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LETTER

Letter to the Editor

X-ray observations during a Her X-1 anomalous low-state

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Abstract. Results of a 1999 July 8–10 BeppoSAX observation during an anomalous low-state of Her X-1 are presented. The standard on-state power-law and blackbody continuum model is excluded at high confidence unless partial covering is included. This gives a power-law photon index of 0.63 ± 0.02 and implies that 0.28 ± 0.03 of the flux undergoes additional absorption of $(27 \pm 7) \times 10^{22}$ atom cm^{-2}. 11% of the observed 0.1–10 keV flux is from the 0.068 ± 0.015 keV blackbody. 1.237747(2) s pulses with a semi-amplitude of $2.1 \pm 0.8\%$ are detected at $>$99.5% confidence and confirmed by RXTE measurements. This implies that Her X-1 underwent substantial spin-down close to the start of the anomalous low-state. The spectral and temporal changes are similar to those recently reported from 4U 1626-67. These may result from a strongly warped disk that produces a spin-down torque. The X-ray source is then mostly viewed through the inner regions of the accretion disk. A similar mechanism could be responsible for the Her X-1 anomalous low-states. Shadowing by such an unusually warped disk could produce observable effects in the optical and UV emission from the companion star.

Key words: accretion, accretion disks – stars: individual: Her X-1 – stars: neutron – X-rays: stars

1. Introduction

Her X-1 is an eclipsing X-ray pulsar with a pulse period, $P_s = 1.24$ s and an orbital period of 1.70 days. The source usually exhibits a 35 day X-ray intensity cycle consisting of a $\sim$10 day duration main on-state and a fainter $\sim$5 day duration secondary, or short, on-state. At other 35-day phases Her X-1 is still visible as a low-level X-ray source (Jones & Forman 1976). The effects of X-ray heating on the companion are evident throughout the 35-day cycle (Boynton et al. 1973). The 35-day cycle probably results from a warped accretion disk that periodically obscures the line of sight to the neutron star while partially shadowing the companion (Gerend & Boynton 1976).

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The 35-day cycle has been evident in RXTE All-Sky Monitor (ASM) 1.5–12 keV data with the main-on state being clearly detected every 35 days for $>$3 years (e.g., Scott & Leahy 1999). An exception to this regularity occurred when the on-state expected around 1999 March 23 was not detected (Levine & Corbet 1999). Similar exceptions have been detected twice before. In 1983 June to August EXOSAT failed to detect an X-ray on-state from Her X-1 and instead a faint source, with a strength comparable to that of the low-state emission was observed over a wide range of 35-day phases (Parmar et al. 1985). Optical observations during this interval, and in 1999 April, detected the effects of strong X-ray heating on the companion star (HZ Her) indicating that it was still being irradiated by a strong X-ray source (Delgado et al. 1983; Margon et al. 1999). The anomalous low-state lasted $<$0.8 year with the 35-day cycle returning by 1984 March. Similarly, in 1993 August ASCA failed to observe the expected on-state, again detecting instead a faint X-ray source (Vrtilek et al. 1994; Mihara & Soong 1994). We report here on Target of Opportunity observations of the third known anomalous low-state of Her X-1.

2. Observations

Results from the Low-Energy Concentrator Spectrometer (LECS), the Medium-Energy Concentrator Spectrometer (MECS), the High Pressure Gas Scintillation Proportional Counter (HPGSPC) and the Phoswich Detection System (PDS) on-board BeppoSAX (Boella et al. 1997) are presented. All these instruments are coaligned and referred to as the Narrow Field Instruments, or NFI.

The region of sky containing Her X-1 was observed by BeppoSAX on 1999 July 08 08:16 UT to July 10 06:20 UT. This is just after the expected time of turn-on to the main-on state three 35-day cycles after the non-detection by Levine & Corbet (1999). Data processing was performed in the standard manner using the SAXDAS 2.0.0 analysis package. LECS and MECS data were extracted centered on the position of Her X-1 using radii of $8'$ and $4'$, respectively. The exposures in the LECS, MECS, HPGSPC, and PDS instruments are 45.5 ks, 58.9 ks, 57.2 ks, and 28.5 ks, respectively. Background subtraction for

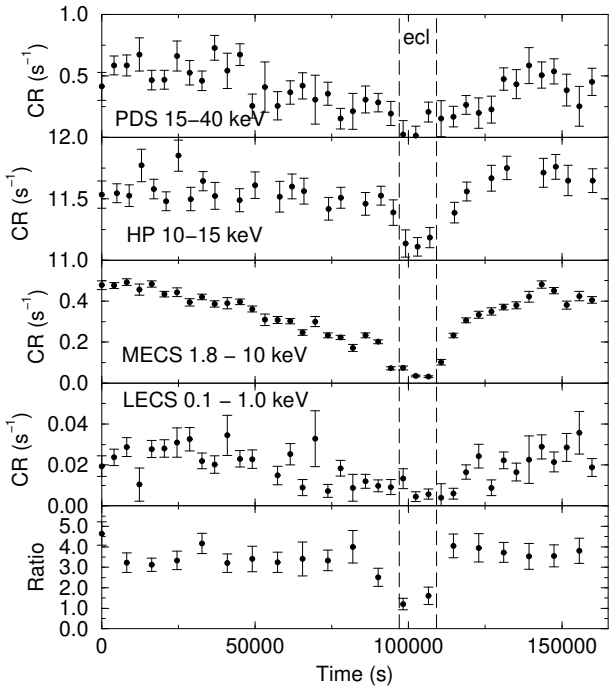

Fig. 1. Background subtracted lightcurves in 4 energy bands with a binning of 4096 s and LECS hardness ratios (4.0–10 keV/0.1–1.0 keV) with a binning of 8192 s. CR is count rate. The predicted on-state eclipse ingress and egress are indicated with dashed lines. Time is from the observation start

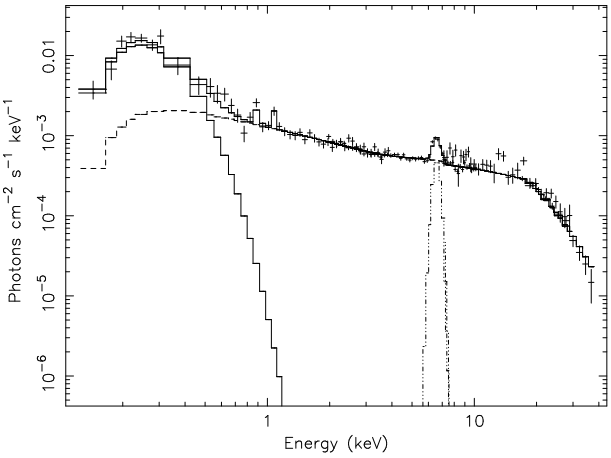

Fig. 2. The NFI Her X-1 non-eclipse spectrum. The solid line shows the unfolded spectrum obtained with a partially covering absorber (see Table 1). The contributions from the blackbody, power-law, and Fe K line are indicated separately

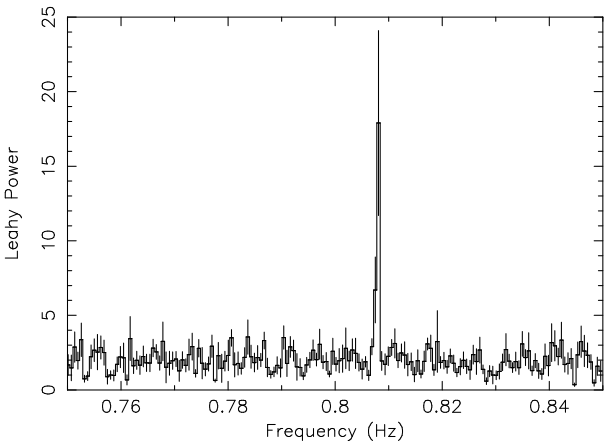

Fig. 3. The power spectrum of Her X-1 obtained with the RXTE PCA during the anomalous low-state showing the clear detection of pulsations

the imaging instruments was performed using standard files. Background subtraction for the HPGSPC was carried out using data obtained when the instrument was looking at the dark Earth and for the PDS using data obtained during intervals when the collimator was offset from the source.

3. Analysis and results

3.1. X-ray lightcurve

Background subtracted lightcurves in 4 energy ranges and the hardness ratio (LECS counts between 4.0–10 keV divided by those between 0.1–1.0 keV) are shown in Fig. 1. The eclipse ingress and egress, based on the ephemeris of Deeter et al. (1991), and assuming an on-state eclipse duration of 5.5 hr, is indicated. The lightcurves show a gradual reduction in flux before the eclipse and a more rapid increase following egress. The eclipse is not total with significant flux remaining. There is no evidence for any significant change in hardness ratio, expect when the eclipse and non-eclipse intervals are compared.

A period search in the range 1.23770–1.23776 s, predicted by extrapolating the spin-period history in Bildsten et al. (1997), was performed using the combined LECS and MECS data. The photon arrival times were converted to the solar barycenter and additionally to the center of Her X-1 mass using the ephemeris of Deeter et al. (1991). A peak at P_s=1.237747 s was found with a χ^2 of 42 for 16 degrees of freedom (dof). Taking into account the number of trials, and the other significant peaks neighboring this period, the chance-probability of detecting such a modulation is estimated to be $<0.5\%$. Given the low strength of the modulation it is impossible to estimate the uncertainty on the period by fitting the pulse arrival times. We instead estimate the uncertainty from the width of the peak to be $\sim 2 \times 10^{-6}$ s. The lightcurve folded over the best-period was fit with a sine curve to give a semi-amplitude of $2.1 \pm 0.8\%$.

To confirm this result public RXTE Proportional Counter Array (PCA) data of Her X-1 obtained on 1999 April 26 09:42 to 15:14 UTC (close to an expected main-on) were analyzed. The exposure time is 10.5 ks. A 2–60 keV lightcurve was extracted from the event data with a resolution of 0.05 s. Barycentering was performed with the FXBARY utility and the conversion to the system center of mass was performed as above. A clear modulation is detected at $>99.999\%$ confidence with a period of 1.237754(6) s, confirming the BeppoSAX discovery (see Fig. 3). The (1σ) uncertainty was estimated by fitting the arrival times of 8 sets of averaged pulses.

Table 1. Partial covering fit to the non-eclipse NFI spectrum. The energies of the narrow Fe-L lines were fixed at values in Mihara & Soong (1994). f is the fraction of flux that undergoes extra absorption N_{PCF}. A distance of 6.6 kpc is assumed

Parameter	
α	0.63 ± 0.02
E_c (keV)	18 ± 0.4
E_{fold} (keV)	9.0 ± 0.8
Blackbody kT (keV)	0.068 ± 0.015
Equiv. BB radius (km)	96 ± 7
N_H ($\times 10^{19}$ atom cm^{-2})	$13.6 \pm^{2.9}_{6.1}$
f	0.28 ± 0.03
N_{PCF} ($\times 10^{22}$ atom cm^{-2})	27 ± 7
Fe-L 0.91 keV EW (eV)	$44 \pm^{47}_{40}$
Fe-L 1.06 keV EW (eV)	49 ± 41
Fe-K line energy (keV)	6.57 ± 0.04
Fe-K line FWHM (keV)	0.60 ± 0.11
Fe-K line EW (keV)	0.665 ± 0.07
Intensity (0.1–10 keV; erg cm^{-2} s^{-1})	4.5×10^{-11}
χ^2/dof	160.5/123

3.2. X-ray spectrum

Two sets of NFI spectra were extracted corresponding to the non-eclipsed and eclipsed intervals in Fig. 1. The summing of all the non-eclipse data is justified by the lack of change in hardness ratio. The spectra were rebinned to oversample the full width half maximum (FWHM) of the energy resolution by a factor 3 and to have additionally a minimum of 20 counts per bin to allow use of the χ^2 statistic. Data were selected in the energy ranges 0.1–4.0 keV (LECS), 1.8–10 keV (MECS), 8.0–20 keV (HPGSPC), and 15–40 keV (PDS). Factors were included in the spectral fitting to allow for normalization uncertainties between the instruments. These were constrained to be within their usual ranges during fitting.

The 0.1–10 keV spectrum of the Her X-1 main-on state and parts of the short-on state are well described by a model consisting of an absorbed power-law and blackbody continuum together with two narrow lines with energies fixed at the best-fit energies of Mihara & Soong (1994) of 0.91 keV and 1.06 keV and a broad line at $\sim$6.5 keV (Oosterbroek et al. 1999; hereafter O99). At higher energies a cutoff is evident, together with cyclotron absorption which may be modeled by a Gaussian feature in absorption (e.g., Dal Fiume et al. 1998). Above an energy E_c the cutoff is modeled as $\exp((E_c - E)/E_{fold})$, where E is energy in keV. The "standard model" used in O99 was therefore modified with these additional high-energy features and fit to the non-eclipse NFI spectrum. This did not give a satisfactory result with a χ^2 of 335 for 142 dof. In addition, the best-fit power-law photon index α is 0.2, much harder than expected.

This spectral shape is similar to that obtained towards the end of the short-on state, or in the low-state by O99 where the effects of significant absorption are clearly seen as a change in spectral shape and increased curvature in the 1–3 keV energy range implying absorption of $\gtrsim 10^{22}$ atom cm^{-2}. However, substantial flux remained $\lesssim$0.5 keV, which should be *completely* absorbed with such a high absorption. This suggests the presence of separate "scattering" and "absorbing" regions which O99 model as partial covering using the PCFABS model in XSPEC. Here a fraction, f, of the emission undergoes extra absorption, N_{PCF}, while the rest is absorbed by a low value of N_H, as before. This partial covering model, modified as above at high-energies, gives a much better fit to the non-eclipse spectrum with a χ^2 of 160.5 for 123 dof (Table 1). The best-fit value of α is now 0.63 ± 0.02, which is still flatter than the main on-state spectrum where $\alpha \approx 0.9$. The equivalent blackbody radius is 96 ± 7 km and the ratio of 0.1–10.0 keV flux in the blackbody compared to the power-law is 11%.

Due to the lower count rate and integration time (the MECS exposure is only 6.9 ks) the quality of the eclipse spectrum is much worse than that of the non-eclipse interval. The NFI spectrum can be fit by a simple power-law model to give $\alpha = 0.77 \pm 0.22$ and a χ^2 of 24.6 for 19 dof. If a blackbody with its temperature fixed at 0.07 keV is included then the χ^2 reduces to 13.5 for 18 dof implying that the blackbody is still present during the eclipse. The best-fit value of α is 0.76 ± 0.25 and the equivalent blackbody radius is $\sim$50 km.

4. Discussion

We report on a BeppoSAX observation of Her X-1 during an anomalous low-state. The 0.1–40 keV lightcurves show a gradual reduction in count rate before the eclipse and then a more rapid rise following egress. There is significant flux remaining during eclipse. The shapes of the BeppoSAX lightcurves are similar to those reported by Parmar et al. (1985) during a much shorter (8 hr) EXOSAT observation centered on an eclipse during an earlier anomalous low-state, although it is possible that the asymmetry in the lightcurves is reversed. Parmar et al. (1985) also measure a very hard 2–10 keV spectrum with $\alpha = 0.52$ and a 6.29 ± 0.25 keV Fe line with an EW of 1.2 ± 0.4 keV. The blackbody component was also detected by the low-energy imaging telescopes on EXOSAT.

The non-eclipse 0.1–40 keV Her X-1 spectrum can be well fit with a blackbody and cutoff power-law continuum model, together with Fe-L and Fe-K emission features, a cyclotron absorption feature, and partial covering. Partial covering of the Her X-1 spectrum is also required during the late phases of the short-on state (O99), during the 1993 anomalous low-state (Vrtilek et al. 1994) and during the low-state (Mihara et al. 1991). The best-fit low-state Fe-K line energy, FWHM and EW of 6.53 ± 0.08 keV, 0.8 ± 0.4 keV, and 1.0 ± 0.1 keV, respectively (Mihara et al. 1991) are all remarkably similar to those reported here (see Table 1), whereas Vrtilek et al. (1994) report a weak line with an energy and EW of 6.31 ± 0.1 keV and 90 ± 30 eV during the 1993 anomalous low-state. Thus, the anomalous low-state spectrum observed here is indistinguishable from that observed during the more commonly occurring low-state.

The pulsations discovered during the anomalous low-state have a semi-amplitude of $2.1 \pm 0.8\%$, consistent with the pre-

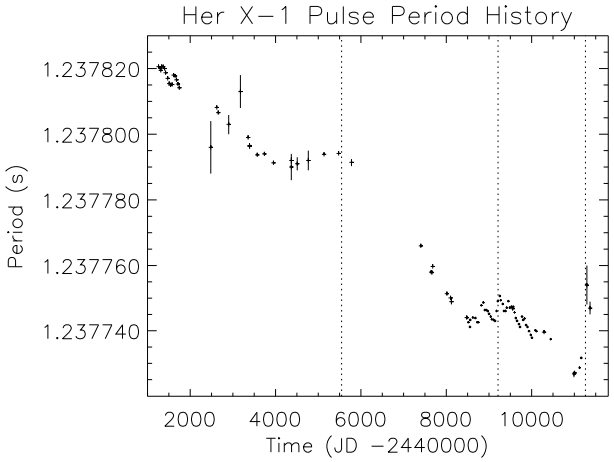

Fig. 4. The pulse period history of Her X-1 from Bildsten et al. (1997) updated using publically available BATSE results. The pulse periods determined here are the last two points. The approximate times of the 3 known anomalous low-states of Her X-1 are indicated with dotted lines

vious upper limits obtained by Mihara & Soong (1994) during the 1993 anomalous low-state ($<$1.5%) and Mihara et al. (1991) during the low-state ($<$2.4%). The pulse periods measured here indicate that Her X-1 underwent an interval of rapid spin-down at around the time of the start of the anomalous low-state (Fig. 4). A similar occurrence is evident in the case of the 1993 anomalous low-state (see Vrtilek et al. 1994), while the 1983 anomalous low-state appears to occur close to the end of an extended interval of spin-down. These measurements therefore strengthen the link between intervals of spin-down and the occurrence of anomalous low-states.

Several pulsars exhibit transitions between intervals of spin-down and spin-up (e.g., Bildsten et al. 1997). Van Kerkwijk et al. (1998) propose that this behavior results from the accretion disk becoming warped to the extent that the inner region becomes tilted by $>90^\circ$, resulting in a retrograde flow and a spin-down torque. This model implies that when spinning-down the X-ray source would be mostly observed *through* the accretion disk. This is unlikely to produce a simple increase in absorption since the inner disk regions are likely to be substantially ionized and scattering may play an important role. Support for this model comes from observations of the 7.7 s pulsar 4U 1626-67. During spin-up the power-law spectrum has $\alpha = 1.5$ while during spin-down $\alpha = 0.4$ (van Kerkwijk et al. 1998). The spin-down spectrum can also be fit using a partial covering model with 0.86 of the flux obscured by 6×10^{23} atom cm^{-2}. Thus, the 4U 1626-67 spectral hardening and torque reversals are remarkably similar to those observed here from Her X-1 suggesting a common mechanism. This implies that anomalous low-states may result from an unusually large amount of warp in the Her X-1 accretion disk. Since the accretion disk partially shadows HZ Her from the X-ray source, this change may produce a noticeable effect in the optical and UV spectra of HZ Her.

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