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VARIABLE X-RAY SPECTRA OF BL LAC 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 A2 detectors during pointing maneuvers on September 30, 1978 and May 31, 1978 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 5 BL Lac objects detected with the A2 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--X-rays: spectra

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I. INTRODUCTION

The first evidence that BL Lac type 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 MK 421. At present this BL Lac together with four others, MK 501, PKS 0548-322, 2A 1219+305 and PKS 2155-304, have been firmly identified as sources of X-rays of energy > 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 A1 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 1980).

The first five BL Lac type objects above have all been detected with the 2-50 keV HEAO-1 A2[1] multiwire proportional counters. In this paper we present spectra of PKS 0548-322 and 2A 1219+305 measured during pointing observations in September and May 1978 respectively, and we make a comparison with spectra determined from two other observations of each source while the satellite was in its nominal scanning mode. We show that the spectra exhibit variability. Similar behavior is evident for MK 501 from comparison of the HEAO-1 A2 scanning measurements of Mushotzky et al. (1978) and Mason et al. (1980) with those from a pointing observation a year later presented by Kondo et al. (1980). Mushotzky et al. (1979a) have

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[1] The A2 experiment on HEAO 1 is a collaborative effort led by E. Boldt of GSFC and G. Garmire of CIT, with collaborators at GSFC, CIT, JPL and UCB.

already reported spectral variability for MK 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 September 1978 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 $f_{\nu} \alpha \nu^{-\alpha}$ (3800-5700 Å), $\alpha = 2 \pm 0.5$. In the visible to ~ 1 μm range, Weistrop, Smith and Reitsema (1979) find a flatter index, $\alpha \simeq 0.3$, consistent with that from radio measurements. Riegler, Agrawal and Mushotzky (1979) show that the index of the hard X-ray tail is also $\alpha \simeq 0.3$ and use this as a basis for discussion of non-thermal (SSC) emission models.

2A 1219+305 is the first example of a BL Lac object discovered through its X-ray properties. This resulted from the optical and radio search of Wilson et al. (1979) in the error box of a then unidentified Ariel 5 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 find 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. (1980). 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 catalogue designation.

II. OBSERVATIONS

The observations were made with the A2 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 I 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 ~ 2.4 10^{-11} erg cm^{-2} s^{-1}, except for 0133+47, 1727+502 and 2155-152 where we have possible detections at the 3-5σ level each corresponding to a 2-6 keV flux of roughly (1-2) 10^{-11} erg cm^{-2} s^{-1}. 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 ~ 3 10^{-12} erg cm^{-2} s^{-1}.

a. PKS 0548-322

The HEAO-1 A2 detectors pointed at the source on September 30, 1978. Figure 1 shows the p.h.a. 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, Γ = 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, March 12-22, 1978, our detectors observed the source while in their nominal scanning mode. Although the statistics are much poorer than for the point observation, we find a marginally steeper power law of index Γ = 5 (+3, -1.5) (90% errors).

The results of the first A2 observation of the source, in scanning mode during September 14-24, 1977, have already been reported by Riegler, Agrawal and Mushotzky (1979). The earlier data are described by two power 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 September 1977 and 1978, most simply described by a vanishing of the high energy flux. Using the value of column density determined by the LED's we find that the best fit power law for the September 78 data, now restricted to $2.2 < \Gamma < 2.6$ (see Figure 1), is different from the low energy fit to the September 77 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 one sigma errors, all three of our observations give the same 2-10 keV energy flux: $(3\pm0.2)\ 10^{-11}$ erg cm^{-2} s^{-1}. For the 6-day periods in March and September 1978 during which the source was observed in satellite scanning mode, using a 5% significance threshold the daily averages satisfy constant intensity. Daily deviations are <25% of the average value.

b. 2A 1219+305

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

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 A3 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 similarity with our other observations of BL Lac type objects, there is no evidence for line emission. The 2-10 keV energy flux is $(4.2 \pm 0.3)\ 10^{-11}$ erg $cm^{-2}\ s^{-1}$ for this observation.

The scanning observation of December 1977 is in good agreement in both spectral shape and intensity. However, something different was seen in December 1978. The spectrum was steeper, $\Gamma = 4\ (+1.8, -0.9)$, and the 2-10 keV energy flux at the lower value of $1.6\ 10^{-11}$ erg $cm^{-2}\ s^{-1}$. 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 December 1977 value agrees well with their measurement during the same month. For each of our 3 scanning mode observations, using a 5% significance threshold the daily averages satisfy constant intensity. Daily deviations are $< 23\%$ 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 timescale of 6 months or less. A second feature is the common requirement for spectral fits with at least two components. Thirdly, 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 I summarizes information for the 5 X-ray brightest BL Lac type objects. Power law parameters only are given in the table although, except for the HEAO-A2 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-A2 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 variability of MK 421 (Mushotzky et al. 1979a) 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 MK 501 required a detector energy resolution of better than 20% for their discovery, since the 2-10 keV counting rates remained almost constant. The MK 501 spectrum is illustrated in Figure 4, where the August 1977 data of Mushotzky et al. (1978) and Mason et al. (1980) are shown together with those of Kondo et al. (1980) from September 1978.

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 fit 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 (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 MK 501 (Kondo et al. 1980) and suggested in the non-simultaneous measurements of 2A 1219+305 (Ledden et al. 1980), 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 non-thermal origin, which is 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, MK 501 and MK 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 emanates 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 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 (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 a synchrotron self-Compton 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.

ACKNOWLEDGMENTS

We thank Dr.D. Lengyel-Frey for her assistance with the HEAO-A2 data analysis of 2A 1219+305, and Dr. A.P. Marscher for helpful discussions.

TABLE 1: X-RAY SPECTRAL PARAMETERS FOR BL LAC OBJECTS

SOURCE	DATE	ENERGY RANGE (keV)	Γ^*	N_H (atoms cm^{-2})	3 keV FLUX cm^{-2}s^{-1}keV^{-1}	REF.	NOTES
PKS 0548-322	Sep 14-24, 77	0.15 - 2	3.2 ± 0.4	2.5 ± 1 10^{20}	2.6 10^{-4}	1	HEAO-A2 scan. 2 components.
		2 - 30	1.3(+0.4,-0.3)	NWD***	7 10^{-4}		
	Mar 12-22, 78	2 - 10	5.0(+3.0,-1.5)		1.7 10^{-3}	2	HEAO-A2 scan.
	Sep 30, 78	2 - 15	2.75(+0.4,-0.3)	< 3 10^{22}	1.8 10^{-3}	2	HEAO-A2 point.
2A 1219+305	Dec 11-16, 77	2 - 20	2.1 ± 0.9	NWD***	2 10^{-3}	2	HEAO-A2 scan.
	May 31, 78	2 - 20	2.03 (+0.2,-0.1)**	< 9 10^{21}	2 10^{-3}	2	HEAO-A2 point.
		1 - 13	1.5 ± 0.5	< 3 10^{22}		3	HEAO-A3 (1σ error)
	Dec 11-16, 78	2 - 15	4.0(+1.8,-0.9)	NWD***	10^{-3}	2	HEAO-A2 scan.
Mk 501	Mar 15-18, 75	1.5 - 15	1.8 ± 0.5	< 5 10^{21}	1.8 10^{-3}	4	Ariel 5. No 2 compt. fit tests.
	Aug 19-31, 77	0.15 - 3	2.5(+3.0,-0.5)	∿ 4 10^{19}	8 10^{-4}	5	HEAO-A2 scan. 2 components.
		2 - 30	1.2 ± 0.4		5 10^{-4}	6	
	Sep 8, 78	2 - 30	2.5(+0.3,-0.2)	<1.6 10^{22}	2 10^{-3}	7	HEAO-A2 point.
Mk 421	Apr 25-26, 76	0.3 - 4	2.1(+0.4,-0.3)	< 3 10^{20}	5 10^{-3}	8	SAS 3.
	May 18-20, 77	2 - 30	0.9(+0.45,-0.5)	< 8 10^{21}	4 10^{-3}	6	OSO 8. Indication of soft excess equal to May 78 observation.
	Nov 20-26, 77	0.2 - 2.5	4.5(+2.0,-1.5)	7.5 ± 5 10^{20}	2 10^{-4}	5	HEAO-A2 scan.
	May 28, 78	2 - 10	3.9(+1.3,-0.7)	< 7 10^{21}	2 10^{-3}	9	HEAO-A2 point.
		1.6 - 7	3.0 ± 1.0	NWD***	2 10^{-3}	3	HEAO-A3 (1σ error)
PKS 2155-304	Nov 11-16, 77	0.15 - 2	2.4 ± 0.3	2.0 ± 1 10^{20}	5.5 10^{-3}	10	HEAO-A2 scan. Daily variability ∿ factor 2.
	Nov 8, 78	1 - 13	2 ± 0.5	NWD***		11	HEAO-A3 (1σ error).

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1. Riegler, Agrawal & 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, Jernigan (1979)
9. Mushotzky et al. (1979a)
10. Agrawal & Riegler (1979)
11. Griffiths et al. (1979)

* Errors are 90% confidence for all except HEAO-A3 data.

** Power law fit significantly better than thermal bremsstrahlung.

*** Not well determined.

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FIGURE CAPTIONS

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

Figure 2 - Spectral variability of PKS 0548-322 is evident from comparison of the point mode MED data of September 1978 (Figure 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).

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

Figure 4 - Spectral variability in MK 501. Here the point mode observation of September 1978 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).

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California - San Diego, La Jolla, CA 92093

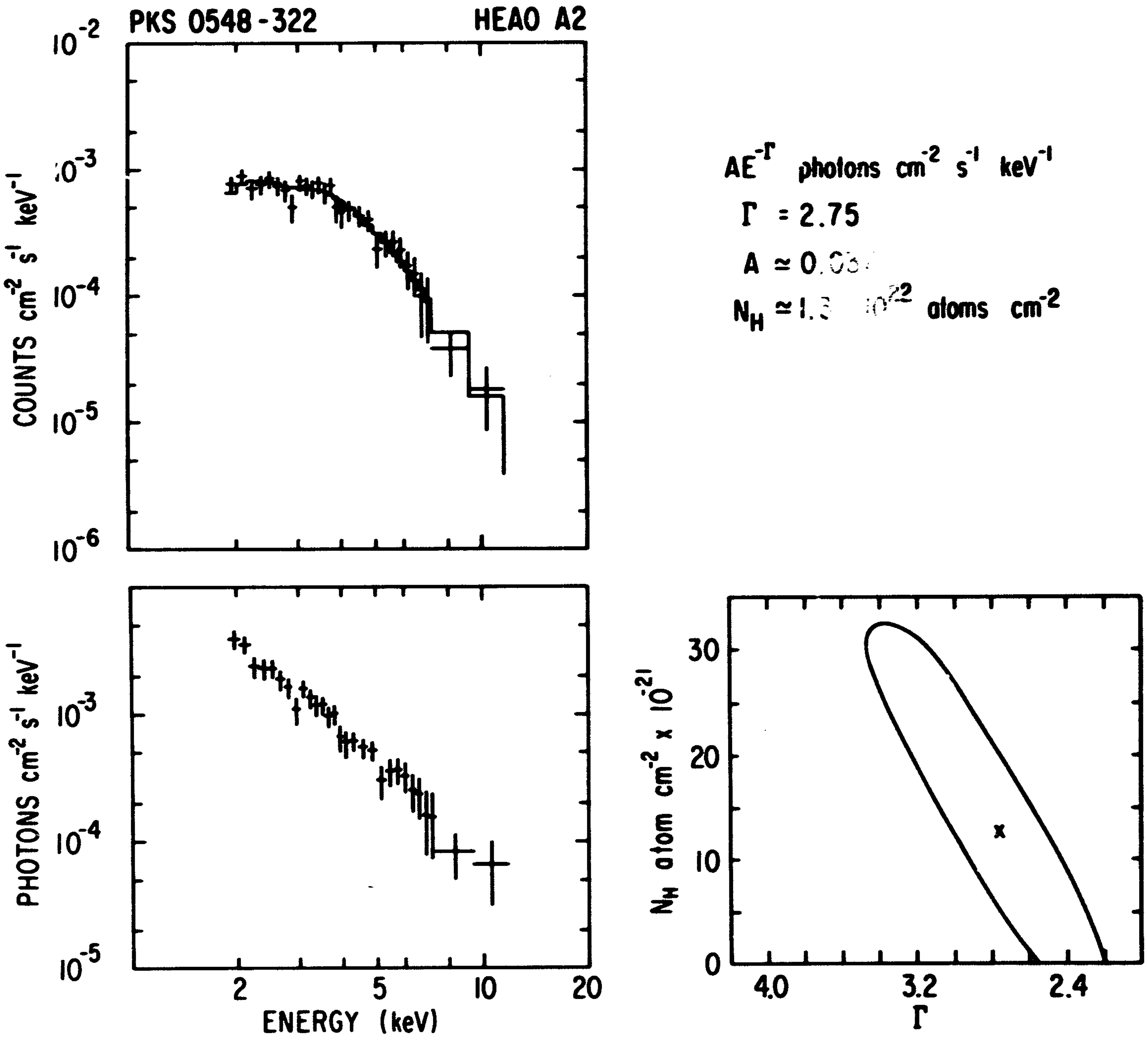
PKS 0548-322
HEAO A2
COUNTS cm^{-2} s^{-1} keV^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
PHOTONS cm^{-2} s^{-1} keV^{-1}
10^{-3}
10^{-4}
10^{-5}
2
5
10
20
ENERGY (keV)
AE$^{-\Gamma}$ photons cm^{-2} s^{-1} keV^{-1}
Γ = 2.75
A ≃ 0.03
N$_H$ ≃ 1.3 10^{22} atoms cm^{-2}
N$_H$ atom cm^{-2} x 10^{21}
30
20
10
0
4.0
3.2
2.4
Γ
x

FIGURE 1

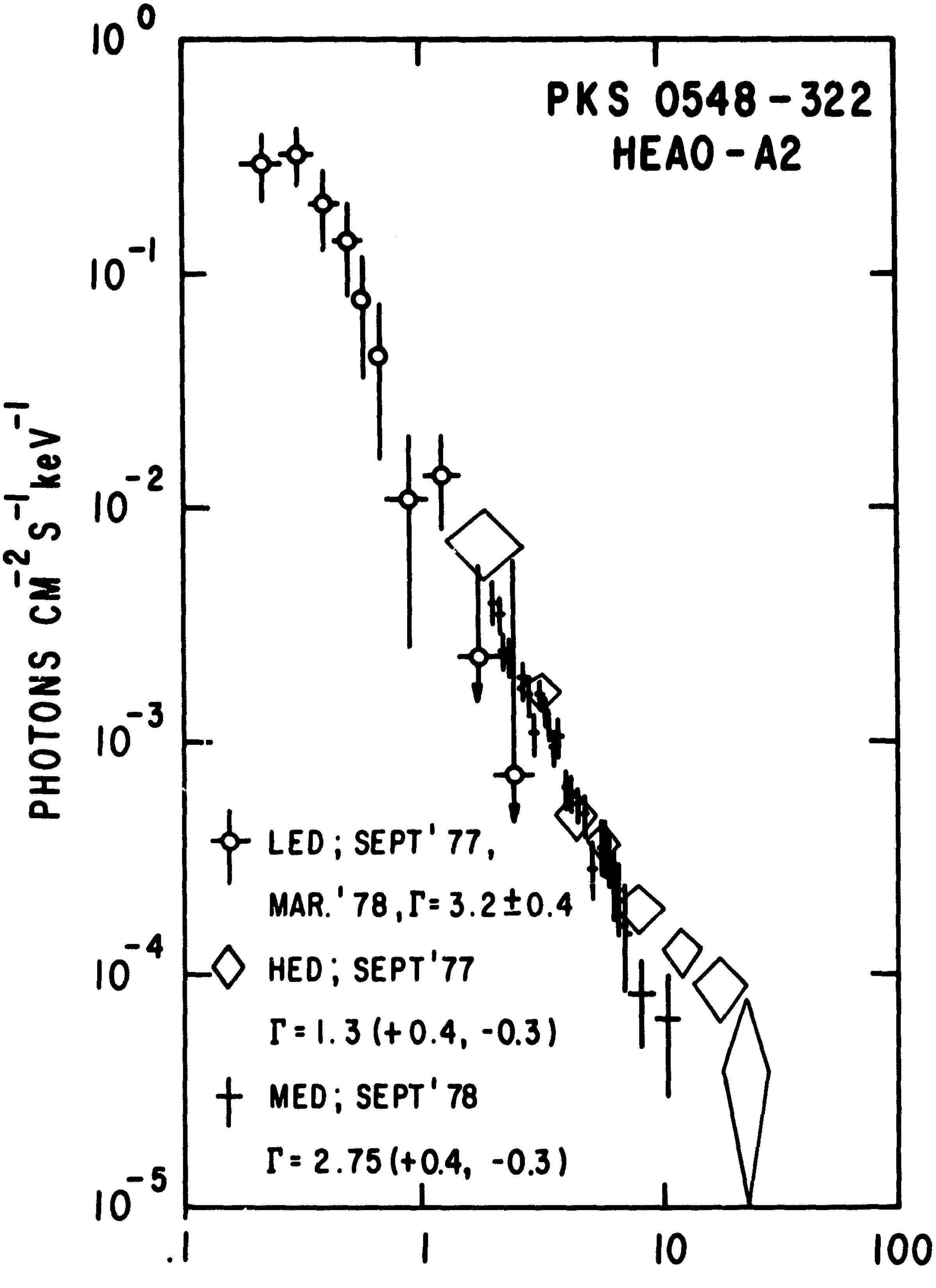
PKS 0548-322
HEAO-A2
PHOTONS CM^{-2} S^{-1} keV^{-1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
.1
1
10
100
ENERGY (keV)
LED; SEPT '77, MAR. '78, Γ = 3.2 ± 0.4
HED; SEPT '77 Γ = 1.3 (+0.4, -0.3)
MED; SEPT '78 Γ = 2.75 (+0.4, -0.3)

FIGURE 2

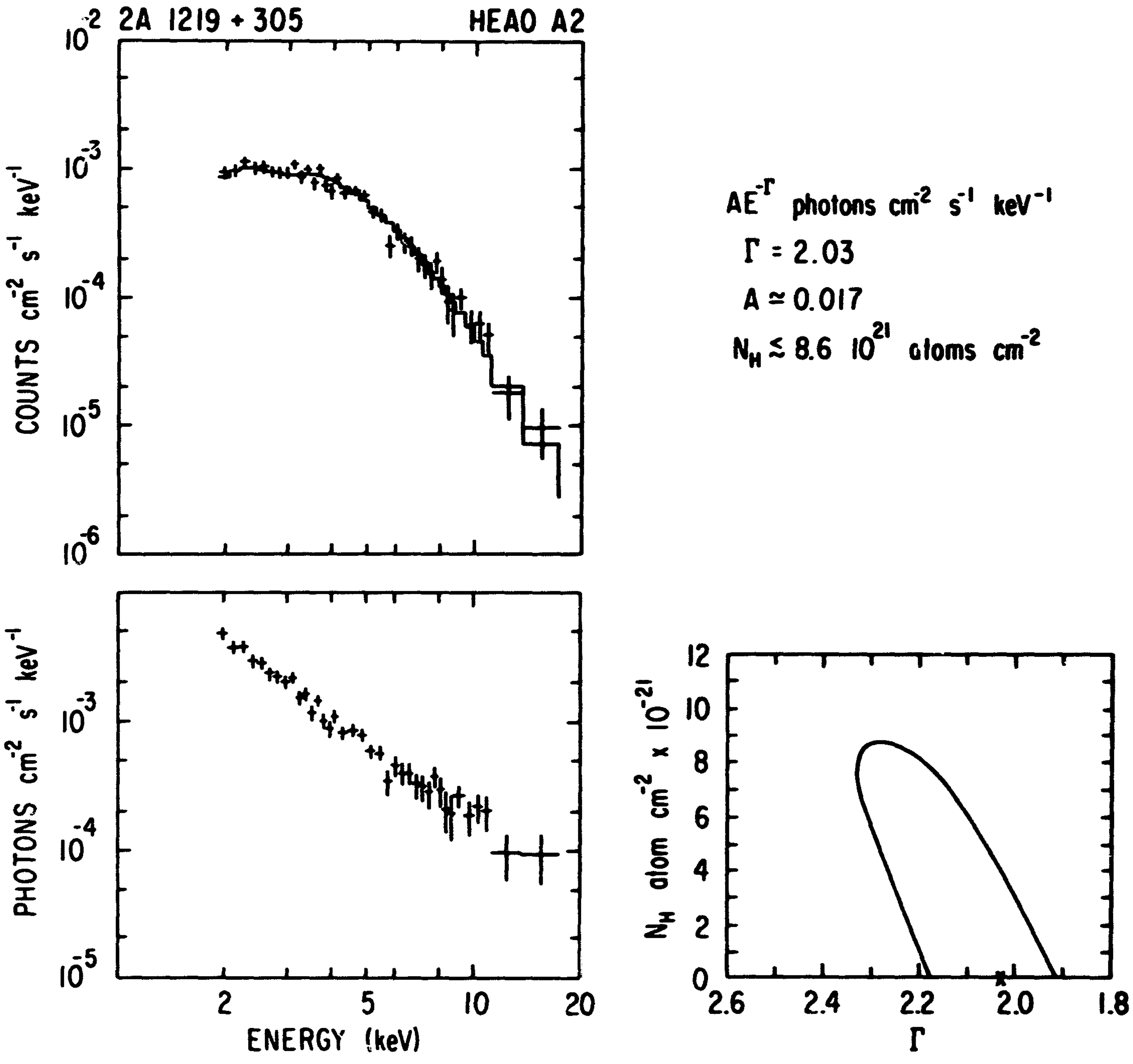
2A 1219 + 305
HEAO A2
COUNTS cm^{-2} s^{-1} keV^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
PHOTONS cm^{-2} s^{-1} keV^{-1}
10^{-3}
10^{-4}
10^{-5}
2
5
10
20
ENERGY (keV)
$AE^{-\Gamma}$ photons cm^{2} s^{-1} keV^{-1}
$\Gamma = 2.03$
$A \simeq 0.017$
$N_H \lesssim 8.6\ 10^{21}$ atoms cm^{-2}
N_H atom cm^{-2} x 10^{-21}
0
2
4
6
8
10
12
2.6
2.4
2.2
2.0
1.8
Γ

FIGURE 3

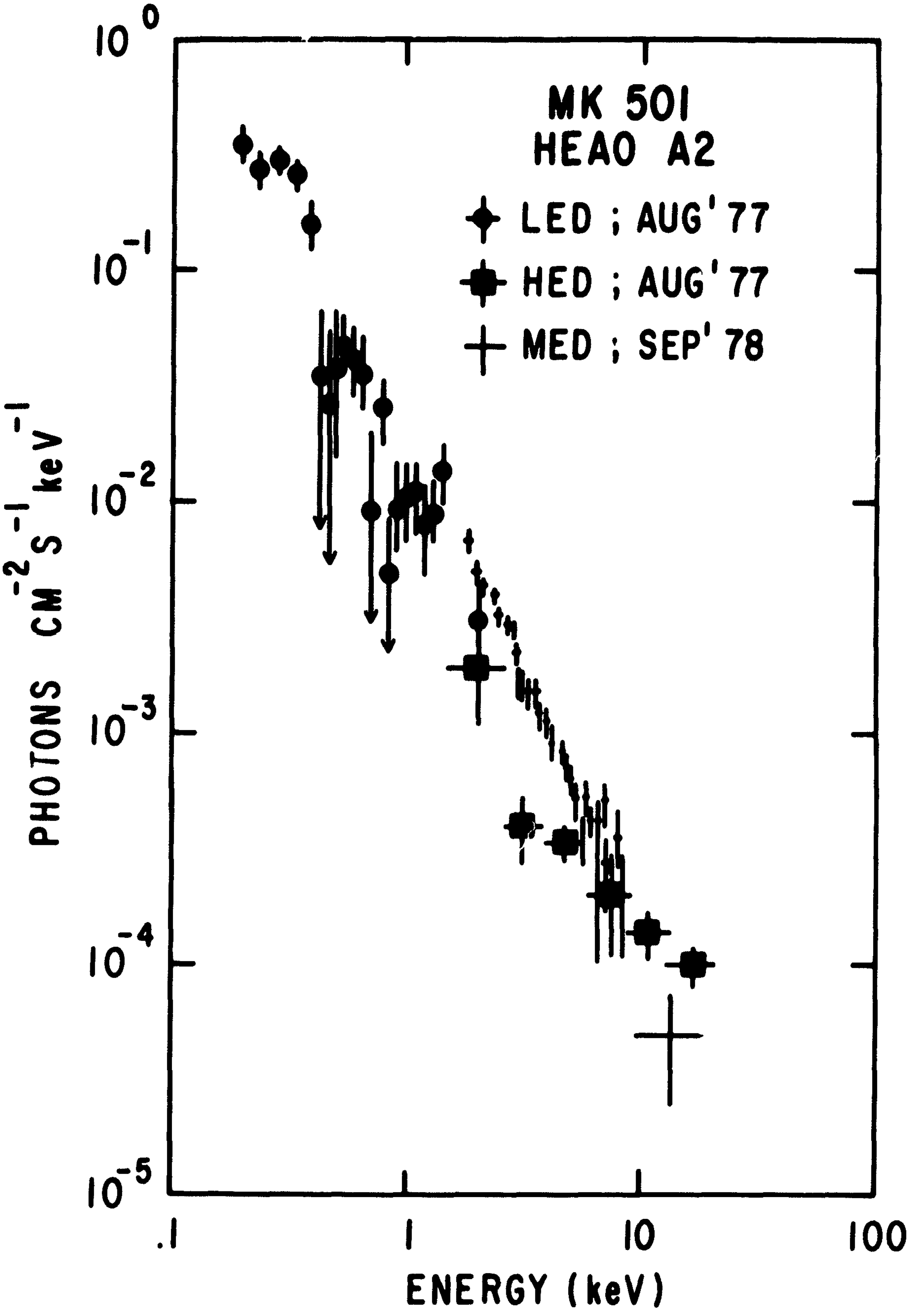MK 501
HEAO A2
LED ; AUG'77
HED ; AUG'77
MED ; SEP'78
PHOTONS CM^{-2} S^{-1} keV^{-1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
.1
1
10
100
ENERGY (keV)

FIGURE 4