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OPTICAL AND RADIO PROPERTIES OF X-RAY SELECTED BL LACERTAE OBJECTS[1]

JOHN T. STOCKE,[2] JAMES LIEBERT, AND GARY SCHMIDT
Steward Observatory, University of Arizona

I. M. GIOIA,[2,3] T. MACCACARO,[2,3] AND R. E. SCHILD
Harvard-Smithsonian Center for Astrophysics

D. MACCAGNI
CNR, Istituto di Fisica Cosmica

AND

HALTON C. ARP
Mount Wilson and Las Campanas Observatories, Carnegi Institution of Washington
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ABSTRACT

The eight BL Lac objects from the *HEAO 1* A-2 all-sky survey and from the *Einstein* medium-sensitivity survey (MSS) form a flux-limited complete X-ray selected sample. The optical and radio properties of the MSS BL Lac objects are presented and compared with those of the *HEAO 1* A-2 sample and with those of radio-selected BL Lac objects. The X-ray selected BL Lac objects possess smaller polarized fractions and less violent optical variability than radio-selected BL Lac objects. These properties are consistent with the substantial starlight fraction seen in the optical spectra of a majority of these objects. This starlight allows a determination of definite redshifts for two of four MSS BL Lac objects and a probable redshift for a third. These redshifts are 0.2, 0.3, and 0.6.

Despite the differences in characteristics between the X-ray selected and radio-selected samples, we conclude that these eight objects possess most of the basic qualities of BL Lac objects and should be considered members of that class. Moreover, as a class, these X-ray selected objects have the largest ratio of X-ray to optical flux of any active galactic nuclei yet discovered.

Subject headings: BL Lacertae objects — galaxies: nuclei — X-rays: sources

I. INTRODUCTION

The largest complete sample of X-ray selected objects available to date is the *Einstein* medium-sensitivity survey (MSS) (Maccacaro *et al.* 1982; Stocke *et al.* 1983; Gioia *et al.* 1984), consisting of 112 sources, all of which have been optically identified. Five sources in the MSS have optical counterparts which share many of the characteristics typical of radio-selected BL Lac objects. Together with four objects detected at brighter X-ray fluxes by the "first-scan" of the *HEAO 1* A-2 all-sky survey (Piccinotti *et al.* 1982), they constitute a composite, complete, flux-limited sample of X-ray selected BL Lac objects.

A study of the number-flux and redshift distributions of these *X*-ray selected BL Lac objects has allowed Maccacaro *et al.* (1984; hereafter Paper I) to show that these objects do not evolve cosmologically, as do quasars. In this paper we present the optical, radio, and X-ray observations which led us to classify the four[4] in the MSS as BL Lac objects (§ II). In § III we evaluate the completeness of the MSS BL Lac sample which is necessary to the conclusions of Paper I. In § IV we critically examine the classification of these X-ray selected objects as BL Lac objects and compare their global spectral properties with those of other classes of active galactic nuclei (AGNs). In particular, we conclude that each of the four MSS objects exhibit enough of the defining properties of the BL Lac class to be so designated. Therefore, we hereafter refer to these four objects and to the four *HEAO 1* A-2 objects (for which the BL Lac nomenclature has already been widely used) as X-ray selected BL Lac objects (XBLs).

II. THE OBSERVATIONS

Table 1 lists the XBLs from the *HEAO 1* A-2 all-sky survey and from the *Einstein* MSS along with their basic properties. Detailed discussions of the *HEAO 1* A-2 XBLs may be found in the literature (e.g., Urry 1984) and will not be repeated here. Finding charts for the five MSS BL Lac objects can be found either in Stocke *et al.* (1983) or Gioia *et al.* (1984).

We have obtained optical spectroscopy, polarimetry, and photometry of the four MSS XBLs and multifrequency radio observations of all eight XBLs.

a) Optical Spectroscopy

The optical spectrum of 0317+186 (Fig. 1) was originally published as part of Figure 4 in Gioia *et al.* (1984) and is

[1] Research reported here used the Multiple Mirror Telescope Observatory (MMT), which is a joint facility operated by the Smithsonian Institution and the University of Arizona.

[2] Visiting Astronomer at the National Radio Astronomy Observatory (NRAO), which is operated by Associated Universities, Inc., under contract with the National Science Foundation (NSF).

[3] On leave of absence from Istituto di Radioastronomia, CNR, Bologna, Italy.

[4] The fifth BL Lac object identified in the MSS (1E0622.5−5256) is an X-ray variable source at $f_x = 2.3\text{–}6.8 \times 10^{-13}$ ergs cm^{-2} s^{-1} in the 0.3–3.5 keV band, too far south to allow the detailed investigation which we present herein for the other four. A spectrum of this object obtained at the Las Campanas 2.5 m DuPont Telescope at 5 Å resolution and covering 3600–6800 Å is featureless at a relatively low signal-to-noise (∼4:1). No polarimetry, photometry, or radio observations are available for this object. The exclusion of 1E0622.5−5256 from Paper I and from this paper does not alter the conclusions reached in either case.

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TABLE 1

Basic Properties of X-Ray Selected BL Lacertae Objects

Object Name	z	5 GHz Flux (mJy)[a] % Polarization	m_v	Optical Polarization Position Angle	X-Ray Flux 0.3–3.5 keV ($\times 10^{-13}$ ergs cm^{-2} s^{-1})	α_{ox} α_{ro}
1E0317.0+1835[b] .... (0317+186)	0.19[a,c]	11.5 <5%	18.22[a]	3.5% ± 0.7%[a] 150°–180°	88.5[c]	0.76 0.39
H0548−322[b] .... (PKS 0548−322)	0.069[e]	84.8 2.7%	15.50[f]	1.5%–2.0%[g] 0°–15°	454.7[h,i]	0.84 0.35
1E1207.9+3945[b] .... (1207+397)	0.59:[a]	6.1 <10%	19.12[a]	4.2% ± 1.3%[a] ...	14.9[j]	0.91 0.41
H1219+305[d] .... (2A1218+304)	~0.13[k]	41.9 <2.6%	16.31[l]	... ...	528.01[h,i]	0.75 0.35
1E1235.4+6325[b] .... (1235+632)	0.297[c,a]	7.0 <12%	18.59[a]	<3.6%[a] ...	17.8[c]	0.97 0.38
1E1402.3+0416[b] .... (1402+043)	?	20.8 <3%	17.08[a]	3.0%–6.0%[a] 100°–125°	11.5[j]	1.27 0.36
H1652+398[d] .... (Mrk 501)	0.034[m]	1293.0 1%	13.73[l]	2%–4%[g] 125°–145°	592.0[h,i]	1.12 0.44
H2154−304[d] .... (PKS 2155−304)	0.117[n]	341.0 1%	14.25[l]	3%–7%[g] 150°–170°	1520.0[h,i]	0.89 0.37

[a] This paper.
[b] Einstein medium-sensitivity survey.
[c] Gioia *et al.* 1984.
[d] *HEAO 1* A-2 all-sky survey.
[e] Fosbury and Disney 1976.
[f] Disney 1974.
[g] Angel and Stockman 1980.
[h] Piccinotti *et al.* 1982.
[i] Maccacaro *et al.* 1984.
[j] Maccacaro *et al.* 1982.
[k] Weistrop *et al.* 1981.
[l] Cruz-Gonzalez and Huchra 1984.
[m] Ulrich *et al.* 1975.
[n] Bowyer *et al.* 1984.

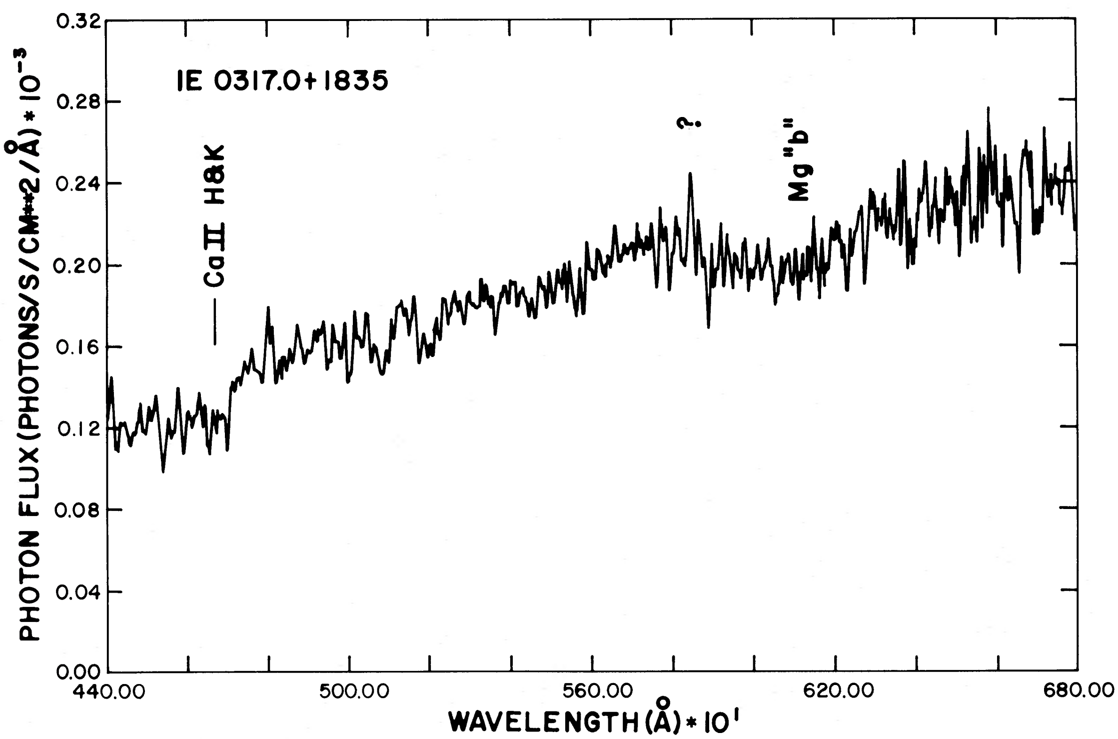

Fig. 1.—Optical spectrum of 0317+186. Ca II H and K and Mg *b* λ5176 absorption features appear at a redshift of 0.19.

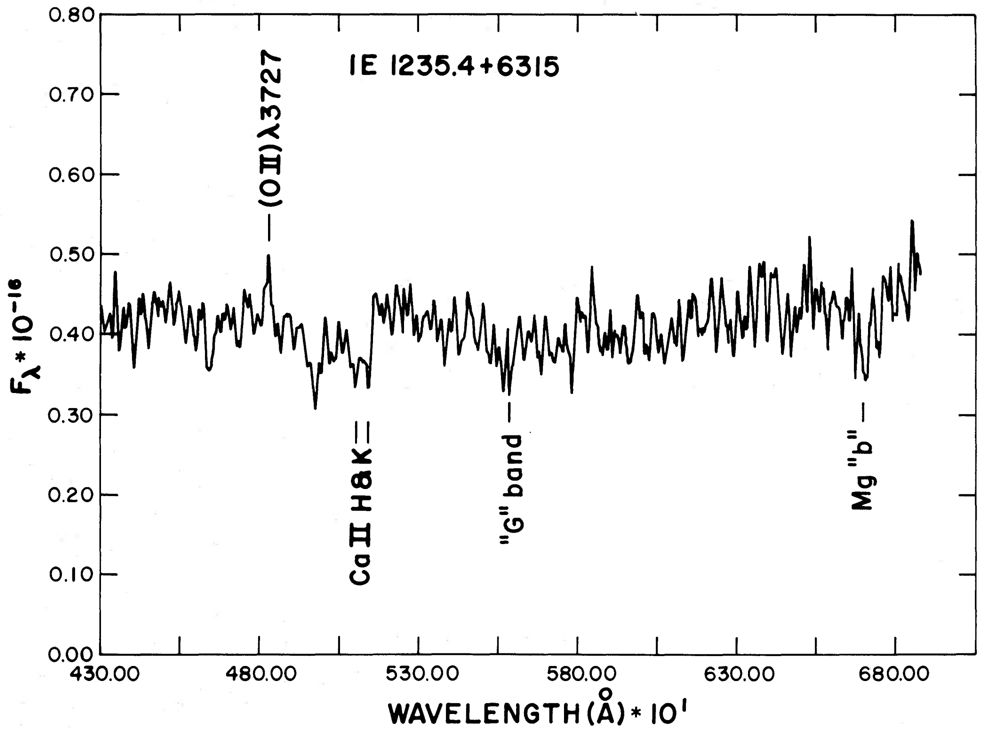

FIG. 2.—Optical spectrum of 1235 + 632. Weak but definite Ca II H and K and Mg *b* λ5176 absorption features are present at a redshift of 0.297.

similar to the spectrum of 1235 + 362 (Fig. 2) in showing weak but definite Ca II H and K absorption and Mg I *b* λ5176 absorption at moderate redshift ($z = 0.19$ and 0.297 for 0317 + 186 and 1235 + 632, respectively). The stellar absorption in these two objects is definitely weaker than in normal elliptical galaxies or in radio galaxies dominated by a thermal continuum (e.g., 3C 31 or 3C 465). No special setup (e.g., observing through an annulus, Oke and Gunn 1974; or at an offset from the nucleus) was used to obtain these spectra, as was necessary to obtain the first redshifts for radio-selected BL Lac objects (e.g., Ulrich *et al.* 1975). The observing apertures were 2".5 circular holes in both cases. Based upon the strength of the observed H and K break, we estimate that the percentage of the stellar contribution to these spectra is 30%–50%.

At a *V* magnitude of ~19 (see Table 2), 1207 + 397 is a much more difficult object in which to detect faint features, and we consider the redshift $z \approx 0.59$ indicated in Table 1 as probable but uncertain. Figure 3*a* shows the spectrum we obtained in ~5 hr of integration time through 1" circular apertures using the Multiple Mirror Telescope spectrograph. Blueward of 6000 Å, where the quantum efficiency of the detector is very good, the object exhibits a featureless $\nu^{-1.2\pm0.1}$ power law. To the red, there is some evidence of structure and a break to a redder continuum slope, albeit at lower signal-to-noise than in the blue. The two features which are marked with tentative identifications appear on both of the two longest individual observations used to construct Figure 3*a*. If at $z \approx 0.59$, Mg II λ2798 would be expected near 4450 Å in Figure 3*a*, and indeed there is a broad, shallow dip in the spectrum near that wavelength. We note that 1207 + 397 had been originally identified as a quasar with $z = 1.8$ (De Ruiter, Willis, and Arp 1977) on the basis of a multichannel scanner spectrum obtained at the Hale 5 m telescope on 1975 January 1 (Fig. 3*b*). If the redshift of the object were 1.8, Lyα would be present in our spectrum at 3400 Å and C IV at 4340 Å, while they obviously are not.

The sharp rise at the blue end of the multichannel spectrum, which was originally identified as Lyα, may be due to the use of a mean ultraviolet extinction to correct the near-UV flux points and thus may be spurious. Although variability could mask the presence of strong emission lines in the more recent MMT spectrum, the indicated *R* magnitude in Figure 3*b* is within a few tenths of a magnitude of the more recent brightness of 1207 + 397 shown in Table 2, and so variability is unlikely to account for the absence of emission lines in Figure 3*a*. However, Figure 3*b* does show a dramatic break in spectral slope at 6200–6500 Å, near the wavelength of the proposed H and K feature in Figure 3*a*. Although these two spectra present

TABLE 2

PHOTOMETRY OF X-RAY SELECTED BL LACERTAE OBJECTS

Object	Date	*R*	(*V* − *R*)	(*B* − *V*)
0317 + 186......	1982 Nov 22	17.47 ± 0.02	0.75 + 0.05	...
	1984 Mar 28	17.38 ± 0.10	...	...
1207 + 397......	1982 May 21	18.97 ± 0.05	0.03	...
	1983 May 9	19.32 ± 0.05	0.09	...
	1983 May 17	19.33 ± 0.05	0.15	...
	1984 Mar 29	18.85 ± 0.05	...	...
1235 + 632......	1982 May 23	18.46 ± 0.03	...	...
	1982 Nov 22	18.32 ± 0.03	1.02 ± 0.05	0.55 ± 0.10
	1982 Feb 16	18.62 ± 0.03	...	...
	1983 May 13	19.02 ± 0.03	1.05 ± 0.05	0.46 ± 0.10
	1984 Mar 28	18.65 ± 0.03	...	...
	1984 Mar 29	18.47 ± 0.03	...	...
1402 + 043......	1982 May 21	16.34 ± 0.05	0.25	0.32
	1983 Feb 16	16.94 ± 0.05	0.17	0.38
	1983 May 11	17.36 ± 0.05	0.19	0.54
	1984 Mar 28	16.52 ± 0.05	...	...
	1984 Mar 29	16.47 ± 0.05	...	...

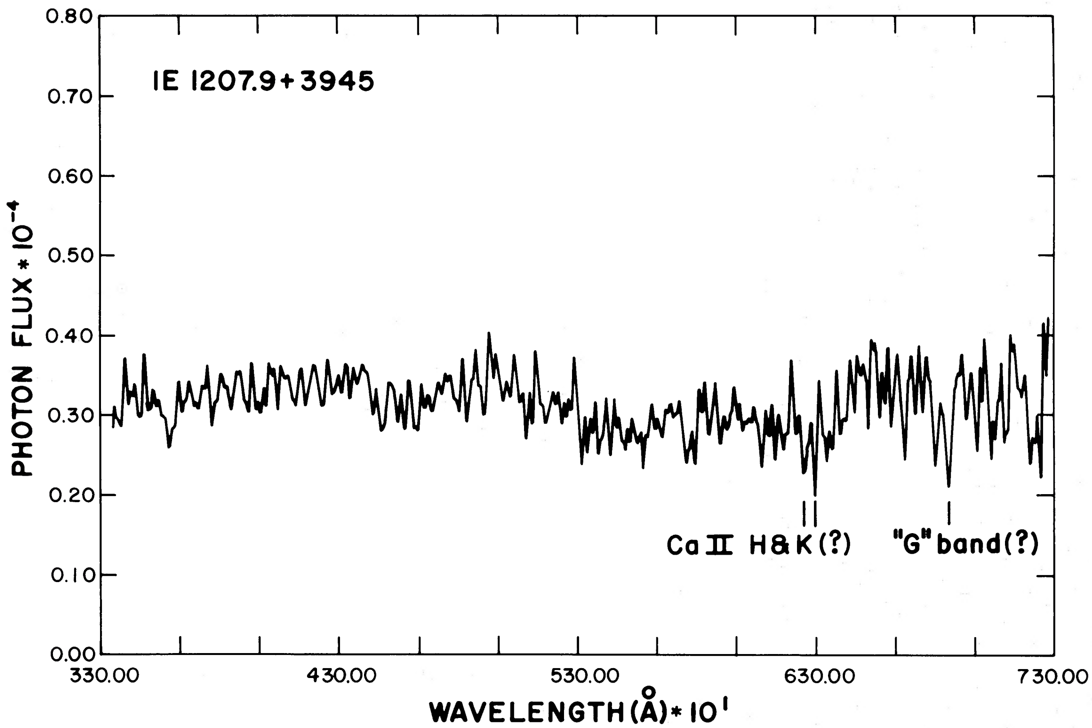

FIG. 3*a*.—Spectrum of 1207+397 obtained in 5 hr of integration time with the MMT spectrograph. The spectrum is featureless blueward of 6000 Å and shows probable Ca II H and K absorption at $z = 0.59$.

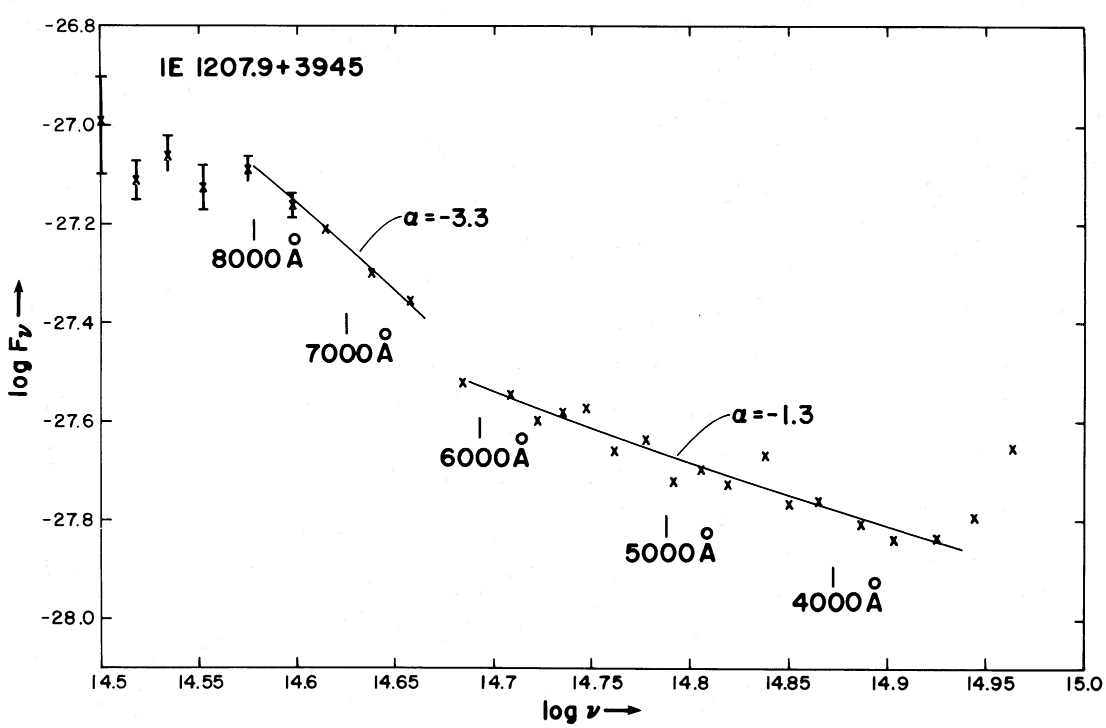

FIG. 3*b*.—Multichannel scanner observation of 1207+397 obtained by one of us (H. C. A.) on the Hale 5 m telescope in 1975 January. Spectral slopes indicated are fits by eye to data in blue and red portions of the spectrum.

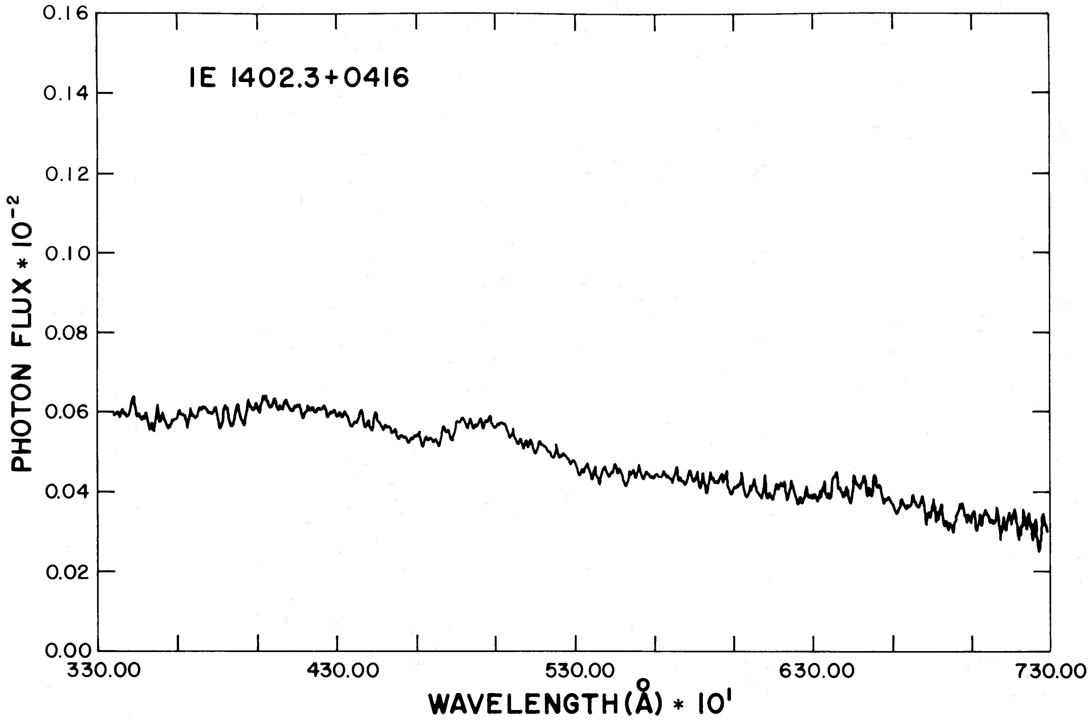

FIG. 4.—Spectrum of 1402+043 obtained in 2 hr of integration time with the intensified Reticon spectrograph on the Steward 2.3 m telescope. Only a single weak, broad feature near 4900 Å is visible.

a consistent redshift, better red data are needed at moderate resolution to confirm these observations.

Figure 4 is a result of 2 hr of integration through 2″.5 circular apertures on 1402+043 with the Steward 2.3 m telescope plus intensified Reticon spectrograph. The spectrum contains only a single weak, broad feature near 4900 Å, for which there is no clear identification. If the weak features at the blue edge of the broad "hump" near 4900 Å are attributed to Ca II H and K, then $z \approx 0.20$, but no corroborating features for this redshift are present. If this broad hump is Mg II $\lambda 2798$ in weak emission, then $z \approx 0.75$, consistent with the stellar appearance of this object on CCD images (see § II*c*). Thus the spectroscopy of 1402+043 does not yield a reliable redshift, and moreover shows no obvious signs of an underlying galaxy component.

From the spectroscopic point of view, these sources are similar to radio-selected BL Lac objects in that they do not show strong emission lines in their spectra. However, all but 1402+043 also show evidence for a large starlight component; in this way they differ from radio selected BL Lac objects where galaxy contributions appear only in very low redshift objects (Cruz-Gonzalez and Huchra 1984).

b) Optical Polarimetry

One other defining feature of BL Lac objects is strong and variable polarization (Angel and Stockman 1980). A journal of optical polarization measurements of the MSS XBLs is shown in Table 3. With the exception of the observation of 1207+397, all the polarimetry was obtained with dual channel photon-counting polarimeters on the Steward 2.3 m telescope. The polarimetry of the very faint object 1207+397 was obtained by H. Roser with a Savart plate in front of a CCD on the Steward 2.3 m telescope (see Roser, 1981, for a description of this

TABLE 3

OPTICAL POLARIMETRY OBSERVING LOG

Object	UT Date	Spectral Region	*P* (%)	P.A.
1E0317+186.......	1982 Sep 22	3200–8600 Å	4.8+/−1.7	12+/−10
	1982 Dec 12	3200–8600 Å	2.8+/−0.9	171+/−10
	1982 Dec 13	3200–8600 Å	4.3+/−1.2	179+/−8
	1982 Dec 8	3200–8600 Å	2.5+/−0.4	175+/−5
	1984 Oct 3	3200–8600 Å	6.4+/−0.4	152+/−2
1E1207+397.......	1984 Mar 2	4000–5000 Å	4.2+/−1.3	...
1E1235+632.......	1982 Dec 15	3200–8600 Å	2.5+/−0.8	138+/−9
	1983 Dec 7	3200–8600 Å	2.4+/−1.2	153+/−13
1E1402+043[a]......	1981 Apr 14	6300–8600 Å	5.5+/−1.0	104+/−5
	1981 June 7	3200–8600 Å	2.8+/−0.5	119+/−5

[a] Reported in Stocke *et al.* 1982.

observing technique). From Table 3 it is clear that while all but one of these objects is significantly polarized, none exhibit the high degree of polarization which characterizes typical radio-selected BL Lac objects. In addition, variability appears either reduced or absent altogether. In these respects, the four MSS XBLs resemble the *HEAO 1* A-2 XBLs (see Table 1) and other BL Lac objects of low luminosity (e.g., Mrk 421 or AP Lib).

c) Optical Imaging and Photometry

The photometric observations were typically made in 10 minute CCD exposures through B, V, and R filters on the 61 cm reflector of the Whipple Observatory. A description of the filter and detector system can be found in Schild and Kent (1981). Tables 2 and 4 give the photometry results for the four MSS XBLs and for their field standards, respectively. No reddening corrections were applied to the data. When no direct error estimates could be determined from repeated observations, the probable error of each measurement is 0.05 mag.

Of the four MSS XBLs, 0317+186 is the most highly resolved on our CCD images compared to nearby field stars. We show photometry for three field stars in Table 4. Because we have multicolor photometry from a single night only, these colors are unconfirmed and have an error which we estimate as 0.05 mag. The second observation at R made 1.3 yr after the original data set does not show a significant variation. A reproduction of a 30 m CCD data frame of 0317+186 is shown in Figure 5 (Plate 8). Clearly, the XBL is not in a rich cluster, although several galaxies of comparable brightness and many fainter galaxies are found.

Our CCD images do not resolve 1207+397 ($<1''$), consistent with its large distance as proposed from the spectroscopy. This object is variable in brightness, showing 0.5 mag fluctuations in the 1.8 yr interval summarized in Table 2. A finding chart to identify the field standards of Table 4 is presented as Figure 6 (Plate 8). Numerous faint sources are seen in Figure 6, but at a redshift for this XBL of $z = 0.59$ only very bright companion galaxies ($M_v \leq -23$) could have been detected in our CCD frame.

For 1235+632 we list magnitudes and colors for three field comparison stars in Table 4 and present an identification chart in Figure 7 (Plate 9). This XBL appears to be in a field of many faint galaxies, and it is possible that the source is in a poor cluster. No redshifts for the faint galaxies are yet available, however. The CCD image of the XBL appears resolved as a bright stellar object surrounded by faint fuzz. Our photometry reveals that the source is variable, with brightness extremes differing by 0.7 mag over the interval of 1.9 yr. Of particular interest is our observation that the optical source varied by 0.18 ± 0.04 mag in one day.

The final MSS XBL, 1402+043, showed the largest brightness fluctuations in our 1.9 yr of monitoring. Between 1982 May 21 and 1983 May 11, the source faded 1.02 mag. The source appears stellar on our best images, taken with the 61 cm telescope in $1''$ seeing, as well as on an R band CCD frame taken at the Steward 2.3 m. This suggests a large distance for this object $z > 0.5$ based upon the previously measured galaxy absolute magnitudes for well-resolved BL Lac objects (Miller, French, and Hawley 1978*a*). A deep, co-added frame of the field is shown in Figure 8 (Plate 9).

TABLE 4

PHOTOMETRY FOR FIELD STANDARDS NEAR X-RAY SELECTED BL LACERTAE OBJECTS

A.

Star	R	$(V-R)$	$(B-V)$
	0317+186 Field		
B	16.75 ± 0.02	0.59 ± 0.05	0.84 ± 0.05
C	15.49 ± 0.02	0.75 ± 0.05	0.92 ± 0.05
D	15.52 ± 0.02	0.57 ± 0.05	0.73 ± 0.05
	1207+397 Field		
B	17.17 ± 0.03	0.34 ± 0.03	...
C	15.92 ± 0.03	1.05 ± 0.03	...
D	15.12 ± 0.03	0.46 ± 0.03	...

B.

Star	V	$(V-R)$	$(B-V)$
	1235+632 Field		
A	13.02 ± 0.02	0.51 ± 0.05	0.56 ± 0.05
B	14.60 ± 0.02	0.68 ± 0.05	0.83 ± 0.05
C	15.01 ± 0.02	0.92 ± 0.05	1.12 ± 0.05
	1402+043 Field		
A	15.07 ± 0.02	0.61 ± 0.03	0.86 ± 0.10
B	14.82 ± 0.02	0.54 ± 0.03	0.66 ± 0.10
C	17.03 ± 0.02	0.54 ± 0.03	0.77 ± 0.10

d) Radio Observations

All eight XBLs listed in Table 1 were observed at all the available wavelengths (20, 18, 6, 2.0, and 1.3 cm) with the NRAO Very Large Array on 1984 June 26 and 29. The array was in the C/D hybrid configuration with an average of 26 antennas operating. Baselines range from 0.1 to 2.1 km. The HPBWs are $\sim 34'' \times 13''$ at 20 and 18 cm, $9'' \times 4''$ at 6 cm, $3'' \times 1''$ at 2 cm, and $2''.5 \times 1''$ at 1.3. Each object was observed for $\sim$30–90 minutes, and their flux densities are bootstrapped from 3C 48 or 3C 286 (H2154−304 only). In a few cases, self-calibration was used to adjust antenna phases. The noise for each map was determined from the rms fluctuations in areas free of radio emission and ranges from 0.2 mJy at 6 cm to 2 mJy at 1.3 cm. Flux densities for the sources are given in Table 5, together with their associated rms errors. The results of these observations are summarized in Figure 9.

The single-epoch spectral indices for these eight XBLs range from 0.0 (Mrk 501) to 0.9 (1207+397 and 0548−322), with only these latter two sources exhibiting spectral slopes outside the usual range seen for radio-selected BL Lac objects (Stein, O'Dell, and Strittmatter 1976). A marked flattening and probably inverted spectrum between 2 and 1.3 cm is evident for 0548−322, but 1207+397 was too weak to be detected at 1.3 cm, and thus we were unable to determine whether or not this source also flattens at high frequencies.

Due to the compactness of these sources, the 6 cm data for the four MSS XBLs are directly comparable with similar measurements made in 1980 October by Fiegelson, Maccacaro, and Zamorani (1982) and in 1982 November by Gioia *et al.* (1983) using the VLA C-configuration. The object 1235+632 has shown a decrease in flux of a factor of 2, and 0317+186 probably also decreased by $\sim$30% in 1.5 yr time. The current data on the *HEAO 1* A-2 XBLs can only be compared with previously published data (e.g., the collections of radio data presented in Angel and Stockman 1980 and Cruz-Gonzalez and Huchra 1984). A 25% increase is likely for 2155−304, with

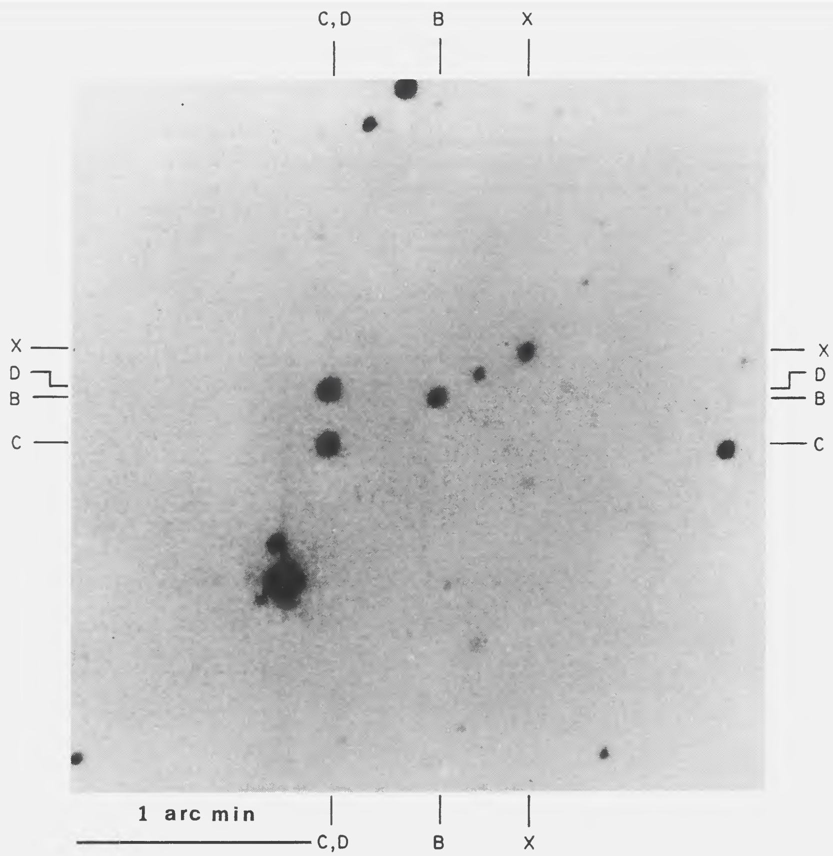

FIG. 5

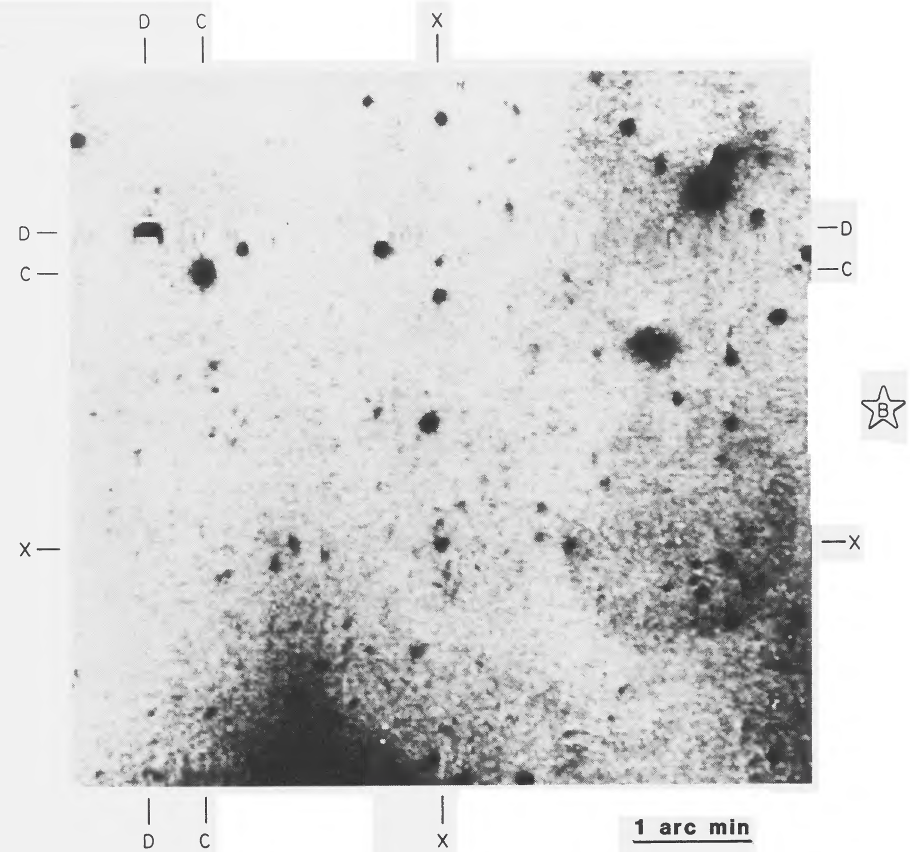

FIG. 6

FIG. 5.—Red CCD frame of the field of 0317 + 186 (indicated by an X) obtained with a 30 minute exposure on the 61 cm reflector of Whipple Observatory. Field standard stars B, C, and D are indicated.
FIG. 6.—Field of 1207 + 397 resulting from 50 minutes of co-added CCD red data taken on the 61 cm reflector of Whipple Observatory. Field standard stars C and D are indicated.

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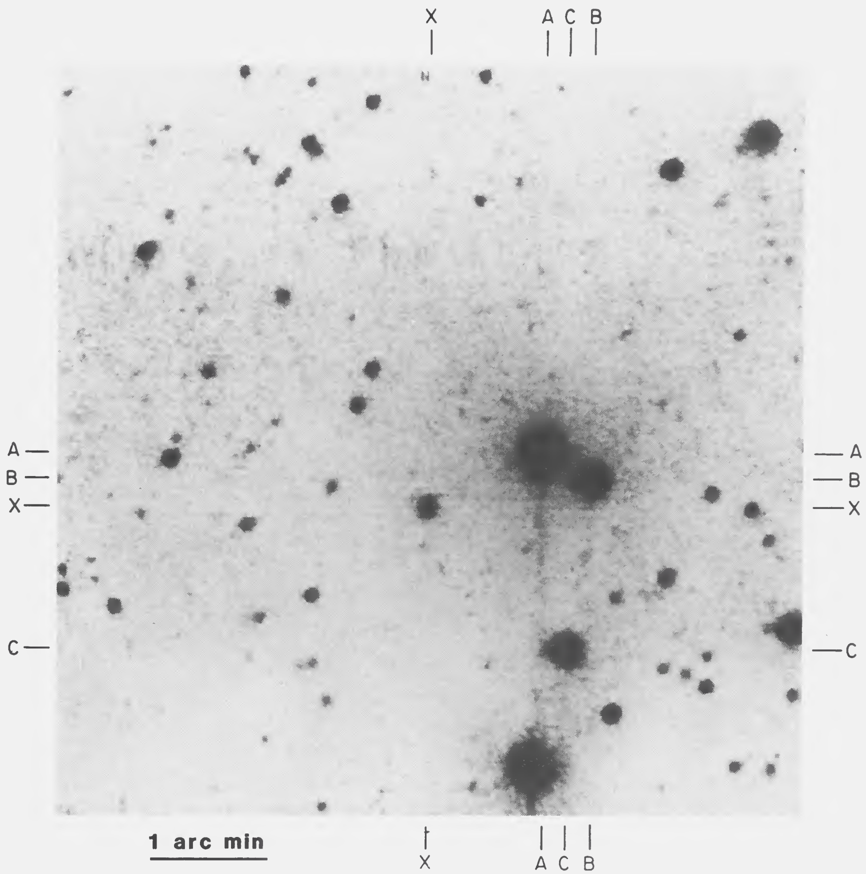

FIG. 7

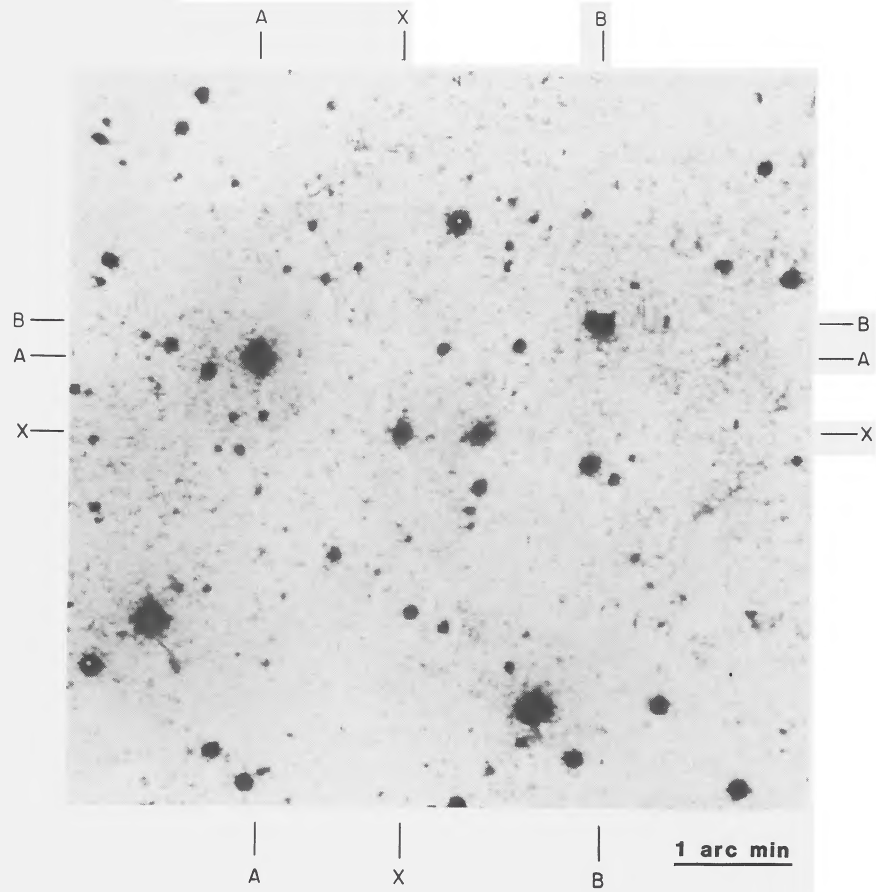

FIG. 8

FIG. 7.—Field of 1235+632 resulting from 50 minutes of co-added CCD red data taken on the 61 cm reflector of Whipple Observatory. Field standard stars A, B, C are indicated. Note faint fuzz surrounding star-like BL Lac object.

FIG. 8.—Field of 1402+043 resulting from 50 minutes of co-added CCD red data taken on the 61 cm reflector of the Whipple Observatory. Field standard stars A and B are indicated. Standard star C is 44″ west of X.

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TABLE 5

RADIO FLUXES (mJy) OF THE X-RAY SELECTED BL LACERTAE OBJECTS

	RADIO FLUX				
SOURCE	20 cm	18 cm	6 cm	2 cm	1.3 cm
0317+186......	17.3 ±0.6	16.5 ±0.8	11.5 ±0.23	5.5 ±0.3	<4.5
0548−322......	269.0 ±1.5	259.0 ±1.5	84.8 ±1.1	37.4 ±0.4	53.3 ±2.4
1207+397......	15.1 ±1.1	18.3 ±1.3	6.1 ±0.4	0.9 ±0.3	<4.2
1219+305......	51.1 ±0.9	56.6 ±1.1	41.9 ±0.7	37.0 ±0.6	50.0 ±2.0
1235+632......	10.7 ±0.5	10.1 ±0.5	7.0 ±0.38	4.6 ±0.3	Not Observed
1402+043......	35.5 ±1.3	38.2 ±1.4	20.8 ±0.4	14.5 ±0.3	8.7 ±1.4
1652+398......	1408.0 ±2.0	1434.0 ±1.8	1293.0 ±2.0	1077.0 ±0.6	1203.0 ±2.3
2155−304......	375.0 ±2.0	370.0 ±2.2	341.0 ±0.6	249.0 ±1.3	166.0 ±2.0

no spectral change between 20 and 2 cm, while 0548−322 shows variations by at least a factor of 2 at 6 cm.

Finally, low-level polarized flux at 6 cm has been detected only for the three strongest sources in our sample, namely 1652+398 ($1.0 \pm 0.05\%$), 2155−304 ($1.0 \pm 0.04\%$), and 0548−322 ($2.7 \pm 0.3\%$). This degree of polarization could not have been detected in the other weaker objects.

e) X-Ray Observations

A meaningful spectral analysis of the MSS XBLs in X-rays is unfortunately prevented by (1) the limited number of counts (<450) at which each was detected, and (2) the fact that these objects were detected well off the axis of the imaging proportional counter (IPC), and thus in regions which have not been accurately mapped for spatial gain variations.

One of the objects, 1207+397, is found in a field observed twice by the *Einstein Observatory*: on 1979 May 18–20 and 1979 December 12–13. The second observation, though shorter (6900 s), was the one used in the MSS because of its better IPC gain history. The counting rate of 1207+397 was $(3.62 \pm 0.24) \times 10^{-2}$ counts s^{-1} on this occasion, while in the May observation (19928 s), the counting rate was $(4.39 \pm 0.15) \times 10^{-2}$ counts s^{-1}. This 20% decrease in counting rate over 7 months has a statistical significance of only 2.7 σ, which, coupled with the strong gain variations the IPC underwent during the May observation, prevents us from concluding that variations occurred in the X-ray flux of 1207+395.

Two of the XBLs (1207+397 and 1402+043) were detected by the *Einstein* high resolution imager (HRI) limiting their spatial extent to less than 6″.

III. THE COMPLETENESS OF THE MSS BL LACERTAE SAMPLE

Because Paper I demonstrated that a deficiency of XBLs exists at faint X-ray fluxes, reclassifying any of the four MSS XBLs discussed here can only strengthen that conclusion. We therefore also need to ask whether any XBLs have been misclassified as something else in the MSS, since the addition of a

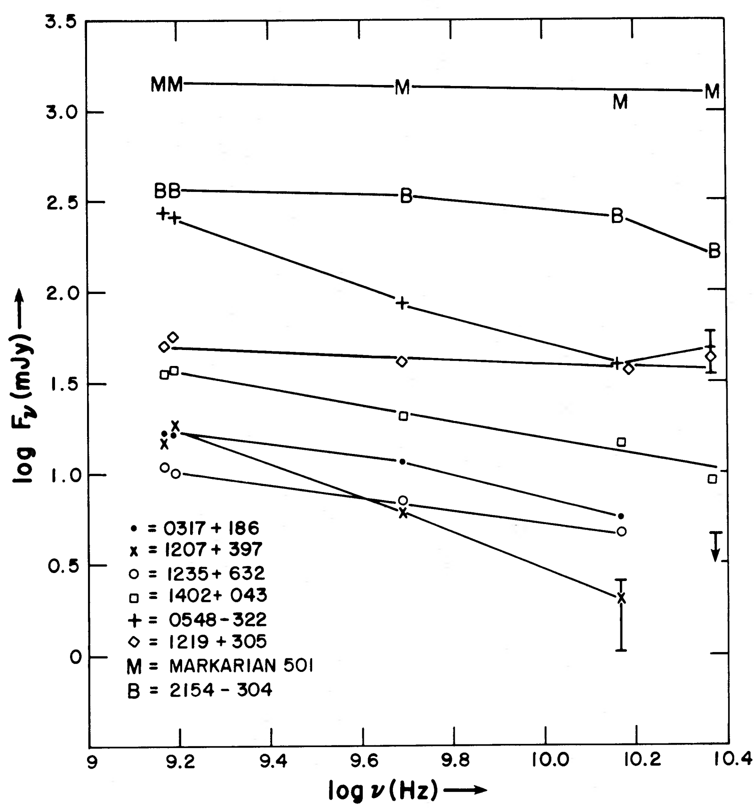

FIG. 9.—Radio spectra of the eight X-ray selected BL Lac objects obtained with VLA C/D hybrid configuration of 1984 June 26 and 29. Errors and upper limits shown in Table 5 have been omitted to avoid confusion. Note large span in flux densities and the rather steep spectral shapes of 0548−322 and 1207+397.

few X-ray faint XBLs to the MSS sample could indeed alter the conclusions in Paper I.

a) The AGNs

Most of the objects classified as AGNs (Seyferts and QSOs) in the MSS possess strong, broad emission lines and are quite blue in color (see Fig. 5 in Gioia *et al.* 1984). The optical spectra of the AGNs with the weakest emission lines and reddest colors are shown in Figure 7 of Stocke *et al.* (1983) and Figure 4 of Gioia *et al.* (1984). In most cases, the red colors of these AGNs ($B-V > 0.8$) are almost certainly due to a substantial starlight contamination, given the presence of stellar absorption lines optically (Fig. 4, Gioia *et al.* 1984) and reddened stellar colors in the near IR (Elston, Rieke, and Lebofsky 1985). There are only three AGNs whose emission lines are weak enough that they could be considered BL Lac candidates: 1E0038.7+3251 ($z = 0.225$), 1E0112.9−0147 ($z = 0.284$), and 1E2204.0−4059 ($z = 0.231$). The former two possess stellar colors ($B-V \approx 1.0$–1.1; $V-R = 0.7$–1.1) and Hβ/[O III] ratios similar to H II regions. Neither are detected as radio sources at 6 cm (Gioia *et al.* 1983), although neither radio upper limit is sufficiently low to clearly separate these two objects from the four MSS XBLs. The AGN 1E2204.0−4059 has not yet been observed in the radio and is especially intriguing given its extremely low α_{0x} (0.89, albeit using an estimated magnitude from the ESO "quick blue" survey plate) and unusual optical spectrum with only strong [O III] emission on top of a weak, blue, featureless continuum (see Fig. 7 in Stocke *et al.* 1983). Even though the optical spectra of the other two AGNs seem to rule them out as BL Lac objects, 1E2204.0−4059 is certainly a candidate optically violent variable quasar or BL Lac object, and requires radio continuum and optical polarization measurements.

b) Clusters of Galaxies

It may also be possible that we have misclassified some sources as clusters of galaxies which actually contain an XBL as a cluster member. After all, at least one BL Lac object appears to be at the center of a rich cluster of galaxies (3C 66A; Butcher *et al.* 1976). Eighteen clusters have been detected in the MSS, one-third of which are resolved X-ray sources. Thus the remaining 12 clusters cannot be proven to be due to diffuse emission from the X-ray data alone. However, good quality optical spectra exist for the dominant cluster galaxies, and in all but one case (1E1220.0+7542) these galaxies possess Ca II H and K "breaks" which reduce the continuum flux by greater than 50%, leaving little possibility for a substantial nonthermal continuum. The continuum break in 1E1220.0+7542 is 30%–40% deep, but the spectrum also contains strong [O II] and moderate [O III] emission, similar to, but somewhat weaker than, 1E0112.0−0147. So although the evidence is somewhat circumstantial, we can see no compelling reason to believe that any of these clusters have been misclassified, but without higher resolution X-ray observations some uncertainty must remain.

It is worth noting that even though the MSS detects clusters out to $z \approx 0.4$, this redshift is still modest for AGNs and BL Lac objects. Thus, if XBLs are hiding as cluster members, they are at low redshift and luminosity and, even if present in small numbers, would not contradict the conclusions of Paper I.

c) Confused Sources

Could XBLs be hiding in X-ray fields assigned to other classes of optical counterparts? Optical identifications were largely based upon finding an object in the error circle belonging to a class of objects detected in X-rays at similar f_x/f_v ratios. Given the typical flux limits for the IPC frames used in the MSS, this requires that stars have $m_v \leq 15$ and quasars $m_v \leq 20$. However, given their extreme f_x/f_v values, XBLs could be as faint as $m_v = 23$. If many of the X-ray sources observed were faint XBLs, clearly there would be quite a few "blank field" sources which we were unable to identify. However, there are no "blank fields" in the MSS, and it would be extremely unlikely ($\ll 1\%$; Gioia *et al.* 1983) to have both a faint XBL and another optical object with an f_x/f_v ratio to make it a plausible optical counterpart in the same IPC error circle.

Based upon the above discussion, the most extreme revision to the log N–log S for XBLs presented in Paper I would be to include both the possible XBL 1E0622.5−4256, mentioned in the footnote in the introduction, and the highly unusual object 1E2204.0–4059 as additional MSS XBLs. The possible inclusion of these two objects does not alter the conclusions of Paper I, especially since both are detected at quite bright X-ray fluxes (6.8×10^{-13} and 1.2×10^{-12} ergs s^{-1} cm^{-2}, respectively).

IV. DISCUSSION

a) The Question of Classification

We are classifying these four X-ray sources as XBLs, and we have used their properties to suggest that the cosmological evolution of BL Lac objects differs decidedly from that of quasars (Paper I). Here we demonstrate that this classification is appropriate for these four objects.

Traditionally, BL Lac objects have been discovered as flat-spectrum, highly variable radio sources. The optical spectra of the counterparts to these sources were found to be featureless, polarized, and variable in total and polarized light. These spectra are also typically very red, sometimes with spectral indices greater than three, leading to their detection as strong infrared sources (however, a few blue BL Lac objects have been found; e.g., Mrk 421 and Mrk 501). At high-signal-to-noise, or in spectra obtained through an annulus or offset from the nucleus, weak absorption or emission features are often seen. Photometry of the "fuzz" surrounding BL Lac objects in conjunction with spectroscopy has led to the general conclusion that BL Lac objects inhabit giant elliptical galaxies (Miller, French, and Hawley 1978*b*). *Einstein* observations (Schwartz and Ku 1983; Maccagni and Tarenghi 1981) found that X-ray emission is a common feature, and indeed most BL Lac objects have now been detected in the X-ray band.

Two Markarian objects (421 and 501) were among the first non–radio-selected BL Lac objects, and presented somewhat different properties than their radio-selected counterparts. Both objects are clearly the nuclei of giant elliptical galaxies (Ulrich 1978), both possess a smaller fraction of polarized light, and exhibit a lower degree of variability than other BL Lac objects. However, they are among the strongest X-ray emitters of their class (Piccinotti *et al.* 1982).

The MSS XBLs in Table 1 all have properties similar to these two Markarian objects. In particular, the optical polarizations of the four MSS XBLs are quite low, but still consistent with being similar to Mrk 421 and Mrk 501. In fact, most of the unusual properties of the MSS XBLs (low polarization, absence of violent variability, and increased starlight fraction as seen in the optical spectrum) can be reproduced by an object of the Mrk 421 or Mrk 501 type at a large enough distance that the observing aperture admits a much larger fraction of starlight contamination.

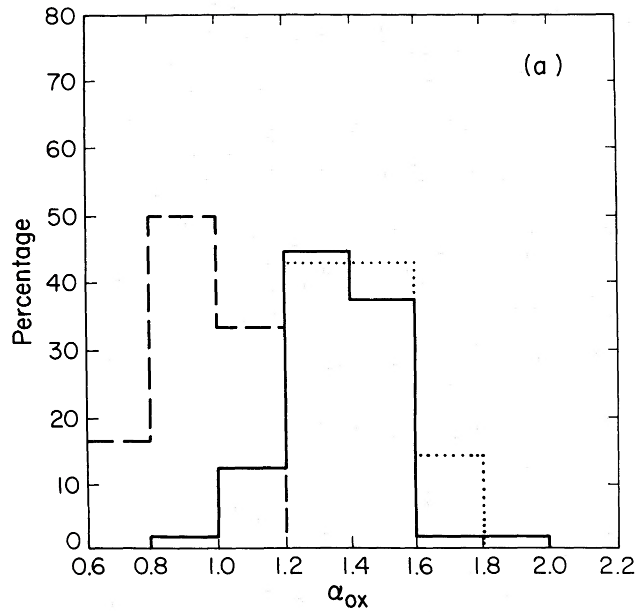

FIG. 10*a*

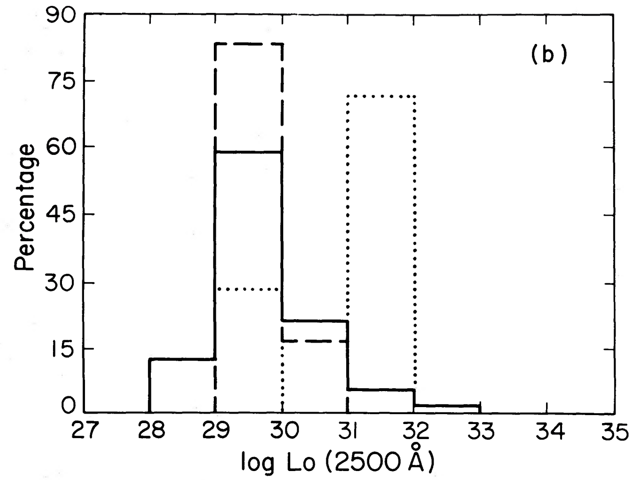

FIG. 10*b*

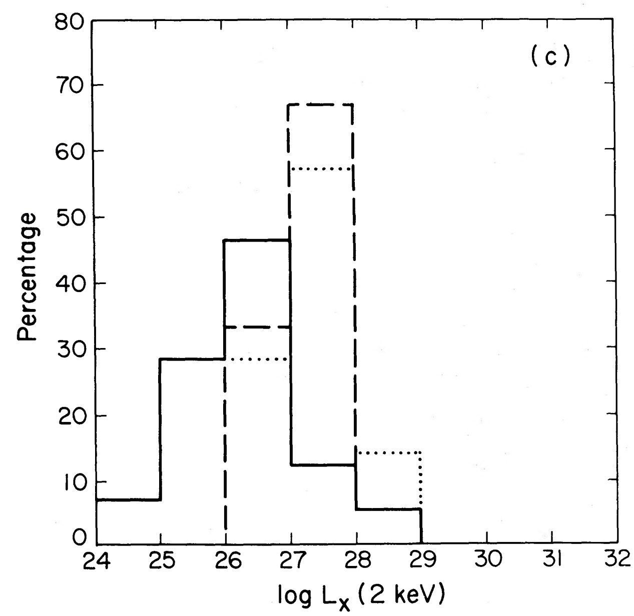

FIG. 10*c*

FIG. 10.—(*a*) The α_{ox} distribution, (*b*) monochromatic (2500 Å) optical luminosity distribution, and (*c*) monochromatic (2 keV) X-ray luminosity distribution for X-ray selected BL Lac objects (*dashed line*), X-ray selected MSS AGNs (*solid line*) and a subset of radio-selected BL Lac objects (*dotted*).

Moreover, each of these four X-ray sources possess at least some of the qualities found in radio-selected BL Lac objects:

1. All but one (1207+397) is a flat-spectrum radio source. Two of these sources (1235+632 and 0317+186) show definite variability from only two epochs of observation.

2. All but one source (1235+632) is optically polarized, although the polarization measurement of 1207+379 is significant only at the 3 σ level. The other two sources exhibit variable optical polarization.

3. Only 1402+043 possesses a featureless optical spectrum, although in all three other cases the stellar absorptions are much weaker than in typical giant elliptical galaxies.

4. All but one source (0317+186) is optically variable at or above the 0.5 mag level.

In summary, 1207+397 and 1235+632 are the sources for which the BL Lac classification is the most uncertain. The nondetection of optical polarization in 1235+632 is particularly unusual for BL Lac objects, and this X-ray source could well be a diffuse source in a distant cluster of galaxies (see Fig. 7). For 1207+397 a diffuse source is apparently ruled out by the HRI detection centered on the optical counterpart (Stocke *et al.* 1983). Moreover, the optical variability of 1207+397, radio and optical variability of 1235+632, and the presence of a nonthermal power law in the optical spectra of both objects argue for their inclusion among BL Lac objects.

b) Comparison of XBLs to Other Classes of AGNs

To assess the nature of the XBLs, we have compared some of their global properties with those of a subset of radio-selected BL Lac objects and with those of X-ray selected AGNs in the MSS. In Figure 10 the distributions of α_{ox} (as defined in Tananbaum *et al.* 1979), monochromatic optical luminosity,[5] and monochromatic X-ray luminosity of the three classes of objects are shown. The XBLs are characterized by lower α_{ox} indices, and while they have X-ray luminosities similar to radio-selected BL Lac objects, their optical luminosities are lower, and thus comparable to the optical luminosities of X-ray selected AGNs. The number of objects involved in this analysis is small and, furthermore, radio-selected BL Lac objects are highly variable objects at X-ray, optical, and radio wavelengths. Both these factors might modify this conclusion, which should therefore be considered as tentative until larger samples can be obtained. However, this conclusion is consistent with the large starlight fraction seen in several of the XBLs.

[5] The optical flux of the XBLs has not been corrected for starlight contamination in either Figs. 10 or 11. Thus α_{ox} and the optical nonthermal luminosity has been somewhat overestimated for these objects. No other class plotted is so affected.

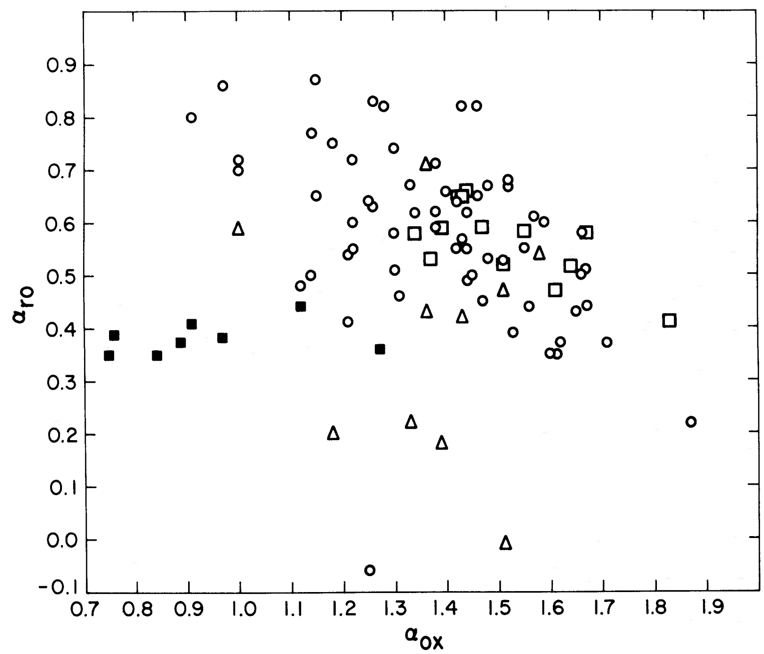

FIG. 11.—$\alpha_{ro} - \alpha_{ox}$ plot for X-ray selected BL Lac objects (*filled squares*), a subset of radio-selected BL Lac objects (*open squares*), the MSS X-ray selected AGNs (*triangles*), and the QSOs found in Zamorani *et al.* (1981) (*open circles*). Radio-quiet QSOs and AGNs fall in bottom right part of the plot. Note that X-ray selected BL Lac objects are all clustered around a α_{ro} value of 0.4 and that six out of eight have a α_{ox} value < 1.0. The two objects with $\alpha_{ox} > 1.0$ are Mrk 501 and 1402+043.

There is another indication that XBLs have peculiar global properties. Figure 11 shows a plot of α_{ro} versus α_{ox} for XBLs, radio-selected BL Lac objects, X-ray selected AGNs, and the QSOs observed by *Einstein*. The radio-to-optical spectral index is defined as $\alpha_{ro} = \log (S_{5\,\text{GHz}}/S_{2500\,\text{Å}})/5.38$. The XBLs occupy a specific and separate region of the $\alpha_{ro} - \alpha_{ox}$ plane. With respect to their optical emission, they are weak radio sources but strong X-ray sources with a very small dispersion in α_{ro}. No radio-quiet QSO or X-ray selected AGN has such a high ratio of X-ray to optical flux. Furthermore, radio-selected BL Lac objects populate the same region as radio-loud quasars. If this peculiarity shown by XBLs was only a selection effect, we would expect to find other X-ray selected AGNs in the low α_{ox} region. Instead, the same X-ray selection yields two classes of objects: at the lower end of the X-ray luminosity distribution we find AGNs, at the higher end we find the lineless objects which we identify as the XBLs.

If other investigators disagree with our classification of these objects as XBLs, as discussed in § IV*a*, then these objects constitute a new class of AGNs, clearly shown in Figure 11. This class is distinguished by extremely strong X-ray emission, but only modest radio emission and an absence of strong optical emission lines. So if these are not BL Lac objects, perhaps they are best called "X-ray galaxies."

Chanan *et al.* (1982) have previously presented two BL Lac candidates, which these authors suggest are the first examples of a class of radio-quiet BL Lac objects. The BL Lac candidate 1704+6077 has α_{ro} and α_{ox} values similar to the values shown in Table 1. And although the α_{ro} for candidate 1408+020 is somewhat lower than the XBLs in the present sample, this object has also not yet been confirmed either as an XBL or as the correct X-ray counterpart. In particular, optical polarization measurements, deep optical imaging to search for the presence of a cluster, and better quality optical spectra are required. Otherwise, there is no strong evidence that these two objects constitute a new class of objects distinct from Mrk 421, Mrk 501, or other XBLs.

c) Selection Effects in Comparing Radio and X-Ray Selected BL Lacertae Objects

It is worth noting that the sample of radio-selected BL Lac objects in Figure 11 or any radio-selected sample may be incomplete for the following reasons:

1. Even in samples for which optical identifications exist for virtually all the radio sources (e.g., Bonn S-5, Kühr 1980; 1 Jy catalog, Kühr *et al.* 1981), BL Lac candidates are chosen spectroscopically on the basis of featureless optical spectra or the presence of only extremely weak emission lines. In a sample of 36 objects chosen from the above two samples in this manner, 31 were observed polarimetrically, with 18 definite BL Lac objects detected ($P > 6\%$; Schmidt 1985), in marked contrast to the XBLs observed here. But how many additional radio sources in these samples beyond those 36 possess optical spectra similar to the XBLs shown in Figures 1–4 (i.e., starlight diluted with a nonthermal power law, and thus classified as radio galaxies) and were, therefore, not chosen for polarimetry observations? Clearly, our comparison of XBL properties to those radio-selected BL Lac objects (see § IV*a*) suffers from any selection criteria used to identify BL Lac objects in complete radio samples.

2. As an extension of the above idea, if radio emission in BL Lac objects is dominated by relativistically beamed radiation, then the parent population for radio-selected BL Lac objects may be much larger in numbers. For example, Wardle, Moore, and Angel (1984) have used the extended radio morphology and luminosity of BL Lac objects to argue that the parent population for BL Lac objects are the Fanaroff and Riley (1974) type 1 radio galaxies, with a relativistic beaming corresponding to $\Gamma > 2$. Although based on very small numbers, we speculate that many of the properties of the XBLs can be

accounted for by assuming that we are viewing a BL Lac object somewhat off its beaming axis; e.g., smaller percentage of nonthermal flux compared to starlight, lower polarization percentages, and most importantly, smaller observed variations in polarization percentages and in position angle than those observed for radio-selected BL Lac objects. Indeed, it has been known for some time (Angel and Stockman 1980; Sitko, Schmidt, and Stein 1985) that radio-selected BL Lac objects with lower degrees of polarization exhibit lesser amounts of variability, both in polarization percentage and in position angle. If the above speculations about XBLs are true, then less X-ray emission must be beamed than the radio emission and could, in fact, be in large part isotropic, contrary to many current arguments (e.g., Urry and Mushotzky 1982). This also suggests that X-ray emission samples the parent population for BL Lac objects more fully than does the radio emission. Clearly, a larger sample of XBLs are needed to investigate these possibilities.

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Note added in proof.—A subsequent spectrum obtained with the red-sensitive Faint Object Grism Spectrograph (FOGS) on the *MMT* of the BL Lac object 1207+397 confirms the Ca II H and K break near 6400 Å seen in Figures 3*a* and 3*b*. A slightly larger redshift of $z = 0.61$ is suggested by these new observations. Also, recent X-ray observations made with the *EXOSAT* CMA detect all four MSS SBLs as pointlike sources (P. Giommi, private communication). In particular, this removes concern that 1235+632 could be a diffuse cluster source.

HALTON C. ARP: Mount Wilson and Las Campanas Observatories, 813 Santa Barbara Street, Pasadena, CA 91101

I. M. GIOIA, T. MACCACARO, and R. E. SCHILD: Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138

JAMES LIEBERT, GARY D. SCHMIDT, and JOHN T. STOCKE: Steward Observatory, University of Arizona, Tucson, AZ 85721

D. MACCAGNI: CNR, Istituto di Fisica Cosmica, via Bassini 15, 20133, Milano, Italy

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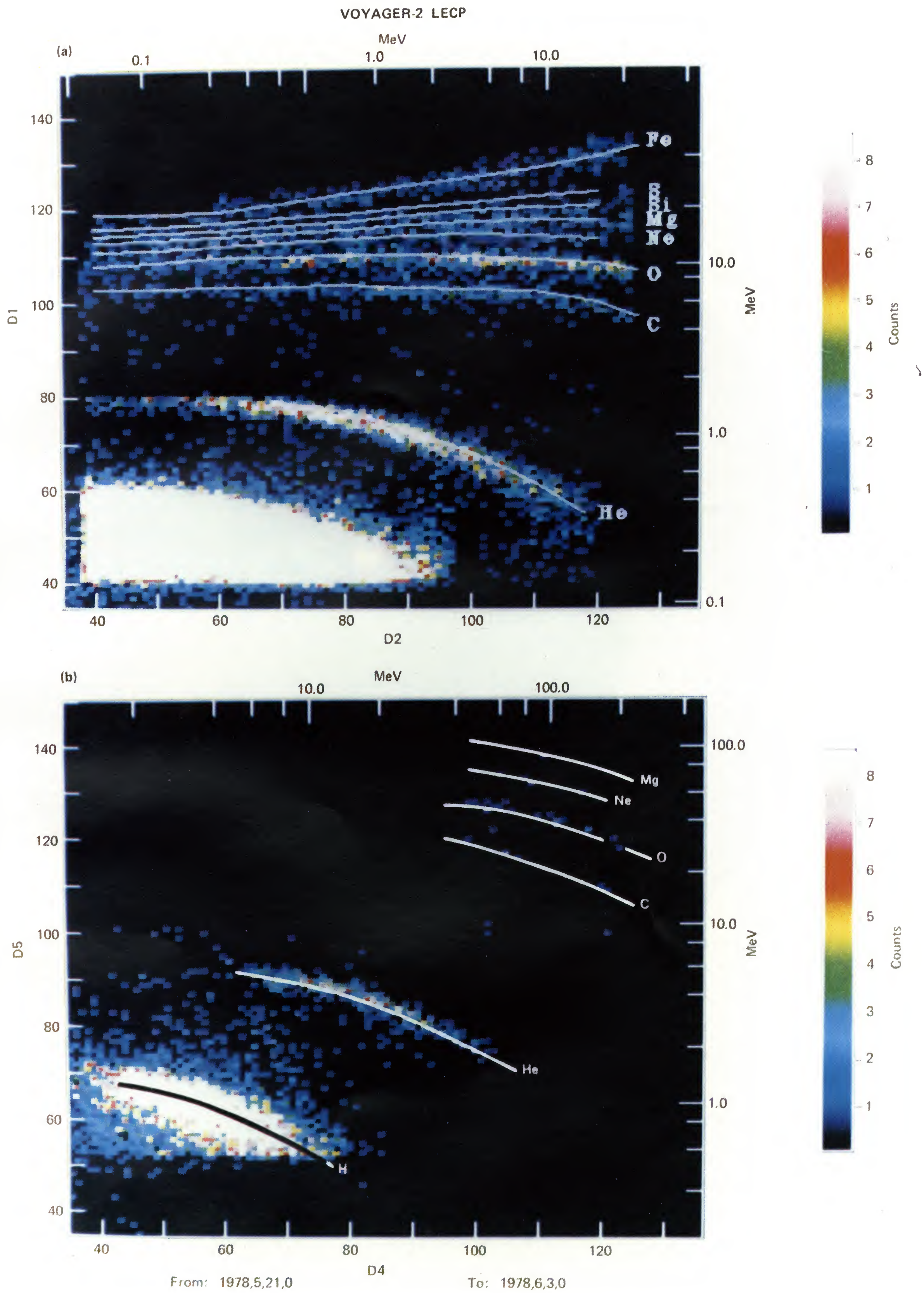

FIG. 2.—(*top*) Matrix of pulse height–analyzed events, where the energy loss in detector D1 (5.4 μm) is displayed vs. the residual energy measured in D2 (152 μm), during the energetic particle intensity enhancements associated with the 1978 January 6 shock wave at *Voyager 2*. The solid curves show expected track locations. (*bottom*) High-energy matrix between detectors D5 (84 μm) and D4 (2500 μm). It is seen that O ions are accelerated to a total energy of $\sim$220 MeV.

SARRIS AND KRIMIGIS (*see* page 678)