Modeling the Pulse Shape of Hercules X-1: Constraints on the Size and Shape of the Accretion Column

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Abstract

Hercules X-1 is the first x-ray pulsar to have observationally determined constraints on the structure of the emission region. The 35-day cycle of pulse shape changes during the 35-day flux cycle ”Main High - Low - Short High - Low” is caused by varying obscuration of the emission region by the accretion disk [9]. The pulse shape changes require the inner edge of the disk to be fairly sharp and also require a ”reversed fan beam” configuration for the beam pattern from the accretion column. Using a newly developed code for modeling accretion column emission, including gravitational light-bending effects, the observed pulse shape of Her X-1 is modeled here.

1. Introduction

Her X-1/HZ Her is an unusual accretion-powered pulsar system exhibiting a great wealth of phenomena. This eclipsing system contains a 1.24 second period pulsar in a 1.7 day circular orbit with its optical companion HZ Her. In addition, the system displays a longer 35-day cycle that was first discovered as a repeating pattern of High and Low X-ray flux states. A Main High and Short High state, lasting about ten and five days each respectively, occur once per 35-day cycle and are separated by ten day long Low states. X-ray pulsations are visible during the High states but cease during the Low states. An updated set of binary parameters is given by [2]. of Her X-1 are presented by [1],[12]. Optical signatures of reprocessing on the companion and accretion disk are discussed by [10]. The properties of the 35-day cycle are of particular interest here as they are caused by a counter-precessing, tilted, twisted accretion disk. These are reviewed by [8]. The disk is responsible for the evolution of the pulse profile [9], for reprocessing much of the emission during Short High state [4], for the 35-day x-ray light curve [6], and for shadowing the x-ray illumination of the companion star HZ Her [3],[5]. The X-ray pulse profile evolution is discussed in [9]. The main conclusion, derived from the change in pulse shape due to occultation by the inner disk edge, was that the emission region was only consistent with a pencil beam from the near pole and a fan beam from the far pole (called the ”reversed fan beam”). The

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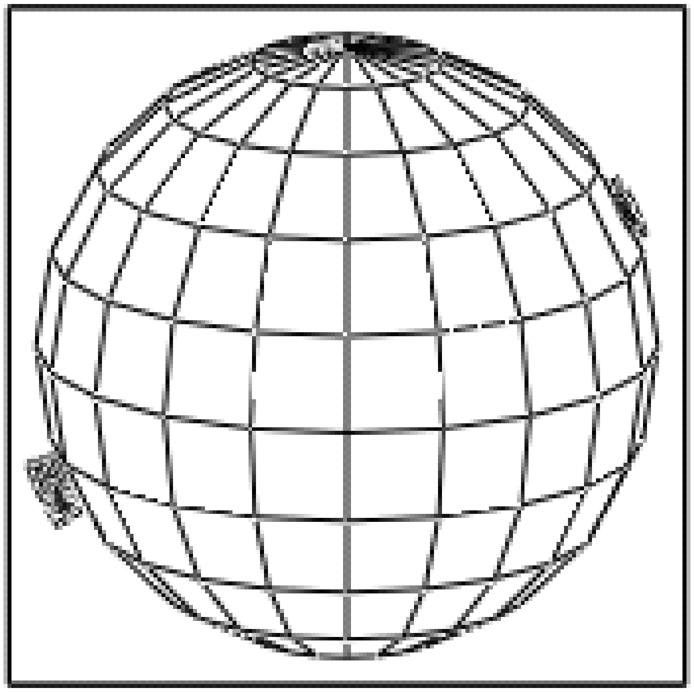

Fig. 1. Flat space image of the emission region on the neutron star.

purpose of this paper is to discuss results of calculating a model of the emission region and comparing it to the observed pulse shape.

2. The emission region model

The emission region is modeled here with the goal to explain the observed pulse shape from Her X-1 when it is seen unobscured by the disk, during the peak of Main High state. The observed pulse profiles in the two energy bands 1.0-4.6 keV and 9.3-14 keV at 35-day phase 0.05 are given by the top curves in the left and right panels of Fig. 6 of [9]. The 1.0-4.6 keV pulse profile consists of two peaks centered on phase 0.9 and 1.2 with the 0.9 phase peak larger. The 9.3-14 keV pulse profile has an additional (brightest) peak at phase 1.0. To produce this pulse profile one needs a pencil beam which is hard (in energy) and appears mainly above 5 keV and a fan beam which is broad (in energy). Here the asymmetry of the peaks at phase 0.9 and 1.2 is ignored and the reproduction of the overall properties (heights, widths and positions) is the goal of the models. The emission region is taken to be axisymmetric. It consists of an accretion column emitting from the top, to produce a pencil beam, and emitting from its sides, to produce

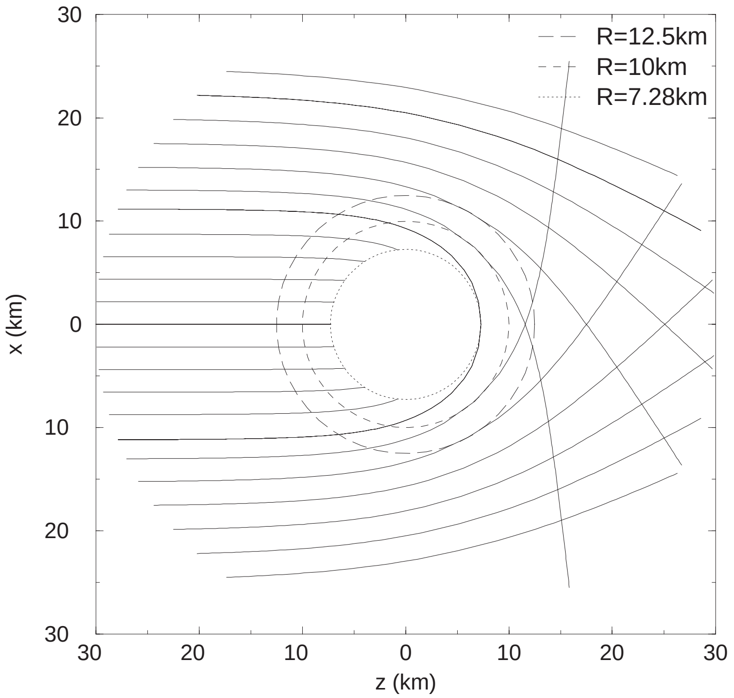

Fig. 2. Light paths around a neutron star of mass 1.4 M_{sun} for parallel incoming rays.

a fan beam. Fig. 1 shows a flat-space image of the neutron star and the two accretion columns at opposite magnetic poles A crucial effect on the observed pulse shape is the gravitational bending of light rays in their propagation from the accretion column to the observer. This is illustrated in Fig. 2 here. The observer at infinity sees more than the front half of the neutron star: only the shadow region, traced by lines tangent to the neutron star surface, is not seen. Different neutron star models give, for a 1.4 M_{sun} mass, radii of 10 to 14 km [1]. The 7.28km radius is shown to illustrate the radius for which the shadow region disappears. Various radii were tested, and good results were obtained for 13.65 km radius, so these are shown here. The observers line of sight to the emission region depends on the inclination of rotation axis to observer and of the magnetic axis to the rotation axis. The view in Fig. 1 is for the case of the calculated models shown in Fig. 3, with the rotation axis the pole of the coordinate grid on the neutron star surface. The method of calculation is described in [7]. The calculated pulse profiles in Fig. 3 are all for the same emission region parameters, they differ only in the ratio of surface brightness of the column top to the column side. The observed pulse in Fig. 3 is for 7-13 keV and has lower phase resolution than the profiles in Fig. 6 of [9]. Model 2 is most like the 9.3-14 keV profile and Model 4 is most like the 1.0-4.6 keV profile.

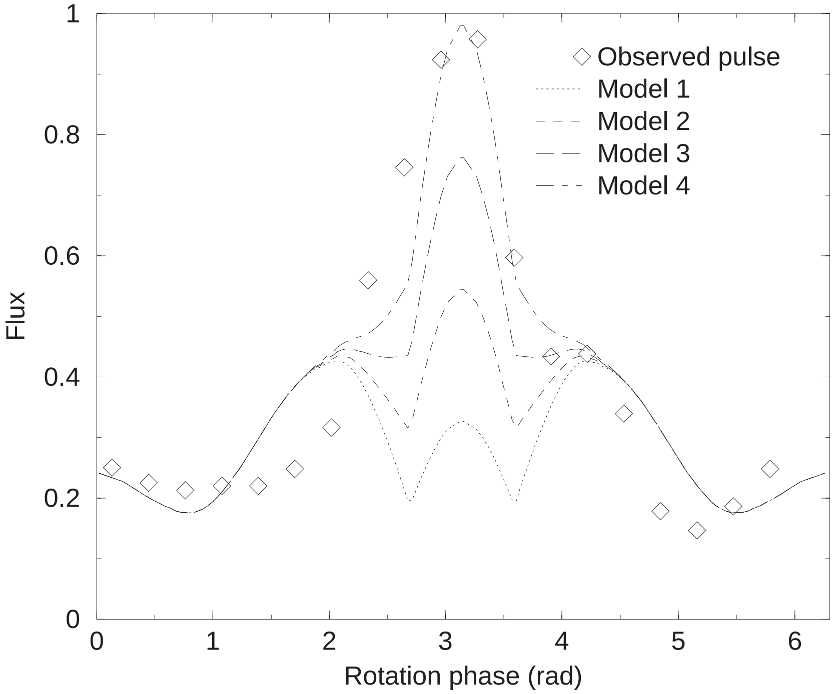

Fig. 3. Observed and model pulse shape for Her X-1 (see text for Models).

3. Summary and Conclusion

The emission model presented here can yield the main features of the observed Her X-1 pulse profile and is consistent with the 35-day pulse evolution [9]. Future steps involve extending the calculation to asymmetric emission regions and studying the energy dependence of the profile. There is great promise to highly constrain the size and shape of the emission region by these methods.

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