Hercules X-1’s light-curve dips as seen by the RXTE/PCA: a study of the entire 1996 February–2005 August light curve

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ABSTRACT

Hercules X-1 (Her X-1) light-curve dips are analysed using the entire set of Rossi X-ray Timing Explorer/Proportional Counter Array observations archived over nine years. 370 new dips are found in 35 different 35-d cycles. This is the largest record of Her X-1 dips acquired as a result of a single study and by the same satellite, and includes 20 post-eclipse recovery dips, over 100 short-high-state dips, 10 possible low-state dips, and 162 subdips, which have never been documented before. The dips were identified by X-ray energy softness ratio (SR) change. The dips’ intensity, based on SR change and derived $N_H$, varies strongly with orbital phase. Dip duration covers a broad range: 32s–15h. The main-high-state and pre-eclipse dips are the most numerous and have the longest lengths and ingresses. There is some evidence that ingress and egress become progressively faster as the orbital cycle unfolds. Symmetry is investigated here for the first time: most dips are highly asymmetric. Duration and symmetry depend on orbital and 35-d phase. The 35-d-phase versus orbital-phase distribution is significantly different than previously reported.

Key words: methods: data analysis – stars: neutron – pulsars: individual: Her X-1 – X-rays: binaries.

1 INTRODUCTION

A great variety of phenomena is observed in the HZ Herculis (HZ Her)/Hercules X-1 (Her X-1) system. The system consists of a 1.24 s accretion-powered pulsar (Her X-1) in a 1.7-d nearly circular orbit around its post-main-sequence stellar companion (HZ Her), whose type varies between late A and early B with the orbital phase (Anderson et al. 1994; Cheng, Vrtilek & Raymond 1995). The system is also characterized by a unique, approximately 35d long, X-ray flux cycle. Each 35-d cycle has a main-high (MH) and a short-high (SH) state that last approximately 11 and 7 d, respectively. The MH state is usually three times as bright and separated from the SH state by a low state (LS) that lasts approximately 8 or 9 d. Deep X-ray flux absorption events can be noticed throughout the high states every 1.7 d, consistent with Her X-1’s eclipse timings, as well as at different time intervals, on a regular basis or not (Scott 1993; Scott & Leahy 1999). Irregular X-ray flux absorption is expected during LSs, as well; however, the reduced count rate of the LSs hampers its detection.

The regular timing and intensity of the 1.7-d absorption events are an indication that the orbital plane is viewed nearly edge-on. Due to its low interstellar absorption, the system may be studied in optical and ultraviolet as well as in X-ray and infrared wavelengths (Boydton et al. 1973; Deeter et al. 1976; Gerend & Boynton 1976; Howarth & Wilson 1983a; Leahy 1995a,b, 2003; Still et al. 1997; Boroson et al. 2000, 2007). This proved crucial in determining Her X-1’s accretion disc shape and the accretion column’s properties based on Her X-1’s X-ray flux and HZ Her’s optical light flux (Leahy 2002, 2004a).

The X-ray absorption phenomena were first noted in the system’s light curve soon after its discovery, almost 40 years ago (Schreier et al. 1972; Tananbaum et al. 1972). Sharp light-curve flux absorptions that occur soon after eclipse egress, before eclipse ingress or in the middle of the orbital cycle and march towards earlier orbital phases, as the 35-d cycle progresses, were first documented by Giacconi et al. (1973) who named them light-curve dips. The properties of Her X-1’s light-curve dips have been observed, documented, and debated ever since (Boynton et al. 1973; Ulmer et al. 1973; Deeter et al. 1976; Gerend & Boynton 1976; Jones & Foreman 1976; Becker et al. 1977; Cossa & Boynton 1980; Howarth & Wilson 1983a,b; Bochkarev & Karitskaya 1989; Leahy 1995a, 1997, 2004b; Reynolds & Parmar 1995; Schandl 1996; Scott & Leahy 1999; Shakura et al. 1999; Leahy, Marshall & Scott 2000; Simon et al. 2002; Klochkov et al. 2006; Igna 2010).

In this paper, we continue to investigate Her X-1’s light-curve dips using the most extensive light curve for this system. The Rossi X-ray Timing Explorer (RXTE) satellite has observed the system since 1996 February (Levine et al. 1996). The Massachusetts Institute of Technology’s Kavli Institute and NASA’s High Energy Astrophysics Science Archive Research Center (HEASARC) archives contain more than 15 yr of continuous RXTE/All-Sky Monitor observations...
2 INSTRUMENTATION AND DATA

The PCA detector consists of five large-area, co-aligned, Xenon proportional counters sensitive to 2–60 keV X-rays. Data are recorded in two standard modes: Standard 1 (Std-1) and Standard 2 (Std-2). Std-2 has a time resolution of 16 s and 129 energy channels (Jahoda et al. 1996). We used the Std-2 mode data, which are available from HEASARC in five energy bands: Band 0 (2–9 keV), Band 1 (2–4 keV), Band 2 (4–9 keV), Band 3 (9–20 keV) and Band 4 (20–40 keV).

The entire archived PCA light curve on Her X-1 contains 98907 Std-2 data points acquired as a result of 23 study proposals. A detailed discussion of these data in relation to orbital and 35-d phase was provided by Leahy & Igna (2011).

We calculated softness ratio (SR) values as the ratio of the number of counts in Band 1 to the number of counts in Band 3. The SR can be used to identify dips (Leahy 1995a,b, 1996, 1997; Leahy & Yoshida 1995). We identified light-curve absorption dips over the entire PCA data time range (1996 February 1–2005 August 2) based on SR change: dip ingress coincides with SR decrease, and SR recovery marks dip egress (Fig. 1). SR change is calculated between the out-of-dip or normal SR baseline value characteristic to a particular 35-d cycle and the minimum SR value in a particular dip (Fig. 2). The change was assessed to be significant if greater than three times the uncertainty of this minimum SR value.

We converted barytime to Dynamical Barycentric Modified Julian Day Time (MJD TDB) for our analysis using the HEASARC time conversion guidelines relevant to the RXTE mission. The barytime was obtained from the mission elapsed time, the time associated with each 16 s interval measured onboard the satellite, and archived by HEASARC. The orbital period was averaged over the 1996 February 1–2005 August 2 interval using the ephemeris of Deeter et al. (1991). The details of the orbital and 35-d phase calculations are covered elsewhere (Igna 2010; Leahy & Igna 2010).

3 ANALYSIS AND RESULTS

The PCA light curve on Her X-1 spans, in segments, the 50114.13–53584.32 MJD TDB interval and covers partially 24 MH, 10 SH and 15 LS 35-d X-ray cycle states. The 15 LSs consist of five post-MH (pMH) and 10 post-SH (pSH) LSs. These high and low states belong to 35 different 35-d X-ray cycles.

The MH, SH and LS 35-d phase boundaries were determined from the folded PCA light curve: 0–0.3 (MH), 0.3–0.57 (pMH LS), 0.57–0.75 (SH) and 0.75–1.0 (pSH LS). The 35-d phase calculation in this study is based on 35-d cycle turn-on (TO) times and lengths determined by Leahy & Igna (2010), who considered the variability of the 35-d cycle length. Assuming a constant 35-d cycle length yields erroneous 35-d phases, as well as high- and low-state designations.

3.1 Classification and general properties of Her X-1’s dips detected by the PCA

The SR change (Section 2) relative to the normal SR baseline (Fig. 2) and characteristic to the PCA dips, ranges from 0.02 to 0.53 (or 8.5 to 99.9 per cent). The largest SR reductions were observed in the pre-eclipse (0.65–0.93 orbital phase) and MH regions.

Her X-1’s dips were put into three main classes: class A, B and C. Class A dips have well-defined and detected start and end through clear SR decrease and recovery, and small statistical SR error bars (Fig. 1a, b). Class B dips have larger statistical SR errors, i.e. twice as large on average as class A dips. It is difficult to identify clearly the dip start or end, and match an SR value to a particular MJD or phase when the SR values have large uncertainties. The rest of PCA dips are missing the start, end or both start and end, and, therefore, were included in class C (Fig. 1b,c). We recorded 370 dips based on these definitions: 111 in class A, 18 in class B and 241 in class C. The entire record of PCA dips for the HZ Her/Her X-1 system, including start and end MJDs, is available in Igna (2010).

The dips in the main classes include, sometimes, two or more subdips (Fig. 1b). We define the subdip as the dip whose ingress or egress begins or ends at an SR value that is smaller than the normal SR baseline value (Fig. 2). We identified a total of 162 subdips based on this definition. Most subdips are found in class A; class B has no subdips, while class C contains only 33 subdips. Nearly all subdips occur in MH and the pre-eclipse region.

The PCA light curve contains data gaps that range from 16 s to more than 300 d. Thus, class C dips may be part of longer dips, which we define as long dips (Fig. 1c). We linked the class C dips across these gaps using an upper gap width of 6 h, which is comparable to the neutron star’s eclipse duration. 96 long dips were obtained in this manner, and ~70 per cent of these dips contain several regular gaps that last between 48 and 73 min. Her X-1’s dips can be classified also in terms of the orbital or 35-d phase of minimum SR. In the orbital phase category we distinguish post-eclipse dips (PostED) for 0.07 ≤ ΦPostED < 0.45, anomalous dips (AD) for 0.45 ≤ ΦAD < 0.65, and pre-eclipse dips (PreED) if 0.65 ≤ ΦPreED < 0.93, where Φ is the orbital phase of minimum SR in each dip. Based on this definition, 236 PreEDs, 63 ADs and 71 PostEDs were found in the main classes of dips. Long dips cover substantial extents of the orbital phase: more than 55 per cent of long dips start as PreEDs and about 65 per cent end as PreEDs. Similarly, ~20 per cent start as and only 13.5 per cent end as ADs.

In 35-d phase, we classify dips as MH, SH, pMH or pSH dips. In class A, 101 dips occur during MH and the other 10 during SH. In class B, there are nine MH, eight SH and one pMH LS dips, whereas class C consists of 134 MH, 98 SH, one pMH LS and eight pSH LS dips. The number of PCA dips observed during SH is by far larger than the nine Uhuru (Crosa & Boynton 1980) and 11 Ginga (Leahy 1997) SH dips. 155 subdips occur during MH and the other seven during SH. Over 50 per cent of long dips start in MH and over 40 per cent start and end, respectively, in SH. About 55 per cent of long dips end in MH. The 10 LS dips were detected very close to the high states’ boundaries; thus their designation is questionable, considering the uncertainties of the TOs’ and 35-d cycle lengths’ calculation (Leahy & Igna 2010) and the fact that LS dips have not been previously observed. A slight change of the average high and low states’ 35-d phase boundaries would yield no LS dips at all (Leahy & Igna 2011).

3.2 Duration

Dip duration was measured at full ΔSR (ΔSRp), i.e. Tp and Tp in Fig. 2, as well as at ΔSRpre per cent (i.e. Tpre per cent and Tpre per cent in Fig. 2). The use of ΔSRpost per cent can reduce errors associated with the uncertain designation of dip start or end. The longest dips reach 37.9 min (40.3 min at ΔSRp) in class A and 58.1 min in class C. The
Her X-1’s RXTE/PCA light-curve dips

shortest, completely detected, dip lasts \(32 \text{s at } \Delta \text{SR}_{50 \text{per cent}} \) (64 s at \( \Delta \text{SR}_p \)) and belongs to class A. The subdips’ durations range from 48 s to 30 min, with an average of 5.6 min and a standard deviation of 5.6 min. The longest subdips in the PCA light curve were detected in mid-MH.

Most of the class A and B dips last less than 10 min (Fig. 3) regardless of which \( \Delta \text{SR} \) is used, whereas most class C dips exceed 10 min. The long dip analysis revealed that Her X-1’s dips can be as long as 15 h. The majority of long dips last 1–2 h at both \( \Delta \text{SR} \) measures. The upper panel of Fig. 3 shows that the dip duration increases with the orbital phase, while the lower panel indicates that dip length peaks at the end of MH.

Table 1 contains the average ingress, egress and full lengths of a combined set including class A, B and the long dips. This set is

Figure 1. SR versus orbital cycle and (a) example of a strong pre-eclipse class A dip with no subdips. The vertical arrow points to the central part of the dip. (b) Example of a sequence of well-defined pre-eclipse class A dips, with multiple subdips, which ends with a class C dip. The vertical arrows point to the central part of the class A dips. (c) Example of a pre-eclipse long dip obtained by linking several shorter class C dips across the gaps among them. The vertical arrows point at the poorly detected class C dips.
Figure 2. Schematic light-curve dip event, which recovers to the same normal SR baseline (i.e. SR = SR_E). The full and 50 per cent SR changes (ΔSR_F and ΔSR_{50\text{ per cent}}) are used to calculate two sets of dip duration measures (see the text for details). The total dip duration is calculated with equations (3) and (4). T (time), F (full), I (ingress) and E (egress).

Figure 3. Dip lengths calculated at ΔSR_{50\text{ per cent}} (equation 4) versus the orbital phase (upper panel) and 35-d phase (lower panel). The orbital and 35-d phases are those of minimum SR in each dip. The plot includes all class A and B dips, and 15 class C dips for which the ΔSR_{50\text{ per cent}} dip duration could be calculated.

Table 1. Average ingress, egress and full duration of class A, B and the long dips.

<table>
<thead>
<tr>
<th>Nr.</th>
<th>PostED (min)</th>
<th>AD (min)</th>
<th>PreED (min)</th>
<th>MH (min)</th>
<th>pMH LS (min)</th>
<th>SH (min)</th>
<th>pSH LS (h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.8(1.8)</td>
<td>2.4(4.2)</td>
<td>8.4(30.6)</td>
<td>7.2(28.8)</td>
<td>0.24(–)</td>
<td>2.4(3.6)</td>
<td>–</td>
</tr>
<tr>
<td>2</td>
<td>1.8(3.0)</td>
<td>11.4(22.8)</td>
<td>9(25.8)</td>
<td>9(24.6)</td>
<td>3(–)</td>
<td>4.8(14.4)</td>
<td>–</td>
</tr>
<tr>
<td>3</td>
<td>3.6(4.8)</td>
<td>13.8(25.8)</td>
<td>17.4(49.8)</td>
<td>16.2(47.4)</td>
<td>3(–)</td>
<td>7.8(18)</td>
<td>–</td>
</tr>
<tr>
<td>4</td>
<td>17.4(52.8)</td>
<td>24.0(48.0)</td>
<td>11.4(30.6)</td>
<td>10.8(29.4)</td>
<td>0.6(–)</td>
<td>28.8(58.8)</td>
<td>–</td>
</tr>
<tr>
<td>5</td>
<td>36.6(45.6)</td>
<td>28.2(31.2)</td>
<td>11.4(27.0)</td>
<td>6.6(15.0)</td>
<td>70.8(–)</td>
<td>55.8(46.8)</td>
<td>–</td>
</tr>
<tr>
<td>6</td>
<td>117.6(210)</td>
<td>144.6(228)</td>
<td>58.2(108)</td>
<td>49.8(90.0)</td>
<td>22.2(23.4)</td>
<td>144.6(210)</td>
<td>9.8(6.4)</td>
</tr>
</tbody>
</table>

Rows 1, 2 and 3 contain the average ΔSR_{50\text{ per cent}} dip ingress, egress and full length, respectively, with the corresponding standard deviation in brackets. Rows 4, 5 and 6 contain the same measures, but at ΔSR_E. These values were calculated for the following dip categories: PostED, AD, PreED, MH, SH, pMH LS, pSH LS in a set of dips consisting of class A, B and the long dips. Each dip category is defined by the orbital or 35-d phase of dip ingress. Missing standard deviation values indicate one-dip samples.
the most representative sample of PCA dips of all lengths. Using 
\( \Delta SR_{50\text{ per cent}} \), dips that start in the pre-eclipse region have longer
 ingress on average than PostEDs and ADs. The dips that start as ADs
 have a longer average egress than PostEDs and PreEDs. Similarly,
 dips that start in MH have a longer average ingress and egress than
 SH and LS dips. PreEDs have a longer average full duration at
 \( \Delta SR_{50\text{ per cent}} \) than ADs, which are longer than PostEDs. Similarly,
 MH dips are longer than SH dips on average. The average full
 length, ingress and egress trends at \( \Delta SR_{50\text{ per cent}} \) are not similar to
 those at \( \Delta SR_F \). Nevertheless, the \( \Delta SR_{50\text{ per cent}} \)-based duration
 is probably more accurate for Her X-1’s dips in the PCA light
curve.

We also calculated the difference between dip durations at \( \Delta SR_F \)
 and \( \Delta SR_{50\text{ per cent}} \) for each dip (equations 1 and 2), and used it
to measure the time-to-ingress (T\(_I\)) and time-to-egress (T\(_E\)). A
long T\(_I\) implies slow dip ingress, while short T\(_E\) marks fast dip
recovery. The upper panel of Fig. 4 shows that T\(_I\) and T\(_E\), relative
to the full dip length T\(_F\) (equation 3), decrease with the orbital
phase. There is no clear trend with 35-d phase, and similar to T\(_F\)
the trend is not a strong trend. Also, the apparently increasing trend of
T\(_{50\text{ per cent} I}\) and T\(_{50\text{ per cent} E}\) relative to T\(_F\), with the orbital phase in
the lower panel of Fig. 4 is not a strong trend, and similar to T\(_F\)
and T\(_E\) there is no clear trend with 35-d phase for T\(_{50\text{ per cent} I}\) and
T\(_{50\text{ per cent} E}\) either. The sum of T\(_I\) and T\(_E\) is less than half the full
dip length for the majority of dips, i.e. Her X-1’s dips spend a larger
time fraction below \( \Delta SR_{50\text{ per cent}} \). Confirming this, the sum of dip
lengths at \( \Delta SR_{50\text{ per cent}} \) divided by the sum of dip lengths at \( \Delta SR_F \)
exceeds 60 per cent for each dip class.

\[
T_I = T_F - T_{50\text{ per cent} I} \tag{1}
\]

\[
T_E = T_F - T_{50\text{ per cent} E} \tag{2}
\]

\[
T_F = T_I + T_E \tag{3}
\]

\[
T_{50\text{ per cent}} = T_{50\text{ per cent} I} + T_{50\text{ per cent} E} \tag{4}
\]

3.3 The 35-d phase–orbital phase trend

Fig. 5 shows the PCA dips in the 35-d phase–orbital phase plane.
Fig. 5(a) displays a distinct clustering pattern for class A and B
dips past orbital phase 0.6 in MH, consistent with the clustering in
Fig. 3. A marching dip trend towards earlier orbital phases, as the
35-d cycle progresses, is seen in the plots of Fig. 5, but only for
PreEDs in MH. This trend is less clear for class C and the long dips,
which contain a large number of SH dips that occur throughout the
orbital cycle with no specific trend.

The dip marching phenomenon was noted for MH PreEDs and
MH ADs soon after the discovery of Her X-1’s light-curve dips
(Giacconi et al. 1973; Crosa & Boynton 1980). The large number of
PCA dips analysed here shows more clearly, particularly in Fig. 5(b),
the full pattern of dip occurrence in the 35-d phase–orbital phase
plot for the HZ Her/Her X-1 system.

3.4 Symmetry

Fig. 6 shows ingress versus egress durations, measured at
\( \Delta SR_{50\text{ per cent}} \), for class A, B and C dips. The majority of dips have
very different ingress and egress durations. The ingress can be
as long as 40 times the egress length. 55.6 per cent of these dips
(52.6 per cent at \( \Delta SR_F \)) have longer ingress than egress. This is con-
firmed also by the average \( \Delta SR_{50\text{ per cent}} \)-based ingress and egress lengths
of class A, C, A+B+C and A+B+I-long dips. Longer egress than
ingress is seen for most long dips, and on average only for class B,
subdips and long dips at both \( \Delta SRs \).

The statistical significance of the difference between ingress and
egress durations was assessed by a generalized \( \chi^2 \) test. Fig. 6 con-
tains only 144 dips out of the 370 dips; hence, we considered the fol-
lowing samples in our statistical analysis: class A, A+B, A+B+C,
subdips, A+B+long dips and A+B+C+long dips+subdips. Because
of the large differences in dip durations in the A+B+C+long
dips+subdips set, e.g., subdips and long dips, we used the ratio
of ingress and egress lengths to the corresponding full dip
length for the statistical analysis of this set. These ratios are nearly evenly distributed above and below the line of equal ingress and egress, similar to Fig. 6 (i.e. the $T_{50 \text{percent}_I} = T_{50 \text{percent}_E}$ line). 40 $\chi^2$ tests were necessary for all these sets. The 16 s PCA bin size was propagated to estimate dip duration uncertainties. Both $\Delta SR_0$ and $\Delta SR_{50 \text{percent}}$ ingress and egress lengths were binned in orbital and 35-d phase, for these tests, using a 0.1 phase bin size and the minimum SR phases. The orbital and 35-d phases of ingress and egress were used only for binning long dip lengths. 36 $\chi^2$ tests yield the ingress and egress durations to be significantly different at confidence levels exceeding 99 per cent, while the 95 per cent level is exceeded by three out of the remaining four tests.

The ADs and the pMH LS dips are the most asymmetric based on the average egress-to-ingress duration ratio. PreEDs and MH dips have similar average asymmetry values, which are lower than those of ADs and pMH LS dips, but higher than those of SH dips and PostEDs.

Figure 5. 35-d phase versus orbital phase graph for (a) class A and B dips, (b) class C dips and (c) the long dips. The orbital and 35-d phases were calculated for the minimum SR of each of class A, B, and C dips, and for the ingress and egress SR of each long dip.
3.5 Intensity

The SR can be used as a measure of dip intensity: the smaller the minimum SR and higher the change relative to the normal baseline (Fig. 2) the more intense the dips. On average, ADs and PreEDs are more intense than PostEDs, while MH dips are stronger than SH and LS dips.

We also calculated neutral hydrogen ($N\text{\textsubscript{H}}$) column densities using HEASARC’s online WebPIMMS (Portable, Interactive, Multi-Mission Simulator) calculator and the dips’ minimum SR values. The derived $N\text{\textsubscript{H}}$ values range from $5.7 \times 10^{22}$ to $9.2 \times 10^{23}$ cm$^{-2}$. PreEDs have larger average peak $N\text{\textsubscript{H}}$ densities than ADs, while ADs are stronger than PostEDs. PreEDs also have the largest peak $N\text{\textsubscript{H}}$ in the orbital phase category, in the PCA light curve. MH dips have larger average peak $N\text{\textsubscript{H}}$ densities than SH dips, although the largest peak $N\text{\textsubscript{H}}$ in the PCA light curve was detected for an SH dip, in both orbital and 35-d phase. In 35-d phase, the largest peak $N\text{\textsubscript{H}}$ densities were detected in the high states.

4 DISCUSSION

4.1 Detailed properties of Her X-1’s light-curve dips

Crosa & Boynton (1980), the most extensive study prior to this study in terms of the number of Her X-1 light-curve dips analysed and the extent of the observation period ($\sim$4 yr), documented a total of 91 dips, which constitute less than a quarter of the dips analysed in this study. The light-curve data analysed by Crosa & Boynton (1980) were recorded by five different satellites and contained much fewer SH dips, and no completely detected PostEDs. The duration of their dips ranges from 2.3 to 18.4 h, and about 40 per cent of them have lengths of 3–4 h.

The PCA light curve contains a larger number of PreEDs (in the orbital phase category) and MH dips (in 35-d phase) than any other type of dips (Section 3.1). The PreEDs and MH dips are the most numerous dips in the Crosa & Boynton (1980) data sample, also. The large number of PreEDs and their long durations (Section 3.2) are consistent with the higher fraction of the observation time in dips in the pre-eclipse region of the PCA light curve (fig. 7 in Leahy & Igna 2011). Nevertheless, the fraction of the observation time in dips is higher in SH than in MH (fig. 8 in Leahy & Igna 2011) despite the larger number of detected MH dips and their long durations. The large number of PreEDs and MH dips was also confirmed by normalizing the number of class A, B and C dips to the number of PCA data points in 0.05-wave phase bins (Igna 2010). This normalization is necessary in order to reduce the biasing effect of having the PCA detector pointed preferentially at Her X-1 while in MH or the pre-eclipse region. Only class C contains a larger normalized number of SH dips, which is probably consistent with Leahy & Igna’s (2011) fig. 8 trend considering the significantly larger number of class C dips and their long durations observed in the PCA light curve.

The dips analysed by Crosa & Boynton (1980) are definitely longer than many of the dips extracted from the PCA data, especially longer than the class A, B and C dips. The long dip analysis in our study supports the existence of dips that last hours. Dip lengths of 1–5 h were reported by Giacconi et al. (1973), Ulmer et al. (1973) and Becker et al. (1977) for Her X-1. Scott & Leahy (1999) measured PreED and AD widths of 5–10 h in the RTXE/ASM light curve. EXOSAT-based dip analyses for Her X-1 indicate that PreEDs last $\sim$3 h and ADs $\sim$1 h (Reynolds & Parmar 1995) or $\sim$0.5 h (Voges, Atmanspacher & Scheingraber 1987). These EXOSAT observations are supported by two Tenma PreED sightings of 0.8 and 2.9 h, respectively (Ushimaru et al. 1989). Nevertheless, Ginga-based observations of 30 s–1 h dip lengths (Leahy 1997) are more consistent with the PCA-based results for class A, B, C dips and subdips in our study.

Despite some similarity between the trends of PCA dips and Crosa & Boynton’s (1980) observations, a linear relation would not describe accurately the plots in Fig. 5 due to the extensive spread of PCA dips in both orbital and 35-d phase. The wide-band of PCA SH dips, best seen in Fig. 5(b,c), is a newly observed feature of Her X-1’s dips, and a consequence of PCA’s superior coverage of the 35-d cycle (Leahy & Igna 2011). Our analysis does not confirm Crosa & Boynton’s (1980) expectation that Her X-1’s dips should march towards earlier orbital phases along fixed diagonal lines, except in the MH pre-eclipse region. Also, our results do not confirm Crosa & Boynton’s (1980) assumption that the TOs observed around 0.3 or 0.7 orbital phase are in fact PreEDs, which recur in future observations. The orbital phases of Her X-1’s 35-d cycle TOs cover homogeneously the entire orbital cycle (Leahy & Igna 2010). Also, very few dips have been observed, by the
PCA, in the region where Crosa & Boynton (1980) predicted the recurrence of PreEDs.

The binned SR of the PCA light curve (Section 2) decreases with the orbital phase (Leahy & Igna 2011) due to the larger number of dips and their increasing strength and duration at higher orbital phases (Fig. 3, upper panel). The SR trend appears stronger when plotted for the dips only (figs 4.8 and 4.13 in Igna 2010). This effect was first noted for Her X-1 by Leahy (1997) based on Ginga light-curve data. The associated $N_H$ values are in good agreement with previously estimated values for Her X-1’s dips (Giacconi et al. 1973; Ulmer et al. 1973; Becker et al. 1977; Howarth & Wilson 1983a; Voges et al. 1985; Bochkarev & Karitskaya 1989; Ushimaru et al. 1989; Mihara et al. 1991; Scott 1993; Choi et al. 1994; Reynolds & Parmar 1995; Leahy 1997; Inam & Baykal 2005). The PCA PreEDs’ higher $N_H$ densities confirm previous EXOSAT (Reynolds & Parmar 1995) and RTXE/ASM (Inam & Baykal 2005) observations.

4.2 The dip production mechanism in the HZ Her/Her X-1 system

The spectra of Her X-1’s dips present evidence of absorption in cool or partially ionized matter, X-ray scattering in the accretion disc’s corona, as well as Thomson scattering in fully ionized gas (Ushimaru et al. 1989; Mihara et al. 1991; Scott 1993; Choi et al. 1994; Leahy 1995a; Reynolds & Parmar 1995).

The production of light-curve dips was attributed to direct or indirect, periodic, occultation of the X-ray source. Several models and scenarios were proposed to explain the occultation mechanism: (i) directly, due to the periodic oscillation of Her X-1’s outer accretion disc edge under the action of the accretion stream torque (Leahy 1997; Shakura et al. 1999; Klochkov et al. 2006); (ii) by intervening material supplied directly by the accretion stream (Giacconi et al. 1973; Crosa & Boynton 1980; Howarth & Wilson 1983a,b; Voges et al. 1985; Bochkarev & Karitskaya 1989; Shakura et al. 1999) or (iii) indirectly through accretion stream-accretion disc impact (Crosa & Boynton 1980; Howarth & Wilson 1983a,b; Voges et al. 1985; Bochkarev & Karitskaya 1989; Schandl 1996; Leahy et al. 2000; Simon et al. 2002; Leahy 2004b; Foulkes, Haswell & Murray 2010; Igna 2010). Many of the earlier models are considered unsatisfactory (Reynolds & Parmar 1995; Leahy 1997; Scott & Leahy 1999). None of the proposed models addresses the observed orbital and 35-d phase trends of Her X-1’s dips’ intensity, duration and number, but focus exclusively on reproducing the timing and occurrence phase of dips.

Our results indicate that light-curve dip production in the HZ Her/Her X-1 system is a very complex process. The large number, long duration and high intensity of MH and PreEDs suggest that the X-ray-absorbing material is denser or the observer’s line of sight to the X-ray source is closer to the site of impact between accretion stream and disc during MH and pre-eclipse. The general marching dip effect can be explained based on the geometry of the accretion stream and disc impact, as well (Schandl 1996; Igna 2010); nevertheless, the marching trend of PCA dips is more complex and detailed. Dips’ properties such as the band of SH dips in the 35-d phase–orbital phase plane, symmetry, time to ingress and egress, subdips and the associated orbital and 35-d phase trends, which were presented and discussed here for the first time, remain yet to be reproduced and explained through modelling. Although not yet observed in the HZ Her/Her X-1 system, the formation of fast-moving jets upon the impact of stream and disc (Richards 2007) might explain the variable density of the X-ray-absorbing material, the production of subdips or the observed symmetry and the time to ingress and egress trends. Modelling the complex production mechanism and detailed properties of Her X-1’s dips is beyond the scope of the current study, and it will be addressed in a future publication.

5 CONCLUSION

In this paper, we analysed 370 new dips from the entire archived PCA light curve on Her X-1, and confirmed previous observations and documented new properties. These dips, which include the first documented sequence of subdips, constitute the most extensive record of Her X-1 dips (available in Igna 2010) produced as a result of a single study.

Overall, the PCA dips’ lengths range from 32 s to nearly 15 h. The longest, completely detected, PCA dip lasts ~40 min, while most completely detected dips are shorter than 10 min. Dip duration depends on the orbital and 35-d phases. The pre-eclipse and MH dips have the longest lengths and ingresses, while MH dips have the longest egresses. There is some evidence of faster dip ingress and egress, as the orbital cycle progresses, but this is not a strong trend.

The marching dip effect towards earlier orbital phases, as the 35-d cycle progresses, is confirmed by our study, but only for pre-eclipse dips in MH. A significantly larger number of SH dips was obtained from the PCA light curve than in any previous study. These dips extend across the entire orbital cycle and SH state offering a unique and more complete representation of the occurrence pattern of Her X-1’s dips in the 35-d phase–orbital phase plane.

Her X-1’s symmetry was investigated here for the first time. Most dips are highly asymmetric. The dips’ asymmetry, evaluated by the ratio of egress length-to-ingress length, depends on the orbital and 35-d phases.

The dips that occur in MH and the pre-eclipse region are the most intense and numerous. The dip intensity, evaluated based on SR change and the associated neutral hydrogen column density ($N_H$), depends strongly on the orbital phase. The results of the $N_H$ analysis are supported by previous studies.

The various properties of Her X-1’s dips indicate that the dip production mechanism is very complex. New and improved models are required to explain these properties.

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REFERENCES
