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X-RAY EMITTING BL LACERTAE OBJECTS LOCATED BY THE SCANNING MODULATION COLLIMATOR EXPERIMENT ON *HEAO 1*

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ABSTRACT

We establish that BL Lacertae objects constitute a class of X-ray emitter by precisely locating X-ray sources identified with Mrk 421, PKS 0548−322, PKS 2155−304 and 2A 1219+305. We report irregular variations $\delta m_B \sim 1$ mag, characteristic of BL Lacertae objects, from the last two objects. Our measurement of an extremely steep X-ray spectrum from Mrk 421, in contrast to previous flat X-ray spectra above 3 keV, suggests that we are observing different structural states of an accretion disk.

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

I. INTRODUCTION

Accurate X-ray positions have established the identification of the BL Lacertae objects Mrk 501 (Schwartz *et al.* 1978*a*) and Mrk 421 (Hearn, Marshall, and Jernigan 1978) with X-ray sources discovered by Forman *et al.* (1978) and Ricketts, Cooke, and Pounds (1976), respectively. The present paper reports precise ($\sim$1 arcmin^2) location of X-ray emission from regions near Mrk 421 and three other BL Lac objects. This brings to five the number of BL Lac objects definitely known to be X-ray emitters, and therefore establishes these objects as a class of X-ray source, as suggested in the fourth *Uhuru* catalog (Forman *et al.* 1978). The X-ray fluxes which we detect in the 2–10 keV band are less than or equal to previous upper limits (Margon *et al.* 1976; Ulmer and Murray 1976) to the X-ray flux from other BL Lac objects. We discuss our location for each object, and a rough summary of the X-ray characteristics of this new class.

II. X-RAY LOCATIONS

The characteristics of the Scanning Modulation Collimator (MC) experiment on the first high-energy astronomy observatory (*HEAO 1*) have been described by Schwartz *et al.* (1978*b*), Gursky *et al.* (1978), and references therein. MC1 denotes the 30″ FWHM collimator and MC2 the 2′ FWHM collimator. Based on observations of previously identified sources, we estimate aspect and systematic errors which are negligible compared to the statistical errors for the location of weak sources, near our threshold of detection. This statistical position error is determined by carrying out many numerical simulations of the detector response to weak sources, and agrees with an analytic estimate at our detection threshold. We use the NRL Large Area Sky Survey (LASS) experiment on *HEAO 1* to establish source existence, apparent flux, and an approximate line of position which reduces the multiplicity inherent to a scanning modulation collimator (cf. Gursky *et al.* 1978).

a) Markarian 421

This was the first BL Lac object suggested to be an X-ray source, following a 20-fold increase in the X-ray flux from this region of sky (Ricketts, Cooke, and Pounds 1976). Subsequently, a steady X-ray counterpart was reported (Cooke *et al.* 1978). Marshall and Jernigan (1978) and Hearn, Marshall, and Jernigan (1978), using the *SAS 3* rotating modulation collimator, have measured the location of a 2–6 keV X-ray source to be within 40″ of Mrk 421. Our X-ray location (Fig. 1*a* [Pl. L1]), obtained during a *HEAO 1* pointed observation on 0300–1200 UT 1978 May 28, is derived from signals of 8 σ (MC1) and 12 σ (MC2), using only the data from the 1–2.5 keV pulse height channel. This is significant since it proves that the extremely soft spectral state described below, and by Mushotzky *et al.* (1978*a*), arises from Mrk 421 and therefore provides increased confidence that the $\frac{1}{4}$ keV source reported by Hearn and Marshall (1978) is indeed the same object.

Figure 2*a* shows the total electromagnetic spectrum of Mrk 421, and Figure 2*b* shows more detailed measurements of the X-ray region. The steep spectrum which we measured on 1978 May 28 contrasts with the flat spectrum reported from the *OSO 8* observations of 1977 May 18–22. Since Mrk 421 is known to have a soft excess at $\frac{1}{4}$ keV (Hearn and Marshall 1978), the situation is suggestive of Cyg X-1 where it is believed that changes in the accretion disk structure cause the steep portion of the spectrum to scatter into the hard X-ray range (2–10 keV) when the X-ray flux increases (cf. Thorne and Price 1975). This is only qualitative due to the seven orders of magnitude difference in the energetics of Cyg X-1 and Mrk 421; however, the 20-fold increase observed by Ricketts *et al.* (1976) may be interpreted as such a structural change, although no spectral information is available for that event. As

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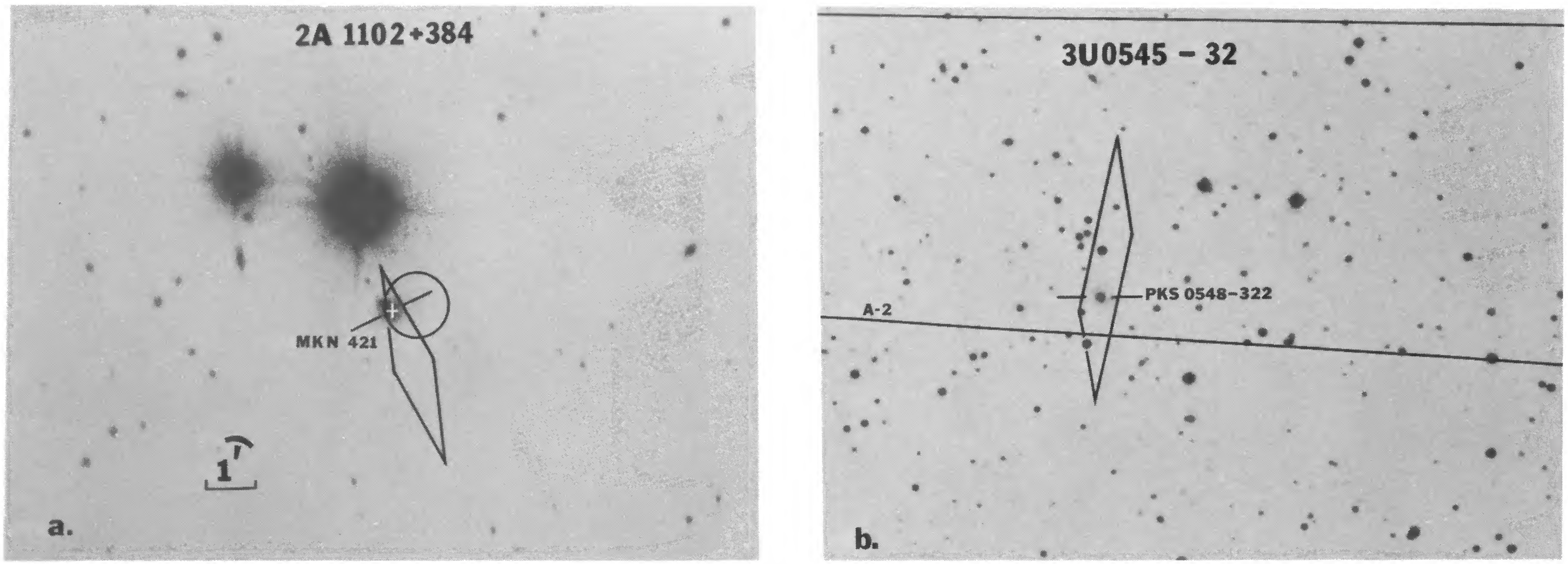

FIG. 1.—MC locations of X-ray emitting BL Lac objects are given by the heavy diamond, on enlargements of the POSS red prints (scale given in 1*a*). East is left in all figures. (*a*) 2A 1102+384 = Mrk 421, located in the 1–2.5 keV channel. Circle is the location given by Hearn *et al.* (1978). Mrk 421 is the elliptical galaxy, containing the radio source B2 1101+384 (*white plus sign*). Another galaxy of the associated cluster is superposed on Mrk 421, ~15″ to the NE. (*b*) 3U 0545−32 = PKS 0548−322. The area between the solid parallel lines is part of the *HEAO 1* A-2 0.35 deg² location uncertainty (Mushotzky *et al.* 1978*b*). The object is an elliptical galaxy of about 25″ diameter (see Disney 1974, Fig. 1).

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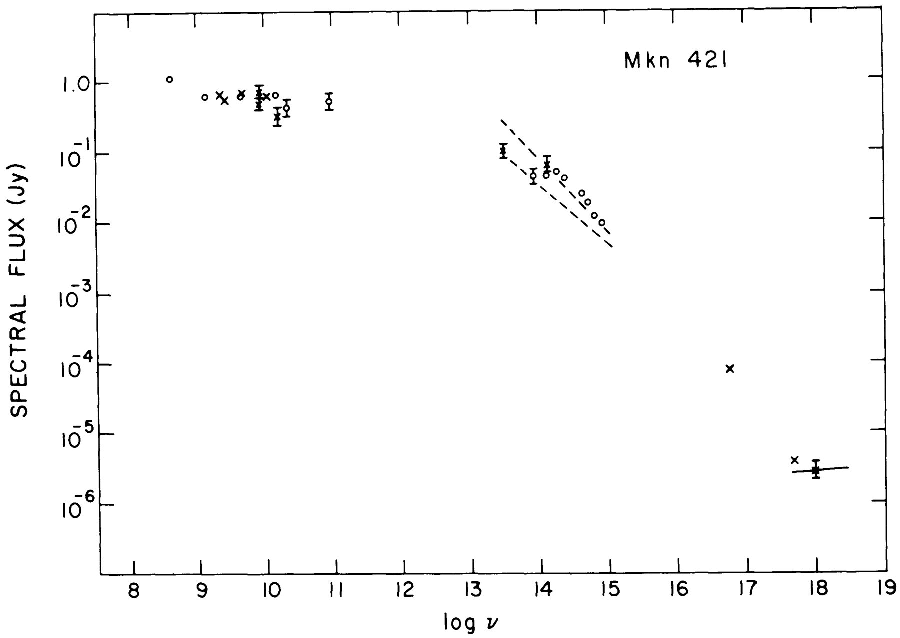
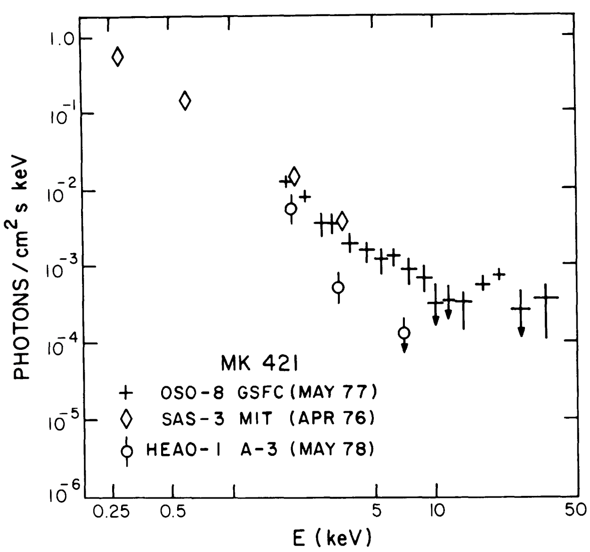
noted by Hearn and Marshall (1978), there is an even stronger similarity to the AM Her system, which is interpreted as accretion onto a strongly magnetic white dwarf. A synchrotron self-Compton model has also been discussed for this object (Margon, Jones, and Wardle 1978).

b) PKS 0548−322

This radio source (Shimmins and Bolton 1974) was the first BL Lac object noted to be in an X-ray error box (Disney 1974), although it was not specifically claimed to be the X-ray source until observed with *HEAO 1* (Mushotzky *et al.* 1978*b*; Kinzer *et al.* 1978). The present MC multiple positions occupy only 1.2% of the area allowed by these experiments, and indeed contain the elliptical galaxy identified with the BL Lac object. The spectrum of this galaxy gives a redshift $z = 0.069$ (Fosbury and Disney 1976). Our location, based on 2.7 σ (MC1) and 4.3 σ (MC2) signals in the scanning data from 1977 September summed with that



a



b

FIG. 2.—(*a*) Electromagnetic spectrum of Mrk 421. Radio data from Dixon (1970), Colla *et al.* (1973), Sulentic (1976), Joyce and Simon (1976), O'Dell *et al.* (1978). Optical data from Ulrich *et al.* (1975), Maza *et al.* (1978). The upper dashed line shows the polarized optical flux, attributed to the BL Lac nucleus (Maza *et al.* 1978). The lower dashed line was attributed to the BL Lac object by Ulrich *et al.* (1975) based on the colors. Soft X-ray flux ($\nu = 10^{17}$ Hz) from Hearn and Marshall (1978). Hard X-ray spectrum (solid line) from Mushotzky *et al.* (1978*b*). (*b*) X-ray spectra of Mrk 421. The *OSO 8* measurements are from 1977 May, *SAS 3* from 1976 April, and the present results from 1978 May 28. The *HEAO 1* MC data fit a power law of slope 3 ± 1, in contrast to the slope of 1 ± 0.5 measured above 3 keV (Mushotzky *et al.* 1978*b*).

of 1978 March, is shown in Figure 1*b*. Our astrometry of the galaxy identified with PKS 0548−322 gives an improved position (1950) R.A. = $5^h48^m48\overset{s}{.}9$, decl. = $-32°17'7\overset{''}{.}4$ with 5″ error. As noted by Disney (1974), there are both a cluster (at $z = 0.042$) and a rich group of galaxies in this region. While we cannot rule out the possibility that they make some contribution to the measured X-ray flux, we consider it unlikely because of demodulation of the X-ray flux from clusters in general due to their finite size (cf. Briel *et al.* 1978; Schwarz *et al.* 1978).

c) 2A 1219+305

Wilson *et al.* (1979) revised the X-ray location of 2A 1219+305 (Cooke *et al.* 1978) and performed a radio and optical study of this region. They found two interesting 1.4 GHz radio emitters; an extended source (RS 2) emitting 266 mJy, and a 57 mJy source (RS 4) which was identified with a $m_v = 16.4$ mag stellar object. Optical studies showed that several other bright stellar objects were normal galactic stars and therefore unlikely X-ray candidates, but that RS 4 had a featureless optical spectrum. They therefore suggested RS 4 to be a BL Lac object, and the X-ray emitter. Figure 1*c* (Plate L2) shows our location of this object based on a *HEAO 1* pointing on 0400–1000 UT 1978 May 31. Our detection is at 6 σ in each collimator. Our three energy channels allow a crude spectrum with a power-law energy index $\alpha = 0.5 \pm 0.5$, and no absorption ($N_H < 3 \times 10^{22}$ H atoms cm^{-2}). The MC position shown is the only possible one inside the revised *Ariel 5* Sky Survey Instrument location. To investigate whether the object is indeed of the BL Lac class, L. Chaisson has searched the Harvard College Observatory plate stack collection for historical variability. As shown in Figure 3, several probable events were found, including a 1.1 ± 0.2 mag variation of m_B within 120 days in 1941. We therefore confirm both the BL Lac nature of this object and its identity as an X-ray source. With a flux of only 54 mJy at 1400 MHz, this may be the best example of a "radio-quiet" BL Lac object.

d) H2155−304 = PKS 2155−304

The second *Ariel 5* catalog (Cooke *et al.* 1978) lists the source 2A 2151−316 as being in a "confused region." Using the NRL LASS data, we immediately noted what is presumed to be a different source, displaced by about 1° in ecliptic latitude, and located six possible MC intersections within the region allowed by the NRL data. Subsequently, a relatively intense source in the 0.4–2.0 keV range was detected with the *HEAO* 1 A-2 low-energy detectors (LED). In a collaborative effort, we used their location uncertainty (Riegler 1978; Agrawal and Riegler 1979) to reduce our position to only two allowed regions, each of about 1 arcmin². We noted that the only distinctive object was an ~14th mag stellar object, at the position (1950) R.A. = $21^h55^m58\overset{s}{.}41$, decl. = $-30°27'54\overset{''}{.}8$ (4″ error), as marked in Figure 1*d*. No nebulosity appears on the POSS red plate. Optical study of this object (Wade, Szkody, and Cordova 1978) showed an extremely blue ($B - V < 0.1$) featureless continuum (at 10 Å resolution). We also noted that PKS 2155−304 was 30″ ± 18″ N of this object. Since the probability of a radio source with $S_{2700} > 0.18$ Jy being in a 1 arcmin² region is only 10^{-4} (cf. Shimmins and Bolton 1974), we identified it with both the X-ray source and the blue stellar object, which therefore suggested its

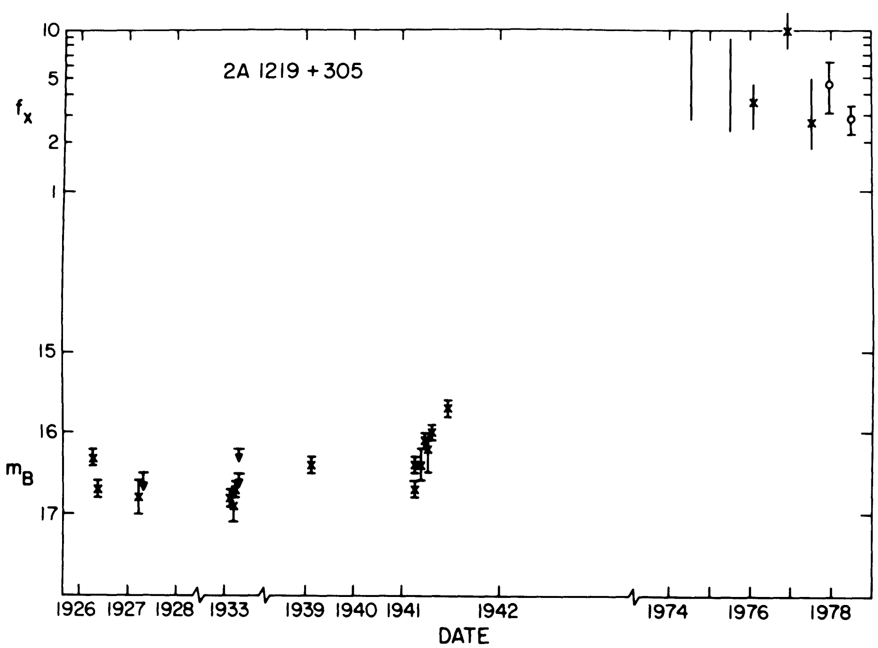


FIG. 3.—Long term light curve of 2A 1219+305 in m_B (*lower vertical scale*) and X-ray flux (*upper vertical scale*). Straight lines: the *Ariel 5* points (from Wilson *et al.* 1979) showing the range of variability over ~6 month intervals. The two MC detections (*circles*) are at the minimum *Ariel 5* flux level. (The horizontal scale has been broken and distorted for convenient display.)

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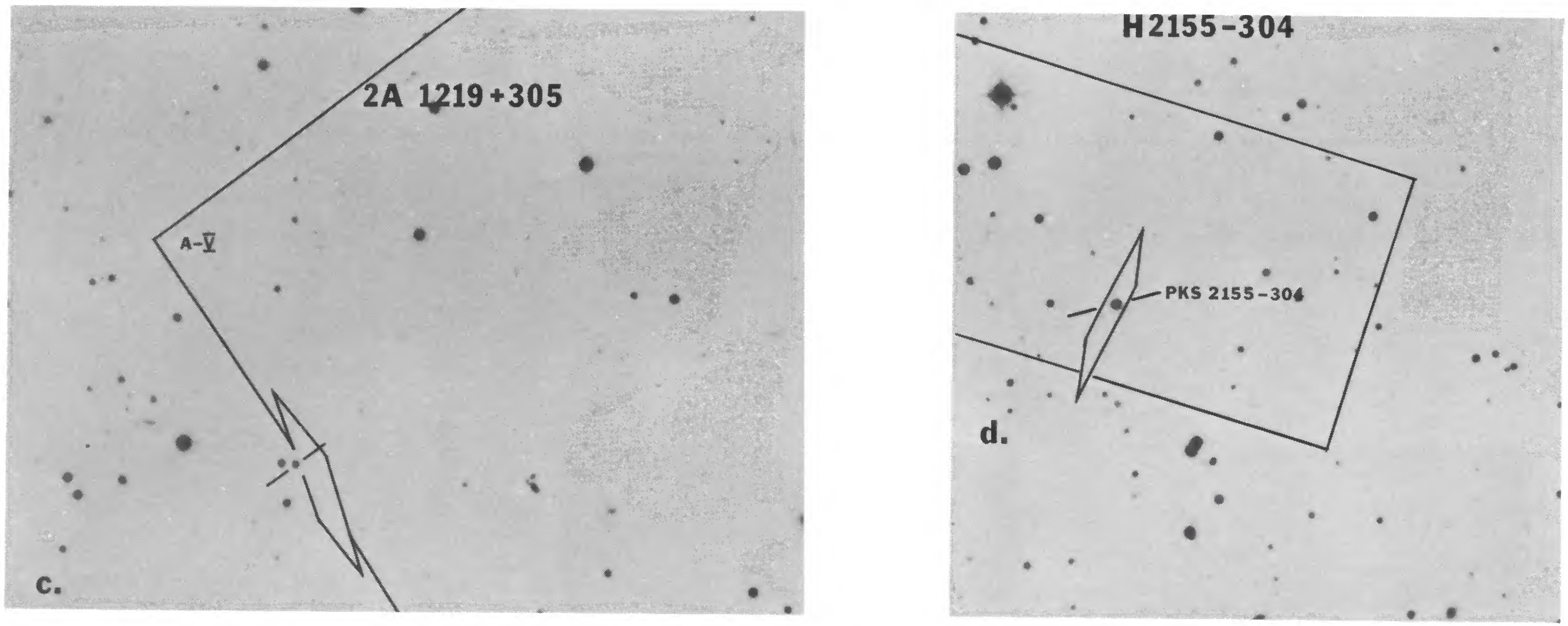

FIG. 1. (*continued*).—(*c*) 2A 1291+305. The revised *Ariel 5* location (Wilson *et al.* 1978) covers the western portion of this figure, and contains only the MC position shown: the extended Radio Source 2 of Wilson *et al.* is outside any possible MC position. (*d*) H2155−304 = PKS 2155−304. The partial rectangle is the western end of the *HEAO 1* A-2 location determined by the soft X-ray emission (Riegler 1978).

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BL Lac nature. Subsequently, Tapia has observed optical polarization of about 5% (Griffiths *et al.* 1979), confirming the BL Lac nature of 2155−304. L. Chaisson (private communication 1978, and Griffiths *et al.* 1979) reports 1.5 mag variability of the optical counterpart in the Harvard plate collection. R. Hjellming (private communication 1978, and Griffiths *et al.* 1979) reports an improved radio position within 5″ of the optical object.

The X-ray source shows a high degree of variability. We measure a flux in 1977 November of at least 3 times greater than the *Ariel 5* survey of this region (Cooke *et al.* 1978). Results from the *HEAO 1* A-2 low-energy detectors have tentatively suggested factor of 2 changes in less than one day, and also in a few seconds during a single scan (Riegler 1978; Agrawal and Riegler 1979). If confirmed, the latter variation would have extreme implications for the distance and nature of this source (cf. Lightman, Giacconi, and Tananbaum 1978).

III. PROPERTIES OF THE CLASS OF X-RAY EMITTING BL LACERTAE OBJECTS

There are now five BL Lac objects which give an X-ray flux $\gtrsim$ 1.5 UFU.[1] According to $N(>S) \propto S^{-3/2}$, we naively predict at least 26 such objects with flux greater than 0.5 UFU. The present establishment of BL Lac objects as a class of X-ray emitters supports the identification of I Zw 1727+501, PKS 0521−365, and PKS 0537−441 as suggested by the NRL LASS experiment, based on their search of about 10% of the sky (Kinzer *et al.* 1978), and that of 3C 371 suggested by Marshall *et al.* (1978). These objects were too weak to be detected by the MC experiment in the first 6 months celestial scan.

Table 1 summarizes some properties of the five definite and four probable X-ray emitting BL Lac objects, and also of BL Lac itself which we did not detect in X-rays during a pointed observation on 1978 June 25. The typical X-ray luminosity (2–6 keV) is $L_x \approx 2 \times 10^{44}$ ergs s^{-1}; however, the X-ray flux from objects with $L_x \approx 10^{43}$ ergs s^{-1} could not be detected beyond 50 Mpc; and if the apparent $L_x/L_B = 10^{0.5\pm0.5}$ as suggested by Table 1, then the objects with $L_x > 10^{45}$ ergs s^{-1} may be so distant that we currently do not recognize the BL Lac nature of their optical counterparts. Of course, the luminosity can only be measured when we can detect a surrounding galaxy, which may bias the subclass of BL Lac objects to which the current L_x values apply. We think that the most suggestive, qualitative feature of Table 1 is the similar amplitude of the optical and X-ray variation, suggesting a basic relation of the source of energy. Giacconi (1978) has made a similar suggestion for type 1 Seyferts, based on their absolute X-ray and optical luminosities. Of course, simultaneous (or at least correlated) variations (which are *not* implied in Table 1) should be observed to confirm this suggestion.

Table 1 is consistent with the original estimate of Schwartz *et al.* (1978) that BL Lac objects only contribute ~3% of the diffuse X-ray background in the 2–6 keV region. However, if their proper volume density evolves in time according to $(1 + z)^6$, as suggested

[1] 1 UFU = 1.7×10^{-11} ergs cm^{-2} s^{-1}, 2–6 keV, ≈ 1.6 μJy at 3.6 keV.

TABLE 1

X-Ray Properties of BL Lacertae Objects

	m_B (faintest)	F_X [μJy, 3.6keV]	L_X (ergs/s, 2–6keV)	Variability □ X-ray	Variability □ Optical	X-ray Size Limit
Mrk 501	14.5*	3.8	1.6×10^{44}	≤ 1.5+	2.5	< 1.5′
Mrk 421	16.3*	2.4	$1\text{-}50 \times 10^{44}$	50	75*	< 1.1′
2A 1219+305	16.9	1.9		4	2.5	< 1.3′
PKS 0548-322	16.1*	3.	6×10^{44}			< 2.5′
PKS 2155-304	14.5	10		> 3	4	< 45″
3C 371	15.8	.5**	7×10^{43}		2++	
I Zw 1727+502	16.9*	.6+			5.9*	
PKS 0521-365	16.0*	1. +		yes+	3.7*	
PKS 0537-441	18.0*	3.1+		yes+	150*	
BL Lac	16.6*	< 1.	$< 2 \times 10^{44}$		42*	

References.—*Stein *et al.* 1976. +Kinzer *et al.* 1978. **Marshall *et al.* 1978*a*. ++Miller 1975. □ Ratio of maximum to minimum flux reported in 2–6 keV range (X-ray) or *B* band (optical).

(Schmidt 1970) for classical quasars, then they could provide the diffuse X-ray background intensity in the 2–6 keV range. With an average luminosity of only 2×10^{44} ergs s^{-1}, they will be sufficiently numerous for their random angular fluctuations to be consistent with the measured isotropy (Schwartz *et al.* 1971; Schwartz 1979), unlike a class of objects which, like 3C273, have $L_x \geq 10^{45}$ ergs s^{-1}.

The upper limits to the size shown in column (7) are based on the maximum amount which the MC1 flux might be demodulated relative to that of MC2 (cf. Schwartz *et al.* 1979). Although X-ray variability implies a pointlike component, our measurements occur near X-ray minima in all cases and therefore the entire flux listed in column (3) could possibly be extended. Of course, if some of the flux arises from a pointlike component, the remaining fraction could be emitted from a region of extent larger than given in Table 1.

The ubiquity of soft (<2 keV) X-ray excesses from BL Lac objects has possible implications for the lack of line emission: it suggests that the absence of ionizing radiation is not the explanation. This leaves the lack of cold gas (cf. Stein, O'Dell, and Strittmatter 1976) as the most likely explanation. This has also been suggested by Mushotzky *et al.* (1978*b*) based on the lack of low-energy X-ray absorption which would be expected from such cold gas.

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