RESULTS FROM LONG-TERM OPTICAL MONITORING OF THE SOFT X-RAY TRANSIENT SAX J1810.8−2609

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ABSTRACT

In this paper, we report the long-term optical observation of the faint soft X-ray transient SAX J1810.8−2609 from the Optical Gravitational Lensing Experiment (OGLE) and Microlensing Observations in Astrophysics (MOA). We have focused on the 2007 outburst, and also cross-correlated its optical light curves and quasi-simultaneous X-ray observations from RXTE/Swift. Both the optical and X-ray light curves of the 2007 outburst show multi-peak features. Quasi-simultaneous optical/X-ray luminosity shows that both the X-ray reprocessing and viscously heated thermal emission can explain the observed optical flux. There is a slight X-ray delay of 0.6 ± 0.3 days during the first peak, while the X-ray emission lags the optical emission by ∼2 days during the rebrightening stage, which suggests that X-ray reprocessing emission contributes significantly to the optical flux in the first peak, but the viscously heated disk origin dominates it during rebrightening. This implies variation of the physical environment of the outer disk, with even the source remaining in a low/hard state during the entire outburst. The ∼2 day X-ray lag indicates a small accretion disk in the system, and its optical counterpart was not detected by OGLE and MOA during quiescence, which constrained it to be fainter than $M_I = 7.5$ mag. There is a suspected short-time optical flare detected at MJD = 52583.5 with no detected X-ray counterpart; this single flux increase implies a magnetic loop reconnection in the outer disk, as proposed by Zurita et al. The observations cover all stages of the outburst; however, due to the low sensitivity of RXTE/ASM, we cannot conclude whether it is an optical precursor at the initial rise of the outburst.

Key words: stars: individual: SAX J1810.8−2609 – stars: neutron

Online-only material: color figures

1. INTRODUCTION

Neutron star low-mass X-ray binaries (LMXBs) are believed to behave similarly to black hole LMXBs (Lin et al. 2007). They spend most of their time in quiescence and occasionally show an outburst with dramatically increased accretion rate. During the outburst, neutron star LMXBs will undergo a similar state transition as black hole LMXBs do, basically from a low/hard state to a high/soft state (Remillard & McClintock 2006). The optical emission of LMXBs has often contributed to thermal emission of the companion star and the outer accretion disk, and sometimes synchrotron emission of a jet. The disk is heated mainly by two physical processes: one is the friction between adjacent layers of the disk when the materials were accreted (Shakura & Sunyaev 1973) and the other is the X-ray irradiation from the inner disk (van Paradijs & McClintock 1994). With the evolution of disk structure and other physical properties, the radiation mechanism of the optical flux will vary, and will be different for neutron star LMXBs and black hole LMXBs.

For black hole LMXBs, the synchrotron emission of a jet was believed to dominate the optical emission during the low/hard state, with possible disk-reprocessed emission (Russell et al. 2006). In the soft state, all the near-infrared and some of the optical emissions are suppressed, a behavior indicative of the jet switching off in transition to the soft state (Russell et al. 2006). Viscously heated disk emission may become the dominant source. The multi-wavelength observation of GX 339−4 provided a perfect example to demonstrate the trend: a good correlation among the fluxes from the X-ray power-law component, the radio, and the optical was found during the low/hard state which suggests jet emission; however, the optical flux dramatically decreased when the source entered the high/soft state. Meanwhile, an approximate two-week X-ray flux delay was found during the high/soft state, which indicates viscously heated disk emission.

For neutron star LMXBs, the jet emission is not important except at a very high luminosity. X-ray reprocessing was believed to dominate the optical emission during the low/hard state, with a possible contribution from a viscously heated disk (Russell et al. 2006). Long-time observation of a neutron star LMXB, e.g., Aquila X-1, shows that neither the optical/near-infrared color nor its brightness changes sharply during an X-ray spectral state transition. So it is believed that for Aquila X-1 the outer accretion disk is not affected by X-ray spectral state transitions (Maitra & Bailyn 2008). The X-ray reprocessing is thought to contribute most of the optical emission during both the low/hard and the high/soft state.

When the optical emission is dominated by viscously heated disk emission, the emission at each radius provides a measure of the instantaneous local accretion rate at that radius. The X-ray and the optical emission, respectively, map the mass flow through the inner and outer disks. Continuous monitoring of both X-ray and optical emission allows us to track the temporal evolution of the system. Cross-correlation of the X-ray and...
optical light curves helps to map the accretion flow direction; the X-ray/optical time delay reflects the viscous timescale of the disk (e.g., Homan et al. 2005). The time lag between the initial point of the outburst in the X-ray and optical emission is believed to be able, to some extent, to test the disk model and the trigger mechanism of the outburst (Narayan et al. 1996).

SAX J1810.8−2609 is a soft X-ray transient (SXT) discovered on 1998 March 10 with the wide field cameras (2–28 keV) on board the BeppoSAX satellite (Ubertini et al. 1998). It was identified as a neutron star LMXB because a strong Type-I X-ray burst was detected (Natalucci et al. 2000). The distance was estimated to be ~4.9 kpc.

On 1998 March 11–12, a follow-up target-of-opportunity observation with the narrow field instrument on board BeppoSAX was performed with a total observing time of 85.1 ks. It showed a hard X-ray spectrum with emission up to 200 keV. The broadband spectrum (0.1−200 keV) can be described as having two components: a soft blackbody component with temperature $T_B \sim 0.5$ keV and a power-law component with photon index $\Gamma = 1.96 \pm 0.04$ (Natalucci et al. 2000).

From 1998 through 2007, SAX J1810.8−2609 had been in a quiescent state. The neutron star system in quiescence was also detected by Chandra on 2003 August 16 (Jonker et al. 2004). It had an unabsorbed X-ray luminosity of $\sim 10^{32}$ erg s$^{-1}$ over the energy range of 0.3−10 keV, given the distance of 4.9 kpc. It showed that the quiescent spectrum could be well fitted by two models: the “neutron star atmosphere + power-law” model and the “blackbody + power-law” model.

In 2007 August, Swift detected a new phase of highly luminous activity (Parson et al. 2007), and the luminosity varied between (1.1 and 2.6) $\times 10^{36}$ erg s$^{-1}$ during this outburst. Considering the time interval of the recurrence, the observed outburst luminosity corresponded to a low time-averaged accretion rate of $5 \times 10^{-12} M_\odot$ yr$^{-1}$ (Fiocchi et al. 2009). The X-ray spectra had shown the evolution during different epochs of the outburst, but a significant power-law component was always present (Fiocchi et al. 2009). It was noted that the source never reached the high/soft state during the outburst.

In this paper, we obtained a 12 year optical light curve of SAX J1810.8−2609, which covers two outbursts. We cross-correlated the optical light curve with the X-ray light curve from the RXTE/ASM and Swift/BAT archive. Section 2 describes the observations and data calibration. In Section 3, we identify the optical counterpart and analyze the temporal morphology of the outburst. In Section 4, we show the results of the cross-correlation and discuss their implications. Section 5 contains a summary.

2. OBSERVATIONS

2.1. OGLE Light Curve

The region containing SAX J1810.8−2609 has been regularly observed by the Optical Gravitational Lensing Experiment (OGLE) project during 11 observing seasons from 1997 to 2009, including the outbursts in 1998 March and 2007 August.

The OGLE data were collected using a dedicated 1.3 m Warsaw telescope located at Las Campanas Observatory, Chile, and operated by the Carnegie Institution of Washington. During 1996−2000 OGLE used a single 2048 $\times$ 2048 CCD chip (with a pixel size of 0′′.417) operating in drift-scan mode (OGLE-II; Udalski et al. 1997). For OGLE-III (2001−2009), the camera was upgraded to a mosaic of eight 2048 $\times$ 4096 CCD chips with pixel size of 0′′.26 (Udalski 2003). During OGLE-II and OGLE-III, for the Bulge fields each observation was exposed for 120 s. The observations were usually made in the $I$ band.

Data sets from both phases of OGLE were processed using the same photometric package based on difference image analysis (Wozniak 2000). The method requires creation of a template/reference image, composed of the best available images of a given field. The template is then convolved with the point-spread function of an image to be analyzed and subtraction is performed, revealing residuals due to changes in the objects’ fluxes or to the appearance of new objects. The flux residuals are then measured with aperture photometry, and light curves are created (Udalski et al. 2008).

In templates for both OGLE-II and OGLE-III, we found a faint star with a constant $I \approx 19.5$ mag, 0′′44 away from the outburst position, as shown in Figure 2. Because there was no object at the outburst position on the templates, all the residual flux from the outbursts was attributed to this faint star. Therefore the composite light curve, shown in Figure 1, contains both the baseline fluxes from the template object and outbursts, and the faint template object contributes a negligible amount of emission during outbursts.

2.2. MOA Light Curve

This source is labeled in the Microlensing Observations in Astrophysics (MOA) microlensing alert catalog as MOA_2007_BUL_365 (Bond et al. 2001). MOA was also operating in the $I$ band. In quiescence, this source is also well below the detection threshold of MOA. It was monitored during the 2007 outburst. We calibrated the MOA light curve using the quasi-simultaneous OGLE light curve.

2.3. X-Ray Monitoring Data

The All Sky Monitor (ASM) (2−12 keV) on board the Rossi X-ray Timing Explorer (RXTE) has provided the longest continuous coverage of luminous X-ray sources (Levine et al. 1996). In its quiescent state, SAX J1810.8−2609 was not detected by the ASM, but the ASM detected and monitored both outbursts. The second outburst was also monitored by APPENDIX A: \cite{http://www.phys.canterbury.ac.nz/moa/microlensing_alerts.html}
Figure 2. Image of the source during the quiescent phase (left) and during the outburst phase (right) from OGLE. The red circle marks the location of the outburst. There is no detection during quiescence. The green "×" represents a nearby faint star with a constant $I \approx 19.5$ mag. (A color version of this figure is available in the online journal.)

The *Swift* Burst Alert Telescope (BAT; $\sim$15–50 keV) through the Hard X-ray Transient Monitor program (Barthelmy et al. 2005). We retrieved both data sets from their respective Web sites. In addition, *Integral*/IBIS (22–68 keV) detected this source during this outburst (Fiocchi et al. 2009); however, we did not include the *Integral* data because the monitoring was not frequent enough near the peak.

3. IDENTIFICATION AND THE OUTBURST MORPHOLOGY

3.1. Identification

In the optical band, the outburst is located in OGLE III field BLG251.8 with coordinates (R.A. = $18^h 10^m 44^s.47$, decl. = $-26^\circ 09' 01''.7$). This position is consistent with the position of SAX J1810.8–2609 (R.A. = $18^h 10^m 44^s.47$, decl. = $-26^\circ 09' 01''.2$) determined by *Chandra* (Jonker et al. 2004), with an uncertainty of 0.6. It is also consistent with the optical counterpart position of (R.A. = $18^h 10^m 44^s.4$, decl. = $-26^\circ 09' 00''.0$) with an uncertainty of 1" determined by Greiner et al. (1998). The non-detection by MOA and OGLE constrains the source to be fainter than 21 mag in the $I$ band during quiescence (Figure 2).

In the optical light curve, we indicate the 1998 outburst with light blue "⋄" symbols and the 2007 outburst with dark blue "∗" symbols (see Figure 1). It is noted that the light blue points are concentrated on the decay phase in the 1998 outburst because the main part was not observed.

The optical observations were usually made in the $I$ band; however, one observation in the $R$ band was also available. We can use the magnitude difference between the $I$ and $R$ bands to estimate the disk temperature in the outer region. The $R$-band observation is $R = 19.5 \pm 0.5$ on 1998 March 13 (Greiner et al. 1998), and the two OGLE $I$-band observations closest in time are $I = 18.5 \pm 0.1$ mag on March 10 and $I = 18.7 \pm 0.1$ mag on March 16, respectively. So we take the average for the two $I$-band detections, and use it as the proxy for the $I$-band magnitude on March 13. Therefore, we have $R - I = 0.9 \pm 0.6$ mag. Once we make the reduction correction (Sumi 2004), it is $R - I = 0.35 \pm 0.6$ mag, and corresponds to a temperature $= 3400 \pm 1000$ K with a blackbody model, which is consistent with the typical temperature for the outer disk.

The 2007 August outburst was well monitored, and the complete optical and X-ray light curves are shown in Figure 3. The hard (15–50 keV) and soft (2–10 keV) X-ray data are from *Swift*/BAT and RXTE/ASM, respectively. The MOA and OGLE data were combined to form the optical light curve. The similarity of the optical and the X-ray light curve during the 2007

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7 http://xte.mit.edu/ASM_lc.html
8 http://heasarc.gsfc.nasa.gov/docs/Swift/results/transients/
outburst confirms the identification of the optical counterpart. We did not use the Integral/IBIS (22–68 keV) light curve because of the incomplete covering.

In Figure 1, we note that the fluxes on four occasions (which are all out of the outburst phase) were significantly higher than the baseline. Three of these are not likely to be real because the other stars in the field exhibited a similar flux feature during these observations. This means that these flux measurements were affected by systematic uncertainties that may be related to weather, sky background, or instrumental effects. The fourth point with an elevated flux at MJD = 52583.5 is indicated with a red circle. We do not have any direct evidence to show that this point is also affected, but the quality of the image makes it difficult for us to conclude that the system was experiencing a true increase in optical flux. If the flux increase is real, this data point is very interesting, and may represent a short-duration increase in optical flux. If the flux increase is real, this data point is very interesting, and may represent a short-duration increase in optical flux.

We checked all the dwell data because of the incomplete covering. The corresponding X-ray peaks of significant optical peaks are consistent with each other within 1σ error. The optical data are consistent with each other within 1σ error. The optical data are consistent with each other within 1σ error. The optical data are consistent with each other within 1σ error. The optical data are consistent with each other within 1σ error. The optical data are consistent with each other within 1σ error. The optical data are consistent with each other within 1σ error. The optical data are consistent with each other within 1σ error.

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The corresponding X-ray peaks/dips usually follow the optical peaks/dips but with a few days’ lag. The first optical peak occurred at MJD ∼ 54330, while the corresponding X-ray flux peaked slightly later. The optical light curve has a significant dip when it tends to get a second peak at MJD ∼ 54346, then a sudden rise roughly three days later. The dip was followed by the X-ray light curve about two days later. The third significant optical peak occurred at MJD ∼ 54360 and was followed by both the soft and hard X-ray light curve a few days later. The optical light curve also has a wide peak near MJD ∼ 54381 which is very similar to that in the hard X-ray light curve; the optical emission still leads the X-ray emission.

3.2. The Outburst Morphology

The 2007 August outburst showed a multi-peak morphology (see Figure 3). We divided the whole outburst light curve into three parts: (1) an initial rise (54314 < MJD < 54323), where the outburst is detected in the optical but not in the X-ray; (2) the first peak (54323 < MJD < 54337); and (3) the rebrightening stage (54337 < MJD < 54400), which includes all the subsequent peaks. The temporal behavior in the optical and X-ray bands is very similar. The solid lines in Figure 3 are used to separate these three different stages. The position of significant optical peaks/dips is indicated with dotted lines. The corresponding X-ray peaks/dips usually follow the optical peaks/dips but with a few days’ lag. The first optical peak occurred at MJD ∼ 54330, while the corresponding X-ray flux peaked slightly later. The optical light curve has a significant dip when it tends to get a second peak at MJD ∼ 54346, then a sudden rise roughly three days later. The dip was followed by the X-ray light curve about two days later. The third significant optical peak occurred at MJD ∼ 54360 and was followed by both the soft and hard X-ray light curve a few days later. The optical light curve also has a wide peak near MJD ∼ 54381 which is very similar to that in the hard X-ray light curve; the optical emission still leads the X-ray emission.

4. CROSS-ANALYSIS OF THE OPTICAL/X-RAY DATA DURING THE 2007 AUGUST OUTBURST

4.1. The Initial Rise of the Outburst

The source was not detected by RXTE/ASM until the flux reached a level of ∼10 mCrab on MJD 54323 (Levine et al. 1996), but the optical emission was detected as early as on MJD ∼ 54314. During the initial rise phase, the optical detection (OGLE and MOA) was earlier than the X-ray detection (RXTE/ASM) by ∼9 days. Similar X-ray delays were found in quasi-simultaneous X-ray and optical monitoring of SXT GRO J1655–40 (Orosz et al. 1997), XTE J1550–564 (Jain et al. 2001), 4U 1543–47 (Buxton & Bailyn 2004), and Aquila X-1 (Shahbaz et al. 1998; Maitra & Bailyn 2008), among which the initial point of outburst in X-rays lagged that in the optical by 3–11 days. The X-ray delays at the initial rise reflect the timescale of the thin disk, which determines the time it takes for the accretion flow to arrive at the inner region where the X-ray emission comes from. It already takes into account the timescale for the material to fill in the advection-dominated accretion flow (ADAF) region, which can extend to a large radius in the quiescent state (e.g., Narayan & Yi 1995). For all the aforementioned systems, the initial X-ray rises of the outbursts were all determined by linear extrapolations of the RXTE/ASM light curve.

We note, however, that the detection threshold for RXTE/ASM is much higher than the flux of the source in the quiescent state. The X-ray flux might have increased by a factor of a few tens before being detected. Furthermore, the flux may actually increase in a manner much slower than the linear increase previously detected by RXTE/ASM; the initial point found by linear extrapolation may be actually much later than the actual starting point (Homan et al. 2005). Here, we apply a power-law extrapolation to the X-ray/optical data points during the rise phase of the outburst, as shown in Figure 4. It would make a big difference if the flux increased exponentially rather than linearly. The X-ray luminosity was calculated to have a distance of 4.9 kpc (Natalucci et al. 2000). Based on Chandra observations, its quiescent luminosity is ~10^{32} erg s^{-1} (Jonker et al. 2004). Figure 4 shows an extrapolation that indicates that the optical flux may have begun to rise at MJD 54288^{+10}_{−2} with 23.2 > I > 21 mag in quiescence. The fit to the X-ray data has a large uncertainty; it gives an X-ray initial rise at MJD ∼ 54293^{+12}_{−35}. The start points of the optical and X-ray flux are consistent with each other within 1σ error, which is significantly different from the start points directly detected.
We cannot confirm the X-ray delay at the start of the outburst owing to the limited data.

4.2. Optical and X-Ray Cross-Correlation

We conducted cross-correlations of the optical and X-ray emission for the first peak and the rebrightening phases. During the first peak, we cross-correlated only the soft X-ray (RXTE, 2–12 keV) and optical light curves. However, during the rebrightening stage, we cross-correlated optical and soft X-ray, optical and hard X-ray (Swift, 15–50 keV), and soft and hard X-ray emission.

For the convenience of performing the cross-correlation, we made a linear interpolation to each light curve with a time interval of 0.1 days. The cross-correlation between two interpolated light curves gave a cross-correlation factor (CCF) function with uniform time lags. The CCF tells us how strong the correlation is, and it is defined as $CCF = (1/n - 1) \sum((f_i - f_0)(h_i - h_0)/\sigma_f \sigma_h)$, where $\{f_i\}$ and $\{h_i\}$ represent the data series with finite length, $f_0$ and $h_0$ are the averages of $\{f_i\}$ and $\{h_i\}$, and $\sigma_f$ and $\sigma_h$ are the variance of $f_i$ and $h_i$, respectively. One caveat is that the value of the CCF may not be zero even if the two data series are not correlated at all; e.g., if the data series are short, the noise may produce a non-zero CCF.

We therefore conducted a Monte Carlo (MC) simulation to create faked X-ray and optical light curves using the same temporal interval and uncertainty of each data point from the observed ones. In order to make sure that the faked light curves have no correlation, we assume that each value on them is taken from a Gaussian distribution (its central value is set to zero, and $\sigma$ of the distribution is set to be the same as the observed uncertainty at each epoch). The faked light curves generated in this way resemble pure noise. Once one set of these curves is generated, we make a linear interpolation and cross-correlate the interpolated light curves, obtaining the time lag and the maximum CCF.

After repeating this process 2000 times for the first peak phase and the rebrightening phase, we computed the distribution of the maximum values of the CCF, and then derived the 3$\sigma$ confidence level of the CCF of each phase. The 3$\sigma$ confidence level for the cross-correlation for the first peak is CCF = 0.70, which is plotted in Figure 5, and for the rebrightening phase it is CCF = 0.5, as plotted in Figure 6.

Any correlation with CCF above the limit value is likely to be due to the real signal. We employed the area centroid of the CCF function above the limit value to derive the time lag (Koen 2003). The uncertainty in the time lag was obtained by applying an MC simulation described above, taking into account the light curve uncertainties, to compute the distribution of the time lags. All the uncertainties in our results are given except the 1$\sigma$ confidence level.

During the first peak (Figure 5), the soft X-ray and optical emission are positively correlated with a maximum CCF of 0.85, which has a 5.0$\sigma$ confidence level. The soft X-ray lags the optical emission by 0.60 ± 0.30 days. During the rebrightening stage (Figure 6), the soft and hard X-ray emission are correlated with a maximum CCF of 0.61 (4.3$\sigma$ confidence level); they vary simultaneously with no obvious lag (time lag = 0.20 ± 0.61 days). The soft X-ray and optical emission are weakly correlated with a maximum CCF of 0.54 (3.5$\sigma$ confidence level); the soft X-ray lags optical emission by 2.10 ± 0.28 days. The hard X-ray and optical emission are correlated with a maximum CCF of 0.61 (4.3$\sigma$ confidence level); the hard X-ray lags the optical emission by 1.80 ± 0.29 days.

4.3. The Origin of Optical Emission

The luminosities of the quasi-simultaneous optical and X-ray (2–10 keV) observations are shown in Figure 7. The optical–X-ray detection pairs were used when (1) there is an X-ray detection within one day of an optical detection and (2) the confidence level for the X-ray detection is larger than 1$\sigma$. We adopted the approximation $L_{opt} \approx \nu F_{\nu,1}$ to estimate the optical luminosity (we are approximating the spectral range to the central wavelength of the $I$ band), as Russell et al. (2006) did. The optical absorbed flux was dereddened using the extinction map from Sumi (2004). Luminosities were calculated with the distance $d =$ 4.9 kpc (Natalucci et al. 2000).

The disk will be heated by the friction between adjacent layers of the disk when the materials are accreted (Shakura & Sunyaev 1973); we chose the relation $L_{opt} \approx nL_X^{0.5}$ for the intrinsic thermal emission of a viscously heated disk (Frank...
et al. 2002; Russell et al. 2006). The disk can be also heated by X-ray and ultraviolet (UV) emission from the inner disk. In this case, $L_{opt} \sim n L_X^{1.4} a$ was taken for optical emission from X-ray reprocessing (van Paradijs & McClintock 1994), where $a$ is the orbital separation. The flat, optically thick spectrum of the jets of the neutron star can also be extended to the optical regime; we adopted the relation $L_{opt} \sim n L_X^{0.63}$ for neutron star LMXBs in the hard state, most of which are consistent with the X-ray reprocessing model. The Russell et al. (2006) best-fit line is plotted in Figure 4 as an indicator of the contribution from X-ray reprocessing.

In Figure 7, we label the data points at different stages using different symbols. During the initial rise stage, only the upper limit of X-ray luminosity is available, which gives no tight constraint. The luminosity ratios at the first peak and the rebrightening stage are similar, while that at the rebrightening stage is slightly higher. We can see that the jet emission model can hardly contribute such bright optical emission, while both the viscously heated disk model and the Russell et al. (2006) best fit will suffice.

Considering the cross-correlation result, it is likely that the optical emission is a combination of emissions with different origins. The viscously heated disk emission will cause the X-ray emission to delay the optical emission by a viscous timescale. The X-ray and optical emission are simultaneous or the optical lags the X-ray by a few seconds for the X-ray reprocessing and jet mechanisms. In performing cross-correlation between light curves $L_1$ and $L_2$, if $L_1$ is a combination of two light curves with nearly equal flux and different lags ($L_a$ and $L_b$) to $L_2$, it will give a lag between $L_a$ and $L_b$ (Zhu & Zhang 2010).

At the first peak, the $0.6 \pm 0.3$ day X-ray delay is not significant, which suggests that the optical emission may be a combination of emissions from the viscously heated disk and X-ray reprocessing. Each component contributes a large portion of the optical light. The X-ray delay becomes significant, reaching $\sim 2$ days at the rebrightening stage, which suggests that viscously heated disk emission becomes dominant. The prevalence of viscously heated disk emission should have two causes. First, as the luminosity ratio of the optical to the X-ray becomes slightly higher at the rebrightening stage, there should be an enhancement of radiation efficiency of the viscously heated disk. It was believed that the outburst would have a rebrightening stage if the disk were only partly irradiated, i.e., if part of the disk were in shadow at the first peak (Truss et al. 2002). The first peak is caused by the accretion of gas within the irradiation portion of the disk, while the subsequent peaks are caused by accretion of gas in the outer disk, until the whole disk remains in a high-viscosity state. It is natural that the radiation area of the disk at the rebrightening stage will be larger, and the temperature may be higher. The second, reason is that the X-ray reprocessing emission should be suppressed. It is affected by the structure of both the X-ray source and the outer disk; if the X-ray source is elevated above the disk, or the outer disk is warped, it will have high reprocessing efficiency. When the X-ray source becomes aligned with the disk plane, the reprocessing efficiency will decrease. Here, the change of X-ray delay between the first peak and rebrightening stage is significant; the source should evolve the outer disk (possibly also the inner disk) variation during the outburst.

4.4. Extremely Faint Optical Counterpart in Quiescence

The approximate two-day X-ray delay during the rebrightening stage properly reflects the timescale of the disk during the hard state. It also reflects the outside-in disk accretion process, as we discuss in the outburst morphology section; the variation of X-ray flux properly follows the optical. Compared to the $\sim 18$ day X-ray/optical delay of GX 339$-$4 during the rebrightening stage when the source has entered the soft state, the $\sim 2$ day X-ray delay is short. SAX J1810.8$-$2609 should have a very small accretion disk. In addition, the source stays in the hard state during rebrightening; it should take some time to fill the ADAF region within the 2 days. An extremely small disk and small companion star are expected, which is actually what was expected for a faint SXT as SAX J1810.8$-$2609 was classified (Heise et al. 1999; King 2000).

In quiescence, we only have available the detection limits for the optical flux: $m_I > 21$ mag and $m_R > 21.5$ mag (Greiner et al. 1998). They correspond to $M_I > 7.5$ and $M_R > 8.0$ with $d = 4.9$ kpc (Natalucci et al. 2000), respectively. If the source follows the same luminosity ratio during the quiescent state and the hard state, we need to go roughly 2.2 mag deeper in the $I$ band to detect the optical counterpart during quiescence with respect to the viscously heated disk model. The optical counterpart in the quiescent state is extremely faint, consistent with a very small disk.

5. SUMMARY AND CONCLUSIONS

With OGLE and MOA light curves, we have identified the optical counterpart to SAX J1810.8$-$2609 during outburst. Two outbursts, occurring in 1998 and in 2007, were covered by OGLE, and the 2007 August outburst was monitored by both MOA and OGLE. Apart from the two outbursts, there is possibly a short-time optical flare without an X-ray counterpart at MJD = 52583.5, which may imply a magnetic-loop reconnection in the outer disk, as proposed by Zurita et al. (2003).

The initial X-ray rise of the 2007 outburst detected by RXTE/ASM is nine days later than the optical detection by
OGLE/MAO. However, the flux-detection threshold of RXTE/ASM plays a critical role in this kind of X-ray delay. We have shown that an exponential extrapolation is also reasonable for the data, which indicate no X-ray delay at the initial rise. We conclude that no obvious X-ray delay was detected at the initial rise with the present detection threshold.

The optical light curve shows multiple peaks, as does the X-ray light curve during the 2007 outburst. The variation of X-rays properly follows the optical flux, which maps the outside-in disk accretion process. During the first peak phase, the soft X-ray emission lags the optical emission by 0.6±0.3 days; X-ray reprocessing should contribute significantly to the optical flux during the first peak. There is an obvious ∼2 day X-ray delay during the rebrightening stage which suggests that the viscously heated disk emission becomes the dominant optical source. X-ray reprocessing emission usually dominates the optical flux of neutron star LMXBs during the low-hard state (Russell et al. 2006) which is probably the case for the first peak of SAX J1810.8−2609. The rebrightening stage is unusual. Unlike Aquila X-1, the outer disk of SAX J1810.8−2609 should undergo physical environment variations; the physical properties at the inner disk may be different at the first peak and rebrightening stage, even if the source remains in the low hard state during the outburst. The ∼2 day time lag implies a disk with very small radius and a fairly small companion star. The non-detection of the source by either OGLE or MOA at the rise with the present detection threshold.

OGLE and MOA have been observing the Galactic bulge for over a decade. OGLE has published a catalog with ∼2 × 10^5 variable stars based on OGLE II data (Wozniak et al. 2002). The OGLE III data will be available soon. These data sets may contain a large number of potential rebrightening events due to LMXBs and will provide a unique opportunity for the study of LMXBs in the future.

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REFERENCES
Barthelmy, S. D., Barbier, I. M., Cummings, J. R., et al. 2005, Space Sci. Rev., 120, 143
Bond, I. A., Abe, F., Dodd, R. J., et al. 2001, MNRAS, 327, 868
Buxton, M. M., & Bailyn, C. D. 2004, ApJ, 615, 880
Fiocchi, M., Natalucci, L., Chenevez, J., et al. 2009, ApJ, 693, 333
Frank, J., King, A., & Raine, D. J. (ed.) 2002, Accretion Power in Astrophysics (3rd ed.; Cambridge: Cambridge Univ. Press)
Greiner, J., Castro-Tirado, A. J., Boller, T., et al. 1998, IAU Circ., 695, 1
Heise, J., in’t Zand, J. J. M., Smith, M. J. S., et al. 1999, Astrophys. Lett. Commun., 38, 297
Homan, J., Buxton, M., Markoff, S., et al. 2005, ApJ, 624, 295
Jain, R. K., Bailyn, C. D., Orosz, J. A., McClintock, J. E., & Remillard, R. A. 2001, ApJ, 554, L181
Jonker, P. G., Wijnands, R., & van der Klis, M. 2004, MNRAS, 349, 94
King, A. R. 2000, MNRAS, 315, 33
Koen, C. 2003, MNRAS, 344, 798
Lin, D., Remillard, R. A., & Homan, J. 2007, ApJ, 667, 1073
Levine, A. M., Bradt, H., Cui, W., et al. 1996, ApJ, 469, L33
Maitra, D., & Bailyn, C. D. 2008, ApJ, 688, 537
Migliari, S., & Fender, R. P. 2006, MNRAS, 366, 79
Narayan, R., McClintock, J. E., & Yi, I. 1996, ApJ, 457, 821
Narayan, R., & Yi, I. 1995, ApJ, 444, 231
Natalucci, L., Bazzano, A., Cocchi, M., et al. 2000, ApJ, 536, 891
Orosz, J. A., Remillard, R. A., Bailyn, C. D., & McClintock, J. E. 1997, ApJ, 478, L83
Parson, A. M., Barthelmy, S. D., Gehrels, N., et al. 2007, GCN Circ., 6706, 1
Remillard, R. A., & McClintock, J. E. 2006, ARA&A, 44, 49
Russell, D. M., Fender, R. P., Hynes, R. I., et al. 2006, MNRAS, 371, 1334
Russell, D. M., Fender, R. P., & Jonker, P. G. 2007, MNRAS, 379, 1108
Shahbaz, T., Bandyopadhyay, R. M., Charles, P. A., et al. 1998, MNRAS, 300, 1035
Shakura, N. I., & Sunyaev, R. A. 1973, A&A, 24, 337
Sumi, T. 2004, MNRAS, 349, 193
Truss, M. R., Wynn, G. A., Murray, J. R., & King, A. R. 2002, MNRAS, 337, 1329
Ubertini, P., in’t Zand, J., Tesseri, A., Ricci, D., & Piro, L. 1998, IAU Circ., 6838, 1
Udalski, A. 2003, Acta Astron., 53, 291
Udalski, A., Kubiat, M., & Szymanski, M. 1997, Acta Astron., 47, 319
Udalski, A., Szymanski, M. K., Soszyński, I., & Poleski, R. 2008, Acta Astron., 58, 69
van Paradijs, J., & McClintock, J. E. 1994, A&A, 290, 133
Wozniak, P. R. 2000, Acta Astron., 50, 421
Wozniak, P. R., Udalski, A., Szymanski, M., et al. 2002, yCatp, 005005101
Zhu, L., & Zhang, S. N. 2010, Sci. China Phys. Mech. Astron., 53, 196
Zurita, C., Casares, J., & Shahbaz, T. 2003, ApJ, 582, 369