High-mass X-ray Binaries: Illuminating the Passage from Massive Binaries to Merging Compact Objects
Proceedings IAU Symposium No. 346, 2019
L. M. Oskinova, E. Bozzo, T. Bulik & D. Gies, eds.

doi:10.1017/S174392131800772X

Analysis of spectrum variations in Hercules X-1

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Abstract. Hercules X-1 (Her X-1) was observed extensively by the Rossi X-ray Timing Explorer (RXTE) over its 17 year lifetime. Here, the archival RXTE/PCA observations of Her X-1 are analyzed with emphasis on the 35-day cycle dependence. Spectral fits are carried out and the 35-day phase dependences are characterized. The regular behaviours of the changes are interpreted in terms of the precessing accretion disk. We find that the most important variation is caused by the changing illumination of the inner edge of the disk, but other variations with different causes are also seen.

Keywords. X-rays: binaries, accretion, accretion disks, stars: neutron

1. Introduction

HZ Herculis/Hercules X-1, also known as HZ Her/Her X-1, is one of the brightest low-mass X-ray binary systems, and among the most studied, e.g. Gerend & Boynton (1976), Crosa & Boynton (1980), Leahy (2002), Leahy (2003), Ji *et al.* (2009) and Klochkov *et al.* (2009). Leahy & Abdallah (2014) showed the system is located at a distance of ≃6.5 kpc from Earth. It has an A7 type (which varies between late A and early B with the orbital phase) main sequence stellar companion, HZ Her, and a neutron star of approximate masses 2.2 $M_\odot$ and 1.5 $M_\odot$, respectively (Reynolds *et al.* 1997). The system is characterized by a great variety of phenomena, including 1.24 s pulsations, 1.7-day orbital period eclipses, and a 35-day X-ray intensity cycle, e.g. (Scott *et al.* 2000), (Scott & Leahy 1999) and (Boynton *et al.* 1980). Her X-1 is one of the few systems to have low interstellar absorption, which makes it feasible for observation and study at optical, UV and X-ray wavelengths.

The 35-day flux and pulse profile cycles, unique features among the known accretion-powered pulsars, are produced by the counter-precessing, tilted and twisted neutron star accretion disk. This was demonstrated in studies including those of Leahy (2004a), Leahy (2004b), Leahy (2003), Leahy (2002), Scott *et al.* (2000), Scott & Leahy (1999), Wijers & Pringle (1999), Maloney & Begelman (1997), Maloney *et al.* (1996), Larwood *et al.* (1996) and Schandl & Meyer (1994).

The 35-day cycle consists of a Main High (MH) state, a Short High (SH) state and fainter Low States (LS) which separate the MH and SH states. Scott & Leahy (1999) showed that the Main High (MH) state that covers 35-day phases 0 to 0.31, the Short High (SH) state covers phases 0.57-0.79.

The extensive RXTE/PCA archival observations of Her X-1 have been analyzed, in part, previously by our group. Leahy & Igna (2011) analyzed the full set of archival observations to produce light curves in different energy bands folded on the orbital and 35-day cycles, providing orbital and 35-day light curves superior to any produced previously. Dips were shown to occur at all orbital phases: the frequency of dips increases with increasing orbital phase and the fraction of time in dips is higher for Short High state

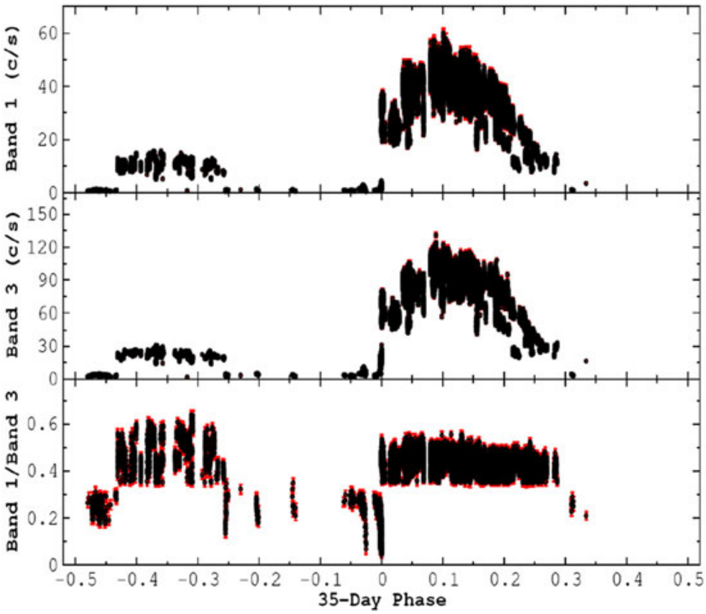

Figure 1. The 2-4 keV (top panel) and 9-20 keV (middle panel) light curves vs. 35-day phase for Hercules X-1, from all RXTE/PCA archival observations but with dips during Main High state (35-day phase 0 to 0.3) and Short High state (35-day phase 0.57 to 0.74) removed. Bottom panel: 2- 4 keV/7-20 keV softness ratio vs 35-day phase.

(average ∼50%) than for Main High state (average ∼15%) at all orbital phases. Igna & Leahy (2011) analyzed the extensive set of dips from Her X-1 and studied their properties, showing dips occur at preferential regions in the 35-day phase vs. orbital phase diagram. Igna & Leahy (2012) used the accretion stream and its impact with the accretion disk to explain the orbital and 35-day phase timing of the dips.

Leahy & Abdallah (2014) used RXTE/PCA timing of eclipse ingresses and egresses to determine the stellar radius of the companion star HZ Her, and combined it with archival spectrophotometry of HZ Her to determine the distance, the companion's stellar properties and its evolutionary state. Abdallah & Leahy (2015) analyzed RXTE spectra during Short High state and showed that a significant component of the flux and spectrum is best explained by X-ray reflection off the face of HZ Her.

Leahy (2015) analyzed all RXTE/PCA eclipse light curves during Main High state to detect a large scale (few times 10^{11} cm) electron-scattering corona in the binary system, and determine its density profile, assuming spherical symmetry. The corona could be a hot wind outflow from the system, or fairly static and supported by thermal pressure. The latter seems more likely as the heating rate by the X-ray flux from the neutron star is adequate to thermally support the corona. In addition, the mass-loss rate for a wind with escape velocity is much higher than the accretion rate onto the neutron star.

2. Summary of new results

The new analysis of the RXTE/PCA observations is systematic spectral fitting of Her X-1 over the 35-day cycle with a single spectral model. Fig. 1 shows the 2-4 keV light curve constructed from the RXTE/PCA data. The rise and fall of Main High and Short High states are clearly seen. To remove the effects of eclipses we omitted orbital phases from 0.93 to 0.07. Next dips were removed by selecting data with 2-4 keV/ 9-20 keV softness ratio characteristic of dips. Plots of individual Main High states (all ∼15 years

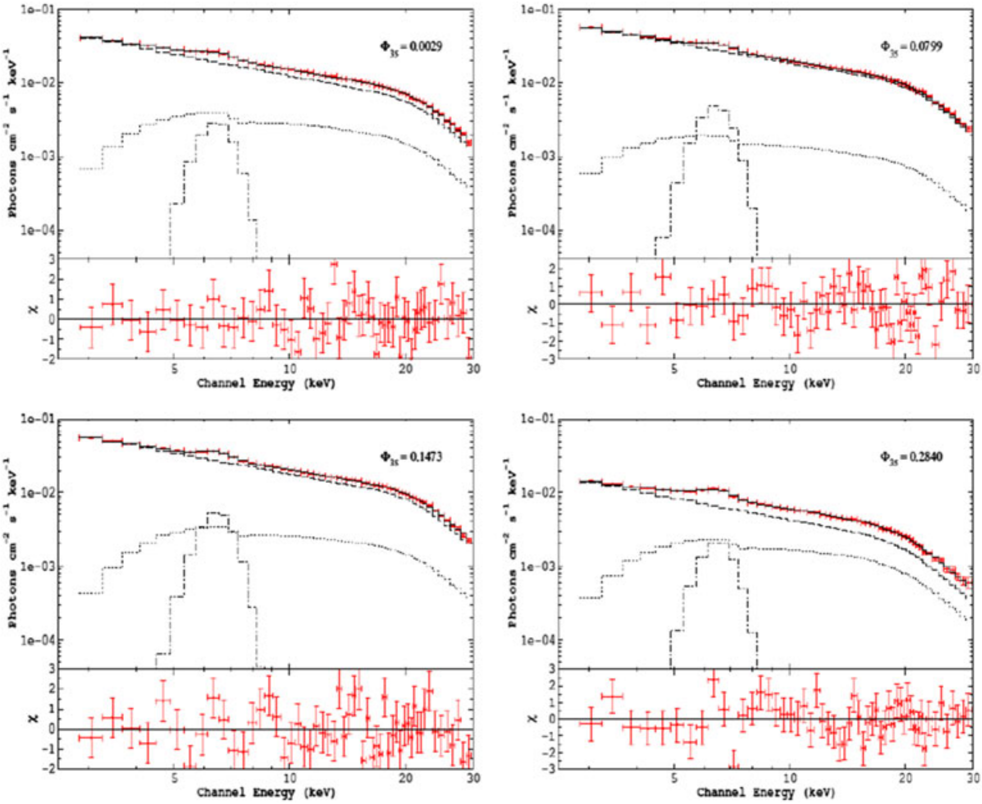

Figure 2. RXTE/PCA spectra of Hercules X-1, at the 4 different 35-day phases during Main High state. The top part of each panel shows the observed spectrum (histogram), and 3 model components (dashed line- unabsorbed continuum component, dotted line- absorbed continuum component, dot-dashed line: Fe line). The lower part of each panel shows the residuals between the model and the observed spectrum.

of RXTE/PCA data) demonstrates that the range of count rates seen in Fig. 2 is due to cycle-to-cycle variation rather than variation within a single cycle.

The spectral model that consistently describes all Main High state data (less eclipse and dip data) is the power-law with exponential cutoff model (powerlaw/highecut in XSPEC). This was multiplied by the partial covering absorption model to yield 2 components: an absorbed and an unabsorbed component. Finally, to describe the data adequately, we added a gaussian line for the well-known fluorescent Fe line. Spectra were extracted for time intervals of 256 s which had constant softness ratio, resulting in several hundred spectra covering Main High state. The spectral parameters and their errors were determined for each spectrum using XSPEC and the XSPEC error command.

Systematic variations of spectral parameters are found during the Main High state that depend on 35-day phase. The main dependencies are as follows. (i) Photon index is constant for phases 0-0.05, then decreases for phases 0.05 to 0.2, and is constant or rising for 0.2-0.3 (end of Main High). (ii) Cutoff energy is constant for phases 0-0.12, then decreases for phases 0.12 to 0.3. (iii) Iron line energy rises for phases 0-0.15, then decreases for phases 0.15 to 0.3.

The interpretation of the spectral variations is based on the disc model for Her X-1 constructed by Leahy (2002), the pulse evolution model of Scott *et al.* (2000) and the pulse beam model of Leahy (2004c). We can understand the variations of the continuum spectrum of Her X-1 during the MH-state as a superposition of three components: (i) the spectrum of the direct emission from the pulsar (fan and pencil beams); (ii) the spectrum of the reflected X-ray radiation off of the irradiated inner disc ring; and (iii) the spectrum of the magnetospheric/coronal emission which is primarily caused by electron-scattering of components (i) and (ii). Significant variations in photon index and cutoff energy are expected if there is a significant contribution of X-rays reflected off the inner disc ring. The shape of the observed variations can be reproduced by including both direct and reflected spectrum components.

The variation of the iron line intensity is nearly sinusoidal with orbital phase during Main High state. This can be understood as follows. The likely sites of the iron K emission line in Her X-1 during MH-state are: (i) reprocessing of the direct emission in the hot magnetospheric/ coronal gas; (ii) reprocessing of the direct emission in reflection by the far illuminated face of the inner disc ring; and (iii) reprocessing of direct emission and/or reflected emission by the illuminated near side of the inner disc ring in transmission. Based on the observed variation, which peaks when the inner disc ring is most visible, the iron emission is dominated by reflection off the inner disc.

3. Conclusion

The RXTE/PCA archival observations of Her X-1 are a rich record of the behaviour of this complex system. The current analysis supports the precessing disk model for the 35-day cycle of Her X-1 and the detailed picture of the twisted tilted disc that has been built up with years of studies of this fascinating system.

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https://doi.org/10.1017/S174392131800772X Published online by Cambridge University Press