OBSERVATIONS OF THE OPTICAL COUNTERPART TO XTE J1118+480 DURING OUTBURST BY THE ROBOTIC TRANSIENT SEARCH EXPERIMENT I TELESCOPE

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ABSTRACT

The X-ray nova XTE J1118+480 exhibited two outbursts in the early part of 2000. As detected by the Rossi X-Ray Timing Explorer (RXTE), the first outburst began in early January and the second began in early March. Routine imaging of the northern sky by the Robotic Optical Transient Search Experiment (ROTSE) shows the optical counterpart to XTE J1118+480 during both outbursts. These data include over 60 epochs from January to June 2000. A search of the ROTSE data archives reveals no previous optical outbursts of this source in selected data between 1998 April and 2000 January. While the X-ray–to–optical flux ratio of XTE J1118+480 was low during both outbursts, we suggest that they were full X-ray novae and not mininoutbursts based on comparison with similar sources. The ROTSE measurements taken during the 2000 March outburst also indicate a rapid rise in the optical flux that preceded the X-ray emission measured by the RXTE by approximately 10 days. Using these results, we estimate a preoutburst accretion disk inner truncation radius of ~1.2 × 10^4 Schwarzschild radii.

Subject headings: novae, cataclysmic variables — stars: individual (XTE J1118+480) — X-rays: bursts

On-line material: color figure

1.INTRODUCTION

On 2000 March 29, the detection of a new X-ray nova with the Rossi X-Ray Timing Explorer (RXTE) All-Sky Monitor (ASM) was announced (Remillard et al. 2000). Subsequent analysis of archival ASM data revealed that the source had been rising since March 5 and had also undergone an earlier outburst during 2000 January 2–29. An optical counterpart was quickly identified at 12.9 mag by Uemura et al. (2000), who also identified an 18.8 mag object from the US Naval Observatory catalog as the probable quiescent optical counterpart. Observations with the Burst and Transient Source Experiment indicate that the energy spectra for both outbursts was characterized by a power law with a photon index of 2.1, and the source was visible up to 120 keV (Wilson & McCollough 2000). The optical spectrum was typical of X-ray novae in outburst (Garcia et al. 2000). Optical data also revealed a sinusoidal variation suggesting a binary system with an orbital period of 4.1 hr (Cook et al. 2000). Quasi-periodic oscillations (QPOs) of 0.08 Hz were found using the RXTE Proportional Counter Array (Revnivtsev, Sunyaev, & Borozdin 2000). No periodic signal was observed in the power spectrum at frequencies greater than 100 Hz. The above measurements all imply that XTE J1118+480 is a binary accretion system composed of a black hole and an evolved low-mass companion. Recently, observations of the system in quiescence by McClintock et al. (2001) have established that the primary of the system has a mass greater than 6.00 ± 0.36 M☉, thus indicating that it is a very strong black hole candidate.

XTE J1118+480 exhibits some features that are atypical of X-ray novae. The X-ray–to–optical flux ratio is very low, which would generally indicate a high-inclination system; however, no eclipses have been observed (Uemura et al. 2000). The source is near the Lockman Hole (Lockman, Jahoda, & McCammon 1986) and does not suffer from high interstellar absorption, thereby allowing observations with the Extreme Ultraviolet Explorer (EUVE). The EUVE observations show no periodic modulation, suggesting the inclination is low enough that no obscuration by the disk rim occurs (Hynes et al. 2000). This implies that the source is intrinsically faint in X-rays.

Due to the strange behavior of the source, optical data during the initial stages of these outbursts provide useful constraints on the possible structure of the accretion disk and the mechanisms involved. The Robotic Optical Transient Search Experiment I (ROTSE-I) imaged the source throughout both the January and March outbursts. These data are presented below.

2.INSTRUMENT AND OBSERVATIONS

The ROTSE program consists of several robotic telescopes designed to search for optical transients, particularly those associated with gamma-ray bursts (Kehoe et al. 2001). These robotic telescopes rapidly respond to satellite-derived triggers of astrophysical transients in various wave bands. The first generation of the ROTSE telescopes is ROTSE-I, which consists of an array of four Canon 200 mm f/1.8 lenses, each equipped with a thermoelectrically cooled 2048 × 2080 pixel CCD camera. Each lens/camera pair has an 8′1 × 8′1 field. Each image pixel subtends 14′′4. To maximize sensitivity, the system is currently operated without filters. The system allows each camera to expose simultaneously so that the array acts as a single telescope with a 16′ × 16′ field.

When not responding to triggered events, the ROTSE telescopes perform regular patrol observations. A typical ROTSE-I sky patrol consists of a series of 80 s exposures covering the area of sky visible above 20′ elevation. Each field is imaged twice consecutively to allow for the elimination of false detections caused by cosmic rays, satellite trails and glints, hot pixels, etc. The mount is moved slightly between exposure pairs to better facilitate the background rejection by shifting the celestial co-

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The ASM fluxes are 2 day averages. The peak fluxes used for the scaling were between images. Also, since XTE J1118 was inactive from 1999 December 30 to 2000 January 4 in preparation for the year 2000 rollover. As a result, we do not have data on the initial stages of the January outburst. The object is especially well covered from mid-February through March. After mid-April, our coverage dropped significantly, and we did not observe the final stages of the second outburst. For the analysis presented here, the data was normalized to the observation from March 1 to ensure proper relative photometry between images. Also, since XTE J1118+480 was relatively close to our detection threshold in some of the shorter exposures, we took the weighted average of each pair of sky patrol observations. A search of the ROTSE-I archives during periods of new Moon going back to 1998 April reveal no indication of this source. The location of XTE J1118+480 is typically not observed by ROTSE-I during the fall months of the year (approximately August through October).

The ROTSE-I light curve from the January burst has a similar morphology to the RXTE/ASM light curve. Both display a rapid rise that peaked around January 6. The X-ray data indicate that the object reached peak flux in less than 10 days. Although the initial stages of the January outburst were poorly sampled by ROTSE-I, the early limits indicate that the optical rise must have been quite rapid as well. The object then proceeded to dim at a relatively linear rate in flux over the next month in both the optical and X-ray. The later stages of the decay were well monitored by ROTSE-I. Figure 1 suggests that the optical emission lagged the X-ray emission during the declining phase of this burst by ~5 days.

ROTSE-I detected the second outburst of XTE J1118+480 on 2000 February 26, 7–8 days before the first significant detections by the ASM. The optical intensity rapidly rose to half its peak intensity by March 1 and achieved a peak intensity of 13.3 mag 5 days later. In contrast, the X-ray emission reached half its peak intensity by March 11, approximately 10 days after the optical reached half its peak intensity level. XTE J1118+480 remained near magnitude 13.3 through 2000 June. The January outburst also peaked near magnitude 13.3, possibly indicating that this is a natural limit based on the structure of the accretion disk.

3. RESULTS

The ROTSE-I archive provides data on the optical counterpart to XTE J1118+480 throughout the January outburst and most of the 2000 March outburst (Fig. 1 and Table 1). The ROTSE-I system was inactive from 1999 December 30 to 2000 January 4 in preparation for the year 2000 rollover. As a result, we do not have data on the initial stages of the January outburst. The object is especially well covered from mid-February through March. After mid-April, our coverage dropped significantly, and we did not observe the final stages of the second outburst. For the analysis presented here, the data was normalized to the observation from March 1 to ensure proper relative photometry between images. Also, since XTE J1118+480 was relatively close to our detection threshold in some of the shorter exposures,

4. DISCUSSION

Optical precursors have been observed previously in black hole X-ray novae. Just prior to an X-ray outburst of GRO J1655–40 in 1996 April, Orosz et al. (1997) obtained filtered optical data on the source showing an optical rise preceding the X-ray outburst by about 6 days. Optical observations of the 1993 August minioutburst of GRO J0422+32 also indicated optical emission preceding the detection of X-rays by 16 days (Castro-Tirado, Ortiz, & Gallego 1996). Hynes et al. (2000) have suggested the outbursts of XTE J1118+480 are more like minioutbursts seen in GRO J0422+32 than a full X-ray nova. The X-ray delay observed in the March outburst of XTE J1118+480 is significantly less than the delays typically seen in other systems.
J1118+480 is also analogous to the well-known UV delay observed for dwarf novae (Warner 1995 and references therein).

While the peak X-ray luminosities for both outbursts of XTE J1118+480 (∼10^{36} erg s^{-1} in the 3–100 keV energy range, assuming the source distance of 1.1 kpc) were rather low, the general properties of its long-term variability are similar to that of other bright X-ray transients. For example, XTE J1150–564 also underwent two consecutive outbursts of comparable duration to XTE J1118+480 beginning in late 1998 (Jain et al. 2001). Moreover, the normalized profiles of the second outbursts in both systems are very similar. This fact suggests that this outburst of XTE J1118+480 is a full X-ray nova rather than a minoutburst. The low peak luminosity of the source can probably be attributed to the properties of the binary system. The binary period of XTE J1118+480 is known to be one of the shortest among the low-mass X-ray binary transient systems, implying a smaller size of the primary Roche lobe and different parameters of the accretion disk (like mass and accretion rate). The X-ray and optical properties of XTE J1118+480 (Revnivtsev et al. 2000; Hynes et al. 2000) resemble the properties of another well-known Galactic black hole candidate GX 339−4 during its hard/low state outbursts (at comparable luminosity level of 10^{35}−10^{36} erg s^{-1}) (Motch et al. 1983). Both sources demonstrate a high optical–to–X-ray flux ratio and simultaneous low-frequency QPOs in X-ray and optical bands (Motch et al. 1983; Revnivtsev et al. 2000; Hynes et al. 2000).

To explain the origin of dwarf novae and X-ray transients, the disk instability model (DIM) was proposed (Smak 1981; Mineshige & Wheeler 1989). In the framework of this model, the UV/X-ray delay is a result of propagation of the heating front through the accretion disk (Meyer 1984). This front transforms the disk from the cold (quiescent) state to a hot state, raising the optical and UV/X-ray flux from the disk. However, the standard DIM fails to explain the delay quantitatively: the calculated travel time of the heating front, which should be near the sound speed of the medium, is less than 1 day for a typical system—a value that is much shorter than commonly observed (Pringle, Verbunt, & Wade 1986; Hameury et al. 1997).

A number of accretion flow models have been proposed to explain the hard X-ray emission of X-ray binaries and cataclysmic variables in the quiescent and hard/low spectral states (Chakrabarti & Titarchuk 1995; Meyer & Meyer-Hofmeister 1994; Narayan, McClintock, & Yi 1996). These models involve a hot optically thin inner region that is surrounded by an optically thick standard accretion disk. This two-component geometry of the accretion flow seems to resolve the problem of the standard DIM. The inward moving heating front should stop at the inner edge of the optically thick disk. Then the inner edge of the transformed disk moves toward the compact object on the viscous timescale, which is much longer than the heating front propagation time. As the transition radius moves inward, a growing fraction of the emitted photons are intercepted and Comptonized by the hot corona, giving rise to the hard X-ray emission. The X-ray delay times predicted by this model are in much better agreement with observations.

One proposed model involving a hot optically thin inner region of the accretion disk is advection-dominated accretion flow (ADAF; Narayan et al. 1996). In this model, the accretion disk evaporates into an optically thin, quasi-spherical corona. The corona, or ADAF region, consists of a two-temperature plasma in which the ions and electrons interact weakly, which results in much of viscous heat being advected into the black hole instead of being radiated away through Comptonization. Esin et al. (2001) have applied the ADAF model to multiwavelength observations of XTE J1118+480 during outburst in optical, EUV, and X-ray. These multiwavelength measurements are well fitted by an ∼9 M_☉ black hole at a distance of ∼1.1 kpc in which the ADAF transition radius r^\nu is at 55 R_g, where R_g is a Schwarzschild radius.

Hameury et al. (1997) use the ADAF model and the results of Orosz et al. (1997) to estimate the transition radius of the quiescent optically thick accretion disk in GRO J1655−40 to be on the order of ∼10 R_g. Assuming the same mechanism for the outburst of XTE J1118+480 and given the X-ray delay time observed in the March outburst of XTE J1118+480 (∼10 days), we can estimate the value of the inner radius of the quiescent accretion disk in this system. The characteristic viscous timescale for a gas pressure–dominated accretion disk with dominant free-free opacity (Shakura & Sunyaev 1973) is

\[ t_{\text{visc}} \approx 3.7 \times 10^5 \alpha^{4/5} M_{16}^{3/10} m_{14}^{1/4} \rho_{54}^{-3/4} \text{s}, \]

(1)

where \( \alpha, M_{16}, m_1, \) and \( R_g \) are the disk viscosity parameter, disk accretion rate in units of 10^{16} g s^{-1}, mass of the compact object in solar units, and distance from the compact object in units of 10^{10} cm, respectively. Here and elsewhere we use the symbols \( R \) and \( r \) to denote distance in physical and Schwarzschild units, respectively (\( r = R R_g = R_c/2GM_c \)). The accretion rate can be estimated using \( L \sim L_{\text{Edd}} \sim 0.1 \dot{M} c^2 \). Using an ASM count rate of 2.8 counts s^{-1} and a distance of 1.1 kpc, the peak X-ray luminosity should be \( \sim 1.3 \times 10^{36} \text{ ergs s}^{-1} \) (Fender et al. 2001), implying an accretion rate of \( \dot{M} \approx 1.5 \times 10^{16} \text{g s}^{-1} \).

Assuming the X-ray delay time \( t_d \) to be equal to the viscous time \( t_{\text{visc}} \), one can calculate the initial value of the transition radius \( R_{\text{in}} \):

\[ R_{\text{in}}^6 \approx \left( \frac{t_d}{3.7 \times 10^5 \text{ s}} \right)^{4/5} \alpha^{-16/25} M_{16}^{24/25} m_1^{1/5}. \]

(2)

Using the values from the Esin et al. (2001) model and our own observations—\( \alpha = 0.25, m_1 = 9, M_{16} = 1.5, \) and \( t_d = 10 \)—one obtains \( R_{\text{in}}^6 \approx 3.4 \) and \( r^\nu \approx 1.2 \times 10^4 \).

We can estimate the outer radius of the accretion disk, \( R_{\text{out}} \), for comparison to the transition radius calculated above. Using numerical integration, Eggleton (1983) approximates the effective radius of the Roche lobe as

\[ R_o \approx a - 0.49q^{2/3} a \left( 0.6q^{2/3} + \ln \left( 1 + q^{1/3} \right) \right), \]

(3)

where \( R_o \) is the radius of the primary Roche lobe, \( a \) is the binary separation, and \( q = M_2/M_1 \). Using \( M_1 = 9 M_\odot \) and \( M_2 = 0.5 M_\odot \), we obtain \( R_o \approx 0.825a \). Using the orbital parameters from McClintock et al. (2001), we have \( a \sin i \approx 2.35 \pm 0.05 R_o \), where \( a \) is the distance from the secondary to the center of mass and \( i \) is the inclination of the system. Assuming \( i \approx 70^\circ \) and \( a = a_s (M_1 + M_2/M_1) \), we get \( R_o \approx 1.5 \times 10^{11} \text{ cm} \). If we then assume the outer radius of the accretion disk is some fraction of \( R_o \) (Lin & Papaloizou 1979), say, 80%, then \( R_{\text{out}} \approx 1.2 \times 10^{11} \text{ cm} \) and \( r_{\text{out}} \approx 6.7 \times 10^4 \).

While our estimated value for \( r^\nu \) of XTE J1118+480 is similar to that calculated for GRO J1655−40 by Hameury et al. (1997), the outer disk radius \( r_{\text{out}} \) is likely smaller than found in typical X-ray novae. According to the DIM model, it is the outer radius that should determine the total mass stored in the...
accretion disk before the onset of the outburst. If we assume a constant coefficient of mass conversion into emission, the accretion disk mass then determines the integral flux emitted during outburst. This model may explain qualitatively why the level of X-ray emission detected from XTE J1118+480 was unusually low, whereas the temporal evolution of the outburst was similar to other typical X-ray novae, such as XTE J1550−564 (Jain et al. 2001).

5. SUMMARY

We have presented data from the ROTSE-I telescope that show the optical counterpart of XTE J1118+480 during two outbursts in the early part of 2000. A comparison of the ROTSE-I optical data with the RXTE/ASM X-ray data during the second outburst show that XTE J1118+480 appeared first in the optical band, approximately 7 days before appearing in X-rays. In addition, the optical flux rose at a much greater rate than the X-ray flux during the initial stages of the second outburst. At the half-power point, the delay was approximately 10 days.

A possible explanation for the X-ray delay is that the accretion flow consists of two components. The outer component is a classical geometrically thin, optically thick disk. This flow then becomes an optically thin corona, such as an ADAF, as it moves inward toward the central compact object. During outburst, the radius at which this transition occurs moves inward on a viscous timescale, eventually resulting in X-ray emission. By measuring the delay between the onset of the optical emission and the X-ray emission, the initial radius of the transition region may be estimated. In the case of XTE J1118+480, we may approximate the initial transition radius by using the delay between the ROTSE-I and ASM observations of the March outburst. Given a 10 day delay, we estimate the transition radius to have been \( \sim 1.2 \times 10^4 \) Schwarzschild radii, or \( \sim 3.4 \times 10^5 \) km.

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