On the Rebrightenings of Classical Novae during the Early Phase

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Abstract

We report on the spectral evolution of 6 classical novae, V1186 Sco, V2540 Oph, V4745 Sgr, V5113 Sgr, V458 Vul, and V378 Ser, based on the low-resolution spectra obtained at the Fujii-Bisei Observatory and the Bisei Astronomical Observatory, Japan. In the light curves, these 6 novae show several rebrightenings during the early phase lasting ~10 days after the first maximum in fast novae, and ~100 days in slow novae. The early spectra of all of these novae had emission lines with a P-Cygni profile at the maximum brightness. The absorption component of the P-Cygni profiles then disappeared after the maximum, and reappeared when the novae brightened to the next maximum. We suggest that the re-appearance of the absorption component at the rebrightening is attributable to re-expansion of the photosphere after it once shifts sufficiently inside. From the light curves, we found that the time intervals of the rebrightenings of these 6 novae show a similar systematic trend, which is applicable to all types of novae: fast and slow, and Fe II type and hybrid type. Moreover, we note the difference between the spectra at the rebrightenings during the early phase and at the rebrightening in V2362 Cyg, and at the oscillation during the transition phase in V1494 Aql, which means difference of the physical mechanism of the rebrightening during the early phase and the later oscillations.

Key words: stars: novae, cataclysmic variables

1. Introduction

Novae are a kind of cataclysmic variable stars, i.e. close binary systems consisting of a white dwarf and a low-mass normal star (for a review, see Hellier 2001). The cause of the nova eruption is considered to be the thermonuclear runaway reaction on the surface of the white dwarf. Matters transferred from the secondary are accumulated and compressed on the white dwarf. When the temperature and density increase sufficiently, nuclear reactions occur to cause the nova eruption (Starrfield et al. 1976).

The nova eruption is a very exciting phenomenon, and the nova systems are the best classically known transient objects. Payne-Gaposchkin (1964) reported the classification of the nova light curve based on the time in days for the decline by 2 magnitudes from the maximum, \( t_2 \). Duerbeck (1981) reported that there are some light curve types of novae. They suggested a classification system for nova light curves, including dust dips. Williams (1992) divided the early post-outburst spectra of novae into two classes, the Fe II type nova and He/N type nova, based on the emission lines. They proposed that Fe II type spectrum was formed in a continuous wind, while He/N type spectrum was formed in a discrete shell. The diversity of light curves of the novae (see Kiyota et al. 2004, Strope et al. 2010), however, has not been fully understood. The initial decline after the maximum is usually smooth in the optical, especially in fast novae. Some slow or moderately fast, but not fast novae, however, have been known to show oscillations having a large amplitude during the early phase (for example HR Del: Duerbeck 1981, DO Aql: Vogt 1928, RR Pic: Spencer 1931), although it is not clear how these novae accomplish these rebrightenings (Duerbeck 1981). There are, on the other hand, some novae having oscillations during the transition phase. While all of such novae having oscillations during the transition phase may have been slow nova (e.g. V4745 Sgr, Ak et al. 2005), some fast novae showing several peaks during the early phase have been recently discovered (e.g. V458 Vul, Tarasova 2007). Strope et al. (2010) reported the classification and properties of the nova light curve. They reported that there are at least 14 novae, showing the rebrightenings during the early phase, in 93 novae of their sample. The mechanism of these rebrightenings has been still unclear.

In this paper, we present the results of the spectral monitoring of the 6 novae: V1186 Sco, V2540 Oph, V5113 Sgr, V4745 Sgr, V458 Vul, V378 Ser, showing several brightness maximum during the early phase. The details of our targets of our observations are presented in section 2. Our spectral observations are summarized in section 3. The results of the spectral monitoring of the 6 novae are described in section 4. We discuss the properties in the light curves, the spectral evolutions during several rebrightenings, and some interpretations in section 5. Conclusions are stated in section 6.
2. On the targets

In this section we briefly summarize the research history of our targets.

2.1. V1186 Sco

V1186 Sco was discovered at 2004 July 3.1 (UT) by Pojmanski et al. (2004) at V = 11.98. We then obtained the earliest spectrum at 2004 July 6.51 (UT), about 3 days before the visual maximum. This spectrum is presented later in this paper. Schwarz et al. (2007) reported Target of Opportunity observations by Spitzer Space Telescope. They also showed that t2, the time to decline by 2 mag, was 20 days. They derived an absolute magnitude $M_V = -5.5 \pm 0.5$, using the best-fit photoionization model. They reported that E(B−V) = 0.45 ± 0.1 and the derived distance was 5.5 ± 0.5 kpc. Burlak & Henden (2008) derived $t_2$ of 17 days and $t_3$ of 46 days, suggesting that V1186 Sco is a fast nova. They also estimated the absolute magnitude $M_V = -7.8$. 

2.2. V2540 Oph

V2540 Oph was independently discovered by Katsumi Haseda and Yuji Nakamura on 2002 January 24 at V = 9.0 (see Nakamura et al. 2002). Seki et al. (2002) reported that this nova already reached V = 8.9 on 2002 January 19. Retter et al. (2002) classified this nova as an Fe II type nova, based on H and Fe II lines. Kato et al. (2002) reported that the absolute magnitude of the nova progenitor was $M_V = 5.7$ and the expected absolute V-band magnitude at the maximum was $M_V = -7.0 \pm 0.5$. In addition, they proposed that the nova should have either a short orbital period or a high inclination. Ak et al. (2005) estimated the maximum absolute visual magnitude of $M_V = -6.2 \pm 0.4$ mag and the distance of 5.2 ± 0.8 kpc. Moreover, they derived its orbital period of 0.284781 ± 0.000006 d, and the secondary mass of about 0.75 ± 0.04 M⊙ from the mass-period relation of Smith & Dhillon (1998). Burlak & Henden (2008) derived $t_2$ of 167 days and $t_3$ of 305 days, suggesting that V2540 Oph is a slow nova. They also estimated the absolute magnitude $M_V = -5.5$. 

2.3. V5113 Sgr

V5113 Sgr was discovered by Brown et al. (2003) at 2003 September 17.52 (UT) at 9.2 mag (Brown et al. 2003b). They estimated that this nova was 8.8 mag at September 18.43. They also reported that there were Hα lines in emission with a narrow absorption component of the P-Cygni profile blue-shifted by 590 km s$^{-1}$ at September 19.104 (UT). Ruch et al. (2003) reported that there were Hβ, Hγ, Hδ and Fe II lines with the absorption components of P-Cygni profiles at September 19.10 (UT). The thermal velocity of the absorption component was 800 km s$^{-1}$. The optical and IR spectra obtained 9 months after outburst contained the coronal lines of [Si VI] and [S VIII] as well as He II lines (Rudy et al. 2004).

2.4. V4745 Sgr

V4745 Sgr was independently discovered by Brown and Yamamoto on 2003 April 25 and 26 (see Brown et al. 2003a). Ashock & Banerjee (2003) reported the spectral observation showing Balmer series with P-Cygni profiles and classified this nova as an Fe II type nova. Csák et al. (2005) reported that P-Cygni profiles appeared at and around peaks of rebrightenings. They suggested that this behavior was due to multiple episodes of mass ejection. They derived the absolute magnitude, $-8.3 \pm 0.5$ mag and the distance of 9 kpc. Dobrotka et al. (2006) reported that the orbital period is 0.20782 ± 0.00003 d, above the period gap, and the beat period between the orbital and spin period is 0.017238 ± 0.000037 d. They suggested that this nova was an intermediate polar candidate, and obtained the secondary mass of 0.52 ± 0.05 M⊙.

2.5. V458 Vul

V458 Vul was discovered by H.Abe at 2007 August 8.54 (UT) (see Nakano et al. 2007). The spectra were acquired by Fuji at 2007 August 9.48 (UT) (see Buil & Fuji 2007), which is presented later in this paper. Poggiani (2008) reported that V458 Vul is a fast nova, with $t_2$ and $t_3$ of 7 and 15 days, respectively. They derived the absolute magnitude of $M_V = -8.8$, and a roughly estimated distance of 6.7-10.3 kpc. They classified this nova as a hybrid nova, which evolved from the Fe II nova toward the He/N nova. Arai et al. (2009) reported the spectral evolution of V458 Vul. They found that the absorption component of the P-Cygni profile was present at maximum brightness of the rebrightening. Moreover, they reported that He I lines showed unnatural double-peaks during the early phase. Rodriguez-Gil et al. (2010) reported the optical spectroscopy during 15 months starting 301 days after the discovery. They derived the orbital period of 98.09647 ± 0.00025 min by using the radial velocity curves of He II lines. They proposed that V458 Vul is the planetary nebula central binary star with the shortest period known. They suggested that V458 Vul is a post-double common-envelope binary system composed of a M1 ≥ 1.0 M⊙ dwarf and a M2 ∼ 0.6 M⊙, post-AGB star.

2.6. V378 Ser

V378 Ser was discovered by Pojmanski at 2005 March 14.389 (UT) (Pojmanski et al. 2005). Ederoclite et al. (2005) reported the spectroscopic observations carried out at April 5.38 (UT) at La Silla with a 2.2-m telescope. They identified this nova as an Fe II type nova, with a spectrum dominated by strong Hα and O I 7773 and 8446. In addition, they reported that there were Fe II, Na I and Ca I lines in emission. All the Balmer and O I lines were flanked by strong, double absorption components of the P-Cygni profiles.

3. Observation

Most of our low dispersion spectra with a resolution of $\lambda/\Delta\lambda = 600$ (at 5852 Å) have been taken with the
FBSPEC1 and FBSPEC2, which have been developed by one of the authors (MF), attached to the 28 cm telescope of the Fujii-Bisei Observatory (Okayama, Japan). The spectrum of V2540 Oph on 2002 January 27 was taken with a low-resolution spectrograph ($\lambda/\Delta\lambda \approx 1,000$), attached to the 101 cm telescope of the Bisei Astronomical Observatory (Okayama, Japan). The spectral coverage is 3800 to 8400 Å. The spectra of each object were obtained in 2 - 10 nights during the early phase when the targets were brighter than $V = 10-11$ mag. The signal-to-noise ratio is typically 10 to 30. The reduction of the spectra was carried out with NOAO IRAF. Table 1 gives the journal of our spectroscopic observations.

4. Result

4.1. V1186 Sco

Figure 1 shows the light curve of V1186 Sco collected from the VSNET (Kato et al. 2004), AAVSO\(^1\) and ASAS-3 (Pojmanski 2002 ) archives. This nova shows three peaks during the early phase. The spectra were obtained in 6 nights between July 6 (JD 2453193.10) and August 5 (JD 2453223.02), 2004. All of these spectra are presented in figure 2. On July 6 (JD 2453193.10), before the first maximum brightness, the spectrum covering 3800 to 8400 Å is characterized by strong emission lines of the Balmer series. The next spectra were obtained on July 13 and 14 (JD 2453200.01 and 2453201.00), after the first maximum brightness. Fe II and O I lines appear in emission. Thus this nova can be classified as an Fe II class object. On July 7 (JD 2453206.99), just at the second maximum brightness, we identified Na I D line accompanied by a P-Cygni profile having a velocity of about $-1250$ km s\(^{-1}\) between the peaks of the absorption and emission components. This absorption feature is also present in Fe II emission lines. On July 26 (JD 2453213.00), at the third maximum, we can identify the Balmer series and Na I, Fe II and O I lines. The weak absorption component of the P-Cygni profile is present in Fe II, and Na I D line. O I 7773 has developed. The last spectrum on August 5 (JD 2453223.02) shows the presence of the emission lines of H, Na I, Fe II, O I, [N II] and [O I]. O I and [O I] lines are stronger compared to the other lines.

4.2. V2540 Oph

Figure 3 shows the light curve of V2540 Oph. This nova exhibits several brightness maxima during the early phase. We obtained the spectra of V2540 Oph in 5 nights between January 27 (JD 2452302.40) and May 19 (JD 2452414.14), 2002. All of the spectra are displayed in figure 4. The first observation was carried out on January 27 (JD 2452302.40), at the pre-maximum. We can identify the emission lines of H, Fe II, O I, [O I], Na I, He I, N III, C II and Ti II. On February 24 (JD 2452330.31), just after the third brightness maximum, the spectrum shows the presence of emission lines of H, Fe II, [Fe II], O I, [O I], Na I, He I, N III, and C II. The spectrum suggests that this nova is classified as an Fe II nova. On April 12 (JD 2452377.26), on the fifth brightness maximum, we identified the same emission lines as the previous spectrum. The profiles of Fe II lines, however, show absorption components of the P-Cygni profiles at about $-1310$ km s\(^{-1}\) and about $-1230$ km s\(^{-1}\) from the peak of the emission component for Fe II 5018, and 5169 lines, respectively. These P-Cygni profiles disappear at the next observation on May 1, between the fifth maximum of brightness and the sixth brightness maximum, and then reappear at about $-1300$ km s\(^{-1}\) and about $-1090$ km s\(^{-1}\) for Fe II 5018, and 5169 lines, respectively on May 19 (JD 2452414.14), just at the sixth brightness maximum (figure 5). The last spectrum, observed on May 19 (JD 2452414.14), hardly exhibits the other changes, compared with the last observation.

4.3. V5113 Sgr

Figure 6 displays the light curve of V5113 Sgr. This nova also exhibits several peaks. The spectra were obtained on 6 nights between September 21 (JD 2452903.96) and October 24 (JD 2452936.88), 2003. On September 21

\(\text{http://www.aavso.org}\)
Table 1. Spectroscopic Observations of Classical Novae Showing Several Peaks

| Object name  | Date            | Spectral range | JD (2450000+) |
|--------------|-----------------|----------------|---------------|
| V1186 Sco    | 2004 July 6     | 3800-8300      | 3193.10       |
| V1186 Sco    | 2004 July 13    | 3900-8400      | 3200.01       |
| V1186 Sco    | 2004 July 14    | 3900-8400      | 3201.00       |
| V1186 Sco    | 2004 July 20    | 3900-8400      | 3206.99       |
| V1186 Sco    | 2004 July 26    | 3900-8400      | 3213.00       |
| V1186 Sco    | 2004 August 5   | 3900-8400      | 3223.02       |
| V2540 Oph    | 2002 January 27 | 4800-6800      | 2302.40       |
| V2540 Oph    | 2002 February 24| 4500-7100      | 2330.31       |
| V2540 Oph    | 2002 April 12   | 4400-7100      | 2377.26       |
| V5113 Sgr    | 2003 September 21| 3900-8400     | 2903.96       |
| V5113 Sgr    | 2003 September 22| 3900-8400     | 2904.96       |
| V5113 Sgr    | 2003 September 27| 3900-8400     | 2909.93       |
| V5113 Sgr    | 2003 September 30| 3900-8500     | 2912.95       |
| V5113 Sgr    | 2003 October 8  | 3900-8500      | 2920.90       |
| V5113 Sgr    | 2003 October 24 | 3900-8400      | 2936.88       |
| V4745 Sgr    | 2003 April 28   | 4600-7200      | 2758.26       |
| V4745 Sgr    | 2003 April 30   | 4600-7200      | 2760.28       |
| V4745 Sgr    | 2003 May 8      | 3900-8400      | 2768.29       |
| V4745 Sgr    | 2003 May 28     | 3900-8400      | 2788.23       |
| V458 Vul     | 2007 August 9   | 3800-8300      | 4321.98       |
| V458 Vul     | 2007 August 10  | 3800-8300      | 4323.15       |
| V458 Vul     | 2007 August 12  | 3800-8200      | 4325.16       |
| V458 Vul     | 2007 August 15  | 3800-8200      | 4328.03       |
| V458 Vul     | 2007 August 16  | 3800-8200      | 4329.03       |
| V458 Vul     | 2007 August 25  | 3800-8300      | 4338.01       |
| V458 Vul     | 2007 September 5| 3800-8300      | 4349.12       |
| V458 Vul     | 2007 September 10| 3800-8200    | 4353.99       |
| V458 Vul     | 2007 September 25| 4600-6700     | 4368.91       |
| V458 Vul     | 2007 October 6  | 4600-6700      | 4379.99       |
| V378 Ser     | 2005 April 4    | 3900-8400      | 3465.30       |
| V378 Ser     | 2005 April 22   | 3900-8400      | 3483.24       |

Fig. 5. Normalized spectra of V2540 Oph from 2002 January 27 to May 19. The spectra are the same as those in figure 4, but the part around 5000 Å is expanded. We can see reappearance of the absorption component of Fe II lines at the 6th rebrightening on 2002 May 19.
files are weaker. On October 8 (JD 2452920.90), before the third brightness maximum, the spectrum exhibits the emission lines of H, Fe II, O I, Na I, N II, N III, [O I], [O II] and [N II]. In addition, absorption components of the P-Cygni profiles reappear in Fe II and Na I lines at about $-680 \text{ km s}^{-1}$ and about $-1280 \text{ km s}^{-1}$ respectively. On October 24 (JD 2452936.88), after the third brightness maximum, C II emission line (7234 Å) become stronger, and Hβ weaken compared to Fe II lines. P-Cygni profiles are still present. Each blue-shift velocity is higher, presented in table 2.

4.4. V4745 Sgr

Figure 8 displays the light curve of V4745 Sgr. This nova shows six (and possibly more) peaks. We obtained the spectra on 4 nights between April 28 (JD 2452758.26) and May 28 (JD 2452788.23), 2003 (figure 9). On April 28 and 30 (JD 2452758.26 and 2452760.28), just after the first brightness maximum, Balmer series and several Fe II lines appear in emission, indicating that this nova is an Fe II nova. In addition, there are Na I, N II, [N II], O I, [O I] and C II lines, while, strangely, there are no prominent lines on a redder region than Hα. On May 8 (JD
Fig. 7. Normalized spectra of V5113 Sgr from 2003 September 21 to October 24. For visuality, the data after September 21 are vertically shifted.

Fig. 8. Light curve of V4745 Sgr taken from VSNET, AAVSO and ASAS-3. The epochs of our spectroscopic observations are marked with the tick marks.

2452768.29), at the second brightness maximum, the spectrum has remarkably changed compared to the previous spectrum. Many lines show P-Cygni profiles with a blue-shifted absorption component. The blue-shift velocities measured by using the peaks of the absorption and emission components are about $-1700$ km s$^{-1}$, depending on the lines (table 2). The existence of He I lines indicates that this nova may be a hybrid nova, not an Fe II nova. On May 28 (JD 2452788.23), just at the third brightness maximum, the Balmer lines exhibit P-Cygni profiles, having higher blue-shift velocities. Csák et al. (2005) reported that the absorption component of P-Cygni profiles weakened between two peaks on May 8 (JD 2452768.29) and May 28 (JD 2452788.23). We can thus conclude that P-Cygni profiles once disappeared after the maximum and then reappeared on the next third brightness maximum.

4.5. Other objects showing several peaks

V458 Vul and V378 Ser also show several rebrightenings during the early phase. We obtained spectra of these novae on 10 nights and 2 nights respectively. We did not however take the spectra just on the brightness maxima except the first maximum. The light curve of V458 Vul, presented in figure 10, shows three rebrightenings during the early phase. In addition, this exhibits an oscillation-like feature during the transition phase, which is similar to the behavior of V1494 Aql (see e.g., Iijima & Esenoglu 2003). On August 9 (JD 2454321.98), just at the initial brightness maximum, Balmer series and many He I lines appear in emission (figure 11). We can identify strong absorption components of the P-Cygni profiles of these lines. On August 10 (JD 2454323.15), there are also Na I, Fe II, O I and N II lines. Therefore we can classify this nova as a hybrid nova. Here, P-Cygni profiles are not present in our observations except the spectrum on August 9 (JD 2454321.98) and 10 (JD 2454323.15).

The light curve of V378 Ser is presented in figure 12. On April 4 (JD 2453465.30), there are the Balmer series and Fe II, O I, N II, He I, C III, [OI] and possibility Ca I lines (figure 13). The absorption components of P-Cygni profiles appear in H$\alpha$, H$\beta$ and Fe II lines. On April 22 (JD 2453483.24), it is difficult to discriminate emission lines other than H and He because of the poor signal-to-noise ratio (figure 14).

5. Discussion

5.1. Properties of the early rebrightenings of the light curve

We obtained the spectra of 6 classical novae with several rebrightenings during the early phase. The light curve of V1186 Sco is presented in figure 1. The amplitude of the first peak (JD 2453195.9) measured from the minimum before the second peak in the visual magnitude is about 1.2 mag. The amplitude, between the second peak and the minimum after the second peak (JD 2453204.9-2453209.5), is approximately 1.0 mag. The last rebrightening reached its maximum on JD 2453213.1, only $\sim$17 days after the peak of the first maximum on JD 2453195.9.

The light curve of V2540 Oph is presented in figure 3. The average peak-to-peak amplitude is approximately
Fig. 9. Normalized spectra of V4745 Sgr from 2003 April 28 to May 28. For visuality, the data after April 28 are vertically shifted.

Fig. 10. Light curve of V458 Vul taken from VSNET, AAVSO and ASAS-3. The epochs of our spectroscopic observations are marked with the tick marks.

Fig. 11. Normalized spectra of V458 Vul from 2007 August 9 to October 6. For visuality, the data after August 9 are vertically shifted.

Fig. 12. Light curve of V378 Ser taken from VSNET, AAVSO and ASAS-3. The epochs of our spectroscopic observations are marked with the tick marks.
Table 2. Blue-shift velocities (km s\(^{-1}\)) of absorption components of the P-Cygni profiles

|   | Atomic identification | Rest wavelength (Å) | V1186 Sco | V2540 Oph | V5113 Sgr | V4745 Sgr | V458 Vul |
|---|-----------------------|---------------------|-----------|-----------|-----------|-----------|-----------|
|   |                       |                     | 7/20      | 4/12      | 9/21      | 5/8       | 8/9       | 8/10      |
|   |                       |                     | 4/19      | 5/19      | 9/27      | 10/8      | 10/24     |           |
|   |                       |                     | 4/12      | 5/19      | 9/21      | 5/8       |           |           |
|   |                       |                     | 4/12      | 5/19      |           |           |           |           |
| Fe II | 5018                   | −1000 ± 100         |           |           |           |           |           |           |
| Fe II | 5169                   | −1000 ± 100         |           |           |           |           |           |           |
| Na I  | 5896                   | −1220 ± 100         |           |           |           |           |           |           |
| O I   | 6155                   | −1070 ± 100         |           |           |           |           |           |           |
| Hβ    | 4861                   | −1360 ± 150         |           |           |           |           |           |           |
| Fe II | 5018                   | −1540 ± 100         | −820 ± 100| −1290 ± 100|           |           |           |           |
| Fe II | 5169                   | −1420 ± 100         | −1160 ± 100|           |           |           |           |           |
| Na I  | 5896                   | −740 ± 100          | −1250 ± 100| −1410 ± 100| −1800 ± 100|           |           |           |
| Ho    | 6563                   | −1070 ± 100         |           |           |           |           |           |           |
| Hβ    | 4861                   | −1180 ± 100         |           |           |           |           |           |           |
| Fe II | 5018                   | −1070 ± 100         |           |           |           |           |           |           |
| Fe II | 5169                   | −1380 ± 200         | −820 ± 100| −1290 ± 100|           |           |           |           |
| Na I  | 5896                   | −740 ± 100          | −1250 ± 100| −1410 ± 100| −1800 ± 100|           |           |           |
| Ho    | 6563                   | −1070 ± 100         |           |           |           |           |           |           |
| Hβ    | 4861                   | −1650 ± 100         |           |           |           |           |           |           |
| Fe II | 5018                   | −1640 ± 100         | −2480 ± 150|           |           |           |           |           |
| Fe II | 5169                   | −1740 ± 200         |           |           |           |           |           |           |
| Na I  | 5896                   | −1600 ± 100         |           |           |           |           |           |           |
| Ho    | 6563                   | −1740 ± 100         | −2230 ± 100|           |           |           |           |           |
| Hβ    | 4861                   | −1720 ± 100         | −1930 ± 100|           |           |           |           |           |
| He I  | 5015                   | −1480 ± 100         |           |           |           |           |           |           |
| He I  | 5876                   | −1360 ± 100         |           |           |           |           |           |           |
| Ho    | 6563                   | −1920 ± 100         | −1840 ± 100|           |           |           |           |           |
| He I  | 6678                   | −1450 ± 100         |           |           |           |           |           |           |

**Fig. 13.** Spectrum of V378 Ser on 2005 April 4.

**Fig. 14.** Spectrum of V378 Ser on 2005 April 22.
1.5 mags and the duration of the rebrightening phase was about four months after the discovery. These rebrightenings show six or seven peaks and the time interval between successive maxima increases gradually (figure 15). Pejcha (2009) also reported this trend of the interval elongation. The mean visual magnitude of V2540 Oph scarcely varies during the rebrightenings.

The light curve of V5113 Sgr is presented in figure 6. It shows three peaks during the early phase. The amplitude of the first rebrightening is approximately 2.2 mag (JD 2452901.8-2452903.9), and the average amplitude is approximately 1.8 mag. This light curve is different from the light curves of the other novae in this paper, in that the rise of the rebrightening is slower than the decline. The duration of the rebrightening phase is about one month.

The light curve of V4745 Sgr is presented in figure 8. It shows more than seven peaks. It seems similar to the light curve of V2540 Oph during the early phase (figure 3), while the mean visual magnitude slowly declines during the rebrightening phase in V4745 Sgr. The average amplitude is approximately 2.6 mag except the second mini outburst (JD 2452761.8) and the duration of the early rebrightening phase is about six months. The time interval between successive maxima increases gradually during the early phase. Csák et al. (2005) reported this increasing nature of the recurrent time, which was also reported previously in GK Per and DK Lac by Bianchini et al. (1992).

The light curve of V458 Vul is presented in figure 10. It exhibits three peaks with the average amplitude of about 1.8 mags during the early phase, and the rebrightenings with a smaller amplitude during the transition phase after JD 2454370. The duration of the rebrightening phase is approximately two weeks (JD 245322-245335). Note that this light curve sometimes shows small oscillations with an amplitude of smaller than 1 mag.

The light curve of V378 Ser is presented in figure 12. It exhibits many rebrightenings or oscillations during the early phase. The amplitude between the third maximum and the minimum after that maximum (JD 2453476.3-2453478.2) is about 1.7 mags and the average amplitude is approximately 1.5 mag.

V1186 Sco, V5113 Sgr, and V458 Vul are identified as fast novae, while V2540 Oph, V4745 Sgr and V378 Ser as slow or moderately fast novae. A clear difference between the former and latter is the number of experienced rebrightenings, ~3 in the fast novae, while ~6 in the slow novae. The duration of the rebrightening phase is ~10 days in the fast novae, while ~100 days in the slow novae. The rebrightenings during the early decline have been also observed in the novae V1178 Sco (moderately fast nova), V4361 Sgr (slow nova) (Kato & Fujii 2001), V2214 Oph (slow nova) (Lynch et al. 1989), and V686 Cen (fast nova) (Williams et al. 2003). The light curves of these novae trace this trend of the duration of the rebrightening phase.

As noted above, the time interval between successive maxima increases gradually (see Csák et al. 2005 ; Pejcha 2009). Stroe et al. (2010), on the other hand, reported that it appears that the timing of the rebrightenings is random within the interval over which they occur. We plotted the successive recurrence times versus time from the first maximum in figure 15. We can find that the time intervals of the rebrightenings of our 6 targets exhibit a similar systematic trend. We first confirmed that this trend is applicable to all types of novae: fast and slow, and Fe II type and hybrid type. We find that this trend follows the equation:

$$\log(t_i - t_{i-1}) = a \log(t_i - t_{\text{max}}),$$

where $a$ is the slope. The least-squares fit to all data of 6 novae yields $a = 0.79 \pm 0.01$. Pejcha (2009) derived $a$ of $0.88 \pm 0.04$ for DK Lac and $0.79 \pm 0.04$ for V4745 Sgr. The values are close to that of our result.

5.2. Common character of the spectral evolutions

In 6 novae, V1186 Sco, V2540 Oph, V5113 Sgr, V4745 Sgr, V458 Vul and V378 Ser, we found that some of the lines in the spectra at and around the brightness maximum show P-Cygni profiles, and they do not have the absorption components of the P-Cygni profile in the interval between successive maxima. These facts suggest the following scenario. First, the photosphere of the nova rapidly expands after the nova eruption. The temperature of the photosphere decreases as the photosphere expands. Next, when the radius of the optically thick envelope becomes maximum, the nova reaches its maximum brightness in the optical and the spectrum has stronger absorption lines. Although the optically thin envelope continue to expand, the photosphere then start to shrink. The continuum of the optical spectrum decays, as the photosphere shifts inside. Consequently, the absorption components disappear and the emission lines become stronger due to decay of the optical continuum, and expansion of the optically thin gas envelope. After that, the optical continuum rises again, without growth of the emission lines, in some novae. This behavior proves reexpansion of the photosphere.

Based on the observations of V4745 Sgr, Csák et al. (2005) mentioned that the reappearance of the P-Cygni profile suggested mass ejection at the rebrightening. Pejcha (2009) concluded that the rebrightening...
ening were likely caused by hydrogen-burning instabilities. As noted above, we proposed that rebrightening without growth of the emission lines, and reappearance of the absorption component of the P-Cygni profile indicate re-expansion of the photosphere, which is not inconsistent with the interpretations by Csák et al. (2005) and Pejcha (2009).

Table 2 summarize the variability of the blue-shift velocity of the absorption component of the P-Cygni profiles in 5 novae except V378 Ser. We can not find a common trend of this variabilities. In V2540 Oph, all the blue-shift velocities of Fe II lines decreased with time. In V5113 Sgr, the velocities of Fe II 5169 do not exhibit a simple trend, while the velocities of Na I increased progressively. In V4745 Sgr, all the velocities increased greatly.

5.3. Comparison with the second rebrightening in V2362 Cyg

There are several types of the light curves of novae, although no two novae show exactly the same light curves. In this paper, we presented the light curve of the 6 novae showing a few to several rebrightenings during the early phase. In this and next subsections, we will compare these novae to some different types of novae.

V2362 Cyg, a slow nova, caused the rebrightening eight months after the initial maximum (see Kimeswenger et al. 2008; Lynch et al. 2008; Poggiani 2009). Munari et al. (2008) presented the spectral evolution of V2362 Cyg. They reported that, at the second maximum, the underlying continuum was much hotter and the absorption lines, He I lines (for example 5876 Å), were present. This is inconsistent with our idea that reappearance of the P-Cygni profile is related to re-expansion of the photosphere, since the photosphere expansion means decrease of the effective temperature. The mechanism of the rebrightenings observed in our targets is thought to be different than that in V2362 Cyg.

Similar rebrightenings long time after the maximum have been also observed in V1493 Aql and V2491 Cyg (see e.g., Bonifacio et al. 2000; Kiyota et al. 2004; Hachisu & Kato 2009). Hachisu & Kato (2009) suggested that the mechanism of the rebrightening is the strong magnetic re-connection between the white dwarf and the companion star. Kato et al. (2009) reported that the light curves of V1493 Aql and V2362 Cyg are composed of the power-law decline and exponential brightenings. They proposed that the rebrightening can be caused by a shock resulting from a secondary ejection and its breakout in the optically thick nova winds.

5.4. Comparison with the oscillation during the transition phase in V1494 Aql

The light curves of some novae, like the fast nova V1494 Aql, show oscillations during the transition phase, at about 3.5 magnitude below the brightness maximum (see e.g., McLaughlin et al. 1943; Iijima & Esenoglu 2003). This oscillation seemingly mimics rebrightenings during the early phase. Iijima and Esenoglu (2003) presented the spectra during transition phase of V1494 Aql. They suggested that the origin of this oscillation was high velocity jets, because high velocity broad components appeared in the red and blue sides of Balmer lines during the transition phase. Such high velocity wings, however, do not appear in our observations. Moreover, the emission lines in V1494 Aql did not have a P-Cygni profile at the maximum brightness. We thus suggest that the origin of rebrightenings during the early phase is different from that of the oscillations during the transition phase.

6. Conclusions

The light curves of the novae V1186 Sco, V2540 Oph, V5113 Sgr, V4745 Sgr, V458 Vul and V378 Ser display several rebrightenings during the early phase. Some slow or moderately fast, but not fast novae, have been known to show rebrightenings having a large amplitude during the early phase, although it is not clear how slow novae accomplish these rebrightenings. We found that three fast nova V1186 Sco, V458 Vul, and V5113 Sgr caused such rebrightenings. Moreover, the recurrence time of the rebrightening increase with a power law of the time from the first maximum (the index of 0.79(1)). This trend is applicable to all types of novae: fast and slow, and Fe II type and hybrid type.

Our low-resolution optical spectra revealed spectroscopic changes during the early rebrightenings. The spectra at the first brightness maximum of these rebrightenings show many emission lines with P-Cygni profiles. We found that the absorption component of these P-Cygni profiles once disappear after the brightness maximum, and then reappear at the next brightness maximum, in some lines. We suggest that the rebrightening is due to enhancement of the continuum, and not due to growth of the flux of the emission lines. These means re-expansion of the photosphere at rebrightenings.

In addition, we compared 6 novae in our observations with other novae showing rebrightenings/oscillations during the transition phase. We are unable to find the common features between our spectra and the spectra at the second maximum in V2362 Cyg, and the spectra during the transition phase in V1494 Aql. It suggests that the physical origin of the rebrightenings in our 6 targets in the early phase is different from that in V2362 Cyg and V1494 Aql.

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