OPTICAL AND SUPERSOFT X-RAY LIGHT CURVE MODELS OF CLASSICAL NOVA V2491 CYGNI: A NEW CLUE TO THE SECONDARY MAXIMUM

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ABSTRACT

V2491 Cygni (Nova Cygni 2008 No.2) was detected as a transient supersoft X-ray source with the *Swift* XRT as early as 40 days after the outburst, suggesting a very massive white dwarf (WD) close to the Chandrasekhar limit. We present a unified model of near infrared, optical, and X-ray light curves for V2491 Cyg, and have estimated, from our best-fit model, the WD mass to be $1.3 \pm 0.2 M_\odot$ with an assumed chemical composition of the envelope, $X = 0.20$, $Y = 0.48$, $X_{\text{CNO}} = 0.20$, $X_{\text{Ne}} = 0.10$, and $Z = 0.02$ by mass weight. We strongly recommend detailed composition analysis of the ejecta because some enrichment of the WD matter suggests that the WD mass does not increase like in RS Oph, which is a candidate of Type Ia supernova progenitors. V2491 Cyg shows a peculiar secondary maximum in the optical light curve as well as V1493 Aql and V2362 Cyg. Introducing magnetic activity as an adding energy source to nuclear burning, we propose a physical mechanism of the secondary maxima.

Subject headings: novae, cataclysmic variables — stars: individual (V1493 Aql, V2362 Cyg, V2491 Cyg) — stars: mass loss — X-rays: binaries

1. INTRODUCTION

Classical novae show a wide variety of timescales and shapes in the optical light curves (e.g., Payne-Gaposchkin 1957). Among various shapes of nova light curves, V1493 Aql (Nova Aquilae 1999 No.1) shows an impressive secondary maximum about 50 days after the outburst (e.g., Bonifacio et al. 2000, Venturini et al. 2004), although the physical mechanism of the secondary maximum is not understood yet. Recent two novae, V2362 Cyg (Nova Cygni 2006) and V2491 Cyg (Nova Cygni 2008 No.2), also show a similar type of single secondary maximum, at about 250 and 15 days after the outburst, respectively. These three novae form a wide variety set of timescales, i.e., about 15, 50, and 250 days at the secondary maximum and of secondary peak heights, i.e., 1.1, 3.8, and 3.6 mag, respectively, (see, e.g., Kimeswenger et al. 2008), which provide us a new clue to the mechanism of the secondary maxima.

In this Letter, we propose a strong magnetic activity as the mechanism of the secondary maxima observed in V2491 Cyg, V1493 Aql, and V2362 Cyg, using the white dwarf (WD) parameters obtained from light curve fittings based on an optically thick wind model of nova outbursts (Kato & Hachisu 1994). In §2, we briefly describe our numerical method and light curve fitting of V2491 Cyg. In §3, we propose an idea of strong magnetic activity in the WD envelope and estimate the timescales of the secondary maxima. V1493 Aql and V2362 Cyg show very different timescales of the secondary maximum, both of which are also explained by the same mechanism in §4. Conclusions follow in §5.

2. MODELING OF NOVA OUTBURSTS

2.1. Optically thick wind model

After a thermonuclear runaway sets in on a mass-accreting WD, its photospheric radius expands greatly to $R_{\text{ph}} \gtrsim 100 R_\odot$ and the WD envelope settles in a steady-state. We have followed evolutions of novae by connecting steady state solutions along the decreasing envelope mass sequence. We solve a set of equations, that is, the continuity, equation of motion, radiative diffusion, and conservation of energy, from the bottom of the hydrogen-rich envelope through the photosphere assuming spherical symmetry. Winds are accelerated deep inside the photosphere so that they are called “optically thick winds.” As one of the boundary conditions for our numerical code, we assume that photons are emitted at the photosphere as a blackbody with the photospheric temperature of $T_{\text{ph}}$. X-ray flux is estimated directly from the blackbody emission, but infrared and optical fluxes are calculated from free-free emission by using the physical values of our wind solutions. We neglect the effect of ash helium layer, which may be piled up beneath the hydrogen burning zone, for all nova calculations except the RS Oph case (Hachisu et al. 2007). Our method and various physical properties of these wind solutions have already been published (e.g., Hachisu & Kato 2001a,b, 2004, 2006, 2007, Hachisu et al. 1996, 1999a,b, 2000, 2003, 2007, Kato 1983, 1997, 1999, Kato & Hachisu 1994).

The light curves of our optically thick wind model are parameterized by the WD mass ($M_{\text{WD}}$), chemical composition of the envelope ($X$, $Y$, $X_{\text{CNO}}$, $X_{\text{Ne}}$, and $Z$), and the envelope mass ($\Delta M_{\text{env,0}}$) at the outburst (day 0). Details of our light curve fittings are described in Hachisu & Kato (2006, 2007) and Hachisu et al. (2003, 2008).

2.2. Light curve fitting (V2491 Cyg)

V2491 Cyg was discovered by Nishiyama and Kabashima at mag 7.7 on 2008 April 10.728 UT (Nakano et al. 2008). The nova was not detected on April 8.831 UT (limiting mag 14). The exact outburst day is unknown, so we assume here that $t_{\text{OB}} = 2454566.0$ (April 9.5 UT) is the outburst day (day...
Y = 0

1. The orbital period of $P_{\text{orb}} = 0.0958$ days was derived by Baklanov et al. (2008) from the modulations with an amplitude of 0.03 – 0.05 mag.

The rise or decay time of supersoft X-ray flux is an important indicator of the WD mass (e.g., Hachisu & Kato 2006, 2007, Hachisu et al. 2008). The best fit model with the Swift observation (Page et al. 2009) is the WD mass of $1.3 \pm 0.02$ $M_\odot$ as shown in Figure 1. Here we adopt the chemical composition of $X = 0.20$, $Y = 0.48$, $X_{\text{NeO}} = 0.20$, $X_{\text{Ne}} = 0.10$, and $Z = 0.02$. Large open triangles: Observational X-ray (0.2 – 0.6 keV) count rates obtained with Swift (Page et al. 2009). Optical and near IR observational data of $I$ (open diamonds), $R$ (circles with a plus), $V$ (filled squares), $y$ (filled circles), and visual (small open circles) are taken from AAVSO (American Association of Variable Star Observers) and VSOLJ (Variable Star Observer League in Japan). The $F_3 \propto r^3$ law (magenta) is added for the nebular phase, i.e., after the wind stops, where $t$ is the time after the outburst.

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3. MAGNETIC ACTIVITY (V2491 Cyg)

V2491 Cyg shows a single secondary maximum in the optical and near IR light curves, which we cannot reproduce by our evolution model. Here we propose magnetic activities as a new energy source of the secondary maximum.

The prenova X-ray was detected in V2491 Cyg with Swift (Ibarra & Kuulkers 2008). Ibarra et al. (2008) suggested that the prenova X-ray spectra are more like those seen from magnetic rather than non-magnetic cataclysmic variables. Takei et al. (2009) reported the first detection of superhard X-rays (15 – 60 keV) with the Suzaku HXD at day 10, the spectrum of which has a power law distribution, suggesting a non-thermal origin, and unlikely to arise from thermal emission from internal shocks. This superhard component was not seen in their second Suzaku observation at day 30. These two observations point toward strong magnetic activities on the WD surface.

Therefore, our idea on the secondary maximum is based on additional energy release associated with rotating magnetic field. We assume that V2491 Cyg is a polar system with magnetic field as strong as $B_\theta \sim 10^7$ G on the WD surface (e.g., Warner 1995). Before the nova outburst, the WD magnetic field rotates synchronously with the WD spin as well as the binary orbital motion. After the outburst, the nova envelope expands largely and rotates differentially due to local angular momentum conservation. Then, the magnetic field no more rotates synchronously with the WD spin because the magnetic tension is not strong enough to keep the whole envelope rotating with the WD spin. We expect that the differential rotation amplifies magnetic field which drives strong magnetic activities. As the nova outburst proceeds, the density of the WD envelope is gradually decreasing due mainly to wind mass loss and then the magnetic field eventually recovers synchronous rotation. The strong magnetic activities end at this stage, cor-
responding to the end of a secondary maximum. Since the additional energy source disappears, the light curve goes back to a “normal” one as shown in Figure 1.

To confirm this idea we estimate the total thermal energy of gas plus radiation $\varepsilon_{\text{th}} = \varepsilon_{\text{th, gas}} + \varepsilon_{\text{th, rad}}$, rotational kinetic energy $\varepsilon_{\text{rot}}$, wind kinetic energy $\varepsilon_{\text{wind}}$, and magnetic energy $\varepsilon_{\text{mag}}$, which are calculated from

$$\varepsilon_{\text{th}} = \frac{3}{2} kT \mu m_{\text{H}} \rho + aT^4,$$

$$\varepsilon_{\text{rot}} = \frac{1}{2} \rho \left( r \Omega_{\text{spin}} \right)^2 ,$$

$$\varepsilon_{\text{wind}} = \frac{1}{2} \rho v_{\text{wind}}^2 ,$$

$$\varepsilon_{\text{mag}} = \frac{B_0^2}{8\pi} \left( \frac{r}{R_{\text{WD}}} \right)^{-4}.$$

The temperature $T$, density $\rho$, and wind velocity $v_{\text{wind}}$ are taken from our wind solutions of the best-fit model of V2491 Cyg (1.3 $M_\odot$, WD). Here we assume the dipole magnetic field of $B_0 = 3 \times 10^7$ G at the WD surface (e.g., Warner 1995, for V1500 Cyg) and that the WD spin period is the same as the orbital period, $2\pi/\Omega_{\text{spin}} = P_{\text{spin}} = P_{\text{orb}}$. Figure 2 shows the energy densities for five sequential stages during the nova outburst. The first model (thick solid) has the largest photospheric radius and corresponds to a stage at/near the optical maximum. We see that at/near the optical maximum, $\varepsilon_{\text{mag}} \lesssim \varepsilon_{\text{rot}}$ at $r \gtrsim 2 \times 10^8$ cm. This indicates that the magnetic field is differentially rotating outside of $r \sim 2 \times 10^8$ cm. Then, the rotation energy density decreases with time and eventually $\varepsilon_{\text{mag}}$ becomes comparable to $\varepsilon_{\text{rot}}$ at the stage of the smallest photospheric radius. After that, the magnetic field probably gains synchronous rotation with the WD spin. We expect that the magnetic activities have a peak at $\varepsilon_{\text{mag}} \approx \varepsilon_{\text{rot}}$. This condition is satisfied at day 15 for our best-fit model, being very consistent with the time of the secondary maximum.

Next we estimate the epoch when the companion emerges from the nova envelope. If the mass of the donor star is estimated from Warner’s (1995) empirical formula, i.e.,

$$\frac{M_2}{M_\odot} \approx 0.065 \left( \frac{P_{\text{orb}}}{\text{hours}} \right)^{5/4}, \quad \text{for} \ 1.3 < P_{\text{orb}} < 9 \ (5)$$

we have $M_2 = 0.18 \ M_\odot$, which corresponds to the separation of $a = 1.0 \ R_\odot$, and the effective Roche lobe radius of the primary component (WD) of $R_1 = 0.55 \ R_\odot$. When the photospheric radius of the nova envelope shrinks to near the orbit (the separation $a$), the condition of $\varepsilon_{\text{rot}} \lesssim \varepsilon_{\text{mag}}$ is satisfied as shown in Figure 2. This indicates that the epoch of the secondary maximum is shortly after the companion emerges from the nova envelope. We here implicitly assume that strong magnetic field connects the WD and the companion (like in polar systems). The mechanism of activity we suppose is magnetic reconnection. Strong magnetic reconnection occurs between the WD and the companion. When the WD photosphere is larger than the companion’s orbit, magnetic reconnection may occur deep inside the photosphere but the gas pressure (or gas thermal energy) at the reconnection region is much larger than the magnetic pressure (magnetic energy), so the gas is not easily accelerated by magnetic force. On the other hand, when the gas pressure becomes smaller than the magnetic pressure, i.e., when the photosphere shrinks to the orbit (see Fig 2), then the gas is easily accelerated by magnetic force and the envelope gas is massively ejected. Thus this process increases the mass-loss rate around/near the secondary maximum.

4. V1493 Aql and V2362 Cyg

V1493 Aql was discovered by Tago at mag 8.8 on July 13.558 UT. The nova was not detected on his films of July 5 and 9 (limiting mag 11 and 10.5, respectively). Therefore, we assume here that the outburst day is $t_{\text{on}} = 2451372.0$ (July 12.5 UT). Figure 3 shows optical and near infrared light.
curves of V1493 Aql. Our theoretical light curves of free-free emission reasonably fit with the observation until day ~ 100 except the secondary maximum. The best-fit model is the WD mass of 1.15 ± 0.05 M⊙ for the chemical composition of X = 0.55, Y = 0.30, X_{CNO} = 0.10, X_{Ne} = 0.03, and Z = 0.02. The V and visual magnitudes deviate from our model light curve about 100 days after the outburst. This is due probably to the contribution of emission lines such as [O III] in the nebular phase. The orbital period of P_{orb} = 0.156 days was obtained by Dobrotka et al. (2006) from the modulations with a very small amplitude of 0.015 mag. The mass of the donor star is estimated to be M_2 = 0.34 M⊙ from equation [5]. The corresponding separation is a = 1.4 R⊙ and the effective radius of the WD Roche lobe is R_{\rm WD} = 0.68 R⊙. We have obtained the epoch of ε_{mag} ≈ ε_{tot} to be day 49 for our 1.15 M⊙ WD model as listed in Table [1]. This timescale is consistent with the peak of the secondary maximum and also the emergence of the companion star from the WD envelope.

V2362 Cyg was discovered by Nishimura at mag 10.5 on 2006 April 2.807 UT. The nova was not detected on his films taken on March 28 (limiting mag 12) or on earlier patrol films back to 2001. Therefore, we assume here the outburst day of t_{OB} = 2453827.0 (April 1.5 UT). Optical and near infrared light curves are plotted in Figure 4. Our theoretical light curves of free-free emission again reasonably fit with the I observation until day ~ 500 except the secondary maximum. The best-fit model is the WD mass of 0.7 ± 0.05 M⊙ for the chemical composition of X = 0.45, Y = 0.18, X_{CNO} = 0.35, and Z = 0.02 (see, e.g., Munari et al. 2008, for observed values). The R and Y magnitudes slightly but the V and visual magnitudes largely deviate from our model light curve after the secondary maximum. The orbital period of P_{orb} = 0.207 days was obtained by Goranskij et al. (2008) from the modulations with an amplitude of 0.11 mag. If we take the donor mass of M_2 = 0.48 M⊙ from equation [5], the separation is a = 1.6 R⊙, and the WD Roche lobe is R_{\rm WD} = 0.66 R⊙. We have examined the epoch of ε_{mag} ≈ ε_{tot} to be day 240 for our model of 0.7 M⊙ WD as listed in Table [1]. This timescale is again reasonably consistent with the peak of the secondary maximum and also the emergence of the companion star from the WD envelope.

5. CONCLUSIONS

We have estimated the WD mass of the classical nova V2491 Cyg by comparing our free-free light curves with the optical and near infrared observations as well as by comparing our blackbody X-ray light curves with the Swift XRT data. The best-fit model is the 1.3 ± 0.02 M⊙ WD for the chemical composition of X = 0.20, Y = 0.48, X_{CNO} = 0.20, X_{Ne} = 0.10, and Z = 0.02. We strongly recommend composition analysis of the ejecta because the enrichment of WD matter provides information whether the WD mass increases or not. We have also estimated the WD mass of V1493 Aql and V2362 Cyg to be M_{WD} = 1.15 ± 0.05 and 0.7 ± 0.05 M⊙, respectively. For these three novae, the epoch of secondary maximum is consistently explained by our magnetic activity model if the magnetic activity reaches maximum at ε_{mag} ≈ ε_{tot} in the WD envelope. We strongly recommend search for magnetic activities for these three novae even in quiescence.

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REFERENCES

Baklanov, A., Pavlenko, E., & Berežina, E. 2008, The Astronomer’s Telegram, 1514
Bonifacio, P., Servelli, P. L., & Caffau, E. 2000, A&A, 356, L53
Dobrotka, A., Friedjung, M., Retter, A., Hric, L., & Novak, R. 2006, A&A, 448, 1107
Goranskij, P. V., Metlova, V. N., & Burenkov, N. A. 2008, The Astronomer’s Telegram, 928, 1
Hachisu, I., & Kato, M. 2001a, ApJ, 553, L161
Hachisu, I., & Kato, M. 2001b, ApJ, 558, 323
Hachisu, I., & Kato, M. 2003b, ApJ, 590, 445
Hachisu, I., & Kato, M. 2004, ApJ, 612, L57
Hachisu, I., & Kato, M. 2006, ApJS, 167, 59
Hachisu, I., & Kato, M. 2007, ApJ, 662, 552
Hachisu, I., Kato, M., & Cassatella, A. 2008, ApJ, 687, 1236
Hachisu, I., Kato, M., Kato, T., & Matsumoto, K. 2000, ApJ, 528, L97
Hachisu, I., Kato, M., & Luna, G. J. M. 2007, ApJ, 659, L153
Hachisu, I., Kato, M., & Nomoto, K. 1996, ApJ, 470, L97
Hachisu, I., Kato, M., & Nomoto, K. 1999a, ApJ, 522, 487
Hachisu, I., Kato, M., Nomoto, K., & Umeda, H. 1999b, ApJ, 519, 314
Hachisu, I., Kato, M., & Schaef er, B. E. 2003, ApJ, 584, 1008
Ibarra, A., & Kuulkers, E. 2008, The Astronomer’s Telegram, 1473, 1
Ibarra, A., et al. 2008, The Astronomer’s Telegram, 1478, 1
Iglesias, C. A., & Rogers, F. J. 1996, ApJ, 464, 943
Kato, M. 1983, PASJ, 35, 507
Kato, M. 1997, ApJ, 113, 121
Kato, M. 1999, PASJ, 51, 525
Kato, M., & Hachisu, I. 1994, ApJ, 437, 802
Kato, M., & Hachisu, I. 2007, ApJ, 657, 1004
Kimeswenger, S., Dalnodar, S., Knapp, A., Schafer, J., Unterguggenberger, S., & Weiss, S. 2008, A&A, 479, L51
Munari, U., et al. 2008, A&A, in press (arXiv:0810.2387)
Nakano, S., Reize, J., Jin, Z.-W., Gao, X., Yamaoka, H., Haseda, K., Guido, E., Sostero, G., Klingenberg, G., & Kadota, K. 2008, IAU Circ., 8934, 1
Nakano, S., Tago, A., & Nakamura, A. 1999, IAU Circ., 7223, 1
Page, K. L., et al. 2009, in preparation
Payne-Gaposchkin, C. 1957, The Galactic Novae (Amsterdam: North-Holland)
Takei, D., Tsuji, M., Kitamoto, S., Ness, J.-U., Drake, J. J., & Takahashi, H. 2009, in preparation
Tomov, T., Mikołajewski, M., Brozek, T., Ragan, E., Swierczynski, E., Wychudzki, P., & Galan, C. 2008, The Astronomer’s Telegram, 1485
Venturini, C. C., Rudy, R. J., Lynch, D. K., Mazuk, S., & Puetter, R. C. 2004, AJ, 128, 405
Warner, B. 1995, Cataclysmic variable stars, Cambridge, Cambridge University Press