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Constraining the shape of the accretion disk in Her X-1: II. EUV observations

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Abstract. The bright X-ray binary pulsar Hercules X-1 has a 35-day cycle in hard x-ray intensity: "Main High state – low state – Short High state – low state". This is caused by a tilted-twisted precessing accretion disk. What is less well known is that during low states the soft x-rays and extreme ultraviolet radiation are modulated at the orbital period . This radiation is mainly due to reflection off of the companion star HZ Her. Here a model of the accretion disk and the companion star is constructed to model the observations of Her X-1 by the Extreme Ultraviolet Explorer (EUVE). It is found that there is also an EUV emission component from the accretion disk. The accretion disk shape is constrained from the shadowing effect on HZ Her.

1 Introduction

Hercules X-1 is an 1.7 day orbital period X-ray binary pulsar exhibiting many phenomena of great interest. A companion paper (Leahy (2001)) gives a brief review of properties of Her X-1. The properties of the 35-day cycle (Scott, Leahy (1999), Shakura et al. (1998)) are of particular interest here as they are caused by a precessing, tilted, counter-rotating accretion disk. The disk is responsible for the evolution of the pulse profile (Scott, Leahy, Wilson (2000)) and the 35-day x-ray light curve (Leahy (2001)), but is also responsible for shadowing and occulting the x-ray illumination of the companion star, HZ Her (Leahy, Marshall, Scott (2000), Leahy, Marshall (1999)). Her X-1 has been observed a number of times in the EUV energy range (Leahy, Marshall, Scott (2000); Leahy, Marshall (1999); Rochester et al. (1994); Vrtilek et al. (1994)).

Here the topic of interest is learning about the accretion disk by studying the EUV emission. The EUV emission is of particular interest since it is dominated by the reflection of emission off of the companion, but is strongly modulated by the accretion disk shadowing and occultation (Leahy, Marshall, Scott (2000)). EUVE observations of Her X-1 from a number of previous observing campaigns are modelled with the same model to help understand the geometry of the accretion disk.

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2 Observations

Background subtracted light curves were obtained for the EUVE/DS observations of Her X-1 from the 1993, 1996 and 1997 observing campaigns. Figures 2, 3, 4 and 5 below show the data along with model curves which are described below.

3 The emission model

The basic model is described in Leahy, Marshall, Scott (2000), although only results for the case of orbital phase 0.5 (near face on) were presented. Her X-1 is taken to be an isotropic source of x-rays which illuminates the face of HZ Her except for regions shadowed by the accretion disk. The twisted tilted disk model is well known and is illustrated in e.g. Leahy, Marshall, Scott (2000). Fig. 1 here shows the resulting shadow pattern that the disk casts on the sky with the neutron star as a point source at the center of the disk. The companion star HZ Her has an angular radius of $25°$ viewed from the neutron star. It moves through this disk shadow as it orbits Her X-1 with the 1.7 day period, and as the shadow precesses in the opposite direction with the 35-day period. The surface of HZ Her is assumed to be coincident with the critical Roche lobe for the system. Orbital parameters were taken from Leahy, Scott (1998). The observer is taken to be at a co-inclination of $5°$. The Compton-reflected emission from the unshadowed portion of HZ Her which travels in the direction of the observer is calculated as a function of time, taking into account the correct disk shadowing and the correct orbital geometry of HZ Her at each instant of time.

The model here is improved from that in Leahy, Marshall, Scott (2000) in the following ways: i) the model has updated accretion disk twist and tilt parameters (from Scott, Leahy,

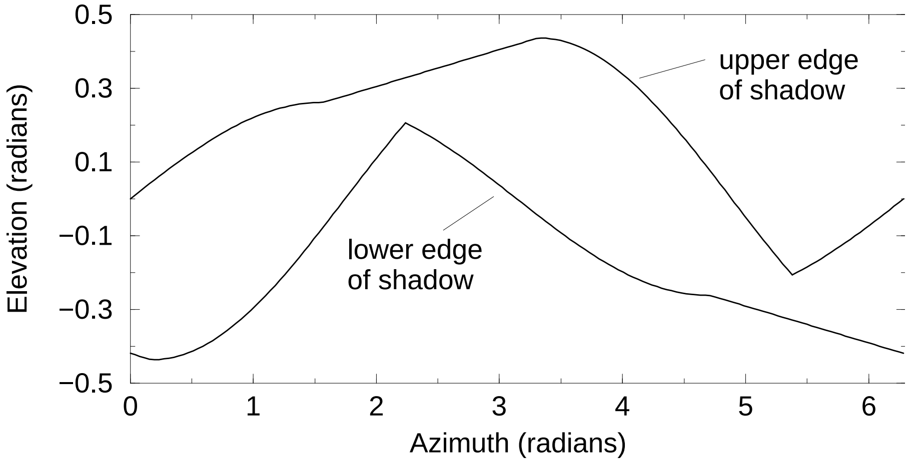

Fig. 1. The shadow cast on the celestial sphere surrounding Her X-1 by the twisted-tilted accretion disk.

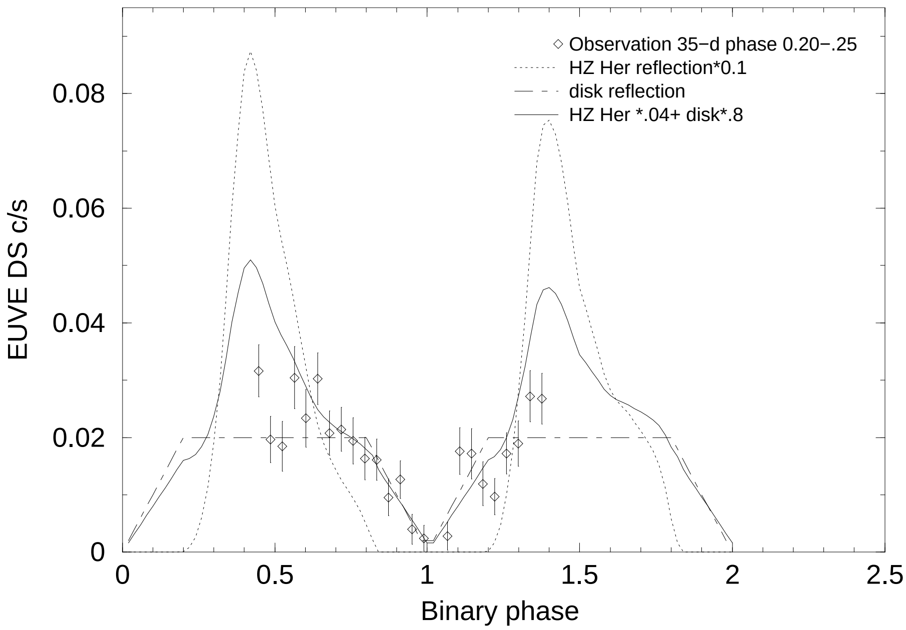

Fig. 2. EUV light curve of Her X-1 for 35-day phase 0.2-0.3 compared to the models (see text).

Wilson (2000)); ii) the model is used to calculate full light curves vs. time and compared to the data at several 35-day phases; iii) an accretion disk emission component is added to the model.

The HZ Her reflection component of emission is shown in Figs. 2, 3, 4 and 5 as the dotted curves (with a single arbitrary normalization constant). It is clear that the observed emission has an extra component above that of the model between orbital phases of approximately 0.7 to 0.3. The extra component is best explained as due to disk emission. The disk emission is likely to be dominated by Compton reflection of neutron star/ inner disk emission reflected off of the surface of the disk. The disk emission model here is a simplified model. The disk precesses smoothly with a 35-day period, so the uneclipsed emission is taken to be constant for any single 1.7 day orbit. The emission is taken as variable from orbit to orbit to allow for the different viewing of the illuminated disk region, which will be occulted differently by outer regions of the twisted tilted disk as a function of 35-day phase. The eclipse ingress and egress emission from the disk is taken to be a linear function, which is appropriate for a uniform brightness disk eclipsed by a stellar limb which is much more extended than the disk in the direction perpendicular to the orbital plane. The resulting disk emission component is shown by the dot-dash lines in Figs. 2, 3, 4 and 5. The solid line in the figures is the total emission model which consists of a constant amount of the variable reflection model plus a variable amount of the disk emission model, as indicated by the figure captions.

4 Results and Discussion

The fits to the EUVE/DS lightcurves of Her X-1 are quite good, considering that no optimization of any of the model

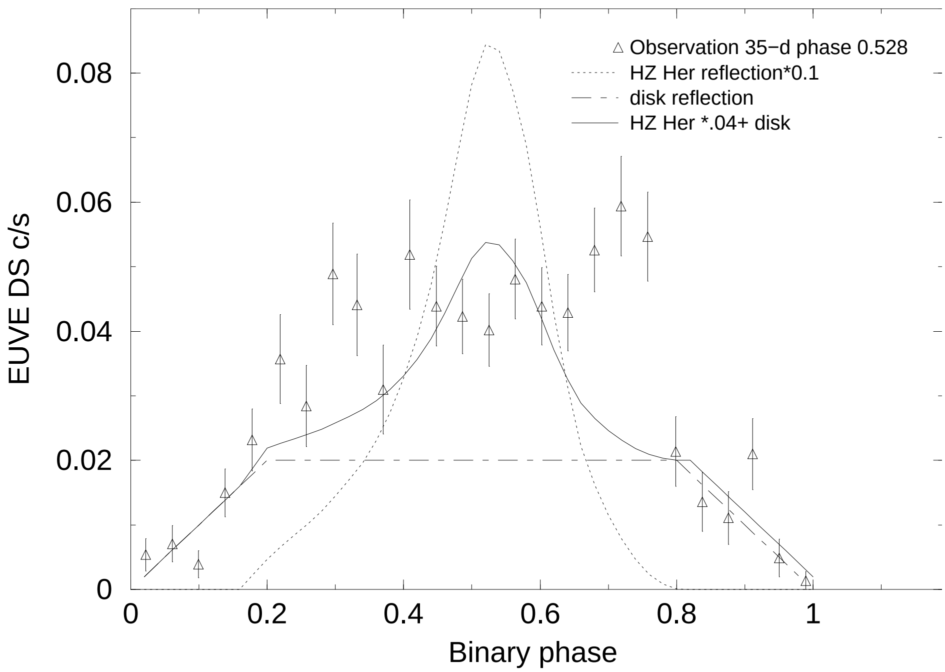

Fig. 3. EUV light curve of Her X-1 for 35-day phase 0.528 compared to the models (see text).

parameters, except normalization, was done. The normalization of the reflection component from HZ Her is kept constant, which basically is in agreement with a constant flux from the pulsar on HZ Her except for shadowing variations over 35-day phase. The disk emission contribution varies significantly between the various datasets, with relative intensities of 0.8, 1, 0.5 and 0.5 for 35-day phases 0.25, 0.53, 0.8 and 0.84, resp. The disk emission component is the major emission component for orbital phases 0.0-0.2 and 0.8-1.0. But it also contributes a significant amount (≃20-50%) at other orbital phases. Of the fits to the different 35-day phases, the one for 35-day phase 0.528 is worst. The model does not give the bright emission at binary phase 0.7-0.8. However this data is from the orbit immediately prior to short-high turn-on (Leahy, Marshall, Scott (2000)), so may be contaminated by another source of emission which is not in the model, such as the inner edge of the accretion disk. The fits for 35-day phases 0.795 and 0.844 have deeper dips at orbital phase 0.5 than the model. However this is probably due to too large of an accretion disk component in the model, which can be removed by adjusting disk shadowing and disk emission parameters. It is also noted that there are sharp dips in the light curve (e.g. at orbital phase 0.73 in Fig. 4 and orbital phase 0.3 in Fig. 5) which may be due to the accretion stream, and which are not included in the current model.

Work in progress includes: varying the disk tilt and twist parameters as fit parameters, but within the range allowed by x-ray light curve observations; updating the constraints on the disk twist and tilt from x-ray light curve studies (see Leahy (2001)); allowing for the effect of disk occultation of the surface of HZ Her; and calculating a more realistic disk emission model. The calculation of disk occultation has already been incorporated, but variations of disk parameters on disk occultation have not been studied. For the nomimal disk parameters, disk occultation turns out to have negligible effects on the calculated light curves. This is due to the geometry: when the disk crosses the line of sight of observer to HZ Her, most of the occultation is of areas of HZ Her which are already in the shadow of the disk. Another limitation is the quality of the EUV/DS observations: improvement in disk parameters can be achieved by fitting the HZ Her reflection component, but the error bars are large enough for ingress and egress from eclipse, that it will be difficult to put strong constraints on the disk emission model.

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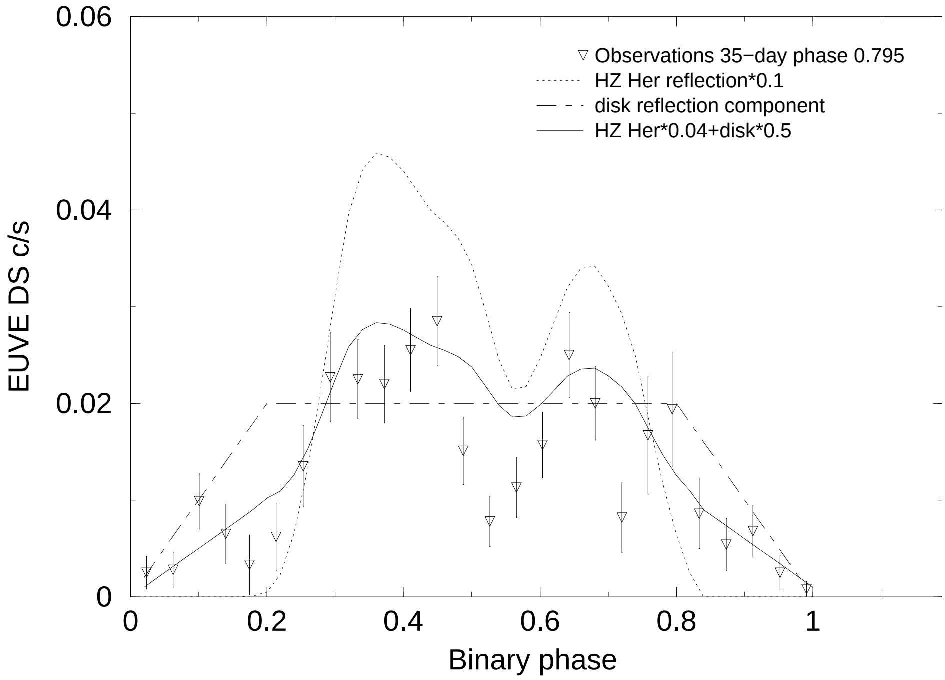

Fig. 4. EUV light curve of Her X-1 for 35-day phase 0.795 compared to the models (see text).

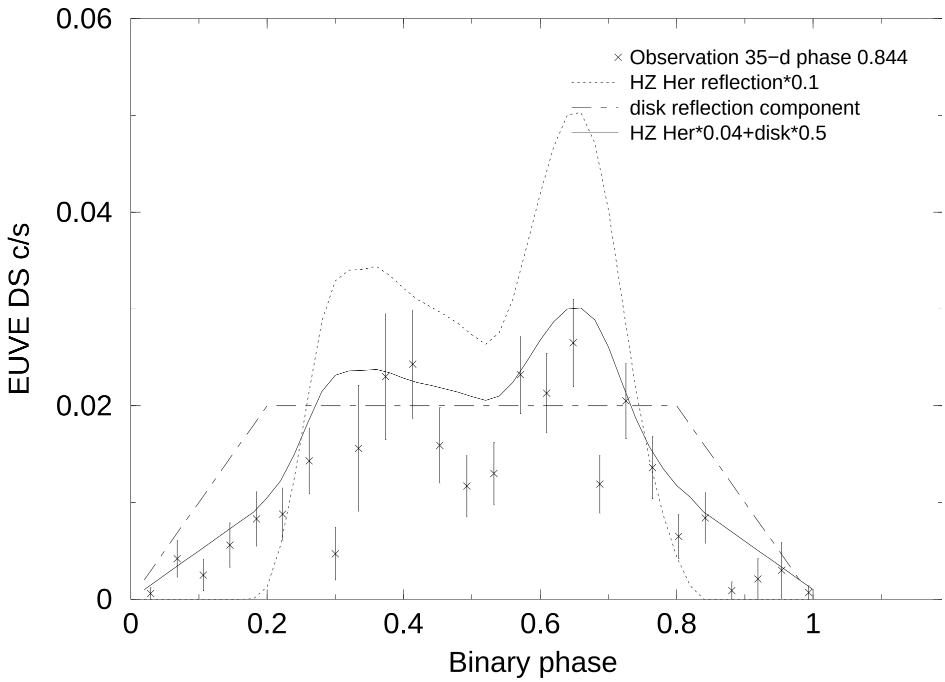

Fig. 5. EUV light curve of Her X-1 for 35-day phase 0.844 compared to the models (see text).