SUPERSOFT X-RAY LIGHT CURVE OF RS OPHIUCHI (2006)

IZUMI HACHISU
Department of Earth Science and Astronomy, College of Arts and Sciences, University of Tokyo, Komaba 3-8-1, Meguro-ku, Tokyo 153-8902, Japan

MARIKO KATO
Department of Astronomy, Keio University, Hiyoshi 4-1-1, Kouhoku-ku, Yokohama 223-8521, Japan

AND

GERARDO JUAN MANUEL LUNA
Instituto de Astronomía, Geofísica e Ciências Atmosféricas, Universidade de São Paulo, Rua do Matão 1226, Cid. Universitaria, 05508-900, São Paulo, Brasil


ABSTRACT

One of the candidates for Type Ia supernova progenitors, the recurrent nova RS Ophiuchi underwent the sixth recorded outburst in February 2006, and for the first time a complete light curve of supersoft X-ray has been obtained. It shows the much earlier emergence and longer duration of a supersoft X-ray phase than expected before. These characteristics can be naturally understood when a significant amount of helium layer piles up beneath the hydrogen burning zone during the outburst, suggesting that the white dwarf (WD) is effectively growing up in mass. We have estimated the WD mass in RS Oph to be $1.35 \pm 0.01 M_\odot$ and the growth rate of the WD mass to be at an average rate of about $1 \times 10^{-4} M_\odot$ yr$^{-1}$. The white dwarf will probably reach the critical mass for Type Ia explosion if the present accretion continues further for a few to several times $10^5$ years.

Subject headings: binaries: close — binaries: symbiotic — novae, cataclysmic variables — stars: individual (RS Ophiuchi) — supernovae: general — white dwarfs

1. INTRODUCTION

Recurrent novae are binary star systems in which mass is transferred onto a white dwarf (WD) primary from a main-sequence or a red giant secondary. The eruption is well-modeled as a thermonuclear runaway (hydrogen shell flash), which occurs when a certain amount of mass ($\Delta M_{\text{ig}}$) is accumulated on the surface of the white dwarf (e.g., Prialnik & Kovetz [1995]). From their short recurrence periods (from a ten to several tens of years) and very rapid optical declines, it is believed that their white dwarfs are very massive and close to the Chandrasekhar mass (e.g., Hachisu & Kato [2001]). If the WD mass increases after every outburst, it will soon explode as a Type Ia supernova (e.g., Nomoto [1982], Hachisu et al. [1994]). It is, therefore, crucially important to know how close the WD mass is to the Chandrasekhar mass and how much mass is left on the white dwarf after one cycle of nova outburst.

The WD envelope rapidly expands and blows winds (e.g., Kato & Hachisu [1994]) as a result of hydrogen-flash, and its photospheric radius reaches a maximum and then gradually shrinks. Since the total luminosity is almost constant during the outburst, the photospheric temperature increases in time. We easily understand this from Stefan-Boltzmann’s equation,

$$ L_{\text{ph}} = 4\pi R_{\text{ph}}^4 \sigma T_{\text{ph}}^4, $$

where $L_{\text{ph}}$, $R_{\text{ph}}$, and $T_{\text{ph}}$ are the photospheric luminosity, radius, and temperature, respectively. The main emitting region moves from optical to ultraviolet, and then finally to supersoft X-ray, corresponding to from $T_{\text{ph}} \sim 10^6 K$ through $T_{\text{ph}} \sim 10^5 K$. The photosphere drastically shrinks at the end of the wind phase and a supersoft X-ray phase starts (e.g., Kato [1999]).

We are able to constrain the WD mass and its growth rate if turn-on/turnoff of a supersoft X-ray phase are detected, because they indicate the durations of wind mass loss (how much mass is ejected) and hydrogen shell burning without wind mass loss (how much mass is left).

The sixth recorded outburst of RS Oph was discovered on 2006 February 12 by a Japanese amateur astronomer H. Narumi (Narumi et al. [2006]) when it was shining at 4th magnitude. Figure 1 shows the optical development of the outburst (taken from Hachisu et al. [2006]). The visual light decayed rapidly during the first week and then the decay gradually slowed down (“early decline phase”). It remained at about 10th magnitude from 40 to 80 days after the optical maximum, i.e., for about 40 days (“mid-plateau phase”). The final decline started about 80 days after the optical maximum (“final decline phase”). It eventually decayed to 12th magnitude (“post-outburst minimum”), which is a magnitude darker than that in usual quiescent phase.

A very bright supersoft X-ray phase of RS Oph was extensively observed by the Swift XRT (e.g., Bode et al. [2006a], Osborne et al. [2006a]) and reported the emergence of highly variable soft X-ray flux between 30 and 40 days after the optical maximum. Then the supersoft X-ray flux was stabilized at about 40 days and reached a maximum at about 50 days, followed by a linear decline between 60 and 80 days from ~200 to ~100 counts s$^{-1}$ for 0.2–10 keV (Osborne et al. [2006b]).

It rapidly declined at about 90 days. Thus the duration of supersoft X-ray phase is about 60 days (Osborne et al. [2006b]).

In this Letter, we calculate theoretical light curve models based on the optically thick wind theory and reproduce both the supersoft X-ray and optical light curves. The main difference from our previous models (Hachisu & Kato [2006a]) is to include the effect of heat exchange between the hydrogen burning layer and the helium layer built up beneath the hydrogen burning zone.
In §2, we present a complete light curve of supersoft X-ray for the RS Oph 2006 outburst. The numerical model of our theoretical light curves and their fittings with the observation are presented in §3. Discussion and conclusions follow in §4.

2. X-RAY DATA

We analyze Swift XRT observations available in the HEASARC\(^1\) database following the standard procedures. Observations were taken in PC (photonic counting) and WT (windowed Timing) modes depending on the arrival count rate. Source photons were extracted from a circular region of 40\(\times\)40 pixels in PC mode and 40\(\times\)15 pixels in WT mode. No background subtraction was performed as it represented less than 1% of the emission during the analyzed phases of the outburst and therefore its effect was negligible. In Figure 1 we summarize an average value of the supersoft X-ray count rates in every 2000s bin. A narrow energy band of 0.3–0.55 keV was adopted in order to avoid possible contamination by a tail of hard X-ray photons coming from high temperature plasma at the shock (e.g., Bode et al. 2006a).

Osborne et al. (2006a) reported an oscillatory behavior in the Swift XRT count rate during 30 and 31 days after the optical maximum, corresponding to the period in which the supersoft X-ray count rate first quickly rose (Fig. 1). The count rate began to rapidly decline at about 80 days, which is coincident with the final decline of the optical light curve as pointed out by Hachisu et al. (2006).

The optical mid-plateau phase of RS Oph is first clearly identified by the \(V\) light curve in the 2006 outburst (Hachisu et al. 2006). Such mid-plateau phases are also observed in the other recurrent novae, U Sco and CI Aql, which is interpreted as a disk irradiated by the central hot white dwarf (e.g., Hachisu et al. 2000; Hachisu & Kato 2003). The irradiated disk is bright when the central white dwarf is as luminous as that for hydrogen shell-burning phase, and it becomes dark when the shell-burning ends. Therefore the fact that the end of a supersoft X-ray phase is coincident with the end of a mid-plateau phase clearly indicates that this corresponds to the termination of hydrogen shell-burning on the white dwarf at about 80 days after the optical maximum.

3. MODEL OF SUPERSOFT X-RAY PHASE

We calculate nova light curves based on the optically thick wind theory (Kato & Hachisu 1994). Our theoretical model is consisting of a white dwarf, a disk around the white dwarf, and a red giant companion. Irradiation effects of each component are included (Hachisu & Kato 2001).

In the previous paper (Hachisu & Kato 2006a), we predicted the duration of a supersoft X-ray phase of the RS Oph 2006 outburst. Figure 1 shows our calculated supersoft X-ray fluxes by using the same method as in the previous paper, i.e., we assumed an adiabatic condition at the bottom of the hydrogen burning layer (Kato & Hachisu 1994), so heat did not flow inward but only outward. We cannot reproduce the early emergence (day 30–40) and long duration (60 days) of the supersoft X-ray phase at the same time.

Here we introduce a new treatment by which we include the effect of heat exchange between the hydrogen burning zone and helium layer. After the optical maximum, convection descends in time. So no more processed helium is carried upwards but it accumulates underneath the burning zone. The accumulated helium layer keeps a large amount of thermal energy because the temperature of burning zone is as high as \(\sim 10^8\) K. The temperature of burning zone gradually decreases in the later phase of the outburst. Then heat flux from the hot helium layer becomes important in the luminosity. This heat flux from the thermal reservoir makes the lifetime of a supersoft X-ray phase much longer. Figure 2 represents such new light curves for \(X = 0.08, 0.20,\) and 0.35. It is very clear that both the earlier emergence and longer duration of a supersoft X-ray phase are realized at the same time.

Our numerical model should reproduce not only the supersoft X-ray light curve but also the visual light curve. Figure 3 compares the observational visual light curve with our

---

\(^1\) http://heasarc.nasa.gov/
Numerical ones. In the early decline phase, free-free emission from the optically thin ejecta dominates the visual light (Hachisu et al. 2006; Hachisu & Kato 2006b). The irradiation effects of the disk and the companion red giant dominate the optical light in the mid-plateau phase, whereas the WD photosphere does not contribute because it shrinks to 0.005–0.01 $R_{\odot}$, much smaller than the disk. The final decline started at about 80 days, corresponding to the decay of hydrogen-burning.

In the model with $M_{\text{WD}} = 1.35 \, M_{\odot}$ and $X = 0.17$, optically thick winds stopped at $t_{\text{w}} = 40$ days after the optical peak. At this epoch, hydrogen of $10^{-5} M_{\odot}$ still exists and can supply more 14 days luminosity by nuclear burning. The heat stored in the helium layer, $\sim 10^{34}$ ergs, can also supply a total luminosity of $2.8 \times 10^{38}$ ergs s$^{-1}$ for another 20 days to the supersoft X-ray phase. Therefore these energies can maintain the supersoft X-ray phase for a total of 34 days. As a result, steady hydrogen shell-burning on the white dwarf ends roughly at $t_{\text{steady}} = 75$ days.

Another critically important value is the mass accretion rate, which can be estimated as follows: In our model with $M_{\text{WD}} = 1.35 \, M_{\odot}$ and $X = 0.17$ ($X = 0.12$), the envelope mass at the optical peak is $\Delta M_{\text{en}} \sim 4 \times 10^{-4} M_{\odot}$, This implies that the average mass accretion rate onto the white dwarf is $\dot{M}_{\text{acc}} \sim 2 \times 10^{-7} M_{\odot} \, \text{yr}^{-1}$ during the quiescent phase between 1985 and 2006. Here we neglect a dredge-up of core materials mainly because carbon and oxygen was not enriched in the ejecta. Among the accreted matter, the wind carries away about 70%–75% (50%), i.e., $\Delta M_{\text{wind}} \sim 2.8 \times 10^{-7} M_{\odot}$ ($\Delta M_{\text{wind}} \sim 2 \times 10^{-6} M_{\odot}$); this is much larger than the X-ray observational indication of $\sim 1 \times 10^{-7} M_{\odot}$ by Sokoloski et al. (2006), but roughly consistent with the infrared observational indication of $\sim 3 \times 10^{-6} M_{\odot}$ (Das et al. 2006; Lane et al. 2007). Note that the wind duration is $t_{\text{wind}} = 40$ days (32 days). The residual, $\sim 1.2 \times 10^{-7} M_{\odot}$ ($\sim 2 \times 10^{-6} M_{\odot}$), accumulates on the white dwarf. So the white dwarf is growing at an average rate of $\dot{M}_{\text{He}} \sim 0.6 \times 10^{-7} M_{\odot} \, \text{yr}^{-1}$ ($\dot{M}_{\text{He}} \sim 1 \times 10^{-6} M_{\odot} \, \text{yr}^{-1}$) during 1985–2006.

4. DISCUSSION AND CONCLUSIONS

In the present work, we reproduce the duration of a supersoft X-ray phase by introducing heat flux from the helium layer underneath the hydrogen burning zone. In our previous works (Kato & Hachisu 1994; Kato 1999; Hachisu & Kato 2001, 2006a,b, Hachisu et al. 2006), we had included heat flux from the helium layer only during the cooling phase, for simplicity. When the WD mass is not so massive ($M_{\text{WD}} \lesssim 1.0 \, M_{\odot}$) and the hydrogen content is not so small ($X \gtrsim 0.3$), this effect can be neglected because only a small part of nuclear energy is absorbed into the helium layer. However, we found that this effect cannot be neglected when the WD mass is so massive as the Chandrasekhar mass ($\sim 1.3 \, M_{\odot}$) and the hydrogen content is very small ($X \lesssim 0.3$), as seen in Figures 1 and 2.

We have assumed that the chemical composition is uniform throughout the envelope for simplicity. As mentioned earlier, a gradient of the hydrogen content is reasonable if convection descended in time during the rising phase of the nova outburst. Although the hydrogen content of RS Oph ejecta has not been estimated in detail, a very low hydrogen content $X \sim 0.1$ was reported in the late phase of the U Sco 1979 outburst (Barlow et al. 1981). An interesting trend was also found in the latest 1999 outburst of U Sco: Iijima (2002) reported a rather high value of $X \sim 0.6$ at 16 hours after the optical maximum and Anupama & Dewangan (2000) obtained a value of $X \sim 0.4$ at 11–12 days after the optical maximum. The hydrogen content, $X$, may not be uniform but gradually increase outward.

We assume $X = 0.20$ but, in the plateau phase, we increase the hydrogen content from $X_{\text{nuc}} = 0.20$ to $X_{\text{nuc}} = 0.40$ at the hydrogen burning zone, where $X_{\text{nuc}}$ is the hydrogen content at the nuclear burning zone. As shown in Figure 4, the more hydrogen content extends the supersoft X-ray phase.

In the previous work (Hachisu et al. 2006), we have estimated the WD mass to be 1.35 $\pm 0.01 \, M_{\odot}$ from the optical light curve fitting. Here we have estimated the WD mass and obtained the same results, that is, 1.35 $\pm 0.01 \, M_{\odot}$. A more massive white dwarf (1.37 $M_{\odot}$) can be rejected because the
optical light curve decays too fast in the early decline phase and the duration of the supersoft X-ray phase is too short (see Fig. 4). A less massive one (1.33 \(M_\odot\)) can also be excluded because we must assume a very low hydrogen content to reproduce the early emergence of supersoft X-ray but its supersoft X-ray phase lasts too long and the visual decline is too slow as can be easily seen from Figure 4.

The supersoft X-ray flux from our model has been calculated from a blackbody photosphere. Although the supersoft X-ray flux may not be a simple blackbody, our flux is a reasonable indication of the supersoft X-ray phase, because we intend to approximately explain the duration of the supersoft X-ray peak (not the detailed behavior).

A few groups resolved a size of near infrared emission for the RS Oph 2006 outburst (Monnier et al. 2006; Lane et al. 2007; Chesneau et al. 2007). Monnier et al. (2006) reported that a size of \(\sim 3\) mas is consistent with the binary size if the distance is as short as 0.6 kpc (Hachisu & Kato 2001) but it is much larger than the binary size when the distance is as long as 1.6 kpc (Hjellming & Kato 1986). Recently, Hachisu et al. (2006) revised their value and proposed a range of \(d = 1.3 - 1.7\) kpc. Lane et al. (2007) obtained that the angular diameter of infrared emission increased once to \(\sim 4\) mas at about day 20 and then decreased to \(\sim 2\) mas at about day 100. Our optically thick wind model suggests that the radius of near infrared (2\(\mu\)) photosphere is about 1 AU, estimated from equation (11) of Wright & Barlow (1975), near the optical maximum when free-free emission dominates infrared continuum. The radius quickly decreases because the wind mass-loss rate soon decreases and free-free emission becomes optically thin. This maximum radius of infrared free-free photosphere is smaller than the binary orbit (\(a \sim 1.5\) AU at the distance of 1.6 kpc), so that a size of \(\sim 2 - 4\) mas infrared emission may originate from circumbinary matter as discussed by Monnier et al. (2006) and Lane et al. (2007).

Thus the supersoft X-ray light curve has led us to know various physical parameters of the white dwarf. In this work, the optically thick wind is essentially important to understand the nova optical light curve and its supersoft X-ray duration because, without winds, the nova duration is too long to be compatible with the observation (Kato & Hachisu 1999). Moreover, the wind duration (together with \(X\)) determines the amount of ejected mass and processed helium mass eventually left on the white dwarf. Now we can conclude that the WD mass, \(1.35 \pm 0.01 M_\odot\), is now increasing. In fact the WD mass is currently increasing at \(M_{\text{He}} \sim (0.5 - 1) \times 10^{-7} M_\odot\) yr\(^{-1}\).

We may predict the future of the white dwarf. After it has come through many recurrent nova outbursts, the mass of the helium layer reaches a critical mass and a helium shell flash occurs. Its strength is weak (Kato & Hachisu 1999). Therefore, only a small part of the helium layer will be blown off in the wind, and virtually all of the helium layer will be burnt into carbon-oxygen and accumulates in the white dwarf (Kato & Hachisu 1999). The WD mass can grow though many recurrent nova outbursts and helium shell flashes. If the companion will supply matter by the same rate as the present one for another hundred thousand years, we expect an Type Ia supernova explosion of the white dwarf.

We acknowledge Milvia Capalbi and Lorella Angelini for their help with \textit{Swift} data reduction. We are also grateful to the anonymous referee for useful comments that improved the manuscript. This research has been supported in part by Grants-in-Aid for Scientific Research (16540211, 16540219) of the Japan Society for the Promotion of Science. G.J.M.L. acknowledges CNPq for his graduate fellowship (Process 141805/2003-0).

REFERENCES

Kato, M. & Hachisu, I. 1999, 513, L41
Osborne, J. et al. 2006a, The Astronomer’s Telegram, 770, 1
Osborne, J. et al. 2006b, The Astronomer’s Telegram, 838, 1