X-RAY FLASHES IN RECURRENT NOVAE: M31N 2008-12a AND THE IMPLICATIONS OF THE SWIFT NONDETECTION

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ABSTRACT

Models of nova outbursts suggest that an X-ray flash should occur just after hydrogen ignition. However, this X-ray flash has never been observationally confirmed. We present four theoretical light curves of the X-ray flash for two very massive white dwarfs (WDs) of 1.380 and 1.385 $M_{\odot}$ and for two recurrence periods of 0.5 and 1 yr. The duration of the X-ray flash is shorter for a more massive WD and for a longer recurrence period. The shortest duration of 14 hr (0.6 days) among the four cases is obtained for the 1.385 $M_{\odot}$ WD with a 1 yr recurrence period. In general, a nova explosion is relatively weak for a very short recurrence period, which results in a rather slow evolution toward the optical peak. This slow timescale and the predictability of very short recurrence period novae give us a chance to observe X-ray flashes of recurrent novae. In this context, we report the first attempt, using the Swift observatory, to detect an X-ray flash of the recurrent nova M31N 2008-12a (0.5 or 1 yr recurrence period), which resulted in the nondetection of X-ray emission during the period of 8 days before the optical detection. We discuss the impact of these observations on nova outburst theory. The X-ray flash is one of the last frontiers of nova studies, and its detection is essential for understanding the pre-optical-maximum phase. We encourage further observations.

Key words: novae, cataclysmic variables – stars: individual (M31N 2008-12a) – white dwarfs – X-rays: binaries

1. INTRODUCTION

A nova is a thermonuclear runaway event that occurs on an accreting white dwarf (WD) e.g., Starrfield et al. 1974; Nariai et al. 1980; Iben 1982; José et al. 1993; Prialnik & Kovetz 1995). Figure 1 shows a schematic H-R diagram for one cycle of a nova outburst on a very massive WD. The thermonuclear runaway of hydrogen sets in on an accreting WD at point A. The luminosity increases toward point B, at which the nuclear luminosity ($L_{\text{nuc}}$) reaches its maximum. After that, the envelope on the WD greatly expands and reaches point D (the maximum expansion of the photosphere: corresponding to the optical peak). An optically thick wind begins to blow at point C and continues until point E through D. A part of the envelope mass is lost in the wind. From point C to E, the hydrogen-rich envelope mass decreases owing to wind mass loss and nuclear burning. After point E, it decreases owing to hydrogen burning. The hydrogen burning extinguishes at point F.

The decay phase of optical and near-infrared (NIR) light curves corresponds to the phase from point D to E. The supersoft X-ray phase corresponds to the phase from point E to F. These phases have been well observed in a number of novae in various wavelength bands (e.g., Hachisu & Kato 2006, 2010, 2014, 2015, 2016a; Schwarz et al. 2011; Osborne 2015, and references therein). The evolution of nova has been modeled by the optically thick wind theory (Kato & Hachisu 1994), and their theoretical light curves for D-E-F have successfully reproduced the observed light curves including NIR, optical, UV, and supersoft X-rays. From point D to E, the optical/IR light curves are well explained in terms of free-free emission (Gallagher & Ney 1976), the fluxes of which are calculated from the mass-loss rate of the optically thick winds (Wright & Barlow 1975). From point E to F, the duration of the supersoft X-ray phase is theoretically reproduced. Detailed comparison with theory and observation enables us to determine/constrain the nova parameters such as the WD mass, distance, and extinction, in many novae (Hachisu & Kato 2014, 2015, 2016a, 2016b). Thus, the characteristic properties of a nova from D to F have been well understood in both observational and theoretical terms.

The X-ray flash is the stage from point B to C, which occurs just after the hydrogen ignition (Kato et al. 2015; Hachisu et al. 2016), but before the optical discovery. This stage has not been theoretically studied well, partly because of numerical difficulties and partly because of insufficient observational data to guide the theoretical models. In general, we cannot know in advance when and where a nova will erupt. Thus, soft X-ray flashes have never been detected in any kind of nova with any X-ray satellite. X-ray flashes represent one of the last frontiers of nova eruption studies, and their detection will open a new landscape of nova physics.

The X-ray flash of novae has been predicted from theoretical models for many years (e.g., Starrfield et al. 1990; Krautter 2002), but its observation had not been attempted until

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Finally, the star cools down to point A. The optically thick wind starts at point C. The photospheric radius reaches maximum at point D. A part of the envelope matter is blown away in the wind. The optically thick wind starts at point C. The photospheric radius reaches maximum at point D. A part of the envelope matter is blown away in the wind. The optimally thick wind continues until point E. Hydrogen nuclear burning extinguishes at point F. 

by Kato et al. (2015) and suggests that theoretical models are still incomplete, especially in the rising phase. Because no observational detection of soft X-rays and their properties has ever been obtained in the pre-optical-maximum phase, we are unable to constrain the theoretical models. In the present paper we describe the theoretical light curves of X-ray flashes for massive WDs and present the observational results. We also address the implication of a nondetection of a flash.

This paper is organized as follows. Section 2 describes our improved numerical calculations and presents theoretical light curves of X-ray flashes, as well as the physical properties of expanding envelopes in the early phase of shell flashes. Section 3 describes the Swift observations of the 2015 outburst of M31N 2008-12a, which resulted in the nondetection of an X-ray flash. In Section 4, we identify the reason why X-ray flash emission was not detected. Discussion and conclusion follow in Sections 5 and 6.

2. EARLY EVOLUTION OF SHELL FLASH

2.1. Numerical Method

We calculated recurrent nova models on 1.38 and 1.385 M⊙ WDs accreting hydrogen-rich matter (X = 0.70, Y = 0.28, and Z = 0.02 for hydrogen, helium, and heavy elements, respectively) with mass-accretion rates of (1.4–2.5) × 10⁻¹⁰ M⊙ yr⁻¹, corresponding to recurrence periods from 1 to 0.5 yr (Darnley et al. 2015b; Henze et al. 2015a). We also calculated models for a 1.35 M⊙ WD with 1.0 and 12 yr recurrence periods for comparison. Table 1 summarizes our models. The WD mass and mass-accretion rate are the given model parameters, and the other values, including recurrence periods, are calculated results.

We calculated several outburst cycles until the shell flashes reached a limit cycle. We used the same Henyey-type code as in Kato et al. (2014, 2015) and Hachisu et al. (2016) but adopted a thinner static boundary layer (2 × 10⁻¹⁰ M⊙) for the outermost surface layer and smaller time steps and mass zones. These technical improvements enabled us to calculate the photospheric values much more accurately in the extended phase (after point B in Figure 1) until the optically thick wind begins to blow at log Tₚ (K) ~ 5.5. The X-ray light curves are calculated from the photospheric luminosity Lₚ and temperature Tₚ, assuming blackbody emission.

Our report here is focused on the very early phase of nova outbursts, i.e., the X-ray flash phase. The occurrence of the optically thick wind in our models is judged using the surface boundary condition BC1 listed in Table A1 of Kato & Hachisu (1994).

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Table 1

| WD Mass (M⊙) | Mₑₑ (10⁻² M⊙ yr⁻¹) | tᵣₑₑ (yr) | tₓᵣ-flash * | Lₓᵣ-max (10⁴ Lₒ) | Tₓᵣ-max (10⁵ K) |
|--------------|---------------------|-----------|-------------|------------------|------------------|
| 1.385        | 2.0                 | 0.54      | 0.90        | 2.3              | 1.74             |
| 1.385        | 1.4                 | 0.97      | 0.59        | 5.1              | 1.84             |
| 1.38         | 2.5                 | 0.47      | 1.4         | 1.5              | 1.66             |
| 1.38         | 1.6                 | 0.95      | 0.78        | 3.9              | 1.77             |
| 1.35         | 2.6                 | 1.0       | 2.5         | 1.5              | 1.54             |
| 1.35         | 0.5                 | 12        | 0.37        | 29               | 1.89             |

Note.

* Duration of the X-ray flash: Lₓᵣ(0.3–1.0 keV) > 10⁴ Lₒ.
Figure 2. Evolution of the nuclear burning luminosity, \( L_{\text{nuc}} \), photospheric luminosity, \( L_{\text{ph}} \), and gravitational energy release rate, \( L_G \), of a shell flash on a 1.38 \( M_\odot \) WD. A large amount of nuclear luminosity is produced but is absorbed in the burning shell, as expressed by a large negative value of \( L_G \). As a result, the outward radiative luminosity, i.e., the photospheric luminosity, \( L_{\text{ph}} \), is very small. Thin lines denote 10 times the photospheric luminosity, \( L_{\text{ph}} \times 10 \). Solid lines denote those for a \( P_{\text{rec}} = 0.95 \) yr model, while dotted lines represent those for a \( P_{\text{rec}} = 0.47 \) yr model.

2.2. Energy Budget

Figure 2 shows the energy budget in the very early phase of shell flashes on a 1.38 \( M_\odot \) WD for two recurrence periods: \( P_{\text{rec}} = 0.95 \) yr (\( M_{\text{acc}} = 1.6 \times 10^{-7} M_\odot \) yr\(^{-1} \); solid lines) and \( P_{\text{rec}} = 0.47 \) yr (\( M_{\text{acc}} = 2.5 \times 10^{-7} M_\odot \) yr\(^{-1} \); dashed lines). The nuclear luminosity,

\[
L_{\text{nuc}} = \int_0^M \epsilon_x dM_r,
\]

takes a maximum value of \( L_{\text{nuc}}^{\text{max}} = 3.9 \times 10^6 L_\odot \) for the \( P_{\text{rec}} = 0.95 \) yr case and \( L_{\text{nuc}}^{\text{max}} = 1.5 \times 10^6 L_\odot \) for the \( P_{\text{rec}} = 0.47 \) yr case. Here \( \epsilon_x \) is the energy generation rate per unit mass for hydrogen burning, \( M_r \) is the mass within the radius \( r \), and \( M \) is the mass of the WD including the envelope mass. The maximum value is lower for the shorter recurrence period. A shorter recurrence period corresponds to a higher mass-accretion rate, and ignition starts at a smaller envelope mass because of heating by a larger gravitational energy release rate. We define the hydrogen-rich envelope mass as the mass above \( X = 0.1 \), i.e.,

\[
M_{\text{env}} = \int_{X > 0.1} dM_r,
\]

and the ignition mass, \( M_\text{ig} \), as the hydrogen-rich envelope mass at the maximum nuclear energy release rate, i.e., \( M_\text{ig} = M_{\text{env}} \) (at \( L_{\text{nuc}} = L_{\text{nuc}}^{\text{max}} \)), because the envelope mass is increasing owing to mass accretion even after hydrogen ignites. The ignition mass is \( 2.0 \times 10^{-7} M_\odot \) for \( P_{\text{rec}} = 0.95 \) yr and \( 1.6 \times 10^{-7} M_\odot \) for \( P_{\text{rec}} = 0.47 \) yr. For a smaller envelope mass, the pressure at the bottom of the envelope is lower and therefore the maximum temperature is also lower. As a result, the maximum value of \( L_{\text{nuc}}^{\text{max}} \) is lower for a shorter recurrence period.

Although a high nuclear luminosity (\( \sim 10^6 L_\odot \)) is produced, most of the energy is absorbed by the burning shell, as indicated by the large negative values of the gravitational energy release rate, \( L_G \), which is defined by

\[
L_G = \int_0^M \epsilon_x dM_r = \int_0^M -T \left( \frac{\partial s}{\partial T} \right)_M dM_r,
\]

where \( \epsilon_x \) is the gravitational energy release rate per unit mass, \( T \) is the temperature, and \( s \) is the entropy per unit mass (see, e.g., Kato et al. 2014; Hachisu et al. 2016).

As a result, the photospheric luminosity \( L_{\text{ph}} \) (\( \approx L_{\text{nuc}} - |L_G| \) because neutrino loss is negligible) is two orders of magnitude smaller than the peak value of \( L_{\text{nuc}}^{\text{max}} \). Shortly after the ignition, the photospheric luminosity approaches a constant value. This constant value is close to but slightly smaller than the Eddington luminosity at the photosphere,

\[
L_{\text{Edd,ph}} = \frac{4\pi cGM_{\text{WD}}}{\kappa_{\text{ph}}} = 2.0 \times 10^{38} \text{erg s}^{-1} \times \left( \frac{M_{\text{WD}}}{1.38 M_\odot} \right) \left( \frac{0.35}{\kappa_{\text{ph}}} \right),
\]

where \( \kappa_{\text{ph}} \) is the opacity at the photosphere. In other words, the photospheric luminosity stays below the Eddington luminosity in this early phase of a shell flash.

2.3. H-R Diagram

Figure 3 shows the H-R diagram of the rising phase of recurrent nova outbursts for various WD masses and recurrence periods. X-ray flashes correspond to the phase approximately from point B to C (the same marks denote the same stage in Figure 1). A more massive WD reaches a higher photospheric luminosity and maximum photospheric temperature; therefore, we expect larger X-ray luminosity during the X-ray flash on a more massive WD.

The track in the H-R diagram depends not only on the WD mass but also more weakly on the recurrence period. For a longer recurrence period, the ignition mass is larger and the envelope begins to expand at a lower luminosity. Thus, the track locates slightly lower and toward the right (redder) side compared to that of a shorter recurrence period.

2.4. X-ray Light Curve

Figure 4(a) shows the photospheric temperature and luminosity during the X-ray flashes for the 1.38 and 1.385 \( M_\odot \) WD models in Table 1. The photospheric luminosity quickly rises near the \( L_{\text{nuc}} \) peak (\( t = 0 \)) and reaches a constant value. The photospheric temperature reaches its maximum immediately after the time of ignition and decreases with time. When the envelope expands and the photospheric temperature decreases to a critical temperature, the optically thick wind occurs (this epoch corresponds to point C in Figure 1). This critical temperature is indicated by small filled circles in Figure 4(a). Shortly before this epoch, the temperature drops quickly, corresponding to the opacity increase near the photosphere, which will be discussed in Section 2.6.

Figure 4(b) shows the X-ray luminosity in the supersoft X-ray band (0.3–1.0 keV). The duration (\( \log L_{\text{x}}/L_\odot > 4 \)) of the X-ray flash is 14–19 hr (0.59–0.78 days) for \(~1\) yr recurrence period novae and 22–34 hr (0.9–1.4 days) for \(~0.5\) yr period
Figure 3. H-R diagram for the rising phase of recurrent novae. The WD mass and recurrence period are indicated by different colors. The maximum nuclear luminosity at point B, \( L_{nuc} = L_{nuc}^{max} \), and the occurrence of the optically thick wind mass loss point C are indicated by the small filled circles. For less massive WDs (\(<1.3 M_\odot\)) point C is located at \( \log T_{ph} (K) < 5.4 \), beyond the right edge of the figure. The dotted lines indicate the shorter recurrence period models of 1.38 and 1.385 \( M_\odot \).

Figure 4. (a) Photospheric temperature \( T_{ph} \) (solid lines) and luminosity \( L_{ph} \) (dotted lines), and (b) X-ray luminosity \( L_X \) (solid lines; 0.3–1.0 keV) and luminosity \( L_{ph} \) (dotted lines) during X-ray flashes, against time after the ignition. The origin of time \( t = 0 \) is defined as the point B where \( L_{nuc} = L_{nuc}^{max} \). The blue lines denote the model of 1.385 \( M_\odot \) with \( P_{rec} = 0.97 \) yr, orange lines mark 1.385 \( M_\odot \) with \( P_{rec} = 0.54 \) yr, black lines mark 1.38 \( M_\odot \) with \( P_{rec} = 0.95 \) yr, and red lines mark 1.38 \( M_\odot \) with \( P_{rec} = 0.47 \) yr. Point C is indicated by a dot, but point C on the X-ray light curves is located below the lower bound in panel (b).

Figure 5. (a) Nuclear burning luminosity \( L_{nuc} \) (thin solid line) and photospheric temperature \( T_{ph} \) (thick solid line) for our 1.35 \( M_\odot \) model with \( P_{rec} = 12 \) yr (black) and 1 yr (red). (b) Photospheric luminosity \( L_{ph} \) and X-ray luminosity \( L_X \) for the same models as in panel (a).

For a shorter recurrence period, the ignition is weaker, as explained before, so the expansion is slower than in longer recurrence period novae. The shortest duration among these four models is 14 hr (0.59 days) for 1.385 \( M_\odot \) with \( P_{rec} = 0.97 \) yr. As 1.385 \( M_\odot \) is almost the upper limit of a mass-accreting WD with no rotation (Nomoto et al. 1984), a duration of 14 hr (0.59 days) would be the minimum for novae with recurrence periods shorter than 1 yr.

The ultrashort recurrence period nova M31N 2008-12a shows a supersoft X-ray source phase (SSS) of 10 days (Henze et al. 2014a, 2015b; Tang et al. 2014). In general, the SSS phase (from E to F in Figure 1) is shorter for a more massive WD. The duration of the SSS phase of M31N 2008-12a is consistent with a \(~1.38 M_\odot\) WD (Henze et al. 2015b). Such an SSS phase duration allows us to exclude WDs much more massive than 1.385 \( M_\odot \). Similarly, we can also exclude a 1.35 \( M_\odot \) WD because its SSS duration would be too long. The duration of the X-ray flash in a 1.38–1.385 \( M_\odot \) WD (> 14 hr) is long enough to be detectable with the 6 hr cadence of our Swift observations (see Section 3).

2.5. Various WD Models and Flash Duration

We have calculated shell flash models on a 1.35 \( M_\odot \) WD with \( P_{rec} = 1 \) and 12 yr for comparison. The corresponding mass accretion rates are listed in Table 1. Figure 5(a) shows the evolution of the nuclear luminosity and photospheric temperature. The outburst in the \( P_{rec} = 1 \) yr case (red lines) is much weaker than in the \( P_{rec} = 12 \) yr scenario (black lines), as indicated by the lower nuclear energy generation rate \( L_{nuc} \). As a result, in the \( P_{rec} = 1 \) yr case, the photosphere slowly expands; therefore, the photospheric temperature decreases slowly, which results in a much longer X-ray flash, as demonstrated in Figure 5(b).
The opacity is taken from Iglesias & Rogers (1996) for the structure of an extended wind solution with $T_{\text{ash}}(K) = 4.0$ on the $1.38 M_\odot$ WD. The small open circle labeled “Wind starts” denotes the critical point. The main element responsible for each opacity peak is indicated by its atomic symbol. When a nova envelope expands and the photospheric temperature decreases to $T(K) \sim 0.02$, the opacity is taken from Iglesias & Rogers Figure 6. The Astrophysical Journal, the main text for more details.

Table 1 lists the maximum value of the nuclear energy generation rate $L_{\text{nuc, max}}$ and the maximum temperature in the hydrogen nuclear burning region $T_{\text{nuc, max}}$. There are three models of similar recurrence period, $P_{\text{rec}} \sim 1$ yr, for $1.35$, $1.38$, and $1.385 M_\odot$. Both $T_{\text{nuc, max}}$ and $L_{\text{nuc, max}}$ are larger in more massive WDs. This means that the shell flash is stronger and hence evolves faster in a more massive WD with the same recurrence period because of the stronger gravity of the WD. On the other hand, for a given WD mass, both $T_{\text{nuc, max}}$ and $L_{\text{nuc, max}}$ are smaller for a shorter recurrence period. This tendency is clearly shown in the two $1.35 M_\odot$ models, in which $L_{\text{nuc, max}}$ is 19 times larger in $P_{\text{rec}} = 12$ yr than in $P_{\text{rec}} = 1$ yr. The duration of the X-ray flash is 6.8 times longer for the shorter recurrence period.

To summarize, more massive WDs undergo stronger shell flashes, but their flashes become weaker for shorter recurrence periods. Thus, the duration of X-ray flash is shorter in more massive WDs but longer for shorter recurrence periods. Even in WDs as massive as $1.38 M_\odot$, the X-ray flash could last $\sim 0.5$ days.

2.6. Internal Structure at the End of X-Ray Flash

The X-ray flash ends when the envelope expands and the optically thick winds start blowing. In this subsection, we examine the possibility that the optically thick winds are accelerated much earlier (i.e., before point C in Figure 1), which shortens the duration of the X-ray flash.

Before going into the details of the envelope structure, it would be instructive to discuss the opacity in the envelope, which is closely related to the envelope expansion and occurrence of wind mass loss. Figure 6 shows the run of the OPAL opacity (Iglesias et al. 1987; Iglesias & Rogers 1996) with solar composition in an optically thick wind solution with $T_{\text{ash}}(K) = 4.0$ on the $1.38 M_\odot$ WD. This model has a very large envelope mass and a uniform chemical composition that does not exactly correspond to the structure of a very short recurrence period nova, but it is sufficient to show the characteristic properties of the OPAL opacity. In our evolution calculation, the chemical composition varies from place to place, and the photospheric temperature is much higher than in this case.

The opacity has several peaks above the constant value of the electron scattering opacity $\log n_e$ = $\log [0.2(1 + X)] = \log 0.34 = -0.47$ for $X = 0.7$. The peak at $T(K) = 4.5$ corresponds to the second helium ionization. The prominent peak at $T(K) \sim 5.2$ is due mainly to low/mid-degree ionized iron found in opacity projects (Iglesias et al. 1987; Seaton et al. 1994). Hereafter, we call it the “Fe peak.” The peak at $T(K) = 6.2$ relates to highly ionized Fe, C, O, and Ne. We call it the “C/O peak.” A tiny peak around $T(K) = 7.0$ is due to the highly ionized heavy elements Ar–Fe. The opacity is smaller than that of electron scattering at the highest temperature regime because of the Compton effect.

A large peak in the opacity causes the envelope expansion and accelerates the optically thick winds. In the model in Figure 6, the critical point of the optically thick winds (Kato & Hachisu 1994), in which the velocity becomes equal to the isothermal sound velocity, appears just on the inside of the Fe peak. A critical point appears in the region of acceleration, which means that the envelope is accelerated outward where the opacity quickly increases outward.

Figure 7 shows the internal structures at the end of the X-ray flash in our $1.38 M_\odot$ WD model with $P_{\text{rec}} = 0.95$ yr. The solid line represents the structure at point C in Figures 1, 3, and 4, and the dotted line corresponds to the stages shortly after point C. From top to bottom we show the escape velocity $\sqrt{2GM_{WD}/r}$, wind velocity $V$, temperature $T$, density $\rho$, radiative luminosity $L_r$, which is the summation of diffusive luminosity and convective luminosity, and local Eddington luminosity defined by

$$L_{\text{Edd}} = \frac{4\pi c GM_{WD}}{\kappa},$$

where $\kappa$ is the opacity. As the opacity depends on the local temperature and density, the local Eddington luminosity also varies. Note that Equation (4) represents the photospheric value of Equation (5). The velocity is not plotted for the solution at point C.

The local Eddington luminosity in Figure 7 shows a small dip at $\log r (\text{cm}) \sim 9.2$ corresponding to the C/O peak at $T(K) = 6.2$ in Figure 6. Here, the local Eddington luminosity is slightly lower than the diffusive luminosity, i.e., locally the luminosity is super-Eddington. However, this C/O peak does not result in the occurrence of optically thick winds. Instead, the temperature and density profiles become shallower in this region.

When the envelope expands enough and the photospheric temperature approaches the prominent Fe peak, optically thick winds occur. The Fe peak is so large that the local Eddington luminosity decreases to much below the radiative luminosity. The critical point (Kato & Hachisu 1994) appears near the photosphere, which corresponds to the inner edge of the Fe peak in Figure 6.

If the winds were accelerated by the C/O peak, the X-ray flash durations would be much shorter because the expansion and acceleration occur much earlier. We have confirmed in all of our calculated models that the wind is driven by the Fe peak.
and not by the C/O peak. Thus, we conclude that the X-ray flash should last at least half a day, as in Table 1, and could not be much shorter than that.

3. SEARCH FOR THE X-RAY FLASH IN THE 2015 ERUPTION OF M31N 2008-12a

3.1. Observing Strategy

The multiwavelength coverage of the 2013 and 2014 eruptions of M31N 2008-12a (Darnley et al. 2014, 2015b; Henze et al. 2014a, 2015b) resulted in significantly improved predictions of future eruptions. Moreover, Henze et al. (2015a) combined new findings with archival data to arrive at a 1σ prediction accuracy of ±1 month (and suggest a recurrence period of 175 ± 11 days). Based on this updated forecast, we designed an observational campaign to monitor the emerging eruption and catch the elusivelyX-ray flash.

The project was crucially reliant on the unparalleled scheduling flexibility of the Swift satellite (Gehrels et al. 2004), whose X-ray telescope (XRT; Burrows et al. 2005) provided a high-cadence monitoring. Similarly, the unprecedented short recurrence time and predictability of M31N 2008-12a made it the only target for which such an endeavor was feasible.

Starting from 2015 August 20 UT, a 0.6 ks Swift XRT observation was obtained every 6 hr. After the first week of the monitoring campaign, the exposure time per observation increased from 0.6 to 1 ks, because the actual exposure time often fell short of the goal. The nova eruption was discovered on August 28 (Darnley et al. 2015a), slightly earlier than predicted by Henze et al. (2015a), without any prior detection of an X-ray flash. Because of this early eruption date and the last-minute improvement in prediction accuracy, based on the recovery of the 2010 eruption (Henze et al. 2015a), only 8 days’ worth of observations were obtained before the 2015 eruption. All individual observations until after the optical discovery are listed in Table 2. The campaign continued until the end of the SSS phase, and the analysis of the phase is presented by Darnley et al. (2016).

3.2. Data Analysis

All Swift XRT data were obtained in photon counting (PC) mode and were reduced using the standard Swift and HEASARC tools (HEASOFT version 6.16). Our analysis started from the cleaned level 2 files that had been reprocessed locally with HEASOFT version 6.15.1 at the Swift UK data center.

We extracted source and background counts in xselect v2.4c based on the XRT point-spread function (PSF) of M31N 2008-12a observed during previous eruptions. We applied the standard grade selection 0–12 for PC mode observations. Based on the early SSS phase detections, we chose a circular region with a radius of 22″, which corresponds to a 78% PSF area (based on the merged detections of the 2013/4 eruptions), to optimize the ratio of source to background counts in the source region. The background region excluded the locations of nearby faint X-ray sources as derived from the merged data of the 2013 and 2014 eruption monitoring campaigns (see Henze et al. 2014a, 2015b). All counts were restricted to the 0.3–1.0 keV band (refer to the X-ray spectrum of the eruption discussed in Darnley et al. 2016).

We checked for a source detection using classical Poisson statistics and determined 3σ count rate upper limits using the method of Kraft et al. (1991). The number of background counts was scaled to the source region size and corrected for the differences in exposure, derived from the XRT exposure map, between the regions for each individual observation. To improve the signal-to-noise ratio of the detection procedure, the data set was smoothed by a two-observation-wide boxcar function to achieve a rolling ~12 hr window. The added source and background counts were analyzed in the same way as the individual measurements. Note that, therefore, successive upper limits are not statistically independent.

3.3. Results

The monitoring campaign was executed exceptionally well, with a median cadence of 6.3 hr between two consecutive observations. At no point was there more than a 10 hr gap between successive pointings. Therefore, the minimum flash duration of 14 hr (0.59 days) would have been covered by at least one observation, more likely two, during the entire 8 days prior to the eruption.

In Figure 8 the resulting 3σ and 5σ XRT count rate upper limits are shown for the individual and merged observations, respectively. The 5σ upper limits are in the range of (2–4) × 10⁻² counts s⁻¹ for the individual observations, which roughly corresponds to the variability range of the SSS phase around maximum (Henze et al. 2015b). The combined 5σ
upper limits for each two successive merged observations (i.e., a rolling ∼12 hr period) were almost entirely well below the expected flash count rate of 2 × 10⁻² counts s⁻¹. This prediction assumes a similar luminosity and spectrum for the X-ray flash and the SSS phase (see Figure 1 and compare Henze et al. 2015b; Kato et al. 2015).

The time of eruption ($T_e$) is defined as the midpoint between the last nondetection by the Liverpool Telescope (MJD 57262.16) and the first Swift UVOT detection (MJD 57262.40; see Darnley et al. 2016, for both). Therefore, $T_e = MJD 57262.28 ± 0.12$ (August 28.28 UT), with the error corresponding to half the interval between both observations. The rightmost data points in Figure 8 feature the start of the SSS phase to compare the signatures of an actual detection. Additionally, the number of counts in the source region always remained below 2 for individual observations, except for the emergence of the SSS emission.

The strict 5σ limits indicate that we should have seen the X-ray flash if it had occurred with the predicted luminosity and spectrum during the time of the monitoring. The restrictive 3σ limits can be used to constrain the X-ray flux in a meaningful way. The corresponding data are given in Tables 2 and 3.

4. IMPLICATION OF NONDETECTION OF X-RAY/UV FLUXES

We have confirmed theoretically that the X-ray flash should last 14 hr (0.59 days) or longer (in Section 2). The X-ray flash was not, however, detected in our 6 hr cadence, 8-day observations preceding the 2015 outburst. In this section we examine two possible reasons for the nondetection: (1) the X-ray flash had occurred during the Swift observation period, but all the photons were obscured by surrounding neutral hydrogen, or (2) the X-ray flash had occurred earlier than our
the early SSS detections, for comparison. The estimated onset of the SSS phase is the 2015 eruption date on August 28.28. The dashed vertical line marks the rate respectively. The dashed horizontal line marks the expected XRT ash count rate. Figure 8. Swift XRT upper limits based on Kraft et al. (1991) for the count rate of M31N 2008-12a assuming confidence levels 5σ (open diamonds) and 3σ (filled circles). Panels (a) and (b) show the individual and merged observations, respectively. The dashed horizontal line marks the expected XRT flash count rate (see Henze et al. 2015b; Kato et al. 2015). The solid vertical line indicates the 2015 eruption date on August 28.28. The dashed vertical line marks the estimated onset of the SSS phase (see Darnley et al. 2016) and is followed by the blue data points, which indicate the formal upper limits corresponding to the early SSS detections, for comparison.

Swift observation period, i.e., more than eight days before the optical discovery.

4.1. Absorption by Surrounding Neutral Hydrogen

A WD in a binary is possibly surrounded by ionized/neutral material originating from the companion star. If the WD is surrounded by a substantial amount of neutral hydrogen, X-ray photons emitted from the WD surface could be mostly absorbed, and thus one may not detect the X-ray flash. It is, however, poorly known whether the mass-accreting WDs in recurrent novae are surrounded by ionized or neutral matter in their early outburst phase.

The companion of M31N 2008-12a has not yet been identified. If the companion star is a Roche-lobe-filling subgiant, we can expect that the mass transfer is mainly through the accretion disk and a small proportion of the mass lost by the donor is spread over the circumbinary region. If the companion is a red giant, the binary could be embedded within the cool neutral wind, which absorbs supersoft X-ray photons from the WD.

Darnley et al. (2014) compared the spectral energy distribution (SED) of M31N 2008-12a in its quiescent phase with those of the Galactic recurrent novae, RS Oph, T CrB, and U Sco. Based on the similarity of the RS Oph SED, rather than U Sco, which is much fainter, the authors suggested that M31N 2008-12a likely contains a red giant companion with a significant accretion disk component that dominates the near-UV and optical flux. The authors note, however, that the possibility of a face-on subgiant companion remains because U Sco is an eclipsing binary and its edge-on disk may not be bright.

Hachisu & Kato (2016b) classified 40 classical novae into six classes according to their evolutionary path in the color–magnitude diagram and found that the different paths correspond to differences in the nova speed class and thus the envelope mass. These authors also displayed the color–magnitude evolution during the 2014 outburst of M31N 2008-12a and found that its characteristic properties are similar to those of U Sco and CI Aql, which are both recurrent novae with a subgiant companion, but different from RS Oph, which has a red giant companion (see their Figures 72(c), 72(d), and 76(b)). This suggests that M31N 2008-12a has a subgiant companion.

The Galactic object RS Oph is a well-observed recurrent nova. Its recorded outbursts were in 1898, 1933, 1958, 1967, 1985, and 2006 (Evans et al. 2008). In the 1985 outburst very soft X-ray emission was detected 251 days after the optical maximum (Mason et al. 1987). Hachisu & Kato (2001) regarded this X-ray emission to be due to the accretion luminosity and suggested that the accretion rate had dropped by a factor of six after the outburst. Dobrzycka & Kenyon (1994) also pointed out a decrease in the mass accretion rate from line fluxes in H I and He I that decreased by a factor of four after the 1985 outburst. Day 251 falls in the period of the postoutburst minimum of days ~100–400, after which the visual luminosity increased by about a magnitude (Evans et al. 1988). X-rays were also observed in 1992 with ROSAT (Orio 1993), but the supersoft flux (<0.5 keV) was very weak. One possible explanation is absorption by the massive cool wind (e.g., Shore et al. 1996) from the red giant companion, as suggested by Anupama & Mikolajewska (1999). After 21 yr of accumulation, the overlying RG wind reaches (2–5) × 10^{22} cm^{-2} (Bode et al. 2006; Sokoloski et al. 2006) in the 2006 outburst. However, the absorption effect of this overlying RG wind is quickly removed (Osborne et al. 2011). After the outburst, the mass-accretion rate had dropped in the post-outburst minimum phase and soft X-rays were observable because the ejecta swept away the red giant cool wind. After day 400, the mass transfer had recovered and the hot component could be surrounded by neutral hydrogen.

If the accretion disk is completely blown off by the ejecta, it may take a few orbital periods until a significant amount of the red giant wind falls onto the WD. Hachisu & Kato (2001) roughly estimated the resumption time of mass transfer in RS Oph to be Δt = a/v ~ 300R_C/10 km s^{-1} = 300 days, where a is the binary separation and v is the velocity of infalling matter. This is roughly consistent with the recovery of the quiescent V luminosity 400 days after the 1985 outburst (see Figure 1 in Evans et al. 1988; Figure 2 in Hachisu & Kato 2006; Worters et al. 2007; also Darnley et al. 2008). M31N 2008-12a shows an ultrashort recurrence period of 1 or 0.5 yr. It is unlikely that systems like RS Oph produce successive outbursts with such a short recurrence period because of a long interruption of mass transfer unless the disk survives the eruption. Thus, we expect that M31N 2008-12a does not have a red giant companion.

U Sco is another well-observed Galactic recurrent nova with a subgiant companion. Ness et al. (2012) examined an X-ray eclipse during the 2010 outburst in detail and concluded that the mass accretion resumed as early as day 22.9, midway during the SSS phase. In a binary with a subgiant companion, thus, we can expect the mass accretion to resume just after an outburst.

For these reasons, we may conclude that M31N 2008-12a has a subgiant companion. In the case of close binaries, the transferred matter is mostly distributed in the orbital plane (see, e.g., Sytov et al. 2009, for a 3D calculation of mass flow in a close binary). Note that, in our binary models, the WD radiates L_v ph = 200–500 L_{⊙} at T_v ph = (4–5) × 10^5 K in its quiescent phase. Therefore, we expect that the matter surrounding the
WD may be kept ionized during the quiescent phase. Thus, we consider that an X-ray flash should have been detected if it had occurred during our observing period.

### 4.2. Slow Evolution after X-ray Flash

The other explanation of the undetected X-ray flash is that the flash had already occurred and finished when we started our observations 8 days before the UV/optical discovery. This means that the evolution time from C to D in Figure 1 was longer than 8 days, and the optical/UV bright phase, from D to E, lasted about 5.5 days (Darnley et al. 2015b; Henze et al. 2015b). Darnley et al. (2015b) pointed out that M31N 2008-12a showed slow rise to the optical peak magnitude in the 2014 outburst. This suggests a slow evolution toward point D.

The timescale from C to E can be roughly estimated as follows. The decrease of the envelope mass from C to E is due to both nuclear burning and mass ejection. For example, in a 1.38 M⊙ WD with \( P_{\text{rec}} = 0.47 \) yr, the envelope mass is \( 1.5 \times 10^{-7} M_\odot \) at C and decreases to \( 7.5 \times 10^{-8} M_\odot \) at E. In the 2014 outburst, the ejected hydrogen mass was estimated to be \( M_{d,\text{H}} = (2.6 \pm 0.4) \times 10^{-8} M_\odot \) (Henze et al. 2015b), which corresponds to \( M_d = 4.7 \times 10^{-8} M_\odot \) for \( X = 0.55 \) (the hydrogen mass fraction is smaller than the initial \( X = 0.7 \) because of convective mixing with the nuclear burning region).

Darnley et al. (2015b) derived a total ejected mass of \( \gtrsim 3 \times 10^{-8} M_\odot \). Here we assume the mass ejected by the wind to be \( M_{d,j} = 4.7 \times 10^{-8} M_\odot \). Thus, nuclear burning had consumed the rest of the mass, \( \Delta M_{\text{env}} = 1.5 \times 10^{-7} M_\odot \), \( -7.5 \times 10^{-8} M_\odot \), and \( 4.7 \times 10^{-8} M_\odot \) during the period from C to E. If we take the mean nuclear luminosity as \( \log L_{\text{nuc}} / L_\odot = 4.65 \), the evolution time from C to E is roughly estimated as \( \Delta T_{\text{env}} \times X / \epsilon_H) / L_{\text{nuc}} = 14.8 \) days, where \( X = 0.55 \) and energy generation of hydrogen burning \( \epsilon_H = 6.4 \times 10^{13} \text{erg g}^{-1} \). So we obtain the duration between epochs C and D in Figure 1 to be 14.8 – 5.5 = 9.3 days. For a longer recurrence period, \( P_{\text{rec}} = 0.95 \) yr, we obtain, in the same way, \( (1.9 \times 10^{-7} M_\odot - 7.3 \times 10^{-8} M_\odot - 4.7 \times 10^{-8} M_\odot) \)
In this way we may explain that the X-ray flash had occurred 15.5 days (\(P_{\text{rec}} = 0.95\) yr) or 9.3 days (\(P_{\text{rec}} = 0.47\) yr) before the optical/UV peak. These values should be considered as rough estimates because they are sensitive to our simplified value for the mean \(L_{\text{acc}}\), besides other parameters such as the WD mass and recurrence period (i.e., mass accretion rate), even though these estimates suggest that the nova evolution is slow between C and D, and the X-ray flash could have occurred before our observing period (8 days before the optical/UV detection), rather than immediately before the optical maximum (Kato et al. 2015).

Observations of recurrent novae have shown that they evolve much faster than typical classical novae, which is demonstrated by their very short X-ray turn-on time (duration between the optical peak and the X-ray turn-on; see, e.g., Page et al. 2015, for the shortest 4-day case of V745 Sco). By analogy, and without observational support, we suspect that the rising phase of recurrent novae must also be fast. However, our 8 days of nondetection prior to the optical/UV peak suggest that it may not be as fast as predicted. It is partly suggested by our calculation that \(L_{\text{max}}\) is rather small in very short recurrence period novae even though the WD is extremely massive. The small nuclear burning energy generation rate renders the recurrent nova eruption relatively weak. Because time-dependent calculations have many difficulties in the expanding phase of nova outbursts, no one has ever succeeded in reproducing reliable multiwavelength light curves that included the rising phase. We expect that the detection of X-ray flashes can confirm such a slow evolution in the very early phase of a nova outburst.

5. DISCUSSION

5.1. Comparison with Other Works

Many numerical calculations of shell flashes have been presented, but only a few of them provided sufficient information on the early stages corresponding to the X-ray flash. Nariai et al. (1980) calculated hydrogen shell flashes, in which the evolution time from \(L_{\text{acc}}\) (defined as \(t = 0\)) to a stage of log \(T_{\text{ph}}\) (K) \(\sim 5.45\) is 1.5 hr for a 1.3 \(M_{\odot}\) WD with \(M_{\text{acc}} = 1 \times 10^{-6} M_{\odot}\) yr\(^{-1}\). Iben (1982) showed the timescale from \(t = 0\) to log \(T_{\text{ph}}\) (K) =5.5 is about to be 100 days for a 0.964 \(M_{\odot}\) WD with \(M_{\text{acc}} = 1.5 \times 10^{-6} M_{\odot}\) yr\(^{-1}\) (in his Figure 8). For a 1.01 \(M_{\odot}\) WD, it is about 20 days with \(M_{\text{acc}} = 1.5 \times 10^{-7} M_{\odot}\) yr\(^{-1}\) and about 1 day for \(M_{\text{acc}} = 1.5 \times 10^{-8} M_{\odot}\) yr\(^{-1}\) (in his Figures 15 and 21). These studies are based on the Los Alamos opacity data that have no Fe peak, so the optically thick wind does not occur, resulting in a much longer total duration of the nova outburst. However, the timescales in the very early phase corresponding to the X-ray flash (defined by log \(T_{\text{ph}}\) (K) \(> 5.6\)) should not be much affected by the Fe peak because the photospheric temperature is higher than the Fe peak. We see a tendency of a longer X-ray flash for a less massive WD and for a larger mass accretion rate (i.e., a shorter recurrence period). This tendency agrees with our results.

Hillman et al. (2014) showed evolutionary change in the effective temperature of nova outbursts with the OPAL opacities. Their Figure 3 shows an X-ray flash duration (defined by log \(T_{\text{eff}}\) (K) \(> 5.5\)) of a few hours for a 1.4 \(M_{\odot}\) WD with a mass accretion rate of \(10^{-8} M_{\odot}\) yr\(^{-1}\). This accretion rate corresponds to the recurrence period of 20 yr (Prihalnik & Kovetz 1995). Considering the tendency that a longer-duration X-ray flash is obtained for a less massive WD and larger mass-accretion rate, their duration of a few hours is consistent with our results of 0.5–1 day (Table 1).

5.2. General Relativistic Stability of Massive WDs

The masses of our WD models are very close to the Chandrasekhar mass limit, above which nonrotating WDs cannot exist. This limit is \(1.457 (\mu_e/2)^{-2} M_{\odot}\) for pure degenerate gas (e.g., Equation (6.10.26) in Shapiro & Teukolsky 1983), where \(\mu_e\) is the mean molecular weight of the electron. According to Shapiro & Teukolsky (1983), Kaplan (1949) first pointed out that general relativity probably induces a dynamical instability when the radius of a WD becomes smaller than \(1.1 \times 10^3\) km. Chandrasekhar & Tooper (1964) independently showed that a WD of mass \(> 1.4176 M_{\odot}\) is dynamically unstable when its radius decreases below \(1.0267 \times 10^3\) km. This means that the instability occurs at radii much larger than the Schwarzschild radius \(R_s = 2GM/c^2\). In our model, the 1.38 \(M_{\odot}\) WD has a radius of \(\sim 2000\) km, much larger than the Schwarzschild radius \(2G (1.38 M_{\odot})/c^2 = 4.1\) km, and the above stability limits of general relativity, \(R_{\text{CR}} \sim \sim 1000\) km.

Assuming the polytropic relation \(P \propto \rho^\gamma\), Shapiro & Teukolsky (1983) derived a different stability criterion (see their Equation (6.10.30)), i.e.,

\[
\Gamma = \frac{4}{3} = 1.125 \left(\frac{2GM}{R_c c^2}\right).
\]

In our 1.38 \(M_{\odot}\) model with \(M_{\text{acc}} = 1.6 \times 10^{-7} M_{\odot}\) yr\(^{-1}\) (\(P_{\text{rec}} = 0.95\) yr), the right-hand side of Equation (6) becomes maximum at point A in Figure 1, that is, \(1.125 \times 0.00215 = 0.00242\). Thus, the stability criterion becomes \(\Gamma > 1.3358\). For the 1.385 \(M_{\odot}\) model with \(1.4 \times 10^{-7} M_{\odot}\) yr\(^{-1}\) (\(P_{\text{rec}} = 0.97\) yr), this criterion is \(\Gamma > 1.3359\), essentially the same as for the 1.38 \(M_{\odot}\) model. We calculated the distribution of \(\Gamma\) in the accreting phase as shown in Figure 9. The black line depicts \(\Gamma = d \log P/d \log \rho\) of the 1.38 \(M_{\odot}\) model, while the red line represents the 1.385 \(M_{\odot}\) model. Both the red and black lines are located above the horizontal dashed line of \(\Gamma = 1.336\). Therefore, both models satisfy the stability condition (\(\Gamma > 1.336\)). Note that the central part hardly changes during the flash. Thus, we conclude that our 1.38 and 1.385 \(M_{\odot}\) WD models are stable against the general relativistic instability.

5.3. The Soft X-ray Transient MAXI J0158-744

MAXI J0158-744 is an X-ray transient, believed to be a Be star plus WD binary that appeared in the Small Magellanic Cloud (Li et al. 2012; Morii et al. 2013). MAXI detected a brief (<90 minutes) X-ray flux (<5 keV) of very high luminosity (several \(\times 10^{39} - 10^{40}\) erg s\(^{-1}\)). Follow-up Swift observations detected soft X-ray emission (~100 eV) that lasted 2 weeks (Li et al. 2012), resembling an SSS phase on a massive WD. Li et al. (2012) attributed the origin of the early brief X-ray flux to the interaction of the ejected nova shell with the Be star wind.
Morii et al. (2013) concluded that the X-ray emission is unlikely to have a shock origin, but they associated it with the fireball stage of a nova outburst on an extremely massive WD.

In this paper, we have considered the very early phase of shell flashes in the extreme limit of massive WDs and high mass-accretion rates. Our calculations have shown that, in this limit, the evolution is very slow (X-ray flash lasts ~1 day) and the X-ray luminosity does not exceed the Eddington luminosity ($\sim 2 \times 10^{38}$ erg s$^{-1}$). The wind mass loss does not occur during the X-ray flash, and the energy range of the X-ray photons is up to 100–120 eV. These properties are incompatible with the bright (super-Eddington), high-energy (<5 keV), very short duration (<90 minutes) X-ray emission seen early on in MAXI J0158-744. Therefore, we conclude that the brief early X-ray flux in MAXI J0158-744 is not associated with that expected in the extreme limit of massive nonrotating WDs with high mass-accretion rates.

6. CONCLUSIONS

Our main results are summarized as follows.

1. In a very early phase of a recurrent nova outburst, the photospheric luminosity rises very close to the Eddington luminosity at the photosphere and the temperature reaches as high as $T_{\text{ph}} \sim 10^6$ K in WDs as massive as $1.38 M_\odot$. We expect bright supersoft X-ray luminosities in this X-ray flash phase, as large as $L_X \sim 10^{38}$ erg s$^{-1}$.

2. We present light curves of X-ray flashes for 1.35, 1.38, and 1.385 $M_\odot$ WDs. The duration of the X-ray flash depends on the WD mass and the recurrence period, shorter for a more massive WD and longer for a shorter recurrence period. The duration of the X-ray flash would be a good indicator of the WD mass and mass-accretion rate because it depends sensitively on these values.

3. The optically thick wind arises at the end of the X-ray flash ($\log T_{\text{ph}} (K) \sim 5.6$) owing to acceleration by the Fe opacity peak. As no strong wind mass loss is expected during the X-ray flash, we could observe a naked photosphere, i.e., the spectrum is close to that of a blackbody with $T_{\text{ph}}$.

4. We observed with a 6 hr cadence the 2015 outburst of M31N 2008-12a with Swift from 8 days before the optical discovery. Although our theoretical prediction of the X-ray flash duration was long enough, as long as 0.5–1.5 days, no X-ray flash was detected.

5. We examined two possible reasons for the nondetection. Absorption by the surrounding matter originating from the companion is unlikely. Instead, we suggest that the X-ray flash could have occurred before our observations started, because short recurrence period novae undergo a very slow evolution.

6. The X-ray flash is one of the last frontiers of nova studies. We encourage further attempts at observational confirmation in the near future. Any detection of X-ray flashes would be essentially important to explore the pre-optical-maximum phase and to ultimately understand the complete picture of nova eruptions.

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