CATACLYSMIC VARIABLES:

ERUPTIONS AND FLICKERING

Hydrogen and Helium Flashes in Cataclysmic Variables

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Abstract: Light curve analysis for the decay phase of novae gives estimates of the white dwarf mass, the luminosity (or distance) and the chemical composition of ejecta. Differences in these parameters among nova subclass, i.e. fast, slow and recurrent, are briefly summarized to speculate on their cause. Helium shell flashes occur in mass-increasing white dwarfs, their theoretical light curves are given in UV and visual wavelength bands. An evolutional scenario for fast, slow and recurrent, and slow novae through a helium nova/EUV source-stage toward a type Ia supernova/neutron star formation-stage is given.

1 Hydrogen shell flashes in cataclysmic variables

A nova explosion is a thermonuclear runaway event (TNR) on the white dwarf of a close binary system. A hydrogen shell flash on the white dwarf causes the outburst in which the star quickly brightens up and the hydrogen-rich shell greatly extends. The envelope is eventually blown off. This extended development of a nova outburst can be modelled by the optically thick wind theory which has been so far the only method in reproducing nova light curves. The optically thick wind is a continuum-radiation driven mass loss in which the acceleration occurs deep inside the photosphere. The structure of the envelope is obtained by solving the equations of motion, continuity, radiative transfer in diffusion approximation, and energy conservation. Steady-state and spherical symmetry is assumed. The new OPAL opacity is used. The nova decay phase is described as a sequence of the steady wind solutions. The numerical methods are summarized in detail by Kato & Hachisu (1994).

2 Light curve analysis of the decay phase of novae

Novae can be divided into three subclasses, i.e. fast, slow and recurrent novae. Fast novae brighten by more than 10 magnitudes within a few days and after the luminosity peak, they almost return to their pre-outburst magnitude with time scales of months to a year. The chemical composition of ejecta deviates very much from the solar abundance and is abundant in He, C, O and other heavy

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elements. Slow novae show a decline time of several months to years. Helium enrichment is observed in some slow novae. Recurrent novae have a short decline time of 10 days to several months and usually a relatively small amplitude. The outburst repeats every few decades. No heavy element enhancement has been reported.

The first example of light curve fitting is for the fast classical nova V1668 Cyg (Nova Cyg 1978). Fig. 1 shows the theoretical light curves in optical and UV regions as well as the observed data. TNRs on massive white dwarfs show a rapid evolution because of the small envelope mass. Both the optical and UV data show a good agreement with the model of a 1.0 $M_{\odot}$ white dwarf. The distance to the star can also be estimated from the comparison between observed apparent magnitude and the theoretical absolute magnitude and turns out to be 2.9 kpc (UV) and 3 kpc (optical). The theoretical expansion velocity at the photosphere is also consistent with *IUE* data. Details are published by Kato (1994) and Kato & Hachisu (1994).

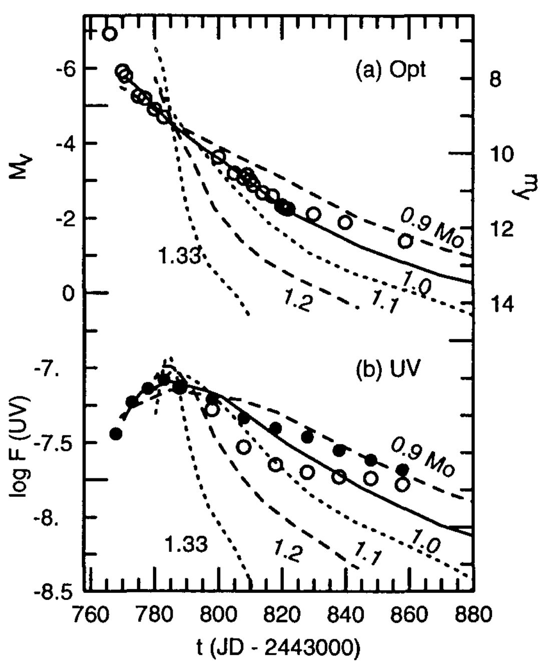

Fig. 1. Light curve fitting for the fast classical nova V1668 Cyg. Theoretical curves are denoted by thick curves, which are labelled by the white dwarf masses. (a) Optical light curves. The left ordinate shows the absolute visual magnitude for the theoretical curves and the right ordinate the apparent y-magnitude for observed data. Data are taken from Gallagher et al. (1980). (b) UV light curves. Open circles denote the UV flux (1140 Å- 3290 Å) and filled circles give the summation of the UV and IR fluxes (> 12000 Å) in units of erg/cm^2 sec^{-1} (Stickland et al. 1981). In theoretical UV flux, $F = L_{UV}/4\pi D^2$, the distance to the star $D = 2.88$ kpc is assumed.

Another example of a classical nova is GQ Mus (Nova Muscae 1983). Kato (1995) shows that the light curves of UV, optical, and IR bands are well fitted by models with the white dwarf of mass $0.5-0.6\ M_{\odot}$. These results indicate that the white dwarfs in classical novae be not always as massive as the Chandrasekhar limit as has been assumed in many papers.

As an example for the light curve fitting of a slow nova, Kato (1995) investigated RR Pic and gives an estimate of the white dwarf mass of $0.8-0.9\ M_{\odot}$.

Recurrent novae show very rapid decline rates and short recurrence periods. Such a rapid evolution can be obtained only in very massive white dwarfs. Fig. 2 shows the light curve fitting of V394 CrA. This figure shows theoretical light curves with different sets of chemical composition for a $1.377\ M_{\odot}$ white dwarf as well as observational data.

Kato (1995) shows that three other recurrent novae, U Sco, V745 Sco and T CrB, have very similar light curves to V394 CrA so that light curve fitting gives also very massive white dwarfs in these objects.

From these results of light curve fitting and observational characters, we can summarize differences in physical parameters among nova subclasses. Fast classical novae have relatively small white dwarf masses as small as $1.0\ M_{\odot}$ or less with heavy element enrichment in ejecta. Metal enrichment causes strong wind even on less massive white dwarfs. Slow classical novae show a long decay time, which is explained by models with small white dwarf mass and almost solar abundance of heavy elements. Rapid evolution in recurrent novae is explained by models of very massive white dwarfs, close to the Chandrasekhar limit.

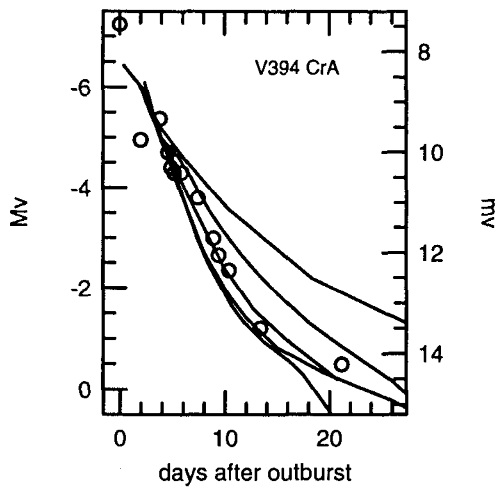

Fig. 2. Light curve fitting for V394 CrA. Dots denote the observational data by Duerbeck (1988). Theoretical curves show the dependence on the chemical composition; from upper to lower, (X,Z)=(0.5, 0.002), (0.1 0.004), (0.1,0.01), (0.7, 0.02), and (0.1, 0.02) are assumed. The white dwarf mass of $1.377\ M_{\odot}$ is assumed.

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3 Does the white dwarf mass increase or decrease?

Now, we will consider whether the white dwarf mass increases or decreases after many cycles of hydrogen shell flashes. The envelope mass, accreted from the companion, will be lost in part by the wind during the nova outburst, and the rest of it remains on the white dwarf. From the wind models fitted to observational light curves, we can estimate the amount of mass ejected by the wind and the amount of helium processed by nuclear burning. The ratio of matter that remains on the white dwarf after one cycle of hydrogen shell flash to the matter accreted is estimated to be a few percents for fast and slow novae, whereas it is a few tens of percents for recurrent novae.

This ratio further decreases if we include the effect of mixing of white dwarf matter into the hydrogen-rich envelope. There are two kinds of mechanisms proposed for mixing; One is hydrogen diffusion into the white dwarf matter (Prialnik & Kovetz 1992) and the another is shear mixing due to differential rotation (Fujimoto 1993). Such mechanisms mix the white dwarf matter into the upper envelope during the quiescent phase and then hydrogen ignites deep inside the envelope where heavy elements are enriched. Convection carries such material upward and mixes it into the upper envelope that will be ejected by the wind. In such a case the white dwarf losts more mass that it had accreted.

The heavy element enrichment observed in fast classical novae is, therefore, the evidence of dredge up of white dwarf material. In these objects the white dwarf mass will decrease after it suffers many cycles of nova outbursts. It is to be noted that neon novae, i.e. novae with neon rich ejecta, not necessarily contain a massive white dwarf, although stellar evolution theory concludes ONeMg white dwarfs should be massive ($> 1.35\ M_\odot$) at their birth.

In the case of slow classical novae, the helium enhancement in ejecta suggests that the white dwarfs have a helium layer under the hydrogen-rich envelope, and a part of the helium layer is dredged up by the same mechanisms as in the previous class.

In the case of recurrent novae, there is no evidence of heavy-element enrichment in ejecta. This suggests that no white dwarf matter is dredged up. Helium enhancement can be explained in part by hydrogen burning that is strong on very massive white dwarfs, and in part by dredged up material from the helium layer. When these observational aspects are combined with light curve fitting, we can conclude that the white dwarf keeps a part of the accreted material and will grow in mass.

4 Helium shell flashes

When a part of the accreted matter remains after the hydrogen shell flash, the white dwarf develops a helium layer under the hydrogen burning zone. This helium layer will grow in each hydrogen shell flash and when the mass of the helium layer reaches a critical value, unstable helium burning occurs to trigger a nova-like phenomenon. Energy generated by helium burning is consumed partly

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by the gravitational work to push matter upward and is partly radiated away. When most of the helium layer is burnt or blown off, the star becomes faint and the helium shell flash finishes.

Figure 3 shows light curves of helium flashes obtained by the optically thick wind theory. The radius of a hot white dwarf is assumed (Iben 1982). The light curve of helium novae is similar to that of typical novae but the development is very slow. When the helium shell flash is weak because of small ignition mass, the light curve starts from the middle part of curves in Fig. 4. In this case the star is observed as a bright UV source but it is faint at optical wavelengths.

Observational identification of a helium shell flash is important for the study of a relation between novae and type Ia supernovae. A helium shell flash occurs only on mass increasing white dwarfs, and will be observed as helium nova or a bright UV source with a composition which is highly deficient in hydrogen.

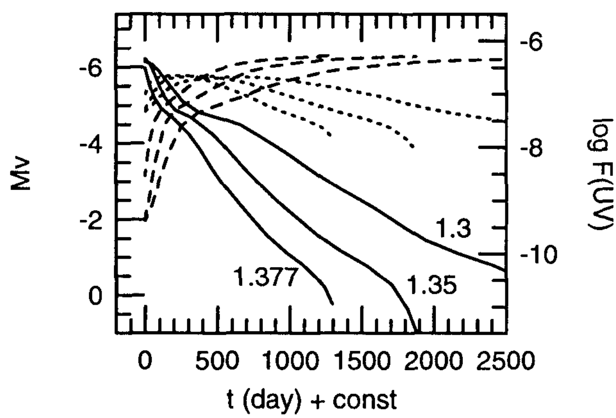

Fig. 3. Theoretical light curves of helium shell flashes on a white dwarf. Each curve is labelled by the corresponding white dwarf mass. Light curves in the visual, ultraviolet, and extreme ultraviolet bands are denoted by solid, dotted and dashed curves, respectively. In UV and EUV fluxes, a distance of 2.2 kpc is assumed.

5 Connection between novae and type Ia supernovae

Figure 4 summarizes the fate of white dwarfs in nova systems. In fast classical novae, the white dwarf has no helium layer under the hydrogen envelope and the white dwarf mass decreases after a nova outburst.

For slow classical novae, the white dwarf has a helium layer, a part of which will be lost after one nova outburst cycle. When all of the helium layer will be gone after many outburst cycles, the white dwarf becomes naked and then a part of the white dwarf matter will be mixed into the envelope and blown off during the next outburst. Therefore, this outburst is a fast classical nova outburst.

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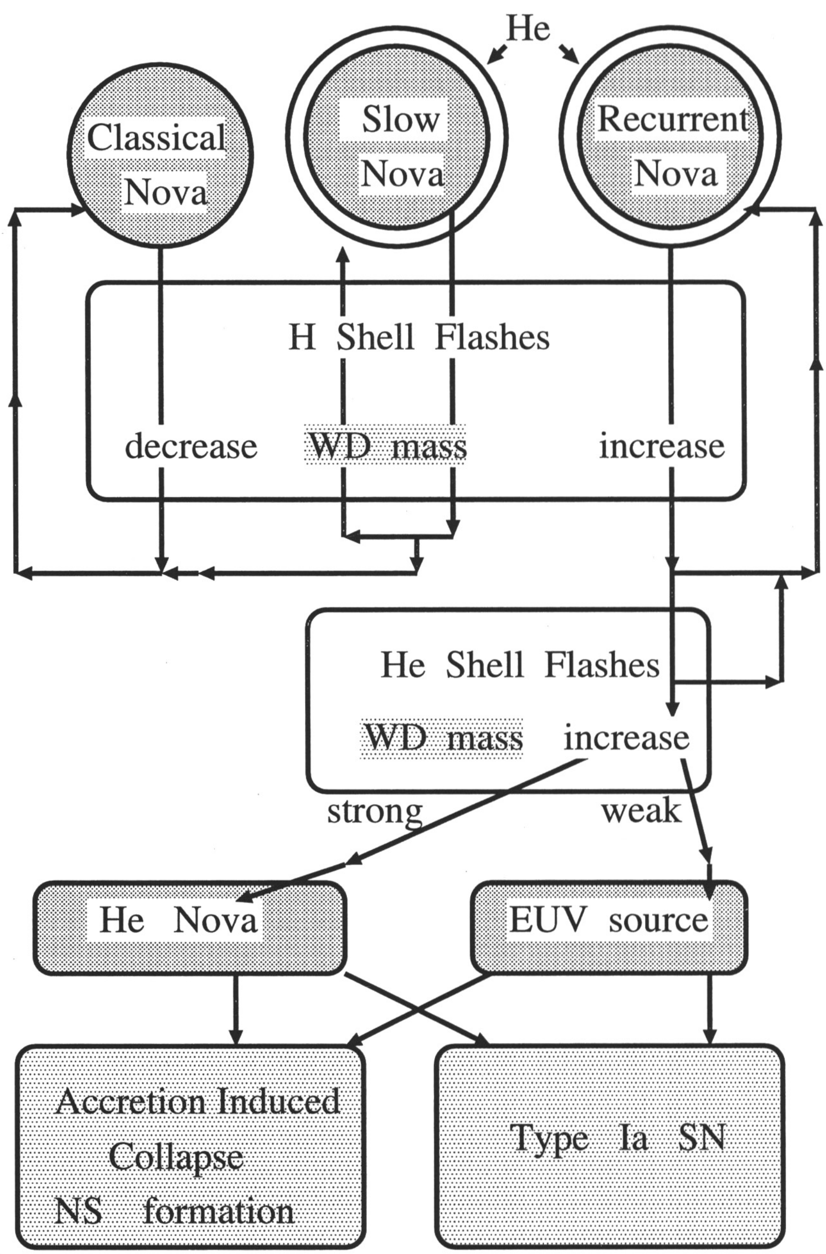

Fig. 4. Connection between novae and type Ia supernova/neutron star formation

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In recurrent novae, on the other hand, a part of the envelope mass remains on the white dwarf after shell flashes and the white dwarf grows in mass. A helium layer develops under the hydrogen burning zone and when its mass reaches a critical value, an unstable helium shell flash occurs to trigger a helium nova. If the shell flash is strong enough, it will be observed as a bright slow nova-like object with hydrogen deficient abundance, and if the shell flash is weak, it will be a bright EUV/UV source with a faint optical counterpart. In such a object, the white dwarf grows to close the Chandrasekhar limit and will be a type Ia supernova or a neutron star via accretion induced collapse depending on the initial and internal conditions of the white dwarf (Nomoto & Kondo 1991).

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M. Shapiro: In connection with Dr. Kato's proposal of the relation of recurrent novae to supernovae of type Ia, the following may be of interest: To explain the relative deficiency of H and He in the cosmic rays, I suggested in 1985 (ICRC Proceedings, La Jolla, USA) that one component of the cosmic rays, mainly the "heavy nuclei" ($Z > 5$) originate in large part from SN Ia, since these show virtually no H and He. This idea was developed more thoroughly by Hayakawa et al. (ICRC Proceedings, Adelaide, Australia), but the cosmic ray composition they deduced was rather contrived, depending on uncertain parameters.

L. Pustil'nik: You talked about novae with surface thermonuclear detonation. But a new type of objects of completely different nature (unstable accretion on a black hole), manifest themselves in the optical as recurrent novae, but show up as strong X-ray sources. Have you any test in the light curve (from your models) which may be used to distinguish between absolutely different objects when only the optical light curve has been observed (e.g. in the past when no X-ray observation was available)?

M. Kato: Some of the X-ray novae show very similar light curves to those of recurrent nova. To distinguish these two kinds of objects, we need more observational information such as expansion velocities, detection of X-rays, light curves in UV, EUV, soft X-ray etc.

J. van Paradijs: Apart from your proposed He burning massive white dwarfs there is another potential progenitor of SN Ia's and AIC formed neutron stars, i.e. the supersoft sources detected with *ROSAT*. They are generally considered to be steadily hydrogen burning massive white dwarfs. What are the expected relative formation rates of the two different progenitors?

M. Kato: To estimate the number of H burning white dwarfs and He burning white dwarfs is complicated and not yet be done. It is closely related to the binary evolution which include mass loss due to the optically thick wind and the angular momentum loss of the system. The observational properties of H burning white dwarfs and He burning white dwarfs may be similar, so that a part of the supersoft X-ray sources is possibly from the contribution of He burning white dwarfs.