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Soft X-ray Spectrum Changes over the 35-Day Cycle in Hercules X-1 Observed with AstroSat SXT

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Abstract: Observations of the X-ray binary system Her X-1 by the AstroSat Soft X-ray Telescope (SXT) were carried out in 2020 through 2023 with the goals of measuring X-ray spectrum changes with the 35-day disk precession phase and measuring eclipses at different 35-day phases. Her X-1 exhibits a regular flux modulation with a period of \( \approx 35 \) days with different intensity levels at various 35-day phases (called "states"). The four multi-day long observations were scheduled to cover most of these states. Each 35-day phase was determined using monitoring observations with the Swift Burst Alert Telescope (BAT). Nine eclipses were observed in the range of 35-day phases, with at least one eclipse during each observation. Data with dips were separated from data without dips. The variation in X-ray spectral parameters vs. 35-day phase shows the following: eclipse parameters are nearly constant, showing that the scattering corona does not change with 35-day phase; dips show an increase in covering fraction but not column density compared to non-dip data; the 1 keV line normalization behaves similarly to the powerlaw normalization, consistent with an origin near the powerlaw emission region, likely the magnetospheric accretion flow from the inner disk onto the neutron star; and the blackbody normalization (area) is large (\( \approx 3 \times 10^5 \) km\(^2\)) during the Main High and Short High states, consistent with the inner edge of the accretion disk.

Keywords: binaries; eclipsing star; neutron stars; individual (HZ Her/Her X-1)

1. Introduction

Hercules X-1 (Her X-1) is a persistent X-ray binary pulsar, of considerable interest because its pulsations and near edge-on inclination have allowed the precise determination of binary parameters. Another reason for interest in this system is its regular 35-day cycle caused by its precessing accretion disk ([1] and references therein). The binary consists of a neutron star (Her X-1) and its stellar companion (HZ Her) with masses \( \approx 1.5 M_\odot \) and \( \approx 2.2 M_\odot \), respectively [2,3].

The X-ray binary system Her X-1/HZ Her radiates in optical, ultraviolet, extreme ultraviolet (EUV), and X-ray bands. Ref. [4] showed that systematic variations of the 1.7 d optical lightcurve of HZ Her gave strong evidence for a Roche-lobe filling companion star with its X-ray heating modulated by the accretion disk. EUV emission comes from the inner disk and from the irradiated surface of the companion star [5]. Hard X-rays (>1 keV) are created by accretion of matter onto the polar cap [6–8] of a rotating neutron star. The phase shift of the soft X-ray pulsations was identified with reprocessing in the inner disk [9]. The system has been found to exhibit a positive correlation between cyclotron line energy and maximum X-ray luminosity, revealing attributes of the emitting regions on the neutron star surface [10,11].

The different parts of the 35-day cycle with different X-ray flux levels are labelled states. The brightest part is called Main High (MH), which is preceeded by a sharp rise in flux called MH turn-on (TO) and followed by a slow decline called MH decline. This is followed by a faint interval called Low State (LS or LS1 for the first Low State), then
an interval of intermediate flux called Short High (SH). After SH there is a second faint interval called LS2 (for second Low State). The 35-day cycle then repeats with the next TO, MH, MH decline, LS1, SH, and LS2. These different flux states are clearly visible in the average 35-day lightcurve of Her X-1, as observed by the RXTE/ASM instrument [12,13] or Swift/BAT and MAXI instruments [14,15].

The 35-day cycle in X-ray and optical flux are caused by a precessing accretion disk [4,16] which also causes the 35-day cycle in pulse shape variations [1]. This 35-day cycle and accretion disk have been modelled by [12,13,17–19]. The neutron star is directly visible during the MH State and, for a short time, during the SH State, but not during LS. Absorption dips [20], also called dips, were shown to be caused by the accretion stream [21]. A study of X-ray eclipses observed by the Rossi X-ray Timing Explorer (RXTE) confirmed the presence of an optically thin scattering corona in the system, with an electron temperature of ∼1 keV [22]. Thus, Her X-1 exhibits complex behaviours that can be understood in terms of the geometry of the binary, the accretion disk, the accretion stream, and the larger-scale corona in the system.

AstroSat [23] has four co-pointing science instruments that provide simultaneous coverage over a wide energy range. The bands are near ultraviolet (NUV) and far ultraviolet (FUV) with the UVIT instrument, and soft through hard X-rays with the SXT, LAXPC and CZTI instruments. SXT covers the energy ranges ∼0.3–8 keV and is described in [24]. LAXPC is sensitive to the 3–100 keV band and CZTI is a coded mask imager in the 25–150 keV band.

Here, we analyze AstroSat SXT observations of Her X-1. The goals are to study the X-ray spectral changes of Her X-1 over the 35-day cycle in its various states and to measure spectral changes in eclipses and in dips within the 35-day phase. In Sections 2 and 2.1, we describe the observations and lightcurves, which are used to select data for spectral analysis. In Section 2.2, we analyze the spectrum of Her X-1 during MH, SH, LS, eclipse and dips and give the main results in Section 3. We discuss our results and compare with previous work in Section 4.

2. Data and Analysis

Her X-1 was observed in multiple observing sessions with the AstroSat SXT in PC mode, with a time resolution of 2.3775 s. The observations were carried out for the program of one of the authors (D.L.) as Astrosat proposal numbers A07_113, T03_197, A10_005 and A12_004. The observation dates were 21–24 February 2020 for A07_113, 28–30 April 2020 for T03_197, 17–21 September 2021 for A10_005 and 26 February–1 March 2023 for A12_004. See Table 1 for a summary of the observations.

The resulting data were downloaded from the AstroSat Data Archive (website http://astrosat-ssc.iucaa.in/data_and_analysis) during the first week of May 2023. We used the LEVL2 data for our analysis, which were generated by the AstroSat Team from LEVL1 data with the software pipeline ‘sxtpipeline’. This pipeline removes bad events, updates good time intervals (GTIs) and headers, and generates clean, filtered event files that can be used for analysis with standard HEASoft tools (website https://heasarc.gsfc.nasa.gov/docs/software.html) during the first week of May 2023. To select source events, a source region was chosen as a circle of 15 arcmin radius centred on Her X-1.

Each observation included several event files, with each file corresponding to a ∼90 min long orbit of the satellite around the Earth. These event files may contain multiple records of events that need to be identified and rejected, and then the different orbits need to be merged. This was carried out using the SXTMerger tool. The tool reads the LEVL2 event lists, bad pixel lists, and the GTIs from the event files of different orbits, checks for overlapping event data, and retains only unique events and merges the event lists.
Table 1. Data selection for spectra.

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<th>Duration(s)</th>
<th>Exposure(s)</th>
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</table>

Since the target source and the satellite are in non-inertial (accelerating) frames, the arrival times of the source photons at the detector need to be corrected to a common reference frame where both the emitter and receiver are placed in inertial frames. Additionally, there are relativistic effects due to the motion of the receiver in gravitational fields, which also need to be accounted for. Special relativity implies a difference in time systems between the source and observer caused by motion, and general relativity implies a different rate of time passage for the observer in the gravitational fields of the Earth and Sun. These effects are small compared to the timescales of interest here, but are important for accurate pulse timing on second timescales. Barycentric correction uses the satellite orbit ephemeris and the position of the target (RA, Dec) and modifies the photon arrival times by placing the satellite at the Solar System’s barycenter. This was carried out by passing the merged event files and the SXT orbit files to the AstroSat Barycentric Correction Code.
2.1. Lightcurve Analysis

To make lightcurves, we used the HEASoft tool Xselect to select the energy ranges, set the time bin size and extract counts for each time bin. The time bin size was set to 38.04 s (16 times the time resolution of the PC mode). We selected the energy range of 0.3–8 keV (PI channels 30-799) to create SXT full energy range lightcurves. Lightcurves were also extracted for the energy ranges 0.3–2 keV (PI channels 30-199), 2–4 keV (PI channels 200-399) and 4–8 keV (PI channels 400-799) and used to calculate softness ratios vs. time.

The orbit number (integer plus fraction) of Her X-1 at a given time in MJD is given by

$$n_{\text{orb}}(t) = \frac{(\text{MJD}(t) - T_0)}{P_{\text{av}}(t)}$$

where $T_0 = 46359.871940$ (MJD) is taken as the reference time (orbital phase 0 for orbit number 0, with orbital phase 0 defined as mid-eclipse of the neutron star by its companion), and $P_{\text{av}}(t)$ is the average orbital period between $T_0$ and MJD(t), given by

$$P_{\text{av}}(t) = \frac{(P(T_0) + P(MJD(t)))}{2}$$

Here, $P(T_0) = 1.700167590$ d is the orbital period at the reference time, and the period at MJD(t) is given by

$$P(MJD(t)) = P(T_0) + (MJD(t) - T_0) \dot{P}.$$ 

The period derivative is taken to be constant with value $\dot{P} = (-4.85 \pm 0.13) \times 10^{-11}$ days/day.

The values of $\dot{P}$, $P(T_0)$, and $T_0$ are from [25]. The orbital phase is the fractional part of $n_{\text{orb}}$.

The HEASoft FITS viewer tool FV was used to add columns for MJD, orbit number and orbital phase (integer and fractional part of $n_{\text{orb}}$) to each lightcurve file produced by Xselect. The MJD corresponding to each time stamp $t$ (in seconds) was calculated using $\text{MJD}(t) = t/86,400 + \text{MJD}_{\text{ref}}$, where MJD$_{\text{ref}} = 55,197$ is the day from which all Astrosat SXT times $t$ are measured.

Figure 1 shows the SXT 0.3–8 keV band lightcurve for the A07_113 observation vs. 35 day phase, which was determined from the Swift/BAT observations. Here, we use the definition of 35-day phase 0 from [14], which is the peak of the 35-day cycle. The top panel shows the Swift/BAT lightcurve for the same 35-day cycle as the SXT A07_113 data, which is scaled by a constant of 0.003 to match the BAT countrate. The Swift/BAT individual measurements (“Orbit” data) are shown in blue and the Swift/BAT daily averages are shown in red. The bottom panel shows the SXT data vs. orbit number at higher time resolution unscaled (at the original countrate scale). The eclipses are clearly visible each orbit between orbital phases of 0.93 and 0.07. Where the countrate decreases prior to orbital phase 0.93 indicates pre-eclipse dips, which was verified using the softness ratios.

Figures 2–4 show the Swift/BAT and SXT lightcurves for the T03_197, A10_005, and A12_004 observations, respectively. The MH TO (or TO for short) and MH rise are clearly seen in the SXT lightcurve in the lower panel of Figure 2, with TO defined by the sharp rise in flux at orbit number 7416.27, and MH rise occurring slowly between orbit numbers 7416.27 and $\simeq 7416.7$. The TO and MH rise are regular features, distinct from each other and from the $\sim$constant flux of peak of MH (seen in Figure 1), of the 35-day lightcurve.
Figure 1. Astrosat/SXT A07_113 full energy band (0.3–8 keV) lightcurve (count rate vs. 35-day phase) of Her X-1 (green points) during MH State. For comparison, the data for one full 35-day cycle from Swift/BAT are plotted, with daily-average data in red, with error bars, and orbit data in blue. Bottom panel: The Astrosat/SXT A07_113 0.3–8 keV lightcurve (count rate vs. orbit number) shown at higher time resolution with error bars. Mid-eclipse occurs at integer values of orbit number (7376, 7377, and 7378).
Figure 2. Top panel: Astrosat/SXT T03_197 full energy band (0.3–8 keV) lightcurve (count rate vs. 35-day phase) of Her X-1 (green points) during Turn-On. For comparison, the data for one full 35-day cycle from Swift/BAT are plotted, with daily-average data in red, with error bars, and orbit data in blue. Bottom panel: The Astrosat/SXT T03_197 0.3–8 keV lightcurve (count rate vs. orbit number) shown at higher time resolution with error bars. Mid-eclipse occurs at integer values of orbit number (7416).
Figure 3. Astrosat/SXT A10_005 full energy band (0.3–8 keV) lightcurve (count rate vs. 35-day phase) of Her X-1 (green points) during Short High State. For comparison, the data for one full 35-day cycle from Swift/BAT are plotted, with daily-average data in red, with error bars, and orbit data in blue. Bottom panel: The Astrosat/SXT A10_005 0.3–8 keV lightcurve (count rate vs. orbit number) shown at higher time resolution with error bars. Mid-eclipse occurs at integer values of orbit number (7714, 7715, and 7716).
The goal of the observations was to cover the different states of the 35-day cycle and to measure eclipses in the different states. A commonly-used definition of 35-day phase...
0 (the “start” of the 35-day cycle) is TO (e.g., [12,13]). Here, we prefer to use instead the peak of MH [14], because it is more easily measured with monitoring instruments than TO. The 35-day phase intervals (using peak of MH as phase 0) for the different states is given by [15] (their Table 2) using long-term observations of Her X-1 by Swift/BAT and MAXI instruments. Another determination was carried out using RXTE/PCA observations [26] (their Table 3), with higher sensitivity but less phase coverage. The peak of MH defined by peak countrate (used by [26]) is uncertain because the countrate is nearly constant at the peak (their Figure 3), such that peak could have been defined anywhere between 35-day phase ≥0.92 and 1.0, i.e., earlier by ≥0.00 to 0.08 in 35-day phase. The peak of the cross-correlation function (used by [15]) is well-defined; thus, we recommend here that values in Table 3 of [26] be adjusted. The lightcurves from Astrosat/SXT and Swift/BAT for the current data set show good agreement with the state intervals of [15] thus we use those intervals. This also indicates that the values in Table 3 of [26] should be shifted earlier by 0.07 to 0.08.

The A07_113 observation covers the peak of the 35-day cycle and includes two eclipses and part of a third eclipse (seen in the bottom panel of Figure 1); the T03_197 observation covers end of Low State 2 and Turn-on to MH state with one eclipse (bottom panel of Figure 2); the A10_005 observation covers the declining part of Short High state with three eclipses (bottom panel of Figure 3); and the A12_004 observation covers the middle part of Low State 2 with two eclipses (bottom panel of Figure 4). Thus, the goal was largely achieved.

2.2. X-ray Spectrum Analysis

The goals are to study the spectral changes of Her X-1 over the 35-day cycle and to analyse the spectrum of eclipses and search for possible changes over the 35-day cycle. As shown by the lightcurves for the four data sets above, Her X-1 was observed in the different states of the 35-day cycle: turn-on and rise to MH (T03_197), MH (A07_113), SH (A10_005) and LS (A12_004 and part of T03_197). Eclipses were observed in each state, and dips, which occur commonly [27,28], were observed in the states except for LS, which is too faint for detection of dips.

Thus, we use the light curves to choose data intervals for constructing spectra. Spectra were constructed for each state outside of eclipse or dip, and separate spectra were constructed for eclipses and for dips. Eclipses are defined by the companion blocking the X-rays from the neutron star, which is essentially a point source, and occur for the orbital phase interval 0.935 to 1.0 and 0.0 to 0.065, or for Orbit number the same plus any integer. Dips are defined as drops in count rate that show cold matter absorption, and are not detectable during eclipses or LS when the count rate is very low. The cold matter absorption in MH or SH shows up as a drop count rate and in softness ratio. Here, we defined softness ratio by the 0.3–2 keV count rate divided by the 2–4 keV count rate. The softness ratio decreases during dips because the photoelectric absorption cross-section is higher for lower X-ray energies, so that absorption reduces the 0.3–2 keV count rate more than the 2–4 keV count rate.

For example, for SH, first the eclipse data were selected based on orbital phase, then dip data were selected based on drop in count rate (in this case below 5 c/s for orbit 7714 and below 3.8 c/s for orbit 7715). Finally, the normal (no eclipse, no dip) SH spectra were selected to be the remaining higher count rate intervals.

The details of the data selections for the four observations are given in Table 1. A07_113 and T03_197 were divided into 8 intervals each, A10_005 into 14 intervals and A12_004 into 5 intervals. For most cases, the data intervals include times when the source is blocked from view by Astrosat by the Earth or by other constraints. This means there are data gaps for most intervals resulting in net exposure times significantly less than the durations of the intervals. For each interval, spectra were constructed using the interval start and stop times. The most recent SXT background spectra and response matrices were obtained from the Science Support Cell website. All spectra were binned in energy to give a minimum
of 10 counts (net) per energy bin. For spectral fitting a systematic error of 2% and energy range of 0.5 to 7.0 keV (recommended by the SXT analysis support team) were used.

The resulting SXT spectra for the 35 intervals were fit by model spectra using the Xspec software (https://heasarc.gsfc.nasa.gov/docs/software.html (accessed on 16 January and 22 June 2023)). We started by fitting the spectrum with the best statistics (largest number of counts), which is spec3MH. A number of different spectral models were tested, and we verified that the best fit model was nearly the same as the model found by [29]. The procedure for testing spectral models was as follows. The spectrum was fit first by a powerlaw only, then other components were added (or replaced) one at a time until it was found that adding further components did not statistically improve the fit (by >3σ). A large number (~100) of combinations were tested, including previously published models for Her X-1 and their subsets.

The adopted Xspec model is

\[ pcfabs < 1 > (powerlaw < 2 > +bbodyrad < 3 > +gaussian < 4 > +gaussian < 5 >) \] (4)

The emission components are subject to partial covering absorption (pcfabs<1>, with parameters column density, \( N_H \), and covering factor, \( f_c \)). The partial covering absorber has the form \( f_c \exp(-N_H \sigma(E)) + (1-f_c) \), with \( \sigma(E) \) the photoelectric absorption cross-section. The model was first introduced for the spectrum model for Her X-1 by [30]. The part of the radiation that is blocked by optically thick material \( (N_H > 10^{24} \text{ cm}^{-2}) \) will not be included in \( f_c \), rather it is implicitly included by decreases in the norms of the emission components (<2> through <5>). That is, the model has four emission components: a powerlaw<2> (PL, parameters norm and index \( \alpha \)) representing the emission from the neutron star; a blackbody (bbodyrad<3> or BB, parameters norm and \( kT \)) representing reprocessed emission from the inner edge of the accretion disk; a gaussian<4> centered near 1 keV (parameters norm, line energy and line-width) representing the emission from the Fe L line complex and a gaussian<5> centered near 6.4 keV (parameters norm, line energy and line-width) representing Fe K line emission. An example spectral fit is given in Figure 5 showing the observed spectrum for spec7MH and its best-fit spectrum model using Equation (4).

Because the signal-to-noise ratio for the other spectra is lower than for spec3MH, not all parameters could be constrained for the other spectra. The general procedure is to fix some parameter if the spectral fit for a given spectrum could not constrain that parameter. The value that it was fixed at was determined from the MH spectral fit (spec3MH) that could constrain the parameter.

The 1 keV linewidth was \( 0.17 \pm 0.01 \text{ keV} \) for spec3MH. The other MH and SH spectra were consistent with this value (no increase in \( \chi^2 \) compared to fits with free linewidth), so it was fixed at 0.17 keV for the other spectra. The 1 keV line energy was \( 0.92 \pm 0.02 \text{ keV} \) for spec3MH. The other MH and SH spectra were consistent with this value within errors. For spectra other than MH and SH, the 1 keV line energy was not constrained, and fixed at 0.92 keV. For eclipses the 1 keV line norm was consistent with 0, so the 1 keV line was omitted for eclipse spectra fits.

The 6.4 keV Fe line energy was only well constrained for spec3MH with value \( 6.43 \pm 0.05 \text{ keV} \). For all other spectra, the Fe keV line energy was subsequently fixed at 6.43 keV. For MH, the fits with fixed Fe line energy then showed that the line was weak (with norm no more than 1σ different than 0) except for one other MH spectrum (spec6MH). Thus, for the final set of fits, the Fe K line was omitted from the spectral fits except for spec3MH and spec6MH.

Table 2 gives the list of free and fixed parameters for spectral fits for MH, SH, dip, LS, and eclipse. MH turn-on and MH rise spectra were fit with the same model as the MH spectrum listed. Table 2 also gives the best-fit spectral parameters and their errors for spec3MH and for example spectra for the other spectral states.
Figure 5. Top panel: Example Her X-1 SXT spectrum (plus shaped symbols) and its best-fit model (solid line). Lower panel: Fit residuals. The spectrum is spec$_{7}$MH, see text for model description. The residuals at 2 keV are a SXT instrument feature.

Table 2. SXT Spectrum models for the 35-day States $^a$.

<table>
<thead>
<tr>
<th>State/Example</th>
<th>$N_H$ (10$^{22}$ cm$^{-2}$)</th>
<th>Covering Factor, $f_c$</th>
<th>PL Norm (Photons/keV/cm$^2$/s at 1 keV)</th>
<th>PL $\alpha$</th>
<th>1 keV Line Norm (Photons/cm$^2$/s)</th>
<th>BB Norm ($R_{km}^2/D_{10}^2$) $^b$</th>
<th>BB kT (keV)</th>
<th>Fe K Line Norm (Photons/cm$^2$/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MH</td>
<td>free</td>
<td>free</td>
<td>0.18 ± 0.01</td>
<td>0.94 ± 0.03</td>
<td>0.069 ± 0.010</td>
<td>(5.0 ± 2.2) × 10$^5$</td>
<td>0.100 ± 0.008</td>
<td>free</td>
</tr>
<tr>
<td>spec3MH</td>
<td>12.6 ± 1.9</td>
<td>0.24 ± 0.03</td>
<td>free</td>
<td>free</td>
<td>free</td>
<td>0.100 ± 0.008</td>
<td>free</td>
<td></td>
</tr>
<tr>
<td>SH</td>
<td>free</td>
<td>free</td>
<td>0.078 ± 0.010</td>
<td>1.06 ± 0.06</td>
<td>0.023 ± 0.004</td>
<td>(2.5 ± 1.4) × 10$^5$</td>
<td>0.096 ± 0.009</td>
<td>free</td>
</tr>
<tr>
<td>spec19SH</td>
<td>13.2 ± 3.2</td>
<td>0.28 ± 0.05</td>
<td>free</td>
<td>free</td>
<td>free</td>
<td>0.100 ± 0.008</td>
<td>free</td>
<td></td>
</tr>
<tr>
<td>LS</td>
<td>free</td>
<td>free</td>
<td>free</td>
<td>fixed</td>
<td>free</td>
<td>0.100 ± 0.008</td>
<td>free</td>
<td></td>
</tr>
<tr>
<td>spec33LS</td>
<td>12.5 ± 3.7</td>
<td>0.52 ± 0.05</td>
<td>(3.3 ± 0.4) × 10$^{-3}$</td>
<td>0.95</td>
<td>(2.5 ± 1.3) × 10$^{-4}$</td>
<td>(1.8 ± 0.3) × 10$^4$</td>
<td>0.100 ± 0.008</td>
<td>free</td>
</tr>
<tr>
<td>dip</td>
<td>free</td>
<td>free</td>
<td>fixed</td>
<td>free</td>
<td>fixed</td>
<td>fixed</td>
<td>fixed</td>
<td></td>
</tr>
<tr>
<td>spec4dip</td>
<td>73 ± 31</td>
<td>0.92 ± 0.07</td>
<td>0.032 ± 0.022</td>
<td>0.95</td>
<td>0.001 ± 0.002</td>
<td>(6.3 ± 5.4) × 10$^4$</td>
<td>0.100 ± 0.008</td>
<td>fixed</td>
</tr>
<tr>
<td>eclipse</td>
<td>fixed</td>
<td>fixed</td>
<td>free</td>
<td>fixed</td>
<td>free</td>
<td>fixed</td>
<td>fixed</td>
<td></td>
</tr>
<tr>
<td>spec34eclipse</td>
<td>13</td>
<td>0.24</td>
<td>(4.7 ± 0.7) × 10$^{-4}$</td>
<td>0.95</td>
<td>1600 ± 1400</td>
<td>0.100 ± 0.008</td>
<td>fixed</td>
<td></td>
</tr>
</tbody>
</table>

$^a$ The spectral parameters for all spectra (1 to 35, see Table 1) are given in the figures. $^b$ For the units of BB norm, $R_{km}$ is the radius in units of 1 km, and $D_{10}$ is the distance in units of 10 kpc.
3. Results

There are five spectra during normal MH: three from A07_113 and two from T03_197. Normal here means that they are not during eclipse, nor do they contain significant dips. The spectra during MH turn-on and MH rise from T03_197 are fit with the same model as for MH. There are three spectra during normal SH from A10_005, and four spectra during normal LS, one from T03_197, and three from A12_004. There are 12 dip spectra, 4 during MH (from A07_113 and T03_097) and 8 during SH. The eclipse spectra are during MH turn-on, MH, SH, and LS.

The powerlaw is the dominant contributing factor for all 35-day states, for dip and for eclipse. Figure 6 shows the powerlaw norm during normal (no dip, no eclipse) states and during dips vs. 35-day phase. The powerlaw norm times \((1 - f_c)\) has a shape similar to the \(0.3–8\) keV count rate (top panels of Figures 1–4). The powerlaw index is consistent with a constant for states (MH turn-on, MH rise, MH, and SH) for which it can be measured, with a value of \(0.95 \pm 0.05\).

The partial covering absorber has the parameters of column density and covering factor. Figure 7 shows column density vs. 35-day phase, with MH turn-on, MH rise, MH, SH, and LS2. There were no observations during LS1, which is the LS between MH and SH. The column density is roughly constant vs. 35-day phase with a value of \(\sim 2 \times 10^{23}\) cm\(^{-2}\), but with a small increase to \(\sim 3 \times 10^{23}\) cm\(^{-2}\) at MH turn-on and during dips. During eclipse, the signal-to-noise was not enough to constrain the column density, so the column density and covering factor were fixed at the values found for MH (from spec3\(_{MH}\)).

The covering factor, \(f_c\), shown in Figure 8, has a value of \(\sim 0.2\) during normal MH, but is higher during MH turn-on (\(\sim 0.75\)) and MH rise (\(\sim 0.5\)). During normal SH \(f_c \simeq 0.35\) and during LS \(f_c \simeq 0.5\). \(f_c\) is variable during dips with values as high as 0.9. Previous work has shown high and variable \(f_c\) during dips [27,31].
The next most significant component in the spectral fits is the blackbody component with parameters norm and kT. The norm is defined as the area of the blackbody in km$^2$ if the source was placed at a distance of 10 kpc. Because Her X-1 has a distance of 6.1 kpc [3], the norm has to be multiplied by a factor of 0.372 to give area in km$^2$. The blackbody norm, shown in Figure 9, is consistent with a value of $\sim 3 \times 10^5$ ($\sim 1 \times 10^5$ km$^2$) during normal MH and SH states. During dip, the norm drops to values of $\sim 2 \times 10^4$ to $\sim 2 \times 10^5$ ($\sim 7 \times 10^3$ to $\sim 7 \times 10^4$ km$^2$). During normal LS, the norm is smaller with values of $\sim 1 \times 10^4$.
to $\sim 2 \times 10^4$ ($\sim 4 \times 10^3$ to $\sim 7 \times 10^3$ km$^2$). The norm is lowest during eclipse with similar values for MH, SH, and LS eclipse of $\sim 4000$ ($\sim 1500$ km$^2$).

After the blackbody, the next most significant component in the spectral fits is the 1 keV line, with the parameters norm, center energy, and width. The 1 keV line could not be detected during dip, LS, or eclipse. The 1 keV line width was consistent with a constant value for the normal MH and SH fits, with a value of 0.17 keV. The 1 keV line center energy (in units of keV) and 1 keV line norm (in units of photons/cm$^2$/s multiplied by 10) are shown in Figure 10. The line energy is consistent with a constant value of $0.92 \pm 0.03$ keV. The line norm shape vs. 35-day phase is similar to that of the powerlaw norm: the 1 keV line norm divided by powerlaw norm is consistent with a constant value of $\sim 0.35$ during normal MH and SH and with a smaller value of $\sim 0.1$ during normal LS.

The least significant component of the spectral model was the 6.4 keV Fe line. The 6.4 keV line was detected only during two of the MH spectra with highest signal-to-noise, $\text{spec}3_{\text{MH}}$ and $\text{spec}6_{\text{MH}}$. For these two spectra, the line norm was $9.3 \pm 3.7 \times 10^{-4}$ and $6.2 \pm 5.4 \times 10^{-4}$, respectively. The 6.4 keV line center energy was measured only for $\text{spec}3_{\text{MH}}$ with value $6.43 \pm 0.05$ keV.
Figure 10. 1 keV line norm (in units of photons/cm$^2$/s multiplied by 10, blue symbols) and 1 keV line center energy (in units of keV, red symbols) vs. 35-day phase for normal states (no dip, no eclipse). The keV line energy could not be measured during LS (35-day phase 0.65–0.9). The 1 keV line was not detected during eclipses. MH turn-on is the first blue point and MH rise is the second blue point.

4. Discussion

4.1. Lightcurve of Her X-1

The four observing sessions of Her X-1 with Astrosat SXT covered the different states of Her X-1: MH with A07_113; MH turn-on and MH rise with T03_197; SH with A10_005 and LS with A12_004. The known features of the 35-day cycle were observed, as illustrated by the agreement between the low signal-to-noise Swift/BAT monitoring observation and the SXT high-sensitivity observations, and shown in Figures 1–4.

The X-ray lightcurve of Her X-1 has been observed for short periods (10s of ks) many times previously, usually during peak of MH in order to obtain high count rate to constrain the spectrum of emission from the neutron star. Longer duration observations have usually been restricted to lower sensitivity instruments such as RXTE’s All Sky Monitor (ASM) or Swift’s BAT or MAXI. The signal-to-noise of these instruments is low (e.g., as illustrated by the BAT Daily average lightcurves given in the top panels of Figures 1–4 here), but these observations have given highly useful measurements of the 35-day cycle of Her X-1 ([15] and references therein).

A comparable measurement of the lightcurve of Her X-1 with similar sensitivity has been made using archival measurements with RXTE PCA over a ~15-year period [26]. The spectral resolution of those observations was lower than that of the current data, so that the current Astrosat SXT observations give a better picture of spectral changes over the 35-day cycle.

4.2. Spectrum of Her X-1

The X-ray spectrum of Her X-1 over a full range of 35-day states, including dips and eclipses, has not been measured before. Spectral changes during MH TO and MH rise were studied by [32]. An analysis focusing on X-ray timing was carried out by [33] for three intervals of MH and two intervals of SH and an analysis focusing on the 37 keV cyclotron line was carried out by [34] for three intervals of MH. The current study is the first spectral study over a 35-day cycle, and to do it with the same instrument so cross-calibration of different instruments is not a problem here. A summary of the spectral changes is given here and compared to previous work in the next section.
One result seen for the first time is that the powerlaw normalization does not vary much from eclipse to eclipse over 35-day phase (Figure 6). This can be explained because the entire accretion disk is covered by the companion star during eclipse, so the flux that is observed is only the flux scattered by the corona or extended wind [22] at scales larger than than of the companion radius of $3 \times 10^{11}$ cm. This result implies that the scattering corona does not change with 35-day phase.

The column density has been measured as a function of 35-day phase for the first time, in normal states and in dips. The column density during dips is is similar to that outside dips (Figure 7). During LS, the column density is consistent with the values seen during MH and SH ($\sim 1.5 \times 10^{23}$ cm$^{-2}$). Instead, the main factor distinguishing dip spectra from non-dip spectra is covering factor $f_c$: it is significantly larger for dips (Figure 8) Both column density and covering factor are well constrained by the spectrum fits. The goodness of fit ($\chi^2$) was significantly better when both column density and covering factor are free parameters compared to fits where only one of the two parameters was free. A strong factor in the good constraints on column density and covering factor is the good low-energy sensitivity of the SXT instrument. Outside of dips, $f_c$ has a clear pattern: a decrease during MH turn-on from $\sim 0.8$ and during MH rise to a low value of $0.2$ during MH, then a slow increase during SH (to $\sim 0.4$ and during LS2 (to $\sim 0.6$). Accretion disk models for Her X-1 will have to be adjusted to be consistent with this new result.

Outside of eclipses and dips, the powerlaw norm has similar behaviour to the count rate, including the rise to a peak during MH (compare Figure 2 and Figure 6) and slow decline during SH (compare Figure 3 and Figure 6, although the third point for SH in Figure 6 is only lower than the first point by $1.8\sigma$).

For the first time we compare the blackbody norms between MH, SH and LS (Figure 9). To compare the blackbody norm vs. 35-day phase with powerlaw norm, we replot both on the same scale in Figure 11. The decrease from MH to SH appears to be less for blackbody norm than for powerlaw norm, but the large error bars of blackbody norm prevent one making a clear conclusion: the ratio of SH to MH blackbody norm is $1.5 \pm 0.9$ compared to the ratio of SH to MH powerlaw norm of $0.46 \pm 0.06$ (only different by $1.3\sigma$). The decrease of blackbody norm from MH to LS (the LS to MH ratio) is $0.029 \pm 0.003$, similar to the decrease of powerlaw norm from MH to LS, with LS to MH ratio of $0.029 \pm 0.002$. To compare the shapes of the powerlaw norm and blackbody norm vs. 35-day phase, we compute their $\chi^2$ difference, with a free scaling factor, $C$:

$$
\chi^2 = \sum_i (pln_i - C \times bbn_i)^2 / (plner_i^2 + C^2 \times bbnerr_i^2)
$$

(5)

with $pln$ the PL norm and $plner$ its error, $bbn$ the blackbody norm and $bbner$ its error. The sum was carried out over all points in Figure 11, or just for the six points in MH (all but the first MH turn-on point). The result was $\chi^2 = 212$ when using all points, or $\chi^2 = 84$ when using the six MH points. Thus, the PL norm and BB norm have statistically different shapes, either for the whole 35-day cycle or for just the MH part of the cycle.

The powerlaw is from the accretion column ($\sim 1$ km in size), whereas the blackbody is from the inner edge of the disk ($\sim 400$ km in radius [1]), based on pulse shape studies [9]. Our low signal-to-noise finding that the blackbody is less reduced from MH to SH than the powerlaw norm is consistent with this. The decrease in both powerlaw norm and blackbody norm should be similar from MH to LS because both regions are expected to be small compared to the outer regions of the disk, which obscure the central regions during LS. During TO and dips, the neutron star and blackbody are behind optically thick ($N_H > 10^{24}$ cm$^{-2}$) matter of size larger than either, so the radiation that is seen is scattered radiation (of larger scale than the optically thick matter), part of which is absorbed by material with $N_H < 10^{24}$ cm$^{-2}$.
Figure 11. PL norm, blackbody norm (scaled by $1/3.6 \times 10^6$), and 1 keV line norm (scaled by $1/0.36$) vs. 35-day phase for normal states (no dip, no eclipse), plotted to compare their 35-day dependencies. The scaling factors were chosen so that the scaled mean values of BB norm and keV line norm were the same as for PL norm for the 6 points of MH.

The turn-on of MH is measured here to occur over $\sim 0.1$ orbit ($\sim 4$ h), and rise of MH to occur more rapidly, over $\sim 0.01$ orbit ($\sim 20$ min). The turn-on and rise are caused [1] by uncovering by the outer edge of the accretion disk at distance of $\sim 10^{11}$ cm from the neutron star. Given the outer edge rotates with 35-day period, the outer edge crosses the line-of-sight to the neutron star with velocity $\sim 2.0$ km/s. For an expected emission region size of 1 km on the neutron star, the time of uncovering by a sharp outer disk edge is $\sim 0.5$ s. Because the turn-on and rise times are much longer, this implies the outer edge of the disk is not sharp but has an atmosphere, as shown previously by [17].

The blackbody component has an area of $\sim 10^5$ km$^2$ during MH and SH. This is consistent with the inner edge of the accretion disk, which would be heated by X-rays from the neutron star. The inner edge is located at $R_{in} \sim 400$ km from the neutron star [1] and with height $h_{in} \sim R_{in}$ [17]. Studies by [35,36] have shown that the small radius of the inner disk (magnetosphere) can be explained by the presence of a complex non-dipole magnetic field of Her X-1. A pure dipole magnetic field decays more slowly and would likely result in an inner disk radius $\sim 3700$ km for the parameters (magnetic field strength, accretion rate, radius, etc.) of Her X-1 (see Equation (2) of [36]). $R_{in} \sim 400$ km yields an estimated projected area of $\sim R_{in} h_{in} \sim 2 \times 10^5$ km$^2$, of which $\sim 1/2$ or more will be occulted by outer parts of the disk depending on the 35-day phase [17]. The blackbody norm drops significantly from MH and SH normal values during dips. The drop is consistent with partial covering by an optically thick absorber.

In addition to the X-rays emitted with blackbody spectrum by the inner edge of the disk there is an expected component of scattered blackbody emission from the corona [22], with contribution of $\sim 1\%$ of that from the inner disk edge. The blackbody area observed during eclipses has values $\sim 1500$ km$^2$, consistent with the expected scattered amount. During LS, the blackbody norm is approximately $\sim 4000$–$7000$ km$^2$. During LS, the inner disk is blocked from view by the outer disk [17], but the outer part of the disk blocks much less of the inner corona than that blocked by the companion star, so the scattered amplitude should be higher than during eclipse, as observed.
The 1 keV line energy is constant with the 35-day phase (Figure 10). The 1 keV line norm has similar behaviour to the powerlaw norm, in particular the ratio of 1 keV line norm to powerlaw norm varies only a small amount (see Section 3, \( \sim 0.4 \) for MH and SH and \( \sim 0.15 \) for LS and eclipse). This is illustrated in Figure 11, which shows the 1 keV line norm on the same scale as PL norm and BB norm. For the 1 keV line norm, the SH to MH ratio of 0.44 \( \pm \) 0.07, same as for PL norm and smaller than the value for BB norm (but only by 1.3\( \sigma \)). The \( \chi^2 \) test of Equation (5) was applied to compare 1 keV line norm with PL norm shape: the result was \( \chi^2 = 46 \) for all points or \( \chi^2 = 6 \) for the six points in MH. The difference in shape between the 1 keV line norm and PL norm is significant for the whole 35-day cycle but not significant for MH. Similarly, the test was applied to compare the 1 keV line norm with BB norm shape: the result was \( \chi^2 = 212 \) for all points or \( \chi^2 = 74 \) for the six points in MH, thus yielding a statistically different shape between 1 keV line norm and BB norm both for the whole 35-day cycle and for just the MH part. The closer statistical similarity of the 1 keV line norm to the PL norm than to the BB norm is consistent with the 1 keV line emission region being compact, similar to the powerlaw emission region, and both being significantly smaller than the blackbody region.

4.3. Comparison with Previous Work

Individual spectra have been studied during MH and SH several times with instruments with good resolution, including the Suzaku spectrum during MH [37] and a joint NuSTAR plus Suzaku observation [34]. The broad-band MH spectrum of Her X-1 [38] is generally fit with a powerlaw with high-energy cutoff at \( \sim 20 \) keV, a low-energy excess fit by a blackbody with \( kT \simeq 0.1 \) keV, a broad Gaussian line feature around 1 keV, a fluorescent 6.4 keV iron line and a cyclotron absorption feature near 40 keV.

Those observations were sensitive to the high-energy part of the spectrum (well above 30 keV), whereas Astrosat SXT measures the 0.5 to 7 keV part. Thus, the powerlaw with cutoff and cyclotron absorption feature appears as a simple powerlaw to SXT, and the undetectable components (cutoff and cyclotron feature) were not included in the spectral model for SXT.

The X-ray spectral fits to Her X-1 require a partial-covering absorber, as first shown for the MH spectra during dip and non-dip by [27,28]. We fit the absorption for Her X-1 with a partial covering neutral absorber (\textit{pcfabs} in Xspec). In comparison, [29] found a partially ionized partial covering neutral absorber (\textit{zxipcf} in Xspec) produced a better fit during MH with \( \sim 2\sigma \) significance (\( \delta \chi^2 = 6.8 \)). We compared the \textit{pcfabs} model with the \textit{zxipcf} model for the spectrum with highest signal-to-noise (\textit{spec3MH}) and found that \textit{pcfabs} provided essentially the same fit (\( \delta \chi^2 = -0.4 \)) compared to \textit{zxipcf}, but has one less parameter. The key difference between the spectral fits is in this work and in [29] is that we use the new and significantly improved calibration and background subtraction for the SXT released by the Astrosat SXT support team. Thus, we conclude there is no preference for a partially ionized absorber for Her X-1, and adopt the \textit{pcfabs} absorber model for Her X-1.

The current work is the first comprehensive study of spectral changes as a function of 35-day phase for Her X-1 with an instrument with good spectral resolution. The spectrum evolution during MH was studied previously by [39] and during SH by [40] with the RXTE Proportional Counter Array (PCA) instrument over the energy range 2.5 to 30 keV. PCA has a lower spectral resolution than SXT and is sensitive to a different part of the spectrum, thus being sensitive to the powerlaw and 6.4 keV iron line, but not sensitive to 0.1 keV blackbody and the 1 keV line components and not as sensitive as SXT to the partial covering absorption parameters. The covering fraction during MH from [39] was consistently \( \sim 0.2 \) during MH, and during SH from [40] varied in the range \( \sim 0.3 \)–0.5 during SH and \( \sim 0.5 \) during LS. These results are in agreement with the current results (Figure 8). The column densities from [39,40] are also in agreement with the current results (Figure 7) for MH and SH.
Her X-1 was observed during MH and SH states using the Imaging X-ray Polarimetry Explorer (IXPE) [41]. This yielded X-ray polarization higher during SH than MH, which gave evidence that the obscuring structure obstructs preferentially the emission from one of the magnetic poles of the NS during SH. This is consistent with the interpretation of the spectral changes of Her X-1 given here. Ref. [42] use IXPE observations to deduce the spin axis (57 ± 2° with respect to line-of-sight) and magnetic inclination of the neutron star (12 ± 4° with respect to the spin axis). These values are approximately consistent with the angles previously deduced from pulse shape fitting [6]. In general, the pulsar emission geometry has little effect on the conclusions of the current work, because the current work uses time averaged spectra for durations of typically 10^4 s (see Table 1), which is long compared to the 1.23 s spin period. The 35-day period is very stable, as shown by numerous other studies, and the flux cycle has explained by occultation of the neutron star by the precessing accretion disk (e.g., [1]). Although it does not seem that neutron star precession is a main cause of the 35-day cycle, there are arguments that the stability of the 35-day cycle is provided by neutron star precession (e.g., [43]). The current study observed four large pieces of the 35-day cycle (Figures 1–4) so it not sensitive to small changes in pulsar spin and magnetic axis, which would not cause a large change in the emission in the direction of the observer, nor in the illumination of the disk and companion to Her X-1.

5. Summary and Conclusions

We have carried out a study of the spectral changes of Her X-1 over its 35-day cycle, including several eclipses, using 0.5–7 keV band spectra observed by the Astrosat SXT instrument. This is the first comprehensive study of how the soft (0.5–7 keV) X-ray spectrum of Her X-1 changes with the 35-day accretion disk rotation period and how eclipses change with 35-day phase. The main new results here are

- The powerlaw normalization is nearly constant during eclipses at all 35-day phases. This means that the scattering corona in Her X-1 is not variable with 35-day phase.
- The column density for dips and outside dips is the same. Dips have a significant increase in covering fraction compared to non-dip times.
- The blackbody component, which originates from the hot inner edge of the accretion disk, was measured as a function of 35-day phase. During dips, it is smaller by a factor of ~2–3. During LS and during eclipses, there are only small residual components of ~4% (for LS) and ~1% (for eclipses), which are emissions scattered by the part of the corona that is larger than the accretion disk (for LS) or larger than the companion star (for eclipses). The blackbody has a different 35-day variability compared to the powerlaw norm, which is likely related to the extended nature of the blackbody (area ~10^5 km^2).
- The 1 keV line norm has similar 35-day variability to the powerlaw norm and different from that of the blackbody norm. This is consistent with the 1 keV component originating from a small region, similar to the powerlaw component. This region may be located along the magnetospheric flow of matter from the inner edge of the accretion disk onto the neutron star.

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Abbreviations
The following abbreviations are used in this manuscript:

- Her X-1: Hercules X-1
- SXT: Soft X-ray Telescope
- MH: Main High
- SH: Short High
- LS: Low State
- BAT: Burst Alert Telescope
- RXTE: Rossi X-ray Timing Explorer
- NUV: near ultraviolet
- FUV: far ultraviolet
- LAXPC: Large Area X-ray Proportional Counter
- CZTI: Cadmium Zinc Telluride Imager
- PC: Photon Counting
- MJD: Modified Julian Date
- MAXI: Monitor for All sky X-ray Instrument
- PL: powerlaw model in Xspec
- BB: bbodyrad in Xspec
- ASM: All Sky Monitor
- PCA: Proportional Counter Array
- NuSTAR: Nuclear Spectroscopic Telescope Array

References

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