HARD X-RAY ASTROPHYSICS

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While many people have come to this workshop to promote various instruments of interest, I have come to promote a specific area of observations. Hard x-ray astrophysics includes observations above 20 keV and up to hundreds of keV, and it can provide much valuable information on the astrophysics of cosmic sources. A review of past hard x-ray and lower energy satellite instruments is in order and is given below.

NAME	AREA (cm^2)
Hard X-Ray Instruments (> 20 keV)	
OSO-3	10
OSO-7	64
Ariel-V	8
OSO-8	28
HEAO-1 A4	220
HEAO-3 C1	86
Hakucho	49
XTE (Proposed)	2000
X-Ray Instruments (2-20 keV)	
UHURU	840
OSO-7	70
Copernicus	18
Ariel-V	580
SAS-3	300
OSO-8	244
HEAO-1 A1	6400
HEAO-1 A2	2400
Einstein	667
Hakucho	210
XTE	10000

Hard x-ray instruments reached one-fourth of the *UHURU* area with the A4 instruments aboard the *HEAO-1* satellite, even though the measured signal for hard x-ray observations is generally down by three orders of magnitude from that in the *UHURU* energy range. The small areas devoted to hard x-ray astrophysics have forced observers to deal with signal-to-background ratios less than one if they wished to study anything other than the brightest sources. *HEAO-1* and recent balloon results show that sources can be detected with conventional techniques at the few per cent of background level. This translates to being able to detect sources at the 1 *UFU* level at 100 keV with a few thousand square centimeters of detector area in a few days. Hence, the pre-Einstein catalog of x-ray sources (*i.e.* > 1 *UFU* sources) can be available for detailed study.

Now that we are in the shuttle era, weight and power are no longer the real factors in experiment design that they were years ago (money is !), and arrays of scintillation counters are no longer at a disadvantage with respect to gas counters. It is possible today to fly thousands of square centimeters of scintillator with no technical development necessary.

In order to calculate possible sensitivities of future arrays, the efficiencies of a one atmosphere-inch gas counter (the *HEAO-1* A-2 xenon-filled HED3) and a 3 mm phoswich scintillator (the *HEAO-1* A-4 NaI LED1) are compared in Figure 1. Above 15 keV the scintillator is more efficient. In order to translate this into sensitivities, 10,000 cm^2 and 100,000 seconds livetime have been assumed, and Figure 2 shows the 3σ minimum detectable flux for both detector types, plus the spectrum of a one *UFU* (or 1.24 μJy) E^{-2} source. Clearly, astrophysics above 20 keV can be better served by a scintillator. In a similar comparison germanium detectors' sensitivity is not much different from that for scintillators, except at high energies where the sensitivity would remain flat and not rise with the loss of efficiency.

Since large area detectors have the sensitivity to measure one *UFU* sources, what about the hard x-ray sky? Is there anything there to see? Figure 3 shows the representation of the preliminary findings of the *HEAO-1* 40-80 keV SKYMAP (Levine, *et al.* 1979). Over 50 sources are presented to a limiting sensitivity of about 3×10^{-5} photons/cm^2 s keV, or about 10 *UFU* for an E^{-2} spectrum. Within this sample are active galaxies, clusters of galaxies, a possible quasar, x-ray binaries, radio pulsars, globular clusters, bulge sources, and even a nova. Hence, a wealth of sources are available to study astrophysical problems. I shall now address myself to some of these questions.

PHYSICS OF ACTIVE GALAXIES AND THE DIFFUSE BACKGROUND

Many aspects of testing the massive black hole model of the power source in active galaxies are related to the total luminosity (Lightman 1981). Measurements of this luminosity must be made in the hard x-ray range, where most of the power resides in the case of active galaxies. The lower energy 2-20 or 0.5-5 keV spectra cannot be extrapolated to higher energy arbitrarily , since a break in the hard x-ray spectrum at something like the characteristic energy must occur. In the past, breaks at 40 keV were predicted, based on the break in the diffuse background spectrum. Figure 4 shows the mean *HEAO-1* 2.1-165 keV spectrum of 10 active galaxies -- the majority of which are Seyfert 1 galaxies -- and no 40 keV break is seen (Rothschild, *et al.* 1981). Fitting the data confirms what is apparent -- that is, no break is seen up to 100 keV. Breaks around 100 keV have been invoked in the *HEAO-1* analysis of Cen A (Baity, *et al.* 1981a) and NGC 4151 (Baity, *et al.* 1981b). Other published results have claimed breaks in Seyferts as high as 3 MeV (Perotti, *et al.* 1979). The break energy must be measured, not hypothesized Otherwise, only upper limits to system parameters will be obtained.

Another important hard x-ray astrophysical question relates to the relationship between active galaxies, including quasars, and the diffuse x-ray background. In the lower energy 2-40 keV regime no one class of discrete distant objects contributes more than half of the observed background in the form of unresolved point sources. Quasars are 30-40% (Giacconi, *et al.* 1979), Seyferts are about 20% (Mushotzky, *et al.* 1980), and clusters are less than 10% (McKee, *et al.* 1981). Hence, comparison of spectral shapes of classes of extragalactic objects to that of the diffuse background yields little information about its nature.

Above 40 keV things change drastically. The diffuse background, shown in Figure 5 and measured by the *HEAO-1* instruments from 2-400 keV (Marshall, *et al* 1980; Matteson, *et al* 1979) and by others above this energy (Trombka, *et al* 1977; Fichtel, *et al* 1977), starts to drop rapidly about 40 keV. Classes of objects with soft spectra, like clusters of galaxies, become unimportant at these high energies. The fraction of the x-ray background due to the remaining classes of objects must increase rapidly with energy if their spectral shapes remain unchanged. Our results mentioned above indicate that the active galaxy power law spectral index holds out to at least 100 keV, and the dashed line in Figure 5 shows their contribution. Active galaxies make up about 40% at 100 keV, and could be responsible for 100% by 250 keV. Active galaxies may also be responsible for the slope change in the diffuse x-ray background spectrum at 300 keV to 3 MeV. If the active galaxies are responsible for the diffuse background at 250 keV and beyond, what has happened to the quasar contribution seen at lower energies? The quasar spectrum then must break before 250 keV, and this has yet to be

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observed. If the quasar spectra do indeed break before the active galaxy spectra do, this might be evidence for evolutionary effects in quasar spectra.

PHYSICS OF BLACK HOLES

Black holes were not mentioned in the theoretical papers at this workshop, but a great amount of interest still exists in the study of these bizarre and fundamental objects. This is another area in which hard x-ray measurements can yield information on the pressing questions in astrophysics. Cyg X-1 is almost unique among galactic x-ray sources due to its $\geqslant$ 50 keV emission. The spectrum of a thermal process as described by Sunyaev and Titarchuk (1980) or by Guilbert and Fabian (1981) would be cutoff at an energy determined by the maximum temperature. Our *HEAO-1* spectrum of Cyg X-1, spanning the broad energy range of the A2 and A4 instruments, 10 keV-8 MeV, are shown in Figure 6. The model shown is the Sunyaev-Titarchuk type which fits quite well up to a few hundred keV, and indicates a temperature near 30 keV for a single thermal or ones near 15 and 40 keV for a dual temperature model. Andy Fabian has indicated that his non-equilibrium model describes this data well also with a temperature near 100 keV As you can see, there is an excess to the model at high energies. Figure 7 displays this excess more clearly, and a broad (640 keV FWHM) 511 keV line has been added to the previously mentioned model. Note, however, that most any additional type of model would fit the excess with the uncertainties involved, and the GRO mission should be able to investigate this in more detail in the future.

We can further study the emission process near black holes by investigating the temporal aspects of the scattering of photons by the hot plasma. Since the higher energy photons may be the result of more scatterings in the plasma than the lower energy photons, one would expect a time delay between the emergence of the low and high energy photons after the injection of some soft photons into the plasma. If such a time delay were confirmed, not only would we be more confident of our understanding of black hole accretion disks, but we might be able to measure the size of the emitting region. *HEAO-1* results (Nolan, *et al.* 1981) indicate a possible 10 ms lag between 20 and 60 keV photons. Instruments aboard the Ariel VI spacecraft have observed a 7 ms lag at lower energies (Fabian, private communication). Future instruments must be able to accomplish this study over as broad an energy range as possible, in order to establish the energy dependence of this time delay, and to determine the physics of the emission region.

Ultrafast temporal variability -- on the order of milliseconds or less -- may contain vital information on both the accretion process and the angular momentum of the black hole itself. General considerations of black holes show that the orbit time for the innermost stable orbit is much shorter for Kerr metrics as opposed to the Schwarzschild metric (Novikov and Thorne 1973). If the energy spectrum of the ultrafast variability is flatter than that of the overall emission above 20 keV, hard x-rays would yield a clearer signal of the bursts and thereby be more able to study the fast temporal behavior. Studying the temporal/spectral variability will, first-of-all, indicate if the millisecond bursts arise from the same process as the slower variable emission. Secondly, it will determine if a time delay occurs between the bursts as a function of energy? Finally, it may answer whether or not the time structure, or of lack of it, persists at higher energies. Such investigations will guide us in formulation of theories of black hole accretion and may link the millisecond bursting to the slower, more persistent, variability.

PHYSICS OF RADIO PULSARS

No totally consistent picture of radio pulsar x-ray emission has yet emerged. Pulsars are spinning neutron stars, but that is about all we are sure of. Presently only a handful of pulsars are seen in x-rays, and only the Crab pulsar is seen to pulse. Yet in the future this will change with the use of more sensitive instruments.

Pulse phase spectroscopy, or more properly, phase resolved spectroscopy, has revealed a new component in the Crab pulsar spectrum. Starting with the lower energy work of Pravdo and Serlemitsos (1981) with OSO-8 data, Knight (1981) has shown from *HEAO-1* hard x-ray data that the interpulse region of the Crab light curve (shown in Figure 8) is significantly different from the peak regions. The two peaks' spectra are nearly identical and are seen over a wide range of energies (Figure 9). The peak emission has been described in terms of the synchrotron process involving high energy electrons in the pulsar magnetic field, and polarization measurements confirm this. The interpulse spectrum, shown in Figure 10, is significantly different. It is flatter and appears to break around 200 keV, possibly indicative of the emission process energy (perhaps the cyclotron energy). Attempts to model this have included a 150 keV thermal bremsstrahlung process, Compton scattering of low energy photons by 25 keV plasma of Thomson depth 5, and scattered radiation from a thick atmosphere in a strong magnetic field. Considerations, such as emission region size, temperature, and field strength pose problems with all these models. Undoubtedly, however, a new component has been revealed -- perhaps originating from quite close to the neutron star itself. Further study of this spectra in the hard x-ray range is essential to a better understanding of radio pulsars.

PHYSICS OF X-RAY PULSARS

Naturally, the most exciting aspect of the hard x-ray astrophysics of neutron stars presently is the prospect of measuring their magnetic field strength by observing the cyclotron features in their spectra. Theoretical work as presented at this workshop is advancing on predicting the size and shape of these features as a function of field strength. Her X-1, shown in Figure 11, is the most prominent example of this phenomenon, and others include 4U0115+63 (Wheaton, *et al.* 1979) and numerous gamma-ray bursts (Mazets, *et al.* 1981). The *HEAO-1* results (Gruber *et al.* 1980) of model fitting the Her X-1 data reveal the cyclotron feature to be broad (28 keV, if in emission) and occuring around 45 keV. (The energy of the centroid depends upon whether it is in emission [48 keV] or absorption [39 keV].) The feature's centroid varies with pulse phase, at least during the pulsed portion of the light curve, as is shown in Figure 12. A 15% or 30% variation is seen, depending upon emission or absorption. We are unable to follow the feature through the "off-pulse" phase region due to inadequate detector area, but the variability is not enough to cause the breadth of the feature. This changing centroid energy is probably a result of viewing the specific geometry of the Her X-1 system from different angles, and thus the geometry is open for study.

Even for those x-ray pulsars without an obvious cyclotron feature, information on their magnetic field strength is available in the form of the hard x-ray spectrum (Boldt, *et al* 1976). As shown in Figure 13, the spectrum conforms to a power law with index around one until about 20 keV, where it breaks to a steeper spectral form. This is caused by the complex interplay of cyclotron and scattering processes in the accretion plasma in the strong magnetic field. Several x-ray pulsars display this behavior and we are confident that this may allow understanding the processes involved and may lead to further measurements of neutron star magnetic field strengths and distributions.

Her X-1 is just the prime example of a class of x-ray binaries. The Hard X-ray and Low Energy Gamma-Ray Experiment aboard *HEAO-1* has discovered long term variability (~ weeks), similar to that seen in Her X-1 (Gorecki, *et al.* 1981), in two other eclipsing binary pulsars: LMC X-4 (Lang, *et al.* 1981) and SMC X-1 (Gruber, *et al.* 1981). This now increases the class of pulsing, eclipsing binaries with additional longer term "on/off" activity to three. The LMC X-4 light curve and the SMC X-1 light curve are shown in Figures 14 and 15. Hence, the x-ray community can begin the detailed study of this class of objects (and hopefully XTE will) in order to determine which characteristics are unique to individual sources and which can be related to the class in general. In order to accomplish this detailed study of accretion onto magnitized neutron stars, large detector areas are necessary. Figure 13 shows the spectrum of Her X-1 and that of SMC X-1. The latter source is about ten times weaker than the former, and consequently, ten times the sensitivity is necessary to study it at the same level as *HEAO-1* studied Her X-1. Perhaps the SMC X-1 spectrum has a cyclotron feature, but we will not know without the higher sensitivity.

A possible source of collimation of the x-ray pulsar beam is the hole in the magnetosphere near the neutron star magnetic poles through which the accretion plasma reaches the x-ray emission region. If this hole is responsible for the overall x-ray pulse shape, the observed pulses should broaden by about 10% as one goes to higher energy due to the change in the Compton cross section with energy. If this effect is not seen, the collimation must be due to the source region. Hence, further information on the pulse formation in x-ray pulsars is available at hard x-ray energies.

PHYSICS OF CLUSTERS OF GALAXIES

Clusters of galaxies are believed to contain an intracluster magnetic field. This basic cluster parameter can be measured by observing the weak hard x-ray component in cluster x-ray spectra (Lea and Holman 1978), due to the microwave photons inverse Compton scattering off of the intracluster electrons that are spiralling around field lines and generating radio emission. This x-ray component will reflect the shape of the electron power law spectrum, and its magnitude will be directly related to the field strength. Thus, even upper limits to the high energy flux will set lower limits to the magnetic field. Hard x-ray spectral components have been detected by the Hard X-Ray and Low Energy Gamma-Ray Experiment aboard *HEAO-1* from the Perseus (Primini, *et al.* 1981) and Virgo clusters and upper limits from Abell 2142 (Lea, *et al.* 1981) were also determined (see Figure 16). The Perseus hard tail is due, however, to the active galaxy NGC 1275 at its center, and thus the limits to the inverse Compton component are even lower. In the case of the Virgo cluster it is questionable whether or not the galaxy M 87 at the cluster core is responsible. In any event we have $B \geq 5 \times 10^{-7}$ Gauss (Virgo), $B \geq 10^{-7}$ Gauss (Perseus), and $B \geq 5 \times 10^{-8}$ Gauss (Abell 2142). These results indicate that the magnetic fields in cluster radio sources must be close to the equipartition values.

CONCLUSIONS

I would like to emphasize the importantance of further research in hard x-ray astrophysics. These investigations could utilize large scintillator arrays, large cooled germanium arrays, coded apertures, Bragg concentrators, etc. Measurements above 20 keV extending to hundreds of keV must be made to attack some of the major identified astrophysical questions before us. Correlated analyses over as broad an energy range as possible is very important for distinguishing between competing models for a given source and for the general knowledge of the phenomonology of cosmic x-ray sources.

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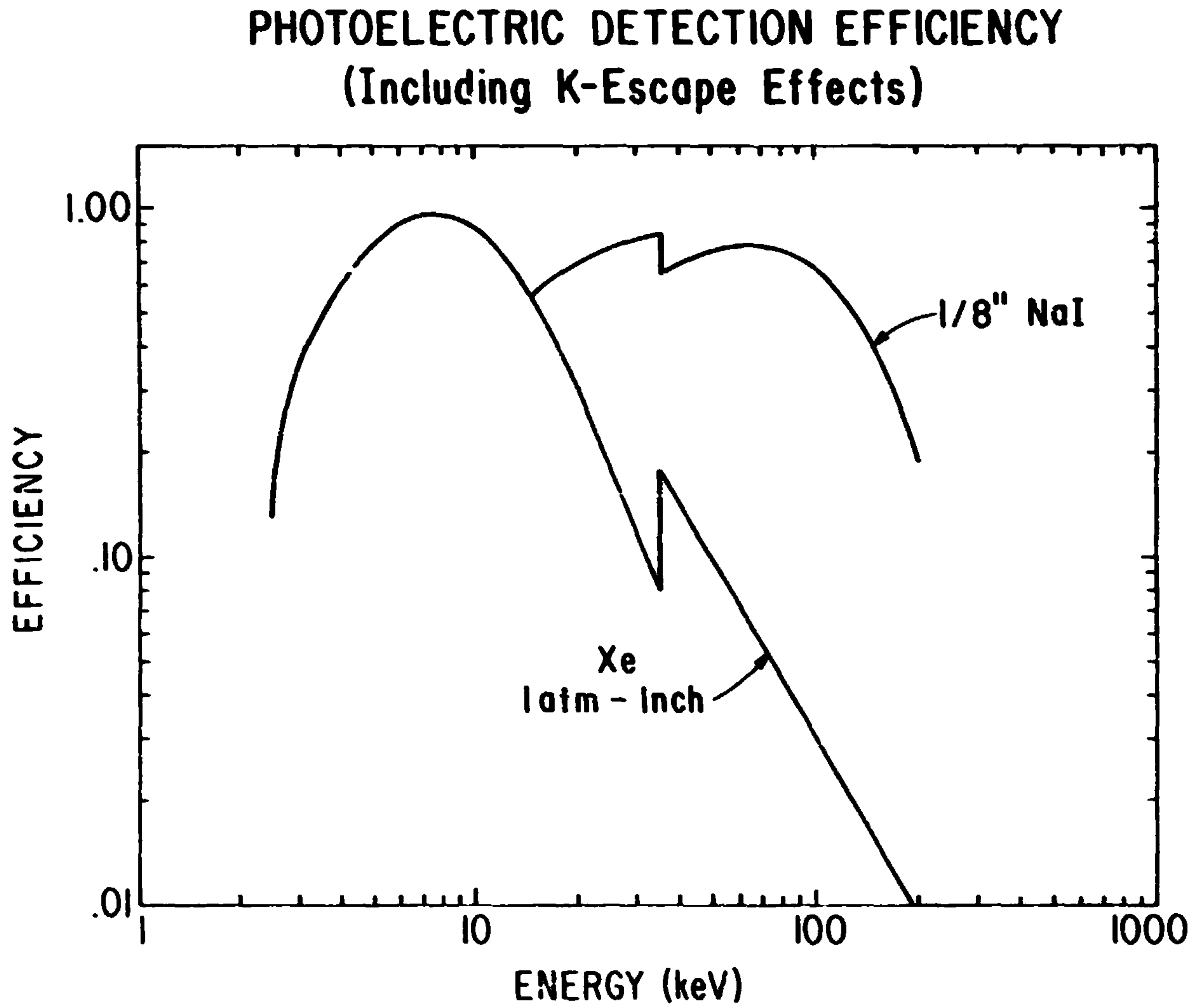

Figure 1: X-Ray efficiencies, including K-escape effects, for a xenon proportionnal counter and a NaI phoswich scintillation counter.

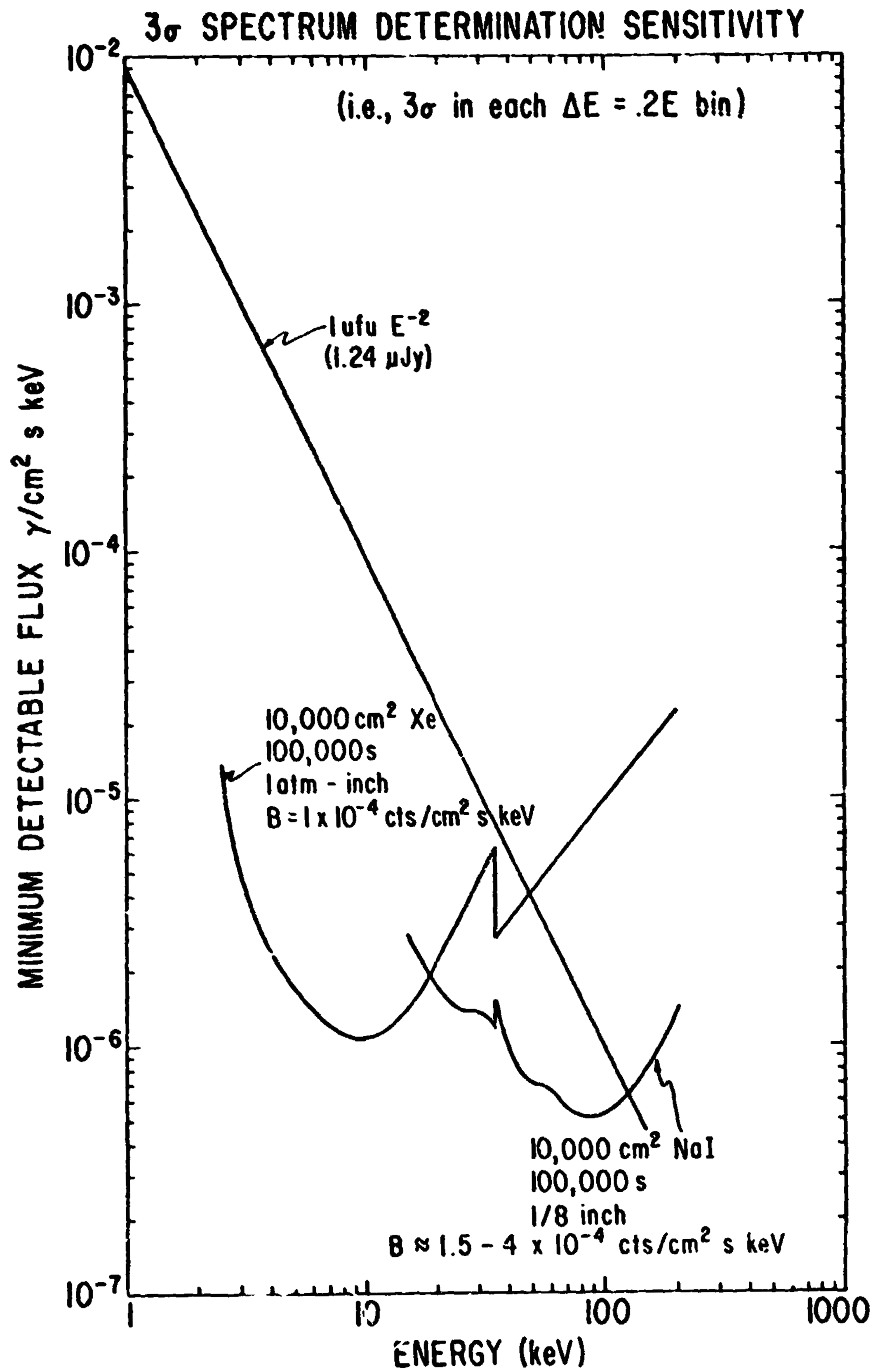

Figure 2: Sensitivities (3σ) for a xenon proportional counter and a NaI phoswich scintillation counter for 10,000 cm^2, 100,000 s and $\Delta E = 0.20\ E$. The spectrum of a 1UFU E^{-2} source is also shown.

40-80 KEV FLUX
> 2.6×10^{-5} PH/CM^2-SEC-KEV
(≃ 1/84 CRAB)
(≃ 11 UFU) for E^{-2} spectrum

HEAO-I UCSD/MIT SKY SURVEY: 40 - 80 keV
(PRELIMINARY, LEVINE, et al. 1980, B.A.A.S., 12, 463)

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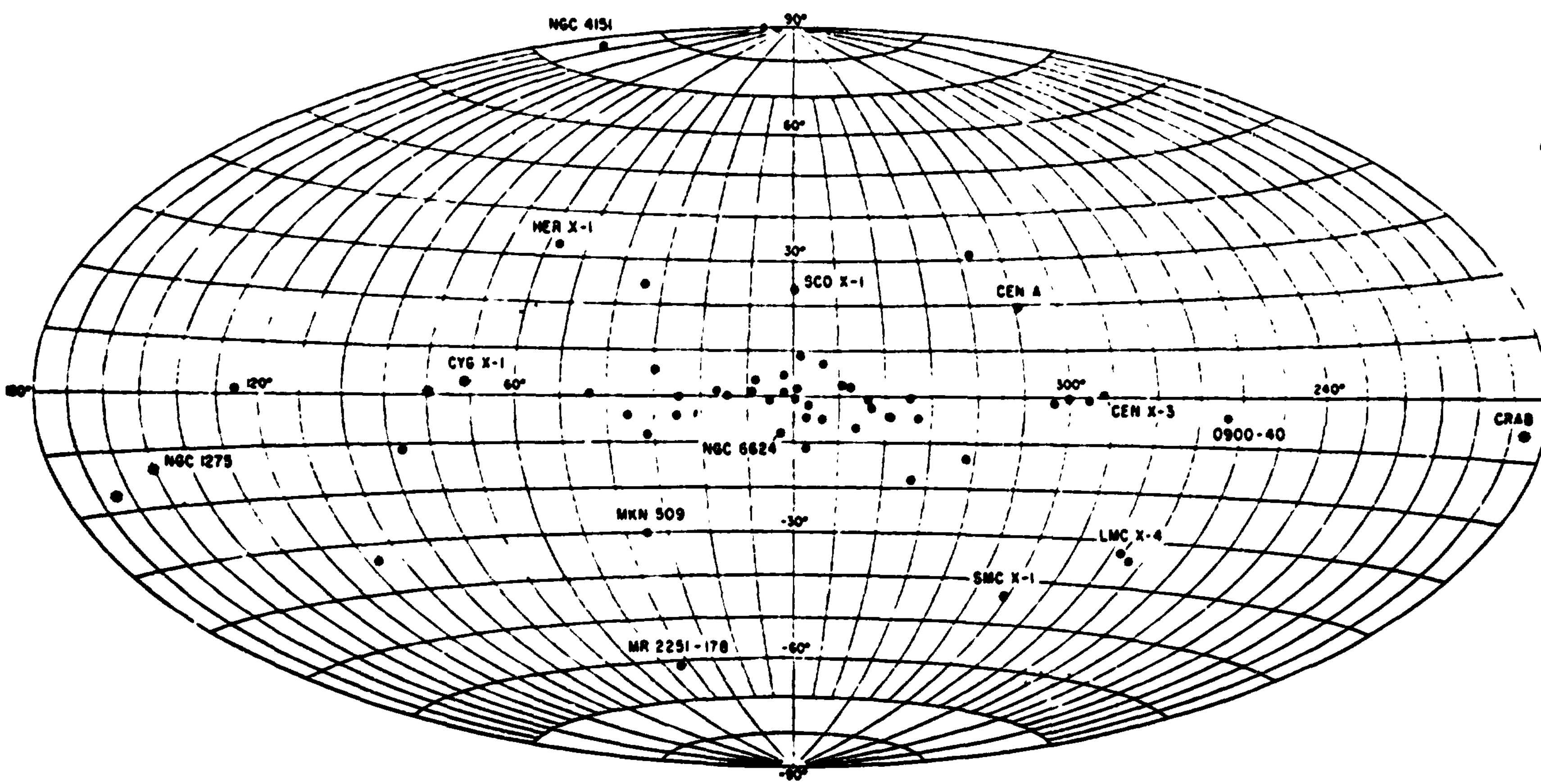

Figure 3: The *HEAO-1* 40-80 keV SKYMAP.

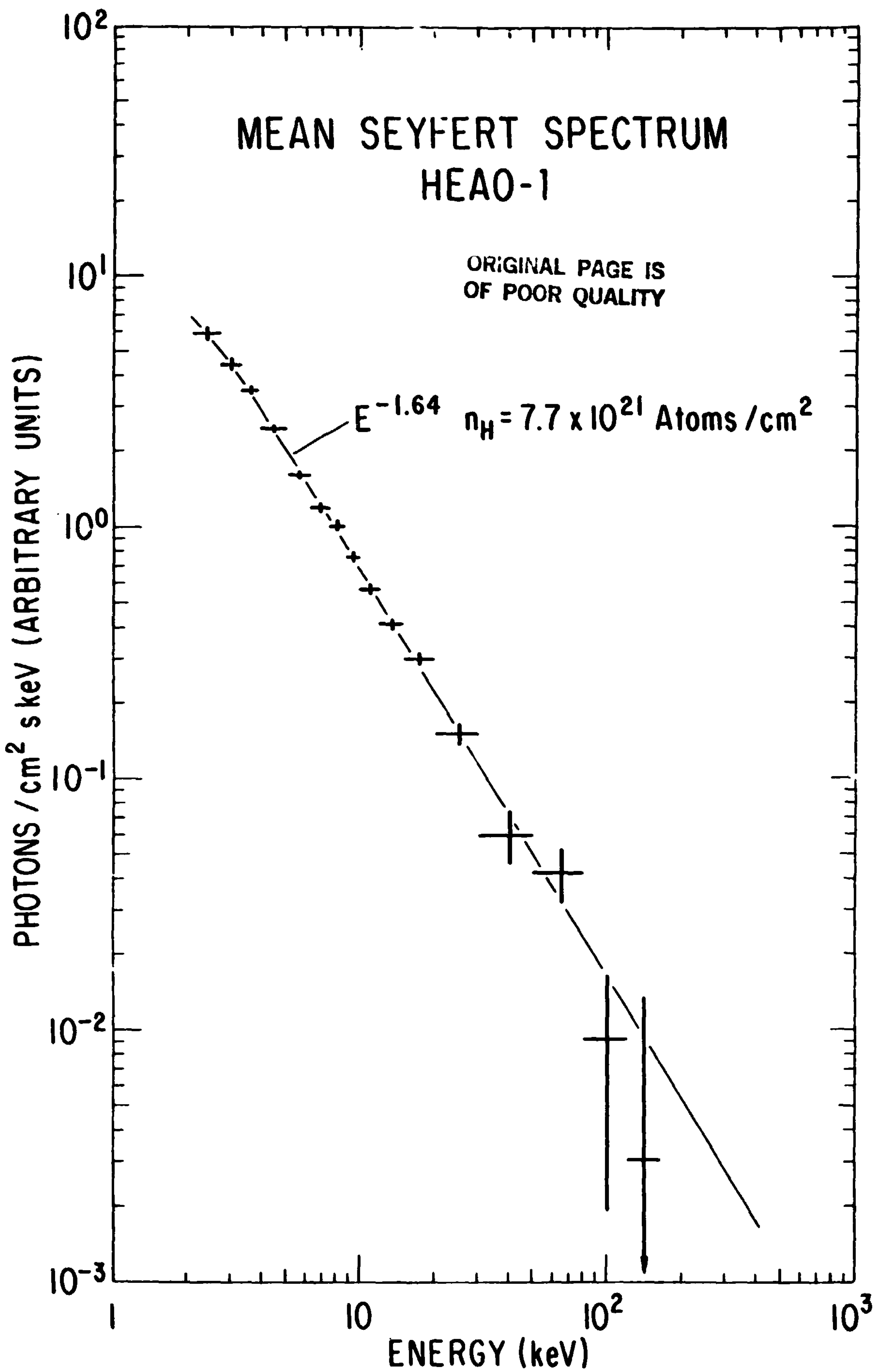

Figure 4: The mean *HEAO-1* spectrum of active galaxies.

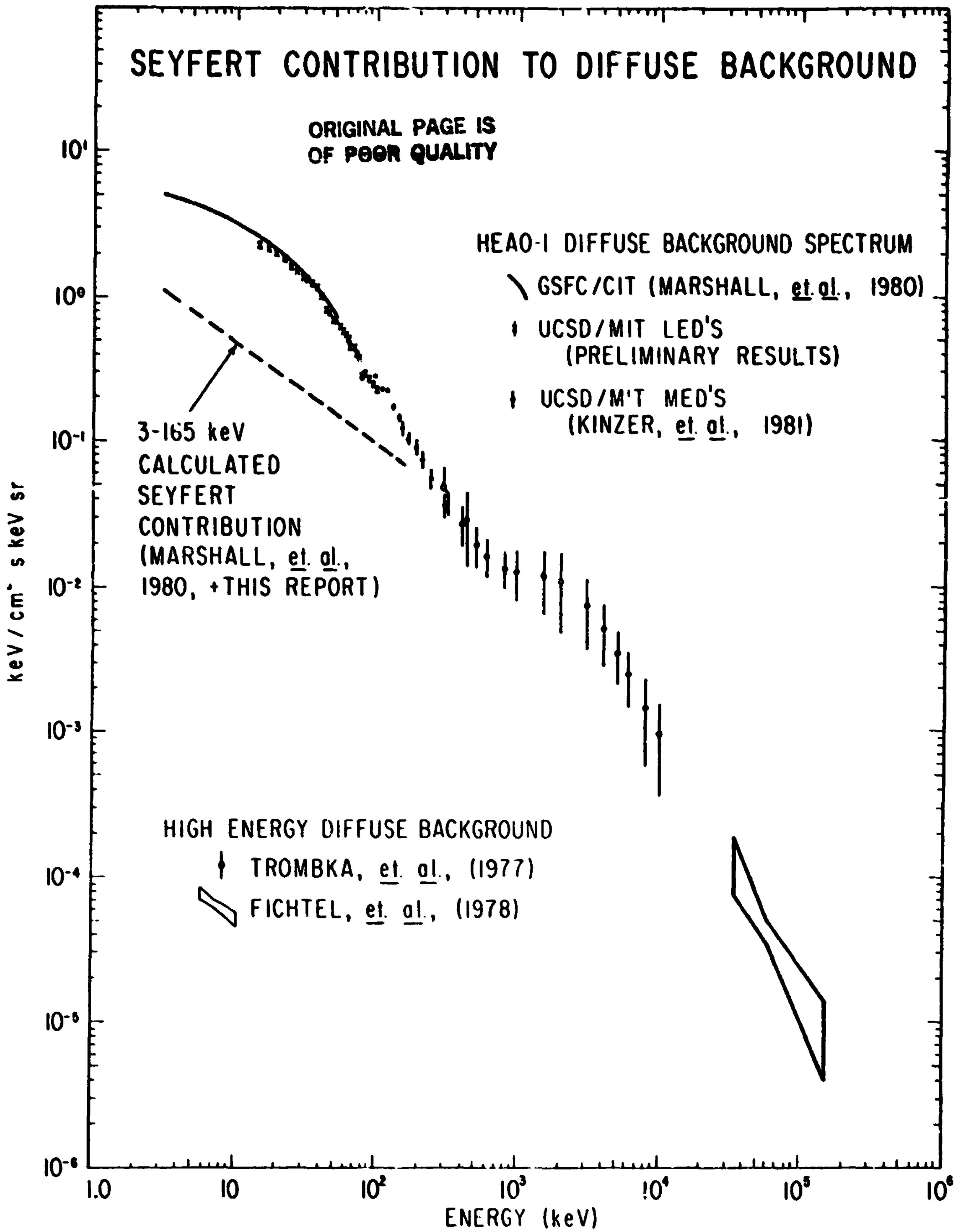

Figure 5: The diffuse x-ray background, along with the contribution of active galaxies

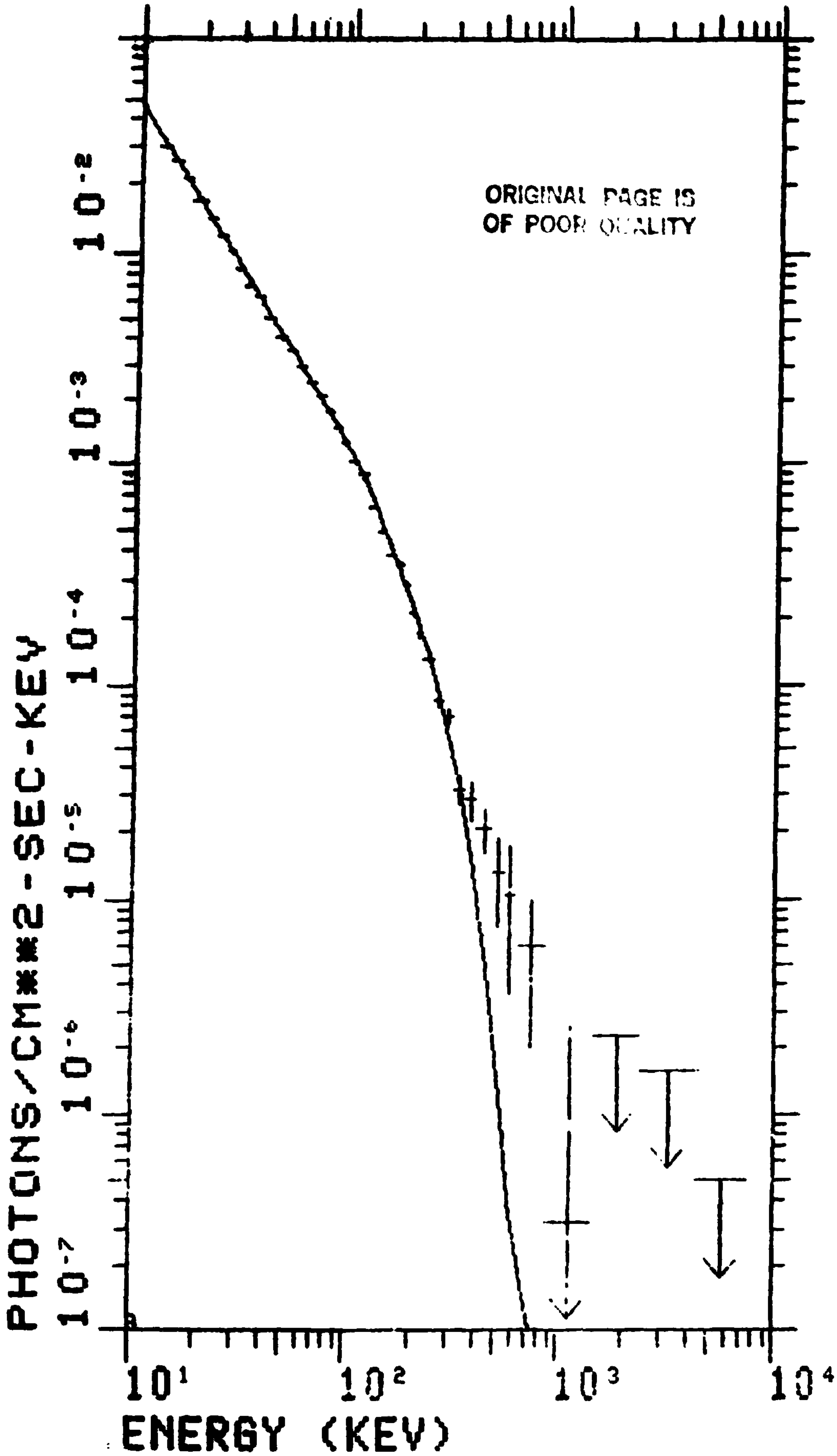

Figure 6: The *HEAO-1* spectrum of Cyg X-1.

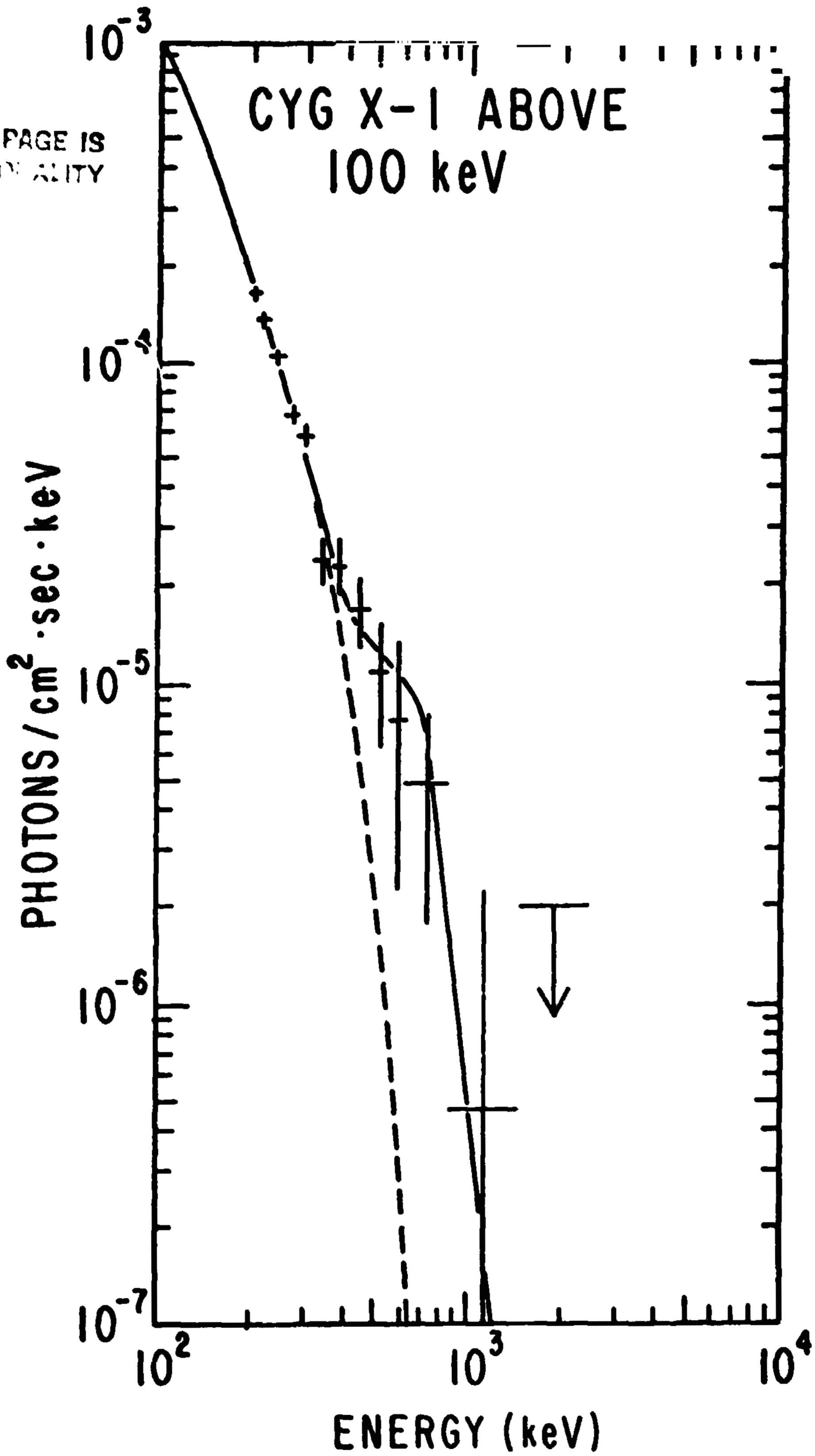

Figure 7: The *HEAO-1* spectrum of Cyg X-1 at high energies.

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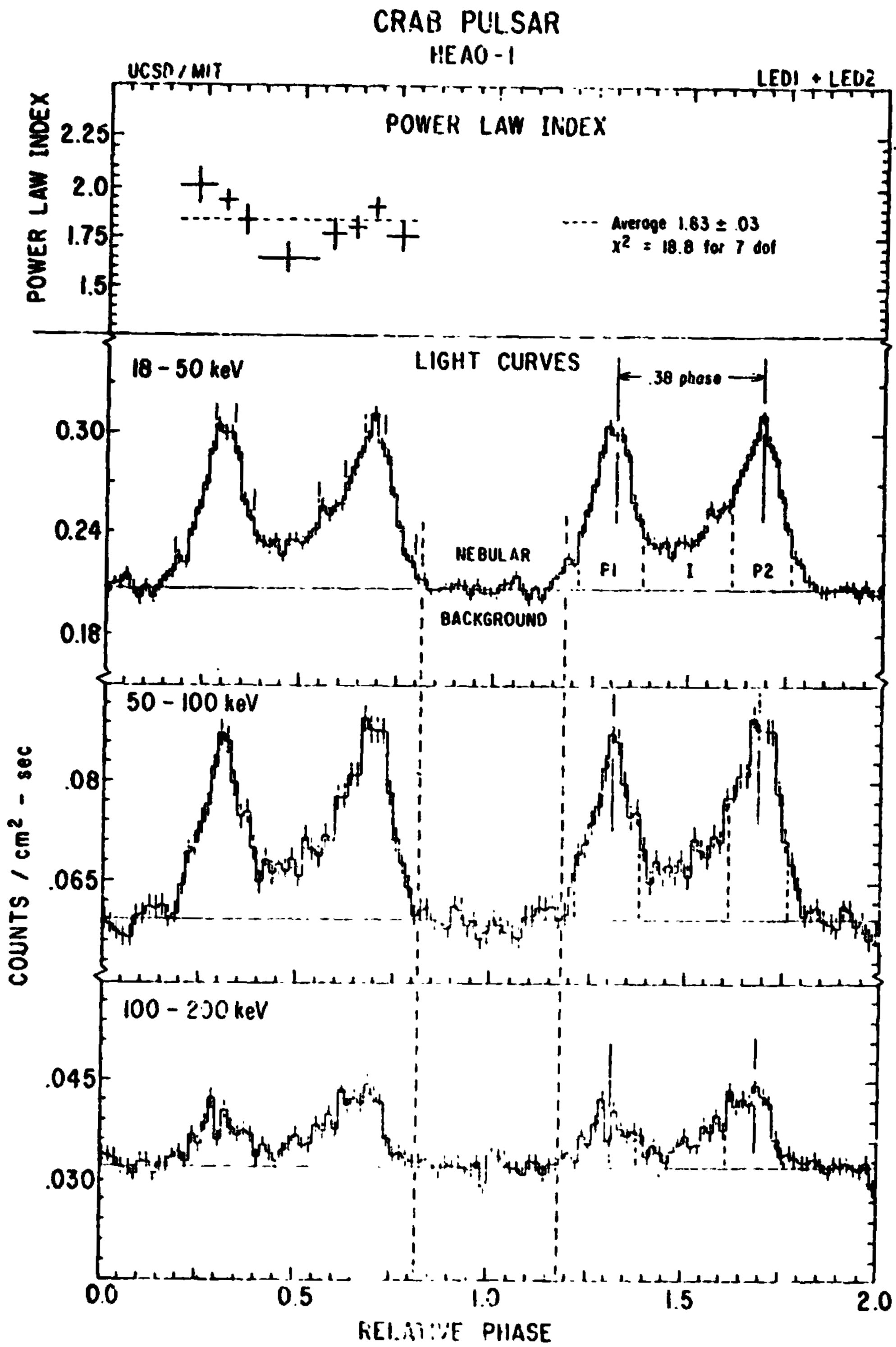

Figure 8: The *HEAO-1* Hard X-Ray and Low Energy Gamma-Ray Experiment light curve for the Crab nebula pulsar. The interpulse region of phase is denoted by " I ".

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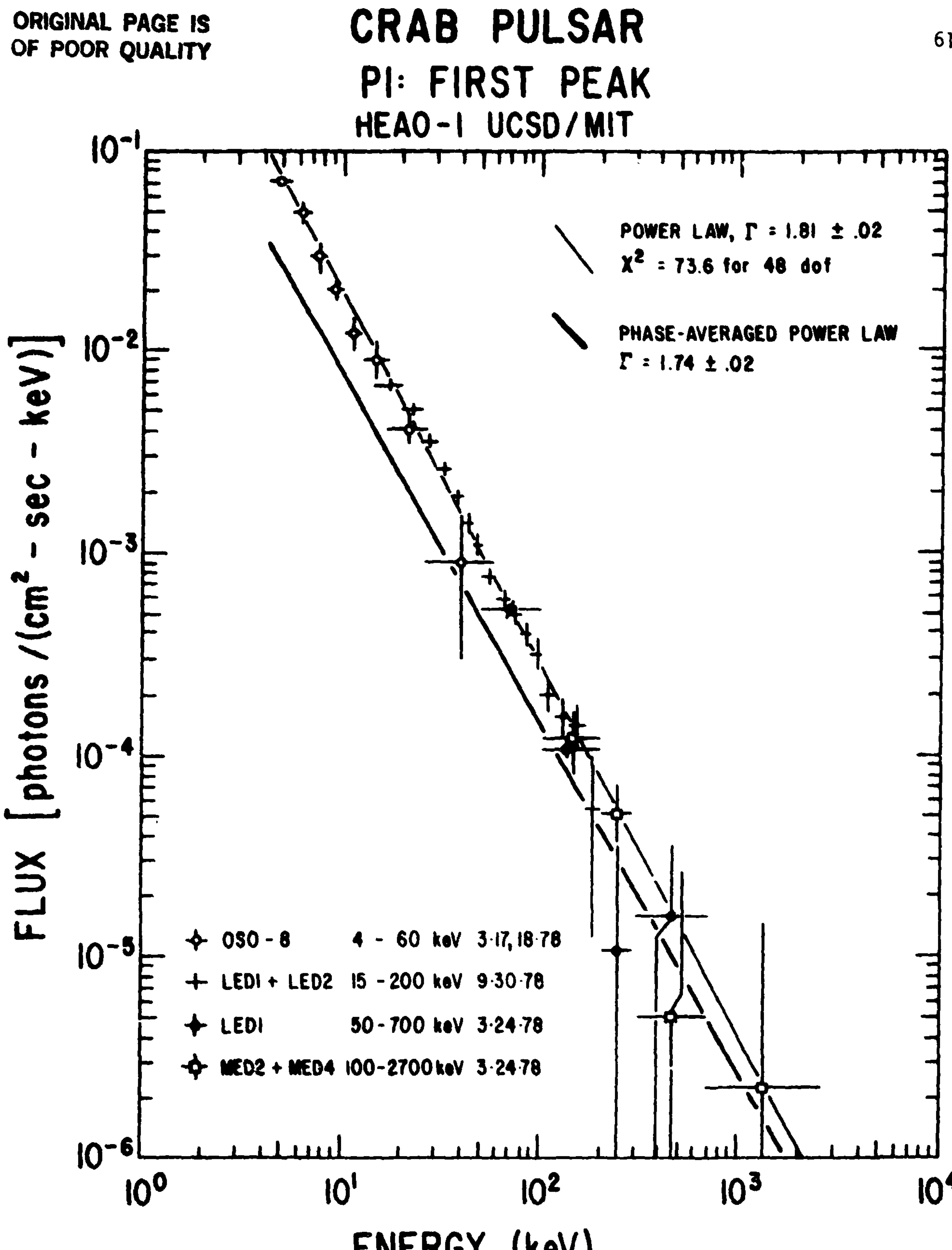

Figure 9: The spectrum of one of the peaks in the Crab nebula spectrum from the Hard X-Ray and Low Energy Gamma-Ray Experiment aboard *HEAO-1*.

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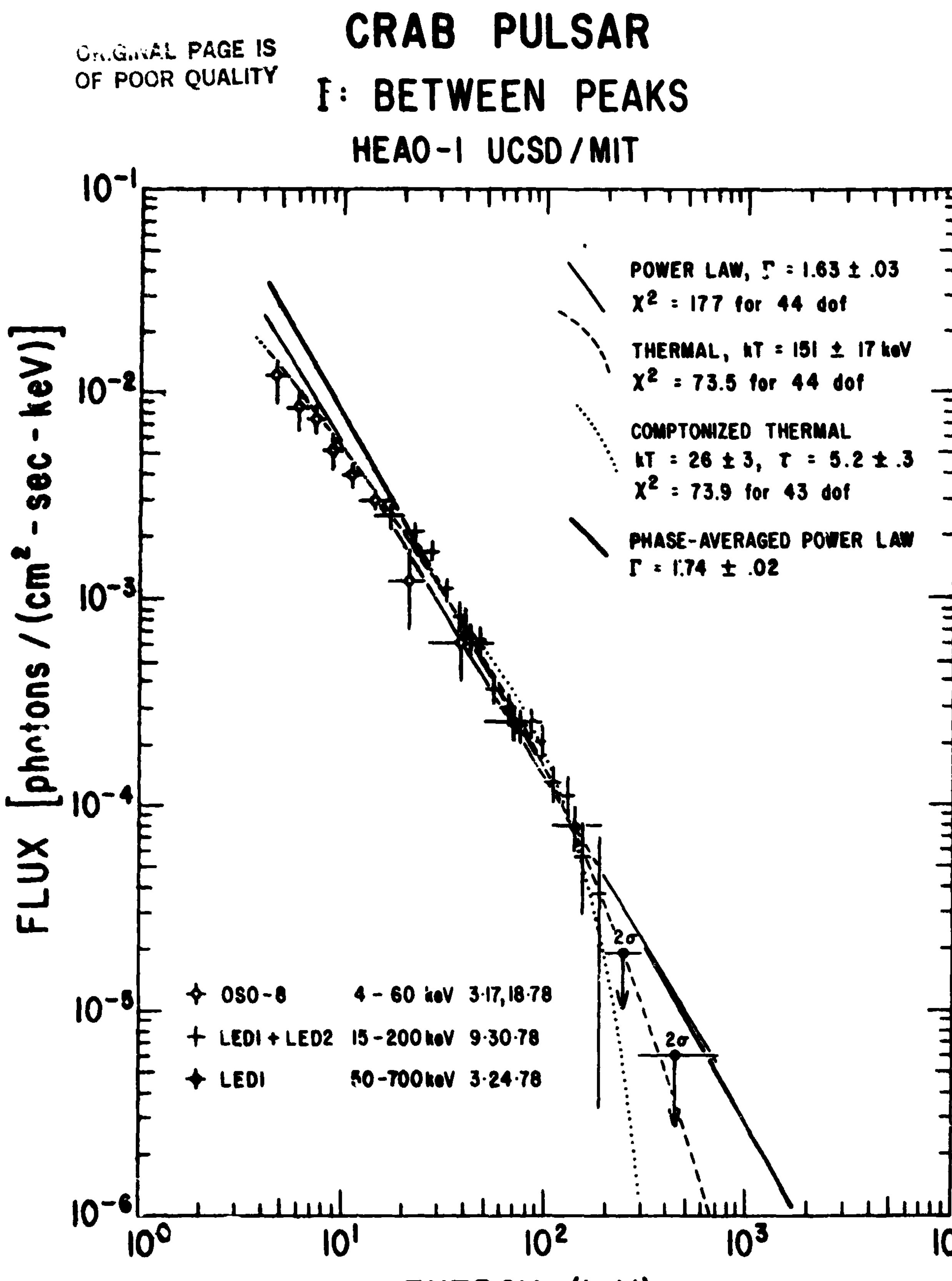

Figure 10: The interpulse spectrum of the Crab nebula from *OSO-8* and *HEAO-1*.

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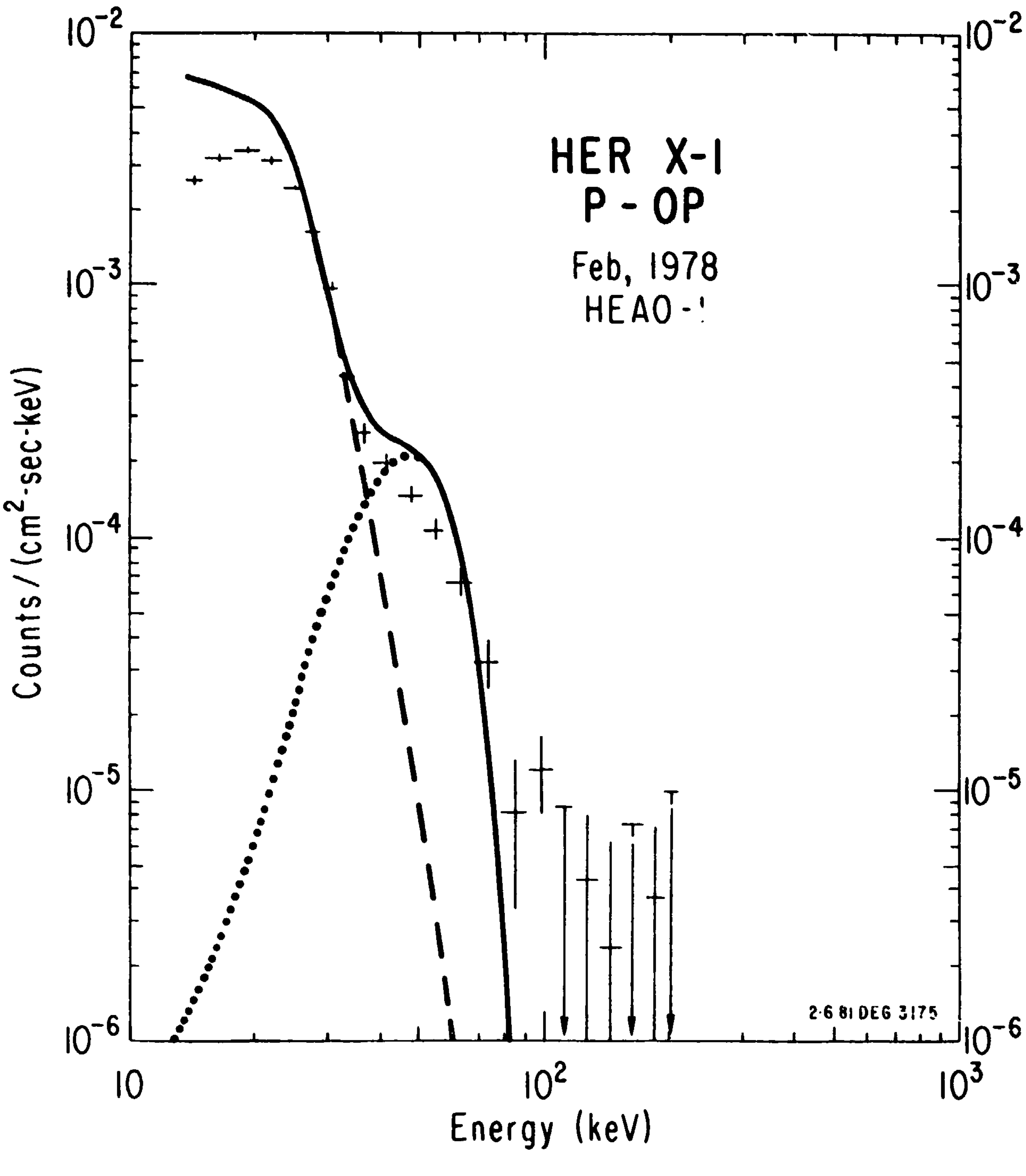

Figure 11: The spectrum of Her X-1 from *HEAO-1*. The model shows both the continuum and the modelled line in emission.

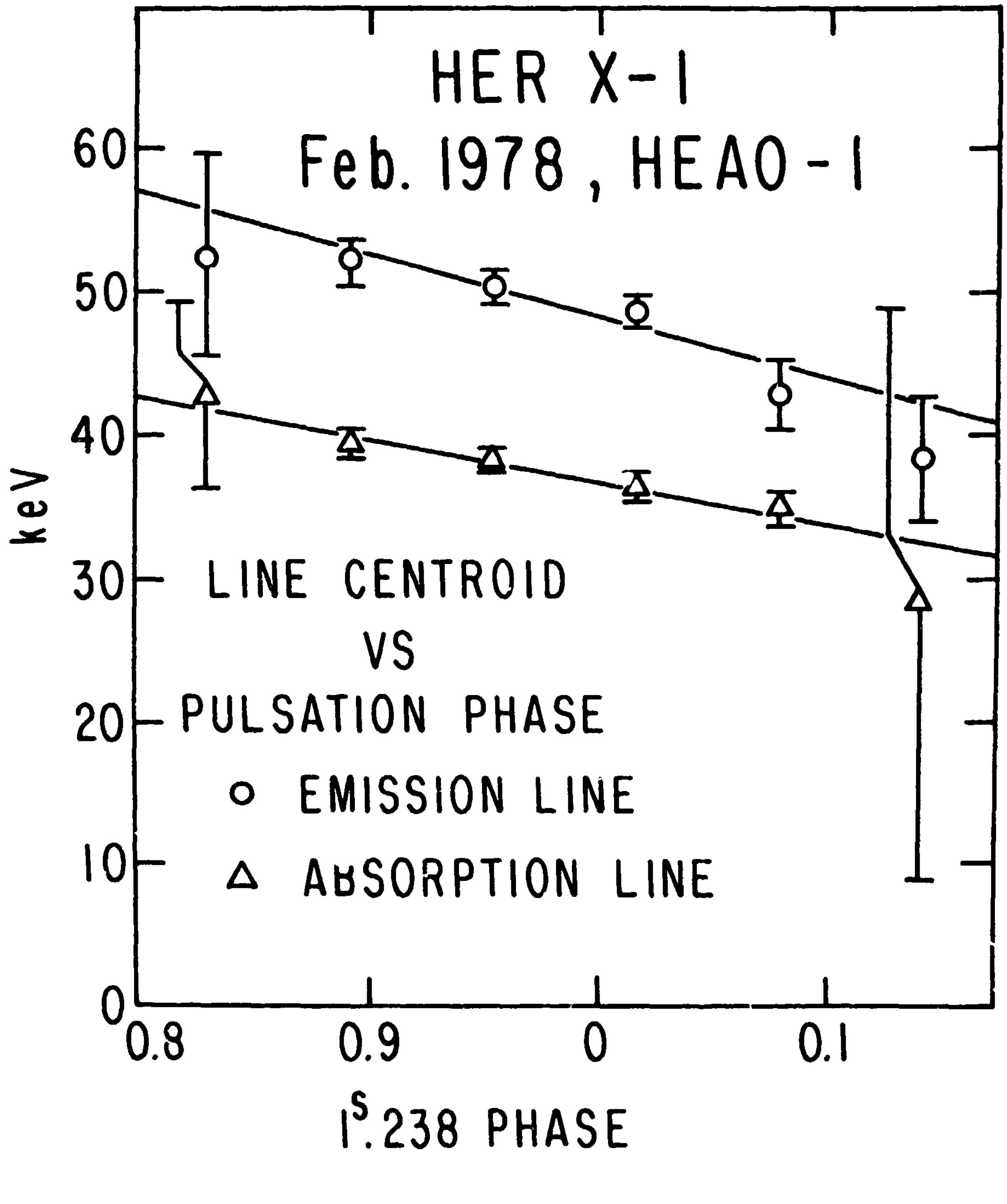

Figure 12: Variation of the centroid of the cyclotron feature in Her X-1 as measured by *HEAO-1*.

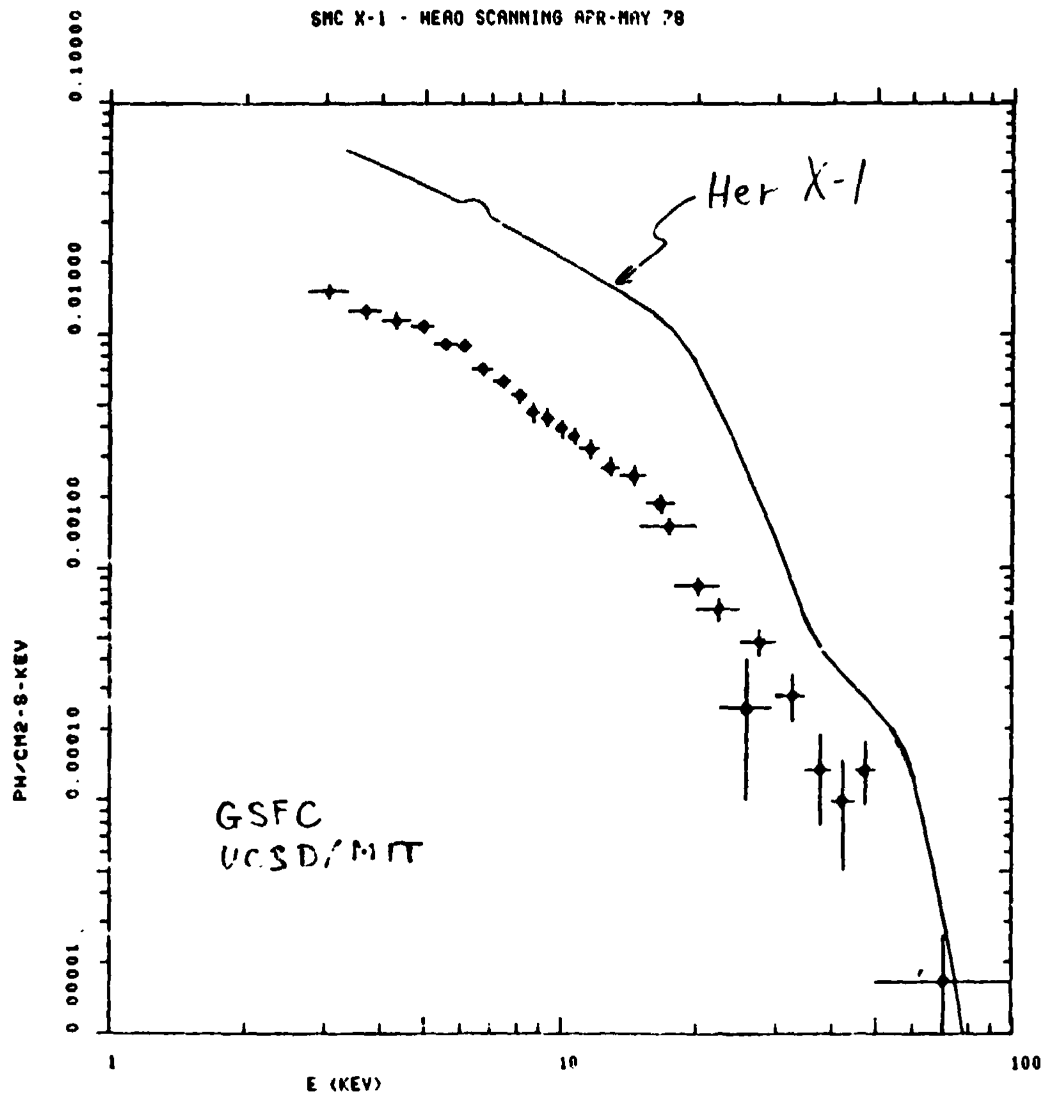

Figure 13: The spectrum of Her X-1 and SMC X-1 from *HEAO-1*. The solid line represents the best-fit model to the Her X-1 data and the data points are for *HEAO-1* observations of SMC X-1.

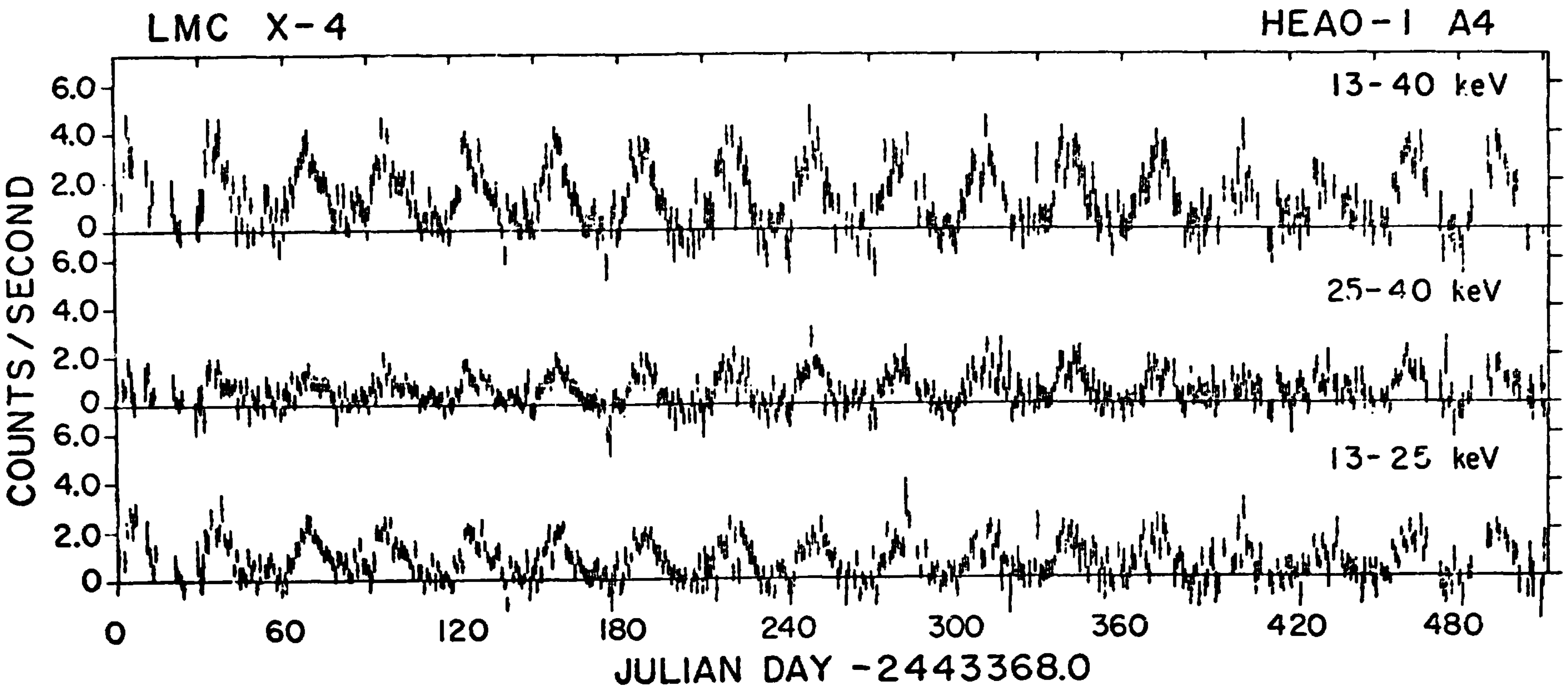

Figure 14: The *HEAO-1* light curve of LMC X-4 above 12 keV.

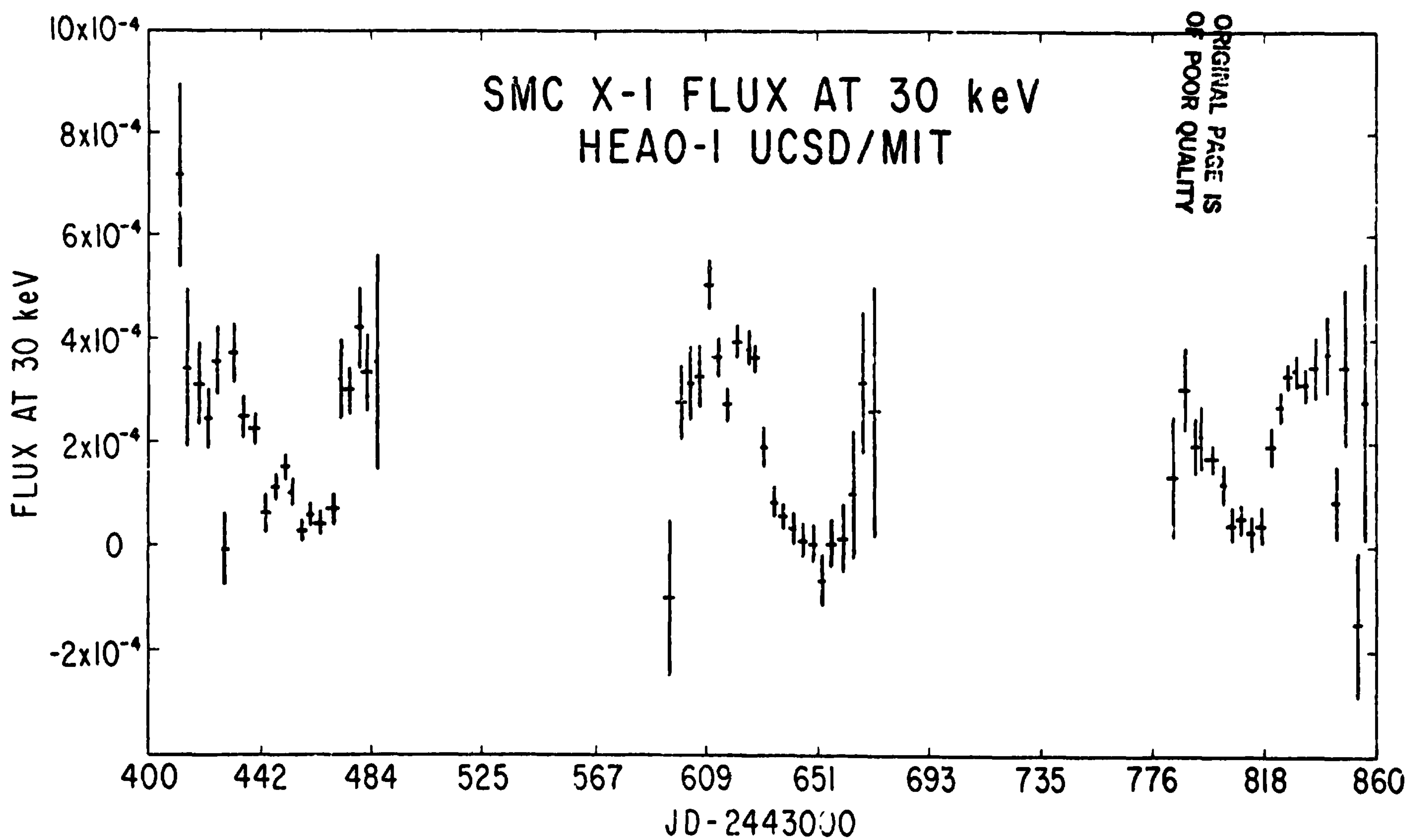

Figure 15: The *HEAO-1* light curve of SMC X-1 at 30 keV.

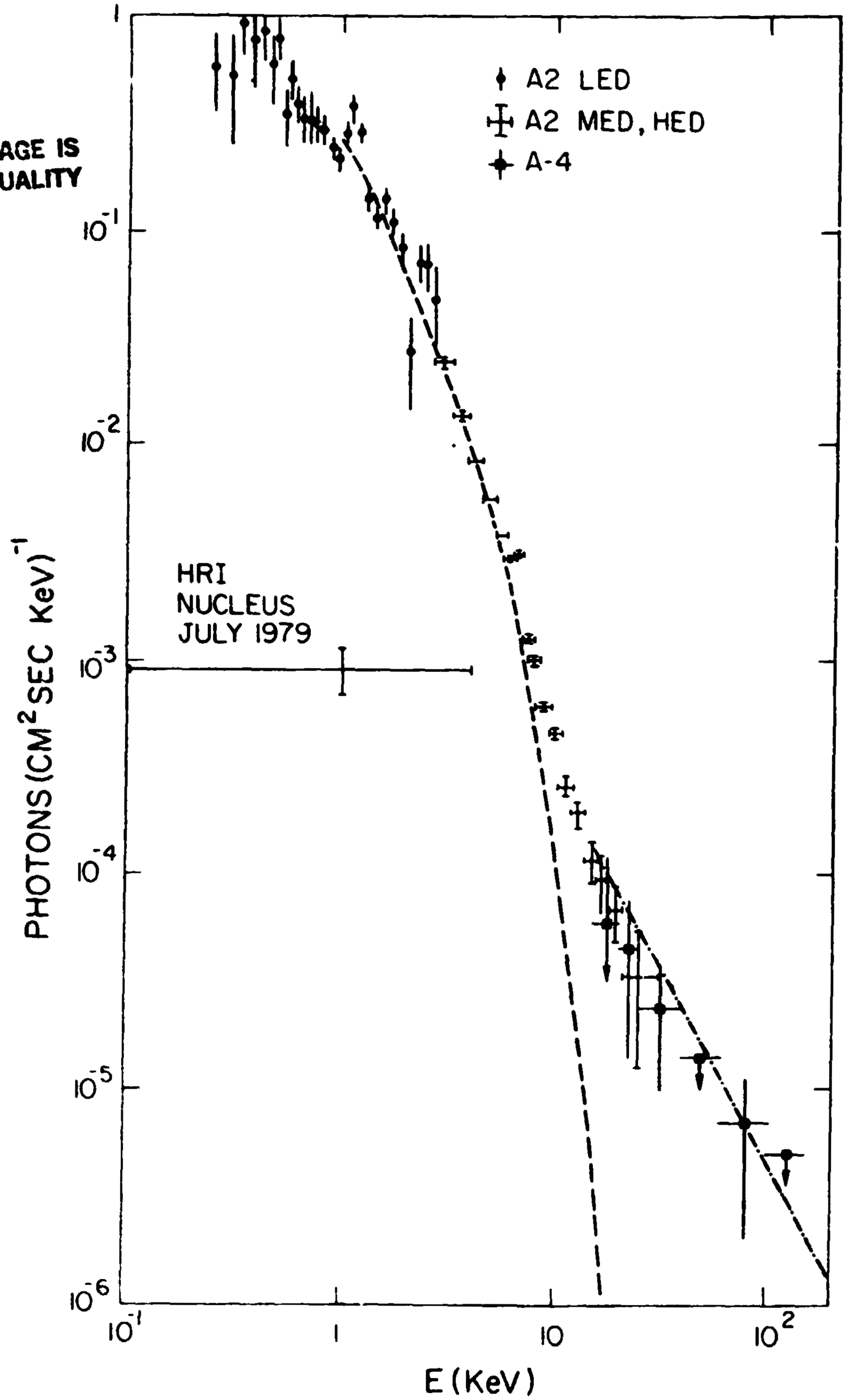

Figure 16: The *HEAO-1* spectrum of the Virgo cluster.