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VARIABLE X-RAY SPECTRA OF BL LACERTAE OBJECTS: *HEAO 1* OBSERVATIONS OF PKS 0548−322 AND 2A 1219+305

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ABSTRACT

We present X-ray spectra for the BL Lac objects PKS 0548−322 and 2A 1219+305 measured with the *HEAO 1* A-2 detectors during pointing maneuvers on 1978 September 30 and 1978 May 31, respectively. Both fit single power-law components with low-energy absorption. For 2A 1219+305, a thermal bremsstrahlung form gives an unacceptable fit. We find, from a comparison with other statistically poorer observations taken at 6 month intervals while the satellite was in its normal scanning mode, that the sources exhibit spectral variability. A summary of measurements of the five BL Lac objects detected with the A-2 experiment is presented, and we conclude that X-ray spectral changes in this class of source are common. Their general X-ray spectral characteristics distinguish BL Lac objects from other classes of X-ray–emitting active galactic nuclei. Analysis of their total spectra indicates that most of the energy is emitted in the 5–100 eV band.

Subject headings: BL Lacertae objects — spectrophotometry

I. INTRODUCTION

The first evidence that BL Lac objects might be emitting a large fraction of their energy in X-rays came from Ricketts, Cooke and Pounds (1976) who, with *Ariel 5*, detected flux possibly associated with MRK 421. At present this BL Lac object together with four others, MRK 501, PKS 0548−322, 2A 1219+305, and PKS 2155−304, has been firmly identified as a source of X-rays of energy greater than 2 keV by modulation collimator experiments (Hearn, Marshall, and Jernigan 1979; Schwartz *et al.* 1978, 1979). Other possible candidates are 3C 371 (Marshall *et al.* 1978) and a few others found with the NRL *HEAO 1* Al detectors (Kinzer *et al.* 1978). The imaging detectors on the *Einstein* Observatory, because of their high sensitivity and the steep low-energy component often shown by these objects (see later), are considerably enlarging the number of X-ray detections of optically selected BL Lac objects below about 3 keV. Eleven new detections have already been reported (Ku 1979; Maccagni and Tarenghi 1979).

The first five BL Lac-type objects above have all been detected with the 2–50 keV *HEAO 1* A-2[2] multiwire proportional counters. In this paper we present spectra of PKS 0548−322 and 2A 1219+305 measured during pointing observations in 1978 September and May, respectively, and we make a comparison with spectra determined from two other observations of each source while the satellite was in its normal scanning mode. We A-2 scanning measurements of Mushotzky *et al.* (1978) and Mason *et al.* (1980) with those from a pointing show that the spectra exhibit variability. Similar behavior is evident for MRK 501 from comparison of the *HEAO 1* observation a year later presented by Kondo *et al.* (1980). Mushotzky *et al.* (1979*a*) have already reported spectral variability for MRK 421, accompanied by a 2–30 keV intensity change of a factor of ~3. With the present measurements, we are able to conclude that spectral changes in BL Lac objects are not uncommon phenomena.

PKS 0548−322 was first reported as the possible identification for the X-ray source H0548−32 by Mushotzky *et al.* (1978). Firm identification followed (Schwartz *et al.* 1979). The 0.15–30 keV spectrum was found in 1978 September to have a two-component form, characterized by a hard power law above 2 keV and a soft excess at lower energies (Riegler, Agrawal, and Mushotzky 1979). Fosbury and Disney (1976) determined the redshift to be 0.069 from its optical absorption lines and find that in the B band the system consists of an elliptical galaxy which emits roughly equal light to a nuclear component. If the latter is represented by $f_\nu \propto \nu^{-\alpha}$ (3800–5700 Å), $\alpha = 2 \pm 0.5$. In the visible to ~1 μm range, Weistrop, Smith, and Reitsema (1979) find a flatter index, $\alpha \approx 0.3$, consistent with that from radio measurements. Riegler, Agrawal, and Mushotzky (1979) show that the index of the hard X-ray tail is also $\alpha \approx 0.3$ and use this as a basis for discussion of nonthermal synchrotron self-Compton (SSC) emission models.

The first example of a BL Lac object discovered through its X-ray properties is 2A 1219+305. This resulted from the optical and radio search of Wilson *et al.* (1979) in the error box of a then unidentified *Ariel 5*

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source (Cooke *et al.* 1978). The firm X-ray identification was provided by Schwartz *et al.* (1979) who have also investigated Harvard optical plates and found variability of 1.1 ± 0.2 mag over 120 days. A sharp spectral break at ~ 1 μm is seen in the infrared–optical measurements of Ledden *et al.* (1981). No lines are seen in the optical spectra, and thus the redshift is unknown. We note that the accurate position of the BL Lac object is actually 1218+304, but in this paper we will continue to use the *Ariel* catalog designation.

II. OBSERVATIONS

The observations were made with the A-2 detectors on the *HEAO 1* spacecraft. For a detailed description of the experiment see Rothschild *et al.* (1979). In addition to those measurements reported here and in previous papers (see Table 1 for references), we have used the all-sky data from the experiment to search for detections using a list of positions of 52 BL Lac-type objects compiled from Stein, O'Dell, and Strittmatter (1976) together with other candidates given in the proceedings of the Pittsburgh Conference on BL Lac Objects (ed. A. M. Wolfe 1978). None were found, thus placing an upper limit on the 2–10 keV flux for each of $\sim 2.4 \times 10^{-11}$ ergs cm^{-2} s^{-1}, except for 0133+47, 1727+502, and 2155−152 where we have possible detections at the 3–5 σ level each corresponding to a 2–6 keV flux of roughly (1–2) $\times 10^{-11}$ ergs cm^{-2} s^{-1}. The object 1727+502 (I Zw 186) is previously reported to have been detected by the A1 experiment on *HEAO 1* (Wood 1979) with a flux of $\sim 3 \times 10^{-12}$ ergs cm^{-2} s^{-1}.

a) PKS 0548−322

The *HEAO 1* A-2 detectors pointed at the source on 1978 September 30. Figure 1 shows the pulse-height analyzed counts per channel for the argon (MED) detector together with those predicted assuming the incident spectrum is a power law with low-energy absorption. The best-fitting incident photon spectrum, $\Gamma = 2.75$, is shown together with numerical values. The error contour for spectral slope, Γ, and hydrogen column density, N_H, is for 90% confidence. A thermal bremsstrahlung fit of temperature 4 keV is equally acceptable. No significant line emission is evident. The xenon (HED) detectors give consistent fits but are not shown because we have no detection above ~ 15 keV.

Six months earlier, 1978 March 12–22, our detectors observed the source while in their normal scanning mode. Although the statistics are much poorer than for the point observation, we find a marginally steeper power law of index $\Gamma = 5$ (+3, −1.5) (90% errors).

The results of the first A-2 observation of the source, in scanning mode during 1977 September 14–24, have already been reported by Riegler, Agrawal, and Mushotzky (1979). The earlier data are described by two power

TABLE 1

X-Ray Spectral Parameters for BL Lacertae Objects

Source	Date	Energy Range (keV)	Γ[a]	N_H (atoms cm^{-2})	3 keV flux cm^{-2} s^{-1} keV^{-1}	Ref.	Notes
PKS 0548−322	1977 Sep 14–24	0.15–2	3.2 ± 0.4	$2.5 \pm 1 \times 10^{20}$	2.6×10^{-4}	1	*HEAO* A2 scan. 2
		2–30	1.3(+0.4, −0.3)		7×10^{-4}		components.
	1978 Mar 12–22	2–10	5.0(+3.0, −1.5)	NWD[b]	1.7×10^{-3}	2	*HEAO* A2 scan.
	1978 Sep 30	2–15	2.75(+0.4, −0.3)	$<3 \times 10^{22}$	1.8×10^{-3}	2	*HEAO* A2 point.
2A 1219+305	1977 Dec 11–16	2–20	2.1 ± 0.9	NWD[b]	2×10^{-3}	2	*HEAO* A2 scan.
	1978 May 31	2–20	2.03(+0.2, −0.1)[c]	$<9 \times 10^{21}$	2×10^{-3}	2	*HEAO* A2 point.
		1–13	1.5 ± 0.5	$<3 \times 10^{22}$		3	*HEAO* A3 (1 σ error)
	1978 Dec 11–16	2–15	4.0(+1.8, −0.9)	NWD[b]	10^{-3}	2	*HEAO* A2 scan.
MRK 501	1975 Mar 15–18	1.5–15	1.8 ± 0.5	$<5 \times 10^{21}$	1.8×10^{-3}	4	*Ariel 5*. No 2 compt. fit tests
	1977 Aug 19–31	0.15–3	2.5(+3.0, −0.5)	$\sim 4 \times 10^{19}$	8×10^{-4}	5	*HEAO* A2 scan. 2
		2–30	1.2 ± 0.4		5×10^{-4}	6	components
	1978 Sep 8	2–30	2.5(+0.3, −0.2)	$<1.6 \times 10^{22}$	2×10^{-3}	7	*HEAO* A2 point.
MRK 421	1976 Apr 25–26	0.3–4	2.1(+0.4, −0.3)	$<3 \times 10^{20}$	5×10^{-3}	8	*SAS* 3.
	1977 May 18–20	2–30	0.9(+0.45, −0.5)	$<8 \times 10^{21}$	4×10^{-3}	6	*OSO 8*. Indication of soft excess equal to 1978 May observation.
	1977 Nov 20–26	0.2–2.5	4.5(+2.0, −1.5)	$7.5 \pm 5 \times 10^{20}$	2×10^{-4}	5	*HEAO* A2 scan.
	1978 May 28	2–10	3.9(+1.3, −0.7)	$<7 \times 10^{21}$	2×10^{-3}	9	*HEAO* A2 point.
		1.6–7	3.0 ± 1.0	NWD[b]	2×10^{-3}	3	*HEAO* A3 (1 σ error)
PKS 2155−304	1977 Nov 11–16	0.15–2	2.4 ± 0.3	$2.0 \pm 1 \times 10^{20}$	5.5×10^{-3}	10	*HEAO* A2 scan. Daily variability $\sim$ factor 2.
	1978 Nov 8	1–13	2 ± 0.5	NWD[b]		11	*HEAO* A3 (1 σ error)

[a] Errors are 90% confidence for all except *HEAO* A3 data.
[b] Not well determined.
[c] Power-law fit significantly better than thermal bremsstrahlung.

References.—(1) Riegler, Agrawal, and Mushotzky 1979. (2) Worrall *et al.* 1979; this paper. (3) Schwartz *et al.* 1979. (4) Snijders *et al.* 1979. (5) Mason *et al.* 1980. (6) Mushotzky *et al.* 1978. (7) Kondo *et al.* 1980. (8) Hearn, Marshall, and Jernigan 1979. (9) Mushotzky *et al.* 1979*a*. (10) Agrawal and Riegler 1979. (11) Griffiths *et al.* 1979.

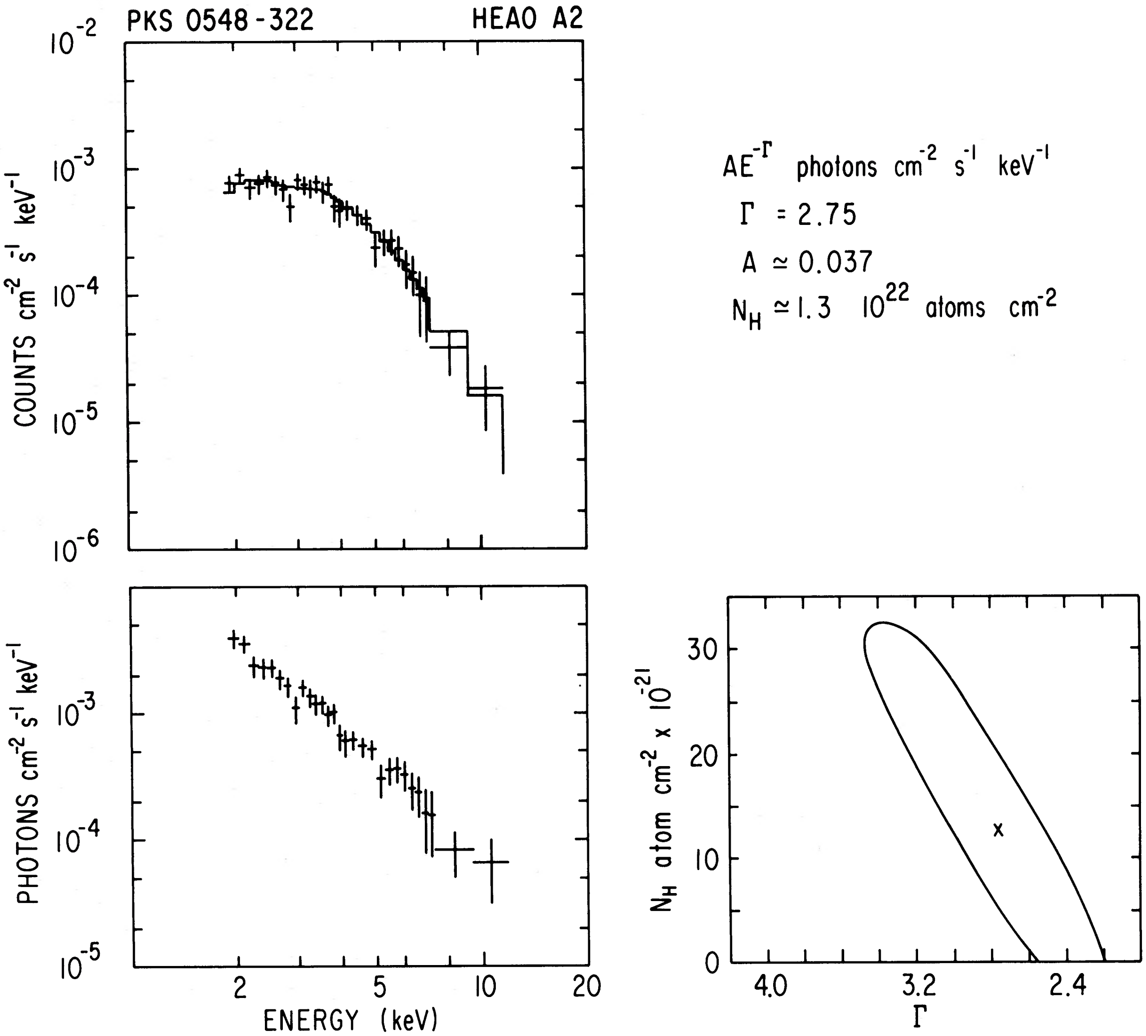

FIG. 1.—Observation of 1978 September 30. Shown are background-subtracted argon detector (MED) counts with the best-fit model, assuming its form is a power law with low-energy absorption, and also the implied incident spectrum after folding through the detector response. This error contour for Γ and N_H is for 90% confidence. A thermal bremsstrahlung form will also fit the data.

laws. Figure 2 shows these (the HED and low energy, LED, measurements) together with the point mode MED observation of Figure 1. The spectral shape probably changed between 1977 September and 1978 September, most simply described by a vanishing of the high-energy flux. Using the value of column density determined by the LEDs we find that the best-fit power law for the 1978 September data, now restricted to $2.2 < \Gamma < 2.6$ (see Fig. 1), is different from the low-energy fit to the 1977 September data. Thus there is evidence that the low-energy continuum had also changed its spectral form. There was no statistically significant change in counting rate in the ~2–10 keV band, and, in fact, to within 1σ errors, all three of our observations give the same 2–10 keV energy flux: $(3 \pm 0.2) \times 10^{-11}$ ergs cm^{-2} s^{-1}. For the 6-day periods in 1978 March and September during which the source was observed in satellite scanning mode, using a 5% significance threshold, daily averages satisfy constant intensity. Daily deviations are less than 25% of the average value.

b) *2A 1219+305*

The observations consist of an extended point on 1978 May 31 and three periods of scanning: 1977 December 11–16; 1978 June 10–15; and 1978 December 11–16.

Figure 3 shows the MED spectrum for the pointed observation in a format identical to Figure 1. The best power-law index is $\Gamma = 2.03$. In rough agreement is the value of 1.5 ± 0.5 given by Schwartz *et al.* (1979) for a simultaneous measurement with the three energy windows of the *HEAO 1* A-3 detectors. We found thermal bremsstrahlung fits to be unacceptable, resulting for the best thermal fit in an increase in χ^2 of 30 over the power-law fit. This is the only example of a BL Lac X-ray spectral component for which our detectors have been able to distinguish a preferred emission model. In similar-

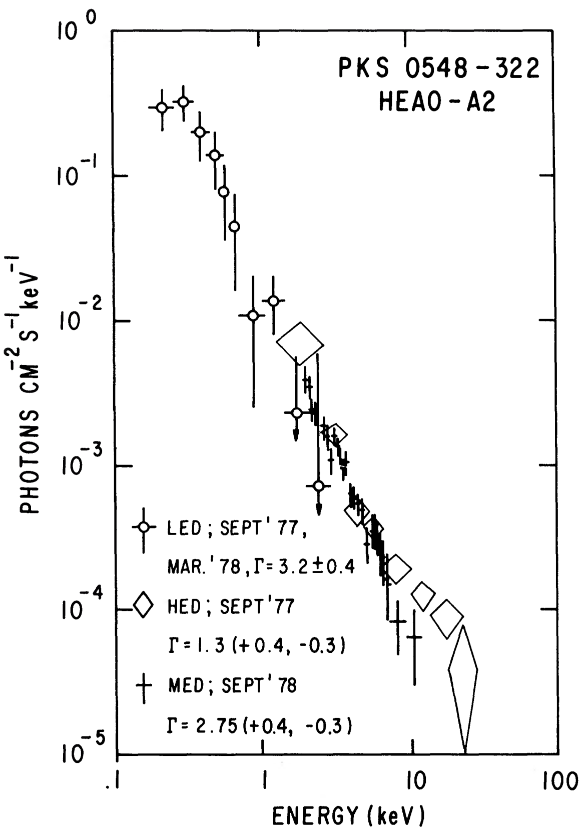

FIG. 2.—Spectral variability of PKS 0548 − 322 is evident from comparison of the point-mode MED data of 1978 September (Fig. 1) with the low-energy detector (LED) and high-energy xenon detector (HED) measurements taken a year earlier in scanning mode and reported by Riegler, Agrawal, and Mushotzky (1979).

ity with our other observations of BL Lac-type objects, there is no evidence for line emission. The 2–10 keV energy flux is $(4.2 \pm 0.3) \times 10^{-11}$ ergs cm^{-2} s^{-1} for this observation.

The scanning observation of 1977 December is in good agreement in both spectral shape and intensity. However, something different was seen in 1978 December. The spectrum was steeper, $\Gamma = 4\ (+1.8, -0.9)$, and the 2–10 keV energy flux at the lower value of 1.6×10^{-11} ergs cm^{-2} s^{-1}. Wilson *et al.* (1979) have already shown from *Ariel 5* measurements that the source intensity is not constant. We confirm this and find the spectral shape to be variable also. Our 1977 December value agrees well with their measurement during the same month. For each of our three scanning mode observations, using a 5% significance threshold, the daily averages satisfy constant intensity. Daily deviations are less than 23% of the average value.

III. DISCUSSION

The general picture that emerges from consideration of all the X-ray data is that BL Lac objects show variation in both their X-ray spectra and their spectral flux density on a time scale of 6 months or less. A second feature is the common requirement for spectral fits with at least two components. Third, there is a strong tendency for the presence of a component satisfying the description of "soft," i.e., photon index $\Gamma \gtrsim 2.5$. By these characteristics BL Lac-type objects can be distinguished from the other classes of X-ray–emitting active galactic nuclei.

To illustrate these characteristics, Table 1 summarizes information for the five X-ray brightest BL Lac-type objects. Power-law parameters only are given in the table although, except for the *HEAO* A-2 pointing observation of 2A 1219+305, thermal bremsstrahlung models provide equally good fits to the data. The first four listed show evidence for spectral variability (*HEAO* A-2 data [Urry 1980, private communication], also provide evidence that PKS 2155−304 is consistent with this picture). The normalization for each component can be discerned from the implied 3 keV flux. The reader is referred to the original papers for statistical accuracies of the measurements.

The spectral vaiability of MRK 421 (Mushotzky *et al.* 1979*a*) was accompanied by a factor of ~3 change in X-ray counting rate in the 2–10 keV band. However, the spectral changes in PKS 0548−322 and MRK 501 required a detector energy resolution of better than 20% for their discovery, since the 2–10 keV counting rates remained almost constant. The MRK 501 spectrum is illustrated in Figure 4, where the 1977 August data of Mushotzky *et al.* (1978) and Mason *et al.* (1980) are shown together with those of Kondo *et al.* (1980) from 1978 September.

The strong contrast between the X-ray spectral characteristics of BL Lac-type objects and those of other X-ray–emitting active nuclei is now becoming apparent. Seyfert 1 galaxies can generally be fitted to power laws of $\Gamma \approx 1.65$, and only in one case, ESO 141−G55, is there evidence for spectral variability (Mushotzky *et al.* 1980). Multiple observations of two quasars, 3C 273 and QSO 0241+622 (Worrall *et al.* 1979, 1980), also give no indication of spectral variability, although the indices for the two are statistically different from each other. These differences in the X-ray energy band between classes of object often interpreted as similar in their emission mechanisms may provide strong observational constraints on possible theoretical models.

Perhaps the strongest feature distinguishing BL Lac-type objects from other active galactic nuclei is their strong optical polarization (see, e.g., Kinman 1978). Synchrotron radiation is a strong candidate for such emission. If the term "optical" is loosely employed to encompass the observable infrared to ultraviolet range, it is true that a continuation between the optical and X-ray spectra is evident in the simultaneous observations of MRK 501 (Kondo *et al.* 1980) and suggested in the nonsimultaneous measurements of 2A 1219+305 (Ledden *et al.* 1981), where in both cases actual breaks are observed in the optical band. For 2A 1219+305 we have been able to rule out a thermal origin for the X-rays, and the most natural explanation would seem to be that favored by Ledden *et al.* in which the X-ray and optical emission have a common nonthermal origin, which is

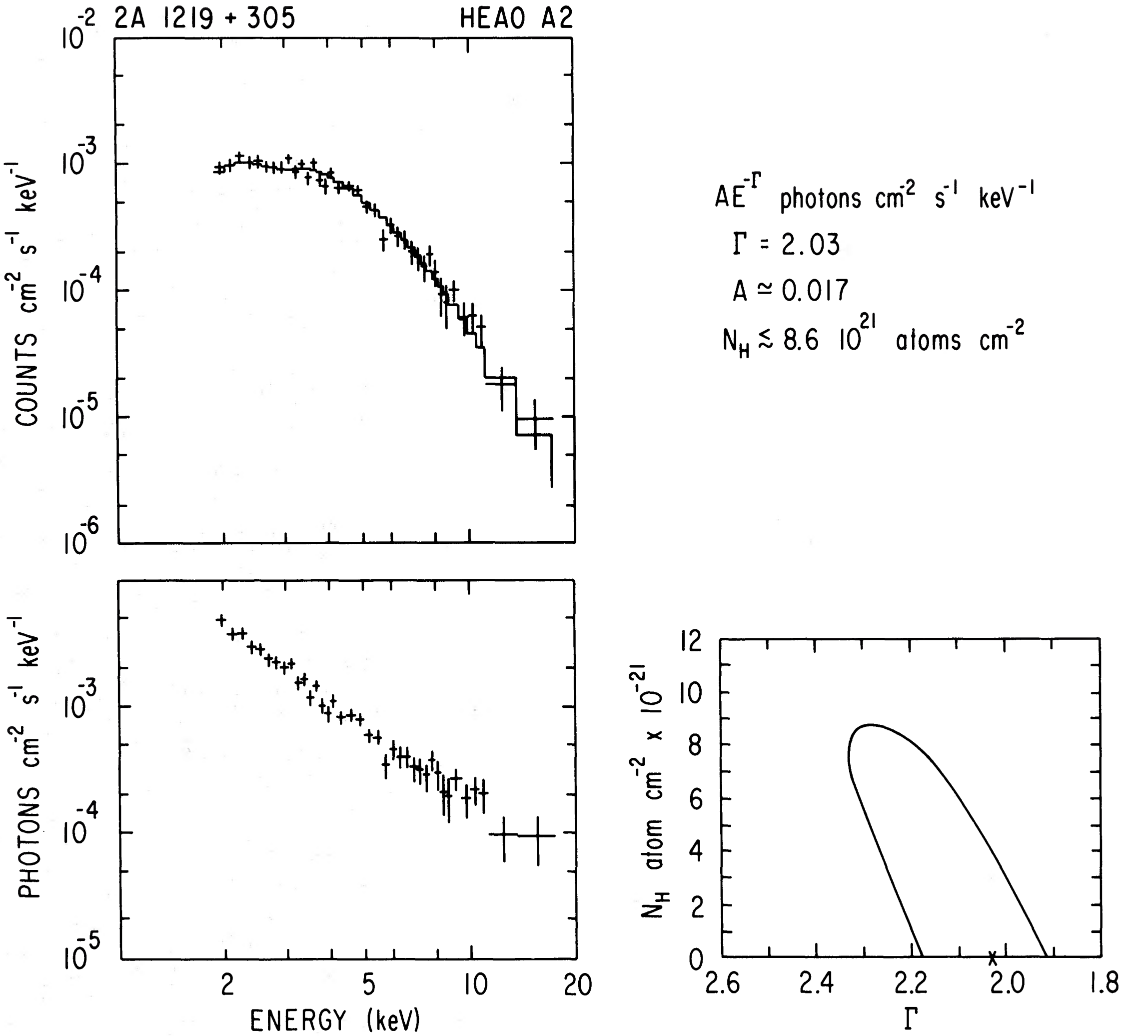

FIG. 3.—Observation of 1978 May 31. The argon detector (MED) data are displayed in the same way as those of Fig. 1. A thermal bremsstrahlung form gives an unacceptable fit.

most likely synchrotron radiation, and where the X-rays are from the high-frequency energy-loss tail. Such an explanation could account for the preponderance of steep low-energy X-ray spectra. If that is indeed the case, almost all the energy emitted by the BL Lac objects appears in the far-ultraviolet band. The integration of the UV-soft X-ray spectrum shows that ~ 2–6 times as much energy is emitted between 5 and 100 eV as in the optical (1–5 eV) or 2–20 keV X-ray band. In a model such as that of Marscher (1980) in which the source size is a strong function of frequency, the energy-loss break frequency, and hence the X-ray spectral shape, could change without heavily influencing the optical continuum below the break. However, variability below the optical break would be expected to have some influence on that above. A monitoring of the optical and X-ray components would allow a more definite statement concerning their possible association.

Despite the small number of high-quality X-ray BL Lac spectra at present, there are already suggestions that the picture is complex and will not allow the same one-component mechanism to describe the X-ray emission of all these objects at all times. Hard ($\Gamma \lesssim 1.5$) variable X-ray components have been observed for PKS 0548−322, MRK 501 and MRK 421 in addition to their soft components. There are too few observations to test whether or not these hard components also have variable spectral indices. If the synchrotron component which dominates the radio, optical, and soft X-ray energy bands emantes from a relativistic jet (Marscher 1980), this hard X-ray component may be our only probe into the central energy source of a BL Lac object. Unfortunately in this case there is no other frequency band with which we might expect correlative studies with the hard X-ray emission to be useful.

However, another possible scenario is that the hard X-ray and radio emission emanate from the same region. For PKS 0548−322, observations have been made in

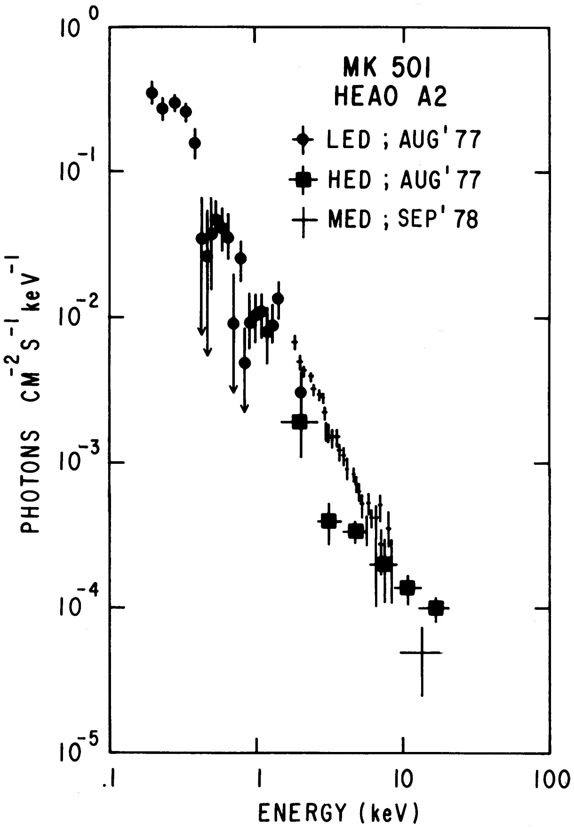

FIG. 4.—Spectral variability in MRK 501. Here the point-mode observation of 1978 September given by Kondo *et al.* (1980) is compared with the scanning mode measurements from the previous year reported by Mushotzky *et al.* (1978) (HED) and Mason *et al.* (1980) (LED).

which the optical and X-ray bands do not smoothly join and yet the radio and optical regions connect with a slope of the same index as that measured in the hard X-ray band (Weistrop, Smith, and Reitsema 1979; Riegler, Agrawal, and Mushotzky 1979). Since the observations were not simultaneous, the equivalence of the two indices may be fortuitous, but it is suggestive of a physical connection. Both sets of authors interpret the data with a model which predicts this spectral characteristic, the synchrotron self-Compton (SSC) mechanism, as formulated for active galaxies by Jones, O'Dell, and Stein (1974). In general the radio spectra of BL Lac objects are flat (see, e.g., Condon 1978) and therefore it would seem quite reasonable to expect a flat spectrum X-ray component from Compton production. This led several authors to apply the SSC model to this class of source (Margon, Jones, and Wardle 1978; Schwartz *et al.* 1978, 1979). Consistency with observations has generally been forthcoming but more simultaneous measurements are required to provide tighter constraints. Since X-ray variability constrains the linear source size, consistency checks with the angular size prediction of the SSC model can be made for the objects whose redshifts are measured. However, high-frequency radio and hard X-ray correlated intensity changes would be required in order to ensure that these emissions are from the same source region.

In conclusion, it now appears that the X-ray spectrum is a distinguishing feature of a BL Lac object. Two components are often present in the 2–50 keV energy range, possibly emanating from different source regions. There is a tendency for the soft X-ray component to be a continuation of the optical–UV emission. Simultaneous monitoring of these two spectral bands would clarify the situation (Kondo *et al.* 1980). There are observational reasons for believing an SSC model may be applicable to the hard X-ray emission, and it will be useful to search for correlated changes of this X-ray component with the radio flux. It may be that synchrotron emission from relativistic jets dominates the central energy source emission at frequencies below and including the soft X-ray in sources with apparent superluminal expansions (Marscher 1980). Such sources, which have remained below the detection threshold of proportional counters in the 2–50 keV energy range, would then appear to be good candidates for the lower energy X-ray detectors of the *Einstein Observatory*.

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