THE ASTROPHYSICAL JOURNAL, **188**:159–162, 1974 February 15

A TEN-DAY OBSERVATION OF HERCULES X-1 FROM THE OSO-7 SATELLITE*

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Received 1973 September 4

ABSTRACT

The MIT X-ray detectors aboard the OSO-7 spacecraft viewed Hercules X-1 from 1972 November 14 to November 24. X-ray turn-on in the 35-day cycle was observed to occur between phases 0.67 and 0.70 (November 18.64–18.70). A significant decrease in the X-ray intensity occurred near mid-orbital phase, approximately 1.5 days after X-ray turn-on. Using the 1–6 keV data obtained during the 35-day OFF state, we conclude that if the optical light curve is due to heating of the large star by a blackbody source of soft X-rays, then the source must be large, radius $> 5 \times 10^8$ cm, and cool, temperature $(kT) < 90$ eV. During one eclipse period (November 20.8–21.0), we find evidence for 1–6 keV X-ray emission.

Subject headings: binaries — stars, individual — X-ray sources

I. INTRODUCTION

The X-ray source Hercules X-1 is a pulsating (1.24 s), eclipsing binary (1.7 day). The X-ray emission is further modulated by an overriding 35-day cycle, during which the X-rays are ON for about 10 days and OFF for about 25 days (Tananbaum *et al.* 1972; Giacconi *et al.* 1973). Both the 1.24-s and 1.7-day periodicities have been observed in the optical counterpart HZ Her (Davidsen *et al.* 1972; Petro and Hiltner 1973).

The MIT X-ray detectors aboard the OSO-7 satellite viewed Her X-1 for 10 days during 1972 mid-November. The observations were performed with 3° (FWHM) collimation and at a minimum time resolution of 3 minutes. The X-rays were recorded in three broad energy channels: 1–6 keV, 3–10 keV, and 15–40 keV. (The low-energy, 0.9–1.5 keV, detector had an unusually high background counting rate during these observations and provided no useful information.) Further details concerning the instrumentation, including detector efficiency curves, have been published previously (Clark *et al.* 1973). Earlier we reported on the position and spectrum of Her X-1 based on two brief observations in 1971 December (Clark *et al.* 1972).

II. COUNTING-RATE DATA AND X-RAY TURN-ON NEAR PHASE 0.68

The Her X-1 counting rates, in each of three energy channels for the period 1972 November 14–24, are presented in figure 1. The data show a number of features which have been previously discussed by the AS&E *Uhuru* Group (Tananbaum *et al.* 1972; Giacconi *et al.* 1973). These features include an extended OFF period (November 14–18.7), a 1.7-day eclipse cycle (November 18.7–24), the presence of pre-eclipse dips (November 20.7, 22.4, and 24.0), and a rapid transition from the 35-day OFF state to the ON state near phase 0.68 (November 18.7).

We find the transition from X-ray OFF to X-ray ON in the 35-day cycle to be abrupt and to occur between phase 0.67 and 0.70 (1972 November 18.64–18.70). This result is in agreement with the AS&E discovery that the 35-day turn-on occurs near two phases of the 1.7-day binary period: 0.23 and 0.68 (Giacconi *et al.* 1973).

III. DECREASE IN INTENSITY NEAR PHASE 0.5

A notable feature in the data of figure 1 is a decrease in the 1–6 keV and 3–10 keV fluxes between November 20.1 and 20.3. The center of the event occurs at approximately phase 0.59 at both energies. This intensity dip is different from the backward-marching, pre-eclipse dips described by the AS&E group (Giacconi *et al.* 1973). It is also different from the two anomalous dips which were observed by the AS&E group in 1972 April and July, both of which occurred 0.6 days after the source turned on at phase 0.23. The event which we have seen occurred 1.54 days after the source turned on at phase 0.68. The AS&E group did not observe a mid-phase dip during any of several observations following a source turn-on at phase 0.68 (Giacconi *et al.* 1973).

The 1–6 keV data presented in figure 1 suggests that two subsequent mid-phase decreases in intensity occurred on November 21.5–21.8 and November 23.25–23.55, respectively. However, neither decrease is statistically significant (see table 1, entries 2 and 9, and entries 3 and 10).

A mid-phase decrease in intensity has been observed for two other binary X-ray sources, 2U 1700-37 (Jones *et al.* 1973) and Cen X-3 (Baity *et al.* 1973).

IV. SPECTRA AND INTENSITY

Fitted values of spectral parameters for thermal bremsstrahlung and power-law trial spectra are

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* This work was supported by the National Aeronautics and Space Administration.

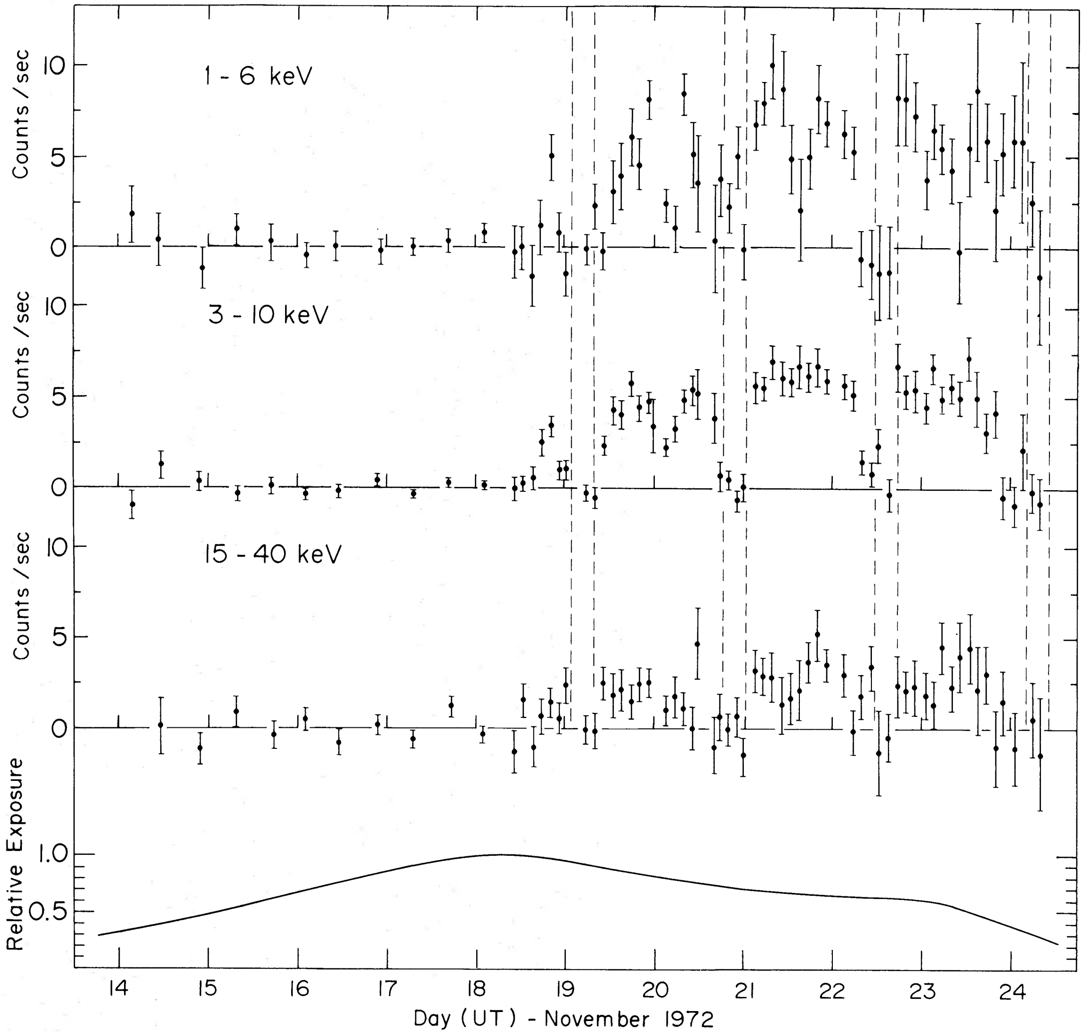

FIG. 1.—Counting rates due to Her X-1 in three energy channels as observed by the MIT X-ray instrument aboard the OSO-7 satellite. The data have been corrected for collimator response and the background counting rates have been subtracted. The dashed, vertical lines indicate the times during which the X-ray source is eclipsed (Giacconi *et al.* 1973).

presented in table 1 for each of the three observation periods during which the source was not eclipsed. Average energy and photon fluxes are presented in table 2 for the OFF state and for the ON state of the 35-day cycle. Because of our limited spectral information, we cannot use our data to confirm the two-component spectrum determined by the UCSD OSO-7 group (Ulmer *et al.* 1973); however, our results are consistent with theirs. We note that the energy fluxes reported by the AS&E group (Giacconi *et al.* 1972) and by the UCSD OSO-7 group, and the results obtained by us are consistent with an energy flux at maximum intensity, averaged over the non-eclipsed portion of one orbit, of 6×10^{-9} ergs cm^{-2} s^{-1} (1–30 keV)$^{-1}$. This value is approximately a factor of 3 greater than the value of the energy flux in the 2–10 keV energy range.

V. CONSTRAINTS ON A SOFT X-RAY HEATING MODEL OF THE OPTICAL LIGHT VARIATIONS

It is a remarkable fact that the optical light curve of HZ Her is only slightly affected, if at all, by the state (ON or OFF) of the X-ray source in its 35-day cycle (Petro and Hiltner 1973; Boynton *et al.* 1973). A number of suggestions concerning this matter have been summarized by Pringle (1973). We use our upper limit on the 1–6 keV flux, obtained during the 35-day X-ray OFF state, to put model-dependent constraints on an hypothesis which has been discussed by Pringle and by others: namely, that the optical light curve is a result of soft X-ray ($\leqslant 1$ keV) heating of the large star, and that the soft X-ray component is not appreciably affected by the 35-day cycle.

The amount of soft X-radiation which is required

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TABLE 1

AVERAGE COUNTING RATES IN SELECTED TIME INTERVALS

ENTRY	TIME Day (UT) – November 1972	1–6 keV (counts s^{-1})	3–10 keV (counts s^{-1})	15–40 keV (counts s^{-1})	SPECTRAL PARAMETERS E_a (keV)	kT (keV)*	α†	COMMENTS
1.....	19.5 – 20.5	4.9 ± 0.4	4.3 ± 0.2	1.6 ± 0.3	1.4 ± 0.4	>40	0.5 ± 0.2	not eclipsed and excluding pre-eclipse dips
2.....	21.2 – 22.2	7.0 ± 0.6	6.1 ± 0.3	3.0 ± 0.4	1.4 ± 0.4	>50	0.3 ± 0.2	
3.....	22.8 – 23.6	5.1 ± 0.7	5.5 ± 0.3	2.6 ± 0.5	1.8 ± 0.4	>50	0.3 ± 0.2	
4.....	14.0 – 18.0	0.19 ± 0.24	0.09 ± 0.12	−0.36 ± 0.20	...	...	...	OFF state of 35-day cycle
5.....	20.81 – 21.01	3.3 ± 1.0	0.3 ± 0.4	−0.2 ± 0.7	...	...	...	eclipse
6.....	22.51 – 22.71	−0.7 ± 2.0	−0.3 ± 0.7	−0.8 ± 1.2	...	...	...	
7.....	24.21 – 24.41	1.7 ± 2.0	−0.3 ± 0.9	−0.7 ± 1.7	...	...	...	
8.....	20.1 – 20.3	2.5 ± 0.7	2.8 ± 0.4	0.5 ± 0.6	...	...	...	periods of decreased counting rate near mid-orbital phase
9.....	21.5 – 21.8	4.5 ± 1.2	6.2 ± 0.5	2.7 ± 0.8	...	...	...	
10.....	23.25 – 23.55	3.5 ± 1.2.	5.4 ± 0.5	3.5 ± 1.0	...	...	...	

* Thermal bremsstrahlung spectrum (Chodil *et al.* 1968) $dN/dE = A \exp[-(E_a/E)^{2.7}]K_0[-E/2kT] \exp[-E/2kT]$.

† $dN/dE = I_0 \exp[-(E_a/E)^{2.7}]E^{-(\alpha+1)}$.

to produce the variations in the optical luminosity is very great. The color indices determined by Boynton *et al.* (1973) and the spectra obtained by Crampton and Hutchings (1972) imply a bolometric correction of ~2.2 for HZ Her at maximum light (phase 0.5), and a maximum optical flux of 9×10^{-10} ergs cm^{-2} s^{-1} at Earth. This is about a factor of 20 greater than the flux at minimum light. We assume that the soft X-rays would come from the vicinity of the small star, and that the large star fills ~4 percent of the sky when viewed from the small star (Crampton and Hutchings 1972). The soft X-ray flux which is incident on the surface of the large star (~1/25 of the total soft X-ray flux), must be at least as great as the observed increase in the optical flux of the large star. That is, the soft X-ray flux at Earth (neglecting absorption by the interstellar medium) must be more than 25 times as great as the increase in the optical flux and must therefore be at least 2×10^{-8} ergs cm^{-2} s^{-1}.

There is a second, independent line of reasoning which leads to approximately the same lower limit on the soft X-ray flux. Optical observations by Petro and Hiltner (1973) and by Boynton *et al.* (1973), throughout the 35-day X-ray cycle (ON ≃ 10 days, OFF ≃ 25 days), show that the "hard" X-ray source (> 1 keV) has at most a 20 percent effect on the optical light curve. Therefore, if the soft X-ray source is to be capable of causing the optical light variations, it must be more than 5 times as luminous as the hard X-ray source, and we conclude that the soft X-ray flux must be greater than 3×10^{-8} ergs cm^{-2} s^{-1}.

We model the hypothetical, soft X-ray emitting region as a blackbody with a radius R at a distance D and at a temperature kT. The photon flux at Earth is then (neglecting absorption by the interstellar medium)

$$\left(\frac{dN}{dE}\right)_{\text{soft}} \propto \left(\frac{R}{D}\right)^2 \frac{E^2}{\exp(E/kT) - 1} \quad \text{photons cm}^{-2}\,\text{s}^{-1}\,\text{keV}^{-1}\,,$$

and it depends on only two parameters: the solid-angle factor, $(R/D)^2$, and the temperature, kT. For the soft X-rays to be energetically capable of producing the optical light variations, we require

$$\int_0^\infty E\left(\frac{dN}{dE}\right)_{\text{soft}} dE > 2 \times 10^{-8}\ \text{ergs cm}^{-2}\,\text{s}^{-1}\,.$$

It follows from the measured upper limit on the 1–6 keV flux (table 2) during the 35-day OFF state that

$$(75\ \text{cm}^2)\int_1^6 \epsilon(E)\left(\frac{dN}{dE}\right)_{\text{soft}} dE < 0.67\ \text{counts s}^{-1}\,,$$

where $\epsilon(E)$ is the response function of the 1–6 keV detector (Clark *et al.* 1972).

As is shown in figure 2, both of these requirements

TABLE 2

AVERAGE ENERGY AND PHOTON FLUXES

Energy Interval	X-ray OFF 1972 Nov 14–18 2 σ upper limits (counts s^{-1})	X-ray ON Entry 2 of table 1 (counts s^{-1})	X-ray ON Energy Flux* 10^{-10} ergs keV^{-1} cm^{-2} s^{-1}	X-ray ON Photon Flux* 10^{-3} photons keV^{-1} cm^{-2} s^{-1}	X-ray ON (counts s^{-1}) / X-ray OFF (counts s^{-1})
1–6 keV.....	< 0.67	7.0 ± 0.6	2.3 ± 0.2	29 ± 4	> 9
3–10 keV....	< 0.33	6.1 ± 0.3	2.5 ± 0.1	28 ± 1.4	>17
15–40 keV....	< 0.40	3.0 ± 0.4	1.7 ± 0.6	4.4 ± 0.6	> 6

* Computed for a thermal bremsstrahlung spectrum with E_a = 1.4 keV and kT = 50 keV (Chodil *et al.* 1968).

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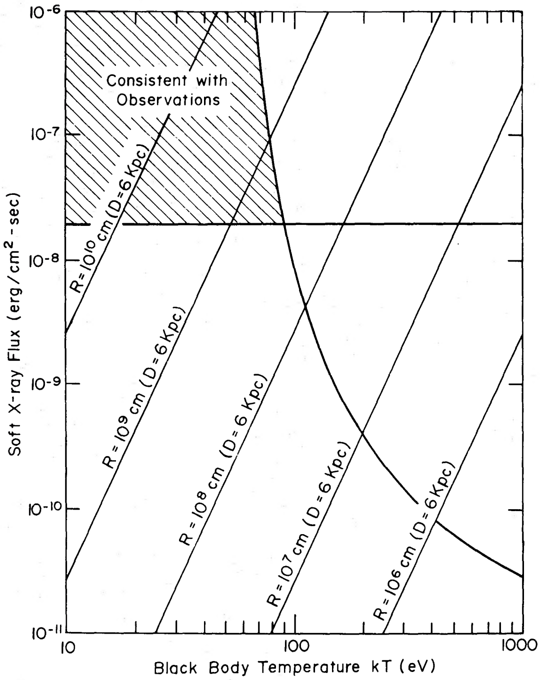

FIG. 2.—Constraints on the size and temperature of a hypothetical, blackbody source of soft X-rays, which has been suggested as the energy source for the observed optical light variations. Only a large, $R > 5 \times 10^8$ cm, and cool, $kT < 90$ eV, source is consistent with the observations and the blackbody model which is described in the text. The diagonal lines represent Stefan's law for different solid-angle factors: Flux $= (R/D)^2 \sigma T^4$. Below the horizontal line, the soft X-ray source would not have sufficient energy to produce the optical light variations. A source to the right of the curved line would have exceeded our upper limit of 0.67 counts s^{-1} 75 cm^{-2} (1–6 keV)$^{-1}$ (1972 November 14–18).

are only met by a large, $R > 5 \times 10^8$ cm ($D = 6$ kpc), and cool, $kT < 90$ eV, source. In particular, the suggestion by Pringle (1973) that the soft blackbody X-rays might originate from the surface of the neutron star ($R \simeq 10^6$–10^7 cm) is definitely not tenable. The surface temperature (kT) of a neutron star would have to be greater than 500 eV in order to have sufficient luminosity to produce the required heating of the large star, and we would have easily detected such a source.

In the above discussion, we have neglected the effects of X-ray absorption by the interstellar medium. Our measurements were performed in the high-energy tail of the Planck distribution (1–6 keV; $kT \simeq 0.1$ keV) and are little affected by interstellar absorption. Measurements of 21-cm line radiation by Tolbert (1970) indicate a hydrogen column density of $\sim 5 \times 10^{20}$ H atoms cm^{-2} in the direction of Her X-1. This corresponds to a cutoff energy (E_a) of 0.4 keV and an absorption of only 10 percent at 1 keV (Brown and Gould 1970). We note that local (distance < 1 kpc) measurements of hydrogen Lα absorption suggest that 21-cm measurements provide an overestimate of the amount of interstellar hydrogen (Savage and Jenkins 1972).

We have measured a somewhat larger cutoff energy than 0.4 keV in the spectrum of the compact X-ray source: $E_a \simeq 1.5 \pm 0.5$ keV (table 1) and $E_a = 1.0 \pm 0.5$ keV (Clark *et al.* 1972). This suggests the presence of absorbing material surrounding the compact X-ray source. Strong evidence for the presence of such material has been given by the AS&E group (Giacconi *et al.* 1973). During intensity dips, they have measured cutoff energies as great as about 4 keV.

VI. AN INDICATION OF 1–6 keV X-RAY EMISSION DURING ECLIPSE

A flux level of about 3σ above background appears in the 1–6 keV data for the second eclipse period (table 1, entry 5). If this flux is due to Her X-1, a simple interpretation would be that the X-rays are emitted by a halo or disk of gas, which surrounds and is heated by the compact source, and which does not undergo total eclipse. A similar soft X-ray spectrum has been observed for Cen X-3 during eclipse (Schreier *et al.* 1972). There is a strong possibility, however, that our observation is an artifact which is due to the charged-particle induced background, to which the 1–6 keV detector is most susceptible. Artifact or not, our discussion in § V is still valid.

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