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UPPER LIMITS FROM HARD X-RAY OBSERVATIONS OF FIVE BL LACERTAE OBJECTS

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ABSTRACT

We report here the results of *HEAO 1* hard X-ray observations of the five brightest X-ray BL Lacertae objects: PKS 0548−322, Mrk 421 (=1101+384), 2A 1219+305, Mrk 501 (=1652+398), and PKS 2155−304. The observations covered the energy range 15–165 keV and the time span of 1977 August to 1978 December. No detections were made at the 3 σ level 12–165 keV for any objects, and 2 σ upper limits to the inferred flux in six broad energy bands are given. When compared to results from *OSO 8* a year earlier and to a balloon measurement 3 years later, the upper limits for flux from Mrk 421 imply variability in the 15–60 keV energy range of a factor of 5 or more. Comparisons of 2–40 keV and 15–165 keV *HEAO 1* data on PKS 2155−304 imply that the spectral component above 10 keV must either be time variable or must steepen beyond 40 keV. If steepening is the case, a synchrotron self-Compton model can relate it to the steepening in the infrared to give a value of 10^2 for the Lorentz factor of the relativistic electrons, or an accretion disk model can yield an electron energy of 15 keV in the inner portions of the disk. The present results still allow the flat hard components reported from these objects to contribute significantly to the total bolometric luminosity, if the components are extrapolated unchanged to 100 keV or beyond.

Subject headings: BL Lacertae objects — radiation mechanisms — X-rays: sources — X-rays: spectra

I. INTRODUCTION

X-ray spectra of the five brightest BL Lacertae objects, PKS 0548−322, Mrk 421 (=1101+384), 2A 1219+305, Mrk 501 (=1652+398), and PKS 2155−304, have been measured with many instruments on board satellites (see Urry, Mushotzky, and Holt [1986] for a review). The spectra below ~5 keV are found to be steep with power-law indices between 2.0 and 4.0 for the photon flux. Some of the spectra indicate flattening at higher energies (Riegler, Agrawal, and Mushotzky 1979; Hall *et al.* 1981; Urry and Mushotzky 1982; Ubertini *et al.* 1984) with photon indices of ~1.0. Urry, Mushotzky, and Holt (1986) conclude from this that apparently discrepant spectral measurements from instruments covering different energy ranges can be reconciled by utilizing the assumption of a two-component spectrum: a steep lower energy component and a flat higher energy component. Variability in both components of the X-ray spectra has also been reported for most of these BL Lac objects (Urry, Mushotzky, and Holt 1986, and references therein).

Because of the low photon flux only upper limits have been reported above 30 keV for BL Lac objects (Coe *et al.* 1979), with the exception of a detection of Mrk 421 from 16 to 62 keV (Ubertini *et al.* 1984). Nevertheless, observations at these higher energies are important, since they can be used to further constrain the hard-component models and since extensions of the flat components to 100 keV would imply that the majority of the energy output by BL Lac objects would be in the hard X-ray and gamma-ray range, as is seen for Seyferts and quasars (see, e.g., Lingenfelter 1987).

II. OBSERVATIONS

The five BL Lac objects were observed with the two low-energy detectors (LED) of the UCSD/MIT hard X-ray and low energy gamma-ray experiment (A4) on board *HEAO 1* between 15 keV and 165 keV. The LEDs consist of NaI(Tl)/CsI(Na) phoswich scintillation counters, each of 103 cm^2 area and a 1°2 × 20° FWHM field of view. For a detailed description of the instrument see Matteson (1978). The A4 detectors are co-aligned with the GSFC/CIT cosmic X-ray experiment (A2) and those of the scanning modulation collimator experiment. All three sets of detectors simultaneously viewed sources on the *HEAO 1* scan plane, but exposures to sources off the scan plane varied due to the different fields of view of the various detector systems. Each source was scanned by the A4 LEDs during three epochs between 1977 August and 1978 December (see Table 1), and each epoch yielded typically 4300 s livetime on a given source with an effective area of ~34 cm^2. The data within one epoch are a set of 10–15 s exposures spaced at multiples of 33 minutes (once per spacecraft rotation), while the spin axis of *HEAO 1* moved through the sky at about 1° per day. The duration of an epoch of scanning of a source is determined by requiring at least 25% of maximum aperture response to the source in any given scan across it. Thus, epochs lasted for at least 1 month and occurred every 6 months. Some scans yielded no livetime on source due to SAA passages, Earth occultations of the source, special data modes, and telemetry dropouts.

No pointed *HEAO 1* observations of these sources were conducted in a mode that enabled A4 background data also to be collected. Hence, no A4 results are simultaneous with A2 results from pointed observations.

III. DATA ANALYSIS AND RESULTS

The LED background was measured for adjacent time intervals before and after each on-source scan. Net source spectra were then determined by subtraction of off-source spectral accumulations from on source accumulations. The inclination of 60° between the two LED collimators allowed for the elimination of data from other detectable sources in either on-source or off-source regions.

The effective area of LED2 was reduced between 1977

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TABLE 1

OBSERVED FLUXES FROM FIVE BL LACERTAE OBJECTS

Source	Observation Days	Energy (keV)	2 σ upper limits (photons per cm^2 s keV)
PKS 0548 − 322	1977 Sep 4–Oct 11	15–20	2.3×10^{-4}
	1978 Feb 25–Apr 5	20–30	5.7×10^{-5}
	1978 Aug 28–Oct 11	30–50	4.9×10^{-5}
		50–80	2.7×10^{-5}
		80–120	1.1×10^{-5}
		120–165	2.6×10^{-5}
Mrk 421	1977 Nov 11–Dec 3	15–20	2.8×10^{-4}
	1978 May 9–30	20–30	4.7×10^{-5}
	1978 Nov 10–Dec 7	30–50	3.7×10^{-5}
		50–80	2.7×10^{-6}
		80–120	1.6×10^{-5}
		120–165	1.6×10^{-5}
2A 1219 + 305	1977 Nov 29–Dec 28	15–20	1.9×10^{-4}
	1978 Jun 3–26	20–30	-1.0×10^{-6}
	1978 Dec 2–26	30–50	2.7×10^{-5}
		50–80	1.2×10^{-5}
		80–120	4.6×10^{-6}
		120–165	2.1×10^{-5}
Mrk 501	1977 Aug 18–Sep 17	15–20	1.9×10^{-4}
	1978 Jan 28–Mar 17	20–30	9.6×10^{-5}
	1978 Aug 3–Sep 19	30–50	3.4×10^{-5}
		50–80	1.9×10^{-5}
		80–120	2.1×10^{-5}
		120–165	2.1×10^{-5}
PKS 2155 − 304	1977 Nov 1–20	15–20	2.6×10^{-4}
	1978 Apr 29–May 24	20–30	5.8×10^{-5}
	1978 Nov 1–25	30–50	2.5×10^{-5}
		50–80	1.6×10^{-5}
		80–120	1.8×10^{-5}
		120–165	2.9×10^{-5}

August 19 and 1978 April 3 and between 1978 September 11 and 1978 October 31 due to the A4 blocking crystal partially obscuring that LED's field of view. A correction factor for this effect was derived from calibrations on the Crab nebula (Nolan 1982).

None of the BL Lac sources was detected in the 12–165 keV range at greater than 3 σ in any scanning epoch. The data from all three epochs for a given source were combined into one data set, and each of the five resulting data sets was found to be consistent with no detection. The inferred 2 σ upper limits to the flux from each of the five sources was estimated in six broad energy ranges assuming a fixed power-law photon index of 2.0. This index was chosen as a crude average representation of previously determined hard-component power-law indices (Urry, Mushotzky, and Holt 1986, and references therein). The intensity of this power law was increased until the fit to the six broad-band data points was no longer acceptable, and the resulting conversion factors were used to estimate the upper limits to the photon fluxes. Variation of this assumed power-law index by ±1.0 changes the results presented here by less than 15%. The 2 σ upper limits are given in Table 1 and are plotted in Figures 1–5 along with contemporaneous lower energy *HEAO 1* data from the A2 instruments, *OSO 8* instruments, and balloon data, when available.

IV. DISCUSSION

a) PKS 0548 − 322

Figure 1 shows the *HEAO 1* hard X-ray 2 σ upper limits established for PKS 0548 − 322, along with the lower energy *HEAO 1* data from the same three epochs (Riegler, Agrawal, and Mushotzky 1979; Worrall *et al.* 1981). The upper limits are consistent over the entire 15–165 keV range with an extrapolation (see solid line in Fig. 1) of the $0.0025\ E^{-1.19}$ fitted to the hard component by Riegler, Agrawal, and Mushotzky. The hard X-ray scanning data are not sensitive enough, however, to test for a break near 100–200 keV, such as suggested by those authors in their double self-Compton interpretation of their data below 25 keV.

b) Mrk 421

The *HEAO 1* hard X-ray 2 σ upper limits on Mrk 421 are shown in Figure 2 along with other results from *HEAO 1*, *OSO 8*, and the HXR 81M balloon observation. The *OSO 8* hard X-ray and lower energy X-ray measurements were made in 1977 May, and the HXR 81M observations were in 1981 July. The *HEAO 1* A4 scanning data upper limits are more than a factor of 8 below the hard X-ray upper limits from the *OSO 8* observations 0.5 to 1.5 yr earlier (Coe *et al.* 1979). The lower energy *OSO 8* points (Mushotzky *et al.* 1978*a*) show higher photon flux from 15–40 keV than the A4 limits would allow ~1 yr later. This is a strong indication of variability above 15 keV in Mrk 421 on a time scale of a year. Mushotzky *et al.* (1979) have previously reported variability below 15 keV. The source was again observed in a bright state 3 yr after *HEAO 1* in 1981 by Ubertini *et al.* (1984). The *HEAO 1* A4 flux upper limits in 1978 between 16.5 keV and 62 keV were at least a factor of 5 lower than the Ubertini *et al.* measurements with a significance of 3.4 σ (99.94% confidence). Finally, the A4 upper limits are consistent with that expected from an extrapolation of the 1978 May *HEAO 1* A2 data (Mushotzky *et al.* 1979), if

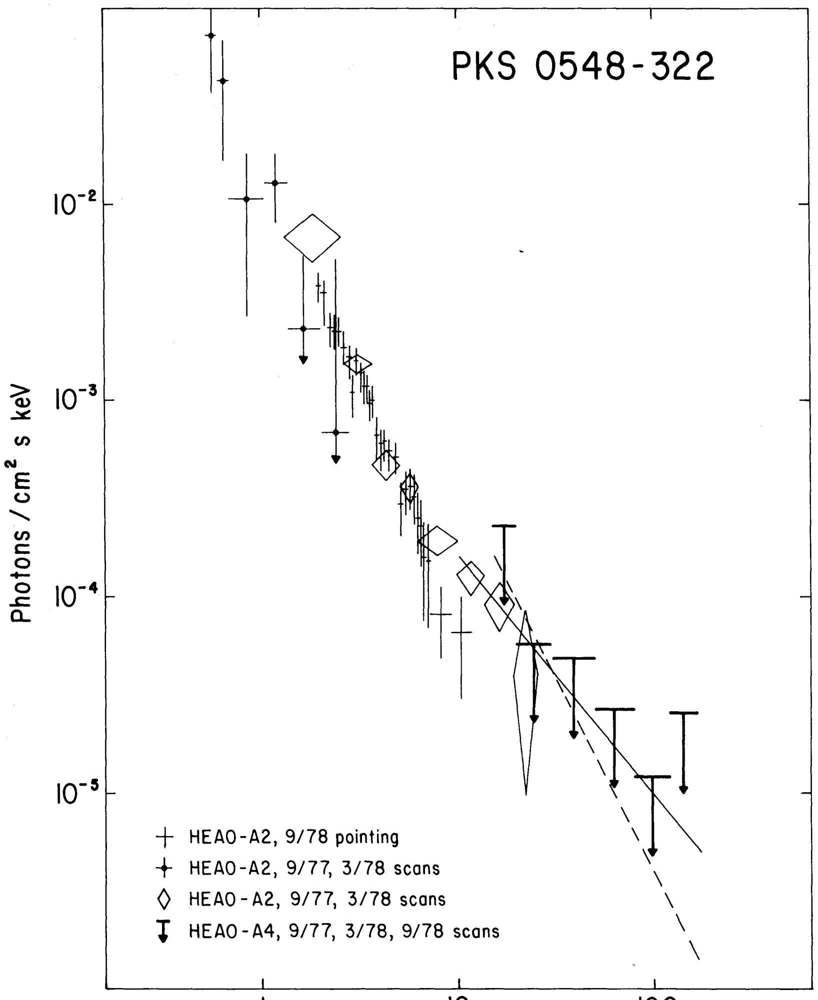

FIG. 1

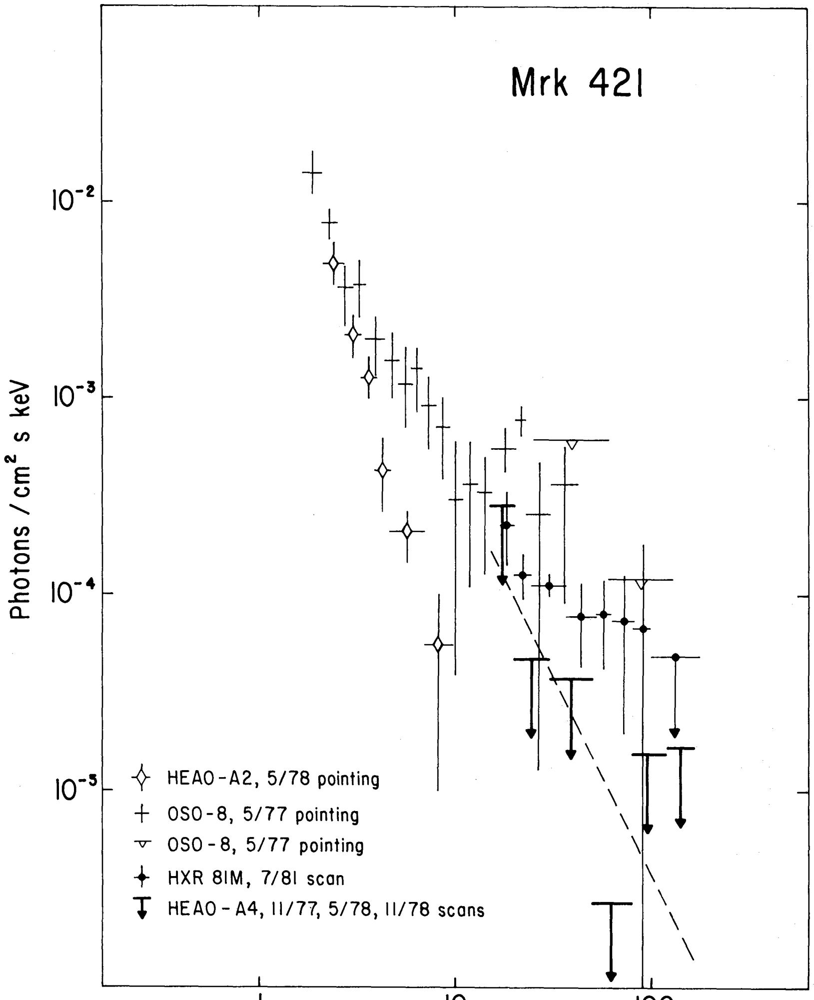

FIG. 2

FIG. 1.—The *HEAO 1* A4 2 σ upper limits to the flux from PKS 0548−322 from 15 to 165 keV. Also shown are the lower energy *HEAO 1* A2 scanning results (Riegler, Agrawal, and Mushotzky 1979) and the A2 pointing results (Worrall *et al.* 1981) taken over the same time period. The solid line represents the 0.0025 $E^{-1.19}$ fit to the hard component by Riegler, Agrawal, and Mushotzky plotted from 10 to 165 keV. The dashed line represents a 4 *Uhuru* count E^{-2} spectrum to give an indication of A4 scanning sensitivity at higher energies.

FIG. 2.—The *HEAO 1* A4 2 σ upper limits to the flux from Mrk 421 from 15 to 165 keV. Also shown are the lower energy *HEAO 1* A2 results (Mushotzky *et al.* 1979) taken from the same time period, results from *OSO 8* a year before using the proportional counters (Mushotzky *et al.* 1978*a*) and the scintillation counters (Coe *et al.* 1979), and results from the HXR 81M balloon observation 3 yr later (Ubertini *et al.* 1984). Variability on approximately yearly time scales above 15 keV must be invoked to resolve the observations. The dashed line represents a 4 *Uhuru* count E^{-2} spectrum to give an indication of A4 scanning sensitivity at higher energies.

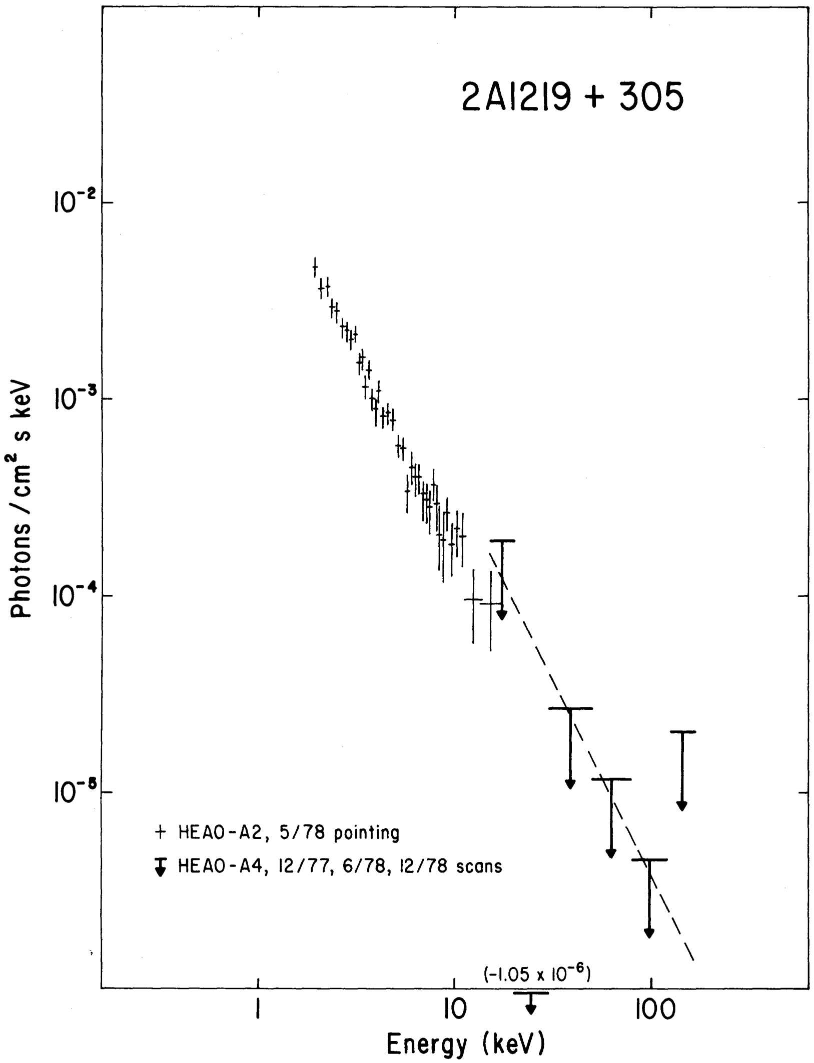

FIG. 3

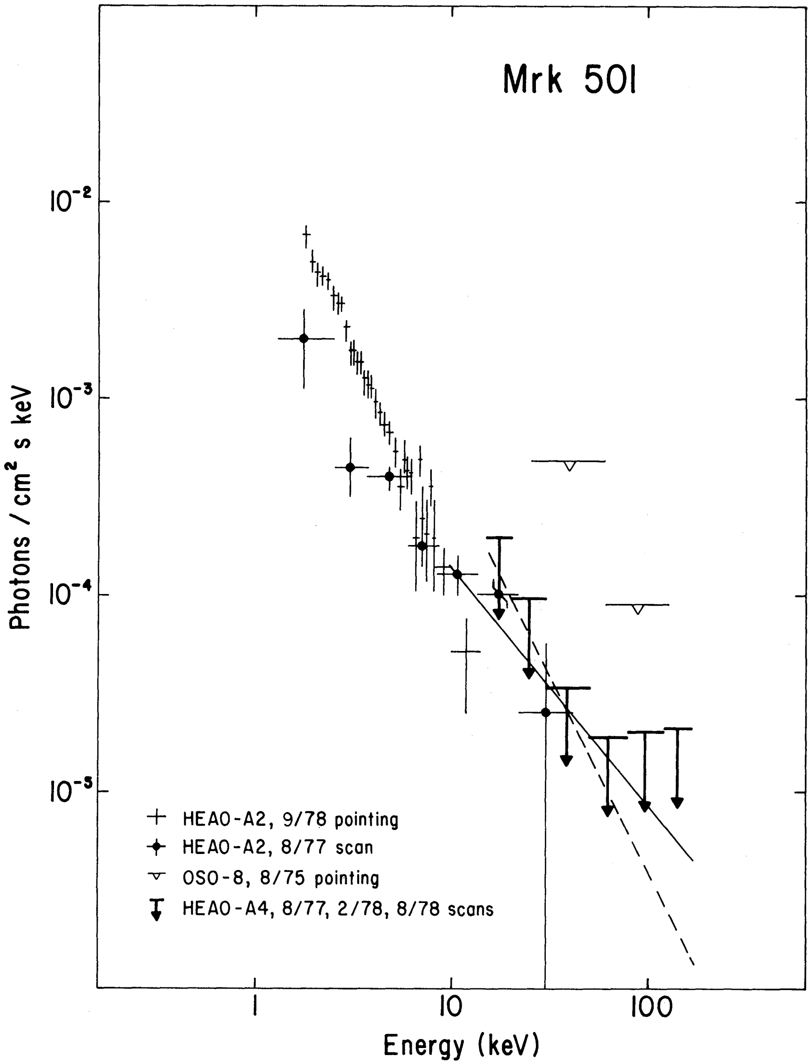

FIG. 4

FIG. 3.—The *HEAO 1* A4 2 σ upper limits to the flux from 2A 1219+305 from 15 to 165 keV. Also shown are the lower energy *HEAO 1* A2 results (Worrall *et al.* 1981) taken during the same time frame. The dashed line represents a 4 *Uhuru* count E^{-2} spectrum to give an indication of A4 scanning sensitivity at higher energies.

FIG. 4.—The *HEAO 1* A4 2 σ upper limits to the flux from Mrk 501 from 15 to 165 keV. Also shown are the lower energy *HEAO 1* A2 results (Mushotzky *et al.* 1978*a*; Kondo *et al.* 1981) taken during the same time period, as well as results from *OSO 8* (Coe *et al.* 1979) from 2–3 yr before. The dashed line represents a 4 *Uhuru* count E^{-2} spectrum to give an indication of A4 scanning sensitivity at higher energies. The solid line represents the best fit from Mushotzky *et al.* extrapolated from 10 to 165 keV.

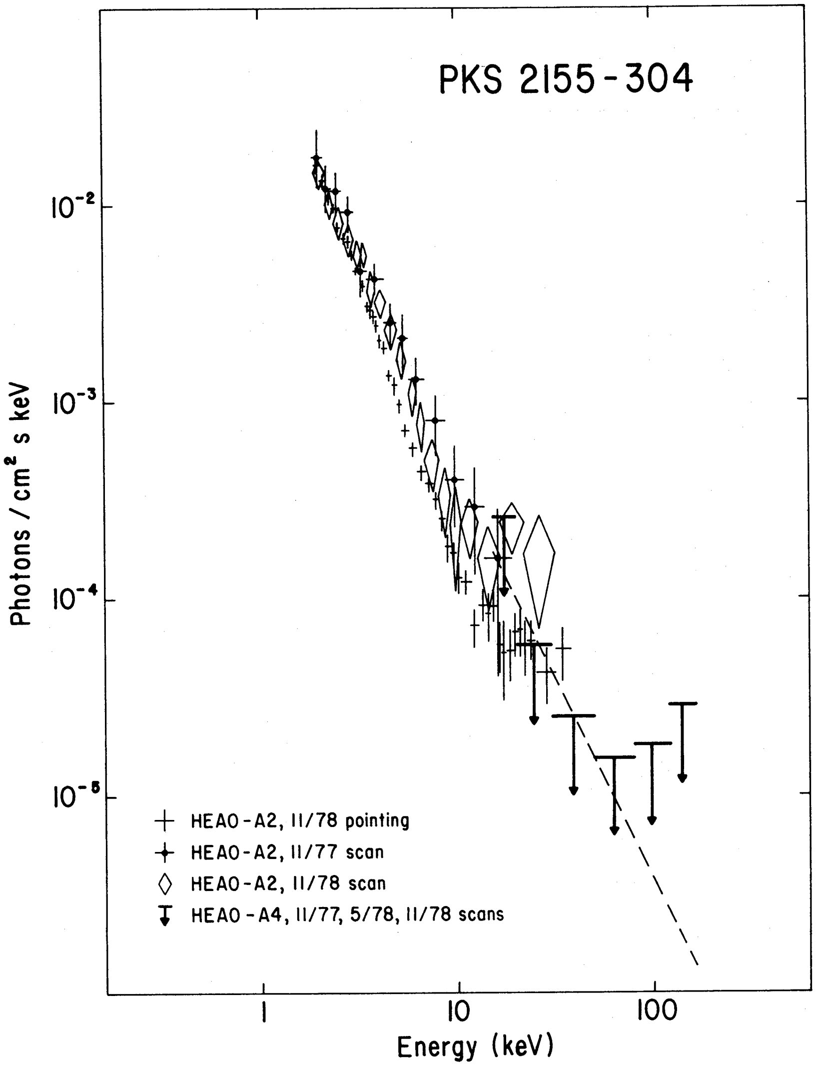

FIG. 5.—The *HEAO 1* A4 2 σ upper limits to the flux from PKS 2155−304 from 15 to 165 keV. Also shown are the lower energy *HEAO 1* A2 results (Urry and Mushotzky 1982) taken from the same time period. The dashed line represents a 4 *Uhuru* count E^{-2} spectrum to give an indication of A4 scanning sensitivity at higher energies.

the spectrum at that time continued with the same slope beyond 10 keV.

c) *2A 1219+305*

As can be seen in Figure 3 the 2 σ upper limits from the present data are consistent with an extension of the *HEAO 1* lower energy observations (Worrall *et al.* 1981) to higher energies. The hard X-ray upper limits indicate that a hard, second component of the 1219+305 spectrum was not detected at the $\sim 10^{-4}$ photons cm^{-2} s keV level above 20 keV, as seen in other BL Lac spectra, e.g., PKS 2155−304.

d) *Mrk 501*

The *HEAO 1* hard X-ray 2 σ upper limits to the flux from Mrk 501 from 1977 August to 1978 August shown in Figure 4 are a factor of 5 less than similar limits from *OSO 8* in the same energy range 2–3 yr earlier (Coe *et al.* 1979). Even though the steep, soft component varied dramatically between 1977 and 1978 (Mushotzky *et al.* 1978*a*; Kondo *et al.* 1981), no hard second component became evident in that data. The present upper limits are in agreement with an extrapolation (*solid line*) to higher energies of the flatter 1977 *HEAO A2* observations as well as those from 1978.

e) *PKS 2155−304*

The *HEAO 1* A4 2 σ upper limits for PKS 2155−304 are generally consistent with A2 data points (Urry and Mushotzky 1982) that show (Fig. 5) a flat, hard component from 10 to 40 keV. The 25–35 keV A2 scanning data point is marginally inconsistent with the 20–30 keV A4 2 σ upper limit, but this may be attributed to variability in the source during the 1 yr observation span, as discussed below. Furthermore, the A4 upper limits are below a constant-flux-per-unit-energy extension of the A2 spectrum beyond its 2–40 keV energy range. This is suggestive of a steepening of the hard component, but one must be cautious, since the A4 scanning data were accumulated over 70 days, the A2 scanning data over just 6 days, and the A2 pointed data over 6 hr. In addition, comparing the A2 scanning results to the A2 pointed results, taken 3 days before, indicates a possible variability in the hard component as large as a factor of 2 in flux. The A4 data are a combination of scanning observations in three epochs covering 1 yr's time.

Consequently, if the hard-component flux was well below the A4 upper limits from 40 to 165 keV for most of the 70 days of A4 scanning and only brightened to the A2 observed levels for short periods of time, the A4 and A2 spectral results would not require a steepening of the hard component. If, on the other hand, the 40–165 keV flux did not vary greatly during the year of *HEAO 1* observing, then the A4 results imply a spectral softening above 40 keV. A similar softening of the flat 0.5–10 keV component above 5 keV for PKS $0548-32$ has been reported recently by Barr, Giommi, and Maccagni (1987).

V. CONCLUSIONS

We have extended the energy range of *HEAO 1* observations of five BL Lac objects from 2–40 keV to 2–165 keV. Even though we did not detect significant flux from any of these sources, we are able to determine that Mrk 421 varies on time scales of years in its hard component. From 1977 to 1978, this source diminished in both its 2–10 keV flux (Mushotzky *et al.* 1979) and its 10–40 keV flux. Similarly, one interpretation of our results on PKS $2155-304$ requires large variability in the hard component on comparable time scales. This variability could be the result of a change in the size of the self-Compton region (e.g., Mushotzky *et al.* 1978*b*), or a change in an accretion disk about the hypothesized black hole powering the object (Schwartz *et al.* 1979). Future multifrequency observations will be necessary to determine the actual correlations between the various components of BL Lac spectra and thereby provide insight into the nature of these sources.

A second interpretation of the PKS $2155-304$ result is that the hard component steepened above ~40–50 keV. If this conclusion is valid, the steepening (near 10^{19} Hz) could be interpreted in the synchrotron self-Compton model (Jones, O'Dell, and Stein 1974) as a consequence of the steepening of the synchrotron spectrum near 10^{15} Hz (Urry and Mushotzky 1982). Since the change in frequency due to Compton scattering is proportional to γ^2, this would imply $\gamma \approx 10^2$, where γ is the Lorentz factor for the relativistic electrons. This would be consistent with Urry and Mushotzky's estimate of $\gamma \geq 10^2$ for this same source.

Alternatively, the spherical accretion Comptonization model (see, e.g., Maraschi, Roasio, and Treves 1982) would predict a steepening in the spectrum at 3 time the temperature of the electrons, kT_e, in the inner portions of the disk. The spectral steepening would imply $kT_e \approx 15$ keV. This is about half the value found for Cyg X-1 (Nolan 1982)—an X-ray source believed to be powered by a very much smaller black hole. Maraschi, Roasio, and Treves have, however, calculated (see their Table 1) the temperature at the inner radius of the accretion disk about black holes of mass 10 $M_\odot$ and 10^8 $M_\odot$ and find that in spite of the great difference in masses, the temperatures still can be comparable, but closer to 150 keV than 15 keV.

The present results would not detect Seyfert-like hard components ($E^{-1.7}$ power laws) for sources weaker than a few *Uhuru* counts, and such components can be significant contributors to the total luminosity of a BL Lac object. For instance, Riegler, Agrawal, and Mushotzky (1979) reported a fit to their PKS $0548-32$ data with a steep low-energy component ($0.008\ E^{-3.6}$) and a flatter hard component ($0.0025\ E^{-1.19}$). The A4 upper limits were above the hard-component fit extrapolated to higher energies. The 0.15–100 keV luminosities of the two components are comparable, and if the hard component extends to 1 MeV, as has been reported for other active galaxies (e.g., Perotti *et al.* 1981), then the hard-component luminosity approaches being an order of magnitude larger than that of the soft component. Consequently, the question of the hard-component contribution to the total bolometric luminosity cannot be answered with the present upper limits, and models requiring significant hard X-ray and gamma-ray fluxes (e.g., Fabian *et al.* 1986) cannot be ruled out.

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