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PULSE PHASE SPECTROSCOPY OF HERCULES X-1

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ABSTRACT

We have simultaneously observed the 6-18 keV and the 40-60 keV X-ray spectrum of Hercules X-1 with the A-2 experiment on HEAO 1. By combining these measurements with the results of an earlier observation of this X-ray pulsar, we find evidence for a component of emission above 40 keV which is above an extrapolation from lower energies, by a factor which is pulse phase dependent. These data are compared to previous hard X-ray observations and possible models are discussed.

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I. INTRODUCTION

The X-ray spectrum of Hercules X-1 has been studied extensively. A power law spectrum between 2-20 keV, α (photon number index) $\sim$ 1 (Clark et al. 1972), is sharply cutoff near 20 keV (Holt et al. 1974). Furthermore, α is variable as a function of pulse phase (Pravdo et al. 1977), as is the nature of the high energy cutoff (Pravdo et al. 1978a, hereafter Paper 1).

High energy results confirmed the very steep nature of the spectrum from 20-40 keV. In addition, a new flux component above 40 keV was discovered (Trumper et al. 1977; Coe et al. 1977) and was interpreted as including a cyclotron line (FWHM < 12 keV) emission feature (Trumper et al. 1978). Such a narrow line places stringent requirements on the physical conditions and geometry of the source (Bussard 1979), i.e., very low electron column densities and a very narrow fan beam of emission (Meszaros 1978). More recent measurements with the A-4 experiment onboard HEAO-1 have also detected an excess flux at energies above 40 keV (Matteson et al. 1978). The excess is broad, and could represent an additional continuum component of flux. If interpreted as a cyclotron emission line, these data imply a line width (FWHM) greater than 17 keV, with a best fit value of $\sim$ 60 keV (Gruber 1979).

We present in this communication the results of the first simultaneous spectral observations of both the low energy and the high energy pulse-phase components. Since the high energy flux appears to exhibit more long-term variability (Trumper 1978; Maurer et al. 1979; this work) than the low energy flux, simultaneous observations such as these are indicated. The observations were performed shortly after the onset of a Her X-1 high state on August 15 and 18, 1978 with an argon-filled (6-18 keV) and a xenon-filled (40-60 keV) proportional counter of the HEAO A-2 experiment[+]

[+]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.

(Rothschild et al. 1979; Pravdo et al. 1978b). In-flight calibration with an Am^{241} source indicates that the xenon detector has an energy resolution of 8 keV at 59.9 keV.

II. RESULTS

The average 6-18 keV intensity, 8.7×10^{-9} erg cm^{-2} sec^{-1}, decreased by < 10% from the August 15 to the August 18 observations, while the average 40-60 keV intensity, 1.9×10^{-9} erg cm^{-2} sec^{-1}, decreased by 30%. The heliocentric pulse period of Her X-1 was $1.23779048 \pm 0.00000051$ s. High and low energy pulse light curves are shown in Figure 1. Based upon our previous results (Paper 1), we have divided the pulse into four regions for spectral analysis. The "beam" corresponds to the center of the spectral pulse (defined as phase zero) and "off-beam 1 and 2" to the ascending and descending wings respectively of the beam. "Off pulse" excludes the spectral pulse.

Figure 2 shows the spectra determined in each of the four pulse regions upon which we have superposed the high energy cutoffs appropriate for each (Paper 1). Note that the presence of additional flux above 40 keV during the observation discussed in Paper 1, would lead to an underestimate of the severity of the $\sim$ 20 keV cutoff. With the exception of the off-pulse spectrum, the observed 40-60 keV flux is above the extrapolation of the cutoff. There is also evidence that this flux excess is larger in the off-beam than in the beam because the high energy cutoff is more severe in the off-beam.

The high energy flux can be modelled as a continuum component or as a broad emission feature. Since the high energy band width in this observation is only 20 keV a feature with FWHM > 15 keV can contain most of the flux. A narrow emission feature is not required in our data, but the relatively large total flux during this observation allows the presence of such a feature at an intensity consistent with that reported by Trumper et al. (1978). We can set an equivalent width upper limit (90% confidence) of 6 keV for a line near 55 keV with FWHM $\sim$ 1 keV. Thus, at least 2/3 of the 40-60 keV flux is not contained in such a line.

III. DISCUSSION

The results of the measurements can be summarized as follows:

1. We confirm the existence of an excess flux above the extrapolated spectra obtained from lower energies.
2. The excess is pulse phase dependent.
3. The high energy data can be modelled as a continuum component or as a broad emission feature but a narrow line would contain < 1/3 the total flux.

These results are related to the following model for the Her X-1 pulsar.

The pulse is formed by occultation of underlying emission by a co-rotating shell of material (Basko 1977). Many other mechanisms for pulse formation at the pulsar surface appear to fail for X-ray luminosities as large as that of Her X-1 (Basko and Sunyaev 1976 and references therein). This is consistent (Pravdo et al. 1977) with the absence of correlation between spectral changes across the pulse (originating at the surface) and intensity changes (caused by the shell). The shell is a source of soft X-rays (Schulman et al. 1975; McCray and Lamb 1976) and of Compton-scattered hard X-rays which form an emission component whose intensity changes with pulse phase but not its spectrum (Paper 1).

The component whose spectrum does change with pulse phase (duty cycle of 0.16) is direct surface emission. The sector labelled "beam" in Figure 2 is centered on this component. We note that there is recent evidence that the X-rays in this same pulse region exhibit significant linear polarization (Silver et al. 1979). Previously, we have speculated that a population of energetic knock-on electrons ($\beta \sim 0.5$ to 0.8) streaming down the magnetic field lines at the polar cap could be responsible for the phase-dependent steepening at $\sim$ 20 keV, via Doppler shifting and cyclotron absorption (Paper 1, Bussard 1979). In this context, the excess flux above 40 keV would be due to broad cyclotron emission, where absorption would no longer be important for two reasons: the electron spectrum would become symmetrized at low energies ($\beta \lesssim 0.4$), and even if streaming still exists at low β, the relativistic beaming effect disappears, and one expects reemission into the backward hemisphere following an absorption.

From Figure 2 it can be seen that the high energy excess is smallest in the off pulse spectrum, where the low energy spectrum has the least dramatic cutoff. If these X-rays represent the component scattered by a corotating shell, then Figure 2 suggests that in this spectrum, the excess above 40 keV is degraded somewhat, perhaps by Compton heating and consequently fills in the cutoff.

Detailed calculations are required to check the consistency between these data and the model. We note that if the high energy component is a cyclotron emission feature, it will vary with pulse phase. However, due to the limited number of counts available, we are unable to test our data in this manner. In the future pulse phase spectroscopy extending above 60 keV together with an understanding of the low energy continuum changes will be crucial in the study of the pulsar surface emission.

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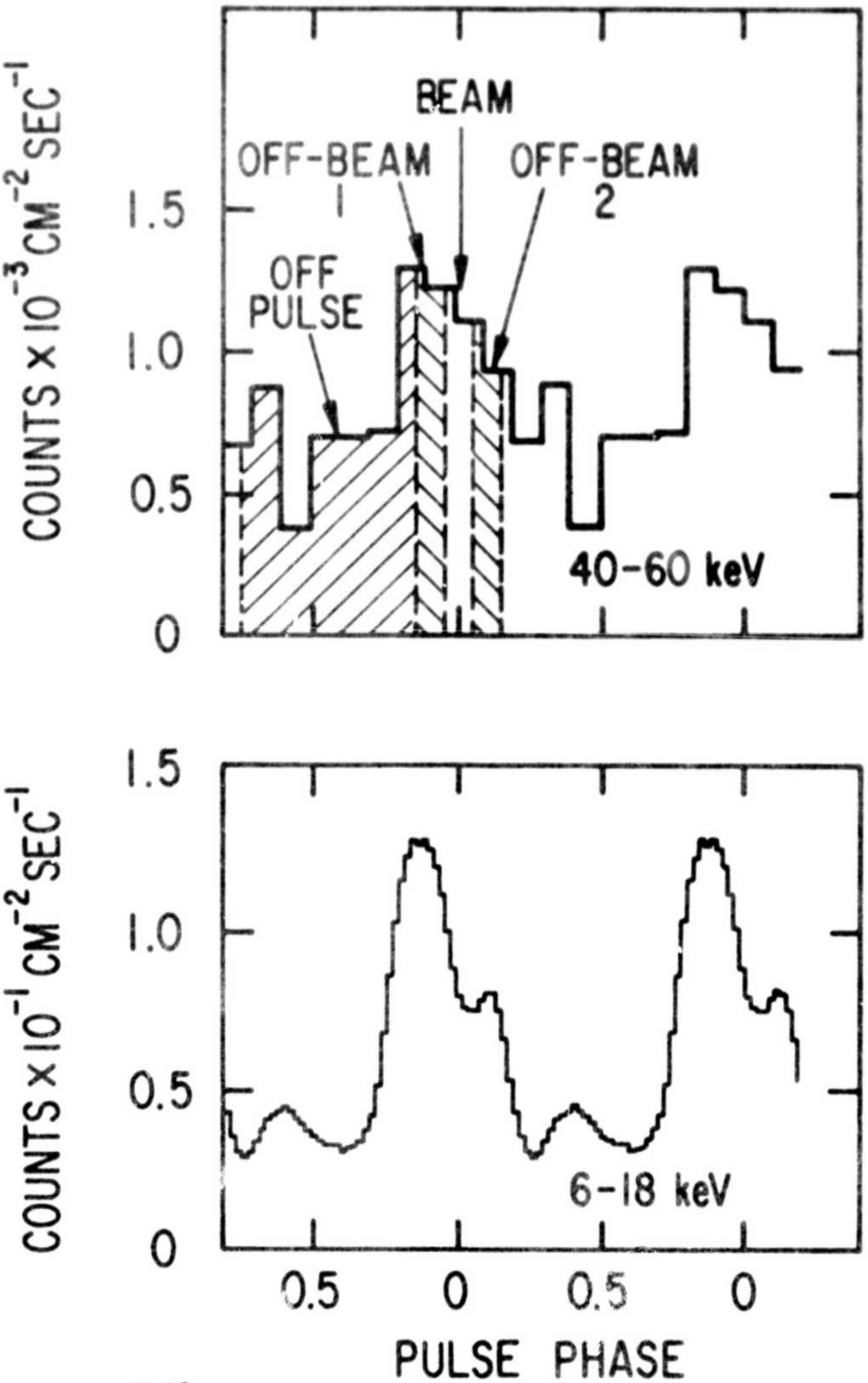
FIGURE CAPTIONS

Figure 1 - The high and low energy pulse light curves of Her X-1. We indicate the pulse regions from which spectra are obtained.

Figure 2 - Spectra of Her X-1 from the pulse regions discussed in the text. Superimposed on the present data are the 20-40 keV spectra, appropriate for each pulse phase region, measured with OSO-8 (Paper 1).

HEAO-A2
HER X-1 PULSE LIGHT CURVES



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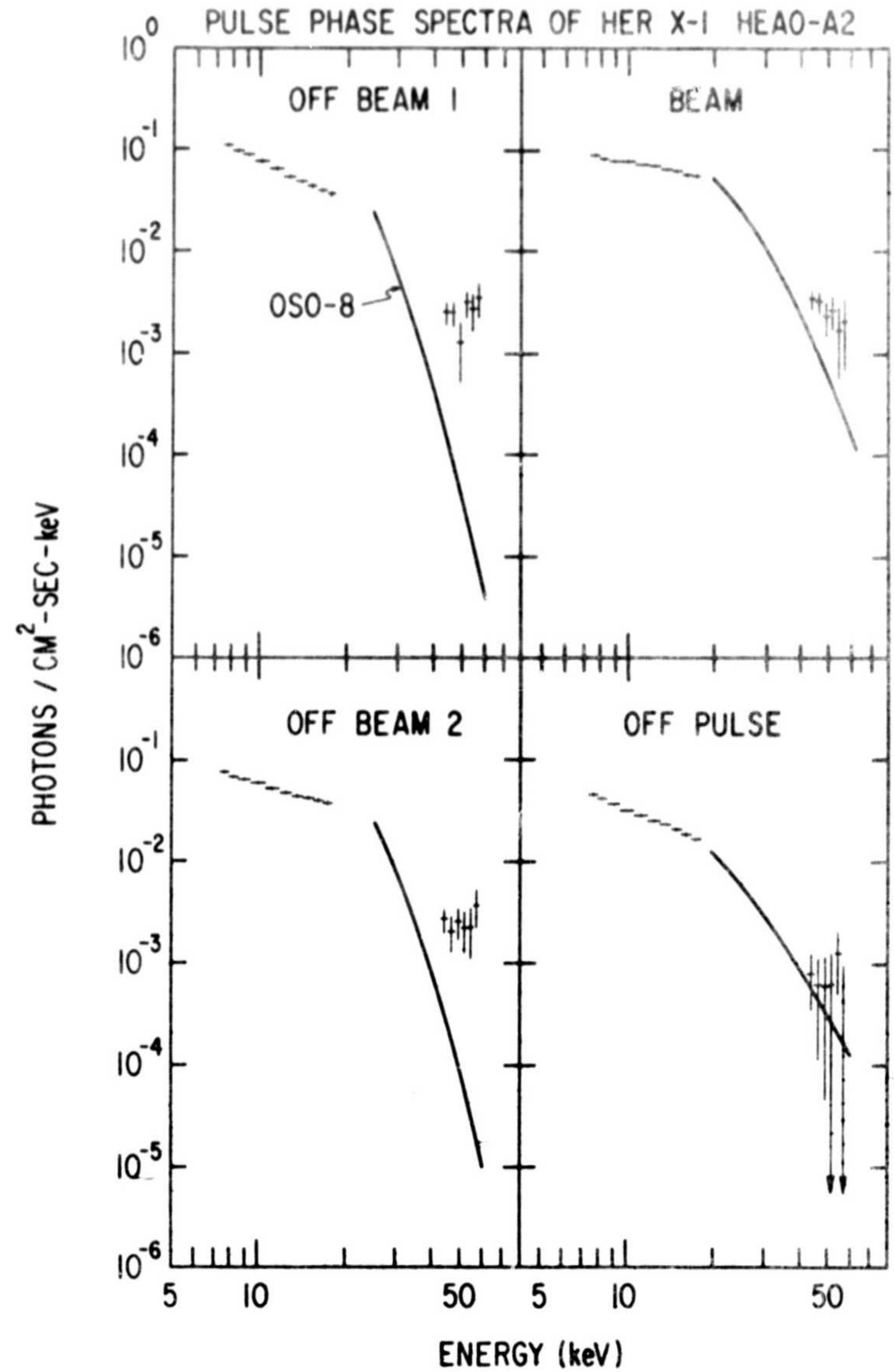
PULSE PHASE SPECTRA OF HER X-1 HEAO-A2
OFF BEAM 1
BEAM
OFF BEAM 2
OFF PULSE
OSO-8
PHOTONS / CM^2-SEC-keV
ENERGY (keV)
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
5
10
50