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ABSTRACT

Her X-1 was observed from 1977 August 30 to September 10 using the High-Energy X-Ray Scintillation Spectrometer on board the OSO-8 satellite. The observation, during which the source was monitored continually for nearly an entire ON-state, covered the energy range from 16 to 280 keV. Pulsed flux measurements as a function of binary orbit and binary phase are presented for energies between 16 and 98 keV. The pulsed flux between 16 and 33 keV exhibited a sharp decrease following the fourth binary orbit and was consistent with zero pulsed flux thereafter. Only weak evidence was found for temporal variation in the pulsed flux between 33 and 98 keV. The pulsed spectrum has been fitted with a power law, a thermal spectrum without features, and a thermal spectrum with a superposed gaussian centered at 55 keV. The latter fit has the smallest value of chi - squared per degree of freedom, and the resulting integrated line intensity is $(1.5^{+4.1}_{-1.4}) \times 10^{-3}$ photons s^{-1} cm^{-2} for a width of $3.1^{+9.1}_{-2.6}$ keV. This result, while of low statistical significance, agrees with the value observed by Trümper (1978) during the same ON-state.

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CONTENTS

I. INTRODUCTION

Recent observations of the high-energy x-ray emission from Her X-1 indicate that the pulsed x-ray spectrum above 20 keV contains one or more spectral features and is highly variable as a function of time (Trümper et al. 1977, 1978; Trümper 1978; Kendziorra et al. 1978; Matteson et al. 1978; Gruber et al. 1978). Trümper reports a decrease by a factor of 2.7 in the intensity of both the pulsed continuum and the 58-keV line feature between 1976 May and 1977 September. Matteson et al. and Gruber et al. report an excess flux in the pulsed spectrum above the low-energy pulsed continuum at a level similar to that observed by Trümper in 1977 September. The measured values of the pulsed fraction also have varied considerably, with values in the energy range from 16 to 45 keV ranging between an upper limit of 10% of the total flux (Iyengar et al. 1974) to a value of 58±8% (Kendziorra et al. 1978).

There also is evidence for considerable fluctuations in the time-averaged spectrum of Her X-1 including the observation of a very strong line feature at 63 keV (Coe et al. 1977). Earlier observations made from balloons suggest, when compared to more recent observations using both balloons and satellites, that the time-averaged spectrum has become significantly steeper since 1973 (Iyengar et al.

1974; Manchanda 1977; Dennis <u>et al.</u> 1978a). It is possible that some of these apparent variations are instrumental in nature, being the result of different instrumentation and analysis techniques used by the different observers. Extended observations of Her X-1 made with a single instrument are, therefore, especially valuable in the search for systematic variability in the high-energy x-ray emission.

Such a long-term observation was performed in 1977 September using the High-Energy X-Ray Scintillation Spectrometer on board the OSO-8 spacecraft. The results from this observation for the time-averaged spectrum and preliminary pulsed flux results were presented by Dennis <u>et al.</u> (1978a, 1978b). The work presented here is a detailed analysis of the observed pulsed flux. It is significant to note that the pulsed spectrum is not affected by the changes in photomultiplier gain which produced large systematic features in the time-averaged spectrum as discussed by Dennis <u>et al.</u> (1978b). The results of the observation indicate that significant changes in pulsed flux intensity can occur from binary orbit to binary orbit. The observed changes, although of limited statistical significance, serve to further characterize the temporal variability of the source.

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A description of the detector and of the analysis techniques is provided in Section II. The experimental results are described in Section III. In Section IV the results from the present work are discussed in relation to previous observations and currently available models for x-ray emission from Her X-1.

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II. ANALYSIS

The characteristics and performance of the high-energy scintillation spectrometer have been described by Dennis et al. (1977). The detector has a sensitive area of 27.5 cm^2, time resolution of 312.5 microseconds, and, for this observation, was sensitive to photons in the energy range from 16 to 280 keV. The energy resolution at the time of the observation, as measured using in-flight calibration data and the observed background spectrum, is described by the expression

$$\Delta E = 1.72\ E^{0.7} \quad \text{(keV)} \qquad (1)$$

where ΔE is the full width at half maximum and E is the photon energy in keV. This corresponds to a FWHM of 30 keV at 60 keV. The detector has a 5° FWHM field of view and is pointed 5° away from the antispin axis of the satellite. As the spacecraft rotates, sources of interest transit the detector field of view once every 10 seconds.

The data analysis procedure involves the accumulation of the integrated pulse profile and the subsequent reduction of count rate spectra to incident photon spectra as a function of pulse phase. The barycentric arrival time of each event was first calculated from the observed arrival time at the satellite, which is accurate to 0.3 ms. The events were then accumulated into phase bins by determining the barycentric arrival time modulo the pulsation period. The binary time-of-flight correction was calculated under the assumption that the orbit of Her X-1 is circular. The relevant timing information is presented in Table 1. The width of each energy interval is equal to 0.425 ΔE (1σ) as calculated from the energy resolution function. For each energy interval the source flux in a particular phase bin is given by

$$f(E,\varphi) = \frac{\sum A_k n_k - B \sum t_k A_k}{\sum t_k A_k^2} \quad \text{counts s}^{-1}\ \text{cm}^{-2} \qquad (2)$$

where

n_k = the number of counts in the kth time interval;

A_k = the projection of the detector sensitive area onto the plane normal to the vector from the satellite to the source;

t_k = the livetime in the kth interval;

B = the mean background rate;

E = the energy loss in the central crystal of the detector; and

φ = the pulse phase.

The corresponding uncertainty in the source flux is given by

$$\sigma_f(E,\varphi) = \sqrt{B\left[\frac{1}{\left[\sum t_k A_k{}^2\right]} + \frac{\left[\sum t_k A_k\right]^2}{N\sum t_{k'}\left[\sum t_k A_k{}^2\right]^2}\right]} \quad \text{counts s}^{-1}\ \text{cm}^{-2} \qquad (3)$$

where $\sum t_{k'}$ is the total livetime accumulated while the instrument was observing the background, and N is the number of phase bins into which the pulse period was divided. The integrated pulse profile so obtained was tested using a chi-squared sweep as a function of pulsation period to verify the timing parameters.

The count-rate spectrum obtained in this way for the pulsed flux is reduced to the incident photon spectrum by the matrix inversion scheme described by Dolan (1972). The effect of the finite energy resolution of the detector is removed by apodization; then the effects of fluorescent escape photons, detector quantum efficiency, and absorption in overlying material are removed using the measured properties of the detector obtained during laboratory calibration.

The pulsed flux was determined using two independent methods. In the first method (hereinafter called Method I), the regions of pulsed and nonpulsed emission are chosen on the basis of the integrated pulse profile. The pulsed flux is then found by subtracting the mean nonpulsed flux from the mean total flux in the pulsed region, where the fluxes are weighted according to the livetime per phase bin. In energy bands where there is no significant pulse profile, the pulsed region is assumed to remain the same as in energy bands with well-defined pulse profiles. Method I is inappropriate when there is evidence of a change in the phase of the pulsed region as a function of energy.

The second method for determining the pulsed flux (hereinafter called Method II) involves the use of Fourier series expansions of the integrated pulse profile (Joss et al. 1976). The pulsed flux is defined by

$$F_p = a_o - m \qquad (4)$$

where a_o is the constant in the series expansion and m is the minimum value of the expansion. The number of terms in the expansion is determined by minimizing the reduced chi-squared of the fit. Thus, the number of terms retained in the series expansion is in general a function of the energy. The uncertainties are calculated explicitly from the expressions for the Fourier coefficients. This method has the advantage that no a priori decisions must be made concerning the nature or size of the pulsed region of the phase distribution. The uncertainties in the results, however, are larger for Method II than for Method I. For the Her X-1 data, the ratio of Method II uncertainties and Method I uncertainties lies between 2 and 5, the exact value depending on the number of terms retained in the Fourier series. It should also be pointed out that in Method II the minimum value of the fit, rather than the mean of a group of low phase bins, is used to define the nonpulsed flux. Consequently, this method systematically overestimates the pulsed flux relative to Method I. For these reasons, Method I was deemed more appropriate for the analysis of the data presented here.

Measurements of both pulsed flux and of pulsed fraction, defined by the ratio of pulsed to total flux, are sensitive to certain systematic errors. The measured value of the pulsed flux depends on the detector response, on the amount of interstellar scattering and, for balloon-borne detectors, on the amount of absorption by the overlying atmosphere (Helmken 1975). It is not sensitive, however, to systematic errors in the background determination and subtraction. The measured value of the pulsed fraction, on the other hand, is independent of the first three of the above effects, but is sensitive to systematic errors in background determination because it requires a knowledge of the time-averaged flux. Both measures of pulsed emission have been used in the literature, and both are presented here.

III. RESULTS

Integrated pulse profiles, obtained by binning each event according to phase, are shown in Figure 1 for energies up to 98 keV. The pulsed emission between 16 and 33 keV clearly occurs during 30% of the profile width. Since the statistical significance of the pulse profiles deteriorates rapidly above 33 keV, the relative phase and width of the pulsed emission region below 33 keV was used to define the pulsed emission at higher energies.

The variation of pulsed flux with binary orbit is shown in Figure 2. It should be noted that the last observed binary orbit, centered on September 11.33, occurred after the end of the ON-state as defined at lower energies (Pravdo 1978). The pulsed flux in the 16 to 33 keV interval is consistent with constant emission during the first four binary orbits and with zero emission thereafter. The pulsed flux in binary orbit 2 was observed to increase in both the 33 to 49 keV and the 49 to 71 keV energy intervals with a combined statistical significance of 1.9σ. During the sixth observed binary orbit, the pulsed flux between 49 and 98 keV was observed to increase with a statistical significance of 2.5σ.

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The distribution of flux as a function of binary phase is shown in Figure 3 for the first four binary orbits (1977 August 30 through September 6) with the binary eclipse occurring between phase 0.93 and 0.07. The noneclipsed data are consistent with constant emission, although there is a systematic trend in the flux between 16 and 33 keV. This trend, while statistically weak, suggests that the pulsed flux increases linearly with binary phase. The low value of flux between phases 0.79 and 0.93 is due to the presence of intensity dips which occurred exclusively in this binary phase bin for the first four binary orbits (Pravdo 1978). The observation of significant (2.2σ) pulsed flux between 71 and 98 keV during eclipse is a surprising result, although McClintock et al. (1974) observed evidence for positive 2-6 keV time-averaged flux during an eclipse. The plotted values of the pulsed flux were computed according to Method I discussed above.

The value for the pulsed fraction of emission between 16 and 33 keV obtained during this observation, and again computed according to Method I, is plotted in Figure 4 along with several previously reported values. The pulsed fraction exhibits no strong dependence on energy between 1 and 88 keV, although there seems to be some fluctuation in the measured values above 20 keV.

The pulsed spectrum of Her X-1 for the time interval 1977 August 30 through 1977 September 6 is shown in Figure 5. The spectrum can be fitted by a power law of the form

$$\frac{dN}{dE} = (1.7 \pm 0.4)\times 10^{-3}\,(E/25.)^{-(5.4^{+5.0}_{-3.2})}\ \text{photons s}^{-1}\ \text{cm}^{-2}\ \text{keV}^{-1} \qquad (5)$$

a thermal spectrum of the form

$$\frac{dN}{dE} = (4.1 \pm 0.7)\times 10^{-2}\ \frac{e^{-\left[\frac{E-25.2}{5.8^{+5.9}_{-2.4}}\right]}}{E}\ \text{photons s}^{-1}\ \text{cm}^{-2}\ \text{keV}^{-1} \qquad (6)$$

and a thermal spectrum with a superposed gaussian

$$\frac{dN}{dE} = (3.6 \pm 0.8)\times 10^{-2}\ \frac{e^{-\left[\frac{E-19.5}{5.7^{+5.2}_{-2.4}}\right]}}{E} + (4.1 \pm 2.6)\times 10^{-2}\, e^{-\frac{(E-55)^2}{4}}\ \text{photons s}^{-1}\ \text{cm}^{-2}\ \text{keV}^{-1} \qquad (7)$$

The uncertainties are derived from the 68% confidence contours in chi-squared space as described by Lampton et al. (1976). For the latter fit, the thermal (line) parameters were held fixed for the determination of the uncertainties on the line (thermal) parameters. The normalization energies (25.2 and 19.5 keV, respectively) for the thermal spectra were chosen so as to circularize the contours of equal chi-squared, thus making the parameters statistically independent. The width, FWHM, of the line centered at 55 keV is $3.4^{+9.1}_{-2.6}$ keV, and the integrated intensity is $(1.5^{+4.1}_{-1.4})\times 10^{-3}$ photons s^{-1} cm^{-2}. The value of chi-squared for the first two fits is 21 for 14 degrees of freedom, while the value for the latter fit is 14 for 12 degrees of freedom.

IV. DISCUSSION

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The intensity envelope for the ON-state, as exhibited by the 16 to 33 keV pulsed flux, differs qualitatively from that observed at lower energies. In particular, the sharp cutoff in intensity following the fourth binary orbit differs from the approximately linear decrease reported by other observers (Giacconi et al. 1973; Pravdo 1976). The occurrence of larger than average intensity dips during the fifth and sixth binary orbits is not responsible for the low flux values. Analysis of those orbits both including and excluding the dips produces the same flux values to within the statistical uncertainty.

The increase in pulsed flux between 33 and 71 keV during binary orbit 2 suggests that changes in flux of the magnitude reported by Trumper can occur from orbit to orbit. The results presented recently by Gruber et al. (1978) also indicate significant variations from binary orbit to binary orbit.

Because there is considerable scatter in the data between 33 and 98 keV, power law and thermal spectra without features fit the data equally well. Because others have observed a feature in the spectrum near 55 keV, a thermal spectrum with a superposed gaussian was fitted to the data. The peak of the gaussian was fixed at 55 keV during the fitting procedure, but its width and intensity were allowed to vary. The resulting integrated intensity of $(1.5 ^{+4.1}_{-1.4}) \times 10^{-3}$ photons s^{-1} cm^{-2} has low statistical significance but agrees with the value of $(1.1 \pm 0.1) \times 10^{-3}$ photons s^{-1} cm^{-2} obtained by Trümper during the same ON-state. The narrow width of the feature leads to the result that the gaussian rises and falls within one 10-keV wide energy interval. The limited statistical significance of the feature makes its interpretation as a line speculative. The goodness of fit as measured by chi-squared, however, is better for the spectrum with the line feature than for either of the spectra without line features. Moreover, the shape of our spectrum is consistent with that obtained by the HEAO A-4 experiment from an observation of Her X-1 in 1978 February (Matteson et al. 1978).

While the presence of a feature in the pulsed high-energy x-ray spectrum of Her X-1 is now well established, the origin of that feature is not yet clear. Trümper et al. (1978) propose a model invoking cyclotron line emission at 58 keV with a fan-beam geometry. This model predicts a large angle (≥70°) between the dipole magnetic axis and the photon emission direction. Kendziorra et al. (1977) state that the emission is inconsistent with pencil-beam geometry. Bonazzola et al. (1978) argue that it is difficult to adequately populate the first and second Landau levels and so generate pure cyclotron line emission. They suggest resonant Compton-cyclotron scattering as the process responsible for the observed high - energy spectrum. Gruber et al. (1978) cannot distinguish between a model involving a cyclotron emission line centered at 56 keV with indeterminate width and one involving a cyclotron absorption line centered at 40 keV with a width of less than 30%. Pravdo et al. (1978) suggest that the emission between 2 and 60 keV is consistent with a pencil-beam geometry. Thus, there is no generally accepted model which consistently explains the high-energy x-ray spectrum of Her X-1.

There is, however, a more fundamental question which must be asked concerning the relationship between spectral changes and the intensity of the integrated pulse profile. Pravdo et al. (1978) have shown that for Her X-1 the region of the integrated pulse profile associated with spectral hardening is asymmetrically located with respect to the region of high intensity. They suggest that spectral changes are only loosely related to the intensity variations in the profile, and that the traditional methods of pulsed flux analysis may be misleading. It would be desirable to determine the spectral index as a function of phase for the data presented here, but statistical limitations prevent us from doing so.

V. CONCLUSIONS

Her X-1 has been observed between 16 and 280 keV for an entire ON-state. Significant pulsed flux was measured during the first four of seven binary orbits observed. This observation, which is the first to continually monitor the source in this energy range for a complete ON-state, suggests that the pulsed emission can vary in intensity by a factor of three from binary orbit to binary orbit.

The spectral data are better fit by a thermal spectrum with a superposed gaussian centered at 55 keV than by power-law or thermal spectra without features. The low statistical significance of this feature in the spectrum, however, makes independent interpretation of it as a line impossible on the basis of our data. In the light of other observations, however, our results add credibility to the existence of a variable feature in the high-energy x-ray spectrum of Her X-1.

VI. ACKNOWLEDGEMENTS

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TABLE 1

Timing Information Used For Data Reduction

Pulsation period*	1.237796600 s
Binary period**	1.70001656 d
Binary Radius**	13.183 light-s
Superior conjunction*	1977 August 31.2778 UT
Speed of light	2.997925d10 cm/s
Light travel time/AU	499.004786 s
Planetary Ephemeris	PEP311(Lincoln Labs)

* Pravdo (1978).

**Pravdo (1976).

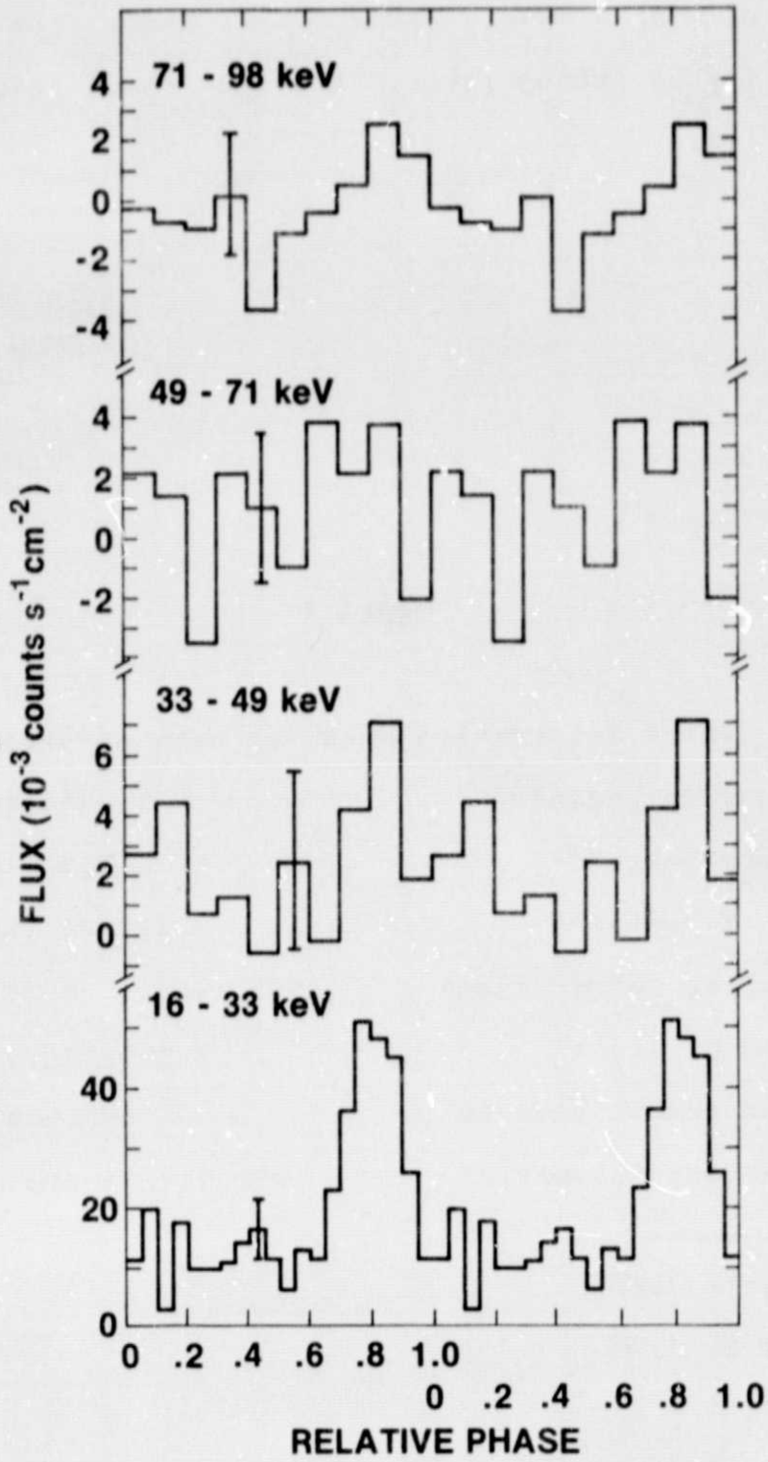

Figure 1. Integrated pulse profiles for the interval 1977 August 30 – September 6, which covers the noneclipsed portion of the first four binary orbits after the start of the observation. No significant pulsed flux was detected above 98 keV.

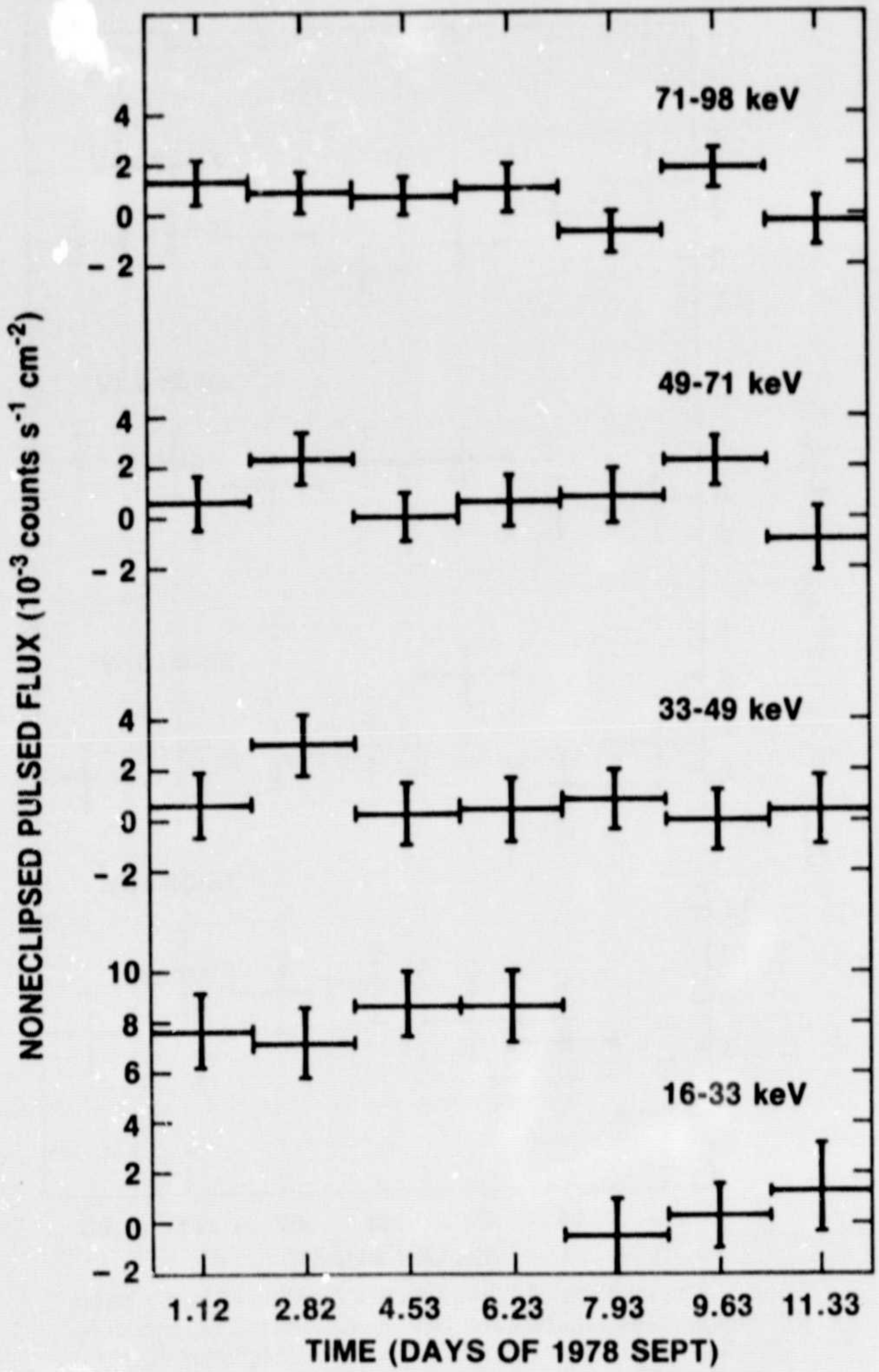

Figure 2. The variation of pulsed flux with binary orbit. The last observed binary orbit, centered at September 11.33, occurred after the end of the ON-state as defined at lower energies (Pravdo 1978).

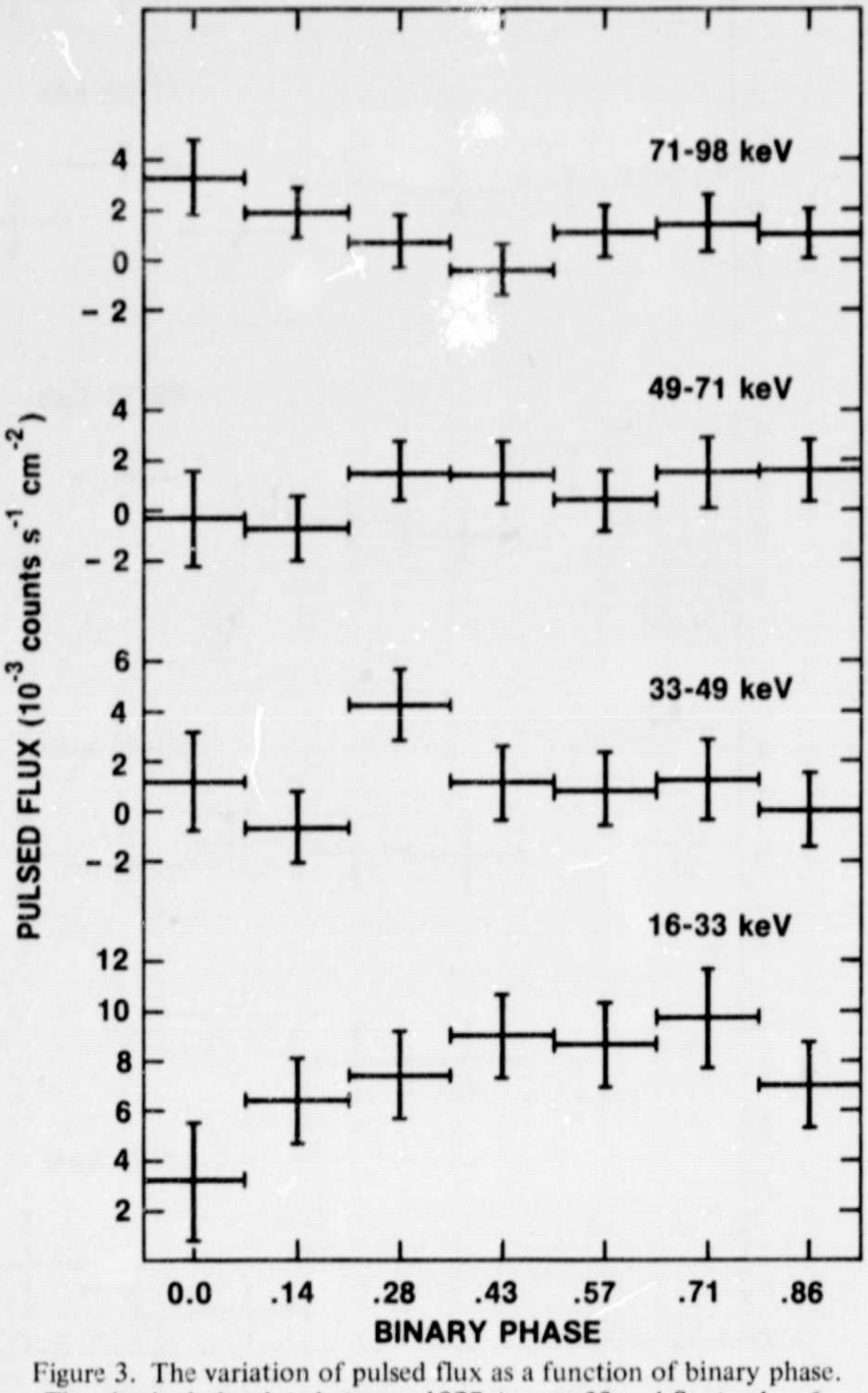

Figure 3. The variation of pulsed flux as a function of binary phase. The plot includes data between 1977 August 30 and September 6, covering the first four binary orbits after the beginning of the observation. The phase interval between 0.93 and 0.07 covers the binary eclipse times and the phase interval between 0.79 and 0.93 includes the times of the absorption dips observed at lower energies.

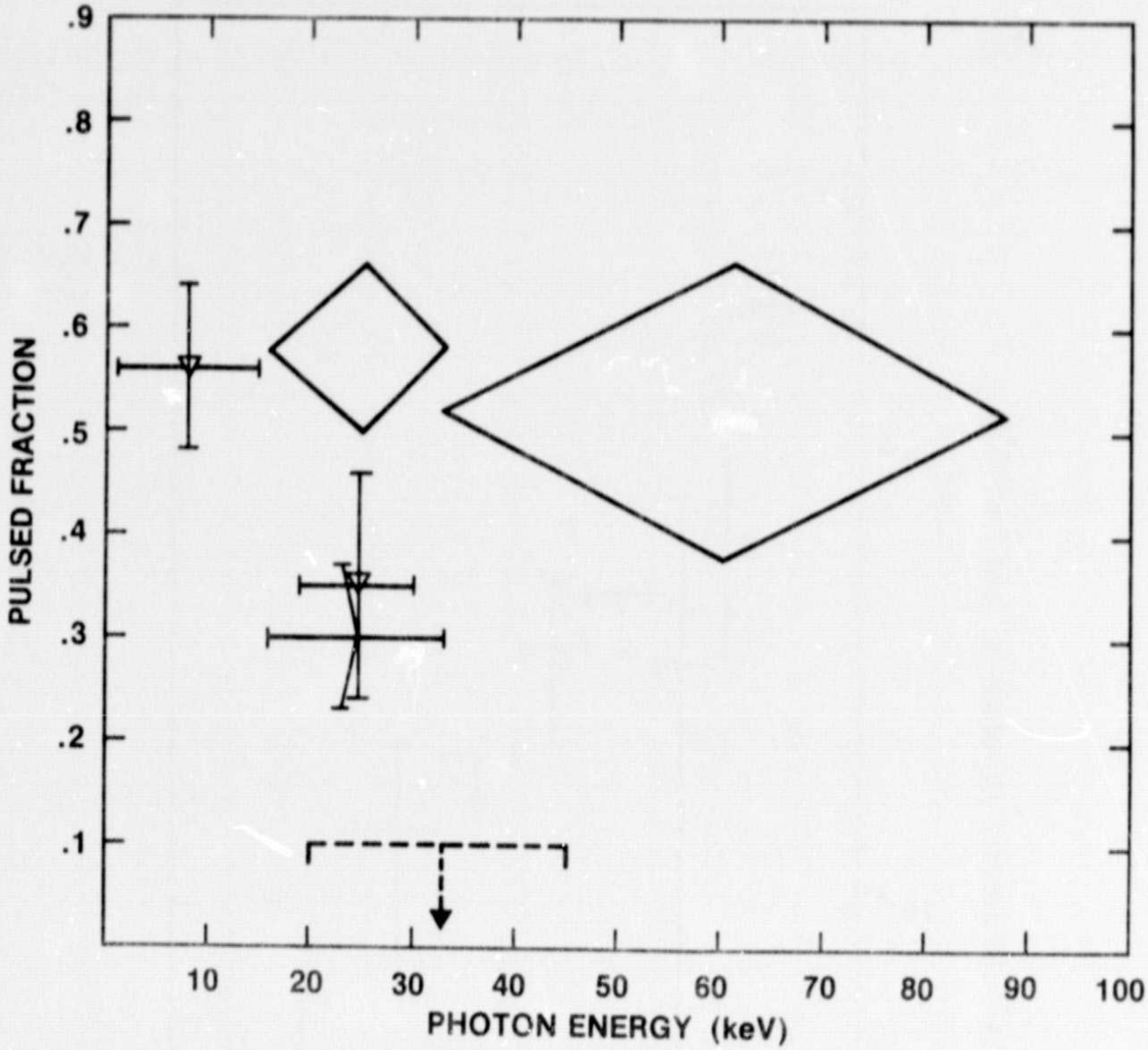

Figure 4. The pulsed fraction as a function of photon energy. Iyengar et al. (1974); Joss et al. (1976); Kendziorra et al. (1978); present observation.

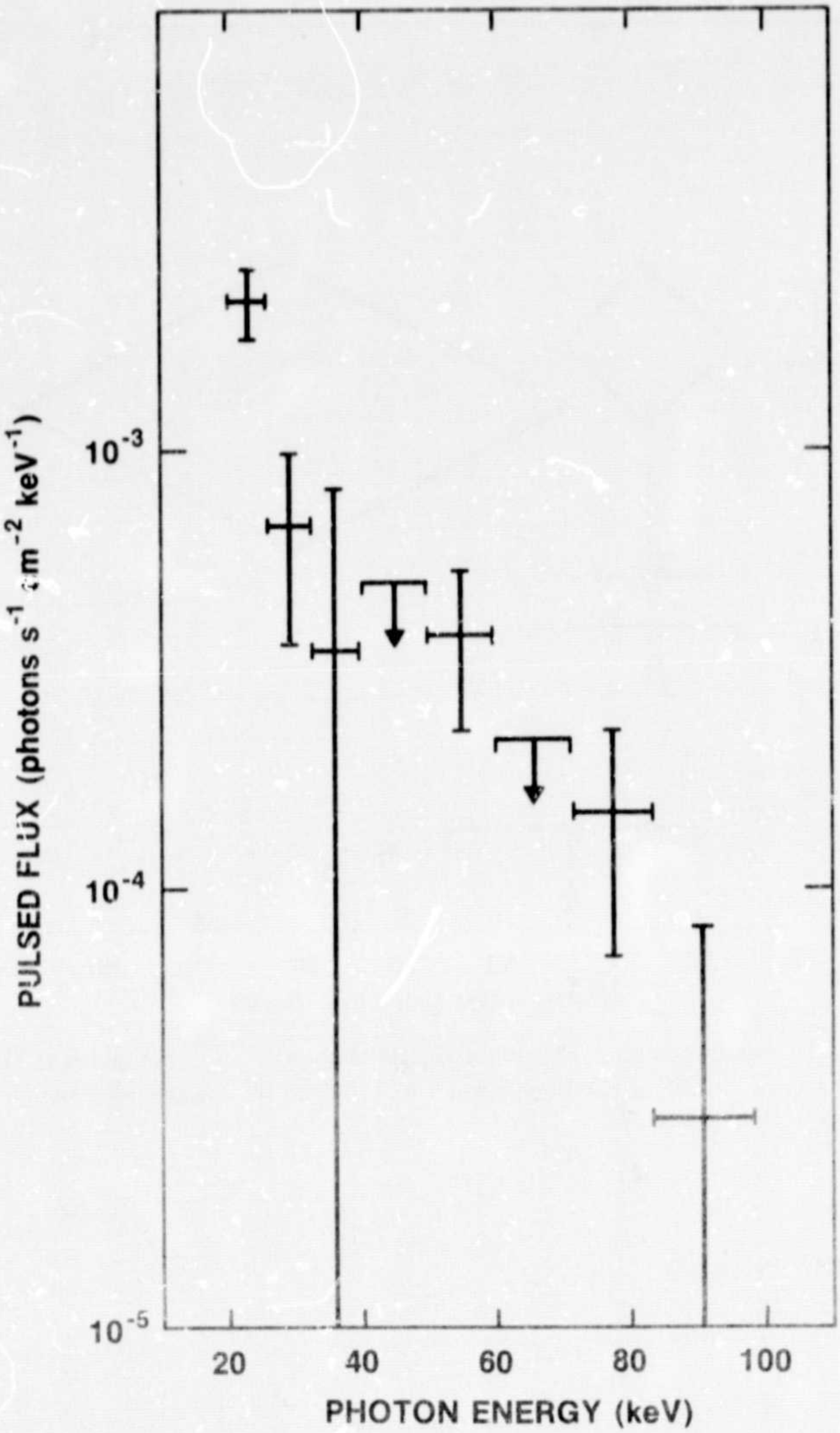

Figure 5. The pulsed x-ray spectrum of Her X-1 for the time interval 1977 August 30 – September 6.