EUVE Observations of Her X-1 at the End of the Short High State

D. A. Leahy
 Dept. of Physics, University of Calgary, University of Calgary, Calgary, Alberta, Canada T2N 1N4
 and

H. Marshall
 M.I.T., Cambridge, MA 02139

ABSTRACT

Observations of Her X-1 by the Extreme Ultraviolet Explorer (EUVE) at the end of the x-ray Short High state are reported here. Her X-1 is found to exhibit a strong orbital modulation of the EUV flux, with a large dip superposed on a broad peak around orbital phase 0.5 when the neutron star is closest the observer. Alternate mechanisms for producing the observed EUV lightcurve are modeled. We conclude that: i) the x-ray heated surface of the companion is too cool to produce enough emission; ii) the accretion disk can produce enough emission but does not explain the orbital modulation; iii) reflection of x-rays off of the companion can produce the shape and intensity of the observed lightcurve. The only viable cause for the large dip at orbital phase 0.5 is shadowing of the companion by the accretion disk.
1. Introduction

Hercules X-1 is one of the brighter, and most studied, of the x-ray binary pulsars. It exhibits a wealth of phenomena, including pulsations at 1.23 seconds, eclipses at the orbital period of 1.7 day, and a 35 day cycle in the x-ray intensity. Her X-1 is reviewed by Scott 1993. Recent discussions of the properties of the 35 day cycle are given by Scott & Leahy 1998 and Shakura et al. 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. 1998 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, Vrtilek and 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 low interstellar hydrogen column density, making EUV observations feasible. Her X-1 has been observed in the EUV previously (Rochester et al. 1994, Vrtilek et al. 1994). Here we report the results of analysis of EUVE observations of Her X-1 covering two complete orbital cycles at the end of the Short High state of Her X-1.

2. Observations

Hercules X-1 was observed with the Extreme Ultraviolet Explorer (EUV) on June 24-28, 1995 (TJD = JD-2440000 = 9893.0 - 9897.1). See Malina et al. 1993 for a description of the EUVE instruments. Using the 35 day ephemeris from BATSE and XTE/ASM observations (Scott, private communication) for phase 0 of 34.85 N + MJD50077.0, the 35 day phase of the EUVE observations is 0.71 - 0.82. Phase 0 is defined as turn on of the Main High state. The shape of the 35 day cycle and durations of the different states has only recently been well determined (Scott & Leahy 1999): the Main High and Short High states cover 35 day phase 0-0.33 and 0.59-0.80. Thus the EUVE observations occur during decline of the Short High state into the low state.

Her X-1 was detected during these observations as a source in the Deep Survey (DS) Spectrometer, with Lexan/B filter. However it is a faint EUVE source so it did not have enough signal to give a usable spectrum. The DS Lexan/B image shows that Her X-1 is clearly detected.

The DS lightcurve 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. The error bars are ±1σ. The orbital modulation at the 1.7 day orbital period of Her X-1 is clearly seen. The EUV flux is within 2σ of zero during the known times of x-ray eclipse, e.g. as measured by GINGA (Leahy 1993). Binary phase is defined here so that binary phase 0.0 is center of eclipse of the neutron star by the companion.

Broad dips are seen at TJD (=JD-2450000) 9894.2 and 9895.9. In addition there are three narrow dips detected in the EUV lightcurve: at JD-2440000 of 9894.54, 9895.53, and 9896.19. The minimum points of the narrow dips differ from adjacent points by 2.3σ, 3.6σ, and 2.7σ respectively. The orbital phases of these dips is 0.707, 0.301 and 0.684, using the orbital ephemeris of Scott 1993. The first and third dips are pre-eclipse dips and show a separation of 1.62 d, The second dip is likely an anomalous dip.

The EUVE lightcurve of Vrtilek et al. 1994 covered a similar time interval (just over 2 binary orbits of Her X-1). The observations occurred during the main high state of the 35 day cycle, but were affected by the onset of an anomalous low state. That EUVE lightcurve had bright phases (~ 0.6 c/s) and faint phases (~ 0.02 c/s). The lightcurve presented here is comparable in intensity to the faint phases of that presented by Vrtilek et al. 1994.

3. Modelling the EUV Lightcurve

Modelling calculations were carried out to compare to the observed EUVE DS lightcurve. The orbital parameters from x-ray timing analysis (Deeter et al. 1991) were used. Additional assumptions were needed for the orbit to calculate light curves: orbital inclination of 85°, a K\text{opt} value of 100 km/s (Reynolds et al. 1997), and a mass ratio of 0.592 (Leahy & Scott 1998). The distance of Her X-1 was assumed to be 6.6 kpc.

3.1. X-ray Heating of HZ Her

One contribution to the EUVE lightcurve is emission from the x-ray heated face of the optical companion HZ Her. That has been calculated here, giving a EUV lightcurve that can reproduce the general shape of the orbital modulation seen in Figure 1, including the dip at orbital phase 0.5, which is produced by the accretion disk occulting HZ Her. For Her X-1, the
column density is \( \sim 1 - 5 \times 10^{19} \text{cm}^{-2} \) \cite{Mavromatakis1993, Vrtilek1994, DalFiume1998}. When we include this and the response of the EUVE DS, the model count rate is smaller than the observed count rate by a large factor. One can achieve a large enough count rate by artificially raising the temperature of the heated face of HZ Her by a factor \( \sim 2 \). However this is far larger than any uncertainties in the calculation (or in the observed temperature of the heated face of HZ Her), so the conclusion is that this x-ray heating model fails to explain the data.

3.2. Accretion Disk EUV Emission

The accretion disk has two sources of EUV emission: the x-ray heated surface (illuminated by the pulsar); and the emission from self-heating by viscous dissipation in the disk.

First we consider a simple model for emission from the heated surface of the disk: a uniform temperature hot spot. The actual size and shape of the heated region which is visible to the observer depends in detail on the geometry of the twisted and tilted disk. The hot spot is taken a blackbody of circular shape (normal to the line-of-sight), with radius \( R \) and temperature \( T \). By requiring the model count rate (including interstellar absorption and the EUVE DS spectral response) to be 0.03 c/s we obtain a single constraint relating \( R \) and \( T \). E.g. for a column density of \( 5 \times 10^{19} \text{cm}^{-2} \), \( T = 10^6 K \) gives \( R = 5.9 \times 10^6 \text{cm} \), and \( T = 10^5 K \) gives \( R = 8.5 \times 10^6 \text{cm} \).

Next we consider the emission from a viscous disk. In this case we use a model which includes both viscous heating and x-ray irradiation \cite{Schandl1994}. This disk has temperature-radius relation: 
\[
T = 1.5 \times 10^6 (R/10^6 \text{cm})^{-0.8} \text{K}.
\]
We include interstellar absorption and then fold an approximation to the spectrum with the EUVE DS spectral response to determine a model EUVE DS count rate. For a face-on, unobscured disk face, and a column density of \( 5 \times 10^{19} \text{cm}^{-2} \), the model count rate is several times the observed count rate. The model emission comes from the part of the disk within \( 10^6 \text{cm} \) of the center, where the disk temperature is more than \( 1.5 \times 10^5 \text{K} \). If one includes the effect of high inclination of Her X-1, and self-occultation by other regions of the disk due to the twist and tilt of the disk (e.g. see the disk model of \cite{Schandl1994}), the model count rate will be reduced by a factor of \( \sim 3 \) to \( > 10 \), which is sensitive to details of the geometry. Thus disk emission is consistent with the observed magnitude of the DS count rate.

The disk as source of the EUV emission (either from x-ray heating or viscous heating) has the following difficulty. The disk in Her X-1 is generally accepted to precess with a 35 day period. The orbital modulation in disk EUV emission models is restricted to eclipse of (small) heated part of the disk by the companion, which is restricted to small range of orbital phases between 0.9 and 0.1. There is no easy way for the disk models to produce the observed strong orbital modulation.

3.3. Reflection of X-rays from HZ Her

Another source of EUV emission is the long wavelength part of the spectrum of scattered x-rays from the system. The x-ray spectrum of Her X-1 below a few hundred eV is dominated by the blackbody component \cite{McCray1982, Vrtilek1994, Mavromatakis1993, DalFiume1998}. From the observers vantage point, by far the largest area for reflecting x-rays is the illuminated surface of HZ Her. This illuminated surface of HZ Her has an outer ionized layer which reflects x-rays by electron scattering.

We have calculated the amount of reflected x-rays as a function of orbital phase, expressed as a fraction of the direct flux from the neutron star. We take the reflecting layer as a thin layer located at the Roche critical surface, and assume that a fraction, \( \eta \), of the incident x-ray flux is scattered isotropically. \( R \) is taken as independent of energy, so that the spectrum of the scattered radiation is the same as that of the incident radiation. The resulting light curve is a smooth function of orbital phase, peaked at orbital phase 0.5 and zero around orbital phase 0. The model light curve for \( \eta=0.5 \) fits the observed data reasonably well, except for the region around orbital phase 0.5. The value of \( \eta \) is fairly high, so indicates that the material scattering the x-rays is mostly ionized. However the value of \( \eta \) is not accurate, due to uncertainties in the normalization and spectrum of the soft x-ray flux and in the distance to Her X-1. We estimate an uncertainty in the value of \( \eta \) by a factor of \( \sim 2 - 4 \).

3.4. Origin of the Dips

Next we discuss the large dips near orbital phase 0.5. The observed dips at TJD9894.2 and TJD9895.8 have intensity reductions of 73% and 56%, resp. First we describe a simple model to fit the observed light
curves including the large dips. The light curve for reflected intensity, with \( \eta = 0.5 \), was calculated as above, then multiplied by a shadowing function. The shadowing function was of the form: \( 1 - \alpha \exp\left(-\left(\phi - \phi_o\right)^2/2\sigma^2\right) \), with \( \phi \) is orbital phase. The parameters \( \alpha, \phi_o \) and \( \sigma \) were allowed to have different values for the two observed orbits, and were varied to achieve a good fit to the data. Since there was no improvement in allowing the two values of \( \sigma \) to be different, they were set to be the same, giving \( \sigma = 30^\circ \). The resulting model light curve is shown in Fig. 2 by the solid line, with the data points plotted as the circles. The resulting parameter values are: \( \alpha = 0.85 \) and \( \phi_o = 189^\circ \) for the first orbit; \( \alpha = 0.8 \) and \( \phi_o = 178^\circ \) for the second orbit.

Next we discuss the physical origin of the dips. One can achieve a reduction in flux by blocking the line-of-sight to HZ Her by the accretion disk. Calculation shows that the reflected x-rays come fairly uniformly from the whole face of HZ Her, so one needs an object nearly the same size as HZ Her to achieve the observed large flux reductions. (In contrast, for the x-ray heating model, the EUV emission was highly concentrated near the L1 point so the accretion disk could easily block the emission). The reduction in reflected flux for the case of a spherical occulting surface of radius \( R \) (centered on HZ Her) is calculated to give an estimate of the required size of an occulter. The results are that the reduction in flux is a smooth function of \( R/R_{HZHer} \). Sample values of the flux reduction are: 10\% at \( R/R_{HZHer} = 0.26 \), 50\% at \( R/R_{HZHer} = 0.61 \), 80\% at \( R/R_{HZHer} = 0.83 \).

The largest object available for occultation in the system is the accretion disk. The radius of the outer edge of the disk is somewhat less than that of the Roche lobe of Her X-1, which is at \( 2 \times 10^{11} \text{cm} \), (calculated using the binary parameters of Leahy & Scott 1983). Schandl & Meyer 1994 gives a better limit on the accretion disk radius, based on the observed orbital period change, of \( 1.7 \times 10^{11} \text{cm} \). The disk model of Schandl & Meyer 1994 has an outer edge inclination of \( \sim 7^\circ \), which results in a flux reduction of 13\% for the most favorable disk orientation, assuming a system inclination of \( 85^\circ \). Thus occultation is not capable of explaining the dips near orbital phase 0.5.

The alternative explanation is that HZ Her is shadowed from the x-ray source by the accretion disk. The accretion disk then only needs to subtend a significant angular extent viewed from the neutron star. For the geometry of Her X-1, the angular radius of HZ Her viewed from the neutron star is \( 25^\circ \). Significant shadowing of this can occur with a twisted tilted accretion disk. An example of a calculated shadow is given by Figure 5 of Still et al. 1997, which shows \( \sim 25\% \) of the front side of HZ Her shadowed for the particular disk parameters they have chosen. Schandl & Meyer 1994 give a sketch of a similar disk (their Fig.13), and a depiction of the shadow the disk casts on the sky as viewed from the neutron star (their Fig. 12).

The amount of shadowing can be calculated from existing disk models. The result depends on the disk tilt and on the disk twist. The maximum tilt is \( \sim 10^\circ \) in the model of Schandl & Meyer 1994 but higher in other models (e.g. Scott 1993 has a maximum tilt of \( 30^\circ \)). Models with a maximum disk tilt of \( 10^\circ \) cannot give a flux reduction, even at most favorable orientation, larger than \( \sim 30\% \). The larger flux reduction is associated with models with larger twist. A flux reduction of 100\% is possible for maximum tilt greater than \( 25^\circ \), for which case the vertical angular extent of the accretion disk is larger than that of HZ Her. The general conclusion is that shadowing can account for the large dips near orbital phase 0.5. However, the observed strength of the dips, as large as \( \sim 60-70\% \), implies that the maximum disk tilt should be larger than \( \sim 20^\circ \).

Further evidence that the dips are due to accretion disk shadowing comes from the timing of the dips. The disk in Her X-1 precesses counter to the orbit over a 35 day period, so the disk shadow moves to earlier orbital phase by \( 18^\circ \) (or 0.05 in orbital phase) during a single 1.7 day orbit. Equivalently, the shadow has a 1.62 day period. Compare this to the observed dips. The separation between the two minimum intensity points (at JD-2440000 of 9894.22 and 9895.86 in Figure 1) is 1.64 day, with an uncertainty of \( \sim 0.2 \) day. (A different way of measuring the same offset is by use of the Gaussian shadow model. It yielded an orbital phase difference between the shadows for the two orbits of \( 11^\circ \).) Thus the observed dips in the light curve are consistent with an origin in the precessing shadow of the accretion disk, but not consistent with a constant period of 1.7 day.

Next we discuss what shadowing is expected from standard disk models as a function of 35 day phase, and in particular, at the 35 day phase of the observations here. The timing (i.e. orbital phase) of the accretion disk shadow can be predicted from the 35 day phase since they both depend on the orientation of the accretion disk with respect to the observer. The
Main High state peaks near 35 day phase 0.12 (Scott & Meyer 1994) so the observer experiences minimum accretion disk blockage at this time. So the shadow on HZ Her should be minimum at orbital phase 0 (when HZ Her experiences the shadow closest to the direction of the observer) closest to 35 day phase 0.12. However we observe the shadow near orbital phase 0.5. To get the shadow at orbital phase 0.5 we just need to rotate the disk by 180°, i.e. change 35 day phase by 0.5. Thus the shadow on HZ Her, at orbital phase 0.5, is minimum at 35 day phase 0.62.

The 35-day phase of maximum of disk shadow to the observer depends on the details of the disk model. Tilted-twisted disk models have rings at each radius the observer depends on the details of the disk model. However we observe the shadow near orbital phase 0.5. To get the shadow at orbital phase 0.5 we just need to rotate the disk by 180°, i.e. change 35 day phase by 0.5. Thus the shadow on HZ Her, at orbital phase 0.5, is minimum at 35 day phase 0.62.

From the orbital phases of the two observed dips we estimate the time that the shadow maximum occurs at orbital phase 0.5. This yields a time of JD-2440000 = 9895 or 35 day phase 0.77, which is different from the above prediction of 0.85. The difference could occur for two reasons: 1. The disk twist and tilt are significantly different than in existing disk models, so that maximum follows minimum shadow by only 0.15 in 35-day phase (55° in azimuth). 2. The minimum obscuration to the observer at 35 day phase 0.12 is offset from the minimum shadowing of HZ Her at orbital phase 0. The latter is hard to achieve, because the observer's inclination to the binary plane is only ∼ 5° (Leahy & Scott 1993). Thus we have evidence here for altered disk parameters which result in a smaller separation of maximum after minimum shadow.

Twisted-tilted disk models with the symmetry described above result in a shadow on HZ Her which repeats twice over the 35 day cycle (except for an inversion about the binary plane). Thus a prediction is that at orbital phase 0.5 and 35-day phase 0.12 the shadowing should be a minimum also. However the EUVE observations of Vrtilek et al. 1994 at this phase show much brighter EUV emission which is pulsed and comes directly from the region of the pulsar. So the much fainter reflected emission off of HZ Her cannot be observed at this phase.

The three narrow dips at JD-2440000 of 9894.54, 9895.53, and 9896.19 are interesting. More observations will be needed to verify their existence. However, if they are verified, they imply a moving structure (with respect to the disk) near the neutron star is causing the shadow. The reason is that a significant (large angular extent) region of HZ Her must be shadowed, but the shadow must move rapidly compared to orbital period for the dip to be of short duration compared to the orbital period. Since two of the narrow dips recur at the same period and orbital phase as pre-eclipse dips, this structure may be the same structure that causes the pre-eclipse dips.

4. Conclusions

Her X-1 has been detected by the EUVE DS at the end of the Short High state of the 35 day x-ray cycle (35 day phase 0.71 to 0.82). We have carried out modelling in order to understand the EUVE DS light curve. The first model considered was a calculation of the x-ray heating effect from Her X-1 on HZ Her, including occultation of the heated surface by the accretion disk. This model can produce the shape of the observed light curve, but is of too low intensity mainly due to the effect of interstellar absorption at EUV wavelengths.

The next model considered was emission by the accretion disk, either by a hot spot or by emission from a disk model including viscous heating and x-ray irradiation. The level of observed emission can be produced, and is sensitive to the details of the disk geometry. However the main difficulty of explaining the observed EUV emission with a disk is that the disk emission should have a 35 day modulation and not a modulation at the orbital period, as observed.

The final model considered was reflection of the soft x-ray emission from the pulsar off of HZ Her. This can give the correct level of emission, and also produce the observed orbital modulation of the light curve. The dip near orbital phase 0.5 is produced by shadowing of HZ Her by the accretion disk. Further support for this model comes from the difference in the times of maximum shadow: it is 1.64 ± 0.2 day, consistent with the expected beat period of 1.62 day between the 1.7 day orbital period and the 35 day disk precession period, but not consistent with the 1.7 day orbital period.

The current observations indicate that we do not
directly see the soft x-ray pulse at any time during our observations. In contrast, the EUVE observations of Vrtilek et al. 1994 had bright phases during which pulsations were detected and during which the spectrum matched that of the soft x-ray pulse. The soft x-ray pulse may come from reprocessing at the inner edge of the accretion disk. In that case this inner edge must be hidden from view during our observation (end of short high state), yet visible during much of the main high state. This is consistent with ideas for explaining the evolution of the hard x-ray pulse (Deeter et al. 1998). The faint part of the EUVE lightcurve during main high shows modulation which may have the same origin as proposed here for end of short high. However the bright phases (see Fig.1 of Vrtilek et al. 1994) prevent one from having a good view of this orbital modulation.

Further observations to determine the EUV light curve at other 35 day phases will be highly valuable in testing the tilted disk model for Her X-1, and will provide an opportunity to do detailed modelling of the accretion disk geometry based on the observed shadowing.

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Fig. 1.— Observed EUVE DS lightcurve of Her X-1.
Fig. 2.— X-ray reflection lightcurve (solid line) for $\eta=0.5$ with the Gaussian shadow model (see text). The EUVE DS data points are shown by the small circles.
