Abstract. Light curve analysis of decay phase of nova outburst are summarized. Nova duration is determined by the strong wind mass-loss which depends only on the white dwarf mass. Fast novae correspond very massive white dwarfs and very slow novae correspond almost lower mass limit of white dwarfs. This relation is shown in both of classical novae and recurrent novae. Light curves are theoretically reproduced for recurrent novae, U Sco, V394 CrA, CI Aql, V2487 Oph, RS Oph, T CrB, V745 Sco and V3890 Sgr, using binary model composed of a white dwarf, an irradiated accretion disk, and partly irradiated companion which is shadowed by the accretion disk. From the light curve fitting, we conclude that most of these objects contain a very massive white dwarf close to the Chandrasekhar mass limit (1.37 $M_\odot$ for U Sco, V394 CrA T CrB and RS Oph, 1.35 $M_\odot$ for V2487 Oph, V3890 Sgr and V745 Sco). They are strong candidates of type Ia SN progenitors. Population II novae have trends of slow evolution and small expanding velocity compared with disk novae.

1. Nova Outbursts and Optically Thick Wind Theory

Nova outbursts are thermonuclear runaway events on white dwarfs. Depending on the binary parameter such as the mass accretion rate, composition of the envelope and the white dwarf mass, nova outbursts shows a wide variety of the recurrence period, its light curve, the duration time and expanding speed of gaseous matter and so on.

Classical nova shows enhancement of carbon and oxygen or other white dwarf material in its ejecta. The recurrence period is as long as ten thousand of years or so and we can observe only one outburst for one nova binary. On the other hand, recurrent novae repeat outbursts every several to several-tens of years and its ejecta shows no enhancement of white dwarf material.

After the onset of shell flash, the white dwarf rapidly brightens up and the envelope greatly extend to a giant size and the strong wind mass-loss begins to blow the envelope mass. After the star reaches the optical maximum the photospheric radius reduces with increasing effective temperature, which causes the decay of visual light curve.

The mass loss during nova outburst is a radiation-driven wind which is accelerated deep inside the photosphere (Friedjung 1966). Such a wind is called
Figure 1. (left) Run of the updated OPAL opacity for the wind solutions of a classical nova model on a $1.0M_\odot$ white dwarf. The heavy element contents is $Z = 0.1, 0.05, 0.02, 0.004$ and $0.001$ from top to bottom. For the detail, see Kato 1997. (light) Change of the velocity, the temperature, and the density of three envelope of a classical nova model. $Z = 0.05$ (dashed line), 0.02(solid line), and 0.001 (dotted line).

as the optically thick wind. The decay phase of nova outbursts is followed by a quasi-evolution theory (summarized in Kato & Hachisu 1994) which is to make a sequence of optically thick wind solutions of expanding envelope.

Figure 1 (left) shows the run of the opacity throughout an envelope of a classical nova model. The OPAL opacity has a strong peak owing to iron lines at $\log T \sim 5.2$ which locates deep inside the photosphere. This opacity peak blocks radiative flux to accelerate the wind mass-loss. As shown in the right figure the wind velocity increases quickly at the temperature region corresponding to this opacity peak. The wind velocity already reaches the terminal velocity at the photosphere. In the optically thick wind the mass-loss rate is very large, because the acceleration occurs deep inside where the density is high. It is naturally understood that the velocity and the mass-loss rate of winds are larger for larger metallicity, i.e., larger in population I than in population II novae.

2. The HR diagram and the Decay Time-Scale

The evolutionary course of the decay phase in H-R diagram is plotted in figure 2. The decay phase of the classical nova and the recurrent nova with different composition is similar to the curves in figure 2 (see Kato 1997 for classical novae, Kato 1999 for recurrent novae).

At the optical peak the star reaches the maximum radius which point locates somewhere in the right side of each curve. As the strong wind blows out the envelope mass, the photospheric radius moves inward and the effective temperature rises, thus the star moves leftward. The wind mass-loss occurs in the dashed parts. After the wind stops, the star still goes leftward until nuclear
burning extinguishes at the small dot. In less massive stars, the acceleration is not enough to cause the optically thick wind.

In massive white dwarfs, the evolutionary speed is short mainly because of the small envelope mass which is blown off within a short time by the wind. Therefore, the nova outburst is fast in massive white dwarfs and slow in less massive stars. In a lowest limit of white dwarfs, the acceleration is weak to cause the optically thick wind.

The wind acceleration also depends on the metallicity as shown in the left figure. The larger iron content, the stronger peak of the opacity that causes a strong wind. In $Z = 0.02$, shell flashes do not occur or very weak in $\leq 0.4M_\odot$ white dwarf for classical novae, and $\leq 0.5M_\odot$ for recurrent/symbiotic novae. In $Z \leq 0.004$, shell flashes do not occur or very weak in $\leq 0.6M_\odot$ for classical nova, and $\leq 0.8M_\odot$ for recurrent/symbiotic nova.

3. Light Curve Analysis and Decay Time-Scale

3.1. Classical Nova

The decay phase of nova outburst is followed by the optically thick wind theory. The method of light curve fitting of nova is firstly established in nova Cygni 1978 (Kato 1994). The wind mass-loss rate depends strongly on the white dwarf mass, therefore, we can determine the white dwarf mass from the light curve fitting. In case of nova Cygni 1978, the two independent fittings of optical and UV light curves give the same values of white dwarf mass of $1.0M_\odot$ and the distance to the star.
Nova Cygni 1978 is a moderately fast nova. More rapid evolution is predicted only in more massive white dwarfs. Light curve fittings of several classical novae show a fast classical nova corresponds to a very massive white dwarf ($\sim 1.3M_\odot$), moderately classical nova such as Nova Cyg 1978, correspond a moderately massive white dwarf ($\sim 1.0M_\odot$), and slow evolution of slow novae, the less massive white dwarf($\sim 0.6M_\odot$ for Nova Mus 1985). It is very interesting that the fastest limit of classical nova corresponds to the massive limit of the white dwarf, and the slowest one the lowest limit.

3.2. Recurrent Novae and Symbiotic Novae

Recurrent nova and symbiotic nova can be treated as a same subgroup of nova, that shows no white dwarf material enhancement. The difference between the two is in the white dwarf mass and the contribution of the companion and the accretion disk. The similar relation to classical nova, i.e., the relation between the evolutionary speed of light curves and white dwarf mass, also stands in these novae. Most rapid evolution of some recurrent novae corresponds very massive white dwarf close to the upper limit ($\sim 1.37M_\odot$ as shown above) and slow evolution the moderately massive white dwarfs (e.g., $\sim 1.2M_\odot$ for T Pyx). Very long duration of some symbiotic novae corresponds low-mass white dwarfs ($\sim 0.6M_\odot$ for symbiotic nova RX Pup).

4. Light Curve Analysis of Recurrent Novae

Using binary models composed by a white dwarf, an accretion disk and a companion, we have calculated theoretical light curve of recurrent novae. In the first phase, the envelope largely expand to about several tens of the binary size, and the companion are deeply embedded by the envelope. As the strong wind carries away most of the expanding envelope, the photospheric radius moves inward, and in the later phase, we can see the companion and the accretion disk again.

The early phase of the light curve is determined by the wind mass-loss rate. In the following plateau phase the accretion disk and the partly irradiated companion contribute the visual magnitude. Therefore, in this stage, we have calculated visual flux summing up of three component, of the white dwarf photosphere, the irradiated accretion disk, and the partly irradiated companion that is shadowed by the accretion disk. We divided their surfaces into 9000 small areas and calculated emission flux from each areas to sum up.

4.1. U Sco type subclass

The recurrent nova U Sco, V394 CrA, CI Aql, and V2487 Oph are members of the subclass of U Sco type that have a slightly-evolved main-sequence companion.

U Scorpii is one of the well observed recurrent novae, characterized by the shortest recurrence period $\sim 8$ yr, the fastest decline of its light curve 0.6 mag per day, its extremely helium-rich ejecta He/H $\sim 2$ by number. The latest outburst in 1999 was well observed from the rising phase to the cooling phase by many observers including eclipses which provide us a unique opportunity to construct a comprehensive model for U Sco during the outburst.
We have reproduced the light curves by binary model as shown in figure 3. To fit the early linear decay phase \((t \sim 1 - 10 \text{ days after maximum})\), we have calculated total 140 \(V\)-magnitude light curves with various WD mass, hydrogen content the envelope, where the heavy element content \(Z = 0.02\) is fixed, and companion mass. We choose \(1.377M_\odot\) as a limiting mass just before the SN Ia explosion in W7 model \((M_{\text{Ia}} = 1.378M_\odot)\) of Nomoto, Thielemann, & Yokoi (1984).

The early 7 days light curve hardly depends on the chemical composition or the companion mass but mainly depends on the white dwarf mass. The \(1.37M_\odot\) light curve is in much better agreement with the observations than the other WD masses. In the middle plateau phase, the irradiated accretion disk mainly contributed to \(V\) light, because the white dwarf photosphere shrinks to a small size and shadowed by the accretion disk.

To fit the cooling phase \((t \sim 30 - 40 \text{ days after maximum})\), we must adopt very small hydrogen content of \(X = 0.05\) among other values. This is because the hydrogen content, \(X\), determines the period of hydrogen steady shell burning, i.e., the period of the mid-plateau phase. In our model, the optically thick wind stops at \(t = 17.5\) days, and the steady hydrogen shell-burning ends at \(t = 18.2\) days.

In the evolutional course of the outburst, the visual magnitude drops and UV and soft X-ray fluxes increases. It is because the photospheric temperature increases after the optical peak, because the main emitting region moves blueward (to UV then to soft X-ray). This picture is very consistent with the BeppoSAX supersoft X-ray detection 19 – 20 days after the optical peak (Kahabka, et al. 1999). In the strong wind phase we cannot expect much of supersoft X-rays because of self-absorption by the wind itself.

In this way, the light curve fitting gives us an estimate for binary parameters, such as the white dwarf mass and chemical composition of the envelope, and if orbital period is available, we further know the mass transfer rate and the growth rate of the white dwarf mass.

V394 CrA is a twin system that shows very similar light curves. In the same way as in U Sco, we have reproduced light curve of V394 CrA and determined the white dwarf mass to be \(1.37M_\odot\) and \(X = 0.05\) with \(Z = 0.02\) as shown in figure 4 (Hachisu & Kato 2000b)

The light curve analysis of CI Aql and V2487 Oph is separately reported in detail in this conference proceedings (Hachisu et al. for V2487 Oph, Hachisu & Kato for CI Aql). The white dwarf mass of these two recurrent novae are also massive, \(1.2M_\odot\) for CI Aql and \(1.35M_\odot\) for V2487 Oph.

### 4.2. RS Oph type subclass

RS Oph, T CrB, V745 Sco and V3890 Sgr are a subclass of recurrent nova with a red giant companion. As the companion substantially contributes the light curve in later phase, we have calculated huge number of binary models with different parameters and choose a configuration which gives the best fitted light curve.

Figure 5 (left) shows the binary configuration of T CrB selected in this way. The cool component (right) is a red giant filling up its inner critical Roche lobe.
Figure 3. (left) Configuration of our U Sco binary model. About 9 days after the maximum, the white dwarf photosphere shrinks to \( R_{\text{ph}} = 1.0R_\odot \). (light) Theoretical light curve (solid line) and observational points. The contributions of the white dwarf photosphere and the accretion disk which is partly irradiated is denoted by dotted and dashed curves, respectively. For details, see Hachisu et al. 2000.

Figure 4. (left) Binary model of V394CrA about 11 days after the maximum. The white dwarf photosphere shrinks to \( R_{\text{ph}} = 1.0R_\odot \). (light) Theoretical light curve for V394CrA (solid lines) with three inclination angles (\( i = 30^\circ \) for the top curve). Observational points are indicated by circles. For details, see Hachisu & Kato 2000b.
Figure 5. (left) Model configuration near the second peak of the recurrent nova T CrB. The photospheric radius of the hot component at the second peak is as small as \( \sim 0.003R_\odot \), about \( \sim 0.00003 \) times the size of the cool component, and the accretion disk radius is \( \sim 6R_\odot \), i.e., about \( \sim 0.07 \) times the inner critical Roche lobe size. They are exaggerated so that it may be seen easily. (light) Light curve fitting of T CrB. Large arrows attached by "min" indicate epochs at the spectroscopic conjunction with the M giant in front. (Dotted line): The total V light of the white dwarf photosphere and the red giant (RG) photosphere without irradiation. Large arrows attached by "min" indicate epochs at the spectroscopic conjunction with the M giant in front. (Dash-dotted line): The total V light of the WD photosphere and the RG photosphere irradiated by the white dwarf. (Solid line): the total V light of the WD photosphere, the RG photosphere with irradiation, and the accretion disk surface heated-up by the hot component. The parameters specifying the light curves are shown in the figure.

Its hemisphere is heated up by the hot component (\( \sim 1.37M_\odot \) white dwarf, left). The surface of the accretion disk is also heated up.

The light curve fitting is shown in the right figure. If we do not include the contribution of irradiation from the companion, the summation of the V light of the white dwarf photosphere and the red giant photosphere is very small in the later phase as shown by the dotted line. The dash-dotted line denotes the case if we include the irradiation from partly heated RG photosphere, and the solid line the case if we further include the irradiation form the accretion disk.

We assume a tilting accretion disk as in the left figure with precession at a period of about 140 days. The disk in T CrB meets the condition of instability against radiation-induced warping (Pringle 1996) with the disk size, bolometric luminosity, the mass of the white dwarf mass accretion rate obtained our light curve fitting. The accretion disks in RS Oph and other two systems do not meet this instability condition mainly because of small disk size. Therefore, we cannot expect the secondary peak for these other three systems. This is the reason that makes T CrB a very unique nova with the prominent secondary peak (Hachisu \\& Kato 2001).

Figure 6 shows light curve fitting of RS Oph. In the early phase the development of light curve is determined by the wind mass loss, which depend only
Figure 6. (left) $V$ Light curve fitting of RS Oph in the very early phase. The metallicity is attached to each line (for $Z = 0.001$, $Z = 0.004$, $Z = 0.01$, $Z = 0.02$). The hydrogen content of the WD envelope is assumed to be $X = 0.70$, since the hydrogen content, $X$, hardly affect the decline rate of the $V$ light curve (Kato 1999). Filled circles indicate observational points with the previous outbursts. (light) The light curve fitting for the entire outburst phase. We assume $M_{WD} = 1.377M_\odot$, $X = 0.7$, and $Z = 0.004$. (Dashed line): Sum of the contributions from the white dwarf photosphere and the nonirradiated red giant photosphere. The RG lies well within the inner critical Roche lobe, i.e., its radius is 0.25 times the Roche lobe size. (Dashed-dotted line): Sum of the WD photosphere and the irradiated RG photosphere. (Solid line): the total $V$ light of the WD photosphere, the irradiated RG photosphere and the accretion disk surface. The thin and the tick solid curves have different shape of the accretion disk (for detail see Hachisu and Kato 2001).

on the white dwarf mass and the heavy element composition of the envelope. There are some observational indication that this object is an old population, thus we have calculated theoretical curves with different metallicities and white dwarf masses. The left figure shows one of such trial fittings that shows, if $Z = 0.004$, the best fit curve is obtained with extremely massive white dwarf $1.377M_\odot$. This is a very critical value just before a type Ia supernova explosion (Nomoto, Thielemann, & Yokoi 1984).

The right figure shows the light curve fitting of entire phase of outburst. In the later phase, the accretion disk and the irradiated companion substantially contribute the $V$ light curve and we determine the shape and the size of the accretion disk (Hachisu & Kato 2000a, Hachisu & Kato 2001). The optically thick wind blows during the period from the first phase of the outburst (HJD 2,446,092) to 79 days after the maximum (HJD 2,446,170). The steady hydrogen shell burning ends at 112 days after maximum (HJD 2,446,203).

The light curve fitting of the other two objects are shown in figure 7. The left figure represents the total $V$ light of the WD photosphere, the irradiated RG, and the irradiated accretion disk. From the light curve fitting we conclude that the white dwarf mass is as massive as $1.35M_\odot$. In the same way, the light curve of V3890 Sgr is reproduced as shown in the right figure. The white dwarf mass is estimated as $1.35M_\odot$. 
Figure 7. (left) V745 Sco; Model light curves and observational points of the 1989 outburst. The solid line represents the best fitted model of $1.35 M_\odot$ WD, the irradiated RG, and the irradiated accretion disk. The dashed line denotes the $V$ light curve of the WD photosphere and the nonirradiated red giant. The dash-dotted line corresponds to the $V$ light from the WD photosphere and the irradiated red giant. The photospheric radius of the white dwarf is indicated above the light curve. The optically thick wind stops at HJD 2,447,819 and the steady hydrogen shell burning ends at HJD 2,447,860. (right) V3890 Sgr; Model light curves are plotted against time (HJD 2,448,000+). Open circles indicate the observational points taken from IAU Circulars of the 1990 outburst.

5. Very Massive White Dwarfs

Seven out of these eight recurrent novae contain a very massive white dwarf close to the Chandrasekhar mass limit $1.35 M_\odot$ for V2487 Oph, V3890 Sgr, and V745 Sco, $1.37 M_\odot$ for T CrB, U Sco, V394 CrA, RS Oph (or more, depending on $Z$). Moreover, the growth rate of the white dwarf mass is estimated to be $0.1 - 1 \times 10^{-7} M_\odot yr^{-1}$ (Hachisu & Kato 2001 and references therein). Therefore, they are strong candidates of type Ia SN progenitors.

6. Population II novae

As mentioned in section 1, the acceleration of nova wind in the decay phase is governed by the iron peak in the opacity, that sensitively changes by heavy element content as shown in figure 1. The wind mass-loss is weak in population II novae, because a small iron peak produces only weak acceleration. Thus, a systemic differences are expected between population II novae and disk novae. A population II nova will show a smaller decline rate, a longer duration time and slower wind velocities compared with those of disk nova on the same white dwarf mass (Kato 1999).

Thus, a statistically trend of slow evolution in light curve is expected in population II novae. Fast novae and recurrent novae observed in LMC, SMC, and a globular cluster indicate that the binaries in such a low iron environment have very massive white dwarfs. Recent studies of stellar evolution suggest that
low metallicity environment intends to produce massive white dwarfs (Umeda et al 1999).

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