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HEAO A - 2 Extragalactic Results

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HEAO A-2 EXTRAGALACTIC RESULTS

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ABSTRACT

The all-sky surveys made with the A-2 instrument aboard HEAO-1[+] involve spectroscopy over a broad enough band width, with sufficient resolution, to obtain the basic spectral characteristics for two extreme aspects of the extragalactic X-ray sky. For the apparently isotropic radiation arising from unresolved discrete sources of emission such as distant quasars and possible diffuse components, the overall spectrum (above 3 keV) is remarkably well described by a thermal model, where the temperature is about a half-billion degrees and the corresponding photon energies are measured in tens of keV. At the other extreme, our detailed broad-band observations of individual sources are restricted to objects within the present epoch. These objects include several individual active galaxies studied in detail for the first time as well as clusters of galaxies. Relating these results to the vast spatially unresolved hard X-ray flux measured with this instrument as well as the softer X-rays (at < 3 keV) spatially resolved to high redshifts with the Einstein Observatory remains a challenge.

[+]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.

I am going to summarize some of the new things that we have learned about the extragalactic X-ray sky from the A-2 experiment. The first category is that of new hard X-ray sources, shown on the map in Figure 1. There are some obvious things that we can say about the new sources. First of all, most of these have been identified with extragalactic objects. In contrast to previous surveys, where clusters of galaxies have dominated the number of sources identified as extragalactic, the extended energy bandwidth of this experiment tends to single out spectra with harder components. As a result most of the identified extragalactic objects on this map are not clusters of galaxies but are isolated galaxies (i.e., active galaxies, BL Lac type objects, N galaxies). For high galactic latitudes, the number of newly identified active galaxies shown here is approximately equal to the total number of active galaxies identified as X-ray sources prior to the launch of HEAO.

Figure 2 is a map that corresponds to all the hard sources detected by the A-2 experiment in the first all-sky scan during the initial six months of the mission. The effective scan path of this experiment transits any given source during a limited time which is measured in days. If a particular source is off or too low during this temporal window, it is not on this map. Since source variability is quite common in X-ray astronomy this map should be considered as an all-sky "snapshot". This is our first A-2 all-sky "snapshot". We are preparing a second one and most of a third.

Shown in Figure 3 is a map of all hard sources ever detected, covering a time period of almost a decade (i.e. with data from Uhuru, Ariel 5, OSO, and SAS-3). Thus, the map consists of all sources seen prior to

HEAO plus the new HEAO A-2 sources.

An important thing to notice is that, during our initial six month all-sky scan, we did not see many sources that had previously been seen. That is, there are well over 100 sources that were not seen with the A-2 experiment, which has an effective threshold for detection that is at least as sensitive as any of the previous scanning experiments. This result probably reflects the temporal variability of the sources that make up the extragalactic X-ray sky. We are now checking our subsequent all-sky scan for this effect. Since our experiment is extremely stable, we can compare one all-sky scan to another and get very good statistics on the overall source variability of the sky.

Figure 4 is an all-sky map of X-ray intensity; it is the first in a series that we will be developing based on the results of this experiment. The major enhancements are associated with the galactic plane. Isolated enhancements correspond to the sources indicated on our source maps. For the most part the rest of this map is quite isotropic. We have established that galactic effects are probably less than about one percent at high galactic latitudes. This brings us to a principal goal of this experiment, which is to investigate this unresolved portion of the hard X-ray sky.

Figure 5 shows the results of an analysis on the spectrum of the unresolved X-ray background as observed at high galactic latitudes away from resolved hard X-ray sources. What is plotted here is the ratio of the observed flux to that predicted for three different thermal models. There are many different symbols used for these plots, corresponding to the fact that the A-2 instrument looked at this problem in many different ways (e.g., different detectors, different layers of different detectors) in order to minimize any systematics problems. What we see here is that the right temperature is about a half-billion degrees (i.e., kT $\gtrsim$ 45 keV). What seems quite remarkable is that one does get such a good fit with a single parameter spectrum. A simple power law is just not an acceptable fit to these data. The statistical error bars below about 15 keV are smaller than the size of the symbols. Hence, it is not a structured spectrum.

Now, if we search around for sources that are thermal, we must of course consider clusters of galaxies. The Perseus cluster is the brightest extragalactic X-ray source; Figure 6 shows its spectrum in terms of photon flux versus photon energy. This is the characteristic spectrum of a plasma at a temperature of about 80 million degrees. The luminosity of this source is about a million times the X-ray luminosity of our entire galaxy. In addition to the fact that this measurement has such fine statistics and provides such a good thermal fit, we have here finally found the first direct evidence for a higher energy transition to the K electron shell of iron (i.e. Kβ line is detected as well as Kα) in a cluster source. More work on clusters has proceeded with the A-2 experiment. In particular, we have collaborated with the Institute of Astronomy of Cambridge University on this topic. Most recently additional clusters have been examined in detail and been found to have a lower temperature component in addition to a thermal component comparable to the Perseus cluster. This characteristic of two thermal components seems to be emerging in lower luminosity clusters.

Isolated galaxies with active nuclei are also strong X-ray sources but spectral information on these was really quite meager before HEAO. We now have spectra for sources representing all known classes of active galaxies, and I am now going to take you on a brief spectral tour of some of these, roughly in order of luminosity.

First of all, we consider the spectrum of the brightest X-ray galaxy, Centaurus A (see Figure 7). It is bright mainly because it is relatively nearby; although its luminosity is about 1,000 times the X-ray luminosity of our galaxy it is much less luminous than most active galaxies. With such good statistics we can clearly say that this is not a thermal spectrum; it is in fact a beautiful power-law spectrum. Below a few kilovolts it shows the pronounced effect of absorption by a large amount of material (an order of magnitude more than the columnar density of gas between here and our own galactic center). Since the brightest Seyfert galaxy (NGC4151) has a similar absorption feature, this sort of spectrum was thought to be typical of active galaxies, at least prior to the launch of HEAO. For comparison, Figure 8 shows a collection of five additional Seyfert-1 spectra observed with HEAO A2. Above a few kilovolts, they all have power law spectra that have essentially the same index as the spectrum for Centaurus A. They range in luminosities from 1,000 times the luminosity of our galaxy (NGC6814) up to 100,000 times the luminosity of our galaxy (MK 509). However, it is really only NGC6814 that shows any significant sort of absorption. As I indicated before, high absorption had previously been considered typical. Now we are led to the conclusion that perhaps absorption is only important for those active galaxies of lowest X-ray luminosity. Figure 9 shows the spectrum of a Seyfert galaxy which was seen both during a HEAO-1 point and then six months prior to that during a scan. Although the spectrum may be represented as a power-law above a few kilovolts, at lower energies one is beginning to see a new effect. The unexpected feature is a steep component which varied by a factor of two during six months.

Moving up in luminosity, Figure 10 shows the spectrum of an N galaxy (3C111) with an X-ray luminosity of 300,000 times that of our galaxy. Again, it has a power-law spectrum with an index approximately that of Centaurus A, but with no significant absorption. The class of strong X-ray sources identified with N galaxies was discovered with the HEAO A-2 experiment.

Figure 11 shows the spectrum of a BL Lac type object (PKS0548-322); this one has a luminosity that is about a million times the total X-ray luminosity of our galaxy. For such extragalactic sources we obtained one of the more important new effects to be seen with this experiment, that of pronounced two-component spectra. In fact, for PKS 0548-322 the luminosity below two kilovolts exceeds the luminosity above two kilovolts. This represents work done in a collaboration between JPL and Goddard. Similar results have been seen for MK 501 and other BL Lac type objects in a collaboration between Cal Tech and Goddard and also for MK 421 in a collaboration between Berkeley and Goddard. MK421 also shows spectral variability; in this instance, the hard component has been seen to vary most. This situation of having two variable spectral components among the highest luminosity extragalactic objects is reminiscent of Cygnus X-1, a galactic source thought to be a black hole. I think that this aspect of the subject is going to be strongly pursued theoretically in the near future.

Going up in luminosity, Figure 12 shows a BL Lac type object (PKS2155-304) which has a luminosity of 20 million times the X-ray luminosity of our galaxy; again, this is a joint project of JPL and Goddard. In this case, the hard component at the time that this was measured was not even observable (if there at all). It turns out that about 90 percent of the luminosity of this object resides below about 2 keV. The contribution of such objects to the X-ray background would necessarily be restricted to soft X-rays, such as now readily resolved with the Einstein Observatory.

Thanks to an 18-hour "ping-pong" maneuver requested by the A-4 experimenters, we were able to get a decent spectrum for a quasar (3C273), shown in Figure 13. While the number index for a single power law fit to the spectrum is 1.41 (i.e., flatter than Cen A), these data clearly exhibit that the spectrum is not that simple. Below about 8 keV, we see good evidence for a steeper component. Unfortunately, this is the only decent quasar spectrum we have available. However, we now see that steep spectral components are quite widespread among the most luminous sources, extending not only to sources like Seyferts and BL Lac type objects but at least to one quasar as well.

Now, back to the diffuse X-ray background. Given that some of the strongest extragalactic sources have now been seen to show two component spectra, we should ask whether the unresolved background also has a steep component. Above 3 keV, we see no evidence for such a component (see Figure 5). Below 3 keV further work is required on this, both with this experiment and with other experiments. Do quasars such as 3C273 make a substantial contribution to the unresolved extragalactic hard X-ray flux? I cannot answer that question, but I think that the spectrum of the background already provides us with some strong constraints. We still need broadband spectra for a reasonable sample of quasars.

FIGURE CAPTIONS

Figure 1 - New hard X-ray sources (at > 2 keV) discovered during the first all-sky scan with HEAO A-2. Positions are given in galactic coordinates (i.e. equator corresponds to the galactic plane).

Figure 2 - All hard X-ray sources detected during the first all-sky scan with HEAO A-2. Positions are given in galactic coordinates.

Figure 3 - All hard X-ray sources ever detected. Indicated symbols distinguish new HEAO-A2 sources from those known prior to HEAO-1. Positions are given in galactic coordinates.

Figure 4 - The surface brightness of the entire X-ray sky (in $3^{\circ} \times 3^{\circ}$ pixels) as obtained with the $1.5^{\circ} \times 3^{\circ}$ collimator section of a xenon proportional counter (HED-3 of HEAO-A2) over the band 2-60 keV. The map is presented in galactic coordinates. Intensity gradations are color-coded in the order black, blue and red (highest). Color print on request.

Figure 5 - The ratio (R) as a function of X-ray energy of the counts observed for the X-ray background to that predicted by convolving with the detector response function thermal bremsstrahlung incident spectra (characterized by kT = 20, 45, 75 keV). Different symbols are used to represent the first layer of the MED and both layers of HED 1 and HED 3. Statistical errors are shown when larger than the size of the symbols.

Figure 6 - Incident thermal spectrum (kT = 6.8 keV) for the Perseus cluster as inferred from data obtained with argon (MED) and xenon (HED) proportional counters of HEAO A2. Prominent lines in the 5-10 keV band correspond to Kα and Kβ transitions in iron ions having only K shell electrons.

Figure 7 - The X-ray spectrum for Cen A as inferred from data obtained with a xenon proportional counter (HED), using the model of a power-law spectrum at the source absorbed by surrounding unionized matter exhibiting iron K fluorescence.

Figure 8 - The X-ray spectra for 5 Seyfert-1 type galaxies as inferred from data obtained with a xenon proportional counter (HED), using the model of a power-law spectrum at the source absorbed by surrounding unionized matter. Except for MCG8-11-11, all spectra shown are from pointed data. All are consistent with a power-law spectrum of photon number index ≈ 1.7; only NGC6814 requires significant absorption to fit the data.

Figure 9 - X-ray spectra for ESO 141-G55 inferred from data obtained six months apart; the initial data shown as diamonds were obtained during the normal HEAO scan while the data obtained six months later are based on a pointed observation.

Figure 10 - The X-ray spectrum for the N galaxy 3C111 as inferred from data obtained with a xenon proportional counter (HED-3), using the model of a power law spectrum.

Figure 11 - The X-ray spectrum for the BL Lac type object PKS 0548-322 as inferred from data obtained by a propane proportional counter (LED results from JPL indicated by crosses) and an argon proportional counter (MED results from GSFC indicated by diamonds).

Figure 12 - The X-ray spectrum for the BL Lac type object PKS 2155-304 (identified with HEAO source H2156-304) as inferred from data obtained by a propane proportional counter (LED results from JPL indicated by crosses) and an argon counter (MED results from GSFC indicated by diamonds.

Figure 13 - The X-ray spectrum for the quasar 3C273 as inferred from data obtained by a xenon proportional counter (HED) during an extended HEAO-1 point.

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GALACTIC DISTRIBUTION OF HEAO-A2 X-RAY SOURCES

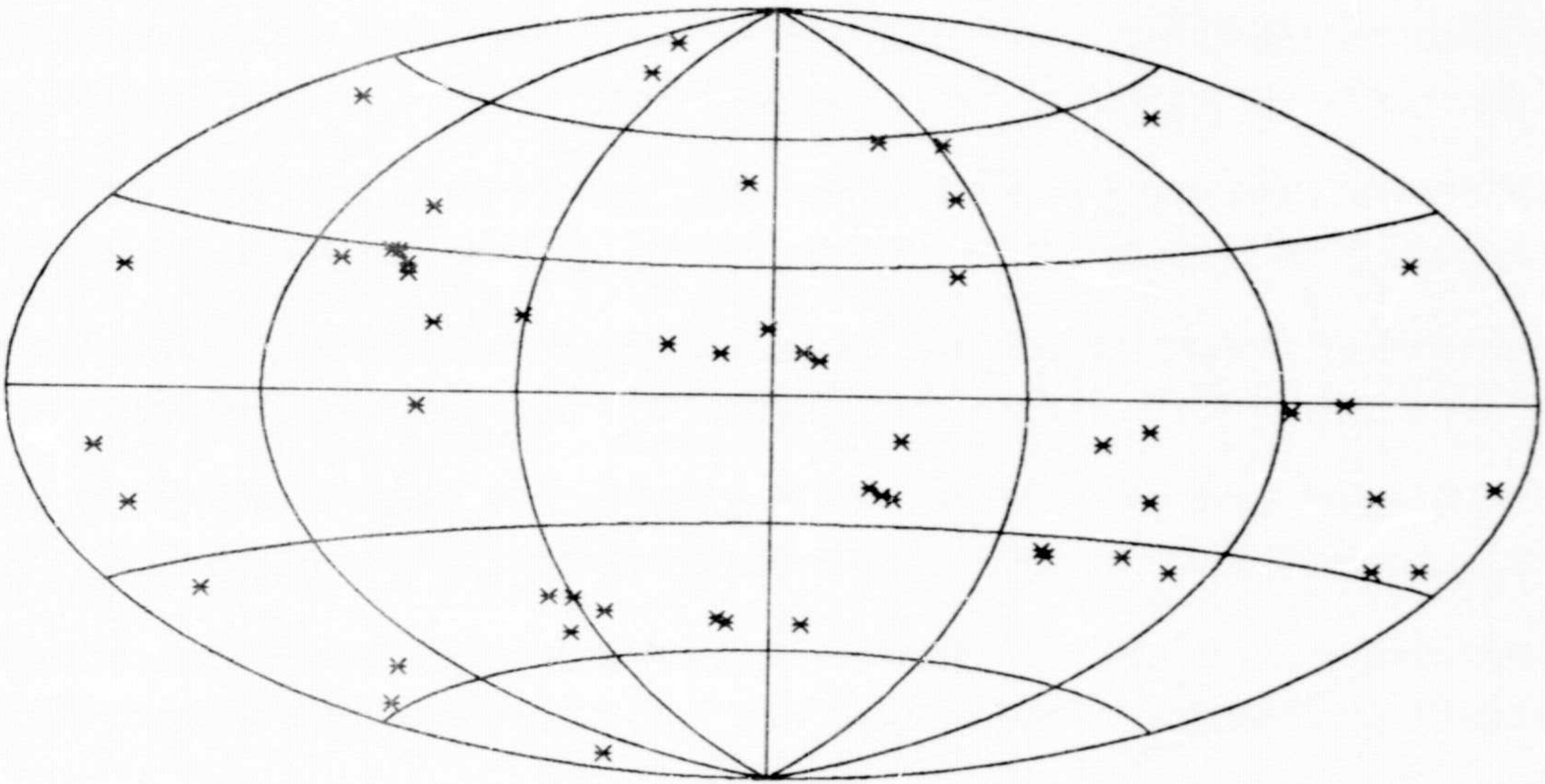


Figure 1

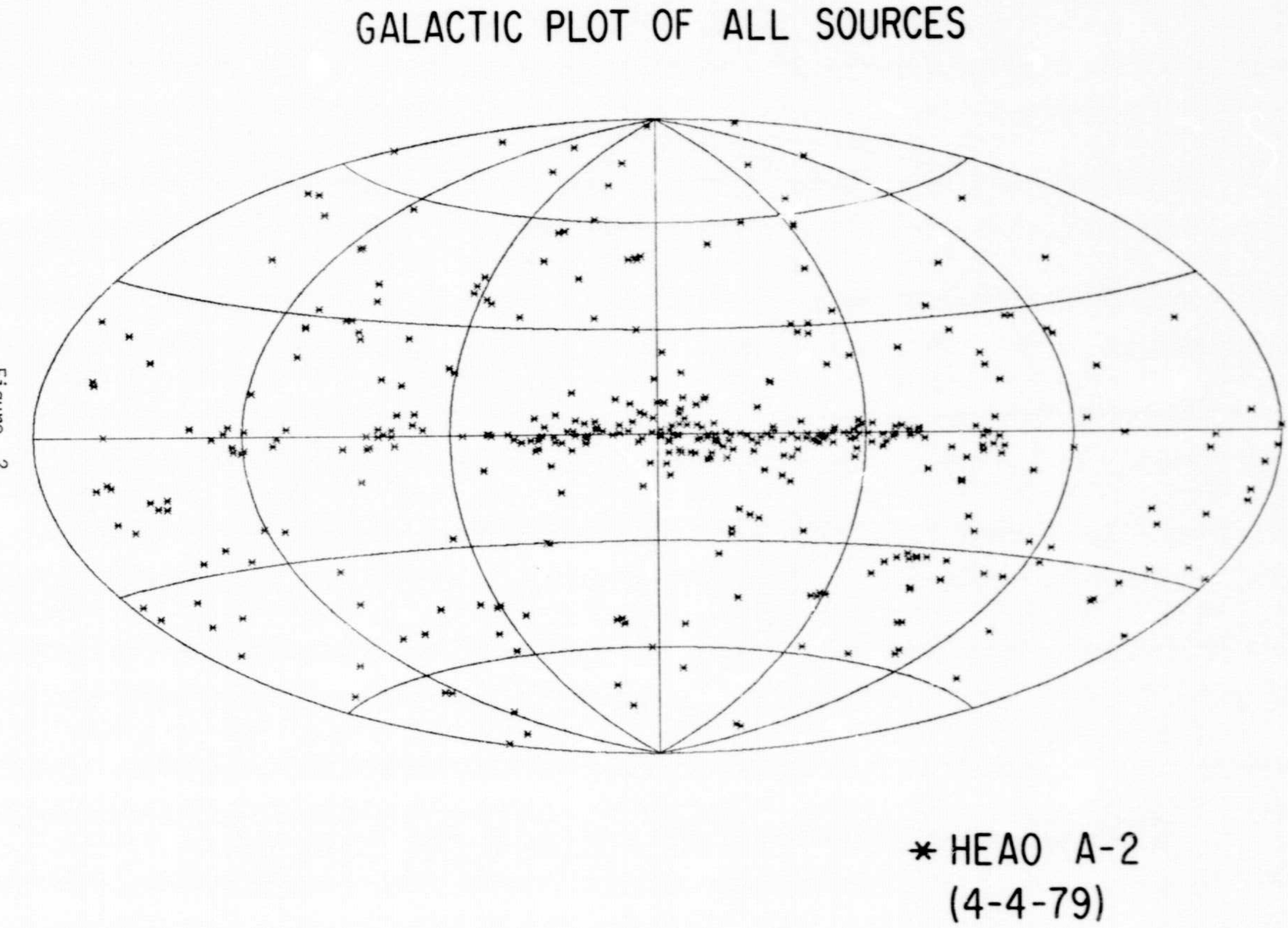
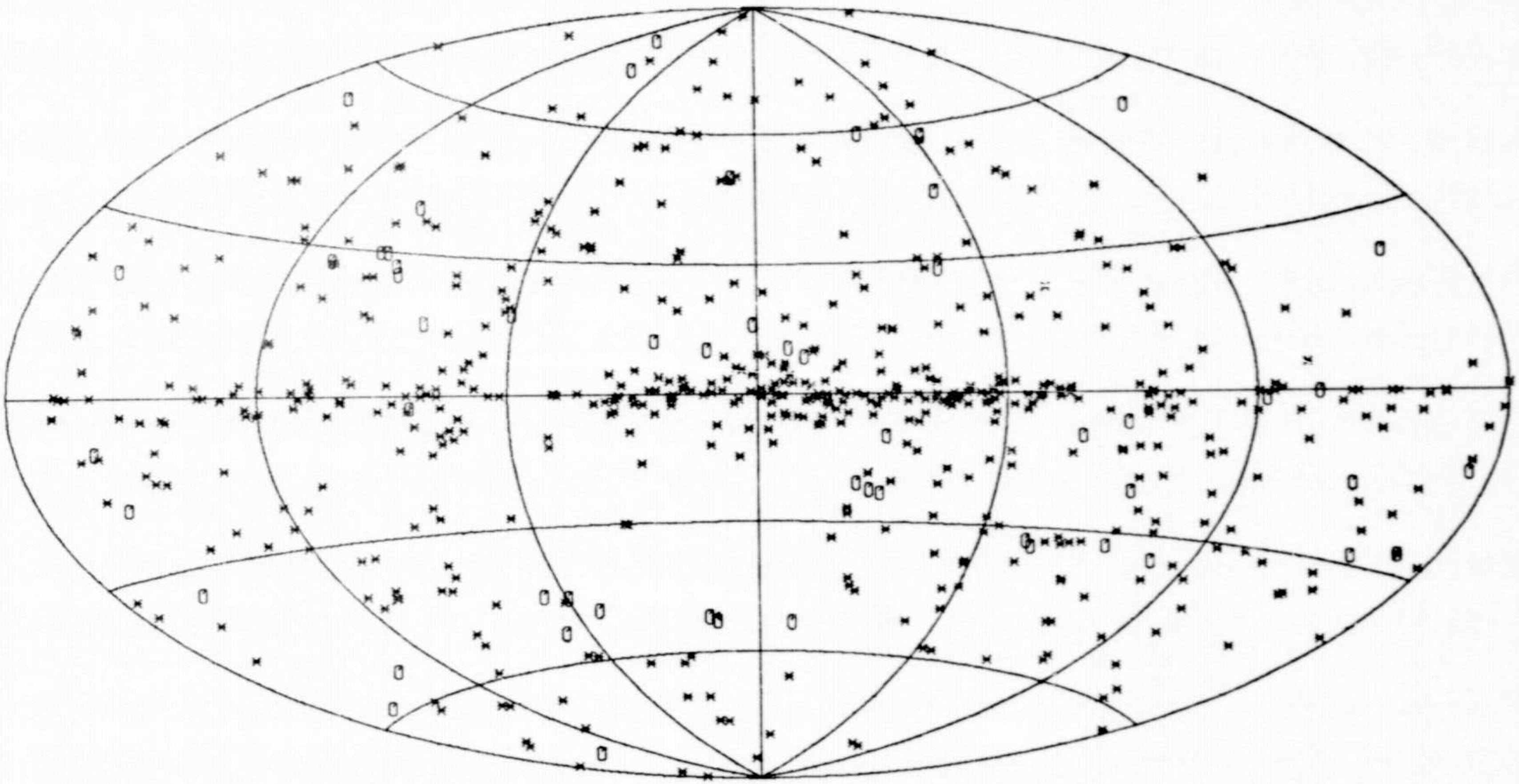


Figure 2

GALACTIC PLOT OF ALL SOURCES



* BEFORE HEAO-1

o NEW HEAO-A2

Figure 3

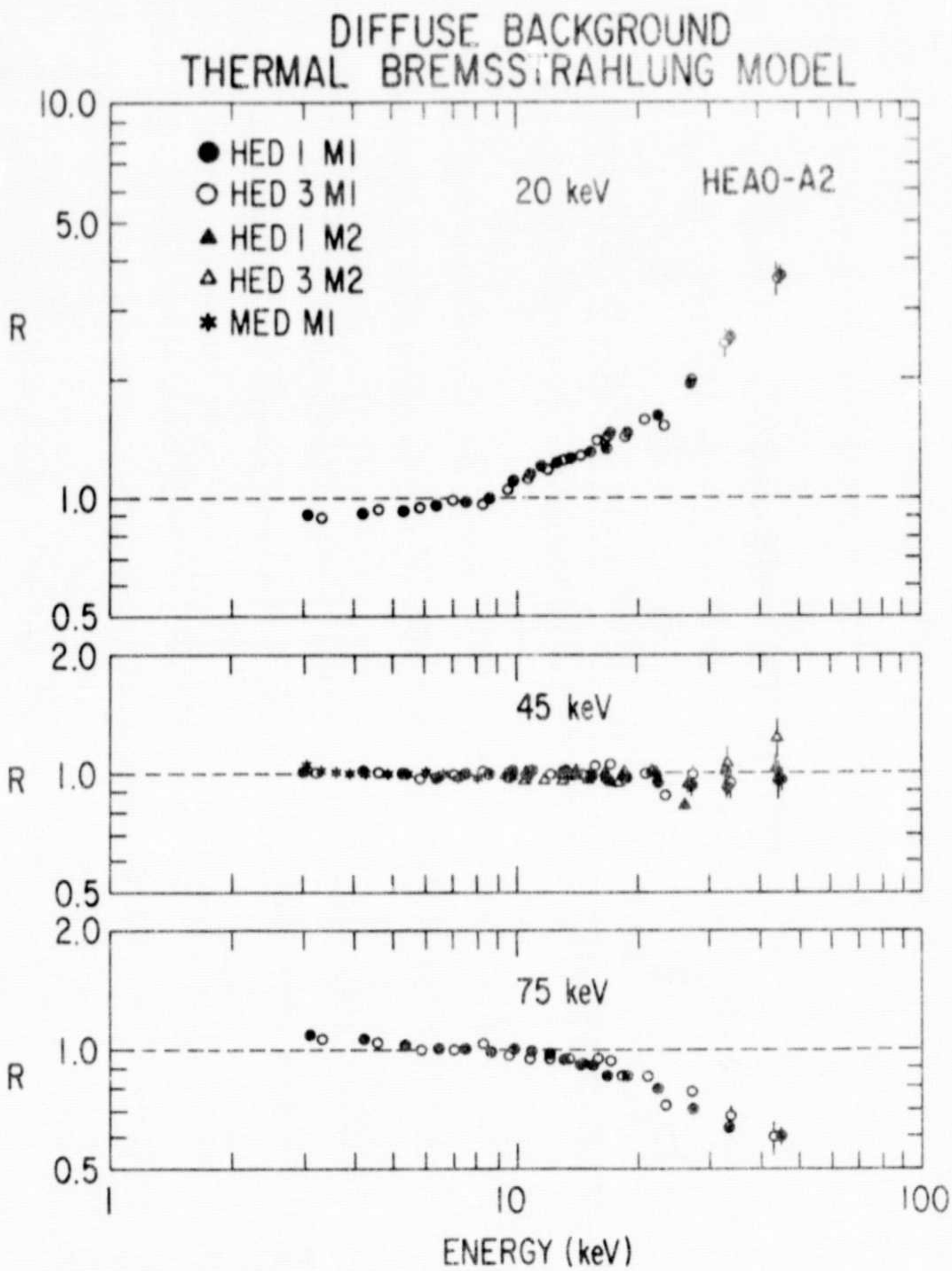

DIFFUSE BACKGROUND
THERMAL BREMSSTRAHLUNG MODEL
HED 1 M1
HED 3 M1
HED 1 M2
HED 3 M2
MED M1
20 keV
HEAO-A2
45 keV
75 keV
R
10.0
5.0
1.0
0.5
2.0
1
10
100
ENERGY (keV)

Figure 5

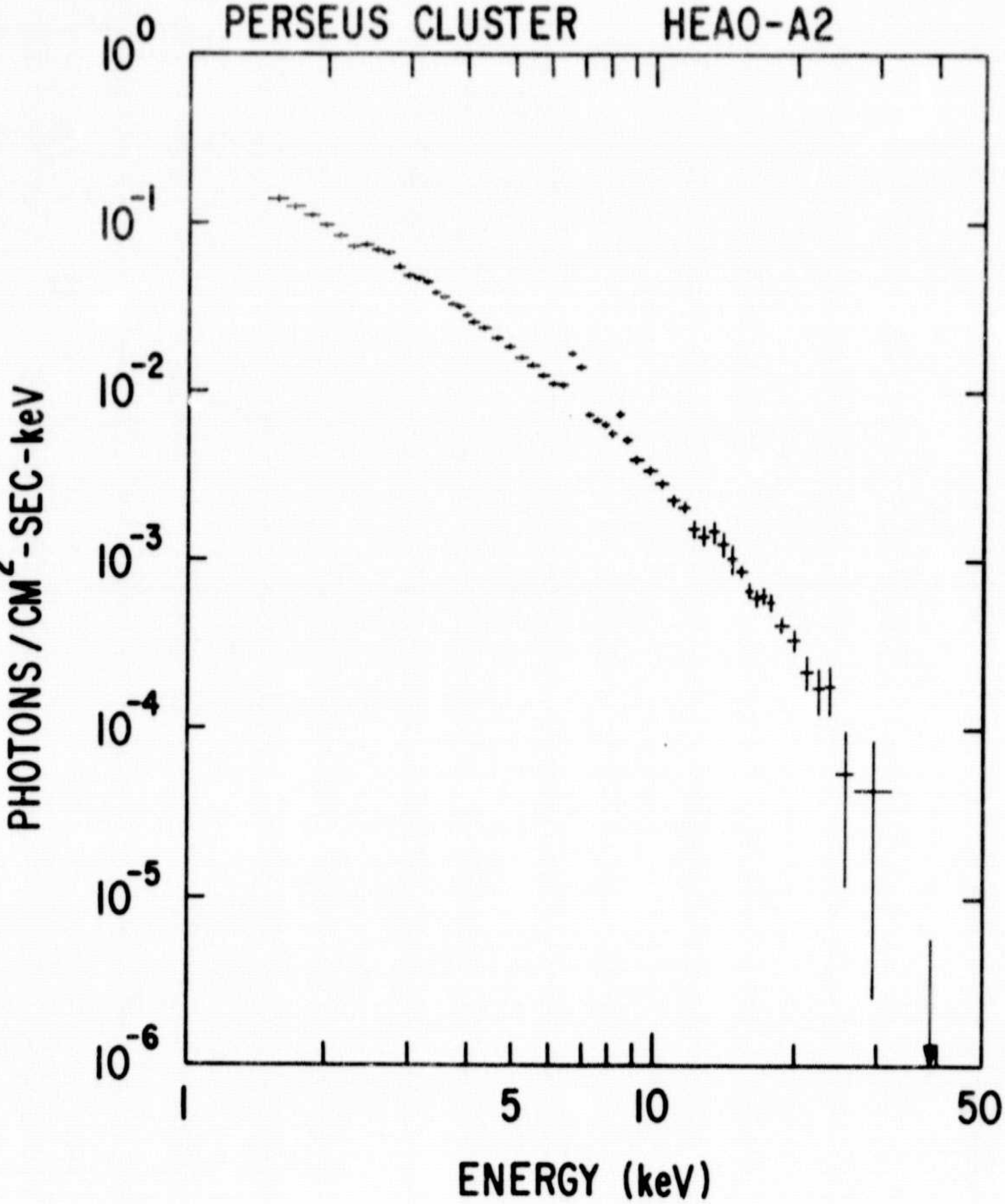

PERSEUS CLUSTER HEAO-A2
PHOTONS / CM^2 -SEC-keV
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
1
5
10
50
ENERGY (keV)

Figure 6

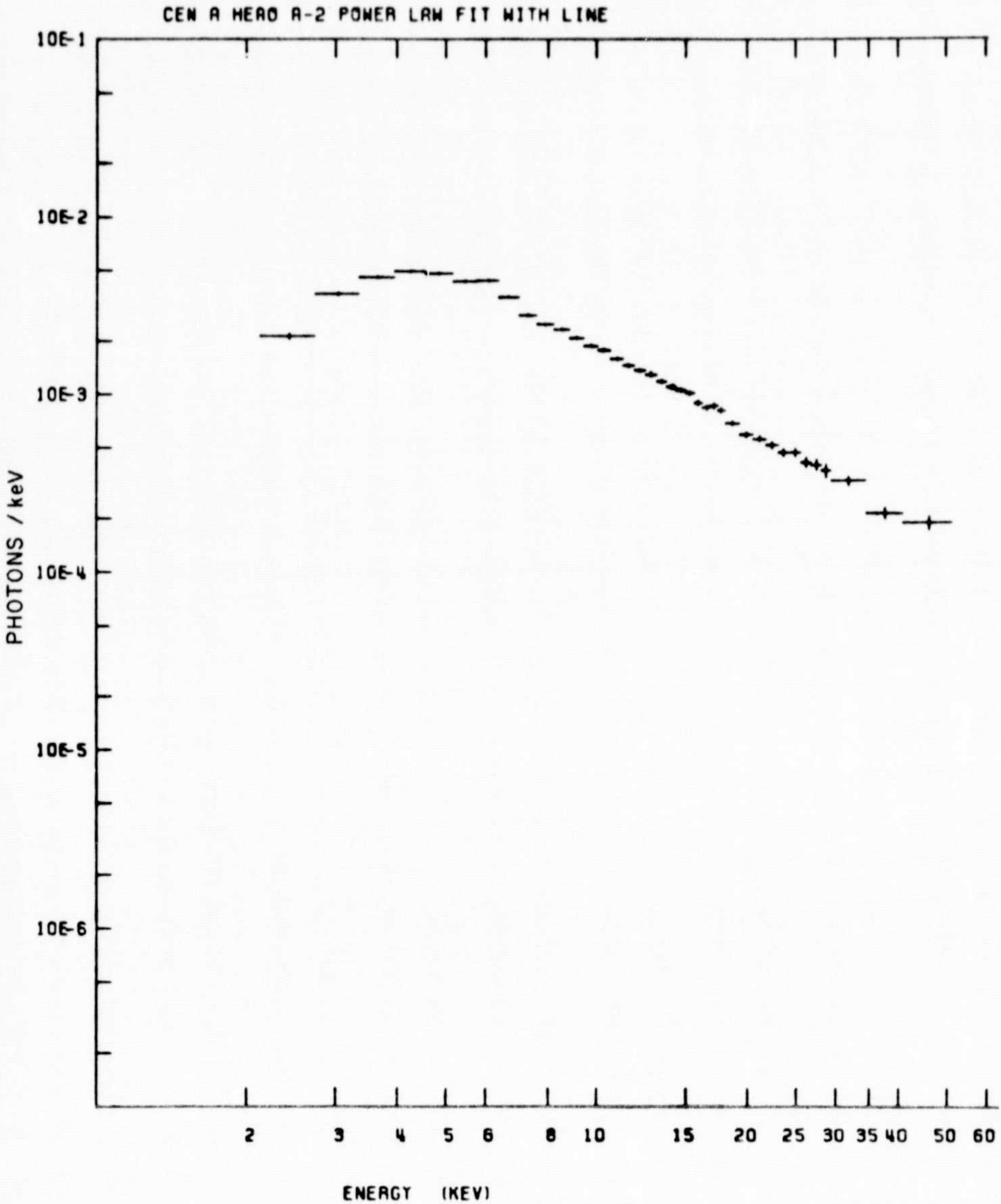

CEN A HEAO A-2 POWER LAW FIT WITH LINE
10E-1
10E-2
10E-3
10E-4
10E-5
10E-6
PHOTONS / keV
2 3 4 5 6 8 10 15 20 25 30 35 40 50 60
ENERGY (KEV)

Figure 7

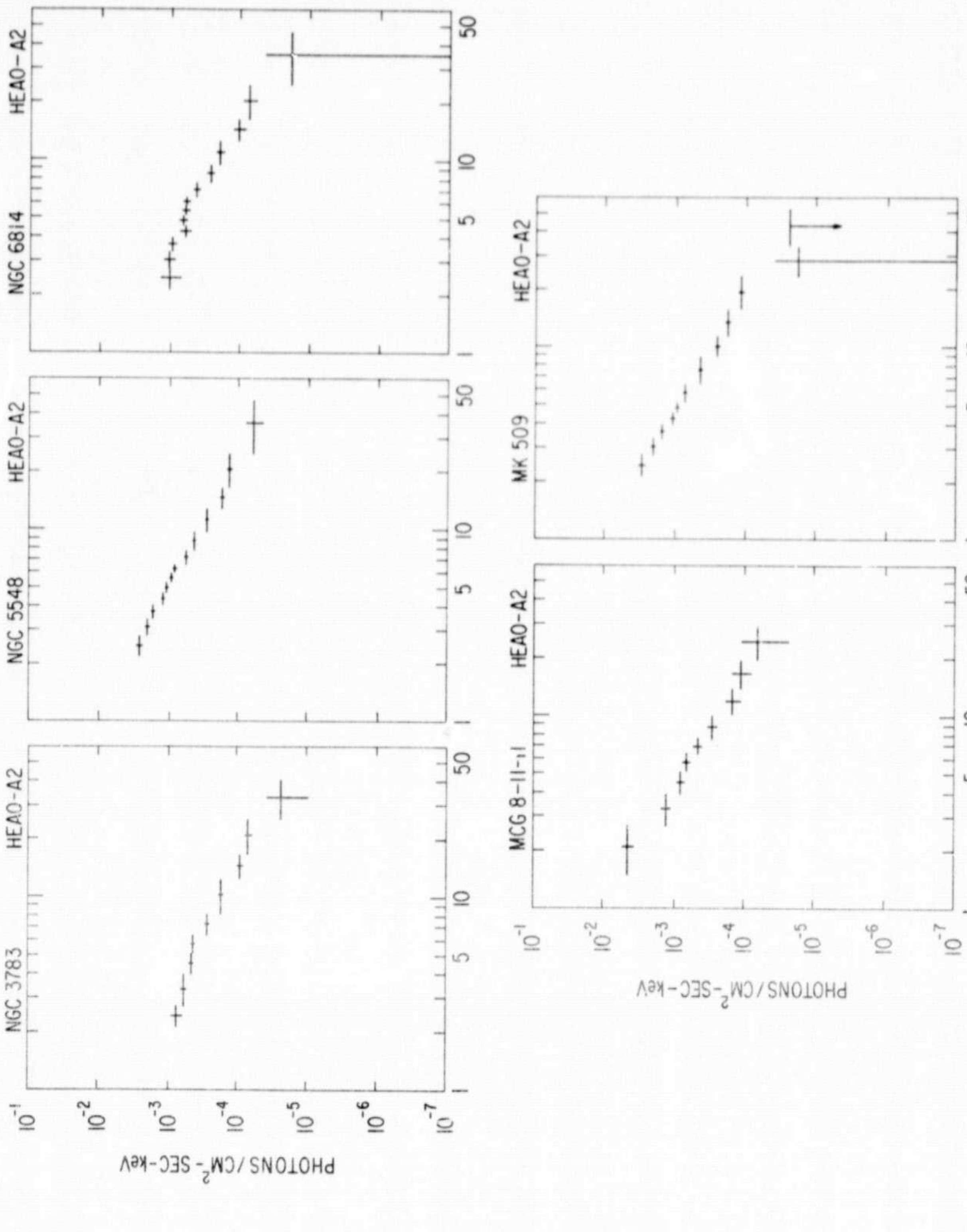

NGC 6814
HEAO-A2
NGC 5548
HEAO-A2
NGC 3783
HEAO-A2
MK 509
HEAO-A2
MCG 8-11-11
HEAO-A2
PHOTONS/CM^2-SEC-keV
ENERGY (keV)

Figure 8

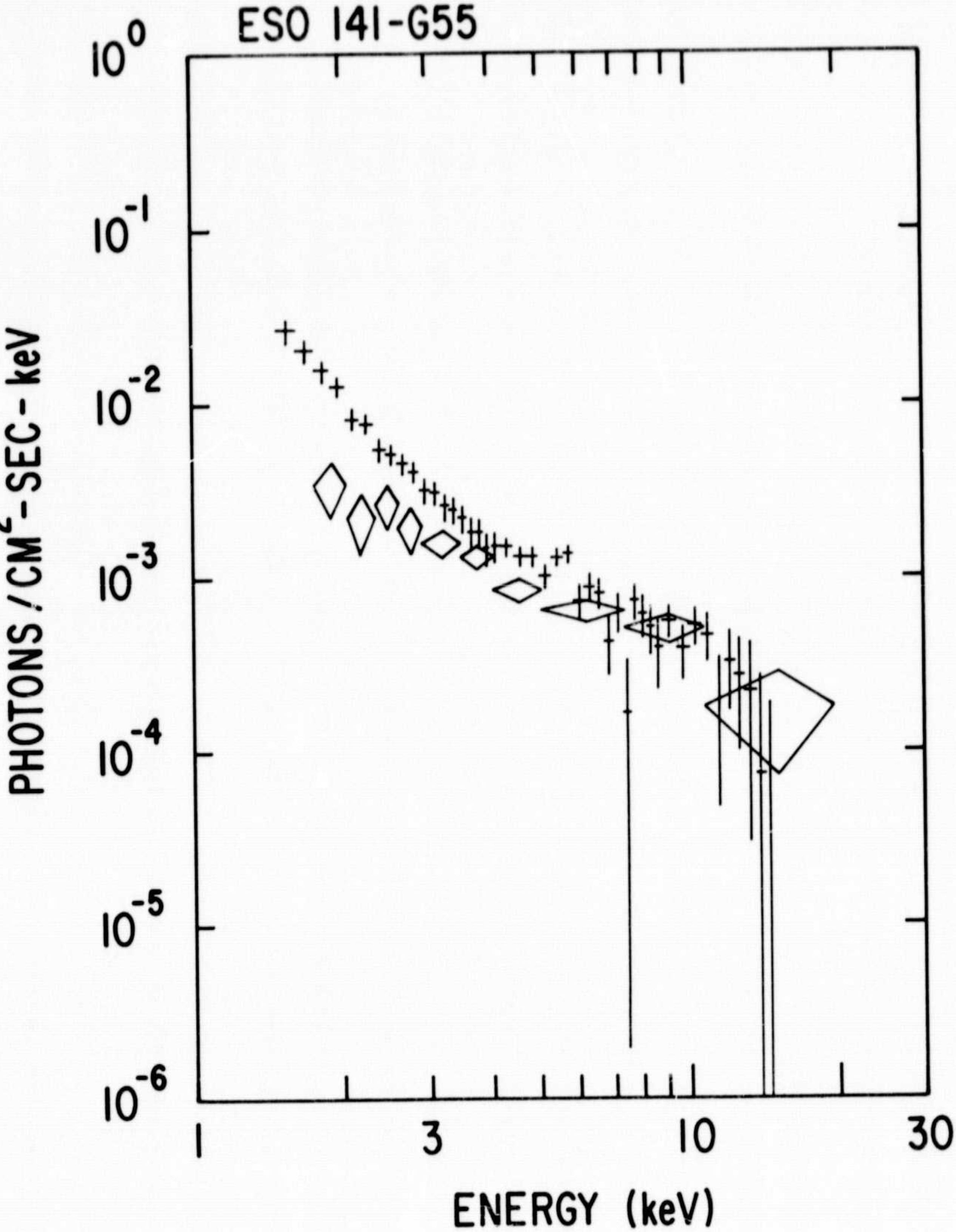

ESO 141-G55
PHOTONS / CM^2-SEC- keV
ENERGY (keV)
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
1
3
10
30

Figure 9

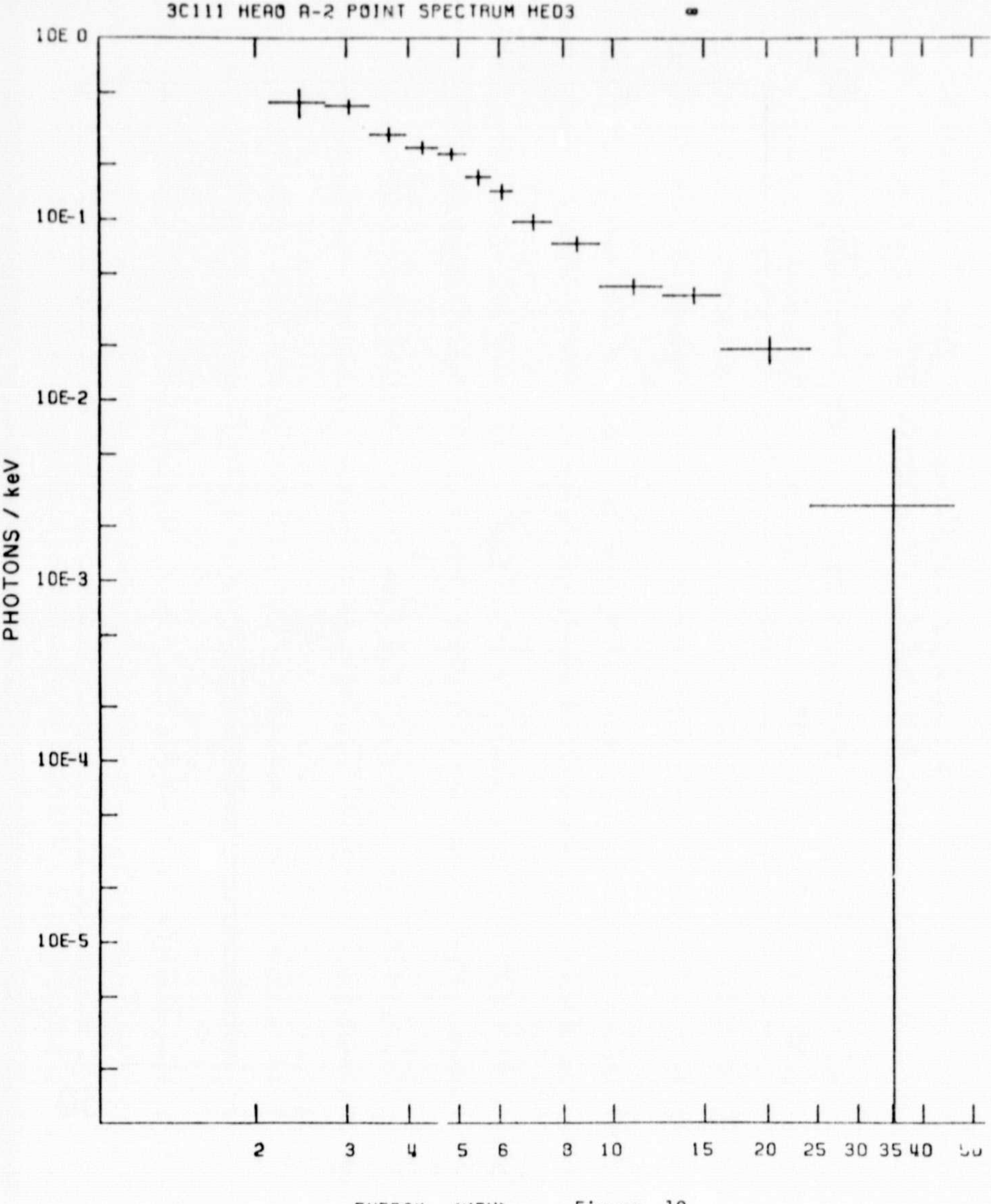

3C111 HEAO A-2 POINT SPECTRUM HED3
10E 0
10E-1
10E-2
10E-3
10E-4
10E-5
PHOTONS / keV
2
3
4
5
6
8
10
15
20
25
30
35
40
ENERGY (KEV)

Figure 10

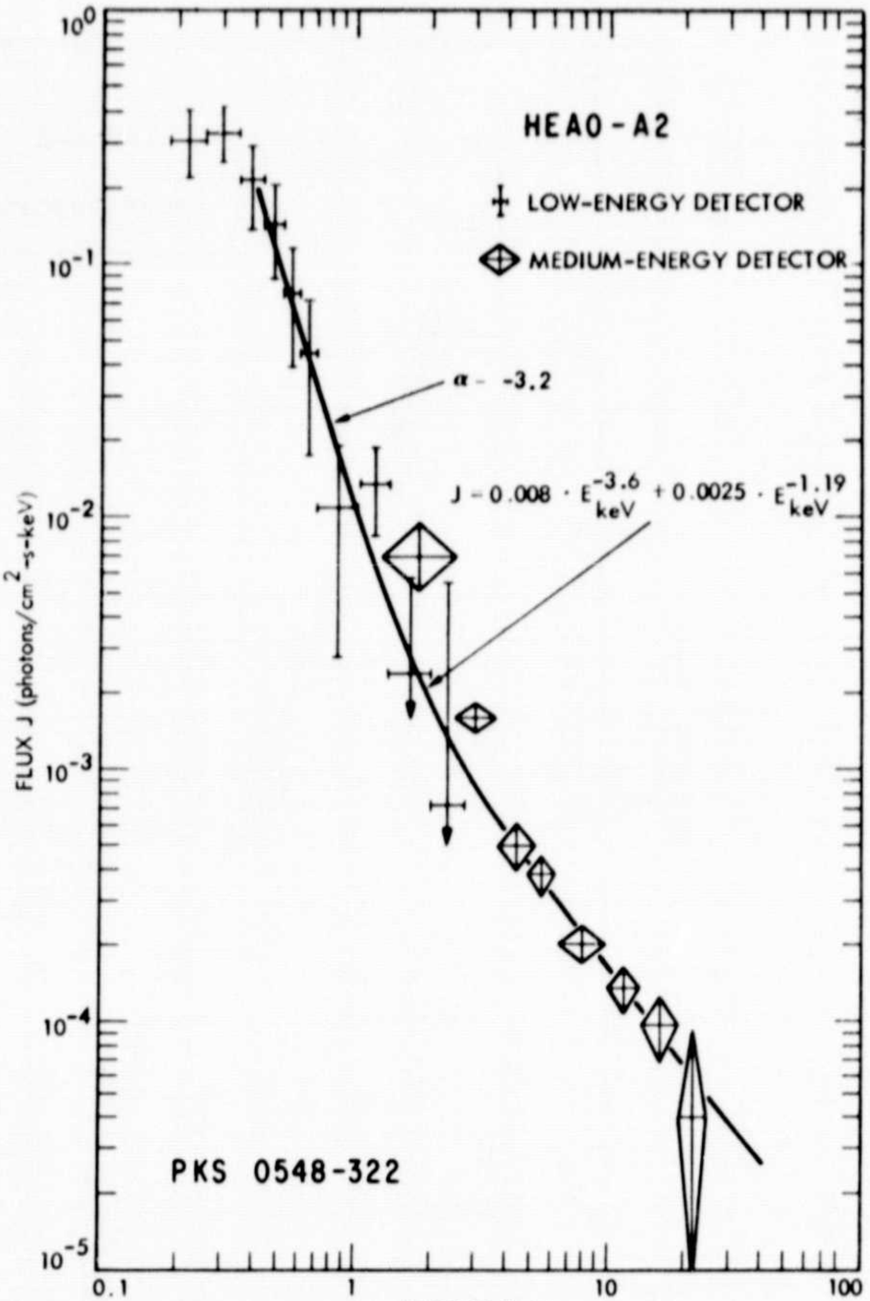

HEAO-A2
LOW-ENERGY DETECTOR
MEDIUM-ENERGY DETECTOR
α = -3.2
J = 0.008 · E$^{-3.6}_{keV}$ + 0.0025 · E$^{-1.19}_{keV}$
PKS 0548-322
FLUX J (photons/cm^2-s-keV)
ENERGY (keV)
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
0.1
1
10
100

Figure 11

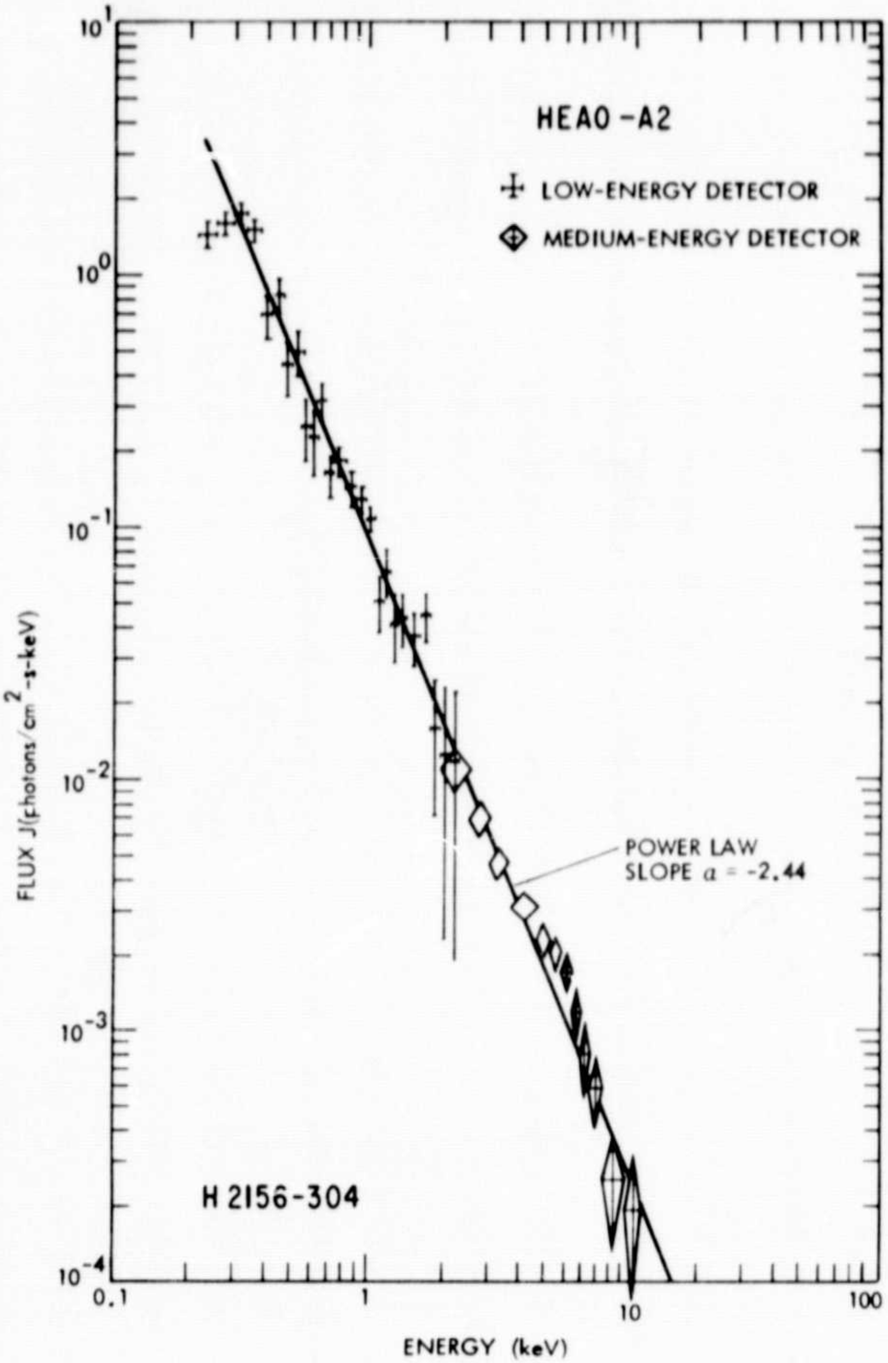
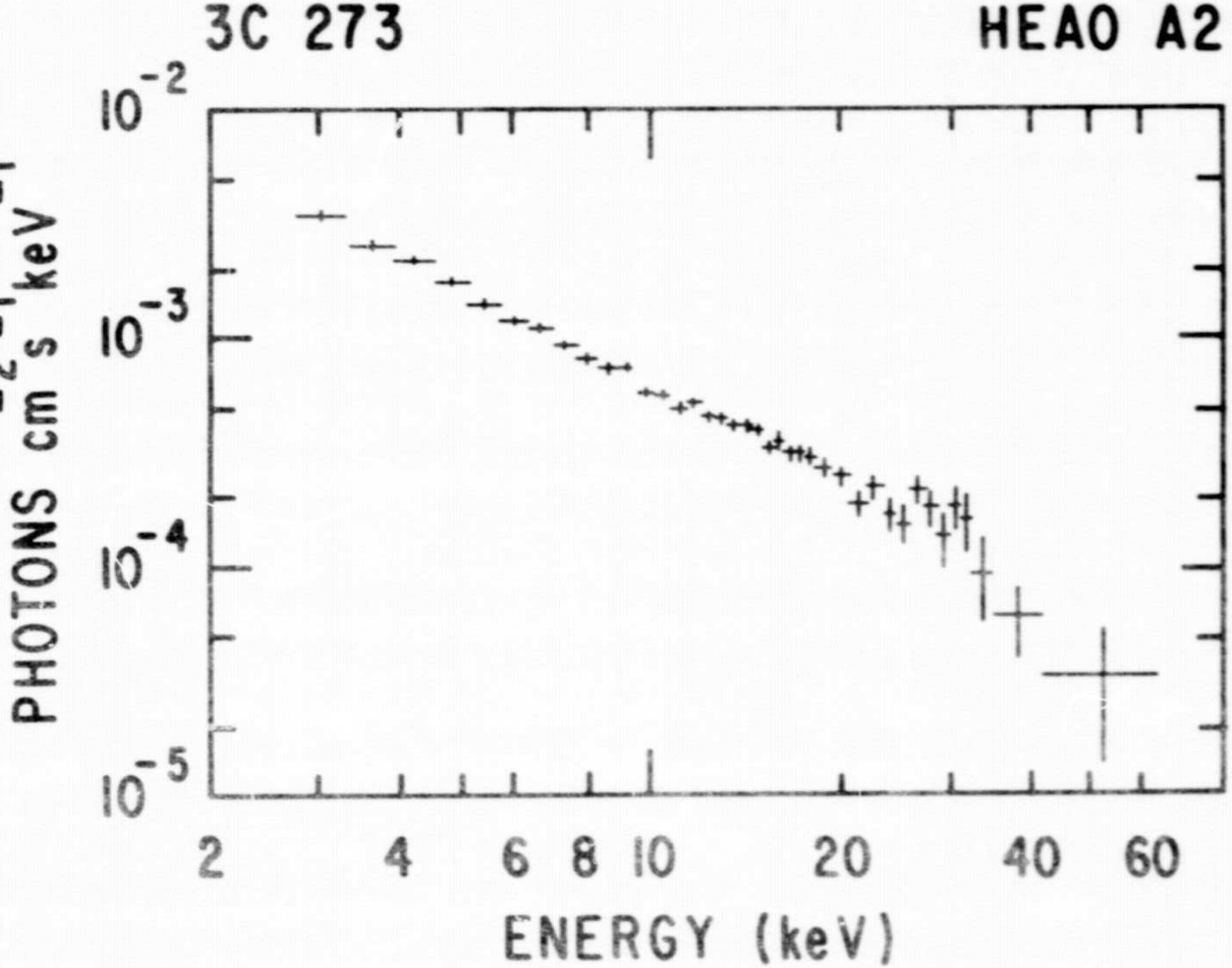

HEAO -A2
LOW-ENERGY DETECTOR
MEDIUM-ENERGY DETECTOR
POWER LAW
SLOPE a = -2.44
H 2156-304
FLUX J(photons/cm^2-s-keV)
ENERGY (keV)
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0.1
1
10
100

Figure 12



3C 273
HEAO A2
PHOTONS cm^{-2} s^{-1} keV^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
2
4
6
8
10
20
40
60
ENERGY (keV)

Figure 13

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16. Abstract

The all-sky surveys made with the A-2 instrument aboard HEAO-1 involve spectroscopy over a broad enough band width, with sufficient resolution, to obtain the basic spectral characteristics for two extreme aspects of the extragalactic X-ray sky. For the apparently isotropic radiation arising from unresolved discrete sources of emission such as distant quasars and possible diffuse components, the overall spectrum (above 3 keV) is remarkably well described by a thermal model, where the temperature is about a half-billion degrees and the corresponding photon energies are measured in tens of keV. At the other extreme, our detailed broad-band observations of individual sources are restricted to objects within the present epoch. These objects include several individual active galaxies studied in detail for the first time as well as clusters of galaxies. Relating these results to the vast spatially unresolved hard X-ray flux measured with this instrument as well as the softer X-rays (at < 3 keV) spatially resolved to high redshifts with the Einstein Observatory remains a challenge.

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