THE HYDROGEN BURNING TURN-OFF OF RS OPHIUCHI 2006

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ABSTRACT

We report a coordinated multi-band photometry of the RS Oph 2006 outburst and highlight the emission line free y-band photometry that shows a mid-plateau phase at y ∼ 10.2 mag from day 40 to day 75 after the discovery followed by a sharp drop of the final decline. Such mid-plateau phases are observed in other two recurrent novae, U Sco and CI Aql, and are interpreted as a bright disk irradiated by the white dwarf. We have calculated theoretical light curves based on the optically thick wind theory and have reproduced the observed light curves including the mid-plateau phase and the final sharp decline. This final decline is identified with the end of steady hydrogen shell-burning, which turned out the day ∼ 80. This turnoff date is consistent with the end of supersoft X-ray phase observed with Swift. Our model suggests a white dwarf mass of 1.35 ± 0.01 M☉, which indicates that RS Oph is a progenitor of Type Ia supernovae.

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

1. INTRODUCTION AND SUMMARY

RS Oph is one of the well-observed recurrent novae and is suggested to be a progenitor system of Type Ia supernovae (e.g., Hachisu & Kato 2001b). It has undergone its sixth recorded outburst on 2006 February 12 UT (Narumi et al. 2006). The five previous recorded outbursts occurred in 1898, 1933, 1958, 1967, and 1985. These short 10−20 yr recurrence periods indicate that the white dwarf (WD) mass is very close to the Chandrasekhar mass and that the mass accretion rate is as large as ˙Macc ∼ 1 × 10^-7 M☉ yr^-1 (see, e.g., Fig.2 of Hachisu & Kato 2001b). If the WD mass increases after each outburst, RS Oph will eventually explode as a Type Ia supernova (e.g., Nomoto 1982, Hachisu et al. 1996). Therefore, it is important to estimate the WD mass and the accreted mass left on the WD after the outburst.

It is well known that the X-ray turnoff time is a good indicator of the WD mass (e.g., Hachisu & Kato 2005, 2006a). When the hydrogen shell-burning atop the WD extinguishes, a supersoft X-ray phase ends (e.g., Hachisu & Kato 2005). In a visual light curve, however, this turnoff is not clear because many strong emission lines contribute to it. To avoid such contamination to the continuum flux, we have observed RS Oph with the Strömgren y-band filter. The y-filter is an intermediate bandpass filter designed to cut the strong emission lines in the wide V-bandpass filter, so that its light curve represents the continuum flux of novae (e.g., Hachisu & Kato 2006b). We have further modeled the light curve of RS Oph and have determined the WD mass by fitting our modeled light curve with the observation.

Our main results are summarized as follows:

1. The y-band light curve observed is clearly divided into...
three phases: (a) the fast early decline phase until day 40 after the discovery (we set \( t_0 = JD 2,453,779.329 \) as the origin of time), (b) a mid-plateau phase at \( y \sim 10.2 \) mag from day 40 to day 75, and (c) the final decline starting on day 75. This mid-plateau phase is first identified by our \( y \)-light curve.

2. Assuming that the binary consists of a red giant companion, a WD, and a disk around the WD, we calculate theoretical light curves and reproduce the observed \( y \) and \( I \) light curves. The WD component dominates in the early decline phase and the irradiated disk component dominates in the mid-plateau phase. The sharp drop of the final decline phase indicates the epoch when the hydrogen shell-burning ends.

3. The turnoff date of steady hydrogen shell-burning is day \( \sim 80 \), which is consistent with the end of a supersoft X-ray phase observed with \textit{Swift} (Osborn et al. 2006).

4. From the light curve fitting, we obtain the white dwarf mass of \( 1.35 \pm 0.01 M_{\odot} \), which is close to the Chandrasekhar mass (1.38 \( M_{\odot} \), see, e.g., Nomoto 1982). This suggests that RS Oph is a progenitor system of Type Ia supernovae.

5. The distance is estimated to be 1.3-1.7 kpc from the \( y \) and \( I \) light curve fittings in the late phase of the outburst.

Section 2 presents our multi-band photometry of the RS Oph 2006 outburst. The light curve fitting of our numerical model with the observation are presented in §3.

### 2. OBSERVATION

Optical observations were started just after the discovery of the 2006 outburst (Narumi et al. 2006). Each observer and their observational details are listed in Table 1. We have put a special emphasis on the Strömgren \( y \)-filter to avoid contamination by the strong emission lines. These \( y \)-filters were made by Custom Scientific Inc. \(^1\) and distributed to each observer by one of the authors (M. Kato). Kiyota, Kubotera, Maehara, and Nakajima (VSOJL members) started observation on February 1 of the authors (M. Kato). Kiyota, Kubotera, Maehara, and Nakajima (VSOJL members) started observation on February 17 and obtained 65 nights data for \( y \)-magnitudes (from February 17 to July 27). Osaka Kyoku University (OKU) team obtained \( V \) and \( y \) magnitudes of 25 nights starting from February 17 (until July 14). The magnitudes of these objects were measured by using the local standard star, TYC2 5094.92.1 (Kiyota) or TYC2 5094.283.1 (the other observers). We adapted the brightness and color of \( (y = V = 9.57, B - V = 0.56) \) for TYC2 5094.92.1 and \( (y = V = 9.35, B - V = 1.23) \) for TYC2 5094.283.1 from Tycho2 catalog.

The \( y \)-magnitudes are plotted in Figure 1 together with \( I \)- and \( V \)-magnitudes. We have also added visual magnitudes of the 1985 outburst from the American Association of Variable Star Observers (AAVSO) for comparison. Our \( y \)-magnitudes show very small scatter and follows the bottom of the 1985 visual magnitude. The essential feature of the light curve is very similar to the previous outbursts.

The \( y \) light curve, however, clearly shows a plateau phase from day 40 to day 75 and the sharp final decline starting from day 75. Such mid-plateau phases are also observed in two other recurrent novae, U Sco (e.g., Hachisu et al. 2000) and CI Aql (e.g., Hachisu & Kato 2001a; Hachisu et al. 2003; Hachisu & Kato 2003). These authors interpreted the mid-plateau phase as a bright disk irradiated by the hydrogen-burning WD and a sharp start of the final decline as the epoch when the hydrogen shell-burning ends.

### 3. LIGHT CURVE MODEL

We calculate nova light curves based on the optically thick wind theory (Kato & Hachisu 1994). Our binary model is essentially the same as that in Hachisu & Kato (2001b), and consists of a red giant (RG) star, which is not filling its Roche lobe, a white dwarf (WD), and a disk around the WD. A circular orbit with the ephemeris given by Fekel et al. (2000) is assumed.

#### 3.1. Photospheric evolution of the white dwarf

After a thermonuclear runaway sets in on a mass-accreting WD, its photosphere expands greatly to \( R_{\text{ph}} \gtrsim 100 R_{\odot} \), and

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\(^1\) http://www.customscientific.com/
the WD envelope soon settles in a steady state. The decay phase of novae can be followed by a sequence of steady state solutions (e.g., Kato & Hachisu 1994). We have calculated light curves, using the same method and numerical techniques as in Kato & Hachisu (1994).

After optically thick winds stop, the envelope settles into a hydrostatic equilibrium where its mass is decreasing by nuclear burning. When the nuclear burning decays, the WD enters a cooling phase, in which the luminosity is supplied from heat flow from the ash of hydrogen burning.

The evolutionary timescale depends very sensitively on the WD mass if its mass is very close to the Chandrasekhar mass (e.g., Hachisu & Kato 2006a,b). This is because the WD radius is very sensitive to the increase in mass near the WD radius (e.g., Kato 1999; Hachisu & Kato 2006a,b). This is because the WD radius is very sensitive to the increase in mass near the WD radius.

3.2. Free-free emission

In classical novae, free-free emission of the optically thin ejecta dominates the optical flux soon after the optical maximum (e.g., Gallagher & Ney 1976). We assume that free-free emission also dominates the continuum flux in the early phase of RS Oph outbursts. This is the main and most important difference from previous Hachisu & Kato’s (2001b) model, in which the blackbody emission is assumed.

The free-free emission of optically thin ejecta is estimated as

$$F_\lambda \propto \int \frac{\dot{M}_{\text{wind}}^2}{\rho v_{\text{ph}}^2} dV \propto \int_{R_{\text{ph}}}^{\infty} \frac{\dot{M}_{\text{wind}}^2}{\rho v_{\text{ph}}^2} r^2 dr \propto \frac{\dot{M}_{\text{wind}}^2}{\rho v_{\text{ph}}^2} R_{\text{ph}}$$  (1)

during the optically thick wind phase, where $F_\lambda$ is the flux at the wavelength $\lambda$, $\dot{N}_i$ and $N_i$ the number densities of electron and ion, $V$ the volume of the ejecta, $\dot{M}_{\text{wind}}$ the wind mass loss rate, $v_{\text{ph}}$ the velocity at the photosphere, $R_{\text{ph}}$. Here, we use the relation of $\rho \dot{M}_{\text{wind}} = \dot{M}_{\text{wind}} / 4\pi r^2 v_{\text{wind}}$, and $\rho v_{\text{wind}}$ and $v_{\text{wind}}$ are the density and velocity of the wind, respectively. These values are calculated from the wind solution.

We cannot uniquely specify the proportional constant in equations (1) because radiative transfer is not calculated outside the photosphere. Instead, we choose the constant to fit the light curve as shown in Figure 2. We added infrared $K$-magnitudes of the 1985 outburst observed by Evans et al. (1988). Very little dependence of the light curve shape on the wavelength is a characteristic feature in the free-free emission light curves as described in equation (1). However, the free-free light curve cannot reproduce the mid-plateau phase, so we introduce a disk irradiation model in the next subsection.

3.3. Disk irradiation

We assume an axi-symmetric disk with the size of

$$R_{\text{disk}} = \alpha R_i^*,$$  (2)

and the thickness of

$$h = \beta R_{\text{disk}} \left( \frac{\sigma}{R_{\text{disk}}} \right)^{1/2},$$  (3)

where $R_{\text{disk}}$ is the outer edge of the disk, $R_i^*$ is the effective radius of the inner critical Roche lobe for the WD component, $h$ is the height of the surface from the equatorial plane,
\( r_{RG} = r_{RG}^2 \),

where \( r_{RG} \) is the effective radius of the inner critical Roche lobe for the red giant component, its mass of \( M_{RG} = 0.7 M_\odot \), and the inclination angle of the binary, \( i = 33^\circ \) (e.g., Dobrzycka & Kenyon 1994). Dobrzycka et al. (1996) suggested \( \gamma \sim 0.4 \) for the distance of 1.5 kpc.

The disk surface absorbs UV and supersoft X-ray photons from the WD and emits a part of it as a thermal emission with a lower temperature than that of the WD photosphere. The disk luminosity depends mainly on the disk size \( (\alpha) \) and the efficiency of irradiation \( \eta_{eff} = \text{radiated energy/absorbed energy} \), but depends very weakly on the other two parameters of \( \nu \) and \( \beta \). Here, we assume \( \nu = 2 \) and \( \beta = 0.05 \). The dependence on these parameters was widely discussed in the previous papers (e.g., Hachisu & Kato 2001b, 2003).

We have obtained three best fit models of the 2006 outburst in Table 2. The calculated light curves for the 50% efficiency are plotted in Figure 5. These models reproduce the mid-plateau phase and the sharp final decline identified as the end of hydrogen shell-burning. The turnoff date of day 83 in our 1.35 \( M_\odot \) WD model is very consistent with the supersoft X-ray turnoff on day \( \sim 90 \) observed with Swift (Osborn et al. 2006).

3.4. Distance

The distance is obtained from the light curve fitting both at the plateau phase and at the post-outburst minimum phase as shown in Figures 2 and 3. The disk luminosity depends mostly on the disk size, \( \alpha \), and the irradiation efficiency, \( \eta_{eff} \).

We have changed these two parameters and calculated the brightness at the mid-plateau phase. Fitting the calculated brightness with the observation, we obtain the apparent distance moduli, i.e., \( (m-M)_0 = (m-M)_V \) and \( (m-M)_I \). Then we calculate the absorption from

\[
A_V = \frac{A_I - A_I^0}{0.518} = \frac{(m-M)_V - (m-M)_I}{0.518},
\]

where we use \( A_I = 0.482 A_V \) (e.g., Rieke & Lebofsky 1985). Once \( A_V \) is obtained, the distance is calculated from \( \log(d) = ((m-M)_V - A_V - 5)/5 \). Thus, we obtained the absorption-distance relation for the irradiated disk as shown in Figure 4. We further restrict the distance with the observed absorption of \( A_V \sim 2.3 \) (Snijders 1987). The same method is applied to the companion star, in which we have changed the companion size, \( \gamma \), and the effective temperature, \( T_{RG} \). The absorption-distance relation for the companion is also plotted.

The largest ambiguity of our model is the irradiation efficiency of the disk. Here, the distance of 0.9, 1.3, and 1.7 kpc are derived for the three different assumed efficiency, i.e., 25%, 50%, and 100%, respectively. The actual efficiency is somewhere between 50% and 100%, so we have a reasonable distance of 1.3–1.7 kpc.

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