Swift/BAT and RXTE/ASM Observations of the 35 day X-Ray Cycle of Hercules X-1

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Abstract
Swift/BAT and RXTE/ASM observations have monitored the X-ray binary system Her X-1 for approximately 14.5 yr each, and both were monitoring Her X-1 for a period of ~5.5 yr. Here we study the 35 day cycle using these observations. Using a cross-correlation method we find the times of peaks of the 35 day cycles for ~150 cycles observed by Swift/BAT and ~150 cycles observed by RXTE/ASM. These cycles include ~60 observed with both instruments. The noise level of the RXTE/ASM measurements is larger than that of Swift/BAT, resulting in larger uncertainty in peak times. The distribution of 35 day cycle lengths can be fit with a Gaussian with mean 34.79 days and σ of 1.1 days. The distribution of orbital phases of 35 day cycle peaks is well fit by a uniform distribution, with 76% of the cycles, plus a Gaussian distribution peaked at orbital phase ~0.5, with 24% of the cycles. We construct the long-term average 35 day lightcurve in the 15–50 keV band from Swift/BAT, and in the 2–12 keV band from RXTE/ASM. The high-energy band shows more variability in the short high state and the low-energy band shows more variability in the main high state. This is consistent with a precessing accretion disk model as the cause of the 35 day cycle.

Unified Astronomy Thesaurus concepts: Hz Herculis x-ray binary stars (777); X-ray photometry (1820); Neutron stars (1108)

Supporting material: machine-readable tables

1. Introduction
Her X-1/HZ Her is an X-ray binary pulsar, a category of object that is the subject of ongoing research. Leahy & Chen (2019) report a spectral analysis of AstroSat Soft X-ray Telescope observations of Her X-1 during the low state, turn-on, the main high state (hereafter MH) and MH during dip. Wolff et al. (2016) use the NuSTAR X-ray spectrum of Her X-1 as a testbed for radiation-dominated radiative shock models of the accretion column. Simon (2015) compares long-term RXTE/ASM X-ray monitoring with AAVSO optical data to show the X-ray MH state fluence is considerably more variable than the optical fluence. Leahy (2015) utilized RXTE/PCA X-ray eclipse observations to detect and measure the extended scattering corona in the binary system. The masses and uncertainties of the neutron star (Her X-1, ~1.5 M⊙) and its stellar companion (HZ Her, ~2.3 M⊙) are reviewed in Leahy & Abdallah (2014) and Reynolds et al. (1997).

The 35 day cycle, consisting of consecutive MH, low state, short high state and low state, has been monitored with a number of satellites. The rapid rise to MH occurs over a timescale of ~3 hr (e.g., Figure 3 of Scott et al. 2000) and is called turn-on. We analyzed 23 cycles from RXTE/ASM observations by were analyzed by Shakura et al. (1998) and by Scott & Leahy (1999). These studies measured accurately the mean 35 day lightcurve for the first time, measured dip behavior, and derived sets of turn-on times. Leahy & Igna (2010) and Staubert et al. (2013) analyzed more than 10 yr of RXTE/ASM observations to characterize cycle length variability. Leahy & Igna (2010) analyzed turn-on phases of the 35 day cycle and found a uniform distribution with orbital phase.

Her X-1 occasionally shows lengthy time periods, anomalous low states (ALSs), during which the 35 day cycle shuts off in X-rays, as first discovered by Parmar et al. (1985), who suggested a change in disk structure as the cause. ALSs are further studied in Parmar et al. (1999) and Coburn et al. (2000), where changes in the warp of the disk or decreases in disk inclination, respectively, were proposed as the causes of the ALS. Subsequent work showed that the 35 day cycle continues in the optical during X-ray ALSs (Jurua et al. 2011). Leahy & Dupuis (2010) analyzed EUV observations of Her X-1 during the anomalous low state. They modeled the orbital modulation of the EUV emission from the heated face HZ Her, and found a thicker accretion disk than that for normal 35 day cycle. The thicker disk is sufficient to block the compact X-ray emission but not to block the emission from HZ Her.

Multiwavelength studies of the Her X-1/HZ Her system are possible because different parts of the system radiate in optical, ultraviolet, extreme ultraviolet (EUV), and X-rays. Systematic variations of the 1.7 day optical lightcurve (Gerend & Boynton 1976) give strong evidence of a Roche-lobe-filling precessing accretion disk. The physics of precessing accretion disks have been successfully modeled by Wijers & Pringle (1999), which yields a disk like that measured for Her X-1 by Leahy (2002). The EUV emission from Her X-1 is from the inner disk and from the irradiated surface of HZ Her (Leahy & Marshall 1999; Leahy 2003). Accretion of matter onto the rotating neutron star produces X-rays (>1 keV).

The X-ray pulsations have been modeled as emission from an accretion column geometry subsequently modified by light-bending in the neutron star’s gravity (Leahy 2004a, 2004b). The pulse shape changes systematically over the 35 day cycle (Leahy et al. 2000 and references therein). The cause of the pulse shape changes is explained by systematic changes in obscuration by the precessing accretion disk (Leahy et al. 2000), or alternately by neutron star free precession (Postnov et al. 2013 and references therein). Staubert et al. (2013) compared turn-on times measured from the flux variations with time from RXTE/ASM observations with turn-on measured using pulse profile variations, mainly from RXTE/PCA observations. The two measurements of turn-on agree,
implying a single clock mechanism behind the 35 day flux cycle and the 35 day pulse shape change cycle and raising serious questions about the free precession mechanism. Subsequently, Postnov et al. (2013) devised a free precession model that gives the approximate agreement of the 35 day flux cycle with the 35 day pulse shape change cycle.

The atmosphere of HZ Her causes X-ray absorption, which is detected during eclipse ingresses and egresses (Day et al. 1988; Leahy & Yoshida 1995). X-rays reflected off the companion star are detected during the low state and short high state (Abdallah & Leahy 2015). Timing of MH ingresses and egresses has enabled accurate determination of the radius of HZ Her (Leahy & Abdallah 2014). Overall, the regular time variations in Her X-1 are understood to be caused by the geometry of the system, i.e., Roche-lobe filling companion, accretion disk, and stream.

The X-ray flux and pulse shape systematic changes over a 35 day cycle. These are caused by the precessing accretion disk in the system (Scott et al. 2000). The disk occults the line of sight to the neutron star during during the low state, and to a lesser extent during the MH turn-on and short high state. The geometry of the accretion disk has been measured by applying tilted-twisted disk models (Leahy 2002, 2004c and Leahy et al. 2020). The well-known X-ray absorption dips are caused by the accretion stream connecting HZ Her to the disk (Igna & Leahy 2011 and Igna & Leahy 2012).

Here we carry out a new study of the long-term properties of the 35 day cycle of Her X-1, by analyzing Swift/BAT and RXTE/ASM monitoring observations. In Sections 2 and 3 we describe the observations and data analysis of the 35 day cycle lightcurve of Her X-1. In Section 4, we discuss the results and what they imply for the physical mechanisms for the 35 day cycle. We summarize the work in Section 5.

2. Observations

2.1. Swift/BAT Observations

The Burst Alert Telescope (BAT) on board the Neil Gerels Swift Observatory is described by Krimm et al. (2013). BAT is used to monitor X-ray sources on a regular basis and to create long-term lightcurves for these sources. The data are available at the website https://swift.gsfc.nasa.gov/results/transients/. For Hercules X-1, we downloaded the data for the energy range of 15–50 keV, covering 14 yr of observation with 71165 points from February 2005 to November 2019. The top panel of Figure 1 shows a sample of the Swift/BAT lightcurve of Her X-1. The 35 day cycle of Her X-1, as quantified by, e.g., Scott & Leahy (1999) and Leahy (2004c), is clearly seen in the data;
the large peak is for the MH state and the smaller peak is for the short high state.

The Swift/BAT orbital lightcurve has time as mission time in units of seconds. We used the standard conversion into fractional Modified Julian date in terrestial time (TT): \( \text{time}_\text{ref} = \frac{\text{time}_{\text{BAT}}}{24 \times 3600} + \text{MJD}_{\text{ref}} \) with \( \text{MJD}_{\text{ref}} = 51,910.00074287038 \). Swift/BAT has time in TT, while the standard time system for astronomical sources is barycentric dynamical time (TDB), which is TT transformed to the solar system barycenter. The maximum correction between the two time systems in the Swift/BAT observations is 0.0016582 s, corresponding to a difference in orbital phase of \( 1.1 \times 10^{-8} \). We ignore the difference in our data analysis.

There is an additional time correction to barycenter from varying light travel time from Her X-1 to Earth throughout the year. For the ecliptic latitude of Her X-1 \( b = 57^\circ.493779 \), the maximum correction is \( \frac{r \cdot \vec{n}}{c} = \left( \frac{1 \text{ au}}{\cos b} \right) \approx 268.17 \text{ s} \), where \( r \) is the vector from barycenter to Earth; \( \vec{n} \) is the unit vector from Earth to Her X-1; and \( c \) is the speed of light. The result is \( \sim 1.8 \times 10^{-3} \) in units of 1.7 day orbital phase or \( \sim 9 \times 10^{-5} \) in units of 35 day phase. This difference is small enough for analysis of the 35 day cycle that we do not include it here.

### 2.2. RXTE/ASM Observations

The Rossi X-Ray Timing Explorer (RXTE) All-Sky Monitor (ASM; Levine et al. 1996) monitored the sky in the 2–12 keV energy band. The RXTE/ASM lightcurves for Her X-1 were obtained from the Massachusetts Institute of Technology (MIT) RXTE project online database at [http://xte.mit.edu/asm/ASM.html](http://xte.mit.edu/asm/ASM.html). Time in the RXTE/ASM observations is in units of MJD (TT). For both the Swift/BAT and RXTE/ASM observations, the orbital phase is not important in this analysis and is ignored. The same conversion to orbital phases as for the Swift/BAT observations is performed. The data cover the time period from 1996 January to 2011 December, with a total number of 95782 points. The sum (2–12 keV) band intensity and uncertainty are used here. The bottom panel of Figure 1 shows a sample of the RXTE/ASM lightcurve of Her X-1. The 35 day cycle is seen in the RXTE/ASM data, but the data have ~twice the noise level as the Swift/BAT data.

### 3. Cross-correlation (CC) Analysis

To identify individual 35 day cycles and determine their timing, we use the CC method. CC measures the similarity of a section of data with a given function or template. The CC value is calculated between the template and the data. For every data point we use a section of data with a length of one 35 day cycle. The CC has a local maximum when the data and the function are best aligned in time. Thus, we use the peaks in CC versus time to determine the peak times of the 35 day cycle in Her X-1.

Because X-rays from Her X-1 are blocked by its companion star during eclipse, the lightcurves contain intervals of sharply lower flux during eclipse. To avoid these eclipses affecting the CC analysis, we remove data during eclipse periods prior to the CC analysis. We use the orbital ephemeris for Her X-1 from Staubert et al. (2009). Orbital phase zero is defined as mid-eclipse of Her X-1 by its companion Her HZ.

Eclipse during the MH state of Her X-1 lasts from orbital phase 0.935 to 1.065 (Leahy & Yoshida 1995). Eclipses can last longer because of dips and other extended structures in the system at different 35 day phases, as shown by Leahy (1995) and Leahy & Igna (2011). Thus, for the CC analysis we removed all data during eclipse plus an extra 0.095 in orbital phase, i.e., we keep data only during the orbital phase interval 0.16 \( \leq \phi \leq 0.84 \). After the above selection, 67.9% of the original data points remain.

To avoid having data gaps caused by eclipse removal, the in-eclipse data were replaced by interpolation between the corresponding edge points in the original observations. The values were drawn from a Gaussian distribution, where the mean is the average of the two edge points, and the standard deviation is the sum of the rate errors of the two edge points. Rate errors are taken as the standard deviation.

The previous analysis of RXTE/ASM data by Leahy & Igna (2010) employed the CC method. This produced a template from RXTE/ASM observations. We use their template as the input template for the first iteration of the CC method, for both the Swift/BAT observations and the RXTE/ASM observations. Then we use the observations to improve the shape of the template iteratively, as described below.

For this study we define the peak of the 35 day cycle to be 35 day phase 0. We can convert to the standard definition of the start of a 35 day cycle as the X-ray turn-on by subtracting the phase difference from the turn-on to the peak of MH. The turn-on has different definitions, but a commonly used one is the time that the lightcurves reach 20% of the peak intensity during the following MH. The conversion from a 35 day cycle peak time to a 35 day cycle turn-on time depends on the shape of the lightcurve. For our final templates for Swift/BAT and RXTE/ASM, turn-on time occurs approximately 0.13 in a 35 day phase prior to the peak time. To avoid having the MH or short high peaks near a boundary in the template function, we define the template phase to range from \(-0.3 \leq \phi_{35d} < 0.7\), where \( \phi_{35d} \) is the 35 day phase.

#### 3.1. Weighted CC Function

The CC method was introduced for Her X-1’s 35 day cycle by Leahy & Igna (2010). We modify the method to be less sensitive to data with large relative errors by introducing a weight to the CC function. The resulting weighted CC function that we use is

\[
CC_n \equiv \sum_{k=0}^{N_\text{pts} - 1} \frac{R_k \times T_k \times \omega_k}{\sum_{k=0}^{N_\text{pts} - 1} T_k \times \omega_k}
\]

where \( R_k \) is the count rate, \( T_k \) is the template value, \( \epsilon_k \) is the count rate error, and \( \omega_k = \frac{1}{\epsilon_k} \) is the weight.

For each data point at time \( t_n \), we calculate the \( CC_n \) value with the following procedure:

1. Find the data point closest to \(-0.3 \times t_{35d} \) days previous in time, \( t_1 \), and the data point closest to \(+0.7 \times t_{35d} \) days later in time, \( t_2 \), where \( t_{35d} = t_2 - t_1 \) is the length of the 35 day cycle for that piece of data. The corresponding number of points is \( N_\text{pts} \) between these two data points.
2. For all points \( t_k \) in this interval \( 0 \leq k < N_\text{pts} \), convert the times of the data \( t_k \) to 35 day phases \( \phi_k \) using \( t_{35d} \).
3. With the list \( \{ \phi_k \} \), we find the corresponding template values \( T_k \) by interpolation from the template. We use cubic spline interpolation because the template is
relatively smooth. We verified that cubic interpolation works better than linear interpolation.

4. We calculate CC with Equation (1) for this point.

After calculating CC values for all data points n, we find the peaks in CC values to obtain the times of the peaks of the 35 day cycles, r_{n,peak}. These peak times correspond to 35 day phase 0 for each cycle.

To avoid peaks from times when the data are noisy, we only keep peaks in CC value above a certain threshold. The nominal value for the threshold is \sim 0.4 of the globally highest CC value, but it is adjusted manually when there is a clear CC peak above the noise. The false peaks due to noise in CC are removed manually using inspection of the CC function and the data. From the set of all detected 35 day cycles, we obtain a list of peak times. Whenever there are two adjacent peak times we calculate the cycle length as the difference in peak time between the current cycle and the subsequent cycle.

To obtain a refined template, we create an average of the detected 35 day cycles for the new template. To obtain the same time sampling for averaging, we linearly interpolate the data from individual cycles. Thus, the output template from CC is constructed with better phasing than the input template.

Thus, with the output template, the CC function is recalculated to obtain a new set of 35 day peak times, new cycle lengths, and a new template.

This iterative process is carried out until convergence of peak times, cycle lengths, and template. We compared the difference in peak times and cycle lengths between one iteration and the next iteration. Convergence is verified by the differences converging to 0. For the Swift/BAT data we used seven iterations.

3.1.1. CC Function for Swift/BAT Data

The top two panels of Figure 2 show a subset of the data and the corresponding CC function from the final CC iteration on the BAT data. The final BAT template from the CC analysis is shown in the bottom panel. As a final step, we linearly interpolate between cycles with peak times measured by the CC analysis to estimate peak times and cycle lengths for those cycles that are not clearly detected by the CC analysis.

3.1.2. CC Function for RXTE/ASM Data

We apply the same analysis to the ASM data. In contrast to the results for the BAT data, the results for the ASM data...
converge for ~4–5 iterations, then cease to converge further. We carried out seven iterations of CC analysis for the ASM data. The top panel of Figure 3 shows the templates for the last three iterations (numbers 5, 6, and 7) from the CC method applied to the ASM data. The template changes slightly from iteration to iteration. The bottom panel shows the histogram of time differences in peak times between successive iterations of the CC method on the ASM data. Most cycles agree within a few hours, as shown by the peak with a time difference close to 0. However, there are a significant number of cycles that do not converge in successive peak times, with time differences between −1.5 and +1.5 days.

We calculated the standard deviation, $SD_{dt}$, of the difference in peak times between iterations. $SD_{dt}$ decreases slowly as more iterations are performed, e.g., between iterations 2 and 7 it decreases from 0.5 days to 0.35 days. However, the SD of the change orbital phase of peak time, $SD_{d\phi_{orb}}$, does not decrease as iteration number increases. This latter result can be explained from the distribution of the change in peak times shown in the bottom panel of Figure 3: the relatively constant fraction of cycles that are not measured well (with $dt$ up to 1.5 days) dominate $SD_{d\phi_{orb}}$.

Despite the less stable behavior of the iterations for the ASM data, the differences compared to the previous iteration are within 1.5 days for all peak times, and within ~0.8 days for 70% of the cycles. We tested separating out the cycles with <0.8 day differences to perform CC iterations. However, we found that the specific cycles with small timing errors changed with each iteration, so overall there was not a significant improvement in results. The results in Section 4 are based on all CC-detected cycles from ASM data.

### 4. Results and Discussion

The outputs of the CC analyses on the BAT and ASM data sets are a list of 35 day cycle peak times and a list of 35 day cycle lengths for BAT and ASM. These are presented as online tables, with the first several entries given here in Table 1 for the BAT data and in Table 2 for the ASM data.

A total of 146 CC peaks are detected in BAT observations. We add the cycles with weak CC peaks manually and label them “1” to distinguish them from ones detected via algorithm (labeled 0). A few cycles have data missing near the 35 day peak; we label these “2” and provide a time range. These cycles have their cycle numbers duplicated, and the cycles right before them are also duplicated to show the range of cycle lengths. For the remaining cycles with missing data in most of the cycle, we divide the lengths in time with the number of cycles in the time period and calculate approximate MH peak times and cycle lengths. In these cases the orbital phases are not applicable, so we assign “−1” in the orbital phase column of Table 1). They are also labeled “1.”
The Astrophysical Journal, 902:146 (12pp), 2020 October 20

4.1. Cycle Lengths

The top panel of Figure 4 shows the cycle lengths versus cycle number for the BAT data. There is no clear change of the 35 day cycle length with time. The lower panel shows a histogram of cycle lengths measured using the BAT data. The top panel includes all cycles (CC-detected and weak cycles), whereas the bottom panel only contains CC-detected cycles.

The top panel of Figure 5 shows the cycle lengths versus cycle number for the ASM data. As for the BAT analysis, there is no clear change of the 35 day cycle length with time. The anomalous low states are visible as the two periods of constant cycle number for the ASM data. There is no clear change of the 35 day cycle length with time. The cycle number for the ASM data.

Table 1

| Cycle | Peak Time (MJD) | Cycle Length (days) | Orbital Phase | Label |
|-------|----------------|---------------------|---------------|-------|
| 0     | 53437.82176    | 37.181              | 0.08430       | 0     |
| 1     | 53475.00306    | 31.212              | 0.95347       | 0     |
| 2     | 53506.21472    | 37.175              | 0.31144       | 0     |
| 3     | 53543.38972    | 32.088              | 0.17691       | 0     |
| 4     | 53543.38972    | 36.650              | 0.17691       | 0     |
| 5     | 53575.42772    | 39.500              | 0.05002       | 2     |
| 6     | 53580.03935    | 34.938              | 0.73336       | 2     |
| 7     | 53614.97704    | 32.547              | 0.28289       | 0     |
| 8     | 53647.52417    | 35.163              | 0.42635       | 0     |
| 9     | 53682.68704    | 35.972              | 0.18382       | 0     |

Table 2

| Cycle | Peak Time (MJD) | Cycle Length (days) | Orbital Phase | Label |
|-------|----------------|---------------------|---------------|-------|
| 2     | 50146.55311    | 38.628              | 0.23719       | 1     |
| 3     | 50185.81415    | 35.844              | 0.95747       | 0     |
| 4     | 50221.02589    | 36.044              | 0.04033       | 0     |
| 5     | 50257.06941    | 33.454              | 0.24028       | 0     |
| 6     | 50290.52330    | 33.940              | 0.91708       | 0     |
| 7     | 50324.46311    | 35.491              | 0.87968       | 0     |
| 8     | 50335.99404    | 36.229              | 0.75461       | 0     |
| 9     | 50396.18293    | 33.875              | 0.06360       | 0     |
| 10    | 50430.58411    | 35.014              | 0.98819       | 0     |
| 11    | 50465.07163    | 36.168              | 0.58232       | 0     |

Note.

a Label 0 stands for cycles detected by an algorithm; 1 with detected orbital phase for weak cycles (relatively low CC peak value and added manually); 1 with orbital phase assigned as ‘“−1.00000” for calculated peak times (cycle lengths averaged with previous and later peak times); and 2 for a range of time due to missing data in between (cycle number duplicated for the cycle and the one before it to show range of cycle lengths). Cycles with orbital phases marked ‘“−1.00000” are not identified by the cross-correlation algorithm. Their MJD time and cycle lengths are calculated from the MJD time of cycles right before and after. The complete table with all 152 cycles is available in machine readable form.

This table is available in its entirety in machine-readable form.

4.2. 35 day Cycle Peak and Relation to Turn-on

Here we investigate the question of the timing of the turn-on relative to the 35 day cycle peak using the results from our CC analysis of the BAT data and of the ASM data. Turn-on is defined as the time prior to MH peak when the flux reaches 20% of the peak flux. We measured the 35 day cycle phase difference between turn-on and peak using the final template lightcurves for BAT and ASM, and obtained 0.13 for BAT and 0.11 for ASM.

The distribution of orbital phases of 35 day cycle peaks is shown in Figure 6 from the CC analysis of BAT data (top panel) and from ASM data (bottom panel). For both cases only CC-detected cycles are shown. For BAT cycles, there is a clear peak near orbital phase 0.5. The distribution is consistent with the sum of a uniform distribution and a Gaussian distribution. The uniform distribution accounts for 76% of the total probability. The Gaussian accounts for the remaining 24% and has a mean phase of 0.512 with σ = 0.048. For ASM cycles, the distribution of orbital phases of 35 day cycle peaks is consistent with a uniform distribution.

The orbital phase of the 35 day turn-on is a regular subject of interest in the literature. Early references often found turn-on to preferentially occur near orbital phase 0.2 or 0.7 (e.g., Scott & Leahy 1999 and references therein). In contrast, Leahy & Igna (2010) analyzed orbital phases of turn-on observed with RXTE/ASM and found a uniform distribution. Here we convert the BAT-determined 0.13 35 day phase difference using the distribution to cycle length, to 4.52 days or 2.66 binary orbits. This converts the 0.51 orbital phase for peak to 0.85 orbital phase for turn-on. In summary, we are finding that ~76% of the cycles have no preferred orbital phase for turn-on, and ~24% of the cycles are clustered around orbital phase 0.85.

4.3. Comparison of BAT and ASM 35 day Templates

The BAT data for Her X-1 cover the energy band 15–50 keV, whereas the ASM data cover the energy band 2–12 keV. The Her X-1 spectrum during different parts of the 35 day cycle is variable and well studied. A recent summary of the spectrum of Her X-1 is given in Leahy & Chen (2019; and references therein). Summaries of spectral variations in terms of changing softness ratios are given by Leahy & Igna (2011; and references therein). For example, Figure 4 of Leahy & Igna (2011) shows
the 2–4 keV to 9–20 keV softness ratio versus 35 day phase. The spectrum is softest at ∼0.3–0.4 during the MH state and harder at ∼0.2–0.3 during the short high state. The softness ratio is ∼0.25 during the low states, similar to that for the short high state. Thus, we expect differences in the 35 day cycle template shape between BAT and ASM.

Figure 7 compares the shapes of the templates output by the CC analysis for BAT (top panel) and for ASM (bottom panel). The SD in rates from different cycles is shown by the crosses and dashed line for both BAT and ASM templates. Overall, the BAT SD has values similar to the BAT count rates, and the ASM SD is similar to the ASM count rates. The BAT (high-energy) template shows the lowest SD during low states, an intermediate SD during the MH state, and the highest SD during the short high state. The ASM (low-energy) template shows the lowest SD during low states, an intermediate SD during the short high state, and the highest SD during the MH state, i.e., the high-energy cycle-to-cycle variability is largest for the short high state, and the low-energy cycle-to-cycle variability is largest for the MH state. At both low and high energies, the cycle-to-cycle variability is smallest for low states.

The disk blocks the direct emission from the neutron star during low states (e.g., Leahy 2003 and Leahy 2002) and only allows the observer to detect X-rays scattered from an extended region. Thus, low variability for the low states is not surprising. Her X-1 spends a high fraction of its time in dips during the short high state compared to the MH state (Leahy & Igna 2011). The MH spectrum has the least amount of absorption, so absorption dips make MG more variable at low energy than they do for the short high state. This is consistent with the results shown in Figure 7. The larger variability at high energy for the short high state is likely caused by variability in the scattering of hard X-rays. The scattering is from the compact the inner edge of the disk, as shown by the models of Leahy (2003).

4.4. Swift/BAT and RXTE/ASM Comparison During 2005–2011

There is an overlap in time for the Her X-1 observations for BAT and ASM. The overlap is from 2005 March 9th (MJD 53,438), to May 24th, 2011 (MJD 55,705), or 2267 days (6.21 yr). During this overlap period, there are 63 maxima in BAT data and 58 in ASM identified by CC. Differences between ASM and BAT in the overlap period are calculated from all cycles (not only CC-detected ones), including weak ones and calculated ones. Of these, 59 agree within one orbital period (1.7 days) of Her X-1. The mean periods and SD for the overlap period are listed in Table 3 and the time differences (ASM-BAT) for each cycle are listed in Table 4. The difference in 35 day cycle peak time between BAT-detected and ASM-detected cycles ranges between ∼−1.5 and ∼+1.5 days.

Figure 8 shows the comparison between BAT and ASM cycle lengths (left panel) and between BAT and ASM derived...
orbital phases of peak (right panel). The error in the times of peak for ASM is estimated to be \( \pm 1 \) day from the bottom panel of Figure 3. This error is enough to yield the scatter in peak times seen in the left panel of Figure 8, and to fully mix the orbital phases of peak, as seen in the right panel. We conclude that the errors in peak time measured with ASM are large enough that the distribution of orbital phases of peak times with ASM does not provide useful information.

From the data during the overlap period, the average time difference (ASM-BAT) in the peak of the 35 day cycle is 0.366 days (0.011 in 35 day phase) and its SD is 0.745 days (0.022 in 35 day phase). Thus, the 35 phase difference between ASM and BAT derived from the overlap period is 0.01 \( \pm 0.02 \).

Table 3

| Analysis Period       | Data/Cycles | Average (days) | SD (days) |
|-----------------------|-------------|----------------|-----------|
| All data              | BAT/CC      | 34.787         | 1.1165    |
| All data              | ASM/CC      | 34.553         | 3.4246    |
| ASM/BAT overlap       | BAT/CC      | 34.755         | 1.1764    |
| ASM/BAT overlap       | ASM/CC      | 34.983         | 1.0520    |

Figure 5 shows average BAT and ASM 35 day cycle templates aligned using an offset of 0.02. This produces a good alignment of the declines from the MH peak over 35 day phase 0.1 to 0.2, and of the rises to the MH state over a 35 day phase, \(-0.15\) to \(-0.10\), and is consistent with the phase difference measured from the overlap period. It is seen that the three dips in the templates, one just before the MH peak and two after, are simultaneous in the BAT energy band and in the ASM energy band. This is confirmation that the alignment of the two templates is correct. The rises and declines for the short high state are also seen to occur at the same time for ASM and BAT.

We compared the histograms of orbital phase of peaks of the 35 day cycle for BAT and ASM from the overlap period. Each histogram is consistent with the corresponding histogram shown in Figure 6 for the full data sets, i.e., the BAT histogram of orbital phases is consistent with a uniform plus Gaussian component centered near orbital phase 0.5, the ASM histogram of orbital phases is consistent with a uniform distribution, and the ASM distribution is not consistent with the BAT distribution. As for the full sets of 35 day cycles, this result for the overlap time period can be explained by the larger uncertainty in the ASM measurements of peak times of the 35 day cycles.
The most complete previous analyses of 35 day turn-on times were by Leahy & Igna (2010) and Staubert et al. (2013). The first study gave a table of 147 turn-on times, found no systematic change in cycle length with time (their Figure 5), and found a uniform distribution for orbital phases of turn-on (their Figure 6). The latter study gave “Observed—Computed” turn-on times, which depend strongly on the Computed model, versus MJD (their Figure 2) from an analysis of the same data plus some earlier observations. If the mean 35 day cycle length of 34.9 days from Leahy & Igna (2010) is used, then the cycle lengths of the two studies are consistent for the time period covered by ASM observations. Here we confirm the uniform distribution for orbital phases of turn-on by reanalyzing the ASM data. However, we attribute the result to the uncertainty in measuring the time of peak (or turn-on) of 35 day cycles.

With the BAT data, the uncertainty in measurement of peak time is smaller and we detect a maximum in the orbital phase distribution at orbital phase of 0.512. We find that 76% of the cycles have a uniform distribution, and 24% show the peak in orbital phase. We convert from time of peak of the 35 day cycle and to time of turn-on by subtracting the orbital phase difference of 2.66 orbits between turn-on and peak. The result is a maximum in turn-on time distribution at orbital phase 0.85 with a spread $\sigma = 0.05$.

5. Summary and Conclusion

Here we analyze long-term observations of Her X-1 with the Swift/BAT instrument and the RXTE/ASM instrument. These instruments have monitored the flux from Her X-1 in energy bands 15–50 keV (BAT) and 2–12 keV (ASM) over the long time period of $\approx 14.5$ yr for BAT and for ASM. The measurements have a cadence of a few per day. With this extensive monitoring, we carry out a study of the 35 day cycle in this system.

The main results are as follows. The ASM data include two periods where there are anomalous low states (ALSs) for Her X-1. ALSs were discovered by Parmar et al. (1985) and a more recent analysis is provided in Leahy & Dupuis (2010). The first ALS is from $\approx$MJD 51,223 to MJD 51,831, with 17 or 18 missing 35 day cycles; the second is from $\approx$MJD 52,915 to MJD 53,232, with 9 cycles missing. The BAT data include no periods of ALS: every cycle is seen in the data, although some are weak.

The BAT data have lower noise than the ASM data, as seen in the sample lightcurves shown in Figure 1. The CC method yields a good measure of the times of peak of the 35 day cycles and converges well for the BAT data. For the ASM data, the times of peak do not converge as well, with about half the times...
converging to better than 0.1 day, and the other half showing a scatter of $\sim 1$ day, as shown in Figure 3.

The average 35 day cycle length from BAT data is 34.79 days, with an SD of 1.1 days. The ASM average cycle length is 34.55 days, with an SD of 3.4 days. The ASM SD is expected to be larger because of the larger timing errors from the CC analysis. The larger timing errors are confirmed by an analysis of the time period where Her X-1 was observed with both BAT and ASM.

The BAT analysis gives the best measurement to date for the orbital phase of turn-on. The analysis revealed a distribution of orbital phases of the peak of 35 day cycle, which is well fit by the sum of a uniform and a Gaussian distribution. We find 76% of the cycles are in the uniform distribution, and 24% of cycles are in the Gaussian, which has a maximum at orbital phase 0.51. The larger errors in timing for the ASM data mean that we do not detect the peak in the ASM analysis. The previous result of no maximum from ASM data analysis (Leahy & Igna 2010) is explained by timing errors caused by noise in the

**Table 4**
ASM and BAT Comparison for the Overlap Period

| Cycle No. for ASM | Cycle No. for BAT | ASM-BAT peak Time Difference (days) | ASM-BAT Orbital Phase Difference |
|-------------------|------------------|-------------------------------------|---------------------------------|
| 97                | 0                | 1.36578                             | 0.80335                         |
| 98                | 1                | 1.01504                             | -0.40295                        |
| 100               | 3                | -0.70143                            | 0.58745                         |
| 101               | 4                | -0.78496                            | -0.64167                        |
| 102               | 5                | -1.23857                            | 0.27152                         |
| 104               | 7                | 1.28828                             | 0.75777                         |
| 105               | 8                | -0.00792                            | -0.00463                        |
| 106               | 9                | -0.55052                            | -0.32378                        |
| 107               | 10               | 0.25653                             | 0.15092                         |
| 108               | 11               | 0.56874                             | -0.66546                        |

*Note.* The complete table with all 59 cycles is available in machine readable form. (This table is available in its entirety in machine-readable form.)

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Figure 7. Top panel: BAT 35 day cycle template (red circles) and standard deviation per bin (SD, black crosses) with an average SD of 0.018 ct cm$^{-2}$ s$^{-1}$ for 142 CC-detected cycles. Bottom panel: binned ASM template (red circles) and standard deviation per bin (SD, black crosses) with an average SD of 0.077 ct cm$^{-2}$ s$^{-1}$ for 115 CC-detected cycles.
ASM data. The maximum in the orbital phase of peak corresponds to a maximum in orbital phase for turn-on of 0.85. This is different than the often reported peaks near 0.2 and 0.7 orbital phase reported in less complete studies (e.g., Scott & Leahy 1999 and references therein).

We present 35 day average lightcurves for BAT, in the 15–50 keV band, and for ASM, in the 2–12 keV band in Figure 7. These include ~14.5 yr of observation for each instrument and constitute the best measures yet of the average 35 day cycle lightcurve.

The MH state and short high state are more variable (higher SD) in the low-energy band than in the high-energy band. This is expected in the precessing accretion disk model for the 35 day cycle (Leahy 2002 and reference therein), and in the origin of dips from the accretion stream (Ignai & Leahy 2012 and references therein). The reason is that absorption by cold matter is one of the main contributors to the shape and variability of the 35 day cycle.

The low (ASM) and high-energy (BAT) bands of the average 35 day lightcurve exhibit 3 dips during the MH state. These can be attributed to the increased dipping behavior seen during MH as the 35 day phase increases. Consistent with this, the cycle-to-cycle SD is highest in the ASM band during these three dip periods. As shown by Leahy & Ignai (2011), the system spends most of its time in dips during the short high state, thus the average of the dips with different timing does not show up as a regular feature during the short high state and the SD is not as high in the ASM band as for the MH. The ASM and BAT lightcurves both have a high SD at the start of turn-on to MH. The SD is high for both because the beginning of turn-on is variable in time and has such a high column density (>10^{24} cm^{-2}) that both energy bands are affected.

The observer’s line of sight is close to the inner ionized edge of the accretion disk throughout the short high state (Scott et al. 2000 and Leahy 2002). The resulting scattering affects the high-energy band as much as the low-energy band, causing the SD in the BAT energy band to be maximum for short high.

In conclusion, the RXTE/ASM and Swift/BAT monitoring observations of Her X-1 have given an unprecedented long-term view of the X-ray emission from this system. The properties of the 35 day cycle are now better measured than previously possible. Future work includes creating a complex
enough model of the Her X-1 system, with enough physics for the accretion disk, to be able to explain the observed properties of the 35 day cycle including the average lightcurves in the low- and high-energy bands.

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Leahy & Wang