



A Light-curve Analysis of the X-Ray Flash First Observed in Classical Novae

Mariko Kato¹, Hideyuki Saio², and Izumi Hachisu³¹ Department of Astronomy, Keio University, Hiyoshi, Kouhoku-ku, Yokohama 223-8521, Japan; mariko.kato@hc.st.keio.ac.jp² Astronomical Institute, Graduate School of Science, Tohoku University, Sendai 980-8578, Japan³ Department of Earth Science and Astronomy, College of Arts and Sciences, The University of Tokyo, 3-8-1 Komaba, Meguro-ku, Tokyo 153-8902, Japan

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Abstract

An X-ray flash, expected in a very early phase of a nova outburst, was at last detected with the SRG/eROSITA in the classical nova YZ Reticuli 2020. The observed flash timescale, luminosity, and blackbody temperature substantially constrain the nova model. We present light-curve models of the X-ray flash for various white dwarf (WD) masses and mass-accretion rates. We have found the WD mass in YZ Ret to be as massive as $M_{\text{WD}} \sim 1.3 M_{\odot}$ with mass-accretion rates of $\dot{M}_{\text{acc}} \sim 5 \times 10^{-10} - 5 \times 10^{-9} M_{\odot} \text{ yr}^{-1}$, including the case where the mass-accretion rate is changing between them, consistent with the SRG/eROSITA observation. The X-ray observation confirms the luminosity to be close to the Eddington limit at the X-ray flash. The occurrence of optically thick winds, with the photospheric radius exceeding $\sim 0.1 R_{\odot}$, terminated the X-ray flash of YZ Ret by strong absorption. This sets a constrain on the starting time of wind mass loss. A slight contamination of the hydrogen-rich envelope by the core material seems to be preferred to explain the very short duration of the X-ray flash.

Unified Astronomy Thesaurus concepts: Classical novae (251); High energy astrophysics (739); Cataclysmic variable stars (203); X-ray astronomy (1810); White dwarf stars (1799)

1. Introduction

A nova is a thermonuclear runaway event on a mass-accreting white dwarf (WD) (see, e.g., Kato et al. 2022, for a recent self-consistent calculation). A hydrogen-rich envelope on the WD quickly brightens up to $L_{\text{ph}} \sim 10^{38} \text{ erg s}^{-1}$ or several $10^4 L_{\odot}$ just after the start of hydrogen-shell burning runaway. Here, L_{ph} is the photospheric luminosity. In an early phase of expansion of the photosphere, its surface temperature increases up to $T_{\text{ph}} \sim 10^6 \text{ K}$, and the nova emits supersoft X-rays at a rate of $L_{\text{X}} \sim 10^{38} \text{ erg s}^{-1}$. The duration of the bright soft X-ray phase is so short that it is called the “X-ray flash” in the rising phase of a nova. Such X-ray flashes have long been expected to be observed, but none were detected until UT 2020 July 7 when the onboard eROSITA instrument Spectrum–Roentgen–Gamma (SRG) scanned the region of YZ Reticuli (König et al. 2022).

The nova outburst of YZ Ret (Nova Ret 2020) was first reported by McNaught (2020) at a visual magnitude of 5.3 on UT 2020 July 15. This object was known as a cataclysmic variable (MGAB-V207), a novalike VY Scl-type variable with irregular variations in the V magnitude range 15.8–18.0 mag (Kilkenny et al. 2015). The nova was classified as an He/N-type by Carr et al. (2020). The distance to the nova is estimated to be $d = 2.53_{-0.26}^{+0.52} \text{ kpc}$ by Bailer-Jones et al. (2021) based on the Gaia/eDR3 data. The galactic coordinates are $(\ell, b) = (265^{\circ}3975, -46^{\circ}3954)$ (ep = J2000), so the nova is located 1.8 kpc below the galactic disk. The galactic absorption toward YZ Ret is as low as $E(B - V) \sim 0.03$ (Sokolovsky et al. 2022). The orbital period was obtained by Schaefer (2022) to be $P_{\text{orb}} = 0.1324539 \pm 0.0000098 \text{ days}$ (=3.17889 hr). Thanks to the short distance, $d = 2.5 \text{ kpc}$, from Earth and very low galactic absorption $E(B - V) \sim 0.03$, the nova was

observed in multiple wavelengths, including optical, X-rays, and gamma-rays, from a very early phase of the outburst until a very later phase through the supersoft X-ray source (SSS) phase. X-ray and γ -ray observations are reported by Sokolovsky et al. (2022) and König et al. (2022).

The most remarkable characteristic of the YZ Ret observation is the detection of an X-ray flash. This is the first positive detection among any type of nova outbursts. König et al. (2022) reported the X-ray flash on UT 2020 July 7 observed with the SRG/eROSITA. This detection was serendipitous during its all-sky survey. Because the X-ray flash of a nova is a brief phenomenon that occurs before the optical brightening, it is not possible to exactly predict when it occurs.

Historically, there have been few attempts to detect an X-ray flash. Morii et al. (2016) searched MAXI data for X-ray flashes that would have possibly occurred during the MAXI survey at the position and time of known nova outbursts, but were unsuccessful. Kato et al. (2016) attempted to detect an X-ray flash just before the expected nova outbursts of the one-year-period recurrent nova M31N 2008–12a. This was the first planned observation, but no X-ray flash was detected in its 2015 outburst.

Theoretical models predict X-ray flashes detectable only for a very short time ($\lesssim 1 \text{ day}$) depending on the WD mass and mass-accretion rate (Kato et al. 2016). In low-mass WDs, the surface temperature does not rise as high to emit much X-rays, and most of the photon energy is far-UV instead of X-ray (e.g., Kato et al. 2017, 2022). Thus, the X-ray flash should be detectable only in massive WDs. The time interval between the X-ray flash and optical maximum also depends on the WD mass and mass-accretion rate, which is, however, poorly understood. A very early phase, before a nova brightens optically, is one of the frontiers in nova studies. Because no planned observations had been successful, only the serendipitous detection of the X-ray flash with the SRG/eROSITA gives us invaluable information on the very early phase of a nova.



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Table 1
Nova Models

Model	M_{WD} (M_{\odot})	\dot{M}_{acc} ($M_{\odot} \text{ yr}^{-1}$)	C mix	t_{rec} (yr)	t_{ML}^{a} (hr)	$L_{\text{nuc}}^{\text{max}}$ ($10^8 L_{\odot}$)	M_{ig} ($10^{-5} M_{\odot}$)	Comment Pass or Not ^b	
A ^c	...	1.0	5×10^{-9}	no	5400	25	2.3	3.0	Figure 3(a), no
B	...	1.2	5×10^{-9}	no	1500	18	3.6	0.82	Figure 3(b), no
C	...	1.35	5×10^{-9}	no	220	6.1	3.3	0.13	Figure 3(c), no
D	...	1.35	5×10^{-10}	no	2900	4.0	8.6	0.16	Figure 3(d), pass
E	...	1.3	5×10^{-9}	yes ^d	300	3.2	16	0.16	Figure 3(e), pass
F	...	1.3	5×10^{-10}	yes ^d	4600	1.5	74	0.25	Figure 3(f), pass
G	...	1.35	5×10^{-9}	yes ^d	120	1.8	12	0.070	Figure 3(g), pass
H	...	1.35	Decreasing ^e	yes ^d	1700	1.1	63	0.10	Figure 3(h), pass
I	...	1.35	5×10^{-10}	yes ^d	1900	1.5	60	0.10	Figure 3(i), pass
J	...	1.35	5×10^{-10}	yes ^f	1200	2.9	3.6	0.066	... , pass

Notes.^a Starting time of optically thick winds since the L_{nuc} peak ($t = 0$).^b Whether or not the detection requirement of the 22nd (no), 23rd (yes), and 24th (no) scans is passed.^c Model taken from Kato et al. (2022).^d Increased carbon mass fraction by 0.1 at ignition.^e Mass-accretion rate is changing from 5×10^{-9} to $5 \times 10^{-10} M_{\odot} \text{ yr}^{-1}$.^f Mass accretion of carbon-rich matter by 0.1.

In this paper, we present theoretical light-curve models of X-ray flashes, the duration of which is short enough to match the SRG/eROSITA observation. Only massive WDs are responsible for the flash like that in YZ Ret.

This paper is organized as follows. Section 2 presents our numerical method and results for the X-ray flash and compares them with the observational data for YZ Ret. Conclusions follow in Section 3.

2. Model Calculation of the X-Ray Flash

We have calculated models of nova outbursts with a Henyey-type time-dependent code combined with steady-state optically thick wind solutions. The numerical method is the same as that in Kato et al. (2022). We list our model parameters in Table 1. From left to right, they are the model name, WD mass, mass-accretion rate, additional carbon mixture in the hydrogen-rich envelope, recurrence period of nova outbursts, starting time of winds since the onset of thermonuclear runaway, maximum nuclear burning rate that represents the strength of a flash, ignition mass, and whether or not the requirement from the scan detection is passed. The $1.0 M_{\odot}$ WD model (Model A) is taken from Kato et al. (2022). The mass-accretion rate $\dot{M}_{\text{acc}} = 5 \times 10^{-9} M_{\odot} \text{ yr}^{-1}$ is close to the median value in the distribution of mass-accretion rates for classical novae obtained by Selvelli & Gilmozzi (2019) while the mass-accretion rate $\dot{M}_{\text{acc}} = 5 \times 10^{-10} M_{\odot} \text{ yr}^{-1}$ is close to the empirical rate (Knigge et al. 2011) for cataclysmic variable systems with an orbital period of $P_{\text{orb}} = 3.18$ hr. Because many old novae are observed to fade significantly on timescales of ~ 100 yr (e.g., Duerbeck 1992; Johnson et al. 2014), we have taken into account a gradual decrease of the accretion rate in Model H, in which accretion resumes at a rate of $\dot{M}_{\text{acc}} = 5 \times 10^{-9} M_{\odot} \text{ yr}^{-1}$ just after the end of a previous flash, while the accretion rate gradually decreases.

We have assumed a solar composition for accreted matter ($X = 0.7$, $Y = 0.28$, and $Z = 0.02$) for all the models except Model J. In many classical novae, heavy-element enrichment is observed in the ejecta (e.g., Gehrz et al. 1998). To mimic such a heavy-element enrichment, one may replace the envelope composition with that polluted by the WD core composition at

the onset of thermonuclear runaway (e.g., Starrfield et al. 2020), or assume a CO enhancement in the accreting matter (e.g., Chen et al. 2019). In Models E, F, G, H, and I, we have increased the carbon mass fraction by 0.1 and decreased the helium mass fraction by the same amount at the onset of thermonuclear runaway. In Model J, we have assumed a carbon-rich mixture ($X = 0.6$, $Y = 0.28$, $X_{\text{C}} = 0.1$, and $Z = 0.02$) for accreting matter.

2.1. Cycle of Nova Evolution in the HR Diagram

Figure 1 shows one cycle of nova outbursts for a $1.0 M_{\odot}$ WD (Model A) and $1.35 M_{\odot}$ WD (Model I) in the Hertzsprung-Russell (HR) diagram. In the quiescent phase (inter-outburst period), the accreting WD stays around the bottom of each loop. After thermonuclear runaway sets in, the WD goes upward, keeping the photospheric radius almost constant. The photospheric temperature increases to maximum, $\log T_{\text{ph}}^{\text{max}}$ (K) = 5.58 in the $1.0 M_{\odot}$ model (Model A) and 6.02 in the $1.35 M_{\odot}$ model (Model I). In these high-temperature phases, the WD photosphere emits X-ray/UV photons, corresponding to an X-ray/UV flash. After that, the envelope expands and the photospheric temperature begins to decrease. Optically thick winds start when the envelope expands and the surface temperature decreases to $\log T_{\text{ph}}$ (K) = 5.32 in the $1.0 M_{\odot}$ model and 5.46 in the $1.35 M_{\odot}$ model (at each open circle).

The filled red circle with error bars indicates the position of the X-ray flash of YZ Ret observed by SRG/eROSITA. The point lies on the evolution track of Model I ($1.35 M_{\odot}$) just before optically thick winds start, which is important because the winds possibly self-absorb soft X-rays as discussed in the next subsection.

When the photospheric radius attains its maximum expansion, the wind mass-loss rate also reaches maximum. The hydrogen-rich envelope mass quickly decreases, mainly due to wind mass loss. The photospheric radius begins to shrink while the photospheric temperature starts to increase. In a later phase, optically thick winds stop (at each open square) and the photospheric temperature becomes as high as $\log T_{\text{ph}}$ (K) = 5.5–6.1 and the WD again emits X-ray/UV photons.

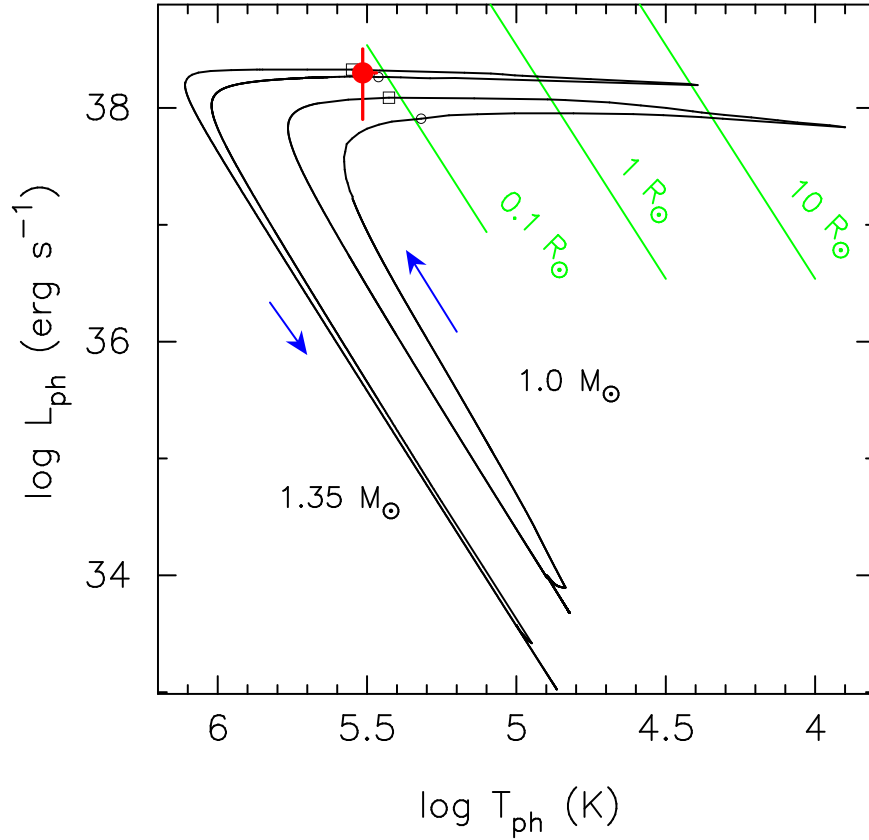


Figure 1. Comparison of nova outbursts in the HR diagram between a $1.0 M_{\odot}$ white dwarf (WD) (Model A) and $1.35 M_{\odot}$ WD (Model I), where L_{ph} and T_{ph} are the photospheric luminosity and temperature, respectively. The green lines show equiradius lines, the value of which is labeled beside each line, based on the relation of $L_{\text{ph}} = 4\pi R_{\text{ph}}^2 \sigma T_{\text{ph}}^4$, where R_{ph} and σ are the photospheric radius and Stefan-Boltzmann constant, respectively. Each arrow indicates the direction of evolution. The filled red circle with error bars corresponds to the X-ray flash in YZ Ret (König et al. 2022). The open squares represent the end of winds.

This phase is called the supersoft X-ray source (SSS) phase in the decay phase of a nova outburst.

The wind phase after the optical maximum and the following SSS phase have been observed well in a number of nova outbursts. However, an early phase before the optical maximum has rarely been studied.

2.2. Optically Thick Winds Absorb X-Rays

Figure 2 shows a close up view of the rising phase on the HR diagram. The optically thick winds starts at the open circles on each line. The wind phase is denoted by the dotted line. The optically thick winds would absorb and strongly weaken the X-ray flux. The optical depth for X-rays is estimated from Equation (9) of Li et al. (2017) as

$$\tau_X \approx 8 \times 10^3 \left(\frac{\dot{M}_{\text{wind}}}{10^{-7} M_{\odot} \text{ yr}^{-1}} \right) \left(\frac{r}{10^{10} \text{ cm}} \right)^{-1} \times \left(\frac{v_{\text{wind}}}{400 \text{ km s}^{-1}} \right)^{-1} \left(\frac{E_X}{\text{keV}} \right)^{-2}. \quad (1)$$

The parameters of our models soon after the start of winds are $R_{\text{ph}} \sim 10^{10} \text{ cm}$ and $\dot{M}_{\text{wind}} \sim 10^{-7} M_{\odot} \text{ yr}^{-1}$. Using these values in Equation (1), we find the optical depth of X-ray in the winds to be as high as $\tau_X \sim 10^6$ for $E_X \sim 0.1 \text{ keV}$. Thus, soft X-ray emission would be absorbed in the wind phase. In other words, the X-ray flash could be terminated by the start of the winds.

König et al. (2022) fitted the X-ray spectrum of YZ Ret with a blackbody spectrum and obtained $T_{\text{BB}} = 3.27_{-0.33}^{+0.11} \times 10^5 \text{ K}$ ($kT_{\text{BB}} = 28.2_{-2.8}^{+0.9} \text{ eV}$). They also derived absolute luminosity to be $L_{\text{ph}} = (2.0 \pm 1.2) \times 10^{38} \text{ erg s}^{-1}$. These estimates are plotted in Figure 2 by an open red circle with error bars. The estimated blackbody flux has a large error bar, but it is consistent only with relatively massive WDs ($M_{\text{WD}} \gtrsim 1.2 M_{\odot}$).

The estimated blackbody temperature is located on the left side of the open circles, that is, before optically thick winds start. Thus, theoretically, no strong emission lines are expected. This is consistent with no prominent emission lines in the observed X-ray spectrum (König et al. 2022).

Sokolovsky et al. (2022) estimated the galactic hydrogen column density to be $1 \times 10^{19} \text{ cm}^{-2} \lesssim N_{\text{H}} \lesssim 1.86 \times 10^{20} \text{ cm}^{-2}$. König et al. (2022) obtained $N_{\text{H}} < 1.4 \times 10^{20} \text{ cm}^{-2}$ toward the nova based on their X-ray spectrum analysis and concluded that there is no major intrinsic absorption during the X-ray flash. Such a small hydrogen column density is consistent with our models in which optically thick winds are absent at the stage of $kT_{\text{ph}} = 28.2 \text{ eV}$.

2.3. Very Short Duration of the X-Ray Flash

König et al. (2022) reported that the SRG/eROSITA scanned the region of YZ Ret 28 times (every 4 hr) and detected YZ Ret at the 23rd scan for about 36 s but did not detect 4 hr before and after this scan. This means that the duration of X-ray flash is shorter than 8 hr.

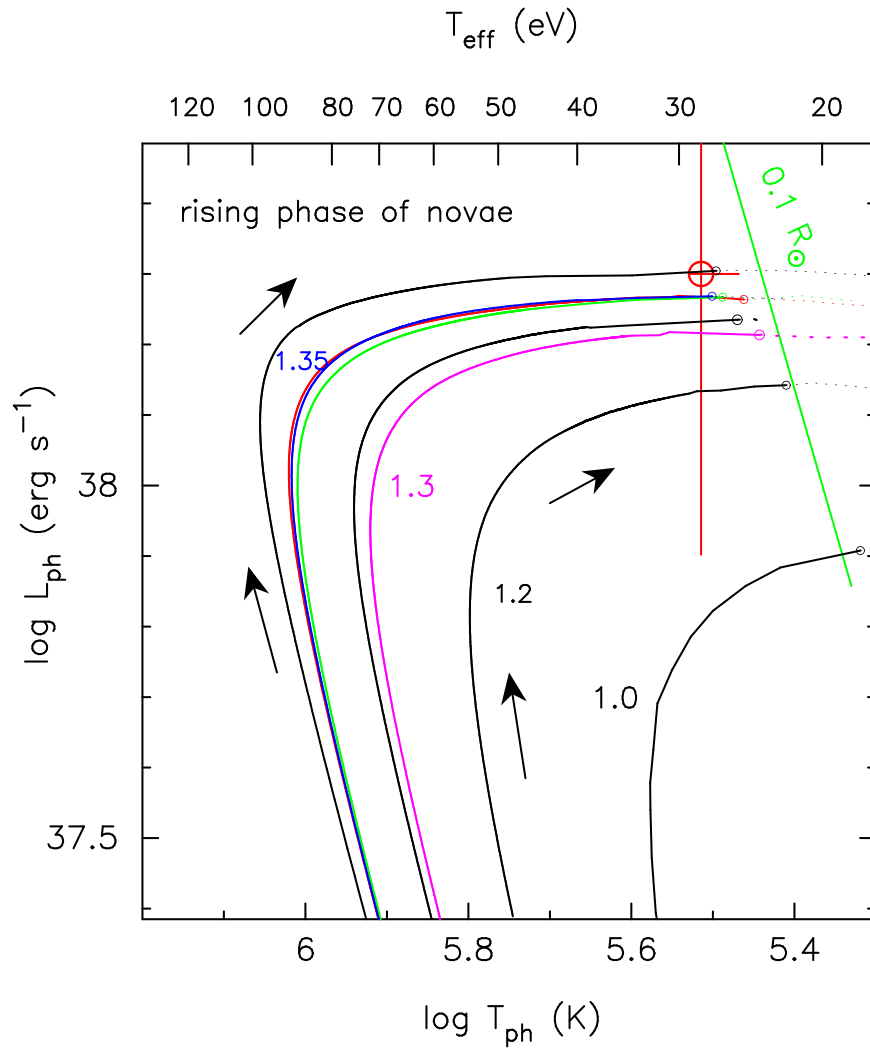


Figure 2. Close-up view only of the rising phases of novae in the HR diagram. Optically thick winds start at the open circles on each track. The track to the right of the open circle (low-temperature side) corresponds to the wind phase, denoted by a dotted line. Each model corresponds to those in Table 1, from upper to lower, black (Model J), red (I), blue (C), and green (D) lines, all for $1.35 M_{\odot}$ WDs, Model E (black) and F (magenta) for $1.3 M_{\odot}$, B ($1.2 M_{\odot}$; black), and A ($1.0 M_{\odot}$; black). The red dot with the error bars denotes $kT_{\text{ph}} = 28.2^{+0.9}_{-2.8}$ eV, $L_{\text{ph}} = (2.0 \pm 1.2) \times 10^{38}$ erg s $^{-1}$, and radius $R_{\text{ph}} = 50,000 \pm 18,000$ km ($= 0.07 \pm 0.026 R_{\odot}$) estimated for YZ Ret (König et al. 2022).

Figure 3 shows the X-ray light curves during the flash for our models in Table 1 except model J. The black lines correspond to the 0.2–10 keV band of the SRG/eROSITA instrument while the red lines indicate the temporal variations of the photospheric temperature. The open circle on each black line indicates the start of optically thick winds. The dotted line extending from the open circle indicates the evolution path with the winds, during which no significant X-ray flux is expected. The large black dot with error bars on each red line shows the epoch when the photospheric temperature decreases to $kT_{\text{ph}} = 28.2^{+0.9}_{-2.8}$ eV. The large red dot on each black line corresponds to the X-ray luminosity at this epoch. Two vertical green arrows indicate 4 hr before/after this epoch. The X-ray luminosity at the epochs of arrows should be smaller than that at the red dot by four orders of magnitude because SRG/eROSITA did not detect X-rays.

Models A, B, and C evolve slowly and should have detectable X-ray fluxes even before and/or after 4 hr of the detection epoch by SRG/eROSITA, contradicting the non-detection. The upward (downward) arrow indicates the

theoretical prediction of detectable (nondetectable) X-ray flux. Model D is marginally consistent with the requirement.

The carbon mixture models evolve much faster and easily fulfill the requirements. The CNO enrichment in the hydrogen-rich envelope makes flash evolution faster because the CNO reaction rates increase. A faster evolution is favorable to be consistent with the constraints from the observation of SRG/eROSITA. Furthermore, the appearance of the optically thick winds would contribute to shorten the duration of the X-ray flash of YZ Ret.

In Model H the mass accretion restarts after a shell flash ends with a rate of $\dot{M}_{\text{acc}} = 5 \times 10^{-9} M_{\odot} \text{ yr}^{-1}$, which gradually decreases to $5 \times 10^{-10} M_{\odot} \text{ yr}^{-1}$ in the first 100 yr of the quiescent phase and keep constant after that. Until the next outburst, long after 1600 yr, the WD thermal structure is adjusted to the lower accretion rate. As a result, the outburst properties should be similar to a model of mass-accretion rate of $5 \times 10^{-10} M_{\odot} \text{ yr}^{-1}$. Model H shows in fact similar properties to Model I, but slightly stronger flash properties, i.e., shorter flash duration and larger $L_{\text{nuc}}^{\text{max}}$ than in Model I.

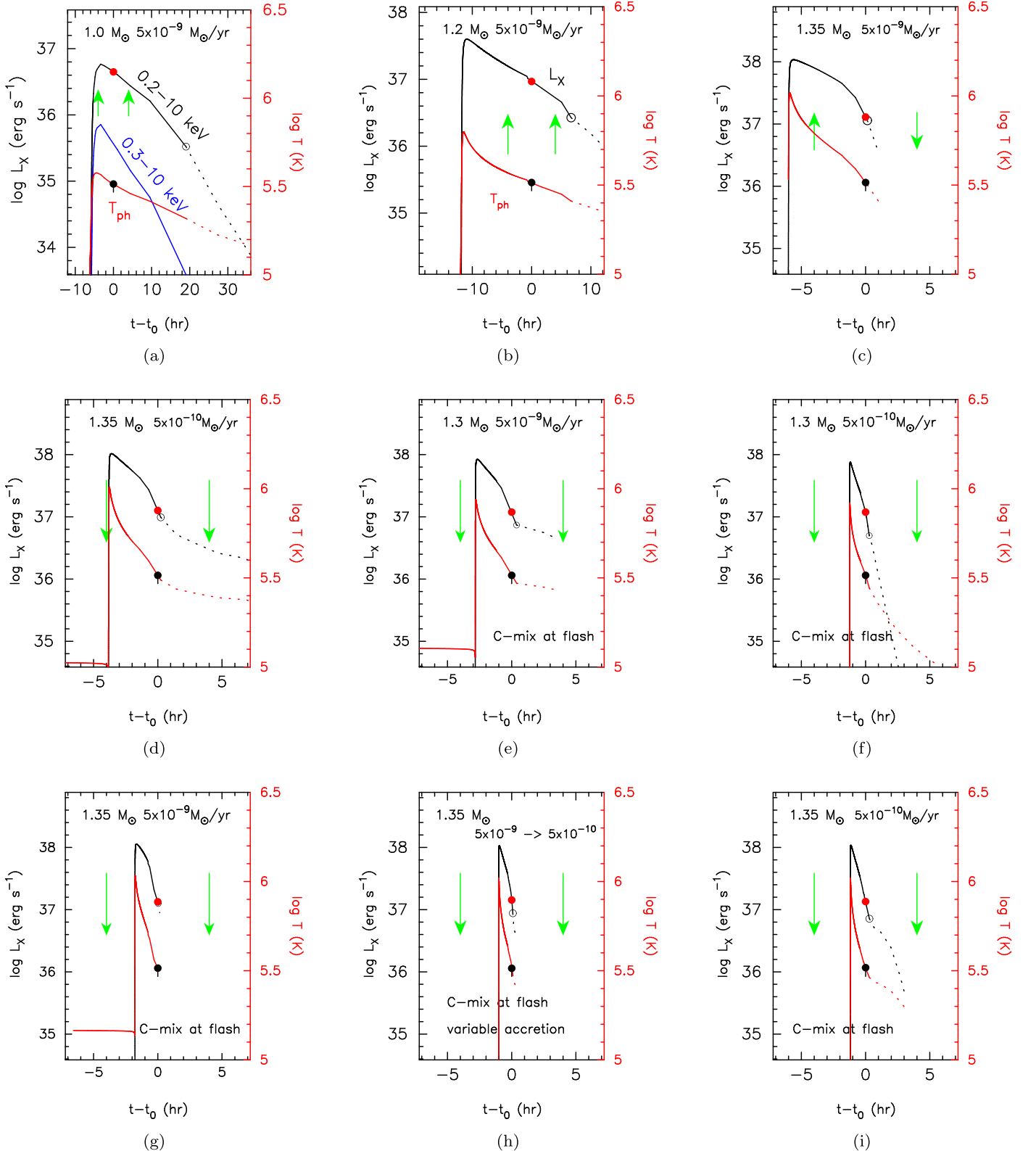


Figure 3. X-ray light curves for the X-ray flash models. Each panel corresponds to each model in Table 1. The red lines are the temporal variations of the photospheric temperature, T_{ph} , which are scaled on the right-side vertical axis in red. The black lines show the estimated 0.2–10 keV (SRG/eROSITA) band flux while the blue line in panel (a) indicates the (0.3–10) keV (Swift/XRT) band flux. They are scaled on the left vertical axis. Each open circle on the black lines corresponds to the epoch when winds start. The dotted part means a wind phase. The large red dots on each black line show the X-ray luminosity at the epoch of $kT_{\text{ph}} = 28.2$ eV ($\log T_{\text{ph}}(\text{K}) = 5.515$), corresponding to the observed blackbody temperature of the YZ Ret flash. The origin of time denoted by t_0 is the observed time with SRG/eROSITA at the 23rd scan. The two green arrows indicate 4 hr before (22nd scan) and after (24th scan) the observation (23rd scan).

König et al. (2022) also reported that the X-ray flux of YZ Ret decreased by about a few to 10% even during the very short 36 s observation period. We estimate the X-ray decay rates of our models to find a few % in Models F, G, H, and I during a 30 s period near the point denoted by the large red dot, being broadly consistent with the observation.

YZ Ret is a novalike VY Scl-type star, in which dwarf nova outbursts are suppressed. To suppress thermal disk instability of a dwarf nova, the mass-transfer rate should be higher than \dot{M}_{crit} . This critical rate is estimated to be $\dot{M}_{\text{crit}} \sim 2 \times 10^{-9} M_{\odot} \text{ yr}^{-1}$ for $P_{\text{orb}} = 3.18 \text{ hr}$ and an assumed total binary mass of $M_1 + M_2 \sim 1.3 + 0.3 = 1.6 M_{\odot}$ (see, e.g., Equations (3) and (4) of Osaki 1996). Our Models E and G (1.3 and 1.35 M_{\odot} WD models with a relatively high mass-accretion rate of $\dot{M}_{\text{acc}} = 5 \times 10^{-9} M_{\odot} \text{ yr}^{-1}$) satisfy this requirement of novalike stars, i.e., $\dot{M}_{\text{acc}} > \dot{M}_{\text{crit}}$.

We should emphasize the importance of the low-energy sensitivity of detector. The blue line in Figure 3(a) shows an X-ray light curve of the 0.3–10 keV band corresponding to the Swift/XRT. The flux is about 10 times smaller than the SRG/eROSITA flux (0.2–10 keV band), clearly showing that, for an efficient detection of X-ray flashes, the low-energy sensitivity (down to 0.2 keV or lower) is important.

2.4. Clue to the Origin of the Super-Eddington Luminosity

We should remark on the importance of the X-ray flash on the super-Eddington problem in novae. The bolometric luminosity of a star in hydrostatic balance cannot exceed the Eddington limit as long as spherical symmetry is assumed. The Eddington limit is defined by

$$L_{\text{Edd}} \equiv \frac{4\pi c G M_{\text{WD}}}{\kappa} = 2 \times 10^{38} \text{ erg s}^{-1} \left(\frac{1.7}{1+X} \right) \left(\frac{M_{\text{WD}}}{1.4 M_{\odot}} \right) \quad (2)$$

for massive WDs with the mass of M_{WD} , where $\kappa = 0.2(1+X) \text{ cm}^2 \text{ g}^{-1}$ is the electron scattering opacity.

YZ Ret reached its optical peak $V = 3.7$ four days after the X-ray flash (McNaught & Phillips 2020). This brightness corresponds to an absolute V magnitude of $M_V = 3.7 - (m - M)_V = -8.4$, which is several times larger than the Eddington limit.⁴ Here, the distance modulus in the V band is estimated to be $(m - M)_V = 5 \log(d/10 \text{ pc}) + A_V = 12.0 + 0.1 = 12.1$.

At the X-ray flash of YZ Ret, however, the total photospheric luminosity was estimated to be $L_{\text{ph}} = (2.0 \pm 1.2) \times 10^{38} \text{ erg s}^{-1}$ (König et al. 2022). Thus, the photospheric luminosity did not largely exceed the Eddington limit (see Figures 1 and 2). This clearly confirms that the nova envelope is in hydrostatic balance at the X-ray flash, when the optically thick winds had not yet started. Thus, we may conclude that the origin of super-Eddington luminosity is closely related to the occurrence of optically thick winds.

3. Conclusions

An X-ray flash in the rising phase of a nova was first detected in the classical nova YZ Ret, which provides us with invaluable information for the nova physics. We may conclude our theoretical analysis as follows.

1. König et al. (2022) found the X-ray spectrum at the flash to be consistent with a blackbody of $3 \times 10^5 \text{ K}$. This is consistent with our hydrostatic evolution models just before optically thick winds start.
2. The blackbody temperature $T_{\text{BB}} \approx 3 \times 10^5 \text{ K}$ and luminosity of $L_{\text{ph}} \approx 2 \times 10^{38} \text{ erg s}^{-1}$ are consistent with our models of very massive WDs ($M_{\text{WD}} \gtrsim 1.2 M_{\odot}$).
3. The very short duration of the X-ray flash ($\lesssim 8 \text{ hr}$) further constrains the mass of the WD ($M_{\text{WD}} \gtrsim 1.3 M_{\odot}$), depending on the degree of WD core material mixing into the hydrogen-rich envelope. The generation of optically thick winds when the photospheric radius exceeds $\sim 0.1 R_{\odot}$ might terminate the X-ray flash of YZ Ret.
4. YZ Ret is a novalike VY Scl-type star, which requires a relatively high mass-accretion rate ($\gtrsim \dot{M}_{\text{crit}} \sim (2-3) \times 10^{-9} M_{\odot} \text{ yr}^{-1}$) to suppress dwarf nova outbursts. If it is the case, our 1.3 and 1.35 M_{\odot} WD models with a relatively high mass-accretion rate of $\dot{M}_{\text{acc}} = 5 \times 10^{-9} M_{\odot} \text{ yr}^{-1}$ (Models E and G) satisfy the requirement of $\dot{M}_{\text{acc}} > \dot{M}_{\text{crit}}$.
5. The nova envelope is in hydrostatic balance at the X-ray flash, just before optically thick winds start. A few days later, the optical luminosity highly exceeds the Eddington limit. This suggests that the origin of super-Eddington luminosity is closely related to the occurrence of optically thick winds.

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ORCID iDs

Mariko Kato  <https://orcid.org/0000-0002-8522-8033>

Izumi Hachisu  <https://orcid.org/0000-0002-0884-7404>

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⁴ The bolometric magnitude is $M_{\text{bol}} = -7.07$ for $L_{\text{ph}} = 2 \times 10^{38} \text{ erg s}^{-1}$. This corresponds to $M_V \approx -7.0$ or -6.0 for the bolometric correction B.C. = -0.07 (8700 K) or B.C. = -1.07 (14,000 K), for example. Then the flux ratio is $10^{(8.4-7.0)/2.5} \approx 4$ or $10^{(8.4-6.0)/2.5} \approx 9$ (times the Eddington limit).