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Rebrightening Phenomenon in Classical Novae

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Abstract

Two classical novae V1493 Aql and V2362 Cyg were known to exhibit unprecedented large-amplitude rebrightening during the late stage of their evolution. We analyzed common properties in these two light curves. We show that these unusual light curves are very well expressed by a combination of power-law decline, omnipresent in fast novae, and exponential brightening. We propose a schematic interpretation of the properties common to these rebrightenings can be a consequence of a shock resulting from a secondary ejection and its breakout in the optically thick nova winds. This interpretation has an advantage in explaining the rapid fading following the rebrightening and the subsequent evolution of the light curve. The exponential rise might reflect emerging light from the shock front, analogous to a radiative precursor in a supernova shock breakout. The consequence of such a shock in the nova wind potentially explains many kinds of unusual phenomena in novae including early-stage variations and potentially dust formation.

1 Introduction

Classical novae are thermonuclear runaways (cf. Starrfield et al. 2000) on a mass-accreting white dwarf in cataclysmic variables (CVs). The light curves of classical novae usually are comprise of rapid premaximum rise and slower decline from the maximum. While many of fast (rapidly fading) novae show a relatively smooth decline, which is often well approximated by a power-law (cf. Hachisu, Kato 2006), slow (slowly fading) novae tend to show more complex behavior.

In recent years, two fast novae (V1493 Cyg and V2362 Cyg) drastically violated this picture. The light curves of these novae initially showed smooth decline typical for fast novae, but was followed by accelerating brightening (hereafter rebrightening), then by a rapid drop (cf. Venturini et al. 2004; Kimeswenger et al. 2008). The overall feature of the light curves in these novae was extremely similar (Goranskij et al. 2006; Munari et al. 2008) suggesting a common underlying mechanism.

We here show that the light curves of these two novae can be very well represented by a combination of power-law decline and exponential brightening and discuss the origin of the peculiar light variation.

2 Data analysis

The photometric data were taken by us and from observations to VSNET (Kato et al., 2004), supplemented for discovery and early observations from IAU Circulars. For V1493 Aql,[1] we adopted visual observations because

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[1] The magnitudes at the epoch of the discovery (m_{pg} = 8.8 on 1999 July 13) were (Nakano et al., 1999) later found to be incorrect due to the problem in comparison stars (vsnet-alert 3254, <http://www.kusastro.kyoto-u.ac.jp/vsnet/Mail/alert3000/msg00254.html>). The resultant t_2 was ~ 4 d, in contrast to the unexpectedly small $t_2 < 3$ d, claimed to be the fastest known nova (Bonifacio et al., 2000).
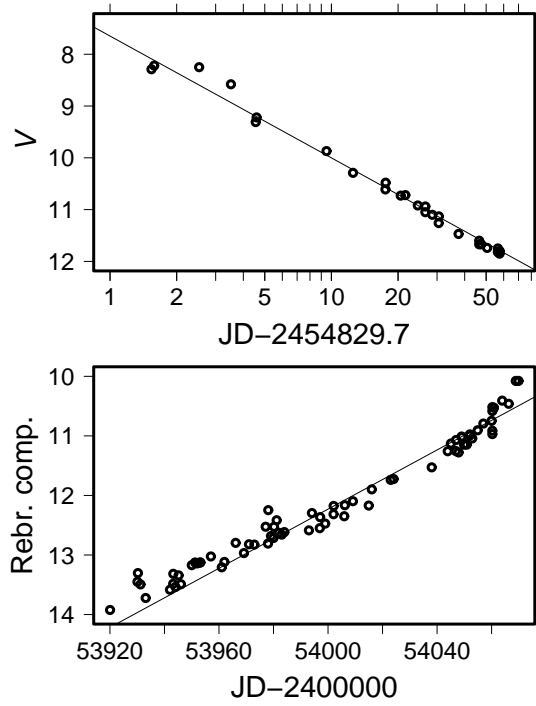
Figure 1: Best fits to the V-band light curve of V2362 Cyg. Individual circles represent observations and straight lines represent fits with parameters equation 4. (Upper): the early decline is well represented by a power law. (Lower): excess rebrightening component (in magnitude scale) is well represented by an exponential rise.
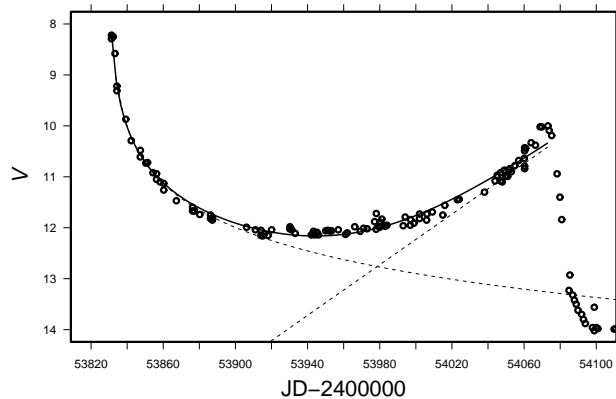
Figure 2: Best fit of the two-component model (equation 3) to the V-band light curve of V2362 Cyg. The thin dotted curve and line represent the components of power-law decline and exponential rise, respectively. The thin curve represents the best fit.

CCD observations did not cover the entire stage of the outburst. For V2362 Cyg, we adopted CCD V observations. The typical errors of visual and CCD V observations were 0.1–0.2 and 0.01–0.03 mag, respectively.

The early part of the light curve is well represented by a power law-type decline (cf. figure 1, upper panel), as is typical for a fast nova. Subtracting the extrapolated power law decline, we found that the excess component of the rebrightening is well expressed by an exponential rise (cf. figure 1, lower panel). Upon this knowledge, we modeled the light curve as a combination (equation 3) of two components: a power-law decline (equation 1) and an exponential rebrightening (equation 2).

$$V_{\mathrm{dec}} = a + b\log(t - c) \tag{1}$$

$$V_{\mathrm{reb}} = d(t - t_0) + e \tag{2}$$

, where $t_0 = 2453920$ is an arbitrary value to avoid large coefficients.

$$V = -2.5\log(10^{-0.4V_{\mathrm{dec}}} + 10^{-0.4V_{\mathrm{reb}}}) \tag{3}$$

The best-fit parameters were

$$a = 7.64(0.16),\ b = 2.35(0.10),\ c = 2453829.7(0.3),$$
$$d = -0.0248(0.0011),\ e = 14.71(0.17) \tag{4}$$

, for the interval of $2453831 < t(\mathrm{JD}) < 2454073$.

Figure 2 shows the overall fit. The observed light curve before the rapid fade following the rebrightening maximum is well expressed by this simple combination of components. We could not, however, reproduce the result by Kimeswenger et al. (2008) reporting that an extrapolation of a power-law decline determined from the first 60 d perfectly fits to the post-rebrightening light curve. This discrepancy could have originated from the different power indices between Kimeswenger et al. (2008) and ours. In order to estimate the effect of this potential uncertainty in determining the power index, we calculated fits to different portions of the early light curve, and a fit to the entire light curve excluding the rebrightening portion (this simulates the result by Kimeswenger et al. 2008) and subtracted each of them from the light curve. The overall trend in unchanged in all cases in that the residual can be well-expressed by an exponential rise. The power law index simulating the result by Kimeswenger et al. (2008) was $b = 3.08(0.04)$, which is significantly smaller than that ($4.4 = 1.75 \times 2.5$) expected from the "universal decline law" of $F \propto t^{-1.75}$ (Hachisu, Kato, 2006).

The same procedure was applied to the light curve of V1493 Aql, yielding the best fit values (equation 5) and the fit (figure 3).

$$a = 8.75(0.43),\ b = 3.27(0.37),\ c = 2451371.8(0.6),$$
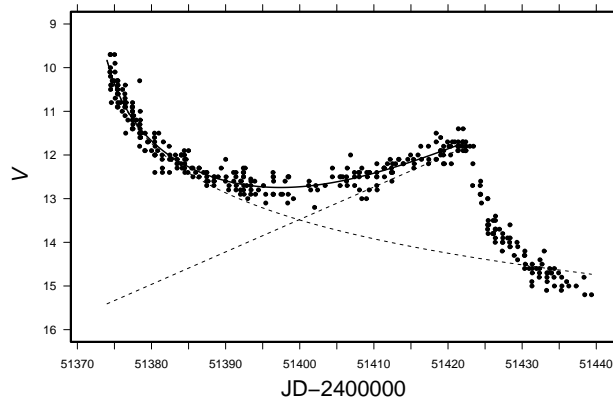$$d = -0.0744(0.0008),\ e = 13.47(0.16) \tag{5}$$

Figure 3: Best fit of the two-component model to the visual light curve of V1493 Aql. The line are curves are as in figure 2.

, for the interval of $2451372 < t(\mathrm{JD}) < 2451422$, using $t_0 = 2451400$.

3 Discussion

3.1 Unusual Rebrightenings and Role of Shocks

Several authors have pointed out that the light curves of these two novae were very unusual but closely resembled each other, but the the phenomenon still awaits physical interpretation.

Kimeswenger et al. (2008) tried to reproduce the rebrightening spike of V2362 Cyg by assuming a temporary expansion of the pseudo-photosphere of the nova and estimated its temperature and radius. Kimeswenger et al. (2008) suggested that this temporary expansion was caused by a fast ejecta reaching the photosphere, resulting a significant increase in the density. Although the authors attributed the rapid fading following the rebrightening peak to dust obscuration, the reason is unclear why and how dust formation took place around the peak. If this interpretation is also applicable to the extremely similar nova V1493 Aql, the apparent lack of evidence of dust formation (Venturini et al., 2004) could be problematic. Furthermore, a drastic expansion of the photosphere should affect the free-free component of the light curve, which is considered to dominate at this stage of nova evolution (see equation 9 of Hachisu, Kato 2006). If such an expanded photosphere was obscured by dust formation, and the remaining light is from a "detached shell", the subsequent evolution of the light curve should follow a steeper decline (corresponding to the epoch after the wind stops, cf. Hachisu, Kato 2006) rather than a smooth extrapolation of the early decline. Emission lines would be also affected, while observations of strength of fitted emission of the main outburst (see figure 4 of Kimeswenger et al. 2008) smoothly declined regardless of the rebrightening. These difficulties probably arise from an assumption of a continuous input of substantial amount of new ejecta into the preexisting one. We probably need a more dynamic, rather than this static, process.

We then propose an alternative idea that the thin shock front formed by a limited amount of newly ejected matter, and potentially its breakout in the optically thick nova winds, comprises the rebrightening phenomenon. The spectra of V2362 Cyg taken around the rebrightening maximum (Munari et al. 2008; Kimeswenger et al. 2008) showed temporary appearance of strong and blue-shifted absorption components in the Balmer-emission-line profiles. Kimeswenger et al. (2008) also noted an enhancement of a new component of emission lines during the rebrightening. Such high-velocity component is expected to collide with the exterior, slower, preexisting winds, and will naturally produce a shock front (cf. Munari et al. 2007). The detection of hard X-rays (Ness, Starrfield, 2006) can also be attributed to the presence of a shock (Balman et al., 1998). The presence of optically thick wind provides a favorable condition that a breakout, if present, of such a shock becomes observable (e.g. Li 2007 for a supernova/GRB case). After the optically thick, geometrically thin shock front reaches the photosphere, and the energy loss via a kinetic motion dominates over the radiative transport, the subsequent rapid expansion and cooling of a thin shell can be naturally expected. The visibility of the high-velocity component only around the peak indicates that the velocity structure dramatically varied around the rebrightening peak. In the present

picture, the matter outside the photosphere would remain largely untouched, preserving the general power law-type decline trend and behavior of emission lines arising from the outer optically thin region. Dust formation may be associated with the quick expansion of the shock front, as discussed later, probably naturally explaining the temporal coincidence of the suggested dust formation around the rebrightening peak.

The rising stage of the rebrightening, the exponential rise, commonly observed in these two novae appears to be harder to explain in any mechanism, and would be a challenge for theoreticians. Within the present picture, we propose a working hypothesis that that photons emerging from a shock front constitute the exponentially rising, excess component. Before the shock front reaches the photosphere, the photons from the shock front have an escape probability of $e^{-\tau}$, where τ is the optical depth from the shock front to the observer. The observer can thus see photons from the shock front attenuated by $e^{-\tau}$ as an additional component. This interpretation corresponds to the "radiative precursor" phase of a shock breakout in a supernova (Schawinski et al., 2008). Under the condition that the front is approaching the photosphere, τ is expected to decrease with time. A simple assumption of a constant rate of decrease of τ can explain an exponential rise. The parameter fits give characteristic time-scales of the rise corresponding to $\Delta\tau = 1$ of 44(1) d and 14.6(2) d for V2362 Cyg and V1493 Aql, respectively. The values of t_2 being $\sim$9 d and $\sim$4 d for respective novae, the result might suggest a positive relation between t_2 and the time-scale of the rise.

Our interpretation is different from that by Kimeswenger et al. (2008) in that they assumed continuous mass input to the photosphere during the entire rising stage of the rebrightening (since day 170, resulting an expansion of the photosphere) while we assume the continuous presence of a shock front under the photosphere before the peak of rebrightening (i.e. the front reaches the photosphere around the time of the peak). Our interpretation in turn requires the presence of optically thick wind at the time of the shock formation. This can be tested whether the light curve follows by $F \propto t^{-1.75}$ or by a steeper ($F \propto t^{-3.5}$) power law (Hachisu, Kato, 2006). We analyzed the fading part after the end of rebrightening ($2454098 < t < 2454283$). The best fit powers p for t^{-p} were 1.6(1) for the V-band and 1.2(2) for the y-band (less affected by emission lines), which were closer to $p = 1.75$. This result suggests that the optical thick winds had not yet stopped at the epoch in question.

The bluer color around the rebrightening peak, compared to the initial maximum (Munari et al., 2008) also favors the presece of a hot shock front. Most recently, Arai et al. (2009) reported $B - K_s$ multicolor light curves and attributed the later infrared peak to transient dust formation. The duration of the infrared peak was unusually short and it quickly decayed despite its optical thickness. This makes a contrast to other well-known novae with substantial dust formation (Bode, Evans, 2008). Although this shortness may be attributed to the only transient formation of the dust, these light curves, alternatively, can be also interpreted as progressively slower maxima with longer wavelengths; the same tendency is inferred from the optical work by Munari et al. (2008). This characteristic may be understood as a manifestation of a shock breakout, analogous to the supernova case (e.g. Klein, Chevalier 1978), although a red $V - I$ color would also require an excess reddening, i.e. the coexisting dust. This dependence between maxima times and wavelengths would be worth further investigation.

3.2 Shock and Dust in Novae

A shock formed in an optically thick wind, and its potential subsequent breakout, is attractive in that it can not only naturally produce a rapid fade but also enable efficient dust production after its compression and subsequent rapid expansion in post-shock cooling as in wind-wind collision binaries (e.g. Usov 1991). In V2362 Cyg, at the epoch following the rapid fade, Rayner et al. (2006) and Kimeswenger et al. (2008) reported an infrared excess and reddening which were attributed to dust formation in the inner region. The dust formation related to the expansion after a shock around the contracted photosphere is compatible with observations only slightly affecting emission lines and the power-law decline component, which is considered to arise from free-free emission in outer ejecta (Hachisu, Kato, 2006).[2]

3.3 Implications to Other Novae and Future Prospects

We note that similar brightening phenomena accompanied by gradual brightening and rapid fade, although less conspicuous, are present in some other novae. The noteworthy examples include the fast nova V2491 Cyg 15 d after maximum (cf. figure 4, vsnet-alert 10129) and the unusual, slowly evolving nova V1280 Sco (Das et al. 2008;

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[2] In V1493 Aql, Venturini et al. (2004) obtained a spectrum around the rebrightening maximum, and detected strong continuum emission and low-excitation emission lines. These findings suggested that a second period of continuous mass loss can be responsible for the phenomenon (Venturini et al., 2004). It is, however, difficult to see whether the shock component was present in the spectrum because of the low resolution and the very broad emission lines. Venturini et al. (2004) did not report evidence for dust formation.
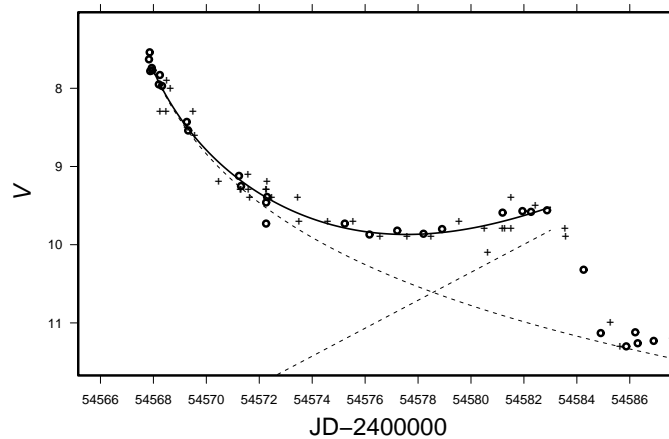
Figure 4: Fit to the V (circles) and visual (crosses) light curve of V2491 Cyg. The line are curves are as in figure 2. The parameters were $a = 6.6(1.2)$, $b = 3.6(1.4)$, $c = -1.1(1.1)$, $d = 0.18(0.08)$, $e = 11.2(0.8)$ for the given $t_0 = 2454575$. The data were from VSNET.

Chesneau et al. 2008), and potentially V5579 Sgr (vsnet-alert 10201). Hachisu, Kato (2009) tried to explain the behavior of V2491 Cyg by introducing the polar-type magnetism and nova explosion-induced asynchronization. Although this interpretation was apparently motivated by the difficulty in reproducing the rapid decline following the rebrightening, we do not consider this possibility in the present paper because the quiescent brightness of V2491 Cyg is incompatible with a polar and because similar anomalies (high quiescent X-ray luminosity) were neither detected in V2362 Cyg nor V1493 Aql.

The fading in V1280 Sco was accompanied by dust formation occurring at an unexpectedly early epoch. Although the mechanism of unusual variation in these novae is not well known, V2362 Cyg/V1493 Aql-type ejection of and shock formation at an early epoch may have played a role in producing unusual light variation and in dust production in a harsh environment (cf. Gallagher 1977). Another commonly seen feature of a bump (maximum) following a premaximum halt in slow novae (Kato et al. 2002 and references therein) might be an extension of the same phenomenon. If this is the case, the fading rate (such as t_2) derived from the fading portion of the bump would easily be an overestimate. The apparent discrepancy between the presence of a premaximum halt and very rapid fading in V463 Sct (Kato et al., 2002) might then be solved.

A model incorporating more elaborate treatment of a shock formation in realistic nova winds and radiative transfer, which is beyond the scope of this paper, is needed for a comparison with observed light curves, color variations, and change in the profile of emission lines. Considering the variety of phenomena potentially arising from this mechanism, a survey in a wide parameter space is encouraged. The reason why only some novae show this kind of late-stage rebrightening is still poorly known. The present interpretation suggests that if a second ejection in the late stage somehow occurs when the optically thick wind is still present, the resultant light curve should generally resemble those of the two objects investigated. Such phenomena may have been overlooked in the past due to the limited high-precision observation. Future systematic multiwavelength photometry and high-resolution spectroscopy are desired to better understand the phenomenon. X-ray observations are also expected to provide evidence for the shock in the nova wind. These observations should be aimed prospectively starting from the early rising stage of rebrightening. A deviation of the light curve from the power-law decline, as empirically shown in this paper, would provide a promising early warning signal for coordinating such observations, that is, real-time examination of nova light curves on $\log t - \mathrm{mag}$ plots will become a powerful diagnostic tool.

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