Is Superorbital Modulation in SMC X-1 Caused by Absorption in a Warped Precessing Accretion Disk?

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Abstract

We present a broadband spectral-timing analysis of SMC X-1 at different intensity states of its superorbital variation using 10 Suzaku and 6 Nuclear Spectroscopic Telescope Array (NuSTAR) observations. The spectrum in all the states can be described by an absorbed power law with a high-energy cutoff and a blackbody component along with an iron emission line. Compared to other supergiant high-mass X-ray binaries, the Fe Kα line equivalent width is low in SMC X-1—from less than 10 eV in the high state to up to ~270 eV in the low states. The spectral shape is dependent on flux, with the hard X-ray spectrum steepening with increasing flux. We also report a highly variable normalization of the power-law component across these 16 superorbital states. Pulses in the hard X-rays for both the instruments were detected in all but two observations. The pulse profiles are near sinusoidal, with two peaks and the relative intensity of the second peak decreasing with decreasing luminosity. These findings suggest that the superorbital modulation in SMC X-1 is not caused by absorption in precessing warped accretion disk alone and there are intrinsic changes in X-rays emanating from the neutron star at different superorbital states. We also note a putative cyclotron line at ~50 keV in the NuSTAR spectra of three bright states, indicating a possible magnetic field of ~4.2 × 1012 G. Finally, with the new pulse period measurements reported here, the time base for the secular spin-up of SMC X-1 is increased by thirteen years and the complete pulse period history shows a sudden change in the spin-up trend around 1995.

Unified Astronomy Thesaurus concepts: High mass X-ray binary stars (733); Compact objects (288)

1. Introduction

Superorbital periods are long-term periodic/quasi-periodic intensity variations at timescales often several times the orbital period seen in X-ray binaries (an optical companion with a compact object). For X-ray binary systems with an accretion disk (e.g., LMC X-4), this superorbital modulation is ascribed ad hoc to the presence of a precessing warped accretion disk (PWAD). These warps in the accretion disk may be caused by an interplay of tidal force (from the companion star), viscous drag of different layers of accretion disk and driven by the intense radiation pressure from the compact object (Larwood 1998; Ogilvie & Dubus 2001). As these warps precess with the disk rotation and cause obscuration of the X-rays from the compact object, we see X-ray intensity variations with superorbital periodicity.

On the other hand, some objects, especially those (but not limited to) that accrete via stellar wind, such superorbital modulations are thought to occur due to changes in mass-loss rate, \( \dot{M} \) (which subsequently change the accretion rate onto the compact object). There have been many explanations as to what causes such variable \( \dot{M} \). For example, oscillations in companion stars can cause such variability in \( \dot{M} \) (Koenigsberger et al. 2006) and subsequent variation in X-ray luminosity—provided there is a mechanism to keep such oscillations stable (Farrell et al. 2008). Other possibilities for superorbital modulation include the existence of corotation interaction regions (e.g., in IGR J16493-4348; Bozzo et al. 2017), accretion bulge formed by collision of the stellar wind with the outer edge of the PWAD (Zdziarski et al. 2009), or the formation of a transient disk (e.g., in 4U 0114+65; Hu et al. 2017), magnetic axis precession (where compact object is a neutron star, e.g., Her X-1; Postnov et al. 2013), presence of a third body, or even jet formation (e.g., SS 433, Margon 1984). Furthermore, new discoveries of superorbital modulation from all kinds of accreting systems (supergiant fast X-ray transients, classical supergiant X-ray binaries, black hole, ultra-luminous X-rays; ULXs) independent of the inclination angles indicate that this effect of superorbital modulation is not caused by viewing geometry alone (Corbet & Krimm 2013). For an review on this topic, we refer the reader to Kotze & Charles (2012) and Corbet & Krimm (2013) and references therein.

In this paper, we will investigate the possible cause(s) for superorbital modulation in another high-mass X-ray binary, SMC X-1. SMC X-1 is an eclipsing binary system discovered in 1971 (Price et al. 1971) located in the Small Magellanic Cloud at a distance of ~60 kpc (Neilsen et al. 2004). The pulsar has a spin period of ~0.71 s (Lucke et al. 1976), an orbital period of ~3.9 days with a B0 I supergiant as the companion, and exhibits superorbital variability with a periodicity in the range of 40–60 days (Gruber & Rothschild 1984; Wojdowski et al. 1998). Given the similarity of SMC X-1 to other sources like Her X-1 and LMC X-4, the superorbital variation in SMC X-1—like these two sources—was ascribed to the PWAD (Wojdowski et al. 1998). Unlike these two sources, however, the superorbital period in SMC X-1 is not periodic but varies within 40–60 days, repeating cyclically after ~7 yr each (Clarkson et al. 2003). Such a variability in the superorbital period for SMC X-1 can theoretically be attributed to the presence of different warping modes in the accretion disk (Ogilvie & Dubus 2001).

It is, however, interesting to note that long-term ASM (1.3–12 keV) and BATSE (20–100 keV) lightcurves of SMC X-1 covering very different energies show similar variations.
in the superorbital modulation (Figure 1 of Clarkson et al. 2003). This similarity in the superorbital modulation across the entire energy range of 1.3–100 keV cannot be explained if the superorbital modulation in SMC X-1 is a result of absorption by neutral matter in the PWAD (since soft X-rays are absorbed more than hard X-rays). Such a lack of absorption signatures was also reported in the original paper by Wojdowski et al. (1998). Later authors also argued that such a complex superorbital behavior in SMC X-1 cannot be understood by assuming simple models of PWAD alone (see the discussion sections of Clarkson et al. (2003) and Trowbridge et al. (2007).

In this paper, we investigate the broadband X-ray spectral and timing characteristics of SMC X-1 at different superorbital phases to examine the proposed scenario of intensity variation by absorption in the precessing warped disk. The X-ray spectrum of SMC X-1 is usually described with two components, a hard power-law component and a soft thermal component, with the latter possibly arising from the reprocessing of soft X-rays (Paul et al. 2002). A remarkable dissimilarity and phase lag of the soft X-ray with the thermal component, with the latter possibly arising from the reprocessing of soft X-rays has also been noted in the literature (Paul et al. 2002; Neilsen et al. 2004; Hickox & Vrtilek 2005).

The X-ray spectrum of high-mass X-ray binaries (HMXBs) also usually features iron Kα emission lines, which are produced by fluorescence emission of either neutral or partially ionized matter in the accretion disk or circumstellar matter around the neutron star. One interesting aspect of SMC X-1 is its remarkably weak iron line in the X-ray spectrum compared to other supergiant HMXBs (Giménez-García et al. 2015).

In this paper, we discuss the broadband spectral and timing variation of SMC X-1 in different intensity states using data from Suzaku and The Nuclear Spectroscopic Telescope Array (NuSTAR). We also present here the first comprehensive view of the different spectral states of superorbital variation through simultaneous broadband spectral fitting using Suzaku and NuSTAR observations. In Section 2, we present the details of the observations and data reduction. In Section 3, we present the details of the data analysis and results, followed by a discussion in Section 4 and a summary in Section 5.

2. Observations and Data Reduction

2.1. Suzaku

SMC X-1 was observed with the Suzaku observatory (Mitsuda et al. 2007) 10 times during 2011–2012. Suzaku consists of two main payloads: the X-ray Imaging Spectrometer (XIS, 0.2–12 keV; Koyama et al. 2007) and the Hard X-ray Detector (HXD, 10–600 keV; Takahashi et al. 2007). The XIS consists of four CCD detectors, of which three (XIS 0, 2, and 3) are front-illuminated and one (XIS 1) is back-illuminated. The HXD comprises PIN diodes and GSO crystal scintillator detectors.

The data reduction was done on the filtered “cleaned” event files following the reduction technique mentioned in the same Suzaku ABC guide. We applied barycentric correction to all event files using aepipeline. For CCD data obtained by XIS, we had to investigate the effect of pile-up, which is defined as two photons of lower energy being read as one with higher energy and can cause artificial hardening of the X-ray spectrum. Therefore, for observations affected by pile-up, we discarded photons collected within the portion of the PSF where the estimated pile-up fraction was greater than 4% determined using the FTOOLS task pileest. XIS lightcurves and spectra were then extracted by choosing circular regions of \(3′\) or \(4′\) radius from the source position, depending on whether the observation was made in one-fourth or zero window mode, respectively. Backgrounds for the XIS were extracted by selecting regions of the same size as mentioned above in a portion of the CCD that was not significantly contaminated by the source X-ray mission.

Being a photon counting detector, data from PIN detector have to be corrected for dead time, which is the time interval for which the detector electronics are processing one photon and thus cannot yet detect the arrival of another. This dead time correction was done using FTOOLS task hxddtcor. For the HXD/PIN, simulated “tuned” non-X-ray background event files (NXB) corresponding to the month and year of the respective observations were used to estimate the NXB (Fukazawa et al. 2009).

The XIS spectra were extracted with 2048 channels and PIN spectra were extracted with 255 channels. Response files for the XIS were created using the CALDB version “20150312.” For the HXD/PIN spectrum, response files corresponding to the epoch of the observation were obtained from the Suzaku guest observer facility. The observation details are presented in Table 1. For brevity, in this paper, we denote each observation by the last two numbers of its observation identification (OBSID; e.g., 706030010 is denoted by 10), except 706030100, which is abbreviated as 100. Observations 10, 20, 50, 70, 80, and 90 were in high states (H), observations 30 and 100 were in medium states (M) and observations 40 and 60 where in low states (L).

2.2. NuSTAR

SMC X-1 was observed with NuSTAR (Harrison et al. 2013) six times during 2012–2016 at various superorbital phases (reported in Table 1). NuSTAR consists of two focal plane modules, FPMA and FPMB, each made up of four pixelated detectors (DETO-DETO3) spanning an energy range of 3–79 keV. We used nupipeline version 0.4.6 to generate cleaned event files, which also provides the recommended source and background regions. We extracted the source spectrum and background spectrum using these corresponding region files. Then we filtered for good time intervals for the duration of the simultaneous observations in FPMA and FPMB.

Finally, following the same naming convention as Suzaku, we label the six NuSTAR observations by the last two digits of their OBSID. For example, 30202004008 is denoted as 08, 30202004002 is 02, and so on. Observations 08, 02, and 03 were in high states (H), 04 was in medium states (M) and 01 and 06 were in low states (L).

4 http://heasarc.gsfc.nasa.gov/docs/suzaku/analysis/abc/

5 https://heasarc.gsfc.nasa.gov/docs/suzaku/analysis/pinbgd.html

6 https://heasarc.gsfc.nasa.gov/docs/heasarc/caldb/suzaku/

7 https://heasarc.gsfc.nasa.gov/docs/nustar/analysis/
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Table 1
Observation Log for SMC X-1 with Suzaku and NuSTAR Ordered Sequentially with Decreasing Brightness States

| Facility | OBSID (alias in this paper) | D.O.O | Useful exposure (ks) | \(P_{\text{up}}\) (s) | P.F. (%) | R |
|----------|-----------------------------|-------|----------------------|---------------------|----------|---|
| Suzuki   | 706030010 (10)              | 2011 Apr 07 | 18.5 | 0.70170860 ± 0.00000089 | 45.8 ± 1.2 | 0.99 ± 0.04 |
|          | 706030070 (70)              | 2011 Sep 21 | 18.1 | 0.70152930 ± 0.00000037 | 45.9 ± 1.4 | 1.35 ± 0.06 |
|          | 706030050 (50)              | 2011 May 25 | 17.8 | 0.70166090 ± 0.00000016 | 45.3 ± 1.4 | 1.10 ± 0.05 |
|          | 706030080 (80)              | 2011 Nov 10 | 19.9 | 0.70147950 ± 0.00000018 | 40.1 ± 1.1 | 0.95 ± 0.04 |
|          | 706030020 (20)              | 2011 Apr 18 | 17.3 | 0.70169900 ± 0.00000029 | 44.7 ± 1.3 | 1.60 ± 0.07 |
|          | 706030090 (90)              | 2011 Dec 12 | 17.3 | 0.70143900 ± 0.00000047 | 50.6 ± 1.5 | 1.71 ± 0.09 |
|          | 706030030 (30)              | 2011 Apr 22 | 15.7 | 0.70169140 ± 0.00000065 | 46.9 ± 1.6 | 2.02 ± 0.14 |
|          | 706030110 (100)             | 2012 Mar 19 | 18.6 | 0.70134440 ± 0.00000032 | 46.5 ± 2.3 | 1.34 ± 0.11 |
|          | 706030060 (60)              | 2011 Jun 28 | 18.7 | ... | <4.0 | ... |
|          | 706030040 (40)              | 2011 May 10 | 17.8 | 0.70167570 ± 0.00000234 | 34.4 ± 6.8 | 2.55 ± 1.58 |
| NuSTAR   | 30202004008 (08)            | 2016 Oct 24 | 20.1 | 0.69953702 ± 0.00000027 | 37.9 ± 0.2 | 0.99 ± 0.01 |
|          | 10002013003 (03)            | 2012 Aug 6  | 17.0 | 0.70118470 ± 0.00000006 | 36.3 ± 0.3 | 1.88 ± 0.03 |
|          | 30202004002 (02)            | 2016 Sep 8  | 20.8 | 0.69958702 ± 0.00000036 | 36.1 ± 0.3 | 1.10 ± 0.01 |
|          | 30202004004 (04)            | 2016 Sep 19 | 19.9 | 0.69957772 ± 0.00000016 | 41.3 ± 0.3 | 1.67 ± 0.02 |
|          | 10002013001 (01)            | 2012 Jul 5  | 33.1 | 0.70122190 ± 0.00000068 | 12.2 ± 0.6 | 4.00 ± 1.38 |
|          | 30202004006 (06)            | 2016 Oct 1  | 19.4 | ... | <1.9 | ... |

Note. The pulse fraction (P.F.) is defined as \(P_{\text{up}}/(P_{\text{max}}+P_{\text{up}})\), where \(P_{\text{up}}\) is the un-pulsed component and \(P_{1}, P_{2}\) are the two peaks. The ratio (R) is \((P_{1}-P_{\text{up}})/(P_{2}-P_{\text{up}})\).

3. Analysis and Results

3.1. Timing Analysis

In order to get an overview of the long-term superorbital intensity variation in these 16 observations, we plotted the 1 day binned Swift/BAT lightcurve filtered for eclipses and ingresses/egressess of the NS. This is shown in Figure 1, where we also mark the Suzaku and NuSTAR observations. Note that we removed the error bars in these lightcurves to assist with visual clarity.

3.1.1. Suzaku Timing Analysis

For timing analysis with Suzaku data, we extracted background-subtracted lightcurves from the available XIS and PIN barycentric corrected event files. Since the spin period of SMC X-1 is ~0.7 s and the lowest available observation mode for XIS was one-fourth the window that collects data at a 2 s interval, we could not use the XIS lightcurves to detect pulsations. The PIN lightcurves were background-subtracted by generating a background lightcurve using the simulated background files\(^8\) (Fukazawa et al. 2009). We use the background corrected PIN data extracted with a resolution of 0.01 s to search for periodicity in the individual observations and creation of lightcurves after relevant orbital corrections. In order to correct for Doppler shift of the pulse period due to the orbital motion of the pulsar, we corrected for arrival time in the PIN lightcurves of individual observations using the orbital parameters from Table 3 of Raichur & Paul (2010) extrapolated to the time of each observation.

3.1.2. NuSTAR Timing Analysis

Similarly, to get a combined lightcurve for each NuSTAR observation, we add the individual FPMA and FPMB barycenter-corrected (using barycorr) lightcurves (binned at 0.01 s). We correct the arrival times of lightcurves for

\[^8\]https://heasarc.gsfc.nasa.gov/docs/suzaku/analysis/pinbgd.html

orbital motion using the orbital parameters from Table 3 of Raichur & Paul (2010) extrapolated to the time of each observation—similar to the approach use for the Suzaku lightcurves above.

3.1.3. Pulse Profile and Pulse Period Evolution

**Pulse profile studies:** the spin period search was carried out on the Suzaku and NuSTAR lightcurves obtained above. Pulsations were clearly detected in 9 out of 10 Suzaku observations and 5 out of 6 observations for NuSTAR. The best-obtained spin period for each observation is tabulated in Table 1 and a plot of the pulse period history is shown in Figure 2. There was no clear pulsation in one Suzaku observation (60), and one NuSTAR observation (06). In order to obtain the pulse profiles for these two observations, we folded the lightcurves at the period corresponding to the highest chi-squared value within the period search range. Folded profiles from all the observations are shown to the left (Suzaku) and right (NuSTAR) of Figure 3. We identify the first “broader” peak as \(P_{1}\) and \(P_{2}\) as the one following it. We notice that although both the peaks evolve with luminosity, the second peak \(P_{2}\) decreases more rapidly with decreasing luminosity. This is especially noticeable in the NuSTAR pulse profiles on the right of Figure 3. In Table 1, we have also listed the ratio (R) of the two peaks \(P_{1}\) and \(P_{2}\) above the un-pulsed component \(P_{\text{up}}\) defined as \((P_{1}-P_{\text{up}})/(P_{2}-P_{\text{up}})\), and the pulse fraction (P.F) defined as \((P_{\text{max}}-P_{\text{up}})/(P_{\text{max}}+P_{\text{up}})\).

**Pulse period evolution:** the pulse period evolution of SMC X-1 has been investigated extensively in the past. Unlike most HMXB pulsars with supergiant companion stars that show both spin-up and spin-down episodes resulting in significant random variations in period evolution over their long-term trends (Bildsten et al. 1997), SMC X-1 has only been found to be spinning up since its discovery. Inam et al. (2010), however, reported some variations in the spin-up rate. Starting from a value of \(\sim 3.6 \times 10^{-11} \text{ Hz s}^{-1}\), since its discovery the spin-up rate halved to a value of \(\sim 1.9 \times 10^{-11} \text{ Hz s}^{-1}\) in about 20 yr and then increased to \(\sim 2.6 \times 10^{-11} \text{ Hz s}^{-1}\) just prior to the
launch of RXTE in 1995, after which there were more period measurements. A sudden change in the spin-up rate around MJD 50,000 is also obvious from the residuals of the linear fit of the period history shown in Figure 2. We discuss the implications of this finding in detail in Section 4.

3.2. Spectral Analysis

3.2.1. Suzaku

We performed spectral analysis of SMC X-1 using data from XIS-0 and the HXD/PIN. Spectral fitting was performed
using XSPEC v12.10.0e. Artificial features are known in the XIS spectra around the Si edge and Au edge and the energy range of 1.75–2.23 keV is usually not used for spectral fitting. For each observation, we fitted the XIS and PIN spectra simultaneously with all parameters tied. The 2048 channel XIS spectra were rebinned by a factor of 10 up to 5 keV, by 2 from 5 to 7 keV, and by 14 for the rest. The PIN spectra were binned by a factor of 2 until 22 keV, by 4 from 22 to 45 keV, and by 6 for the rest to ensure a consistent signal-to-noise ratio across the entire energy band.

We fitted each individual X-ray spectrum of SMC X-1 with standard continuum models used for NS-HMXBs, like an absorbed power law with an exponential cutoff energy, HIGHECUT, and CUTOFFPL. Both models have been used to describe the broadband spectrum of SMC X-1 in earlier works (Naik & Paul 2004; Pike et al. 2019). In addition to this continuum, the spectra also necessitated a blackbody component to fit the soft excess below 2 keV as seen in many X-ray pulsars (Paul et al. 2002; Hickox et al. 2004), as well as a Gaussian line at 6.4 keV for the K_{\alpha} emission of neutral iron. The two continuum models described above fitted the X-ray spectra well, with the $\chi^2$/dof for the Suzaku spectrum with the highest photon counts (706030010) being 1.11/270, and 1.09/271, respectively. We therefore chose the CUTOFFPL model for further spectral analysis. In XSPEC notation, this model (model 1) is

$$\text{constant}(1) + \text{phabs}(2)(\text{cutoffpl}(3) + \text{bbody}(4) + \text{gaussian}(5)).$$

The complete set of parameters for the fitting above is listed in Table 2.

During the course of the spectral fitting above, we noticed that the change in the X-ray intensity of SMC X-1 at different superorbital phases is not limited to the XIS energy band (0.3–10 keV) alone. The hard X-rays (15–70 keV) measured in the HXD/PIN band also change by a large factor with different superorbital states. This variation is of paramount importance to understand the superorbital modulation in SMC X-1. To the best of our knowledge, such a change in the hard X-ray flux at different phases of superorbital modulation has never been discussed in the literature, although there have been reports of changes in hard X-ray flux (Table 6 of Brumback et al. 2020) at different superorbital states of SMC X-1.

In the current prevailing hypothesis, the superorbital intensity variation of SMC X-1 is caused by absorption in a PWAD. Such signatures manifest as a reduction in soft X-rays (below ~5 keV) in the low-intensity states, but the hard X-ray photons should be unaffected by this absorption. Curiously though, we notice that for SMC X-1 in the low superorbital intensity states, the reductions in soft X-rays are also accompanied by a corresponding decrease in the hard X-ray emission. Such behavior contradicts the absorption caused by a neutral absorber. A further signature of absorption in the neutral medium is the fact that the spectral shape, especially below 3 keV, has a strong energy dependence in soft X-rays (see various examples in Figure A.1 of Pradhan et al. 2018). The XIS spectra of the Suzaku observations of SMC X-1, however, do not show such a dependence, characteristic of neutral absorption (top panel of Figure 4).

Motivated by this, we introduced a partially ionized absorber to the above model (say, model 2), which in XSPEC notation is given by

$$\text{constant}(1) \times \text{phabs}(2)(\text{zxipcf}(3) \times \text{cutoffpl}(4)) + \text{bbody}(5) + \text{gaussian}(6)).$$

The use of an ionized absorber is also justified since such high X-ray luminosity, as observed in SMC X-1, also contributes to ionization of matter around the neutron star. This is also supported by the remarkably low value of equivalent width of the neutral iron K_{\alpha} line of SMC X-1 compared to similar systems like LMC X-4. The complete set of parameters for the fitting above is listed in Table 3 and the individual spectra are plotted together in the bottom panel of Figure 4.

### 3.2.2. NuSTAR

We fitted the NuSTAR FPMA and FPMB spectra simultaneously with all parameters tied, except for the relative instrument normalizations, which were kept free. The 4096 channel FPM spectra were rebinned by a factor of 2 up to 20 keV, by 10 from 20 to 60 keV, by 6 for 60–78 keV, and by a factor of 2 for the rest.

The 3–70 keV NuSTAR spectra are used for spectral fitting, employing the same continuum model with a partially ionized absorber as Suzaku. The only difference is that we did not require any blackbody component to fit the soft excess, in contrast to the NuSTAR analysis by Pike et al. (2019). (With the sensitivity of NuSTAR below 3 keV being very poor, a blackbody component with a temperature of ~0.16 keV cannot be constrained with NuSTAR.) The fits for all the observations are tabulated in Table 4 and the individual spectra are plotted in the bottom panel of Figure 4. We also noted an absorption feature in the spectrum reminiscent of a cyclotron resonant scattering feature (CRSF) around 50–60 keV in the three brightest observations (08, 02, 03) with NuSTAR. We used GABS to model this cyclotron absorption feature, which decreased the $\chi^2$/dof from 822/701 to 751/699, 845/700 to 732/698, and 842/700 to 750/698 for observations 08, 02, and 03, respectively. The ratio of data to model for these three
observations, with and without the CRSF component, is shown in Figure 5.

3.3. Joint Spectral Fitting for Different Superorbital States

3.3.1. Suzaku

In the prevailing hypothesis for superorbital intensity variation in SMC X-1 (also LMC X-4), the variation is caused by absorption in a PWAD while the intrinsic luminosity of the source remains nearly constant, as seen in the soft, $\sim 0.1-10\kev$ X-ray spectrum (see, e.g., Wojdowski et al. 1998). The nearly constant peak intensity of the superorbital modulation observed for more than two decades with RXTE–ASM (1.5–12.0 keV band, from 1996 to 2011), Swift–XRT, and MAXI–GSC supports this hypothesis. However, all of these observations are well below 20 keV. The aim of this current work is to investigate if the multiple broadband spectra also show evidence of variable absorption.

To achieve this, we performed a joint spectral fitting of the 10 Suzaku observations. We first fit the continuum of the brightest observation (10) from both XIS and PIN with an absorbed power law and high-energy cutoff coupled with an ionized partial absorber. We then tied all the spectra from other Suzaku observations to this model ($N_{\text{H}}$ was frozen at $0.3 \times 10^{22}$ atoms cm$^{-2}$) for simultaneous fitting. With this continuum (10) as the reference, we therefore performed joint fitting of the spectra obtained in other intensity states while allowing the absorption parameters, i.e., covering fraction ($f$), local absorption column density ($N_{\text{H}_{\text{L}}}$), and ionization parameter $\xi$ to change.

Because Suzaku allowed us to constrain the soft excess component, we let the blackbody normalization vary. Furthermore, we allowed the Gaussian normalization of the 6.4 keV to change as well. With the above procedure, the low-energy part of the spectrum fit considerably well with the low-intensity states exhibiting a higher value of covering fraction. However, the systematic residuals above 10 keV exhibited a misfit in the hard X-ray band. We therefore freed the power-law normalization of the 10 spectra, which drastically improved the fits. The power-law normalization differs by as much as a factor of 6. Seeing such a large change in this power-law component, we cross-checked the peak-to-peak superorbital variation in the long-term BAT lightcurves. Interestingly, we find that the peak-to-peak variation of the superorbital modulation in the long-term BAT lightcurves is only $\sim 15\%$. Such a contrast in the power-law normalization versus the orbit-averaged BAT lightcurves is puzzling. We will discuss this further in Section 4.

3.3.2. NuSTAR

For joint fitting of six NuSTAR observations, we follow the same methodology as above with the same model (without the blackbody component, which cannot be constrained with NuSTAR). We fit the spectrum with the highest statistics (08) and tied the other five spectra with this, while allowing the absorption parameters ($f$, $N_{\text{H}_{\text{L}}}$, $\xi$) and power-law normalization to be free. We again achieve the same results obtained with Suzaku and the power-law normalization varies by a factor of 6. The physical interpretation of this exercise is explained in Section 4.
Table 2

Best-fit Parameters of SMC X-1 during Suzaku with the CUTOFFPL Model (Model 1; Equation 1; See Section 3.2 for Details)

| Parameters | H 10 | H 70 | H 50 | H 80 | H 20 | H 90 | M 30 | M 100 | L 60 | L 40 |
|------------|------|------|------|------|------|------|------|-------|------|------|
| N_{H}      | 0.15 ± 0.02 | 0.15 ± 0.02 | 0.20 ± 0.02 | 0.09 ± 0.02 | 0.22 ± 0.03 | 0.11 ± 0.04 | 0.16 ± 0.04 | 0.14 ± 0.06 | 0.04 ± 0.04 | 0.09 ± 0.09 |
| Γ          | 0.48 ± 0.02 | 0.49 ± 0.03 | 0.43 ± 0.03 | 0.43 ± 0.02 | 0.50 ± 0.03 | 0.57 ± 0.03 | 0.49 ± 0.04 | 0.22 ± 0.04 | −0.42 ± 0.08 | −1.05 ± 0.11 |
| E_{f}      | 9.4 ± 0.3 | 9.5 ± 0.3 | 9.2 ± 0.3 | 9.2 ± 0.3 | 10.8 ± 0.3 | 10.6 ± 0.3 | 9.9 ± 0.4 | 8.2 ± 0.4 | 7.9 ± 0.5 | 5.7 ± 0.4 |
| Γ_{norm}   | 0.067 ± 0.002 | 0.052 ± 0.001 | 0.050 ± 0.001 | 0.046 ± 0.001 | 0.038 ± 0.001 | 0.039 ± 0.002 | 0.026 ± 0.001 | 0.011 ± 0.001 | 0.0005 ± 0.0001 | 0.0002 ± 0.00001 |
| kT         | 0.22 ± 0.008 | 0.22 ± 0.008 | 0.21 ± 0.007 | 0.23 ± 0.01 | 0.21 ± 0.01 | 0.22 ± 0.02 | 0.21 ± 0.01 | 0.17 ± 0.01 | 0.23 ± 0.02 | 0.25 ± 0.03 |
| kT_{norm}  | 2.8 ± 0.3 | 1.7 ± 0.2 | 2.4 ± 0.3 | 1.4 ± 0.2 | 1.4 ± 0.2 | 0.9 ± 0.2 | 0.7 ± 0.2 | 0.3 ± 0.1 | 0.09 ± 0.02 | 0.03 ± 0.01 |
| K_{0}      | 6.38 ± 0.05 | 6.45 ± 0.04 | 6.43 ± 0.05 | 6.36 ± 0.06 | 6.49 ± 0.07 | 6.36 ± 0.03 | 6.27 ± 0.08 | 6.30 ± 0.03 | 6.41 ± 0.02 | 6.35 ± 0.05 |
| EW         | 0.015 ± 0.005 | 0.026 ± 0.007 | 0.022 ± 0.005 | 0.022 ± 0.006 | 0.013 ± 0.006 | 0.038 ± 0.011 | 0.024 ± 0.011 | 0.038 ± 0.011 | 0.135 ± 0.022 | 0.094 ± 0.022 |
| Flux^{c}   | 2.96 ± 0.05 | 2.70 ± 0.04 | 2.58 ± 0.02 | 2.32 ± 0.04 | 1.99 ± 0.02 | 1.73 ± 0.01 | 1.31 ± 0.02 | 0.67 ± 0.02 | 0.27 ± 0.01 | 0.15 ± 0.01 |
| χ^{2}/dof  | 1.09/271 | 1.05/270 | 1.3/270 | 1.09/270 | 1.42/271 | 1.00/271 | 1.07/270 | 1.36/270 | 1.59/271 | 1.23/271 |

Notes. Errors quoted are for the 90% confidence range. The observations are arranged in order of decreasing brightness states, with high, medium, and low states designated as H, M, and L, respectively.

^{a} In units of photons keV^{-1} cm^{-2} s^{-1} at 1 keV.

^{b} In units of L_{90}/D_{10}, where L_{90} is source luminosity in units of 10^{39} erg s^{-1} and D_{10} is the source distance in 10 kpc units.

^{c} In 1–70 keV, in units of 1 × 10^{39} erg cm^{-2} s^{-1}.
The variations of the spectral parameters in the exercises above as a function of X-ray flux are shown in Figure 6.

4. Discussion

Individual broadband spectra of all observations can be fitted with a cutoff power law, along with a blackbody for a soft excess (only Suzaku) and neutral iron Kα line. The equivalent width of the iron line varies from 10 to 250 eV, anti-correlated with luminosity. Through joint fitting of the 16 spectra in different superorbital states, we find that the power-law normalization varies by a factor of up to 6, while the overall variation of the peak of the superorbital modulation obtained from the BAT lightcurves is \( \sim 15\% \). In the event this X-ray variation was caused only through absorption in PWAD, the power-law normalization should not vary beyond the variation in the peak luminosity of the superorbital variation (i.e., up to 15% in case of SMC X-1). This huge difference in the percentage of variation in BAT lightcurves versus power-law normalization can only be explained if we introduce an intrinsic variability of X-ray emission from the source as opposed to superorbital modulation caused by absorption.

Pulsations are detected in all but two observations of Suzaku (15–70 keV) and NuSTAR (3–70 keV). We also note that the pulse fraction in hard X-rays (>12 keV) remains almost constant for 13 out of 16 observations (Table 1). Considerable luminosity dependence is seen in the pulse profile, with the ratio of the second to the first peaks becoming smaller at lower intensities. This variation of pulse profile morphology also supports our hypothesis that there is an intrinsic change in the source spectrum of SMC X-1 along varying superorbital states.

The timing analysis also reveals that interestingly (except for one Suzaku and one NuSTAR observation), the lower-intensity states in Suzaku are also pulsed in hard X-rays. This suggests that perhaps most X-rays travel across the warp instead of being scattered, which would otherwise have caused smearing of pulsations. Detection of strong pulsations and relatively low equivalent width of the iron line compared to other similar systems indicates that even in the low state we are mostly seeing the central object directly and not in scattered radiation.

From the residuals to a linear fit of the period history shown in Figure 2, it is obvious that there was a sudden change in spin-up rate around MJD 50,000 (year 1995). This abrupt change was also noted in ROSAT observations, though it was not specifically mentioned in the report (Kahabka & Li 1999). In the scenario that the superorbital intensity variation of SMC X-1 is due to variable absorption, the accretion torque onto the neutron star should be compared against the peak luminosity of the superorbital variation. We therefore compare the peak luminosity before and after the sudden change in spin-up rate (around MJD 50,000). The long-term flux variation of SMC X-1 was investigated in detail with HEAO 1 for three cycles and they reported a peak flux of \( 2.8 \times 10^{-11} \) erg cm\(^{-2}\) s\(^{-1}\) in the 13–70 keV band (Gruber & Rothschild 1984). In the current observations with Suzaku and NuSTAR, some of which are near the peak of the superorbital modulation, the flux in the same energy band is measured to be much higher (Tables 3 and 4), up to a factor 50 compared to the HEAO 1 measurements. It is therefore likely that there was a significant change in the mass-accretion rate onto SMC X-1, corresponding with the change in spin-up rate some time around around MJD 50,000 (year 1995). After this event, there was a decrease in the superorbital period of SMC X-1 from about 60 to about 45 days and a weak correlation was found between the superorbital period and the short-term spin-up rate (Dage et al. 2019), which may therefore be related to the change in mass-accretion rate. This finding therefore directly support our hypothesis of varying X-ray emission from the source.

We clarify that our findings do not question the presence of a PWAD in SMC X-1, but rather show that the absorption in the PWAD is not the cause of superorbital modulation—at least not wholly—and there are signatures of intrinsic changes in X-rays emitted from the neutron star. To reiterate, in the PWAD model, the warped accretion disk is irradiated by the X-rays from the pulsar beam where these hard X-ray photons get reprocessed to soft X-rays. Therefore, by studying the differences in pulse profiles of the direct (hard) and the reprocessed (soft) X-ray emission, constraints can be placed on the disk geometry (Hickox & Vrtilek 2005). Recently, Brumback et al. (2020) used...
### Table 3

Best-fit Parameters of SMC X-1 during Suzaku with the CUTOFFPL Model with a Partially Ionized Absorber (Model 2; Equation 2; See Section 3.2 for Details)

| Parameters          | H  | H  | H  | H  | H  | H  | M  | M  | L  | L  |
|---------------------|----|----|----|----|----|----|----|----|----|----|
| $N_{\text{H}_1}$    | 0.17 ± 0.01 | 0.17 ± 0.03 | 0.24 ± 0.03 | 0.14 ± 0.02 | 0.26 ± 0.02 | 0.15 ± 0.04 | 0.17 ± 0.06 | 0.15 ± 0.10 | 0.21 ± 0.07 | 0.17 ± 0.02 |
| $N_{\text{H}_2}$    | 23 ± 8 | 30 ± 2 | 48 ± 12 | 23 ± 8 | 95 ± 11 | 23 ± 10 | 81 ± 9 | 32 ± 9 | 41 ± 11 | 25 ± 7 |
| $\xi$               | 1.87 ± 0.66 | 1.90 ± 0.19 | 1.89 ± 0.32 | 1.77 ± 0.34 | 2.04 ± 0.14 | 1.85 (−2.92, 0.96) | 2.14 ± 0.22 | 3.06 ± 0.17 | 1.19 ± 0.36 | 0.85 ± 0.5 |
| $f$                 | 0.10 ± 0.02 | 0.18 ± 0.07 | 0.25 ± 0.03 | 0.09 ± 0.01 | 0.27 ± 0.01 | 0.03 (−0.01, 0.02) | 0.27 ± 0.11 | 0.44 ± 0.07 | 0.75 ± 0.04 | 0.82 ± 0.09 |
| $\Gamma$            | 0.59 ± 0.02 | 0.65 ± 0.01 | 0.60 ± 0.02 | 0.51 ± 0.02 | 0.60 ± 0.02 | 0.59 ± 0.03 | 0.51 ± 0.03 | 0.59 ± 0.03 | 0.59 ± 0.07 | 0.69 ± 0.09 |
| $E_f$               | 9.7 ± 0.2 | 10.1 ± 0.3 | 9.6 ± 0.2 | 9.6 ± 0.3 | 10.4 ± 0.3 | 9.6 ± 0.3 | 9.5 ± 0.62 | 9.8 ± 0.4 | 10.1 ± 0.9 | 12 ± 5 |
| $\Gamma_{\text{norm}}$ | 0.091 ± 0.005 | 0.069 ± 0.01 | 0.078 ± 0.004 | 0.049 ± 0.004 | 0.063 ± 0.008 | 0.036 ± 0.006 | 0.033 ± 0.001 | 0.015 ± 0.0001 | 0.006 ± 0.0003 | 0.003 ± 0.0001 |
| $kT$                | 0.21 ± 0.002 | 0.21 ± 0.01 | 0.19 ± 0.01 | 0.20 ± 0.01 | 0.19 ± 0.01 | 0.19 ± 0.01 | 0.21 ± 0.02 | 0.16 ± 0.03 | 0.17 ± 0.01 | 0.17 ± 0.05 |
| $kT_{\text{norm}}$  | 2.92 ± 0.16 | 1.79 ± 0.26 | 2.79 ± 0.01 | 1.67 ± 0.24 | 1.71 ± 0.30 | 1.15 ± 0.29 | 0.77 ± 0.21 | 0.28 ± 0.32 | 0.17 ± 0.07 | 0.05 ± 0.09 |
| $\delta$            | 6.37 ± 0.04 | 6.46 ± 0.06 | 6.41 ± 0.06 | 6.39 ± 0.06 | 6.52 ± 0.12 | 6.38 ± 0.04 | 6.28 ± 0.10 | 6.32 ± 0.04 | 6.41 ± 0.03 | 6.35 ± 0.06 |
| $\text{EW}$         | 0.014 ± 0.007 | 0.024 ± 0.006 | 0.013 ± 0.007 | 0.020 ± 0.002 | 0.011 ± 0.006 | 0.040 ± 0.011 | 0.015 ± 0.011 | 0.035 ± 0.012 | 0.100 ± 0.017 | 0.053 ± 0.025 |
| Flux$^a$             | 3.62 ± 0.06 | 2.70 ± 0.07 | 2.54 ± 0.06 | 2.51 ± 0.03 | 2.21 ± 0.05 | 1.94 ± 0.05 | 1.43 ± 0.04 | 0.78 ± 0.02 | 0.22 ± 0.01 | 0.17 ± 0.09 |
| Flux$^d$             | 1.44 ± 0.01 | 1.21 ± 0.01 | 1.18 ± 0.01 | 1.16 ± 0.01 | 1.06 ± 0.01 | 0.89 ± 0.01 | 0.66 ± 0.03 | 0.43 ± 0.02 | 0.13 ± 0.10 | 0.10 ± 0.10 |
| $\chi^2$/dof        | 0.81/267 | 0.96/267 | 1.22/267 | 1.00/267 | 1.25/268 | 0.89/268 | 1.0/268 | 1.14/267 | 1.35/267 | 1.00/268 |

**Notes.** The observations are arranged in order of decreasing flux state; High (H), medium (M), and low.

$^a$ In units of photons keV$^{-1}$ cm$^{-2}$ s$^{-1}$ at 1 keV.

$^b$ In units of $L_{30}/D_{10}$, where $L_{30}$ is source luminosity in units of $10^{39}$ erg s$^{-1}$ and $D_{10}$ is the source distance in 10 kpc units.

$^c$ In 1–70 keV, in units of $10^{-5}$ erg cm$^{-2}$ s$^{-1}$.

$^d$ In 13–70 keV, in units of $10^{-5}$ erg cm$^{-2}$ s$^{-1}$. 
Table 4
Best-fit Parameters of SMC X-1 during NuSTAR Observations with the CUTOFFPL Model and a Partially Ionized Absorber (Model 2, minus the Blackbody Component; See Section 3.2 for Details)

| Parameters | OBSID          |         |         |         |         |         |
|------------|----------------|---------|---------|---------|---------|---------|
|            | H  |               | H  |            | M  |            | L  |            | L  |            |
| N_{H_2}    | 0.40 ± 0.11   | 0.46    | 0.46    | 0.46    | 2.0 ± 0.15 | 4.3 ± 0.2 |
| N_{H_1}    | 22 ± 2        | 23      | 11      | 43      | 51 ± 0.77 | 85 ± 2  |
| ξ          | 1.36 ± 0.30   | 2.52 ± 0.07 | 0.19 ± 0.30 | 1.22 ± 0.17 | 1.21 ± 0.10 | 0.71 ± 0.11 |
| f          | 0.22 ± 0.05   | 0.13 ± 0.01 | 0.17 ± 0.01 | 0.34 ± 0.01 | 0.75 ± 0.03 | 0.73 ± 0.01 |
| Γ          | 0.86 ± 0.01   | 0.85 ± 0.01 | 0.85 ± 0.01 | 0.85 ± 0.01 | 0.84 ± 0.02 | 0.85 ± 0.01 |
| E_f        | 11.1 ± 0.1    | 11.05 ± 0.12 | 11.65 ± 0.11 | 10.98 ± 0.08 | 8.69 ± 0.06 | 7.9 ± 0.4  |
| PL_{norm}  | 0.119 ± 0.002 | 0.104 ± 0.005 | 0.091 ± 0.010 | 0.077 ± 0.001 | 0.023 ± 0.002 | 0.021 ± 0.004 |
| K_{o1}     | 6.44 ± 0.06   | 6.50 ± 0.05 | 6.42 ± 0.07 | 6.56 ± 0.07 | 6.38 ± 0.03 | 6.32 ± 0.04 |
| EW         | 0.023 ± 0.005 | 0.030 ± 0.007 | 0.105 ± 0.012 | 0.07 ± 0.01 | 0.17 ± 0.015 | 0.269 ± 0.114 |
| σ          | 9.14 ± 1.05   | 9.77 ± 0.97 | 11.11 ± 1.1 | ...      | ...      | ...      |
| τ          | 10            | 11.87    | 16.39 ± 7.0 | ...      | ...      | ...      |
| Flux^{a}   | 2.04 ± 0.03   | 2.07 ± 0.02 | 1.81 ± 0.01 | 1.36 ± 0.01 | 0.19 ± 0.02 | 0.140 ± 0.010 |
| Flux^{b}   | 0.92 ± 0.02   | 0.85 ± 0.01 | 0.81 ± 0.07 | 0.64 ± 0.05 | 0.11 ± 0.02 | 0.08 ± 0.21 |
| λ^{2}/dof  | 1.07/697      | 1.10/696 | 1.05/698  | ...      | ...      | ...      |
| (without GABS) | 1.19/699      | 1.20/700 | 1.21/700 | 1.35/699 | 1.02/700 | 1.02/699 |

Notes. Errors quoted are for the 90% confidence range. The observations are separated into H, M, and L for high, medium, and low states, respectively.

- In units of photons keV^{-1} cm^{-2} s^{-1} at 1 keV.
- In units of 1 \times 10^{-9} erg cm^{-2} s^{-1}.

Figure 5. Three NuSTAR spectra where a tentative CRSF at \sim 55 keV is spotted (marked with an arrow in middle panel). The middle (lower) panel shows the ratio of data to the model without (with) the CRSF model.

simultaneous XMM-Newton and NuSTAR data that span a complete superorbital cycle to illustrate this model. They found that long-term changes in soft pulse shape and phase are consistent with reprocessed emission from a precessing inner disk for two (08 and 02 in this paper) out of four observations. In this work, too, we note that the variation in the soft thermal component clearly maps the hard X-rays (blackbody versus power-law normalization in Figure 6), thereby indicating that the hard X-rays are reprocessed, possibly in the accretion disk.

We should also mention here that in observation 04, the same authors note a change in the shape of the NuSTAR pulse...
profiles. Such a change in the shape of pulse profiles for obs 04 is also noted in our work (right of Figure 3) and is evidence that indeed there is some intrinsic change in the hard X-ray emission from the central object. Finally, the authors found no pulsations in observation 06, similar to what is reported here. This extinction of pulses (in the first half of observation 01) was explained by Pike et al. (2019) as being caused by obscuration by Compton-thick matter in the accretion disk or inhibition of accretion caused by the onset of the propeller regime, as seen in the case of ULXs. The latter is ruled out since it is characterized by dramatic flux variability as opposed to “continuous” transitions between high and low states like what is seen in SMC X-1. While the former is still a possibility when we consider scattering of the soft X-rays, it is unlikely that the hard X-rays from the neutron star are scattered enough to switch off pulsations altogether.

The broadband timing and spectral characteristics of SMC X-1 as reported here from 10 Suzaku and 6 NuSTAR observations indicate that a variable accretion rate is the possible reason behind the superorbital intensity variation in SMC X-1. Since the X-ray luminosity drives the warp, the configuration of the warp should be sensitive to the mass-transfer rate onto the compact object. This possibility of a variable accretion rate is what we have discussed thoroughly in this paper. We have provided many spectral and timing characteristics to solidify our claim that the superorbital modulation is not alone due to absorption in the precessing warped disk.

One possible explanation for superorbital modulation in SMC X-1, drawn analogously from studies of cataclysmic variables, is the generation of “bright spots.” If the mass-transfer rate from the donor star is quasi-steady, the local values of mass transfer in accretion disks can exceed the actual mass-transfer rate from the companion star (Rutten et al. 1992). In this scenario, there is a creation of “bright spots” in the accretion disk and the warp in SMC X-1 may transport this mass-transfer stream close to the neutron star. As the warp precesses, this bright spot moves through the disk, thus varying the brightness and altering the X-ray spectrum at different superorbital phases like what is seen here. This scenario has been previously studied (see the discussion in Clarkson et al. 2003), but it suffers from a number of drawbacks. In particular, there is no reason to believe that the amount of energy emitted by these bright spots will be significant when compared to X-rays emitted from the neutron star. Additionally, these bright spots, if present, will be formed well above the corotation radius of the accretion disk and are not expected to be pulsed.

In order to gain further insights into the variation of superorbital modulation in SMC X-1, there needs to be analyses of line emissions using high-resolution spectra are needed. The variability of these emission lines can constrain the geometry and dynamics of the line-emitting regions in such sources (e.g., LMC X-4; Neilsen et al. 2009). For instance, the visibility of some Doppler-shifted lines with superorbital phases is direct evidence for the precession of accretion disks. During low (high) superorbital states when the disk is viewed almost edge-on (face-on), the Doppler-shifted lines originating in the inner accretion disk appear (disappear). If the strengths of emission lines do not change with superorbital phases, the emission lines probably originated in a region that subtends a large solid angle to the compact object, possibly the stellar wind (or outer disk). By studying the variability of line fluxes and the energies of emission lines we can investigate the physical origins of the superorbital modulation in SMC X-1. High-resolution spectra can also be used to investigate if the superorbital modulation is caused by vertical columns in the accretion disk (e.g., EXO 0748-676; Jimenez-Garate et al. 2003). Such analyses are beyond the scope of this paper, so we leave them to future works.

5. Summary

The main findings of this work are as follows:

1. We report broadband spectral-timing results using 16 observations of SMC X-1 with Suzaku and NuSTAR. All individual broadband spectra can be fitted with an absorbed high-energy cutoff power-law continuum along with a soft blackbody and a weak iron emission line (model 1). Another spectral model with an absorbed high-energy cutoff power law and a partially ionized absorber (model 2) hint at an increase in covering fraction with decreasing intensity of the source. The line equivalent varies from 10 eV in the high state to 270 eV in the low state.

2. Joint spectral fits using model 2 (without a blackbody component for NuSTAR) from all intensity states cannot be explained as being caused by absorption of an otherwise stable source. The change in the normalization of the power law (factor of ~ 6 in the joint fits) is much larger than expected from changes in the superorbital intensity modulation due to absorption the precessing disk alone. An alternative possibility is the change in the X-ray emission from the source directly that causes such variability.

3. Pulsations are detected in all but one Suzaku and one NuSTAR observation. The detection of pulsation in most of the low-intensity state observations indicates a direct view of the compact object event in the low states, contrary to the prevailing belief of the superorbital modulation being caused by absorption in the precessing accretion disk alone.

4. The pulse profile shows intensity dependence, the second peak becoming less prominent at lower intensities. These changes in the pulse profiles indicate an intrinsic change in the beaming pattern with the intensity states, which could be connected to a change in the accretion rate.

5. A putative CRSF is detected at ~55 keV in the the brightest NuSTAR observations, indicating a surface magnetic field of ∼4.2 × 10^{12} G for SMC X-1.

6. The pulse profile shows intensity dependence, the second peak becoming less prominent at lower intensities.

7. The period history of SMC X-1 is extended by about 13 yr, continuing to spin up. It shows a sudden change in the spin-up rate, perhaps along with a large change in peak luminosity.

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