts of radio-quiet quasars. Our observations could be used to argue that BL Lac objects belong to a slowly evolving class of extragalactic objects, but we point out that they are also compatible with the relativistic beam model.
Subject headings: BL Lacertae objects — polarization

I. INTRODUCTION

It has become increasingly clear that there are strong similarities in the characteristics of active nuclei of galaxies, BL Lacertae objects (here after called BLOs), and quasars. A knowledge of the area and volume densities of these objects is paramount in understanding the luminosity function, evolution, and, ultimately, the nature of these objects and their interrelationship. The local space densities of Seyfert and N galaxies are relatively well known (Véron 1979). Our knowledge of the area and space densities of quasars have come from UV excess searches (Braccesi, Formiggini, and Gandolfi 1970; Schmidt and Green 1983), wide-field spectroscopy (MacAlpine, Smith, and Lewis 1977*a*, *b*; MacAlpine, Lewis, and Smith 1977; Osmer 1980, 1981, 1982), and other techniques (see Véron and Véron 1982 for a summary). On the other hand, the area density of BLOs is poorly known (Véron 1979). This comes about because they lack the conspicuous features (UV excess, strong emission lines) that make quasars easy to detect on wide-field plates. Candidate BLOs have historically been found in radio surveys by their flat radio spectra and are then confirmed with slit spectroscopy or polarimetry (Craine, Duerr, and Tapia 1978). This introduces a bias against radio-weak objects and, because BLOs tend to be weaker radio emitters than quasars, one will detect nearby objects more easily. Recently, X-ray surveys have proven to be powerful tools to discover active nuclei. Schwartz and Ku (1983) have thus determined the local volume density of BLOs. There is still, however, the possibility that there exists a population of radio-weak and X-ray-weak BLOs. Schwartz and Ku (1983) sampled mostly the local volume, and little is known about the more distant volume density of BLOs besides a suspicion that they are rare at high z (Setti and Woltjer 1977; Véron 1979; Maccacaro *et al.* 1982).

Very high polarization in the optical region (as much as 40%) is one of the main characteristics of BLOs (Angel and Stockman 1980); it is thus desirable to make a survey of optical polarization among all faint objects ($m_B > 18.0$) in a few selected areas of the sky. Because one has to observe thousands of objects, this survey cannot be done photoelectrically. We report here the results of a search for highly polarized faint objects using wide-field direct photography. A similar survey has been published by Impey and Brand (1982), covering a wider field but reaching a brighter limiting magnitude than in the present work.

II. TECHNIQUES AND OBSERVATIONS

The observations consist of several baked IIIa-J plates taken with polarizing filters (Polaroid Corporation HN 38). Table 1 lists the central coordinates of the plates used. The survey plates were taken with the CFH 3.6 m telescope and the techniques developed with plates taken with the 1.6 m Mont Mégantic telescope. The central unvignetted parts of the plates (47′) were fully digitized with a 50 μm (0″.7) square aperture and 50 μm discrete steps with the David Dunlap Observatory PDS. The data were computer analyzed with a stellar photometry program written by Rheault (1979) and modified for polarization measurements (Corriveau 1981).

It can be shown that a minimum of three measures through polarizing filters oriented at 0°, 60°, and 120° are needed to define the polarization vector and its orientation. Plates 542 and 546 were taken with this three-image technique. The three exposures are taken on the same plate; the telescope is moved by 20″ (1.4 mm on the plate) between exposures. Exposing the different images on nearby parts of the same

[1] Visiting Observer with the Canada-France-Hawaii Telescope.

TABLE 1
PLATE MATERIAL USED

Plate	α(1950)	δ(1950)	Date	Remarks
CFHT 542	$22^h00^m00^s$	−19°00′00″	1980 Aug 12	Three exposures.
CFHT 546	22 00 00	−20 00 00	1980 Aug 13	Three exposures.
CFHT 961	13 04 54	29 38 42	1981 Mar 4	SA 57. Two exposures.
CFHT 963	13 04 54	29 38 42	1981 Mar 6	SA 57. Two exposures.

plate minimizes any false polarization introduced by differences in emulsion sensitivity and plate development. The sky is, however, exposed 3 times as long as the stars, increasing noise at a given magnitude. A field near the North Galactic Pole (SA 57) was observed with a four-exposures, two-plate technique (Plates 961 and 963). A first Stokes parameter is obtained by taking two exposures on the same plate (separated by 15″) with Polaroid filters oriented at 0° and then 90°. A second plate (Polaroids at 45° and 135°) yields the other Stokes parameter. It takes two plates to determine the polarization vector, but the sky is now exposed only twice on a given plate, resulting in a smaller noise than with the three-exposures technique. After the Stokes parameters have been computed, the reduction method is the same for the two techniques. Although every effort was made to choose exposure times to give similar images on a given plate, this was not accomplished perfectly, because of changes in transparency and seeing during the rather long exposures. This results in an "instrumental" polarization for all the objects on a plate. Because the images used to yield a Stokes parameter for a given object are very near each other on a plate, the instrumental and interstellar polarization should be nearly the same for all the objects on a plate, and it can be subtracted with the knowledge that most objects on a plate are stars and galaxies that are nearly unpolarized. Taking the three (or four) exposures on different plates would have given a higher limiting magnitude but also a second kind of instrumental polarization resulting from the nonuniformity in plate sensitivity and development. This is not the same for all objects on a plate and cannot be subtracted.

Each plate is divided into five regions. Plots of the Stokes parameters Q and U as a function of magnitude show scatter along a straight line. A straight line is then fitted to the data yielding the instrumental polarization line $\lambda = f(m)$. For a given interval of magnitude Δm, the standard deviation is computed from:

$$\sigma_\lambda{}^2(m) = \frac{1}{N-2} \sum_{i=1}^{N} [f(m) - \lambda_i]^2 , \qquad (1)$$

where λ_i is the Stokes parameter measured from every object, and N is the total number of objects in the magnitude interval Δm analyzed. The polarized objects candidates are those that have $|f(m) - \lambda| \geq 3\,\sigma_\lambda$.

Figure 1 shows the linear polarization measured for a few stellar objects in the field of the known BLO OJ 287; $f(m)$ has been subtracted from the data. OJ 287 is clearly seen (*cross*) standing out from the unpolarized field objects. This plate was taken with the Mont Mégantic 1.6 m telescope. At its f/8 Cassegrain in the plate scale (14″ mm^{-1}) is nearly identical to the plate scale of the f/4 CFHT prime focus. OJ 287 was thus measured on 1980 February 21 to have $B = 15.7$, $P = (Q^2 + U^2)^{1/2} = 21\% \pm 4\%$, and polarization angle 90°, in good agreement with what is known of the object (Angel *et al.* 1978).

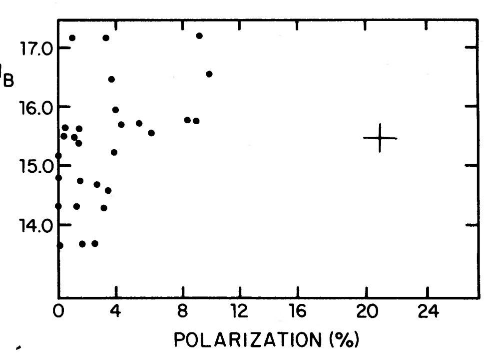

FIG. 1.—Observations of a field around the known BL Lacertae object OJ 287. The object (*cross*) is clearly seen standing at several standard deviations from the locus of unpolarized stars.

The IIIa-J emulsion and Polaroid filter combination define a bandpass very close to the photographic J band, and we use the conversion relation $B = J + 0.28\,(B - V)$ (Harris 1980). We assume that the stars in the field have $B - V \approx 0.7$, a value typical for the stars in our magnitude range (Shanks, Phillips, and Fong 1980). The fields of plates 542 and 546 do not have a photoelectric calibrated sequence. We used, to calibrate those plates, the method described by Hayman, Hazard, and Sanitt (1979). The copy of the Palomar Sky Survey used contains, near the fields of plates 542 and 546, a faint stellar photometric sequence obtained from Savage (1981). As the diameter-magnitude relation we used is thus directly calibrated, the uncertainty in our calibration should be less than 0.2 m (Hayman, Hazard, and Sanitt 1979). The field in SA 57 contains the faint stellar photoelectric sequence to $B = 18.5$ from Kinman, Wirtanen, and Jones (1966). It was extrapolated to fainter magnitudes with the spot sensitometer calibration on the plate. Extrapolating by a couple of magnitudes will introduce a negligible error. Edwards (1983) finds that the calibration between instrumental and true magnitude, using the same program and algorithms, is nearly linear between 19th and 21st magnitude. It is probably still linear to fainter magnitudes, but this could not be checked because of a lack of standards.

We always find several objects per plate standing at more than 3 σ. We then examine visually the image matrix that contains the digitized data. We prefer to inspect the digitized data, rather than inspect the plate itself, because we look at the data actually analyzed by the computer. We then reject many objects that have images different from their twins (or triplets). This condition is usually caused by overlapping images or plate defects. We are then left with only four candidate BLOs in the three fields (Table 2). Objects 1, 2, and 3 were observed by Dr. S. Tapia with a photoelectric polarimeter (Minipol) and the Steward Observatory 90 inch (2.3 m) telescope. The bandpass is defined by an unfiltered GaAs photomultiplier. As we can see from Table 2, none of these objects is confirmed. Time-varying polarization is an unlikely explanation as these observations are sufficiently accurate to detect the typical low state of a BLO. The marginal detection in object 1 is likely to be interstellar as a nearby star was observed to have $P = 0.89\% \pm 0.30\%$ and similar polarization angle.

Over 2000 objects were observed in the three fields, and some 3 σ detections should be expected on statistical grounds alone. As the two (or three) exposures that define a Stokes parameter are separated by about 2 hours of time, any object varying in luminosity will appear polarized after data reduction. Some of the objects in Table 2 could be RR Lyrae stars, flare stars, or other short-term variables.

We are thus left with one possible (but unconfirmed because it is too faint) candidate. In what follows we will assume

TABLE 2

CANDIDATE BL LACERTAE OBJECTS

Object	M_B	$\alpha(1950)$	$\delta(1950)$	Photographic Polarization (%)	Photoelectric Polarization
1	18.7	$21^h59^m23^s$	−20°08′08″	17 ± 4	1.37 ± 0.46
2	18.3	13 04 47	29 44 00	17 ± 4	0.42 ± 0.63
3	18.2	13 04 29	29 42 40	23 ± 4	1.36 ± 0.9
4	19.4	13 04 51	29 42 07	15 ± 5[a]	None

[a] This measures only one Stokes parameter (plate 963); the other one was lost (scratch on plate 961).

that this object is not polarized. The statistics will be little affected by only one object. A finding chart will be supplied, on request, to anyone wishing to observe it.

III. THE SURFACE DENSITY OF FAINT BL LACERTAE OBJECTS

We have a detection threshold, $t_i = 3\ \sigma_i(m)$, which is a function of magnitude and varies from field to field ($i = 1, 2, 3$). The polarization of BLOs varies greatly in time, and the extrema of variation vary from object to object. It is clear that our observations will miss some objects at all times and other objects a fraction of the time. We must compute a correction factor to take these misses into account. After determining $t_i(m)$ for every plate, we compute for every plate the correction factor from (see Appendix)

$$C_i(m) = \int_{t_i(m)}^{100\%} D(p)dp \bigg/ \int_0^{100\%} D(p)dp , \qquad (2)$$

where $D(p)$ is defined in the Appendix. It describes the distribution of polarization among BLOs, including time variations. The parent distribution $D(p)$ is unknown, and we shall use instead a sample of the parent distribution. We obtain this sample distribution from the extensive and systematic monitoring of the polarization of 12 BLOs from Angel *et al.* (1978). The list of BLOs in Angel and Stockman (1980) contains 50 bona fide BLOs; these 12 objects constitute thus a substantial fraction ($\sim 25\%$) of all BLOs known. To give equal weight to all objects, the sample $D(p)$ must contain the same number of observations for every object. As some objects in Angel *et al.* (1978) have only a limited number of observations, we used only five observations per object, for all objects. Although the five observations per object were chosen at random among the measures in Angel *et al.* (1978), we were careful to space our sampling fairly uniformly through the whole time base. We avoided, in particular, to select two observations taken on the same night or on consecutive nights. It is clear that only five observations do not define accurately $\phi_i(p)$ [see the Appendix for a definition of $\phi_i(p)$]; however, we should expect, on statistical grounds, that the majority of these five measurements are near the maximum of $\phi_i(p)$. We should expect thus that the most important portions of the $\phi_i(p)$ of our 12 objects are actually used to compute our sample $D(p)$. Our sample $D(p)$ contains a total of 60 measures. If $D(p)$ is a "well-behaved" function (by "well-behaved" we mean a broad-peaked continuous function such as a Gaussian, a Poisson, or a flat distribution), 60 observations are sufficient to define it reasonably well. Numerical simulations show this to be the case for a Gaussian. Corriveau (1981) has examined the $\phi_i(p)$ of a few BLOs that have extensive monitoring. Although the $\phi_i(p)$ he determined vary from object to object, they appear to be "well-behaved" in the sense defined above. The $\phi_i(p)$ appear smooth, with a single broad peak. As $D(p) = \sum \phi_i(p)$ (eq. [A1]), we should expect $D(p)$ to be "well-behaved" as well. As a simple check on the validity of our procedure, we redetermined our sample $D(p)$ by selecting different sets of observations among the 12 objects. We found no significant (a few percent) changes in the values of $C(m)$ obtained. Table 3 shows $\phi(m)$, $t(m)$, and $C(m)$ for our deepest field (SA 57). The distribution for the other two fields are similar but offset by $\Delta m \sim -1.5$.

We have not detected any BLOs; hence, we cannot discuss their surface density. We will, however, make the common assumption that BLOs are a subset of quasars. Because of the weak statistics involved, we will test only whether the surface density of BLOs is smaller than, equal to, or greater than the density of quasars. Véron and Véron (1982) have summarized the then available data on the surface density of quasars. There are discrepancies in the surface densities of quasars, at a given magnitude, measured by different investigators. These discrepancies are probably due to incompleteness, different techniques used, errors in the magnitude scale, etc. We therefore choose to use numbers based on evolutionary models from Schmidt and Green (1983). These models are based on the Palomar Bright Quasar survey and other complete surveys. The counts predicted by the models we used are compatible with the uncertainties (and discrepancies) of the faint surveys listed in Véron and Véron (1982). The number of BLOs we should have detected, under the assumption that their space density and evolution is the same as for quasars, is given by

$$N = \sum_{i=1}^{3} q_i A_i \int_0^{B_i} C_i(B) n(B, z < 3.5) dB , \qquad (3)$$

TABLE 3

VALUES USED WITH EQUATION (2) FOR THE SA 57 REGION[a]

$B(\pm 0.5$ mag$)$[b]	$\sigma(m)$ (%)	$t(m)$ (%)	$C(m)$
18	3.8	11.5	0.53
19	4.9	14.7	0.31
20	6.2	18.6	0.21

[a] The other two regions have similar values but offset by $\Delta m \sim -1.5$.

[b] Magnitude interval.

where $C_i(B)$ is defined by equation (2), i is a number identifying one of our three fields, q_i is a factor that corrects for the fraction of images lost because of overlapping images, emulsion defects, etc. (from 5% to 10%), A_i is the area searched per plate, B_i the faintest magnitude used per plate, and $n(B, z < 3.5)$ the theoretical number counts for quasars having $z < 3.5$. The predictions of these models are in Table 4. We used Schmidt and Green (1983) coding; HH 1 and HL 1 are for $q_0 = 0.1$ cosmology and use, respectively, a high and a low estimate of the surface densities at 21st magnitude, while HH 5 and HL 5 correspond to the same but for $q_0 = 0.5$. The errors associated with each number reflect counting statistics. Our data seem to indicate an underabundance of BLOs compared to quasars, at faint magnitudes, and, implicitly, high redshifts. The statistical significance is less than overwhelming but confirms similar conclusions reached from independent analysis by Setti and Woltjer (1977) and Véron (1979). Our data are also in agreement with the polarization survey of Impey and Brand (1982), especially considering that none of their candidates has confirming observations. Their estimate of $0.9^{+0.3}_{-0.9}$ BLOs per square degree to $B = 19.0$ is thus actually an upper limit.

IV. DISCUSSION AND CONCLUSION

We find that BLOs are less common than quasars at $m_B \sim 20$. This is in good agreement with the beam theory (Blandford and Rees 1978) that predicts that BLOs should represent $\sim\frac{1}{4}\Gamma^{-2}$ of the quasar population, where Γ is the Lorentz factor ($\Gamma \sim$ 5–10). We would thus expect that less than 1% of the quasars are BLOs.

On the other hand, our observations and the beam model must be reconciled with the observations of Schwartz and Ku (1983). Because the local space density of BLOs is actually greater than the local density of quasars, Schwartz and Ku (1983) find that the predictions of the beam model are grossly violated and that their results argue against beams being the single distinguishing feature of BLOs. Our observations could thus be used to corroborate independent, but marginal, evidence (Setti and Woltjer 1977; Véron 1979) that the space density of BLOs does not show the large increase with lookback time observed in quasars. BLOs would then belong to a distinct population of extragalactic objects that evolves more slowly than quasars, with cosmic time.

Schwartz and Ku (1983) point out that the similarity of the X-ray–selected local BLOs and quasar densities argues against an isotropic X-ray emission and for a beamed X-ray emission. They then proceed to compute the space densities of the possible parent populations (their Table 3). This parent population is clearly distinct from observed quasars and Seyfert galaxies, having much lower luminosities and higher space densities (by about 4 Γ^2, given the similar densities of Seyferts and BLOs). Such a parent population contributes neglibly to the X-ray background and source counts. They conclude that this hypothetical parent population, that is clearly not representative of quasars or Seyferts, would be consistent with being a subset of elliptical galaxies. Here, we suggest that this parent population can be identified with the low-luminosity remnants of evolved quasars. The local BLOs would then be the subset of these objects having a beam pointed in our direction. A full analysis of this hypothesis and its implications will appear elsewhere (Borra 1983). We only point out here that the factors of the order of 10^3 between the local volume density of quasars (from Sramek and Weedman 1978) in Table 2 of Schwartz and Ku (1983) and the densities of the parent population in their Table 3 are of the same order of magnitude of the decrease in the comoving space density of quasars between $z = 2$ and $z = 0$ (Sramek and Weedman 1978). If our hypothesis is correct, our lack of detection of faint polarized objects is then in full agreement with both the beam theory and the equality of the local densities of quasars and BL Lacertae objects.

TABLE 4

NUMBER OF BL LACERTAE OBJECTS THAT SHOULD HAVE BEEN DETECTED BY THIS SURVEY[a]

Model[b]	Number
HH 1	6.8 ± 2.6
HL 1	4.2 ± 2.0
HH 5	7.0 ± 2.6
HL 5	4.40 ± 2.10

[a] Using eq. (3); assuming that BLOs are as common as quasars; using the evolutionary models in Schmidt and Green (1983).

[b] See text and Schmidt and Green (1983) for coding.

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APPENDIX

DETECTION THRESHOLD CORRECTION

BL Lacertae objects have time varying polarization and the mean polarization, as well as the extrema of variation, vary greatly from object to object (Angel *et al.* 1978). Let us monitor continuously the polarization of a given object for a sufficiently long period of time t (several years). The very large number of observations N obtained can be used to construct the distribution of polarization $\phi_i(p)$ for this object. The number of observations having polarization between p and $p + dp$ is thus given by $\phi_i(p)dp$. If we monitor all of the BLOs in the sky during the same time t and obtain, for each, the same number of observations N, we can construct the distribution

$$D(p)dp = \sum_{i=1}^{n} \phi_i(p)dp \ , \qquad \text{(A1)}$$

where n is the total number of BLOs in the sky. Clearly, the probability that a single measure of a BLO chosen at random in the sky be between p_1 and p_2 is given by

$$P = \int_{p_1}^{p_2} D(p)dp \bigg/ \int_0^{100\%} D(p)dp \,. \tag{A2}$$

If we observe a region of the sky containing n BLOs with an instrument having a detection threshold t, the number of BLOs detected is then given by

$$N = n \int_t^{100\%} D(p)dp \bigg/ \int_0^{100\%} D(p)dp \,. \tag{A3}$$

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