

Constraining the shape of the accretion disk in Her X-1: I. X-ray observations

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Abstract. Hercules X-1 is one of the brightest, and most studied, of the persistant X-ray binary pulsars. Her X-1 shows a 35-day cycle in x-ray intensity: "Main High state – low state – Short High state – low state". This is caused by a tilted-twisted precessing accretion disk (e.g. Scott, Leahy, Wilson (2000)). The x-ray emission is primarily from the neutron star accretion column, occulted by the disk to varying degrees over the 35-day cycle. The 35-day cycle in Hercules X-1 has now been well determined by the RXTE/ASM in x-rays (Scott, Leahy (1999)). A model of the accretion disk is constructed and is applied to fit these observations. Perhaps surprisingly, modelling of the shape of the 35-day light curve has not been previously carried out. The results give constraints on the the accretion disk overall geometry and the atmosphere of the disk where it crosses the line-of-sight to the observer.

1 Introduction

Hercules X-1 is one of the brightest, and most studied, of the persistant X-ray binary pulsars. The system displays a great variety of phenomena at many timescales, including pulsations at 1.24 seconds, 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 long low states. The properties of the 35-day cycle are reviewed by Scott, Leahy (1999). Scott, Leahy (1999) and Shakura et al. (1998) present analyses of RXTE/ASM observations of the 35-day cycle. The X-ray pulse profile evolution is discussed in Scott, Leahy, Wilson (2000). Recent X-ray spectra of Her X-1 are given by Oosterbroek et al. (1998) and Dal Fiume et al. (1998) (from BeppoSAX). 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). The properties of the 35-day cycle 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)), the 35-day x-ray light curve, and for shadowing and occulting the x-ray illumination of the companion star HZ Her (Leahy, Marshall, Scott (2000)). New results of modelling the latter effect are presented in Leahy (2001).

Here we report the results of modelling of 35-day light curve of Her X-1. The light curve is compiled from RXTE/ASM observations giving full 35-day coverage. Main high state covers 35-day phase 0-0.31 and short high state covers phase 0.57-0.79, with phase 0 defined by main high turn-on. The basic model is a tilted, twisted accretion disk with an atmosphere. The atmosphere is responsible for the time-dependence of the turn-on and turn-off of both main-high and short-high states of the 35-day cycle and the geometry of the disk is responsible for the timings of turn-on's and turn-off's.

2 Data

The 35-day cycle of Her X-1 starts with a sharp turn-on to main high state. The turn-on's occur preferentially at orbital phases 0.2 and 0.7. The RXTE/ASM has monitored Her X-1 since \sim MJD50144, however Her X-1 went into an anomalous low state in 1999, thus only the data prior to that is of primary interest here, which is basically the same data as considered by Scott, Leahy (1999). The average light curves for 35-day cycles with 0.2 turn-on's and for 35-day cycles with 0.7 turn-on's were constructed by Scott, Leahy (1999). The phase of turn-on for each individual 35-day cycle was determined by using a combination of RXTE/ASM and BATSE observations. Here one of the main goals is in fitting the shape of turn-on and turn-off. Since the 0.2 turn-on 35-day cycles have the turn-on interrupted by eclipse, only the 0.7 turn-on 35-day cycles are considered here.

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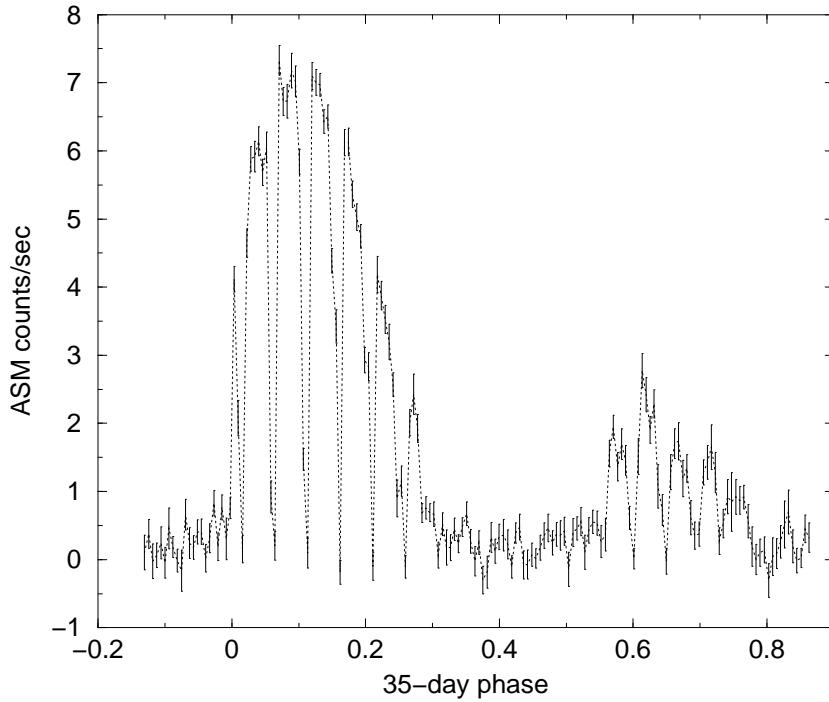


Fig. 1. RXTE/ASM average 35-day lightcurve of Her X-1 for 0.7 turn-on's.

Fig. 1 shows the average 35-day cycle for 0.7 turn-on's. The shape of main high and short high turn-on and turn-off are well defined. Also apparent are the eclipses every 1.7 day orbital period and the pre-eclipse dips. The time-bin size was optimized in producing this lightcurve in order to put all of the eclipse data (orbital phase 0.93 to 0.07) into single time bins, without any eclipse data going into non-eclipse time bins. For the modelling here the eclipse data is excluded as well as identifiable dips.

3 The accretion disk model

A twisted tilted accretion disk is required to be present in Her X-1 to explain both the 35-day light curve and the 35-day pulse evolution (Scott, Leahy, Wilson (2000)). The disk model is illustrated in Fig. 2 (see also Leahy, Marshall, Scott (2000)) here for 35-day phase 0.06, with the observer at 5° above the orbital plane. Thus the neutron star and central part of the disk are fully visible. At other 35-day phases the disk is at a different rotation phase about the orbital axis (which is a vertical line through the center of the disk in Fig. 2). The outer and/or inner edges of the disk will progressively cover and uncover the line of sight to the neutron star as 35-day phase progresses. This covering and uncovering is what is modelled here.

The general idea is that the disk consists of a series of circular rings each with its own tilt and line-of-nodes with respect to the orbital plane. The tilt angle and the angle of line-of-nodes is a continuous function of radius in order to maintain a continuous disk surface. The functions for both are assumed to be monotonic, and for the diagram in figure 2

they are taken as linear functions of radius.

For the modeling here, the tilt angle and the angle of line-of-nodes functions are not specified. What is required is that these functions are smooth enough that the covering and uncovering of the line-of-sight to the neutron star is done by the outer and inner edges of the disk and not some intermediate region. Fig. 3 illustrates the geometry of the line of sight to the neutron star as a function of 35-day phase, for an assumed observer co-inclination of 5° . At any time (35-day phase) the line-of-sight is normal to the figure and directed to the appropriate 35-day phase along the horizontal line at 5° . The disk inner and outer edge rings (and several intermediate radius rings) are illustrated by the wavy lines. Note that the vertical scale (25°) is amplified with respect to the horizontal scale (2 cycles or 720°). When the neutron star emerges from behind the disk outer edge, the x-rays brighten and when the neutron star passes behind the disk inner edge the x-rays become faint. The extents of the atmospheres of the disk for outer and inner edges determines how rapidly the x-rays brighten and dim, resp. For the short high state the line of sight to the neutron star is never clear of the inner and outer disk atmospheres, so the short high reaches a maximum brightness less than for main high.

4 Results and Discussion

The simplest model has the inner and outer disk atmospheres as exponential each with a scaleheight parameter. Other parameters are the location in 35-day phase of the crossings of the line-of-sight by the outer and inner edges of the disk. In addition the tilt angle of the local disk plane with respect

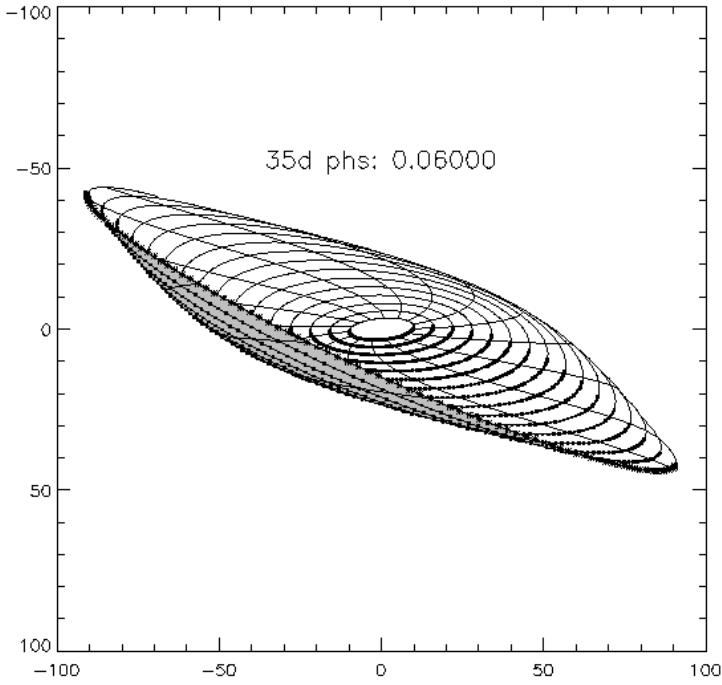


Fig. 2. Twisted tilted disk model for Her X-1.

to the line of sight and the tilt angle of the edge of the disk with respect to the orbital plane are parameters, but these can be incorporated by defining an effective scale height so are not additional free parameters of the model. A least squares method was used to obtain the best fit parameters. The resulting chisquared was 425 for 117 data points. Fig. 4 shows the RXTE/ASM 35-day lightcurve, with eclipses and dips removed, and this model (labelled "single layer"). The single layer model provides a good reproduction of the general shape of the lightcurve, although it is not acceptable on a statistical basis.

The next model is a double layer model. In this case the inner edge of the disk still has a single exponential atmosphere, but the outer edge is given a second more extended atmosphere on top of the first. The basic idea is that the outer disk has a cold thin atmosphere which is responsible for the sharp turn-on of main high, and additionally a more extended, likely hot, atmosphere which is responsible for the gradual increase of main high after turn-on. This model is a much better fit, than the single layer model, and is shown in Fig. 4 by the dotted line.

Work in progress includes: modeling the neutron star emission region by a point source plus an extended scattering region, and specifying the twist and tilt functions for the disk so that the timings of the inner and outer disk crossings can be used to specify the twist and tilt of the inner and outer disk rings. The 35-day phase interval between outer disk crossings is $\simeq 0.574$ and that between inner disk crossings is $\simeq 0.39$ (values vary depending on the disk atmosphere model). This implies that the inner disk is significantly less tilted than the outer disk (which can be inferred from Fig.

3 since a smaller tilt implies a larger difference from 0.5 in phase between disk crossings). Work in progress also includes combining the current constraints with those from modelling the EUV light curve (Leahy (2001)). This will result in giving the system inclination and the absolute values of the tilts in addition to the relative values which come from the current work.

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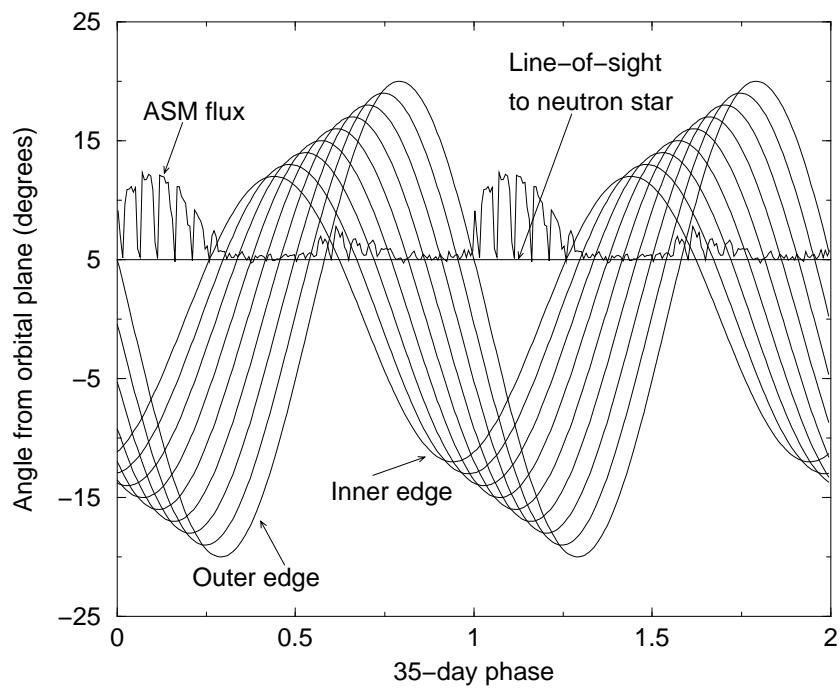


Fig. 3. Disk occultation of line-of-sight to the neutron star compared with RXTE/ASM lightcurve.

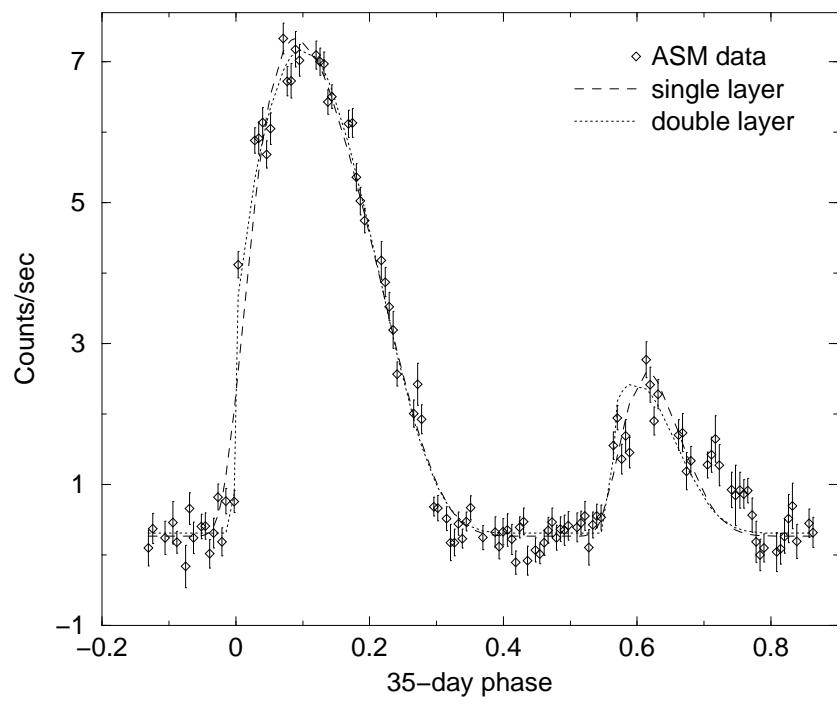


Fig. 4. Two disk occultation models compared to the RXTE/ASM 35-day cycle average light curve.