SMC X-1 AS AN INTERMEDIATE-STAGE FLARING X-RAY PULSAR

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ABSTRACT

We present Rossi X-Ray Timing Explorer observations of the X-ray pulsar SMC X-1. The source is highly variable on short timescales (<1 hr), exhibiting apparent flares occupying a significant fraction (∼ 3%) of the total observing time. The flares seem to occur over all binary orbital phases and correlate with the overall variability in the light curve. We find a total of 323 discrete flares having a mean FWHM of ∼ 18 s. The detailed properties of SMC X-1 do not vary significantly between the flares and the normal state, suggesting that the flare may be an extension of the normal state persistent emission with increased accretion rates. The flares resemble type II X-ray bursts from GRO J1744−28. We discuss the origin of the SMC X-1 flares in terms of a viscous instability near the inner edge of the accretion disk around a weakly magnetized X-ray pulsar and find this is consistent with the interpretation that SMC X-1 is in fact an intermediate-stage source like GRO J1744−28.

Subject headings: accretion, accretion disks — pulsars: individual (SMC X-1) — stars: neutron — X-rays: bursts — X-rays: stars

1 INTRODUCTION

Neutron star X-ray binaries are generally categorized into two groups: low-mass X-ray binaries (LMXBs) and X-ray pulsars. The surface magnetic field of the neutron star in an LMXB is thought to be ∼ 10⁸ G. This mass accretion with this magnetic field is most likely spherical, so that no significant inhomogeneity in the X-ray emission over the neutron star surface is expected—i.e., no persistent coherent pulsations are observed. The strong magnetic field (e.g., ∼ 10¹⁵ G) of an X-ray pulsar, on the other hand, can funnel the accretion matter onto the magnetic pole, which makes the central neutron star appear as a pulsar.

Of particular interest are “intermediate-stage sources” speculated to lie between them, including “the Rapid Burster” (MXB 1730−355; Lewin et al. 1976), “the bursting pulsar” (GRO J1744−28; Fishman et al. 1995), and “the accreting millisecond pulsar” (e.g., SAX J1808.4−3658; in ’t Zand et al. 1998). Both the Rapid Burster and GRO J1744−28 exhibit type II X-ray bursts; however, only the former shows type I X-ray bursts while only the latter has apparent coherent pulsations (Lewin et al. 1996). SAX J1808.4−3658, on the other hand, shows both type I bursts and coherent pulsations (Wijns & van der Klis 1998; Chakrabarty & Morgan 1998) but not type II bursts. The magnetic field strengths of these sources have been inferred to be ∼ 10¹⁰−10¹¹ G (Rappaport & Joss 1997; Psaltis & Chakrabarty 1999; Masetti et al. 2000), between those of LMXBs and X-ray pulsars.

Another possible intermediate-stage source is the X-ray pulsar SMC X-1. It has similar properties to GRO J1744−28, including its fast spin period (∼ 0.72 s for SMC X-1; ∼ 0.47 s for GRO J1744−28), steady spin-up, and inferred magnetic field (∼10¹⁰ G; Bildsten & Brown 1997; Li & van den Heuvel 1997). In addition, once SMC X-1 was observed with an X-ray burst resembling type II bursts (Angelini, Stella, & White 1991). It may be possible, therefore, that SMC X-1 and GRO J1744−28 belong to bursting pulsars, showing both coherent pulsations and type II X-ray bursts (Li & van den Heuvel 1997).

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To investigate this important possibility, we analyze all publicly available Rossi X-Ray Timing Explorer (RXTE) data for SMC X-1, searching for phenomena that may be related to X-ray bursts. We report that SMC X-1 exhibits active flares resembling type II bursts from GRO J1744−28.

2 DATA ANALYSIS AND FLARE SEARCH

We analyzed all publicly available RXTE Proportional Counter Array (PCA) observations toward SMC X-1. Photon arrival times from the Good Xenon mode were transformed to the solar system barycenter using the JPL DE400 ephemeris. The Very Large Event models were used to subtract backgrounds, and only the Standard 2 data obtained from the top xenon layers of Proportional Counter Units 0, 1, and 4 were considered for spectral analysis. Both the data within 30 minutes after passages through the South Atlantic Anomaly and/or with a high (> 0.1) electron ratio were ignored.

The data toward SMC X-1 were occasionally contaminated by outbursts of the nearby (∼ 27° away) transient ∼ 31 s X-ray pulsar XTE J0111.2−7317 (Chakrabarty et al. 1998). We examined the contamination by carefully investigating the Leahy-normalized power-density spectra (PDSs) of the light curves. We excluded any data contaminated by XTE J0111.2−7317 as well as data containing diplike features (e.g., Moon & Eikenberry 2001) or close to the eclipse (i.e., binary orbital phase between 0.9 and 0.1) of SMC X-1. We obtained a total of 150 data segments with an average length of ∼ 1360 s. For spectral analysis, we considered only the spectrum in the 2.5–25 keV range owing to a PCA responsivity problem (R. Remillard 2001, private communication) and assumed a systematic uncertainty of 1%.

In our analysis, we define “flares” to be the part of a light curve that has three or more consecutive data bins with photon counts larger than a threshold value of 3 or Poisson noise above the mean photon count in a given light curve. We analyzed all 150 light curves as follows searching for the flares. First, we binned each light curve to 4 s time resolution and made a flare list. We extended the search with 2 and 8 s time resolutions, excluding the flares already found with different time resolutions. We found a total of 323 flares and fitted them a Gaussian
3. Flare Examples and Correlations with Other Parameters

The rms variability of the 150 light curves ranges from 6% to 16%, and the mean is ~11%. Figure 1 presents three light curves (and their PDSs) having very low (7%), average (11%), and very high (16%) rms variabilities as examples representing three different variability levels. While no flare is found in Figure 1a, three flares are found in Figure 1b. Strong flaring activity is well illustrated in Figure 1c, with several apparent flares lasting for a few tens of seconds. At the flare peak, the photon count rate rises up to ~2.5 times of that outside the flares. The Leahy-normalized PDSs (insets) of the light curves show coherent peaks at $v \approx 1.4$ Hz (and their harmonics) caused by the source’s pulsations, as well as quasi-periodic oscillation-like peaks around 10 mHz, indicating the existence of ~100 s aperiodic variability independent of the flares.

Figure 2 presents the pulse profiles of the three light curves, all showing the double-peaked, smooth profile typical of SMC X-1 (e.g., Levine et al. 1993). They have the same pulsed fractions of ~39%, with their second peaks at phase 0.56 with respect to the first ones placed at phase 0. The ratio of the second peak to the first peak is ~0.78 for Figure 2a, while it is ~0.96 for Figures 2b and 2c. No significant variation in the pulse peak ratio has been found within a given light curve, regardless of whether it is obtained inside or outside flares.

We computed the phase-averaged softness ratio defined to be the ratio of the soft X-ray (2–5 keV) photon count rates to those of the hard X-ray (5–13 keV). The average softness ratios of the three light curves in Figure 1 are invariant: $0.47 \pm 0.03$, $0.47 \pm 0.02$, and $0.46 \pm 0.04$ for Figures 1a, 1b, and 1c, respectively. To examine this invariance more thoroughly, we fitted the 32 s spectra for the largest peak in each of the three light curves to a model spectrum. The model spectrum consists of a power-law component with a high-energy cutoff (for nonthermal magnetospheric emission) and a Gaussian component (for iron line emission), together with a component for photoelectric absorption by intervening interstellar matter. We fixed the central energy of the Gaussian component to be 6.7 keV (e.g., Angelini et al. 1991). Figure 3 compares the observed spectra with the best-fit model spectra, and Table 1 lists the best-fit parameters of the fits. Although all parameters are poorly constrained, the power-law index does not change significantly over the flaring activity—consistent with
Fig. 3.—Comparison of the observed spectra (crosses) of the brightest peaks of the three light curves in Fig. 1 with the spectra (solid histograms) of the best-fit parameters. The energy range is 2.5–25 keV. The bottom panels present the residuals of the fits, which are defined to be the ratio of the observed data to the model predictions.

the softness ratio distribution. (We consider Fig. 3a represents the spectrum of the normal state.) The difference in $N_{\text{H}}$ may be related to the superorbital motion of SMC X-1 (e.g., Gruber & Rothschild 1984), but the lower energy limit of the spectral fits makes it difficult to constrain $N_{\text{H}}$ properly, because the photoelectric absorption by intervening interstellar matter is expected to be most significant in the soft energy band.

To perform statistical analyses, we calculated the flare fraction, which we define to be the ratio of the integrated time that SMC X-1 is flaring (i.e., within FWHMs of the Gaussian fits) to the total observing time of a given parameter and investigate its correlation with the parameter. Figure 4 shows the distribution of the flare fraction as functions of the binary orbital phase (Fig. 4a), rms variability of the light curve (Fig. 4b), and the pulse peak ratio (Fig. 4c). Some important results are worth noticing: the flare fraction (1) is larger than 1.4% over all the orbital phases (with its minimum at the orbital phase of $\sim0.35$), (2) shows a significant variation from phase to phase, and (3) increases with the rms variability of the light curve as well as with the pulse peak ratio. The correlation between the flare fraction and rms variability remained very similar when we used the flare-subtracted rms variability.

4. DISCUSSION AND CONCLUSIONS

SMC X-1 shows active flares that occupy $\sim3\%$ of the total observing time. The flares seem to occur over all binary orbital phases, and the flaring activity is proportional to the rms variability of the light curve. Except for the small change in the pulse peak ratio, no significant change is found along with the flaring activity. All these suggest that the SMC X-1 flares may be just simple extensions of the persistent emission of a normal state with increased accretion rates. If the double peaks in the pulse profile are due to the two magnetic poles of SMC X-1, one simple explanation for the change in the pulse peak ratio may be that the increase in the accretion rate onto the fainter pole is higher than that onto the brighter pole during the flares. On the other hand, the invariant pulse peak ratio in a given
light curve (regardless of flares), together with the correlation between the flare-subtracted rms variability and the flare fraction, indicates the possible existence of a longer timescale ($\sim 100$ s) involving the flares.

The SMC X-1 flares differ from type I X-ray bursts from LMXBs for various reasons, including the shape of profiles and spectral properties. While the profile of type I bursts shows an abrupt increase with an exponential decay in most cases, the SMC X-1 flares have symmetric Gaussian shapes. The X-ray spectrum of the SMC X-1 flare is far from the thermal spectrum of type I bursts (although the thermal spectrum of an X-ray pulsar is not well constrained, so it is not completely excluded that the SMC X-1 flare spectrum is thermal). In addition, the SMC X-1 spectrum does not show any apparent variation within a flare, while a type I burst shows spectral cooling as the burst continues. The SMC X-1 flares recall the type II X-ray bursts found in GRO J1744–28 mainly owing to the spectral invariance over the flaring activity. In fact, the burst spectrum of GRO J1744–28 was found to be very similar to that of SMC X-1, with a similar photon index (1.2) and $e$-folding energy of the high-energy cutoff component (14 keV; Lewin et al. 1996).

One difference is that the SMC X-1 flares lack the postflare dip that often follows the type II bursts from GRO J1744–28. However, the rather gradual rise of the SMC X-1 flares may be responsible for it via offering sufficient time to replenish the material in the accretion disk. This is consistent with the interpretation that the SMC X-1 flares are simple extensions of a normal state with increased accretion rates. Given the apparent difference between GRO J1744–28 and SMC X-1 (i.e., a transient low-mass system vs. a persistent high-mass one), we consider that the magnetic field strength, suggested to be comparable for the two sources, is critical to understanding the type II bursts from GRO J1744–28 and the flares from SMC X-1.

We note that SMC X-1 may be capable of experiencing a viscous instability, namely, the Lightman–Eardley instability (Lightman & Eardley 1974), owing to its relatively weak magnetic moment ($\sim 10^{-6}$ G cm$^2$; Li & van den Heuvel 1997). In this case, the radiation pressure is comparable to the gas pressure around the inner disk radius (i.e., the magnetospheric radius), resulting in a viscous instability with slightly increased mass accretion (e.g., Cannizzo 1996, 1997). Because the instability develops near the inner edge of the accretion disk, it has an advantage in explaining bursts/flares with a short recurrence time. The viscosity parameter ($\alpha$) of the classical accretion disk (Shakura & Sunyaev 1973) at the transition radius between the “inner region” and the “middle region” around a 1.4 $M_\odot$ neutron star is $\alpha \approx 216r_c^{3/2}M_7^{-1}$, where $r_c$ is the viscous timescale in units of seconds and $M_7$ is the mass accretion rate in units of $10^{17}$ g s$^{-1}$. For a typical value $M_7 = 20$ for SMC X-1 (e.g., Woudowski, Clark, & Kallman 2000), the viscosity parameter is $\alpha \approx 0.14$ and 4.4 when $r_c$ is 1000 and 100 s, respectively. The value of 4.4 for $r_c = 100$ s is somewhat larger than generally expected, $\alpha < 1$. However, even larger values ($\alpha \approx 10–100$) were obtained, possibly owing to the patch nature of the accretion disk (e.g., Vrielman, Hessman, & Horne 2002). Alternately, the strong magnetic field of SMC X-1 may help increase the viscosity parameter (R. Love lace 2002, private communication). Or, it may indicate again the existence of a longer timescale involving the flares. We need detailed numerical studies to investigate this scenario more thoroughly.

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**REFERENCES**

Angelini, L., Stella, L., & White, N. E. 1991, ApJ, 371, 332

Bildsten, L., & Brown, E. F. 1997, ApJ, 477, 897

Cannizzo, J. K. 1996, ApJ, 466, L31

———. 1997, ApJ, 482, 178

Chakrabarty, D., Levine, A. M., Clark, G. W., & Tashikawa, T. 1998, IAU Circ. 7048

Chakrabarty, D., & Morgan, E. H. 1998, Nature, 394, 346

Fishman, G. J., et al. 1995, IAU Circ. 6272

Gruber, D. E., & Rothschild, R. E. 1984, ApJ, 283, 546

in’ t Zand, J. J. M., Heise, J., Muller, J. M., Bazzano, A., Cocchi, M., Natalucci, L., & Ubertini, P. 1998, A&A, 331, L25

Levine, A., Rappaport, S., Deeter, J. E., Boynton, P. E., & Nagase, F. 1993, ApJ, 410, 328

Lewin, W. H. G., Rutledge, R. E., Komesar, J. M., van Paradijs, J., & Kouveliotou, C. 1996, ApJ, 462, L39

Lewin, W. H. G., et al. 1976, ApJ, 207, L95

Li, X.-D., & van den Heuvel, E. P. J. 1997, A&A, 321, L25

Lightman, A. P., & Eardley, D. M. 1974, ApJ, 187, L1

Masetti, N., et al. 2000, A&A, 363, 188

Moon, D.-S., & Eikenberry, S. S. 2001, ApJ, 552, L135

Psaltis, D., & Chakrabarty, D. 1999, ApJ, 521, 332

Rappaport, S., & Joss, P. C. 1997, ApJ, 486, 435

Shakura, N. I., & Sunyaev, R. A. 1973, A&A, 22, 337

Vrielman, S., Hessman, F. V., & Horne, K. 2002, MNRAS, 332, 176

Wijnands, R., & van der Klis, M. 1998, Nature, 394, 344

Woudowski, P. S., Clark, G. W., & Kallman, T. R. 2000, ApJ, 541, 963

TABLE 1

| Parameter | Figure 3a | Figure 3b | Figure 3c |
|-----------|-----------|-----------|-----------|
| $N_n$ ($\times 10^{20}$ cm$^{-2}$) | 3.2(0.9) | 1.6(1.5) | 2.2(0.9) |
| $\alpha$ | 1.6(0.3) | 1.3(0.5) | 1.6(0.3) |
| $E_\gamma$ (keV) | 17.2(7.1) | 6.9(3.2) | 14.3(5.2) |
| $E_{\gamma}$ (keV) | 7.8(6.9) | 12.6(10.2) | 14.0(10.6) |
| $\gamma_\gamma$ | 0.81 | 1.3 | 0.81 |
| Flux ($\times 10^{-8}$ ergs cm$^{-2}$ s$^{-1}$) | 1.7 | 2.0 | 2.8 |

Note.—Energy range is 2.5–25 keV, and the 90% uncertainty levels are quoted in the parentheses.

* $N_n$ and $\alpha$ are the hydrogen nuclei column density of the intervening matter and the index of the power-law component; $E_\gamma$ and $E_{\gamma}$ represent the cutoff and $e$-folding energy of the high-energy cutoff component.

** Each spectrum has 48 degrees of freedom.