TRACKING THE ORBITAL AND SUPERORBITAL PERIODS OF SMC X-1

SARAH TROWBRIDGE, MICHAEL A. NOWAK, AND JÖRN WILMS

Received 2007 February 2; accepted 2007 July 19

Abstract

The high-mass X-ray binary (HMXB) SMC X-1 demonstrates an orbital variation of \( \sim 3.89 \) days and a superorbital variation with an average length of \( \sim 55 \) days. As we show here, however, the length of the superorbital cycle varies by almost a factor of 2, even across adjacent cycles. To study both the orbital and superorbital variation, we utilize light curves from the Rossi X-Ray Timing Explorer All-Sky Monitor (RXTE ASM). We employ the orbital ephemeris from P. Wojdowski et al. to obtain the average orbital profile, and we show that this profile exhibits complex modulation during noneclipse phases. In addition, a very interesting “bounc eback” in X-ray count rate is seen during mid-orbital eclipse phases, with a softening of the emission during these periods. This bounceback has not been previously identified in pointed observations. We then define a superorbital ephemeris (the phase of the superorbital cycle as a function of date) based on the ASM light curve and analyze the trend and distribution of superorbital cycle lengths. SMC X-1 exhibits a bimodal distribution of these lengths, similar to what has been observed in other systems (e.g., Her X-1), but with more dramatic changes in cycle length. There is some hint, but not conclusive evidence, for a dependence of the superorbital cycle length on the underlying orbital period, as has been observed previously for Her X-1 and Cyg X-2. Using our superorbital ephemeris, we are also able to create an average superorbital profile over the 71 observed cycles, for which we witness overall hardening of the spectrum during low count rate times. We combine the orbital and superorbital ephemerides to study the correlation between the orbital and superorbital variations in the system, but find that the ASM light curve provides insufficient statistics to draw any definitive conclusions on possible correlations.

Subject headings: accretion, accretion disks — X-rays: binaries

Online material: color figures

1 INTRODUCTION

SMC X-1, first discovered with Uhuru observations (Leong et al. 1971), is a high-mass X-ray binary (HMXB) consisting of a neutron star (an X-ray pulsar with a 0.71 s period; Lucke et al. 1976) and a young B0 supergiant companion (Webster et al. 1976; Liller 1973). An accretion disk is formed around the neutron star, likely partly via wind-fed accretion in which a strong stellar wind from the companion star blows mass beyond its Roche lobe radius and into the gravitational influence of the neutron star. Our view of this system is at high inclination, as we witness X-ray eclipses of the neutron star and disk by the companion star once every orbital period (Schreier et al. 1972).

These previous studies of the SMC X-1 system measured the orbital period to be approximately 3.892 days. As has been observed in similar HMXB systems, SMC X-1 also exhibits a long-timescale (\( \approx 60 \) days) superorbital variation in its X-ray light curve (Gruber & Rothschild 1984). Unlike the superorbital variation in systems such as Her X-1 (Tananbaum et al. 1972), which has a relatively predictable 35 day period length (Staubert et al. 1983), the superorbital cycle length in SMC X-1 is highly variable and follows no obvious pattern (Gruber & Rothschild 1984; Wojdowski et al. 1998). As we elaborate further below, lengths of the superorbital cycles in SMC X-1 can vary by up to a factor of 2.

Accretion disk systems with superorbital variations have been explained with warped disks, seen close to edge-on such that the warp partially obscures our view of the X-ray source (Katz 1973). Such warps are possibly due to an instability driven in the outer disk by radiation from the central X-ray source (Peterson 1977; Pringle 1996; Maloney et al. 1996) or a number of other mechanisms (see Caproni et al. 2006 for a review). Wojdowski et al. (1998) suggested that the superorbital variation seen in SMC X-1 is indeed due to obscuration by such a warped disk, as opposed to intrinsic flux variations, since the flux and spectrum during orbital eclipse are fairly insensitive to whether the system is in a low or high state of the superorbital variation.

It also has been suggested, in order to account for the wide variation in superorbital cycle length, that SMC X-1 possibly has multiple warp modes in its accretion disk (Clarkson et al. 2003). For radiatively driven warps, theoretical studies show a number of possible branches of mode solutions that encompass both prograde and retrograde, as well as stable and damped warps (Wijers & Pringle 1999; Ogilvie & Dubus 2001). On the other hand, observational evidence has been found in similar systems suggesting interaction between the superorbital variations and the orbital period or some other underlying fundamental clock (Boyd & Smale 2004). Such systems have been shown in some cases to have superorbital cycle lengths equal to integer or half-integer multiples of an underlying clock, which in the case of Cyg X-2 is the orbital period, while in the case of LMC X-3 and Cyg X-3 is not simply related to any known dynamical period in the system (Boyd & Smale 2004). (The superorbital variations in LMC X-3, however, are likely due to flux variations rather than obscuration; Wilms et al. 2001.) In Her X-1 the superorbital cycle length mainly exhibits three values randomly, each differing only by half the orbital period (Staubert et al. 1983; Still & Boyd 2004; Klochkov et al. 2005).

In this work we use data from the All-Sky Monitor (ASM) on board the Rossi X-Ray Timing Explorer (RXTE) to make a comprehensive study of the long-term X-ray light curve of SMC X-1. We study and characterize both the average orbital variation and superorbital variations in this system. The outline of our paper is
as follows. In § 2 we discuss the extraction and reduction of the ASM data. We first use these data to characterize the average X-ray properties of the orbital period (§ 3). Next, in § 4 we discuss how we define the ephemeris for the superorbital variations, and then in § 5 we present their average X-ray properties. In § 6 we consider jointly the average X-ray properties of the orbital and superorbital variations. Finally, we summarize our conclusions and make comparisons to other systems, such as Her X-1, in § 7.

2. ASM DATA REDUCTION

The ASM consists of three scanning shadow cameras, each equipped with a position-sensitive proportional counter that views the sky through a set of slits to measure the relative intensities and positions of X-ray sources in the sky (Levine et al. 1996). The detector operates by comparing observations of intensities in any given area of the sky to a catalog of known X-ray sources to obtain a light curve (on timescales as short as 90 s) for each target in the field of view. The ASM records data in three different energy channels. Channels 1, 2, and 3 are sensitive to X-rays of energy 1.5–3 keV, 3–5 keV, and 5–12 keV, respectively.

We obtained definitive light curves for SMC X-1 from the ASM source catalog at the NASA RXTE Web site3 and analyzed data beginning MJD 50,088.4 and ending 54,083.8. As mentioned previously, the ASM data consist of a least-squares fit to the sky’s modeled X-ray spectrum for all the known sources within its field of view. For this reason, the count rate (counts s⁻¹) measurements from the satellite will occasionally fall below zero when the target source counts are lower than the difference between the expected background and the actual background; we have not excluded such negative counts from our extracted light curves.

Our analysis was performed using ISIS version 1.4.2-5 (Houck & Denicola 2000), using custom scripts written in S-lang4 (the scripting language embedded in ISIS), as well as routines publicly available from the S-lang/ISIS Timing Analysis Routines5 (SITAR). Using these routines to read the ASM data, we only retained data points for which the ASM solution had a maximum $\chi^2$-value of <1.5. Before beginning any analysis, we performed a barycenter correction on the light curve to account for the movement of the satellite within the Earth-Sun system.

The ISIS function define_counts allows arbitrary arrays of lo/hi bin, value per bin, and error on that value to be registered as a fittable data set, with presumed diagonal response matrix and unity effective area. We used this functionality to register the folded ASM light curves of §§ 3 and 4 for fitting and used combinations6 of custom-defined S-lang functions to fit these data.

When it was necessary to fit a function to $(x, y)$ pairs, rather than histogram data sets (see § 4), we used the ISIS function fit_array, which takes as input arrays of $x$- and $y$-values, the relative weights of the data points, parameter initial values and limits, and a reference to a single user-defined S-lang fit function.

3. FOLDING THE ORBITAL PERIOD

Our first step in characterizing the behavior of SMC X-1 was to search the ASM light curve for evidence of the aforementioned periodicities. Using a Lomb-Scargle periodogram (Lomb 1976; Scargle 1982), we were able to detect a 55 day period (the average length of the superorbital cycles; see § 4), as well as a period of approximately 3.89 days (i.e., the orbital period). These findings correspond to previous observations of the source (Wojdowski et al. 1998; Wen et al. 2006). We obtained an orbital ephemeris for the source from Wojdowski et al. (1998) that was defined in terms of the initial observation time, the period, and the period first derivative. Using this ephemeris with the SITAR routine sitar_pfold_rate, we folded the ASM light curve into 60 phase bins, as shown in Figure 1.

We had originally thought to search for improvements on the Wojdowski et al. ephemeris by detecting a drift in the zero point of orbital phase (even relative to the known orbital period derivative from that work) over the 11 years of ASM data we analyzed, but found that any possible drift in the ephemeris was well within the observational errors of the ASM. The Wojdowski et al. (1998) ephemeris remains accurate.

Using the folded light curve, we were able to observe several features of the orbital profile. The most interesting of these features is a bounceback phenomenon occurring during the eclipse. Because we are observing the system at high inclination, we expect to have few to no counts during the eclipse phases, when the companion star obscures the line of sight between the satellite and the neutron star-disk system. Surprisingly, we observe the low counts expected on either side of the eclipse, but witness a small rise and fall of counts during the mideclipse phases. We will henceforth refer to this region of recovering count rate as the bounceback. Another interesting feature is a complex modulation, modeled below as sinusoidal, that occurs throughout the signal profile and is very visible during the noneclipse phases.

We were able to obtain a fit to describe these features of the orbital profile using a 10 parameter empirical function. Our final model was obtained as follows. We modeled the bounceback feature in the center of the eclipse with a parabola. Allowing a free parameter for the magnitude of the curvature, which could range to any real value (positive or negative), we noted that the curvature was fit to positive values in all channels. Eclipse ingress and egress were modeled by linear functions, dropping from, or rising to, a constant value outside of eclipse. We multiplied the entire

![Figure 1](https://example.com/figure1.png)
different integer and half-integer values and used the frequency ple of the inverse orbital period. We attempted the fit with several centers of the Gaussian and parabola were fixed at 1, while the possibly due to partial obscuration of potentially extended X-ray the center to account for a broader component of the eclipse, ulation observed in the profile, and subtracted a Gaussian from function by a sine wave plus a constant to account for the mod- three energy channels, and the fit parameters are also presented of features of the system in different energy ranges. Figure 2 shows profiles and fits in each of these energy channels. 

\[
\chi^2_{\text{red}} = \frac{1}{N - M} \sum_{i=1}^{N} \left( \frac{y_i - f_i}{\sigma_i} \right)^2
\]

Notes.—ORBIT function parameters: (Lwidth) width of the eclipse ingress; (Cwidth) width of the eclipse from the low point on the left of the bounceback; (Rwidth) width of eclipse egress; (height) distance from lowest point in the eclipse to the constant in noneclipse phases; (PNorm) height of the parabola fit in the bounceback (center of the eclipse) region. In the Lwidth and Rwidth regions, the profile was modeled with a linear function, and in the Cwidth region, the profile was modeled as a parabola. The center of orbit model and Gauss were frozen at phase = 1, and the sine wave frequency was frozen at \( f = 4 \) (orbital period)^{-1}. Error bars are 90% confidence levels.

\[
\chi^2 = \frac{1}{N - M} \sum_{i=1}^{N} \left( \frac{y_i - f_i}{\sigma_i} \right)^2
\]

Due to count rate uncertainties, it is not initially clear whether or not the bounceback and sinusoidal variation are significant, real features of the orbital profile. In order to further explore the significance of the bounceback, we performed fits of the orbital profile without the parabolic term, resulting in a \( \Delta \chi^2 \) from the fits to the full model described above of 14.1 in the summed channel fit and 1.0, 2.0, and 10.0 in fits of the first, second, and third channels, respectively. We also performed the orbital profile fits without the sinusoidal modulation, which resulted in a \( \Delta \chi^2 \) of 13.2 in the summed channel fit and 5.4, 7.9, and 2.3 in the fits of the first, second, and third channels, respectively, from the \( \chi^2 \)-values obtained using the full model. The statistics are not good enough to allow us to study the bounceback or the sinu-oidal modulation in individual periods. The bounceback is not clearly exhibited in averaging of most short portions of the light curve (i.e., only a few orbital periods), but can only be found with the statistics provided by long averaging times. A more thorough understanding of the bounceback would require better statistics than are presently available from the ASM data.

In order to get a more quantitative idea of the energy distribu-
tion of the emission, we created a folded color light curve, where we defined the color as

\[
C = \frac{\text{ch1} - \text{ch3}}{\text{ch1} + \text{ch3}},
\]

where ch1 is the count rate measured in ASM channel 1, and ch3 is the count rate measured in channel 3. Thus, if the emission at
a certain phase is dominated by hard X-rays, then the value of the color will be negative, and if the emission is dominated by soft X-rays, the color will be positive. The orbital phase-dependent color light curve (with 40 phase bins) is plotted in Figure 3.

Overall, the color light curve demonstrates that the source is relatively monochromatic and dominated, as observed in the channel fits, by hard X-ray emission. We did find that at the edges of the eclipse, where the source was partially obscured by the companion star, that the X-ray emission possibly becomes much harder. This might be attributable to soft X-ray absorption from the outer atmosphere of the companion star; however, this region of the light curve is also where the average channel light curve dips below 0. If we apply a systematic shift upward of 0.05 counts s\(^{-1}\) to each of the light curves, this hardening disappears, although the hardening remains a possibility within the uncertainties. On the other hand, the bounceback emission, in contrast to the emission in the rest of the orbital cycle, clearly becomes softer.

4. DEFINING THE SUPERORBITAL EPHEMERIS

The inherent noise of the light curve and the highly variable nature of the superorbital cycle length provided somewhat of a challenge as far as the definition of the superorbital ephemeris (superorbital phase to date correlation) was concerned. Here we wish to consider only variations on the longer superorbital timescale, and not those produced by the orbital variations. We therefore removed points that fell within the eclipse of the neutron star by the companion from the light curve. Using our orbital fold, discussed in §3, we determined the orbital phases of the eclipse to lie between 0.85 and 1.15 (Fig. 1) and used the Wojdowski et al. (1998) ephemeris to calculate the time ranges during which these phases would occur. We then removed all ASM data points that fell within those ranges.

Using the light curve with the eclipse phases removed, the ASM light curve remains intrinsically noisy. For example, the peaks of each superorbital cycle have a number of prominent dips (see Fig. 4), which appear to be akin to the “preeclipse dips” seen in the long-term X-ray light curves of Her X-1 (Shakura et al. 1998; Stelzer et al. 1999; Klochkov et al. 2005). To further reduce the inherent noise in the ASM light curves of SMC X-1, we applied a simple Gaussian smoothing to the unbinned ASM data via a fast Fourier transform (FFT)\(^7\) with a smoothing scale of 16 data bins (~2.5 days on average). We defined low-count regions by selecting regions of the light curve that were below a cutoff count value (\(\lesssim 1.675\) counts s\(^{-1}\)) and that were wide enough (\(\gtrsim 7\) days) to ensure that they were not residual noise fluctuations from the light curve. We then fit fourth-order polynomials to each of the low-count regions using the ISIS function array_fit, choosing a uniform weighting of the data points (see §2). We completed the definition of the superorbital ephemeris by defining the minima of the polynomials in the low-count regions as points of zero phase. This procedure is illustrated in Figure 4, which shows a portion of the smoothed light curve with the polynomials and minima (zero-phase points) superimposed.

\(^7\) Although only strictly valid for an evenly spaced light curve, this procedure created a well-behaved light curve, comparable to various schemes with weighted averages, or binned schemes with padding for data gaps, that we also tried.
With the ephemeris defined as in Figure 4, we were able to extract the start and stop time of each superorbital cycle. We list the start times in Table 2. We estimate, based on multiple trials with variants of our zero-phase search routines (weighted averages and binned routines, to define the light curve, and several different functional forms, to fit the minima), that our cycle start times have an accuracy of ±2 days. To search for possible patterns, we plotted the length of each superorbital cycle versus the average date during that cycle. This plot is shown in Figure 5. There appears to be a somewhat oscillatory trend, superimposed on a much longer time-scale pattern. The longer term trends, especially the short (40–50 day) superorbital cycles near the beginning of the ASM light curve, are likely what have been identified as multiple warp modes in the disk (i.e., Clarkson et al. 2003).

Specifically, if we apply a sliding Lomb-Scargle periodogram to the ASM data (exactly as we have previously shown with ASM light curves of LMC X-3; Wilms et al. 2001), the rather ragged pattern of Figure 5 appears more as a smooth evolution of superorbital period, as shown in Figure 6. Comparing to Figure 5, however, we see that the smoothness of this trend is partly an artifact of the averaging process and that a sliding Lomb-Scargle periodogram by itself does not reveal the fine detail of the evolution of this source.

We studied the distribution of these varying cycle lengths by creating a histogram of their values. The number of bins in the histogram was chosen because it produced the most easily seen pattern, but it does not significantly change the results of the analysis. For example, doubling the number of bins does not change the shape of the distribution, except to add more noise to the overall trend. We found in this case that the distribution has a distinct double-peaked pattern, similar to other systems of this type. Specifically, such systems as Cyg X-2, LMC X-3, Cyg X-3, and Her X-1 show doubly peaked distributions for histograms of wait times between successive minima (Boyd & Smale 2004). It is possible that the SMC X-1 system is similarly oscillating (somewhat randomly) between two extreme periods. The profile of superorbital cycle lengths is shown in Figure 7.

Once we had defined the ephemeris, we attempted to find some correlation between the length of the superorbital cycles and the X-ray flux from the system. Toward this end, for each superorbital cycle we binned the rates into a histogram and attempted

![Figure 5](image-url) Time evolution of superorbital cycle length. Error bars represent the uncertainty in cycle length due to the uncertainty in the determination of superorbital zero-phase times. The oscillatory structure superimposed on the long-term trend has previously been attributed to multiple warp modes in the disk (Clarkson et al. 2003).
fits with several different functional forms; none of these were successful for all of the superorbital cycles. This was due to the large variance in the shapes of each superorbital variation (including the aforementioned dips), as well as to the lack of data for some portions of the light curve. Instead, we performed five-point spline fits on each of the superorbital cycles. From the spline fits, we extracted the minimum, peak, and mean flux during each superorbital cycle and plotted each of those values against both the superorbital cycle length and the length minus its mean value of approximately 54.4 days. We were not able to find any correlations between the superorbital cycle length and flux with this method, nor by working on a coarser timescale, i.e., by averaging over five consecutive superorbital cycles and searching for correlations between the same variables.

5. FOLDING ON THE SUPERORBITAL PERIOD

With the superorbital ephemeris defined, we were able to assign a superorbital phase to each point on the light curve and proceed to fold the data over all superorbital cycles. We chose to average the ASM light curve in 25 phase bins of the superorbital cycle and plotted each of those values against both the superorbital cycle length and the length minus its mean value of approximately 54.4 days. We were not able to find any correlations between the superorbital cycle length and flux with this method, nor by working on a coarser timescale, i.e., by averaging over five consecutive superorbital cycles and searching for correlations between the same variables.

Fig. 6.—Dynamical Lomb-Scargle periodogram for the entire ASM light curve of SMC X-1. The periodogram is calculated in 315 day intervals, slid 50 days each bin (see Wilms et al. 2001).

Fig. 7.—Histogram distribution of superorbital cycle lengths with a bimodal (sum of two Gaussians) fit superimposed. The fit shown in this figure was used in the simulations described in § 6.2 [See the electronic edition of the Journal for a color version of this figure.].
Fig. 8.—Light curve folded on the superorbital period with a fit of two superimposed Weibull functions. [See the electronic edition of the Journal for a color version of this figure.]

\[ \propto x^3 \exp \left[ -\left( x/\beta \right)^\gamma \right]; \] see Appendix B of Nowak et al. (1999) for historical references and a description of the uses of this distribution function. We elected to use Weibull functions because their asymmetry can reasonably describe the asymmetry of the folded light curve. We used the sum of two curves as this matched the broadly peaked nature of the folded profile much better than did a single function. This was also suggested by the shape of the individual superorbital cycle profiles, many of which were dramatically double peaked. Fit results are presented in Table 3.

As in our analysis of the orbital profile, we once again found that the profile was dominated by high-energy emission. Similar to our analysis of the average energy profile of the orbital variation, we created a color light curve for the superorbital profile by plotting the color versus superorbital phase, again using the definition of equation (1). We present these results in Figure 9. Once again we can see that the emission is fairly monochromatic, with two exceptions. Near phase 0.9 of the superorbital period, there is weak evidence for a softening. More clear, however, is that near phase 0 of the superorbital cycle (i.e., the low count rate region in which the neutron star is likely eclipsed by the disk) the emission appears to become harder, although the color values in this region have relatively large uncertainty. This is in marked contrast to the bounceback region of the orbital period fold, where the emission became softer. As in our color plot for the orbital profile, we have examined the same plot with a systematic shift upward of 0.05 counts s\(^{-1}\) in all channels; however, in this case it does not significantly change the result.

6. JOINT ORBITAL AND SUPERORBITAL PROFILES

6.1. Two-dimensional Phase Folds

To better understand the link between the orbital and superorbital variations in SMC X-1, we created a two-dimensional fold of the SMC X-1 light curve. Once we had defined an ephemeris for both the orbital and the superorbital variations (as discussed in \S\S\ 3 and 4, respectively), we were able to assign every point on the light curve both an orbital and a superorbital phase. We then created a grid of histogram bins with orbital phase on one axis and superorbital phase on the other and sorted the data points into that grid, averaging the intensity measurements in each bin. The result was the two-dimensional histogram shown in Figure 10. While we can observe the asymmetry noted in the superorbital profile in this histogram, it does not contain sufficient statistics to give specific insight as to the evolution of orbital profile features at different superorbital phases and vice versa. The choice of binning is made for maximum clarity. Unfortunately, current statistics are not sufficient, so that finer binning would provide more information.

### Table 3

| ASM Channel | \(\chi^2_{\text{red}}\) (17 dof) | Norm\(_1\) | Peak\(_1\) | \(\alpha_1\) | \(\beta_1\) | Norm\(_2\) | Peak\(_2\) | \(\alpha_2\) | \(\beta_2\) |
|-------------|---------------------------------|-----------|-----------|----------|----------|-----------|-----------|----------|----------|
| 1+2+3       | 1.95                            | 0.39      | 1.28      | 3.34     | 2.03     | 0.26      | 1.30      | 1.57      | 4.76     |
|             |                                 | -0.08     | -0.01     | 0.21     | 0.01     | -0.02     | -0.10     | -0.00     | -0.09    |
| 4           | 2.41                            | -0.04     | 1.24      | 2.1      | 0.16     | 0.28      | 0.33      | 1.520     | 3.25     |
|             |                                 | -0.05     | -0.00     | 0.02     | 0.00     | -0.03     | -0.00     | -0.00     | 0.63     |
| 2           | 2.07                            | -0.04     | 1.23      | 2.5      | 0.29     | 0.27      | 0.33      | 1.590     | -0.03    |
|             |                                 | -0.03     | -0.00     | 0.05     | 0.00     | -0.00     | -0.00     | -0.00     | 0.63     |
| 3           | 1.61                            | 0.16      | 1.27      | 2.03     | 0.20     | 0.69      | 1.54      | 1.54      | 4.5      |
|             |                                 | -0.04     | -0.01     | 0.01     | 0.01     | -0.04     | -0.00     | -0.00     | 0.86     |

Notes.—Weibull functions had the form norm\(_1\)(\(x - x_\theta\)) \exp \left\{-\left[ (x - x_\theta)/\beta_1 \right]^{\gamma} \right\}, etc., where \(x_\theta\) was determined by fixing the location of the function maximum to Peak\(_1\). Error bars are 90% confidence levels.
To gain another visualization of the form of the orbital profile at different superorbital phases, we also created several orbital profiles, each containing only points of the light curve in a small range of superorbital phase, and plotted these profiles on a single set of axes. We present these orbital phase histograms in Figure 11. Here again we find that we have insufficient statistics to demonstrate any definitive trend in the shape of the orbital profile dependent on superorbital phase. Further study of this system with better statistics (e.g., with a series of pointed X-ray observations) is likely necessary to witness any trends.

6.2. Searching for Dependencies on Orbital Period

In accordance with patterns seen in other sources, e.g., Her X-1, where the turn-on of the superorbital cycle is tied to a half-integer multiple of the orbital period (Staubert et al. 1983; Klochkov et al. 2005), or Cyg X-2, where the time between successive minima is an integer multiple of the orbital period (Boyd & Smale 2004), we searched for a correlation between the orbital period length and the superorbital cycle lengths. We used a set of ~3500 values between one-quarter of the orbital period and one-half of the longest observed superorbital cycle to search for a value that divided most evenly into all of the superorbital cycle lengths. For any given member of the set, we tested its relation to the superorbital cycle lengths by dividing each of the 71 observed cycle lengths by that value and summing the noninteger remainders of each of the 71 quotients. A value that fit relatively evenly into the set of superorbital cycle lengths was one that exhibited a minimum value of the sum of noninteger parts. We found 16 values that exhibited minima in this formula, which we define as a point for which the sum of the remainders was ≤31. (The maximum value of the sum of the remainders was ~43.6, while the mean of the sum was ~36.2.) Of the 16 minima, we found 7 that had some integer or quarter-integer relation to the orbital period, i.e., approximately 0.25, 0.5, 1, 2, 3, 5, and 6 times the orbital period.

Fig. 10.—Two-dimensional folded light curve. The variation in orbital phase is plotted along the x-axis, while the superorbital phase is plotted along the y-axis. Top: Color scale.
cycle lengths. We performed 106 such simulations and averaged each of the 3500 trial values with the chosen set of superorbital cycle lengths. The other 9 values that exhibited minima had no obvious relation to the orbital period length.

To test the significance of these observed values, we created a histogram of the sum of noninteger parts from the quotients of orbital cycle length data shown in Figure 7, from which we could randomly choose superorbital cycle lengths. A single simulation consisted of randomly choosing 71 superorbital cycle lengths from this distribution and then performing the same analysis as done for the actual data. Specifically, the main goal was to create a histogram of the sum of noninteger parts from the quotients of each of the 3500 trial values with the chosen set of superorbital cycle lengths. We performed $10^6$ such simulations and averaged all of the resulting histograms to obtain a theoretical distribution.

From this simulated distribution, we could estimate the likelihood of obtaining the sums of noninteger remainders with values less than or equal to those that had been found for the quarter-integer and integer multiples of the orbital period. We found these probabilities to be $4.2\%$, $0.1\%$, $4.2\%$, $3.6\%$, $0.6\%$, $4.2\%$, and $2.5\%$ for the members of the set that were $0.25$, $0.5$, $1$, $2$, $3$, $5$, and $6$ times the orbital period length, respectively. From these simulations, we concluded that while these values appear to have interesting relations to the orbital period and their corresponding sums of noninteger remainders are somewhat rare, they are not rare enough to point conclusively toward a relationship with the orbital period. Further study of this correlation—either via ASM observations with a longer baseline or via pointed observations that can more accurately determine the start and stop times of each superorbital period—may prove useful in determining whether there truly is a relationship between the superorbital cycle and orbital period lengths.

7. SUMMARY

In our analysis of the ASM light curve of SMC X-1, we have observed several interesting features of both the orbital and superorbital profiles. By using the ephemeris provided in Wijers et al. (1998), we were able to fold $\sim$11 years of data on the orbital period to obtain an average orbital profile. The main results of this analysis are as follows:

1. The light curve is characterized by complex modulation during the persistent emission (here modeled as a sinusoid, but it could possibly be fitted by another model within the uncertainty), with a broad, asymmetric eclipse.

2. We were able to witness a count rate bounceback phenomenon when averaging over large numbers of orbital cycles, which consists of a small rise and fall in counts during orbital mid-eclipse phases.

3. The emission becomes somewhat softer during the eclipse/bounceback, while the persistent emission is fairly monochromatic.

Despite several pointed observations during orbital eclipse, in both low and high states of the superorbital period, the bounceback has not been previously seen (Woo et al. 1995; Wijers et al. 1998). We did not have sufficient statistics to observe the dependence of this phenomenon on the superorbital cycle; it is therefore possible that the bounceback is only present in certain superorbital phases or that its presence is only intermittent. Given the relatively few pointed observations of SMC X-1 during eclipse, it is possible that prior pointed observations have simply not observed the state in which the bounceback is most prominent.

The softening during the eclipse might be akin to that seen in so-called accretion disk corona (ADC) sources (White & Holt 1982). Such sources show broad, partial eclipses, with deeper eclipses in the hard X-ray (for example, see the light curves of X1822$-$371; Heinz & Nowak 2001). One model of these sources has a very spatially extended corona scattering X-ray from the central source into our line of sight; however, X-rays traveling through the atmosphere just above the midplane of the disk are preferentially absorbed in the soft X-rays (White & Holt 1982). Thus, the eclipse of the base of this extended corona is preferentially blocking harder X-rays and leads to an overall softening of the spectrum. However, if such is occurring in SMC X-1, this does not explain the bounceback of the light curve. Perhaps additional scattering into our line of sight at orbital phase 0 from the atmosphere of the companion, rather than just an ADC, must also be invoked to explain the bounceback.

The superorbital variation in SMC X-1 is not as easily dealt with as the orbital variation because of the complicated nature of the superorbital ephemeris. The superorbital cycle length is highly variable, and Lomb-Scargle techniques alone are not sufficient to define its structure (Wen et al. 2006). In our analysis, we were able to obtain a superorbital ephemeris from the ASM data by modeling the locations of zero phase for each of 71 cycles. From that ephemeris, we were able to extract an average superorbital profile, as well as information about trends in the superorbital cycle length. Our main results are as follows:

1. In general, we observe an asymmetry in the average superorbital profile, most notable in a sharper rise in the low-state egress than a fall in the low-state ingress.
2. In contrast to the trend in the orbital profile, where we see softer emission during low-count states, we find that emission appears to harden during low states in the superorbital profile.

3. We have found the lengths of the superorbital cycles in SMC X-1 to be bimodally distributed, in agreement with Boyd & Smale (2004), and have also found suggestive, although not definitive, evidence that the variation in length is driven by some internal clock, the fundamental period of which is related to the orbital period as observed in Her X-1 and Cyg X-2 (Boyd & Smale 2004).

4. In contrast to the findings in the analysis of Her X-1 (Still & Boyd 2004), we have been unable to find any correlation between the superorbital cycle length and the X-ray flux.

5. In contrast to Clarkson et al. (2003), who report a smooth evolution of the superorbital cycle length, we observe sharp variations, often with large changes in length between adjacent superorbital cycles.

This latter result is especially evident in observed superorbital cycles 41–44 (MJD 52,372.5–52,598.5), in which the cycle duration rises from $\sim$47 days in cycle 41 to $\sim$72 days in cycle 43 and falls back to $\sim$50 days in cycle 44. Likewise, between superorbital cycles 46–49 (MJD 52,647.6–52,873.2), there is a rise from $\sim$44 days to $\sim$72 days in cycles 46 and 47 and a fallback to $\sim$49 days in cycle 49. Clarkson et al. (2003) also theorize that the evolution of superorbital cycle length is possibly sinusoidal. The lack of a regular, sinusoidal pattern in our data can easily be seen in Figures 5 and 6.

In our spectral analysis of 71 superorbital cycles, we were able to observe a clear superorbital profile in the first channel (1.2–3 keV) of an amplitude similar to that of the modulation in the second channel (3–5 keV; cf. Clarkson et al. 2003, who report little or no variation below 3 keV). The most likely reason for the discrepancies between our analysis and that of Clarkson et al. (2003) is the extended length of the light curve that we were able to analyze (about twice the length of that used in Clarkson et al. 2003) and our more precise definition of the edges of each individual period. The smoothing of the superorbital period length variation that we observed is most likely at least partially an artifact of their use of a sliding Lomb-Scargle periodogram and is similar to that we observed in Figure 6.

The question then arises as to why SMC X-1 shows such extreme variations in its superorbital cycle length, while sources such as Her X-1 and LMC X-4 do not. Several tentative suggestions have been made based on radiatively driven warp models. In such models, the driving force of the warp is the flux from the central source, which scales as $R^{-2}$, being absorbed and reradiated from the outer disk, whose intercepting area scales as $R^2$, thereby yielding a torque that increases linearly with distance. Disks can therefore become unstable to radiative driving of a warp if they are large enough (and the accretion efficiency is high enough; Pringle 1996), which is a function of the system’s orbital period and secondary-to-primary mass ratio. Numerical simulations (Wijers & Pringle 1999) and analytic estimates (Ogilvie & Dubus 2001) indicate that the Her X-1 system is just large enough to have a stable warp. The analytic models, however, also indicate that the underlying equations, which are rather complex in terms of their eigenvalue behavior, only admit stable warp solutions for a finite range of disk sizes (Ogilvie & Dubus 2001). Estimates are that SMC X-1 may be near the upper limit of system sizes that are unstable to warping and therefore may be more likely to exhibit chaotic warp modes. Our results are certainly consistent with that expectation.

Within the framework of a radiatively driven warp, the existence and stability of the warp modes are also dependent on the radius at which matter is injected into the disk (Wijers & Pringle 1999; Ogilvie & Dubus 2001). Being more heavily wind-fed, this may be another way in which SMC X-1 differs from Her X-1. Perhaps variations in the wind speed of the SMC X-1 secondary, leading to variations of the disk circularization radius (equated with the mass injection radius in the majority of theoretical models), may account for the varying cycle lengths. An ASM study like the one presented here, coupled with spectroscopic observations of the secondary’s wind, may be an avenue for exploring such a possibility.

The above speculations, however, do not account for the possibility of a fundamental underlying clock for the SMC X-1 superorbital cycles. In their analysis of several X-ray binary systems, Boyd & Smale (2004) find many systems for which the superorbital excursion lengths are random integer multiples of some fundamental period (Cyg X-2, LMC X-3, and Cyg X-3). They also find, when plotting the light curves of the systems in $X, \dot{X}$ phase space, that each of these sources demonstrates circulation in the phase space about two rotation centers, creating a bimodal distribution in the length of superorbital variations. SMC X-1 shows similar characteristics.

Wijers & Pringle (1999) speculated that for sufficiently large-amplitude warps, the effective mass injection radius (i.e., where the incoming accretion flow interacts with and circularizes into the inclined disk) could greatly fluctuate from one superorbital cycle to the next, causing fluctuations in cycle duration that become tied to the orbital period. An avenue for exploring this possibility may be to model individual cycles of the ASM light curve, to see whether one can discern a changing warp amplitude with each cycle. The fact, however, that we did not find a dependence of cycle duration on mean, minimum, or peak ASM flux may argue against this possibility.

To summarize, using the ASM light curve, we have defined a superorbital ephemeris for SMC X-1 for 1995–2006. It will now be possible to put pointed observations during this period in the context of both the orbital ephemeris from Wojdowski et al. (1998) and the superorbital ephemeris from this work. We have exploited the spectral information from the three channels of the ASM as much as possible and extracted information from the spectrum in both the orbital and superorbital profiles, to guide further observations, as well as theories, e.g., of disk warping, which currently do not describe behavior as complex as that seen here in SMC X-1. It is also now necessary to perform multiple pointed observations in order to observe a variety of superorbital and orbital phase combinations and gather better statistics than provided by the data analyzed in this study. It might then be possible to analyze the superorbital evolution of orbital profile features, including the bounceback. With pointed observations, we might also be able to better analyze the superorbital ingress and egress and the spectral variation in the emission, to obtain more insight into the structure of the HMXB SMC X-1 and other similar systems.

This work was supported by NASA grant SV3-73016. The authors gratefully acknowledge Al Levine for providing the code on which the ASM barycenter correction was based. The authors would also like to acknowledge help and advice from John Houck and Andy Young. The authors thank the anonymous referee, whose comments helped to improve the clarity of this paper.
REFERENCES

Boyd, P. T., & Smale, A. P. 2004, ApJ, 612, 1006
Caproni, A., Livio, M., Abraham, Z., & Mosquera Cuesta, H. J. 2006, ApJ, 653, 112
Clarkson, W. I., Charles, P. A., Cole, M. J., Laycock, S., Tout, M. D., & Wilson, C. A. 2003, MNRAS, 339, 447
Gruber, D. E., & Rothschild, R. E. 1984, ApJ, 283, 546
Heinz, S., & Nowak, M. A. 2001, MNRAS, 320, 249
Houck, J. C., & Denicola, L. A. 2000, in ASP Conf. Ser. 216, Astronomical Data Analysis Software and Systems IX, ed. N. Manset, C. Veillet, & D. Crabtree (San Francisco: ASP), 591
Katz, J. I. 1973, Nature, 246, 87
Klochkov, D., Shakura, N., Postnov, K., Staubert, R., Wilms, J., & Ketsaris, N. 2005, Pis'ma Astron. Zh., 32, 804
Leung, C., Kellogg, E., Gursky, H., Tananbaum, H., & Giacconi, R. 1971, ApJ, 170, L67
Levine, A. M., Bradt, H., Cui, W., Jernigan, J. G., Morgan, E. H., Remillard, R., Shirey, R. E., & Smith, D. A. 1996, ApJ, 469, L33
Liller, W. 1973, ApJ, 184, L37
Lomb, N. R. 1976, Ap&SS, 39, 447
Lucke, R., Yentis, D., Friedman, H., Fritz, G., & Shulman, S. 1976, ApJ, 206, L25
Maloney, P. R., Begelman, M. C., & Pringle, J. E. 1996, ApJ, 472, 582
Nowak, M. A., Wilms, J., Vaughan, B. A., Dove, J., & Begelman, M. C. 1999, ApJ, 515, 726
Ogilvie, G. I., & Dubus, G. 2001, MNRAS, 320, 485
Peterson, J. A. 1977, ApJ, 214, 550
Pringle, J. E. 1996, MNRAS, 281, 357
Scargle, J. D. 1982, ApJ, 263, 835
Schreier, E., Gisconi, R., Gursky, H., Kellogg, E., & Tananbaum, H. 1972, ApJ, 178, L71
Shakura, N. I., Ketsaris, N. A., Prokhorov, M. E., & Postnov, K. A. 1998, MNRAS, 300, 992
Staubert, R., Bezler, M., & Kendziiorra, E. 1983, A&A, 117, 215
Stelzer, B., Wilms, J., Staubert, R., Gruber, D., & Rothschild, R. 1999, A&A, 342, 736
Still, M., & Boyd, P. 2004, ApJ, 606, L135
Tananbaum, H., Gursky, H., Kellogg, E. M., Levinson, R., Schreier, E., & Giacconi, R. 1972, ApJ, 174, L143
Webster, B. L., Martin, W. L., Feast, M. W., & Andrews, P. J. 1972, Nature, 240, 183
Wen, L., Levine, A. M., Corbet, R. H. D., & Bradt, H. V. 2006, ApJS, 163, 372
White, N. E., & Holt, S. S. 1982, ApJ, 257, 318
Wijers, R. A. M. J., & Pringle, J. E. 1999, MNRAS, 308, 207
Wilms, J., Nowak, M. A., Pottschmidt, K., Heindl, W. A., Dove, J. B., & Begelman, M. C. 2001, MNRAS, 320, 327
Wojdowski, P., Clark, G. W., Levine, A. M., Woo, J. W., & Zhang, S. N. 1998, ApJ, 502, 253
Woo, J. W., Clark, G. W., Blondin, J. M., Kallman, T. R., & Nagase, F. 1995, ApJ, 445, 896