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144 SECOND PERIODIC FLUX VARIATIONS DURING X-RAY TURN-ON OF HERCULES X-1

D.A. Leahy[1], A. Yoshida[2], N. Kawai[2], M. Matsuoka[2]

[1]Dept. of Physics and Astronomy,
University of Calgary, Calgary, Canada T2N 1N4

[2]Institute of Physical and Chemical Research
Hirosawa, Wako, Saitama 351-01 Japan

ABSTRACT

Hercules X-1 is a well known bright binary X-ray pulsator. It has a 1.70-day orbital period, a pulsation period of 1.24 second, and a 35 day semi-periodic variability. Here we report the discovery of a new 144 second periodicity in the X-ray emission from Her X-1. The periodicity is seen in X-ray observations of Her X-1 by the LAC instrument on board the Ginga satellite during Aug.-Sept. 1988. The periodic flux variations occur during the time of X-ray turn-on at the beginning of a high-state of Her X-1, in the same time that a pre-eclipse dip also occurs. An analysis of the LAC spectra of Her X-1 during this period is also presented. Large changes in spectral shape occur associated with the dip.

1. INTRODUCTION

The 1.24 s X-ray pulsar Hercules X-1 was discovered by UHURU (Tananbaum et al. 1972). It is an eclipsing system with a 1.70-day orbit. The mass ratio and inclination have been determined by analysis of the optical pulsations (Middleditch and Nelson 1976). The orbital parameters have been accurately determined by analysis of arrival times of the X-ray pulses (e.g. see Deeter et al., 1991 and references therein). In addition the X-ray flux exhibits a regular variation with a 35 day period. This period is not well defined, but whether the variations are due to white noise acting on a precise period, or due to an inherent instability in the clock mechanism is not yet known (Ogelman, 1987).

Her X-1 has been studied in X rays with several previous satellite instruments. Pravdo et al. (1977) and Pravdo et al. (1978) study the OSO-8 high-state spectrum. Becker et al. (1977) find evidence in the OSO-8 spectra for variations in absorption during the turn-on, which are also seen in Tenma observations (Ohashi et al. 1984, Ushimaru et al. 1989). Soong et al. (1990)

report on HEAO-1 observations. Mihara et al. (1990) give unambiguous evidence for the cyclotron absorption feature near 35 keV. Mihara et al. (1991) study the low-state spectrum of Her X-1 and find a two component emission model is needed. Leahy et al. (1991) find a two component model is needed to represent the high state spectrum also.

We report a new periodic flux variation seen from Her X-1 during dipping periods. The results are based on analysis of observations by the GINGA satellite (Makino and the Astro-C Team, 1987) with the Large Area proportional Counter (LAC) instrument (Turner et al. 1989). We also report on variations in the spectrum of Her X-1 during the dipping period. The LAC had a total effective area of 4000 cm^2 and low intrinsic background, thus provided much superior data regarding the details of the X-ray time variability and spectrum of Her X-1 than previous experiments.

2. OBSERVATIONS AND ANALYSIS

The analysis presented here is based on observations of Her X-1 by the LAC on GINGA during the period 1988 Aug. 17 to Sept. 1. Her X-1 was in a low state during the Aug. 17 and 19 observations, and in the high state for the Aug. 28 and Sept. 1 observations. During the Aug. 28 observations extensive dipping behaviour was seen.

The LAC can observe in several data modes. We use modes MPC2h, which records 48 channel pulse-height spectra with 0.0625s time resolution and MPC3h, which records 12 channel pulse-height spectra with 0.0078s time resolution. The data were selected to pass several selection criteria. Then the detector background count rates in the different pulse height channels were determined using the method of Hayashida (Hayashida et al., 1989).

These background subtracted data were used to construct light curves in four energy bands and also a plot of softness ratio vs. time. The energy bands chosen were 0- 4,65 keV (low energy band), 4.65- 9.63 keV (iron line and iron edge band), 9.3- 14.0 keV (medium energy band), and 14.0- 37.2 keV (high energy band).

The light curves and softness ratio curves are shown in Figure 1 for the dipping state on Aug. 28. Light curves for parts of the low state data on Aug. 17 and of the high state data on Sept. 1 are shown in Figures 2a and 2b. The constancy of the count rates and of the softness ratio is apparent for the high state and low state data. This is in great contrast to the strong variability seen during the dipping period.

Inspection of Figure 1 suggests a regular variation of intensity. Visually there appears to be a period of about 70 s. The most significant variations are seen in the 0-4.65 and 4.65-9.3 keV energy bands. The entire data for Aug. 28 was combined and subjected to a period search using the epoch folding technique. This data spans the time period 16 hr 8 min 16.2 s to 19 hr 38 min 4.3 s UT (12588.1 s), with some large data gaps, giving a net observation time of 2383.5 s.

The resulting folded light curves from the epoch folding of the Aug. 28 data in the four energy bands are shown in Figure 3. The period of 143.6 seconds is highly significant- the reduced chisquared values for the four energy bands are 44.3, 53.1, 21.3 and 9.8, in order of low to high energy. There is a clear double peak in the folded light curves. The 143.6 s period is the period of maximum chisquared for both of the higher energy bands. For the two lower energy bands there is a nearby period (140.8 s) with slightly higher chisquared. However, the chisquared vs. period is affected by both the longer timescale dip modulation, and the presence of data gaps. The two higher energy bands are less affected by the dip modulation. The chisquared vs. period plots for these high energy bands more clearly indicate the correct period (see Figures 4a and b), giving strong evidence that the correct period for the flux variations is 143.6 s.

The data from the low state and from the high state were also epoch-folded. There were significant data gaps for the low-state and high-state data similar to those in the dipping-state data. There is no statistically significant period found for either the low-state or high state data. The chisquared vs. period curve for the low state data is shown in Figure 4c.

A spectral analysis for selected periods during the observation was also carried out. As reported by Leahy et al. (1991) only one two-continuum spectral model was found to adequately fit the data. The model consists of: an unabsorbed continuum (power-law-plus-cyclotron-absorption-line); an absorbed continuum of the same form; an iron emission line. The model has 10 parameters (P1 to P10):

POWL(1,2)*CYAB(3,4,5)*(1+P10*ABSM(6))+GAUS(7,8,9)

Here POWL and CYAB are given by:

$POWL=P1\ E^{-P2}$ $CYAB= \exp\{-P3\ E^2 /((E-P4)^2+P5^2)\}$

CYAB is the function used to represent the cyclotron absorption feature seen in the spectrum of Her X-1 (Mihara et al. 1990, and references therein), however we use only the first cyclotron harmonic. ABSM is absorption by neutral gas of cosmic abundance with log of column density given by P6, and using the cross-section given by Morrison and McCammon (1983). GAUS is a Gaussian function with area P7, center energy P8 and width (σ) P9. Figure 5 shows the results of fitting the two component model to the dip onset periods A, B and C of Figure 1.

3. DISCUSSION

The phenomenon of pre-eclipse dips for Her X-1 has been long established. The Ginga light curves, with their superior statistics, show the dipping phenomenon to be much more complex than apparent in previous observations. The well known dips correspond to periods B and C and period D and E in Figure 1, where the total count rate drops by factor of 4 or more, and lasting tens of minutes. However the Ginga data resolves new "minidips", which last about one minute. Two of these are clearly seen during period A, more are seen in periods G and H. Periods G and H also show that the dip can stay at an intermediate count rate for an extended period of time sometimes, in contrast to the sharp decrease seen in the transition between periods A and B.

A periodic flux variation has also been found in the Ginga data. Figure 3 shows this variation at the same 143.6 second period in all 4 energy bands. At this period a highly significant variation with a double peaked profile is seen, thus explaining the apparent 70 second period seen by visual inspection. The two maxima (and two minima) in the folded light curve are not separated by 0.5 in phase, consistent with the finding that there is no real 70 s period.

The 143.6 s periodicity occurs only during the dipping period and is not present in the other days' data. It is suggested here that the period is a Keplerian rotation period in the accretion disk and that the flux variation corresponds to periodic partial obscuration of the neutron star. For a 1.4 solar mass neutron star, this period corresponds to a distance of 5×10^9cm. This places the matter well within the Roche lobe of the neutron star, yet far outside the corotation radius or the Alfven radius. The reason that the disk matter would have an extent enough above the disk to obscure the neutron star at this particular radial distance is unclear.

Vrtilek and Halpern (1985) have reported a 108 s during dipping periods of Her X-1. We do not find any evidence of this phenomenon in the Ginga data, despite that the Ginga data should be more sensitive to such time variations.

The spectral analysis shows that, in contrast to previous work (except Mihara et al. 1991, Leahy et al, 1991), Her X-1 requires a two component spectral model to describe its X-ray spectrum. During the times when dips occur, the spectrum undergoes complex changes. However these can all be adequately modeled with the two-continuum model presented here. Figure 5 shows the spectra during onset of a major pre-eclipse dip (periods A, B and C of

Figure 1). The pre-dip spectrum (A) shows weak absorption. As the dip changes to its full decrease (from B to C) two changes occur: the unabsorbed component decreases in intensity and the amount of absorption of the absorbed component increases. Thus the dips are caused by thick cold matter and which is likely the same matter which has been detected in both the high-state and low-state spectra of Her X-1 (Leahy et al. 1991).

The pre-dip period A shows small dips which have not previously been reported, primarily due to the greatly increased sensitivity of the GINGA LAC compared to previous instruments. These "mini-dips" are very clear in the lowest energy light curve and in the plot of softness ratio (Band 1/ Band 3, Figure 1).

4. SUMMARY

The well known dips of Her X-1 have been shown to be more complex than apparent in previous observations. A new periodicity has been found which is only present during dipping periods.

The X-ray spectrum of Her X-1 has two continuum components- an unabsorbed component and a highly absorbed component. These two components are always present: during high, low and dipping states of Her X-1. The contribution of the absorbed and unabsorbed components and is highly variable during dips. The dips are caused by changes in the amount of unabsorbed continuum and in the amount of absorption.

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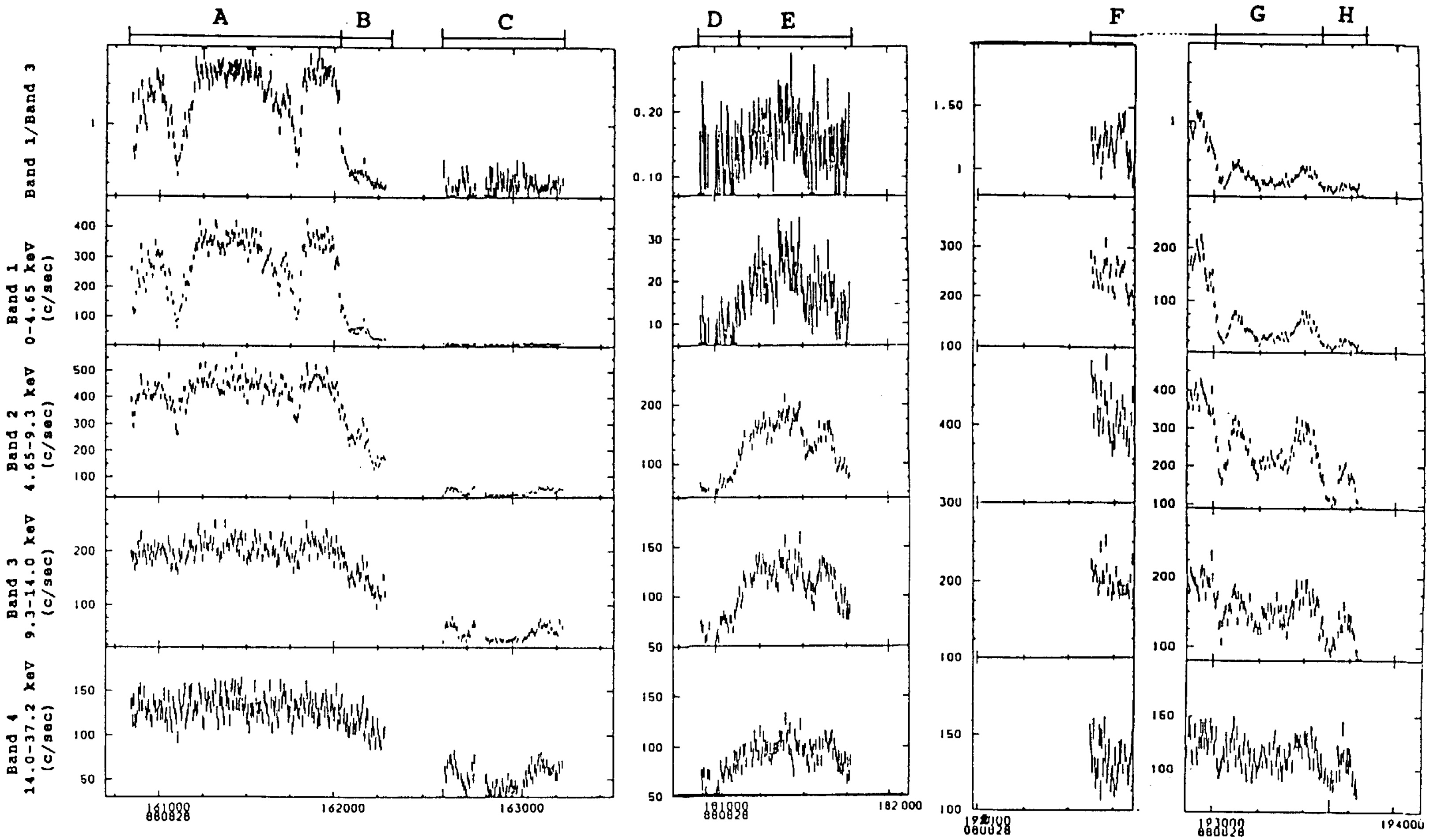

FIGURE 1. Light curves during the dipping state on 1988.08.28 in four energy bands.

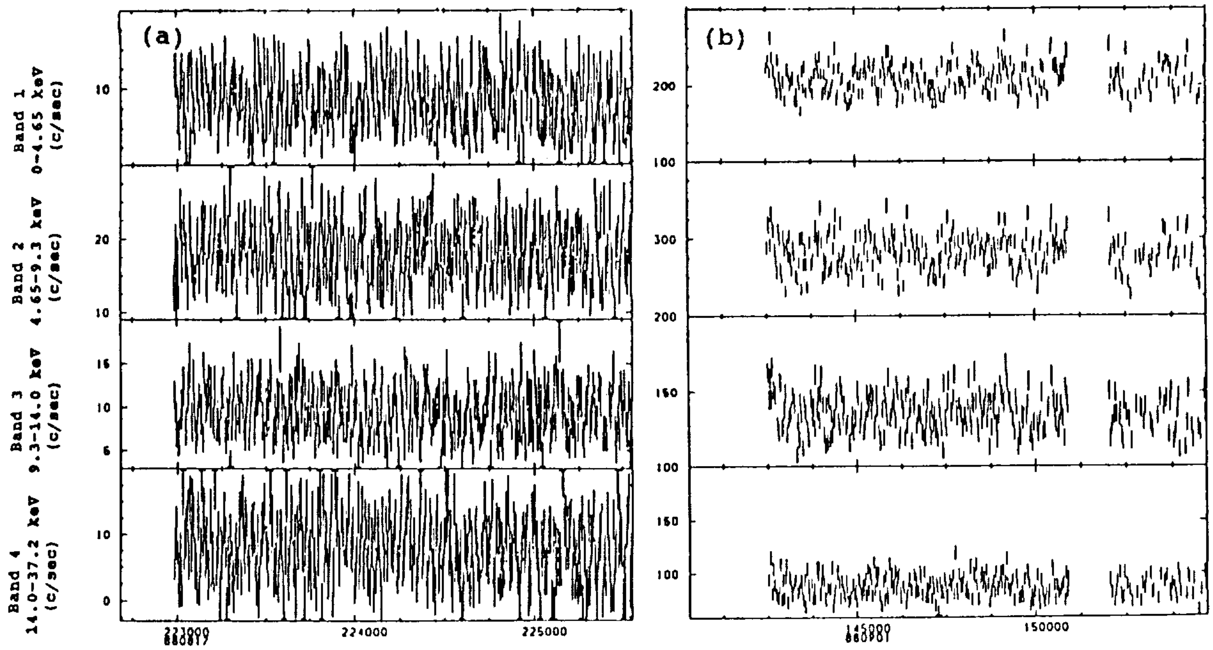

FIGURE 2. Sample light curves in four energy bands during: (a) the low state on 1988.08.17; (b) the high state on 1988.09.01.

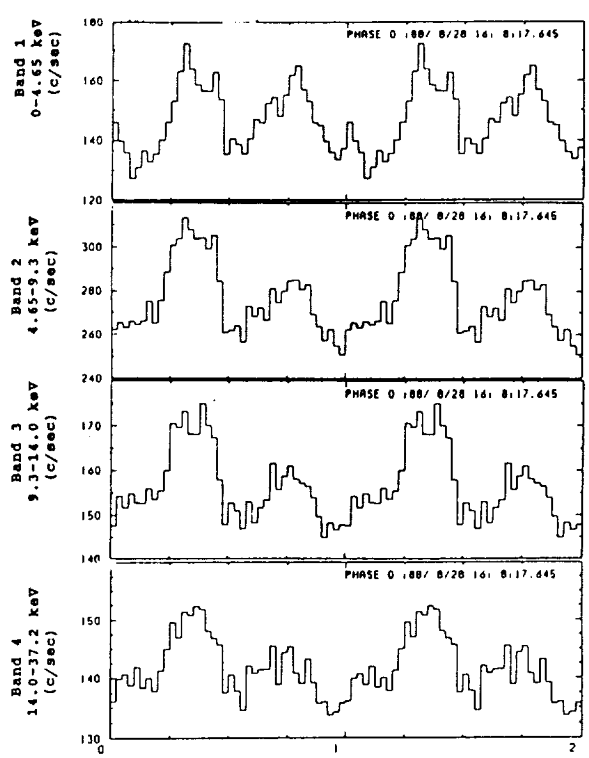

FIGURE 3. Folded light curve of 1988,08,28 data at the period of 143.6 s, in four energy bands.

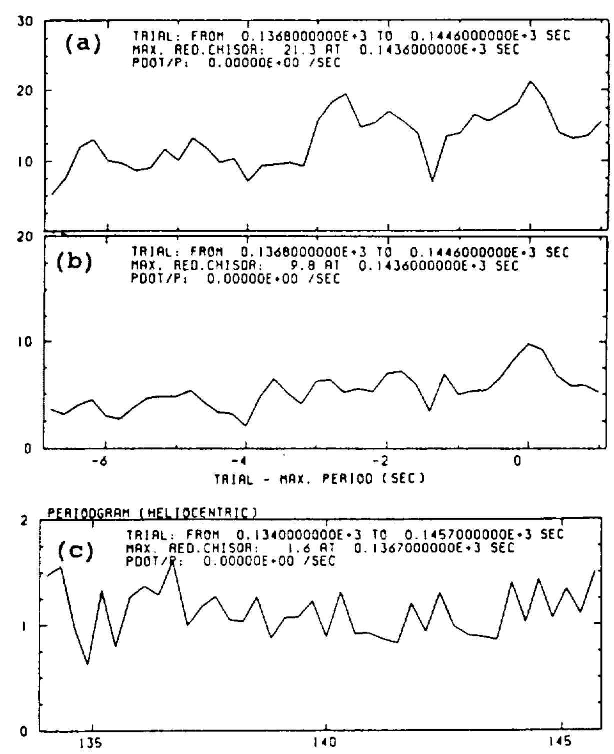

FIGURE 4. Chisquared vs. period for: (a) band 3 and (b) band 4 on 1988.0828; (c) for bands 1 and 2 on 1988.08.17.

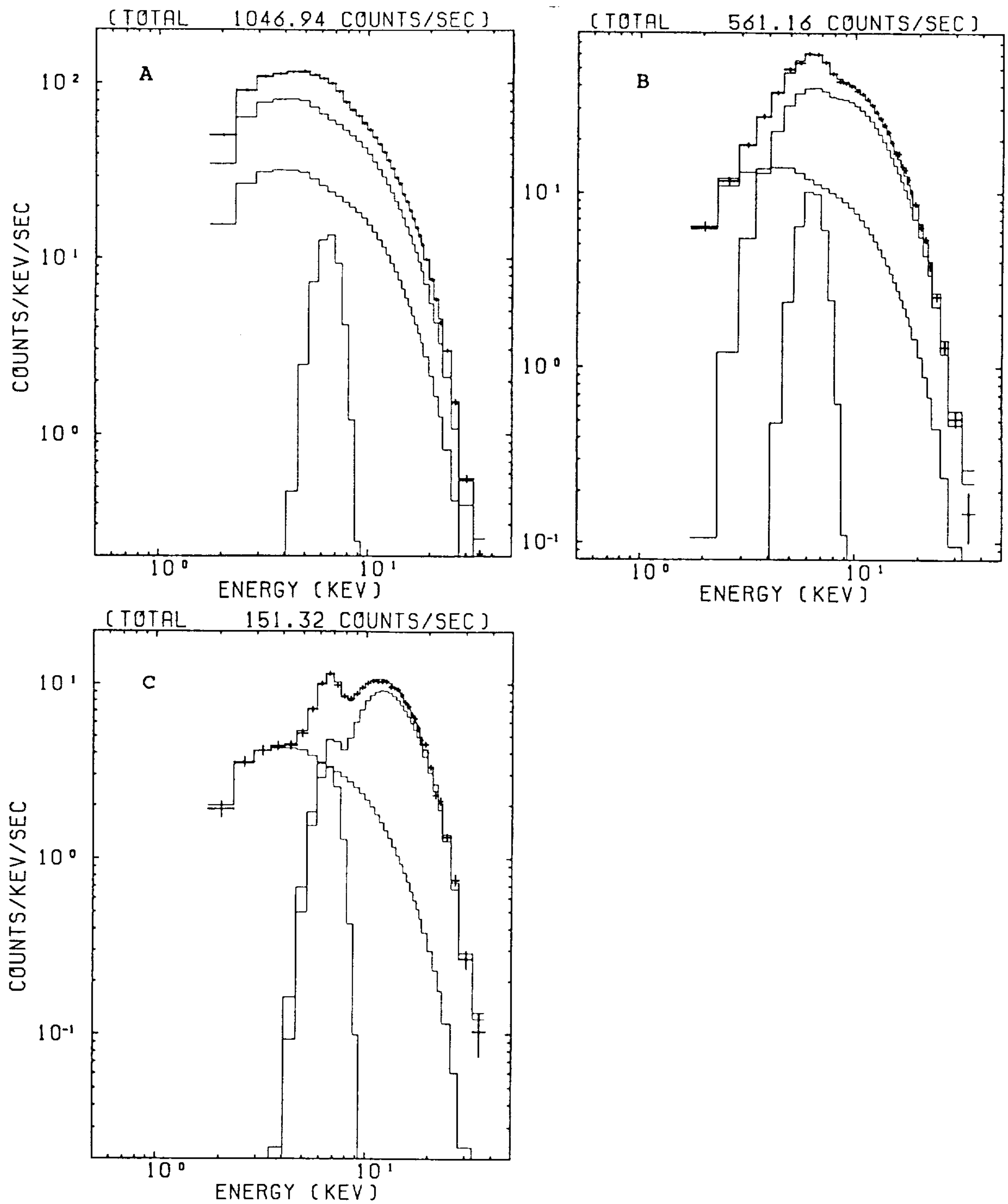

FIGURE 5. Pulse height spectra (right panel, crosses), with best-fit model spectra (histogram) for intervals A, B and C (see Figure 1).