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Abstract

X-ray spectral data from a rocket-borne proportional counter exposure to discrete sources in Cygnus are presented. The data from Cyg X-1, Cyg X-2, and Cyg X-3 have sufficient statistical significance to clearly indicate mutually exclusive spectral forms for the three. Upper limits are presented for X-ray intensities above 2 keV for Cyg X-4 and Cyg X-5 (Cygnus Loop).

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I. INTRODUCTION

All five of the previously reported sources in Cygnus were searched for in a rocket-borne exposure obtained on September 21, 1970. For all except Cyg X-5 (Cygnus Loop), the exposure consisted of a single scan of a 2° (FWHM) wide collimator across the source at a roll rate of $\sim$ 1/2°/sec, with a total collecting area of $\sim$ 1300 cm^2. In the case of the Cygnus Loop, a dwell time of $\sim$ 20 sec was spent with the center of the 2° x 8° collimator response near the center of the supernova remnant.

The data were obtained in two multi-anode, multi-layer proportional counters, each with 2° x 8° FWHM collimation and with net areas of 650 cm^2. In the top layers of each counter there was three-sided anticoincidence for each 1/2" cell, and four-sided anticoincidence in the lower layers. The bottom layer and all anodes adjacent to the side walls were used only for anticoincidence. One of the counters was filled with P10 (90% argon, 10% methane), and the other with xenon-methane in like proportions. The operating range of the argon counter was 1.6 - 24 keV, and that of the xenon counter was 2 - 32 keV. Both counters had windows of 1 mil aluminized mylar supported by the collimators.

The high statistical significance of the data allows us to severely constrain the model parameters for each of the sources. Having two independent counters with different gases, and layers within each counter with differing response owing to the opacity of the higher layers, we can report spectra which are relatively systematics-free as a result of the non-degenerate response functions of the various detecting layers.

II. SPECTRAL OBSERVATIONS

(a) Cyg X-1: Essentially all of the Cyg X-1 spectra reported from both rocket- and balloon-borne experiments are at least as hard as the Crab Nebula, i.e., spectral number index $\lesssim 2$ (c.f. Oda et al., 1971). The spectrum which we measure for Cyg X-1 is considerably softer, as shown in Figure 1:

$$\frac{dN}{dE} = 7.4^{+2.4}_{-1.3} \; E^{-(2.6 \pm .3)} \; cm^{-2} sec^{-1} keV^{-1} \qquad (1)$$

The limits in the above expression are at the 90% confidence level of the χ^2 distribution, as are all other limits in this communication unless otherwide stated. We are reasonably confident that this soft new spectrum does not arise from a systematic effect in our experiment, as both the xenon- and argon-filled counters (as well as the argon layers individually) are in agreement with this spectrum.

It is interesting to note that we observed this spectrum during the same few seconds in which we were able to detect marked variability in the source intensity on time scales of tenths of a second and greater (Holt et al., 1971). The UHURU satellite, in observing similar temporal variations, sees spectral indices for Cyg X-1 which are also > 2 (Giacconi, personal communication, 1971, correcting Oda et al., 1971). Furthermore, balloon measurements in Sept. 1970 at higher energies (Matteson and Peterson, personal communication, 1970) are consistent with the present softer Cyg X-1 spectrum up to 100 keV.

The power law fit is more than adequate. The other "standard" approximation spectra, thermal continua and black-body, cannot be reconciled with our data, at all. This would imply a non-thermal origin for the X-ray output, possibly synchrotron emission as in the case of the nebular X-ray output of the Crab Nebula. As pointed out by Oda, et al. (1971), however, there is good reason to suppose that the Cyg X-1 X-ray emitting source is considerably smaller. There is no visible or radio nebula at the Cyg X-1 position, and the shortest time scale variations observed by us ($\lesssim$ 300 msec), imply a linear dimension for the source region which is smaller than a solar radius.

Because of the relatively high energy threshold of our instrument, we are unable to make a very sensitive measurement of interstellar absorption by cold material in the line of sight. Our data are consistent with no absorption, with a 90% confidence upper limit of 5×10^{21} atoms/cm^2 using the formalism of Brown and Gould (1970). This is to be compared with 1.6×10^{21} atoms/cm^2 as deduced by Gursky et al. (1971) from an analysis of X-ray and 21 cm data.

(b) Cyg X-2: Unlike Cyg X-1, with which a non-thermal spectrum has always been associated, Cyg X-2 has always been reported as being well fit by a thermal continuum. Our measurement confirms this trend, to the extent that a power law cannot be fit to the data in Figure 2. The temperature and intensity are in good agreement with previous measurements:

$$\frac{dN}{dE} = \frac{1.4 \pm .3}{E} \exp \left(- \frac{E}{4.5 \pm .7}\right) \mathrm{cm}^{-2}\mathrm{sec}^{-1}\mathrm{keV}^{-1} \qquad (2)$$

Again, the relatively thick transmission window limits our ability to study interstellar absorption, but the observed Cyg X-2 spectrum is barely reconcilable with no absorption at the 90% confidence level, with an upper limit of 2.1×10^{22} atoms/cm^2. Although the acceptability of equation (2) at the 90% confidence level does not allow us to meaningfully add another parameter to the analysis, we remark that the inclusion of absorption would decrease the best fit temperature by $\sim$ 1/2 keV.

The optical identification of Cyg X-2 (Giacconi et al., 1967) and its interpretation in terms of a binary system (Burbidge et al., 1967) seem to be fairly well established. If an accretion model for Cyg X-2 is correct, we should expect a compact thermal source with X-ray opacity arising from the cold infalling matter, as well as free-free and photoelectric absorption in the source itself which should exceed interstellar photoelectric opacity. Our upper limit on the amount of material in the line of sight does not rule out such self-absorption, as it is more than an order of magnitude above that expected from interstellar opacity alone.

(c) <u>Cyg X-3</u>: The spectrum from Cyg X-3 cannot be adequately fit by any of the three simple forms: power law, thermal continuum or black-body spectrum. Furthermore, the data have high enough statistical significance to also exclude a power law or thermal continuum masked by cold interstellar matter using the approximate forms of Bell and Kingston (1967) or Brown and Gould (1970). The position of the maximum in the observed counting rate at 5 keV implies (if the turnover is absorption induced) more than 10^{23} atoms/cm^2 in the line of sight to Cyg X-3. If absorption by cold material plays an important role in the low energy portion of our observed spectrum, an order of magnitude more exposure might bring out the absorption edges (especially that due to argon) which are hinted at in the present observation. Our data above 15 keV (not displayed in Figure 3), indicate a hardening of the spectrum at higher energies with respect to the best fit displayed.

(d) <u>Cyg X-4</u>: This source, reported by Giacconi et al. (1967), at a strength of ~ .19 keV cm^{-2}sec^{-1} in the energy range 2 - 5 keV, was not detected. The 3 σ upper limit we can place on this object is

~ .04 keV $cm^{-2}sec^{-1}$ in the same energy range, or about 1% of the intensity of Cyg X-1.

(e) Cyg X-5: We did not observe the Cygnus Loop with a 3 σ upper limit of ~ $10^{-2}cm^{-2}sec^{-1}$ above 2 keV, assuming a source of uniform surface brightness coincident with the supernova remnant. This would imply agreement with a thermal model for the source (c.f. Tucker, 1971) as the power law fit to the data of Grader et al. (1970) should have been clearly observable (about an order of magnitude above our upper limit), while the thermal fit to that same data at a temperature of a few hundred eV would be below our threshold of detectability.

III. SUMMARY

Cyg X-1 appears to be a compact non-thermal emitter. Temporal variations in the source on time scales from ~ 100 ms to ~ 1 year have been reported by several groups. The spectra observed by those investigators who have observed rapid temporal fluctuations in Cyg X-1 have a considerably softer non-thermal spectrum than that observed previously from the source (by about a full unit in spectral index).

Cyg X-2 appears to be a compact thermal emitter, consistent with its interpretation as an optical binary system. No rapid temporal variations of the type observed from Cyg X-1 were seen in the Cyg X-2 exposure (which was identical to that from Cyg X-1 in all respects save approximately a factor of two in maximum counting rate). Our best fit without absorption is barely acceptable at the 90% confidence level, and the inclusion of absorption would improve it, in qualitative agreement with the apparent opacity we would expect to see in the direction of a source which is accreting matter.

Cygnus Loop, by its absence above 2 keV, would appear to be an extended thermal source associated with the evolved supernova remnant.

Cygnus X-3 may be a compact source of the X-1 or X-2 variety, with several qualifications. First, it cannot be exactly like X-2 because it has been observed at energies > 30 keV (Peterson, 1970), and is observed to be considerably harder than thermal above ~ 10 keV in our experiment, as well. Second, there are no temporal fluctuations as in the case of X-1. Third, the spectrum is very different than that of the other two, an effect which may arise from absorption or be intrinsic to the source. In either case, the effect is distinct: $\gtrsim 10^{23}$ atoms/cm^2 in the line of sight or a peaking of the X-ray output at 5 keV are both very different situations than obtained for the other Cygnus sources.

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FIGURE CAPTIONS

1. Apparent flux observed from Cyg X-1. The data points represent the observed count rate divided by the nominal exposure and energy range, for the first layer of the xenon-filled counter. No efficiency corrections are made to the data displayed. The solid line represents the best-fit spectrum 7.4 $E^{-2.6}$ folded forward through our complete detector response, and the dashed line represents a spectral shape proportional to $E^{-1.7}$ similarly folded.

2. Apparent flux observed from Cyg X-2. The solid line represents the best-fit spectrum $\frac{1.4}{E}$ exp $\left\{- \frac{E}{4.5}\right\}$ folded forward through our complete detector response.

3. Apparent flux observed from Cyg X-3. The solid line represents the best-fit spectrum 87 f(E, EO)$E^{-3.9}$ folded through the detector response, where f(E,EO) denotes the Brown and Gould interstellar opacity at a characteristic energy EO of 4.0 keV. Note that this best-fit was not acceptable at the 90% confidence level.

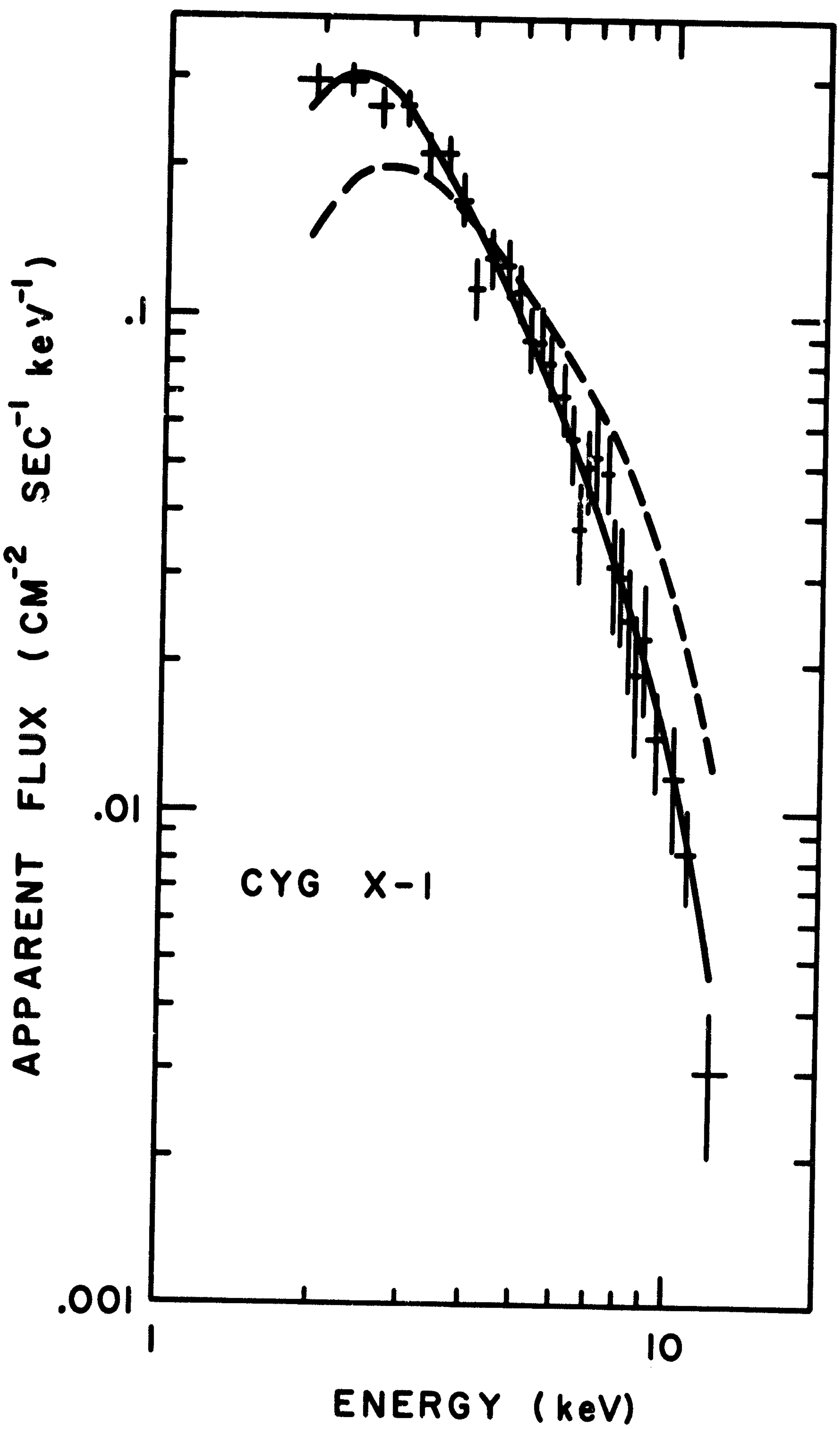

FIGURE 1

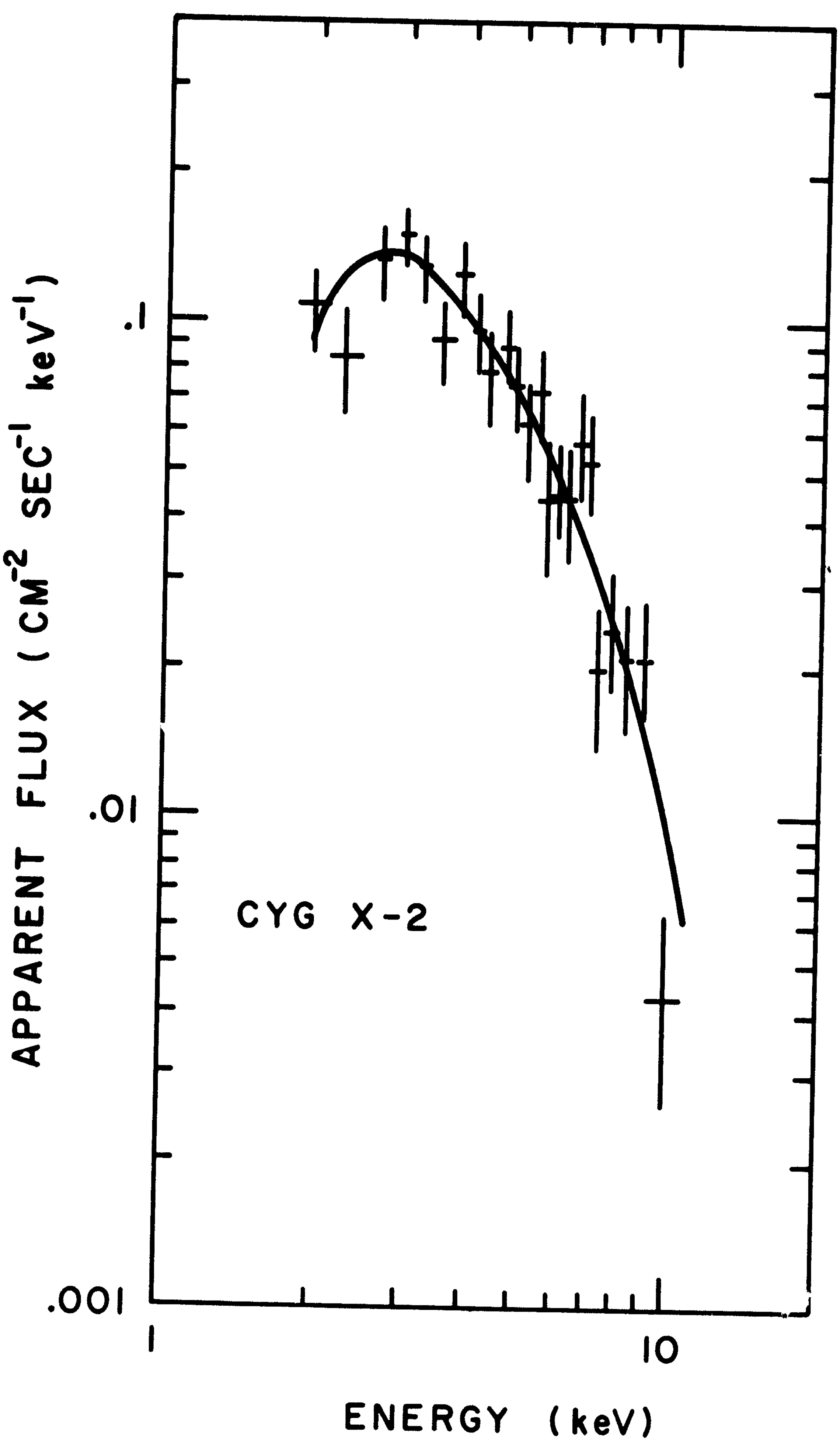

FIGURE 2

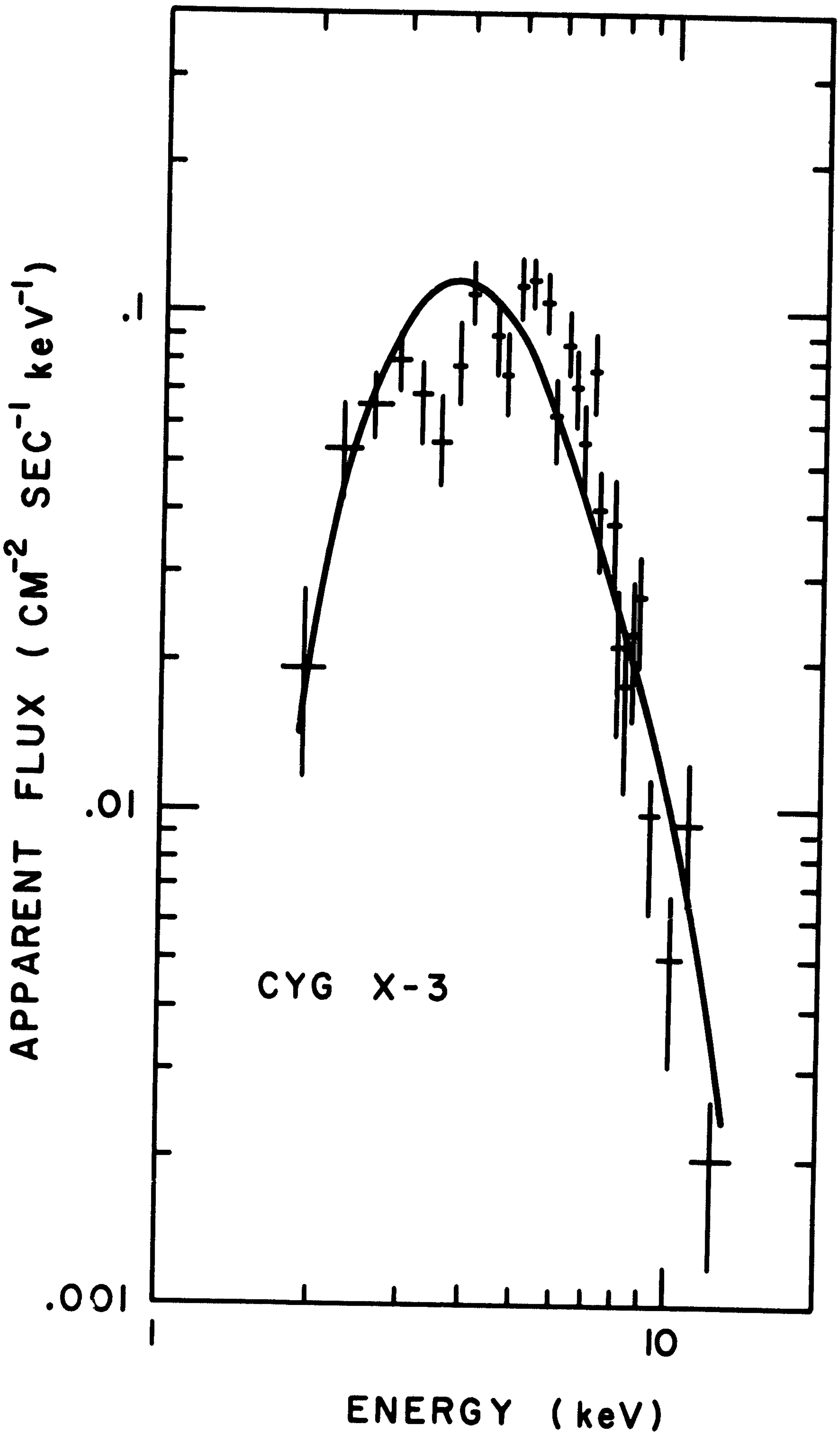

FIGURE 3