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SOFT X-RAY OBSERVATIONS OF TWO BL LACERTAE OBJECTS: MARKARIAN 421 AND 501

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ABSTRACT

In this paper we report on the soft X-ray (0.15–2.8 keV) observations of two BL Lacertae–type objects, viz., Mrk 421 and Mrk 501. The observations were made with the low-energy detectors on the *HEAO 1* satellite during the period 1977 August–1978 December. We find steep, soft X-ray power-law spectra with photon index $\Gamma \approx 3$ for both Mrk 421 and Mrk 501. The power-law models are found to give a significantly better fit than the thermal models to the observed pulse-height spectra of Mrk 421 and Mrk 501. Day-to-day soft X-ray (0.25 keV band) intensity variations are observed only in Mrk 501. No significant change is found in Γ from both the BL Lac objects during our period of observations. However, the sum of all the X-ray observations from 1976 until 1980 can be understood in terms of two spectral components of variable intensity to account for the X-ray emission observed between 0.15 and 20 keV from Mrk 421 and Mrk 501. No correlation is observed between intensity variations and the spectral form.

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

I. INTRODUCTION

The compact extragalactic sources called BL Lacertae objects are known to be strong and variable X-ray emitters. Among these, Mrk 421 and Mrk 501 were the first two BL Lac objects to be identified as X-ray sources (Ricketts, Cooke, and Pounds 1976; Schwartz *et al.* 1978). Since then further observations have confirmed these BL Lac objects as sources of both soft and hard X-ray emission (Mushotzky *et al.* 1978; Hearn, Marshall, and Jernigan 1979; Schwartz *et al.* 1979; Mushotzky *et al.* 1979; Worrall *et al* 1981; Kondo *et al.* 1981). In this paper we report on 0.15–2.8 keV observations of Mrk 421 and Mrk 501 made with the A-2 experiment on board *HEAO 1*.[2] We derive photon spectra for the sources and search for variability in the low-energy flux. In both sources, two spectral components of variable intensity are required to account for the X-ray emission observed between 0.15 and 20 keV.

II. OBSERVATIONS AND ANALYSIS

The *HEAO* A-2 experiment is described in detail by Rothschild *et al.* (1979). It consists of six multiwire, multilayer gas proportional counters sensitive over the 0.15–60 keV band. The X-ray data reported here were taken with the low-energy detector, LED 1, which is sensitive in the 0.15–2.8 keV band and has specially designed mechanical collimators with two fields of view, viz., $1\overset{\circ}{.}58 \times 2\overset{\circ}{.}97$ and $2\overset{\circ}{.}92 \times 2\overset{\circ}{.}80$. The data were obtained from the scanning as well as pointed mode of observation. The collimator design enabled us to infer the separate contributions from a source and the X-ray sky background when the detector was pointed at a single position in the sky. Aspect information acquired from an onboard star tracker was used to determine the position of the source in the detector collimator and to correct for drifts in the pointing direction of the spacecraft during the course of the observation. However, since the source contribution was relatively small, data over long periods of observation were summed and only an average correction due to pointing errors was applied.

An average internal detector background, determined from the epochs when the LEDs were pointed toward the dark Earth, was subtracted from the LED 1 data before the source and X-ray background contributions were inferred. This method was applied to both the scaler data and the pulse-height analyzed (PHA) data obtained during the pointed mode of observation.

Both Mrk 421 and Mrk 501 have been scanned on two occasions by the LED 1 detector, 6 months apart. On each occasion, the sources were visible to the detector for at least 5 days. The observations of Mrk 421 were centered on 1977 November 22 and 1978 May 21; those of Mrk 501 on 1977 August 26 and 1978 February 22. In addition, Mrk 421 was observed in the pointed mode for ~4 hr on 1978 December 5.

a) Markarian 421

Detection of an X-ray source in the energy range of 0.15–2.8 keV at a position consistent with that of Mrk 421 was first reported by Walter, Mason, and Garmire (1978), from a series of scanning observations both in 1977 and 1978. Limiting our investigation to those scans in which the center of the collimator was offset from the source position by less than 2° in the direction perpendicular to that of scan, we find five acceptable sightings of the source both in 1977 and 1978. The aspect corrected mean count rates from the source in the 0.15–2.8 keV energy band were 0.059 ± 0.007 counts cm^{-2} s^{-1} in 1977 and 0.034 ± 0.007 counts cm^{-2} s^{-1} in 1978. The uncertainties quoted are 1 σ errors only. In the 0.15–0.5 keV energy band, the source was detected at nearly the same intensity level during the two scans separated by ~6 months. In the 0.5–2.8 keV energy range, however, the source intensity in 1978 May was more than a factor of 2 lower (barely detectable at 2.4 σ above background) compared to the observed intensity (0.015 ± 0.0024 counts cm^{-2} s^{-1} 6 months earlier. The systematic difference in the average background level at 0.5–2.8 keV measured 6 months apart is only 0.001 counts cm^{-2} s^{-1}, and the maximum observed variation during a scan

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[2] The A-2 experiment on *HEAO 1* is a collaborative effort led by E. Boldt of GSFC and G. Garmire of PSU, with collaborators at GSFC, CIT, JPL, and UCB.

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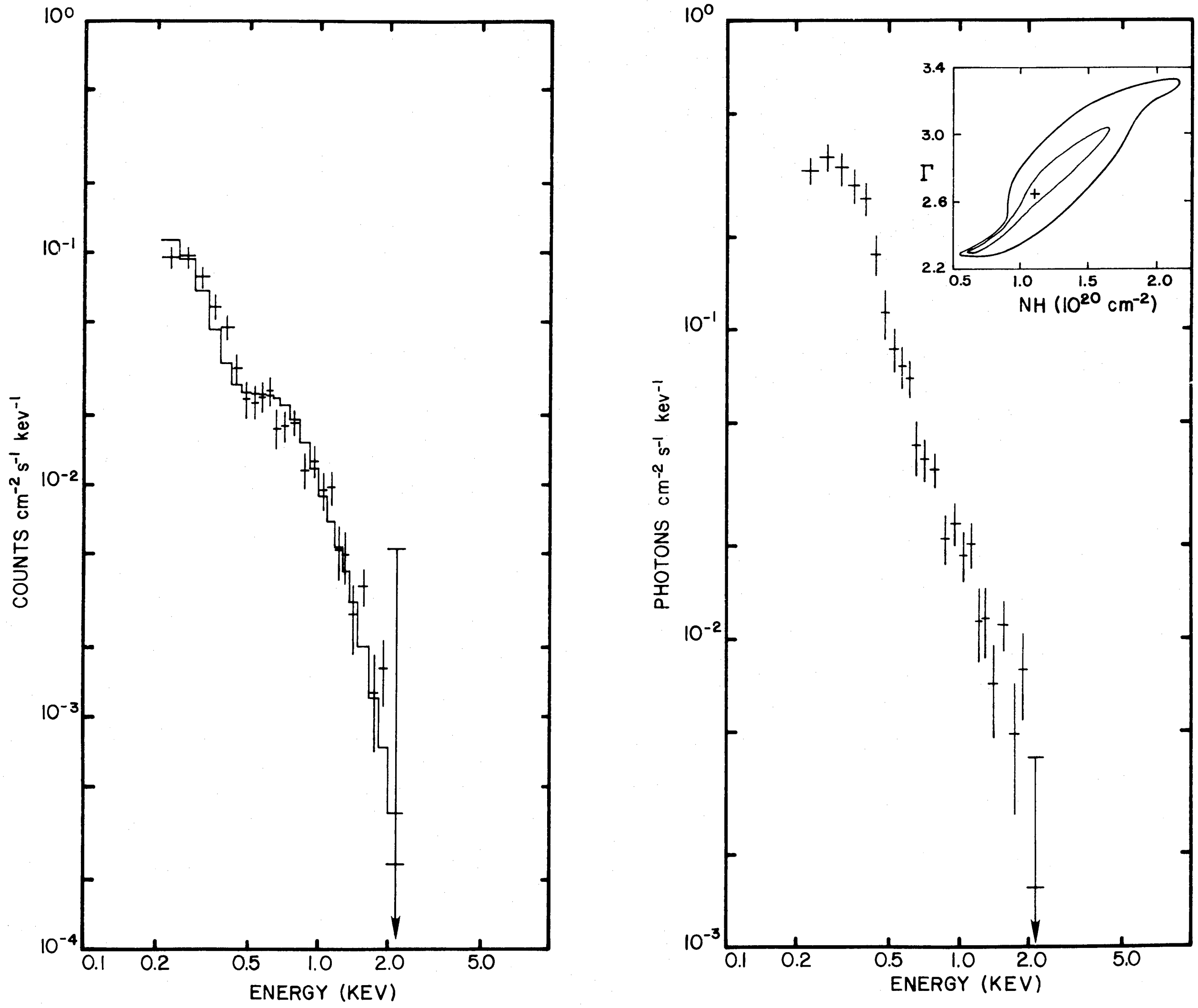
is only 0.003 counts $\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$. Therefore, a variation in the source intensity in 0.5–2.8 keV band is required to account for the observed change in the count rate from Mrk 421. In the pointed mode of observation on 1978 December 5, nearly 6700 s of useful data on Mrk 421 were obtained. The aspect corrected mean count rate due to the source was observed to be 0.032 ± 0.001 counts $\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ in the 0.15–2.8 keV band. The source intensity in the 0.15–0.5 keV band was observed to be about a factor of 2 lower than that observed during the scans in 1977 and 1978, whereas the count rate in the 0.5–2.8 keV was only slightly higher than the 3 σ upper limit obtained during the scans in 1978. No significant variations in the source intensity were observed over typical time scale of 1000 s.

The pulse-height spectra of Mrk 421 were obtained from the 1977 November scan data and the 1978 December pointing data. Both power-law and thermal bremsstrahlung (exponential plus Gaunt factor) models together with a low-energy absorption term were tried for fitting the observed PHA distribution of Mrk 421. In both cases the data were better fitted with a power law (χ^2 of 8.5 for 7 degrees of freedom for the scan data and χ^2 of 36.3 for 21 degrees of freedom for pointing data, respectively) than with the thermal model (χ^2 of 11.5 and 53.5 for the scan and pointing data, respectively). The best-fit power-law distribution obtained from the 1977 scan has a slope (photon index) $\Gamma = 3.5(+1.7;\ -1.3)$, $N_{\mathrm{H}} = [2.2(+2.5;\ -1.1)] \times 10^{20}$ atoms cm^{-2} and normalization constant $= 2.3 \times 10^{-2}$ photons $\mathrm{cm}^{-2}\ \mathrm{s}^{-1}\ \mathrm{keV}^{-1}$. The errors indicated are 90% confidence errors. Figure 1 shows the 1978 December 5 PHA data superposed with the best-fit power-law model histogram (*left*) and the deduced spectrum (*right*). The best-fit power law, in this case, has a slope $\Gamma = 2.7(+0.3;\ -0.4)$, $N_{\mathrm{H}} = [1.1(+0.5;\ -0.6)] \times 10^{20}$ atoms cm^{-2} and normalization constant $= 2.1 \times 10^{-2}$ photons $\mathrm{cm}^{-2}\ \mathrm{s}^{-1}\ \mathrm{keV}^{-1}$. The 90% and 99% confidence contours for Γ and N_{H} derived using the criterion of Lampton, Margon and Bowyer 1976 are also shown in Figure 1. The galactic neutral hydrogen column density in the direction of Mrk 421 is 1.7×10^{20} atoms cm^{-2} (Heiles 1975). Simultaneous high-energy (2–30 keV) observations of Mrk 421 (Mushotzky *et al.* 1978; Mushotzky



LED PHA DATA

LED SPECTRUM

FIG. 1.—X-ray spectrum of Mrk 421 obtained from the pointed mode of observation on 1978 December 5, with *HEAO* A-2 LED 1. *Left:* pulse-height data superposed on the best-fit power-law plus absorption model histogram. The deconvolved incident spectrum is shown on the right.

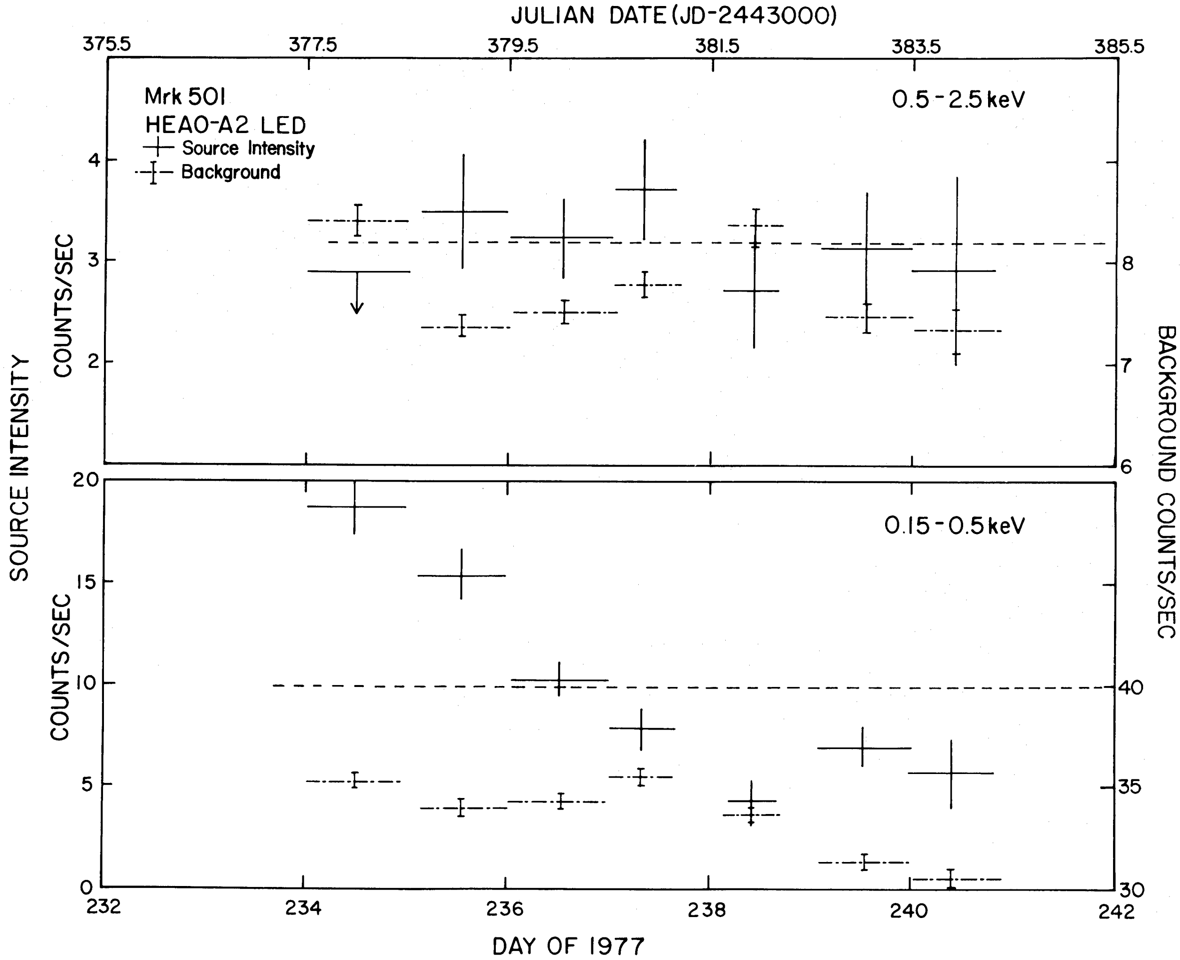


FIG. 2.—Observed count rate from Mrk 501 in the 0.15–0.50 keV band (*bottom*) and 0.5–2.5 keV band (*top*) is shown as a function of time. The background count rate is also shown for the two bands with its scale on the right.

et al. 1979) during scans in 1977 and 1978 did not provide good quality statistical data and, therefore, no simultaneous high-energy spectra were obtained.

b) *Markarian 501*

Markarian 501 was sighted ~95 times during the 1977 August transit of the source. Mrk 501 was sighted more often than Mrk 421 as it is closer to an ecliptic pole through which every scan of the satellite passes. The intensity of the source corrected for the collimator transmission off-axis is shown in Figure 2, as a function of time. There is evidence for a factor of 2 decrease in the low-energy (0.15–0.50 keV) flux, over a time scale of 2 days. Although the background in the 0.15–0.50 keV band is quite structured and not strictly constant, the observed variations in the background are smaller than the observed change in the source flux. The background variations are also shown in Figure 3. No significant variation in the source flux is observed at energies between 0.5–2.8 keV. The mean count rate averaged over the 1977 sightings is 0.039 ± 0.002 count $\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ in the 0.15–2.8 keV energy band. Only six sightings were made in 1978 due to problems in the LEDs, and all except one were at a lower high voltage setting, so that a direct comparison is spectrally dependent. Based on an assumed constant spectral shape, the source intensity in the 0.15–2.8 keV energy range is the same to within 30% over the 6 month interval.

The pulse-height spectrum of the source was obtained from the 1977 August data. Both the power-law and the thermal bremsstrahlung (exponential plus Gaunt factor) models together with a low-energy absorption term were tried for fitting the pulse-height data. The data were better fitted with a power law (χ^2 of 11.0 with 7 degrees of freedom) than with the thermal bremsstrahlung (χ^2 of 26.3) model. The best-fit power-law distribution is shown in Figure 3. The best-fit slope[3] is $\Gamma = 3.4 \pm 0.4$, absorption is $N_{\mathrm{H}} = (1.2 \pm 0.5) \times 10^{20}$ atoms cm^{-2}, and the normalization constant is 1.14×10^{-2} photons $\mathrm{cm}^{-2}\ \mathrm{s}^{-1}\ \mathrm{keV}^{-1}$. The 90% and 99% confidence contours for Γ and N_{H} derived using the criterion of Lampton, Margon, and Bowyer (1976) are shown as inset in Figure 3. The galactic neutral hydrogen column density in the direction of Mrk 501 is about (3–4) × 10^{20} atoms cm^{-2} (Heiles 1975), which would require an even steeper slope for the low-energy spectrum of

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[3] A preliminary result from the analysis of LED data reported in Worrall *et al.* (1981) and Kondo *et al.* (1981) quoted $\Gamma = 2.5(+3.0, -0.5)$. The difference with respect to the best-fit value of Γ reported now is mainly due to the background subtraction. The soft X-ray background is very complex in the vicinity of Mrk 501. Also, the preliminary results used only the front layer data from the LED with the smaller field of view and had poorer statistics.

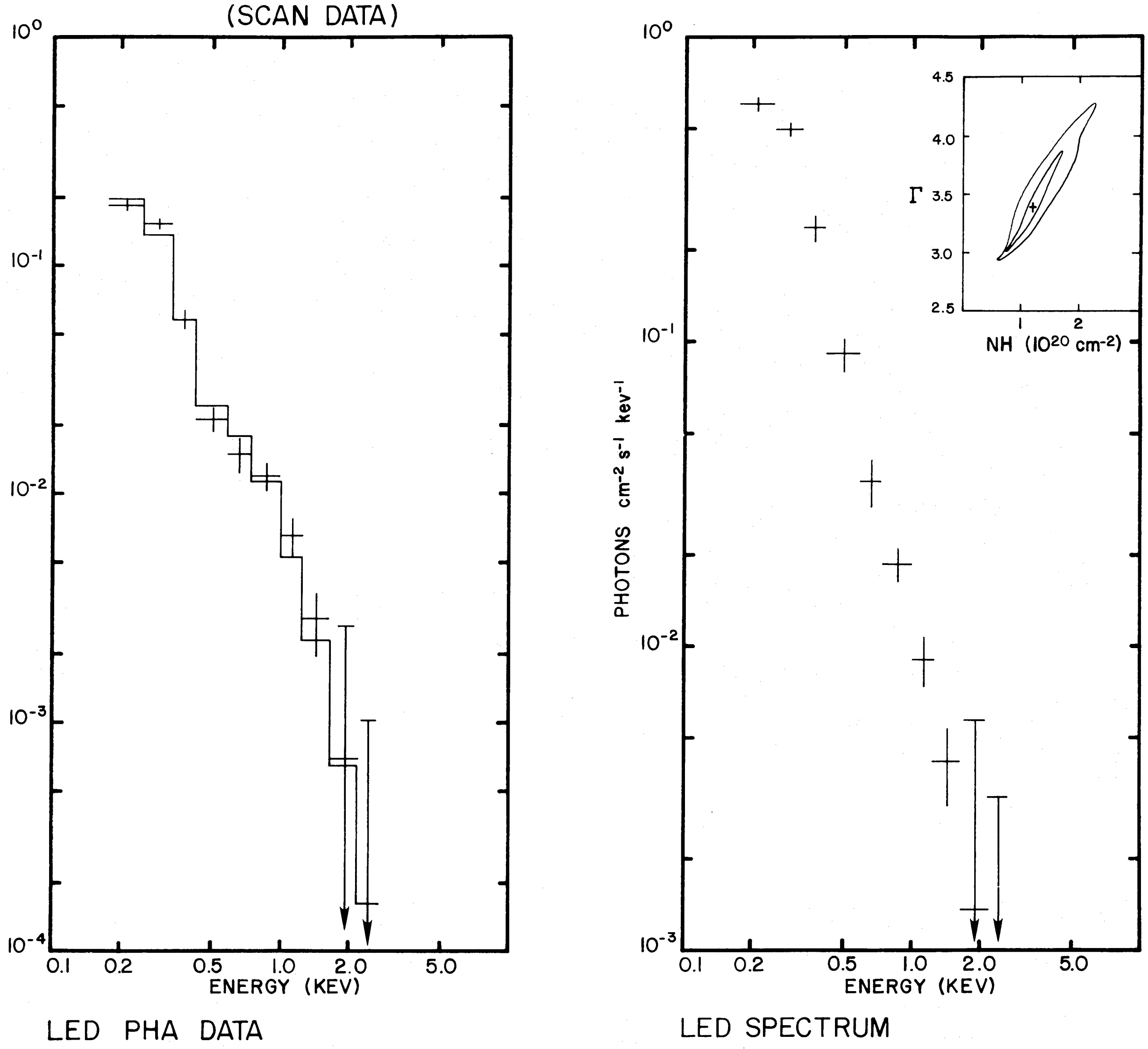

FIG. 3.—Incident photon spectrum of Mrk 501 corresponding to the best-fit power-law model

Mrk 501. A simultaneous high-energy (2–30 keV) spectrum of this was also obtained by Mushotzky *et al.* 1978). The high-energy data also favored a power-law model over the thermal bremsstrahlung model and had the best fit slope $\Gamma = 1.2 \pm 0.2$ (Mushotzky *et al.* 1978), which is significantly different from the slope obtained from the low-energy data. However, the steep, low-energy slope is consistent with the excess flux reported by Mushotzky *et al.* for energies less than 3 keV.

III. DISCUSSION

The X-ray spectral characteristics of Mrk 421 and Mrk 501 observed over the years are summarized in Tables 1 and 2, respectively. Because of the very low energy response of our detector compared with all the other detectors that have measured the spectrum of these BL Lac objects, the $N_{\rm H}$ estimates deduced by us are the best and the lowest so far, indicating a complete lack of absorption internal to these BL Lacertae sources. The spectrum of Mrk 421 was measured almost simultaneously by two different X-ray detectors with overlapping energy ranges on two different satellites (LED on *HEAO 1* and SSS on *Einstein Observatory*) in 1978 December. The spectral slope inferred from both the detectors is in good agreement. The simultaneous LED and MED data on Mrk 501 clearly indicate that at least two spectral components are responsible for 0.15–20 keV emission from this source. The spectrum of Mrk 501 obtained from the LED in this observation is also the steepest ever measured from this source. The shape of the spectrum and also the relative luminosity of the two components are very similar to those found by Riegler, Agrawal, and Mushotzky (1979) for the BL Lacertae-type object PKS 0548 − 322. Two-component spectra has been reported for another BL Lac object H2155 − 304 by Urry and Mushotzky (1982). The simultaneous LED and MED observations of Mrk 421 during 1977 November, however, were consistent with a single steep power-law spectrum. This contrasts with the very flat 2–30 keV spectrum of Mrk 421 obtained by Mushotzky *et al.* (1978) using the *OSO 8* satellite. However, there are two observations of Mrk 421 that seem to have detected both the soft and medium energy X-rays simultaneously, that of Hearn *et al.* (1979) and Hall *et al.* (1981). Hearn *et al.* interpret the spectrum in terms

TABLE 1

MARKARIAN 421

Date	Energy Range (keV)	Γ[a]	N_H (atoms cm^{-2})	0.15–0.45 keV Flux[b]	Hard X-ray Flux[b]	Reference	Notes
1976 Apr 25–26	0.1–6.0	2.1(+0.4, −0.3)	$<3 \times 10^{20}$	4.3[c]	14[d]	1	*SAS* 3
1977 May 18–20 ...	2–30	0.9(+0.45, −0.5)	$<8 \times 10^{21}$		5.3[e]	2	*OSO* 8
1977 Nov 20–26	0.15–2.50	3.5(+1.7, −1.3)	$2.2(+2.5, -1.1)10^{20}$	7.5		3	*HEAO* A-2 scan
	2–10				≲2.8[f]	4	*HEAO* A-2 scan
1978 May 20–24 ...	0.15–2.50			~7	...	3	*HEAO* A-2 scan No flux observed above 1 keV $\Gamma > 4$
1978 May 28	2–10	3.9(+1.3, −0.7)	$<7 \times 10^{21}$		2.8[f]	4	*HEAO* A-2 pointing
	1.6–7.0	3.0 ± 1.0			3.2[f]	5	*HEAO* A-3 (1 σ error)
1978 Dec 5	0.15–2.50	2.7(+0.3, −0.4)	$1.1(+0.5, -0.6)10^{20}$	4.0		3	*HEAO* A-2 pointing
1978 Dec 5–9	0.6–4.5	3.3(+1.3, −1.0)	$2.6(+1.6, -1.2)10^{21}$		4.2(+3.7, −1.5)[g]	6	*Einstein Observatory* SSS
1979 May 10	0.6–4.5	2.3(+0.8, −0.5)	$6(+0.8, -0.6)10^{20}$		0.67(+0.1, −0.06)[g]	6	*Einstein Observatory* SSS
1980 Jan–Feb	1–10	2.9(+0.9, −0.4)	$<6 \times 10^{20}$		6 ± 2[f]	7	*Ariel 6* two-component power law with $\Gamma = 3.4 \pm 0.4$ and $\Gamma_2 = 1.0 \pm 0.8$

[a] Errors are 90% confidence for all except *HEAO* A-3 data.
[b] Flux is in units of 10^{-11} ergs cm^{-2} s^{-1}.
[c] Average flux.
[d] (1.0–6.0 keV) range.
[e] (3–10 keV) range.
[f] (2–10 keV) range.
[g] (0.5–4.5 keV) range.

REFERENCES.—(1) Hearn, Marshall, and Jernigan 1979; (2) Mushotzky *et al.* 1978; (3) present work; (4) Mushotzky *et al.* 1979; (5) Schwartz *et al.* 1979; (6) Urry 1984; (7) Hall *et al.* 1981.

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TABLE 2

MARKARIAN 501

Date	Energy Range (keV)	Γ[a]	log N_H (atoms cm^{-2})	0.15–0.45 keV flux[b]	2–6 keV flux[b]	References	Notes
1971–1972	2–6	...	...		(2.75 ± 0.5)	1	*Uhuru*
1975 Mar 15–18 ...	1.5–15	1.8 ± 0.5	<21.7		(3.6 ± 1.8)	2	*Ariel 5*: two-component fits not tested
1977 Aug 23–30	0.15–2.5	3.4 ± 0.4	$20.08^{+0.15}_{-0.20}$	4.85	...	3	*HEAO* A-2 scan
	2–30	1.2 ± 0.4			~ 5	4	*HEAO* A-2 (two components)
1977 Aug	1–10	...	...		(3.6 ± 1.2)	5	*HEAO* A-3
1978 Sep 8	2–30	$2.5(+0.5, -0.3)$	21.66		$(2.9^{+1.0}_{-0.5})$	6	*HEAO* A-2 point
1979 Jan 25–26	0.6–4.5	$2.2(+0.7, -0.5)$	21.3 ± 0.15		$5.0(+0.9, -0.6)$[c]	7	*Einstein Observatory* SSS
1979 Mar 1–2	0.6–4.5	$1.7(+0.6, -0.2)$	21.08 ± 0.15		$5.9(+1.2, -0.2)$[c]	7	*Einstein Observatory* SSS
1979 Aug 22	0.6–4.5	2.6 ± 0.15	21.25 ± 0.05		$7.4(+0.2, -0.2)$[c]	7	*Einstein Observatory* SSS
1980 Jan 19–20	0.3–3.4	1.4 ± 0.2	20.5 ± 0.2			8	*Einstein Observatory* IPC
	1.1–9.7	1.5 ± 0.2	21.0 ± 0.6			8	*Einstein Observatory* MPC
1980 Aug 15	0.3–5.3	$0.8(+0.5, -0.2)$	$20.3^{+0.3}_{-0.2}$			8	*Einstein Observatory* IPC
	1.1–9.7	1.7 ± 0.2	$21.3^{+0.2}_{-0.8}$			8	*Einstein Observatory* MPC

[a] Errors are 90% confidence.

[b] Flux units are 10^{-11} ergs cm^{-2} s^{-1}.

[c] 0.5–4.5 keV energy band.

REFERENCES.—(1) Forman *et al.* 1978; (2) Snijders *et al.* 1979; (3) present work; (4) Mushotzky *et al.* 1978; (5) Schwartz *et al.* 1978; (6) Kondo *et al.* 1981; (7) Urry 1984; (8) Mufson *et al.* 1984.

of single-component power-law model with photon index of 2.0, which is intermediate to the power-law indices deduced from the soft and medium energy X-rays separately. They, however, did not try two component fits to their data. Hall *et al.* (1981) found that while a single power law of $\Gamma = 2.9$ provided an acceptable fit to the *Ariel 6* data, with the N_H restricted to less than 3×10^{20} cm^{-2}, the best-fit two–power-law model had indices $\Gamma_1 = 3.4$ over the energy band 1–3 keV and $\Gamma_2 = 1.0$ for energies in the range of 3–10 keV. The summary of all the observations of Mrk 421, shown in Table 1, may be understood in terms of two spectral components in accord with the appearance of Mrk 501 and PKS 0548 − 322. These are (i) a steep, low-energy X-ray emission which is essentially isolated during the 1977 November observation; and (ii) a variable high-energy tail which has a relatively flat spectral distribution. The variable nature of the hard power-law component was also observed in Mrk 501 (Kondo *et al.* 1981) and PKS 0548 − 322 (Worrall *et al.* 1981). In addition, Kondo *et al.* interpreted their observations as also suggesting the variability of a soft component in Mrk 501. The present soft X-ray observations of Mrk 421 show that, although the shape of the soft X-ray spectrum of Mrk 421 did not change significantly from 1977 November to 1978 December, its intensity did change by about a factor of 2. The soft X-ray observations of Mrk 501 indicate a day-to-day variability in its 0.25 keV flux. However, the data are not sufficient to test if the spectral shape remains constant during these observations. Similar intensity variations in the soft X-ray flux have been observed in H 2155-304 (Agrawal and Riegler 1979; Agrawal, Singh, and Riegler 1983).

The two-component spectral form of X-ray emission from the BL Lacertae-type objects has normally been explained as due to the process of synchrotron self-Compton (SSC) emission from homogeneous, relativistically moving blobs or relativistically beamed jets aligned closely with the line of sight (see Urry 1984 for detailed references and discussion of all such models). This is an attractive model as the typical spectrum of a BL Lac object across a very broad energy band, radio to soft X-rays, resembles the characteristic form of a synchrotron model with the higher energy X-rays arising due to the inverse-Compton scattering of the synchrotron photons by the same distribution of electrons that produced them. A detailed fitting of such models, however, requires simultaneous broad-band (radio to X-ray) observations of these sources due to their variable nature, and even then many of the parameters of the model are poorly determined (Mufson *et al.* 1985; Urry 1984). In these nonthermal emission models, an increase in intensity could result from an increase in injection of energetic particles and, therefore, the soft and hard X-ray intensity should increase together. However, such a correlation has not been observed due to the lack of sufficient data.

A power-law spectrum can also be generated by the scattering of soft photons by a thermal electron plasma which is hot enough ($T_e \approx 10^7$ K) (Katz 1976). In this case the emergent spectrum develops a high-energy tail whose form is independent of the source spectrum but depends on the Thomson depth τ_T and temperature T_e of the electron distribution. In a modified version of this model, Guilbert, Fabian, and McCray (1982) included the Compton cooling of the hot gas by soft X-ray photons and found that the X-ray spectrum from a cooling gas hardens as the intensity increases and then softens as the intensity decreases. The limited amount of observational data in Tables 1 and 2 do not show any such trend.

Summarizing, we find that the steep power laws fit the observed soft X-ray spectra of Mrk 421 and 501 much better than do the thermal bremsstrahlung models. No intrinsic absorption is observed in these objects. The broad-band X-ray (0.15–20 keV) observations of these sources can be understood in terms of the presence of two spectral components of variable intensity. Future long-term observations with moderate resolution, broad-band X-ray spectrometers will determine whether both the components are always present or not and whether their variations are related in any way. Simultaneous broad-band (radio to X-ray) monitoring of these sources for extended periods is required to distinguish between various possible emission processes and scenarios.

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