EUVE OBSERVATIONS OF HERCULES X-1 DURING A SHORT HIGH-STATE TURN-ON

D. A. LEAHY
Department of Physics, University of Calgary, University of Calgary, Calgary, AB T2N 1N4, Canada

H. MARSHALL
Massachusetts Institute of Technology, Cambridge, MA 02139; leahy@iras.ucalgary.ca

AND

D. MATTHEW SCOTT
Space Science Directorate, SD-50, NASA Marshall Space Flight Center, Huntsville, AL 35812; scott@gibson.msfc.nasa.gov

Received 1999 December 2; accepted 2000 May 23

ABSTRACT

Observations of Hercules X-1 by the Extreme Ultraviolet Explorer (EUVE) covering low state and the early part of the short high state are reported here. This is the first EUV observation of this part of the 35 day cycle of Her X-1. The low-state portion of the EUV light curve (prior to the start of the short high state) has similar properties as that following the end of the short high state. This is evidence that the low-state EUV emission is primarily due to EUV reflection from the companion star HZ Her. The EUV light curve during the short high state is pulsed and closely resembles the average 2–12 keV X-ray short high-state light curve, indicating that the EUV emission, like the X-ray emission, originates near the neutron star. The short high-state EUV spectrum is consistent with a blackbody of temperature \( T \approx 0.13 \) keV and radius \( r \approx 230 \) km. The short high-state EUV spectrum and pulse shape are similar to that in the soft X-rays (0.1–1 keV). The most likely origin of the EUV emission is reprocessed X-rays from the inner edge of the accretion disk, and the radius of the inner edge of the accretion disk is likely to be small, consistent with that determined from analysis of the X-ray pulse shape evolution.

Subject headings: binaries: eclipsing — stars: individual (HZ Herculis, Hercules X-1) — stars: neutron

1. INTRODUCTION

Hercules X-1 is one of the brightest, and most studied, of the persistent X-ray binary pulsars. The system displays a great variety of phenomena at many timescales, including pulsations at 1.24 s, eclipses at the orbital period of 1.7 days, and a 35 day cycle in the X-ray intensity that normally consists of a main high state lasting 10–12 days and a short high state lasting 5–7 days separated by 8–10 day low states. Recent discussions of the properties of the 35 day cycle are given by Scott & Leahy (1999) and Shakura, Postnov, & Prokhorov (1998). Her X-1 is reviewed by Scott (1993). The X-ray pulse profile evolution is discussed in Deeter et al. (1998). Recent X-ray spectra of Her X-1 are given by Oosterbroek et al. (1997) and Dal Fiume et al. (1998) (from BeppoSAX) and Choi et al. (1997) (from ASCA). An updated set of binary parameters is given by Leahy & Scott (1998). Analysis of ultraviolet spectra of Her X-1 are presented by Boroson et al. (1997) and Vrtilek & Cheng (1996). Optical signatures of reprocessing on the companion and accretion disk are discussed by Still et al. (1997).

Her X-1 has the further advantage of a high Galactic latitude, and hence a low interstellar hydrogen column density, making extreme-ultraviolet (EUV) observations feasible. Her X-1 has previously been observed several times in the EUV energy range (Leahy & Marshall 1999; Rochester et al. 1994; Vrtilek et al. 1994). Rochester et al. (1994) detected Her X-1 during a declining phase of the short high state with the ROSAT Wide Field Camera. The Vrtilek et al. (1994) observations occurred over the 35 day phase 0.14–0.245, normally associated with the peak and flux decline of an average main high state (Scott & Leahy 1999). They state that their observations were during an “anomalous low state.” Leahy & Marshall (1999) observed Her X-1 at 35 day phase 0.76–0.88, which covers the end of the short high state and the low state. \(^2\) From Rossi X-Ray Timing Explorer All-Sky Monitor (RXTE/ASM) observations, the average short high state ends at 35 day phase 0.76–0.80 (Scott & Leahy 1999). The count rate during the Leahy & Marshall (1999) observation was \( \sim 0.02 \) counts s\(^{-1}\) and strongly modulated at the binary period. They concluded that most of the observed EUV emission was reflected emission from the companion star HZ Her. In addition to the EUVE observations, soft X-ray observations with BeppoSAX of the middle and latter part of a short high state are reported in Oosterbroek et al. (2000).

Emission from Her X-1/HZ Her covers the optical, ultraviolet, EUV, and X-ray regime, and models for the, often coupled, emission processes must ultimately be consistent. The hard X-rays (>1 keV) are believed to arise mostly as a result of mass accretion onto the neutron star and are modulated by the neutron star rotation and obscuration by the accretion disk (e.g., Scott, Leahy, & Wilson 2000, and references therein), companion star, and moving gas “blobs” that cause the well-known absorption dips (e.g., Crosa & Boynton 1980). A small reflected/reprocessed X-ray component is also present that is observable during the low state and eclipses (e.g., Choi et al. 1994; Leahy 1995). A major portion of the observed optical/ultraviolet emission is believed to arise from X-ray heating of HZ Her

\(^2\) The 35 day phases quoted above are based on nearby main high-state turn-ons observed with the Burst and Transient Source Experiment (BATSE) on the Compton Gamma Ray Observatory (CGRO) at \( JD - 2,440,000.0 = 9205.14 \) and 9936.22 for Vrtilek et al. (1994) and Leahy & Marshall (1999), respectively, rather than the values quoted in those papers that rely on long-term phase extrapolations.

1 Universities Space Research Association.
and the accretion disk. The X-ray heating causes the surface temperature of the side of HZ Her facing the neutron star to be approximately 10,000 K higher than the cooler shadowed side (Cheng, Vrtilek, & Raymond 1995). Observations of the broadband optical emission of HZ Her/Her X-1 have been presented by Deeter et al. (1976) and Voloshina, Lyutyi, & Sheffer (1990), among others. The broadband optical emission exhibits a complex, systematic variation pattern over the course of the 35 day cycle in addition to the orbital modulation due to X-ray heating of HZ Her. This pattern can be explained as a consequence of disk emission and disk shadowing/occultation of the heated face of HZ Her by a tilted, counterprecessing accretion disk (Gerend & Boynton 1976). The precessing disk also causes the alternating pattern of high and low X-ray intensity states by periodically blocking the neutron star from view. The initial rapid flux rise over a few hours marks the start of a high state and is known as the “turn-on.” This event is generally believed to be the emergence of the neutron star from behind the moving outer disk edge (see Scott et al. 2000, and references therein). Between the hard X-ray and optical/ultraviolet band lies the soft X-ray/extreme-ultraviolet band (\( \sim 0.016-1 \) keV). A blackbody spectral component has been detected by many previous observations with a temperature of about 0.1 keV (e.g., Shulman et al. 1975; Oosterbroek et al. 2000) and generally has been attributed to reprocessing of hard
X-rays in the inner region of the accretion disk (e.g., McCray et al. 1982; Oosterbroek et al. 2000).

Here we report the results of an analysis of EUVE observations of Her X-1 covering two complete orbital cycles including the first EUVE observation of a turn-on to the short high state of Her X-1.

2. OBSERVATIONS

Her X-1 was observed with the EUVE on 1997 July 25–29 (Truncated Julian Day [TJD] = JD – 2,440,000.0 = 10,654.7–10,659.0). See Malina et al. (1994) for a description of the EUVE instruments. The 35 day phase interval of the EUVE observation is 0.49–0.62 based on the 35 day turn-on time of the preceding main high state from Scott & Leahy (1999) and a 35 day period $P_{35} = 20.5P_{orb}$, where $P_{orb}$ is the orbital period. Her X-1 was detected during these observations as a source in the Deep Survey (DS) Spectrometer, with the Lexan/B filter.

3. LIGHT CURVE

The DS light curve of Her X-1 is given in Figure 1, which shows the net source count rate in the Deep Survey instrument for the observation period plotted as a function of time, 35 day phase, and orbital phase. The error bars are $\pm 1\sigma$. There is a sharp rise in the EUV flux (by a factor of $\sim 10$) at 35 day phase 0.56. This is consistent with the expected turn-on phase of a short high state following an “0.7” turn-on main high state as this short high does (Scott & Leahy 1999). The main and short high states typically cover the 35 day phase intervals $\sim 0.30$ and $\sim 0.56–0.79$, respectively.

Orbital modulation at the 1.7 day orbital period of Her X-1 is clearly seen both before and after the turn-on. The EUV flux is within $2\sigma$ of zero during the orbital phase of the high-state eclipse as measured, for example, by Ginga (Leahy 1995). Binary phase is defined here so that binary phase 0.0 is the center of the eclipse of the neutron star by the companion.

The faint part of the light curve prior to the turn-on is comparable in intensity to the faint phases of the EUVE light curve observed by Vrtilek et al. (1994) after TJD 9212.4 and the bright part is comparable to the bright phases observed by Vrtilek et al. (1994) before TJD 9212.4 (peak count rate $\sim 0.5$ counts s$^{-1}$).

The orbital phase dependence of the faint part of the light curve is similar to that observed in 1995 following a short high state (Leahy & Marshall 1999). A much broader, shallower dip near orbital phase 0.5 is observed rather than the deeper, narrower dips seen in 1995. The peak count rate is approximately twice the 1995 peak count rate.

4. SPECTRUM ANALYSIS AND PULSATION SEARCH

EUVESWS spectra were extracted for both the faint and bright phases. The faint phase has too few counts to give a useful spectrum. The bright phase spectrum is shown in Figure 2 and covers the wavelength range 65–179 Å in 38 bins of 3 Å width, which translates to 0.069–0.191 keV.

The spectrum was fitted with a blackbody model, giving best-fit parameters of $kT = 0.133 \pm 0.034$ keV, $N_H = 8.6 \pm 1.3 \times 10^{19}$ cm$^{-2}$, and blackbody radius of $230 \pm 40$ km assuming a distance of 6.6 kpc to Her X-1. The fit was statistically good, with a $\chi^2$ of 34.2 for 35 degrees of freedom. This fit is plotted as the histogram in Figure 2 (top panel), with the fit residuals shown in the bottom panel. We also fit the spectrum with a power-law model with photon index 1.0, giving best-fit parameters $N_H = 1.10 \pm 0.15 \times 10^{20}$ cm$^{-2}$ and normalization of $0.32 \pm 0.09$ photons keV$^{-1}$ cm$^{-2}$ s$^{-1}$ at 1 keV. This fit was also statistically good, with a $\chi^2$ of 34.0 for 35 degrees of freedom. The power-law model is indistinguishable by eye from the blackbody model shown in Figure 2. Addition of a low-temperature component to either the blackbody model or power-law model does not improve the fit. The present data do not support the existence of a second, low-temperature component. The interstellar absorption to Her X-1 (e.g., from the blackbody fit) is enough that a low-temperature component (e.g.,

![Figure 2](image-url)
The peak intensity for the current EUV low-state observation, corrected for the dip at orbital phase 0.5 (35 day phase 0.53), is a factor of \( \approx 2 \) higher compared to the corrected peak intensities of the 1995 observations in which orbital phase 0.5 occurred at 35 day phase \( \approx 0.79 \) and \( \approx 0.84 \). The current low-state light curve also lacks a strong, narrow dip at orbital phase 0.5.

The shadow pattern cast by the disk onto HZ Her repeats every 35 days at a given orbital phase as the disk precesses. From the point of view of HZ Her the pattern repeats every 1.62 days: the beat period of the orbital period and the 35 day period. From disk precession, we expect the disk shadow pattern on HZ Her to be equivalent to a shift by \( \sim 0.23-0.3 \) in orbital phase between the 35 day phase 0.76–0.88 observations and the current 35 day phase 0.53 observation. The shadow would appear later in orbital phase for the 0.53 observation since the disk is counterprecessing.

The observed orbital light curve of X-rays reflected from HZ Her requires a detailed calculation including the disk, star, and observer geometry. We have constructed a sample model for shadowing of HZ Her by the accretion disk for a twisted disk geometry with the following parameters. The inner disk is tilted at 15° from the binary plane and the outer disk is tilted at 25°. The outer disk line of nodes trails the line of nodes for the inner disk by 100° in azimuth. These parameters were chosen in order to be approximately consistent with the observed 35 day phases of the start and end of both main, high, and short high states in Her X-1. An illustration of the disk geometry is given in Figure 4. It is drawn from the perspective of the observer (5° above the orbital plane) at 35 day phase 0.06. The resulting shadowing of the celestial sphere, as seen from the neutron star, is shown in Figure 5. The reference for disk azimuth (0°) is the line of nodes of the inner disk and elevation angle is with respect to the binary plane. Also shown in Figure 5 is the limb of HZ Her, which is approximately a circle of radius

![Fig. 3.—Folded light curve at the best-fit pulse period](image)

\( \leq 0.01 \text{ keV} \) would be reduced from its unabsorbed value by several orders of magnitude.

The bright-phase data was used to perform a pulsation search using the epoch folding method with maximum likelihood test. The data times were first corrected to the solar system barycenter and then corrected for the orbit of Her X-1. The faint phase (prior to turn-on) has too few counts to perform a useful search. When all of the bright phase data are folded, best-fit period and an alias are found at 1.237732(1) s and 1.237742(1) s. The Her X-1 pulse frequencies for the main high states immediately before and after the current short high state, as measured with the standard BATSE pulsed monitor, are, respectively, 1.237730 s and 1.237731 s. Based on these measurements, we choose the first of the two EUV periods for making the folded light curve shown in Figure 3. The pulse profile has a modulation of 10%, using a definition of modulation as the ratio of the equivalent amplitude of a sinusoidal variation to its mean value.

5. DISCUSSION

5.1. EUVE Low-State Observation (prior to Short High-State Turn-on)

We have observed a short high-state turn-on in Her X-1 with the EUVE DS/SWS. The observations include just over one orbit of data during low state prior to turn-on, and about 2.4 orbits of data after turn-on. BATSE monitoring revealed normal main high states flanking this short high state, so there is no reason to believe it is atypical.

The low-state light curve is modulated at the orbital period (Fig. 1). It was argued in Leahy & Marshall (1999) that the low-state EUV orbital modulation is caused by the changing orientation of the face of HZ Her reflecting EUV emission from the pulsar toward the observer. The EUV emission from the X-ray heated face of HZ Her is too dim to account for the observed EUV intensity, while EUV reflection from the accretion disk would produce a constant EUV emission component modulated only by eclipses and slow changes over the 35 day cycle. The primary EUV emission originates in a relatively small region near the neutron star and is observable as the high-state EUV emission, while the EUV emission reflected from HZ Her is modified by the disk shadow and by disk occultation. This model was described in Leahy & Marshall (1999) and applied to the 1995 observations at the end of the short high state (35 day phase 0.76–0.88). The occultation of HZ Her by the accretion disk causes the narrow dips in the light curve at orbital phase 0.5.

![Fig. 4.—Illustration of the tilted-twisted disk](image)
orbital phase 0.5 were corrected by a small amount for disk observations. The observed intensities for B, C, and D at day phases for the two orbits of data for the 1995 low-state phase for the 1997 low state and C and D mark the two 3.5 day phases when HZ Her is at orbital phase 0.5 during
motion of the observer, i.e., with the peak of the short high state this also coincides with minimum shadowing in the direc-
tion of HZ Her's shadow. The disk shadow model was used to calculate the reflected intensity by a factor of ~2.7 over disk phase. This is nearly sinusoidal (with a period of π radians, or 0.5 cycles, in disk phase) despite the complicated shadow pattern, due to the integration over the large angular size of HZ Her (as seen from the neutron star).

On Figure 6 we also indicate the phase when the disk shadow on HZ Her is minimum (A). For orbital phase 0.5, this also coincides with minimum shadowing in the direction of the observer, i.e., with the peak of the short high state at 35 day phase ≈0.58. With this reference, we can mark the 35 day phases when HZ Her is at orbital phase 0.5 during the EUVE low-state observations: B marks the 35 day phase for the 1997 low state and C and D mark the two 35 day phases for the two orbits of data for the 1995 low-state observations. The observed intensities for B, C, and D at orbital phase 0.5 were corrected by a small amount for disk occultation of HZ Her (which is not included in the model). The intensities were scaled by a common factor derived from normalizing the B intensity to the reflection model. On Figure 6, these three intensities are marked by asterisks to compare to the model relative intensity. The agreement is good: the increased shadowing of HZ Her by the accretion disk at 35 day phases 0.79 and 0.84 compared to the shadowing at 35 day phase 0.53 is approximately reproduced by the model calculations. Another small (~10%) roughly constant contribution to flux in the model, due to reflection of X-rays from the disk, would reduce the amplitude of the model curve and bring it into agreement with the observations. Thus the current observation of HZ Her X-1 prior to the turn-on is in qualitative agreement with the idea that the EUV emission in the low state is primarily due to reflection of X-rays from HZ Her.

We now consider whether the EUV X-ray reflection model is consistent with optical observations of HZ Her/Her X-1. Voloshina et al. (1990) present 16 year average U, B, and V light curves (Fig. 1 in that paper). They find the average U, B, and V light curves differ by a maximum of 20%–22% between on state (which they defined as 35 day phase 0.85–0.15) and off state (defined as 35 day phase 0.20–0.85). However, due to the large 35 day phase intervals, this is not very useful. Much more useful for comparison is the data presented by Deeter et al. 1976. Optical B-band fluxes as a function of orbital phase are presented in their Figure 1. The variation between different 35 day phases at a fixed orbital phase is large: from a factor of ~1.7 around orbital phase 0.5 to a factor of ~1.3 around orbital phase 0.0. Gerend & Boynton (1976) reproduce the optical orbital light curve and its variation with 35 day period using a model including radiation due to X-ray heating of HZ Her shadowed by the disk, emission by the disk, and occultation of HZ Her by the disk.

We argue that one expects the optical and EUV light curves to be different. The estimated EUV heating flux is far too faint to explain the observed EUV observations (Leahy & Marshall 1999). The EUV reflection model can produce enough flux, and uses the disk shadow to cause a factor of ~2.7 change in reflected intensity at orbital phase 0.5. The EUV reflection flux has a different distribution over the stellar surface than the optical flux, which is due to X-ray heating: the optical flux is more concentrated toward the L1 point. The optical emission from the disk is significant, based on the model of Gerend & Boynton (1976) for the observed optical flux. For an estimate of the disk component of the B flux, Figure 7 of Gerend & Boynton (1976) gives a disk B flux of ~1.5–2.5 (units defined in Gerend & Boynton 1976) which is generally out of phase with the stellar heating contribution (B flux ~0.5–4). On average the disk, in their model, contributes ~40% of the heating flux. The heating flux alone varies by a factor of up to ~7 with orbital phase. If we consider orbital phase 0.5, it varies by a factor ~7 over 35 day phase, which is larger than the observed variation in EUV flux, as expected if the EUV flux is due to reflection.

Thus the variation in EUV and optical emission with orbital and 35 day phase are expected to be different. Empirically, one can compare the observed optical and EUV light curves. A basic result found by Deeter et al. (1976) was that the total optical radiation, when averaged over an orbit, varied by less than a few percent over the 35 day cycle. In contrast, the low-state EUV orbital light
curves observed here and in 1995 (Leahy & Marshall 1999) varied by roughly a factor of 2 in total intensity.

The detailed form of both optical and EUV light curves depend on the shadowing geometry and the amount of disk radiation. Thus EUV data over a wider 35 day phase range (in low state) and more detailed modeling would be very useful to constrain the disk geometry using both EUV and optical data.

5.2. EUVE Observation of the Short High State and the Short High-State Turn-on

This EUVE observation is only the second high-resolution observation of a short high-state turn-on performed to date as far as the authors know. A 5 day long observation of the middle and latter part of a short high state (Oosterbroek et al. 2000). Figure 7 shows the EUV light curve (histogram) at the time of turn-on as a function of time and of 35 day phase. The smooth line in Figure 7 is a fit to the short high-state turn-on observed by Ginga (Scott et al. 2000; Leahy 2000) and is plotted at the observed Ginga 35 day phase without any phase shift to match the EUVE light curve. The timescale for the EUV turn-on transition is $\approx 3.5$ hr, the same as the timescale of turn-on observed by Ginga in 2–37 keV X-rays for both short high state and main high state (Scott et al. 2000). This confirms that the short high-state turn-on is indeed sharp as opposed to the gradual rise predicted in some disk models for Her X-1 (e.g., Schandl & Meyer 1994). There is strong evidence that the X-ray turn-on transition is due to reduced absorption as the outer edge of the disk moves out of the line of sight (e.g., Becker et al. 1997; Scott et al. 2000). Thus the increase in the EUV emission at turn-on is likely due to the same cause, and hence the size of the EUV emission region, like the X-ray emission region, must be small compared with the scale height of the outer edge of the disk.

The first orbit after turn-on shows a strong dip at orbital phase 0.5 followed by a second dip after orbital phase 0.65. The flux rises soon after the eclipse in the second orbit after turn-on, with a dip at orbital phase 0.19 before reaching a maximum. The pattern is similar to that of the first orbit of “0.2” turn-on main high states that show a turn-on, anomalous dip at orbital phase 0.5–0.6, pre-eclipse dip, and a “post-eclipse recovery” (Crosa & Boynton 1980; Scott & Leahy 1999). The average RXTE/ASM short high-state light curves displayed in Figure 3 of Scott & Leahy (1999) also exhibit a similar pattern of turn-on, anomalous dip, and pre-eclipse dip followed by a “post-eclipse recovery.” The BeppoSAX short high-state observation of Oosterbroek et al. (2000) is very similar to the middle and latter part of the average RXTE/ASM short high-state light curve and shows that the pattern of anomalous dip, pre-eclipse dip, and “post-eclipse recovery” continues for each orbit of the short high state. The very close similarity of the EUV, soft X-ray, and 2–12 keV X-ray light curves implies that the same occulting structures cause the modulation observed in both the EUV and X-ray light curves, and the EUV and X-ray emission regions are much smaller in size than the occulting structures. These occulting structures are probably the outer disk edge in the case of the turn-on (for either high-state type) or “blobs” of matter that pass between the observer and the neutron star in the case of the dips (e.g., Crosa & Boynton 1980; Scott et al. 2000).

Our EUVE SWS short high-state bright-phase spectrum is the highest resolution spectrum yet presented in the 0.05–0.2 keV energy range. It demonstrates that the emission from Her X-1 is dominated by continuum and not line emission. Due to previous observations, we reject the power-law model in favor of the blackbody model. Previous observations of the low-energy (below 1 keV) spectrum of Her X-1 have been made during both the main high state and the short high state. The BeppoSAX LECS spectrum at 35 day phase 0.1 (Dal Fiume et al. 1998) is dominated below 1 keV by a blackbody component with $kT \approx 0.092$ keV and $N_H \approx 5.1 \times 10^{19}$ cm$^{-2}$, with blackbody radius $\approx 353$ km (for $d = 6.6$ kpc). Similarly, a BeppoSAX observation of a short high-state peak found a blackbody component with $kT \approx 0.094$ keV and a blackbody radius $\approx 209$ km (for $d = 6.6$ kpc). With the current short high-state bright-phase spectrum, the various measurements of temperature are consistent with the blackbody component having a constant temperature of 0.09 keV throughout main, high, and short high states. The blackbody radius declines during the high states, and the early short high state has approximately half the radius compared to the peak of main high state.

The current detection of EUV pulsations at the X-ray pulsation period during the short high state implies that the EUV emission is coming from a compact region near the pulsar, less than several tenths of a light-second across. The folded EUV pulse profile has a symmetric quasi-sinusoidal form (Fig. 3) consistent with the pulse shape below 0.4 keV in X-rays found during the during main high state (e.g., McCray et al. 1982; Oosterbroek et al. 2000) and the short high state (Oosterbroek et al. 2000). The similarity of the pulse form and spectrum of the EUV emission with the pulse form and spectrum of the short high-state soft X-ray emission suggests that these are simply the same emission component. The BeppoSAX observations of Oosterbroek et al. (2000) clearly show the pulse changing form from a symmetrically peaked quasisinusoid below 1 keV to an asymmetric quasisinusoid above 1 keV. The change in form of the pulse with energy suggests that the soft X-ray/EUV emission and the harder X-ray quasi-sinusoidal pulse emission originate from different physical regions, an idea.

![Fig. 7.—Observed EUVE DS light curve of Her X-1 (with $\pm 1 \sigma$ error bars) at turn-on of short high state at JD = 2,450,656.9. The smooth curve is a fit to the Ginga 1989 short high-state light curve plotted against 35 day phase.](image-url)
reinforced by the corresponding change in the energy spectrum from a thermal form below 1 keV to a power-law form above 1 keV.

The main pulsed emission above 1 keV during the peak of the main high state has a complicated profile and probably originates on the pulsar or within a few radii of the neutron star (Scott et al. 2000). The pulsed emission above 1 keV with a quasi-sinusoidal pulse profile has a power-law energy spectrum like the main pulsed emission so it is likely not reprocessed, but rather scattered. A probable scattering location with a large solid angle for radiation emitted close to the neutron star is the accretion column, which may be optically thin to Thomson scattering for the conditions applicable in Her X-1 (Brainerd & Meszaros 1991). The thermal spectrum of the X-ray/EUV emission below 1 keV suggests that it is reprocessed hard X-ray emission. The reprocessing region must be close to the neutron star to be pulsed, yet not on the neutron star itself because the blackbody radius is too large. Neither could it be an optically thin accretion column. The probable reprocessing location is the innermost region of the accretion disk. The deduced blackbody radius of \( \sim 230 \text{ km} \) from the EUVE/SWS spectrum supports this. This implies a quite small inner edge: only a few hundred kilometers, depending on the details of the geometry. The analysis of the pulse shape evolution (Scott et al. 2000) also requires a small radius for the inner edge of the accretion disk (about \( \sim 400-480 \text{ km} \)). Thus we have good evidence that the 0.1 keV blackbody component from Her X-1 is reprocessed emission from the inner edge of the disk as first suggested by McCray et al. (1982).

The details of the reprocessing depend on the beam pattern from the neutron star and the geometry of the innermost region of the accretion disk. We take a simple disk edge and an inner disk tilt of \( \approx 11^\circ \) discussed by Scott et al. (2000) to explain the pulse evolution. Excluding disk self-occultation, the reprocessed emission should have about the same intensity in either the main or the short high-state peaks since the difference in projected area for an observer elevation (5°) is only a few percent (viewing angles of 16° vs. 6° for the main and short high states, respectively). However, disk self-occultation is important: during the short high state a sizeable fraction of the inner disk edge is blocked from the observer's view, whereas a more open view exists during the main high state (see Scott et al. 2000). This situation is consistent with the ratio of \( \sim 0.25 \) for the observed peak of the short high-state blackbody emission (the current observation and Oosterbroek et al. 2000) to the peak of the main high-state blackbody emission (Dal Fiume et al. 1998).

The short high-state EUV emission shows sharp dips at different orbital phases. The dips may be due to the accretion stream. The stream moves in synchronism with the binary, rather than at the 35 day period, up until the point where it impacts the disk. The dips could also be due to the splash at the impact point which is periodic at the binary period but has a complicated path over the disk surface which depends in detail on the disk tilt and twist. Above we saw that the short high-state EUV emission is blocked from the observer's line of sight after orbital phase 0.75, like the X-ray emission. Feasible explanations are blockage of the line of sight by the accretion stream or disk impact point splash region. The splash region subtends a much larger angle at the neutron star than the stream so is a better candidate for the extended blockage after orbital phase 0.72. It is highly desirable to obtain further observations, such as for later orbits in the short high state in both EUV and X-ray bands, to test the origin of the dips.

This work was supported in part by the Natural Sciences and Engineering Research Council of Canada. The authors thank Robert B. Wilson for providing help with the analysis of the BATSE data used in this paper.

REFERENCES

Becker, R., Boltz, E., Holt, S., Pravdo, S., Rothschild, R., Serlemitsos, P., Smith, B., & Swank, J. 1977, ApJ, 214, 879
Boroson, B., et al. 1997, ApJ, 491, 903
Brainerd, J., & Meszaros, P. 1991, ApJ, 369, 179
Cheng, F. H., Vrtilek, S. D., & Raymond, J. C. 1995, ApJ, 452, 825
Choi, C., Dotani, T., Nagase, F., Makino, F., Deeter, J., & Min, K. 1994, ApJ, 427, 400
Choi, C., Seon, K., Dotani, T., & Nagase, F. 1997, ApJ, 476, L81
Crosa, L., & Boynton, P. E. 1980, ApJ, 235, 999
Dal Fiume, D., et al. 1998, A&A, 329, L41
Deeter, J., Crosa, L., Gerend, D., & Boynton, P. 1976, ApJ, 206, 861
Deeter, J., et al. 1998, ApJ, 502, 802
Gerend, D., & Boynton, P. 1976, ApJ, 209, 562
Leahy, D., & Scott, D. M. 1998, ApJ, 503, L63
Leahy, D. A. 1995, ApJ, 450, 339
———. 2000, MNRAS, 314, 735
Leahy, D. A., & Marshall, H. 1999, ApJ, 521, 328
Malina, R., et al. 1994, AJ, 107, 751
McCray, R., Shull, M., Boynton, P., Deeter, J., Holt, S., & White, N. 1982, ApJ, 262, 301
Oosterbroek, T., Parmar, A., Martin, D., & Lammers, U. 1997, A&A, 327, 215
Oosterbroek, T., et al. 2000, A&A, 353, 575
Rochester, G., Barnes, J., Sidher, S., Sumner, T., Bewick, A., Corrigan, R., & Quenby, J. 1994, A&A, 283, 884
Schandl, S., & Meyer, F. 1994, A&A, 289, 149
Scott, D. M. 1993, Ph.D. thesis, Univ. Washington
Scott, D. M., & Leahy, D. 1999, ApJ, 510, 974
Scott, D. M., Leahy, D., & Wilson, R. 2000, ApJ, 539, 392
Shakura, N., Postnov, K., & Prokhorov, M. 1998, A&A, 331, L37
Shulman, S., Friedman, H., Fritz, G., Henry, R. C., & Yentis, D. J. 1975, ApJ, 199, L101
Still, M., Quaintrell, H., Roche, P., & Reynolds, A. 1997, MNRAS, 292, 52
Voloshina, I., Lyutyi, V., & Sheller, E. K. 1990, Soviet Astron. Lett., 16, 257
Vrtilek, S., et al. 1994, ApJ, 436, L9
Vrtilek, S. D., & Cheng, F. H. 1996, ApJ, 465, 915