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SOFT X-RAYS FROM HERCULES X-1 DURING THE "OFF" STATE

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ABSTRACT

A significant 0.18–0.28 keV flux has been detected from Her X-1 during the OFF portion of the 35 day cycle. The intensity observed in a rocket observation 6 days before turn-on is 4 percent of that previously reported for the ON state. Another observation, made 3 days before turn-on from an *Apollo* spacecraft, failed to detect any soft X-ray emission above 2 percent of the ON state flux.

The soft X-ray flux may be attributed to an opaque shell near the Alfvén surface of the neutron star, with $T = 8.5 \times 10^5$ K and $R = 1.5 \times 10^8$ cm. The varying intensities observed are interpreted in terms of obscuration by the accretion disk.

Subject headings: pulsars — stars: binaries — stars: collapsed — X-rays: sources

I. INTRODUCTION

In a previous paper (Shulman *et al.* 1975, hereafter Paper I), we reported the detection of an intense flux of soft X-rays from Her X-1 during the X-ray ON portion of the 35 day cycle. This has recently been confirmed by Catura and Acton (1975). In Paper I we also reported preliminary results of a second rocket observation designed to search for soft X-ray emission during the OFF portion of the 35 day cycle. A limit of less than 10 percent of the detected ON state flux was obtained, which was sufficient to rule out the suggestion that a constant soft X-ray flux produces the $1\overset{\mathrm{d}}{.}7$ optical modulation while hard X-ray emission ceases during the OFF state (Avni *et al.* 1973, Pringle 1973).

The 10 percent upper limit reported in Paper I was derived using data from only one of the two detectors in the rocket payload, and only a crude knowledge of the rocket maneuvers and pointing. We have since analyzed the data from the narrower field of view and have refined the aspect solution using in-flight star field photographs. We now find clear evidence for a significant low-energy flux during the OFF state which is about 4 percent of that found in the original detection during the ON state.

Another observation of Her X-1, at a different phase of the OFF state, was made from the *Apollo* spacecraft during the *Apollo-Soyuz* mission in 1975 July. No significant flux was detected, and upper limits at all energies are less than 2 percent of the ON state intensity. In this *Letter*, we present the data from these two observations and discuss their interpretation.

II. OBSERVATIONS

The observation of 1974 September 7 was made from an Aerobee-200 sounding rocket launched at 0435 UT from White Sands Missile Range. At this time Her X-1 was in the OFF portion of the 35 day cycle, 6 days before the predicted start of the ON phase as determined by *Copernicus* observations (Davison and Fabian 1974). The binary system was at phase 0.42 of its $1\overset{\mathrm{d}}{.}7$ period (0.0 is the center of eclipse). The payload consisted of two proportional counters of 1080 cm^2 effective area each. Both detectors had 2 μ Kimfol (polycarbonate) windows and used P10 gas (90 percent argon, 10 percent methane) at 15.5 psia. One detector had a circular field of view of 5°, full width at half-maximum (FWHM), and the other detector had a circular field of view of 3° FWHM. The Kimfol window and argon gas absorption combine to produce a detector sensitive in the energy ranges 0.18–0.28 keV and 0.6–10 keV.

The attitude control system was preprogrammed to update the gyro reference system using an optical star tracker which locked on ζ Her, about 5° away from Her X-1, at 305 s after launch. The detectors then scanned up to Her X-1 at a rate of 1° s^{-1} and held orientation for 47 s. Star field photographs indicate that the centers of the fields of view were pointed within $0\overset{\circ}{.}7$ of Her X-1 throughout the hold. The detectors were then scanned to a point 10° away ($\alpha = 17^{\mathrm{h}}30^{\mathrm{m}}$, $\delta = 41\overset{\circ}{.}7$) and back through Her X-1 at a rate of 1° s^{-1}. The center of the field of view passed directly over the source again at 389.5 s.

The 3° FWHM detector count rate in the 1–8 keV energy band is displayed versus time after launch in Figure 1*a*. The strong sources observed are indicated, as are the two ^{55}Fe calibrations from 90 to 100 s and from

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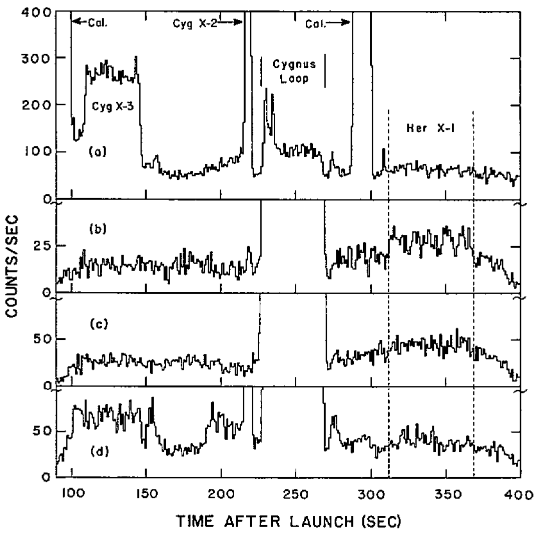

FIG. 1.—Counts in various energy ranges per 1 s bin plotted versus time after launch: (*a*) 1–8 keV, 3° FWHM detector; (*b*) 0.18–0.28 keV, 3° FWHM detector; (*c*) 0.18–0.28 keV, 5° FWHM detector; (*d*) 0.6–2.5 keV, 3° FWHM detector.

290 to 300 s. Also marked is the observation time for Her X-1 although the source was not detected in the 1–8 keV data. Figure 1*b* shows the 0.18–0.28 keV count rate from the 3° detector. The strong sources Cyg X-3 and Cyg X-2 are almost completely absent (the small signal from Cyg X-2 is the recording of higher energy X-rays as low-energy events due to the escape of argon Kα photons), and the Cygnus Loop dominates the plot. As the detector scanned from ζ Her to Her X-1, a marked increase in the count rate is observed (313 s) which persists throughout the 47 s hold on the source. The count rate decreases again when the detectors are scanned away from Her X-1 (368 s). During the second scan through Her X-1 (386–392 s), the rocket was losing altitude rapidly, and there was appreciable soft X-ray absorption due to the atmosphere.

The increase and decrease in the 0.18–0.28 keV count rate coincide with the times predicted from the aspect solution to better than 1 s, or 1° at the rocket scan rate of 1° s^{-1}. Therefore, we believe that we have detected a significant 0.18–0.28 keV flux from Her X-1 during the OFF portion of the 35 day cycle. The count rate attributable to the source is 8 ± 1 counts s^{-1}, which is 5.3 percent of the 0.18–0.28 keV flux observed during the ON state (Paper I).

Figure 1*c* shows the 0.18–0.28 keV count rate from the 5° detector upon which the earlier OFF state upper limit (Paper I) was based. Because of the larger field of view, the distinction between on- and off-source is less sharp, and the soft X-ray background contributes more than twice as much to the total flux. Nevertheless, the Her X-1 signal can also be seen in the 5° detector data. Figure 1*d* shows the 0.6–2.5 keV count rates from the 3° detector. The count rate is significantly higher while the source is in the field of view. However, the count rate appears to rise after the source has been in the field of view for about 5 s and to drop before the source leaves the field of view. This raises a question about the validity of the detection at these energies, although we could be observing source variability. If the increased count rate is due to Her X-1, the average rate for the entire observation is 7 ± 1 counts s^{-1} or again about 5 percent of the flux observed in this energy range during the ON state.

The spectrum obtained from the 3° detector, 313–368 s, is shown in Figure 2. The off-source background subtraction was made using the data from 302–309 s and that from 372–382 s. The error bars shown are the $\pm 1\ \sigma$ statistical errors. The excess at around 0.25 keV is seen, and some evidence for flux in the 1–2.5 keV region is also present. The spectrum can be fitted reasonably well by a single thermal bremsstrahlung component such as was used in Paper I. However, because of the recent interest in optically thick models of the soft component (McCray and Lamb 1975) and because of the more general problem of obtaining a high-luminosity, optically thin component within a reasonable volume, we have chosen to fit the low-energy excess with a blackbody spectrum. The data in Paper I have been reanalyzed using the sum of a power law and a blackbody spectrum and a hydrogen column density of 3.8×10^{20} cm^{-2}.[1] The best fit is given by

$$N(E) = \{A_{\mathrm{soft}}E^2(e^{E/kT} - 1)^{-1} + A_{\mathrm{hard}}E^{-\alpha}\}$$
$$\times \exp\left[-\sigma(E)N_{\mathrm{H}}\right] \text{ photons cm}^{-2}\,\text{s}^{-1}\,\text{keV}^{-1}\,,$$

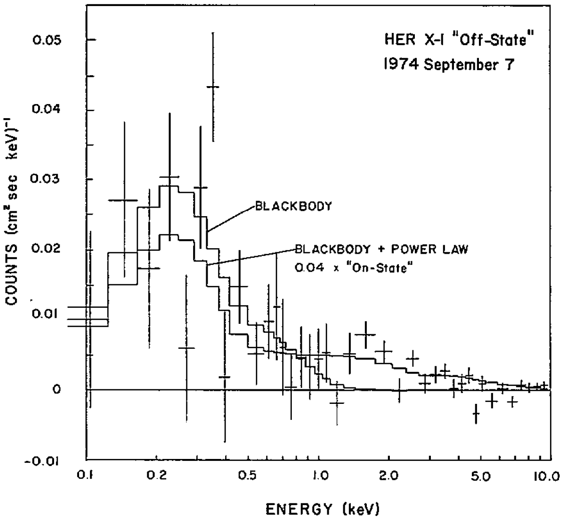

FIG. 2.—Spectrum of Her X-1 in the range 0.1–8 keV during the OFF state. The data are plotted with $\pm 1\ \sigma$ error bars. One solid line is the best fit of a blackbody spectrum alone. The other is the best fit obtained by varying the amplitude of the ON state two component spectrum.

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[1] The hydrogen column density of 5×10^{20} cm^{-2}, used in Paper I, was taken from Tolbert (1971). A more careful estimate based on the finer grid survey of Heiles (1975) gives a value of 3.8×10^{20} cm^{-2}

with $A_{\mathrm{soft}} = 1.08(+0.36, -0.23) \times 10^4$, $T = 8.8 (+0.5, -0.6) \times 10^5$, $A_{\mathrm{hard}} = 0.22 \pm 0.02$, $\alpha = 0.95 \pm 0.10$ and $\sigma(E)$ as given by Brown and Gould (1970). The fit is not significantly different from that obtained using a thermal bremsstrahlung spectrum for the soft component. If we fit the OFF state data with a blackbody spectrum alone, we obtain a best fit temperature of $1.0 (+0.20, -0.25) \times 10^6$ K. However, we can also fit the spectrum simply by scaling down the two-component spectrum found for the ON state. This procedure assumes that the counts in the 0.6–2.5 keV region are real. The best-fit scale factor is approximately 0.04, compared to the 0.05 estimated from the count rates. These fits are shown together with the data in Figure 2.

The observed flux in the 0.18–0.28 keV band in the ON state is 1.6×10^{-10} ergs $\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$. When corrected for the absorption assumed above, this becomes 1.1×10^{-9} ergs $\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$. If a blackbody spectrum is assumed to adequately describe the soft component at unobserved energies, the total flux in this component is 3.7×10^{-9} ergs $\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$. At the same time, the observed flux in the hard component (1–8 keV) is 2.6×10^{-9} ergs $\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$. However, 60 percent of the flux in the hard component is above 8 keV (Holt *et al.* 1974), so we may conclude $L_{\mathrm{soft}} \lesssim L_{\mathrm{hard}}$ for the total luminosities of the two components. Assuming a distance of 5 kpc for Her X-1, the luminosity of the blackbody soft component in the ON state is 1.1×10^{37} ergs s^{-1}. All of the corresponding OFF state fluxes may be obtained by multiplying by 0.04.

We have also examined the 0.18–0.28 keV data for pulsations, but the upper limit of 40–50 percent is far above the 10–20 percent[2] pulsed fraction observed during the Her X-1 ON state (Paper I). No pulsations were detected in the 0.6–2.5 keV band either, with an upper limit on the pulsed fraction of about 50 percent.

The *Apollo* Her X-1 observation was made on 1975 July 22 at 1507 UT. The binary system was at phase 0.72. Her X-1 was in the OFF state of the 35-day cycle approximately 3 days before the turn-on as determined from *Copernicus* data (Davidson and Fabian 1974). The detector was essentially identical to the rocket detectors described previously except that the field of view was 4° FWHM. Her X-1 was observed for 300 s, and about 20 s of background data near the source were also obtained. No significant flux was observed anywhere in the energy range of 0.1–8 keV. The 90 percent confidence upper limits are about a factor of 2 below the positive fluxes reported for the rocket observation, or less than 2 percent of the ON state flux.

III. DISCUSSION

Since there are as yet no long-term satellite observations at 0.18–0.28 keV, it is not possible to determine if the low-energy emission reported here is characteristic of the OFF portion of the 35 day cycle. If our detection in the 0.6–2 keV band is real, then our flux of 1.7×10^{-11} ergs $\mathrm{cm}^{-2}\ \mathrm{s}^{-1}\ \mathrm{keV}^{-1}$ is somewhat above the upper limit reported near 1 keV by the *Copernicus* satellite (Fabian, Pringle, and Rees 1973), and comparable to the upper limit established by the MIT OSO-7 experiment (McClintock *et al.* 1974). Near the center of the OFF state, Fabian, Pringle, and Rees (1973) and Cooke and Page (1975) have observed large fluxes above 2 keV, comparable to the normal ON state flux.

At the present time, the most widely accepted model for the 35 day cycle is one in which precession of the accretion disk obscures our line of sight during the 25-day OFF portion of the cycle (Katz 1973, Roberts 1974, Petterson 1975). At the beginning of the OFF state, electron scattering appears to be responsible for the obscuration as shown by Joss and Fechner (1975), who found that the spectrum is unchanged while the pulsed fraction decreases. At turn-on, photoelectric absorption is probably the dominant obscuration as shown by *Uhuru* (Giacconi *et al.* 1973) and OSO-7 (McClintock *et al.* 1974) spectra, which have measurable absorption below 2–3 keV. The *Copernicus* observation near the center of the OFF state (Fabian, Pringle, and Rees 1973) also indicates that the obscuration is due to photoelectric absorption. However, our observation of low-energy emission approximately 6 days before turn-on suggests electron scattering as the source of the obscuration.

The observations during the OFF state indicate that the central source continues to produce X-rays at a nearly constant rate throughout the 35 day cycle. The continued 1.7 day optical modulations, and the presence of optical pulsations at times during the OFF state (Davidsen, Margon, and Middleditch 1975), strongly support this conclusion. The X-ray variability during the OFF state is most probably due to variable obscuration by the accretion disk. Both the total opacity and the relative contributions of photoelectric absorption and electron scattering are variable. The occurrence of minimum obscuration at the center of the OFF state and maximum obscuration near turn-on is consistent with the detailed disk model of Petterson (1975).

If obscuration by the disk is responsible for the modulation of the soft X-ray emission, it is then not possible to attribute the soft X-rays to an optically thin thermal source, because the emission measure cannot be large enough to explain the observed flux. A model which attributes the soft flux to an optically thick component has been proposed by McCray and Lamb (1975). These authors have suggested that accreting matter may be delayed at the Alfvén radius, where an opaque shell might form. Such a shell would absorb a substantial portion of the hard X-rays and reradiate them at a lower temperature. This idea also appears to be consistent with the detailed calculations of the accretion process near the Alfvén surface by Arons and Lea (1975). Our data yield a radius for such a shell $R = 1.5 \times 10^8\ (d/5\ \mathrm{kpc})$ cm, where d is the distance to Her X-1. This result compares favorably

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[2] In Paper I, the pulsed fraction in the simulated power spectrum was incorrectly stated as 5 percent. The correct value, after accounting for the off-source background, is 10 percent.

with the expected radius of the Alfvén surface ($\sim 10^8$ cm) for a canonical neutron star surface magnetic field ($\sim 10^{12}$ gauss).

Sensitive, long-term satellite observations over the full spectral range of Her X-1 should provide considerable information on the occultation mechanism and the structure and physical condition of the occulting medium. Observations at soft X-ray wavelengths may even elucidate the details of the interaction of accreting matter and the magnetic field of the neutron star.

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