PHYSICS OF MASS EJECTION DURING NOVA OUTBURSTS

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ABSTRACT. During nova outbursts a large part of the envelope mass is blown off. This mass ejection is caused mainly by the radiation driven wind and by the Roche lobe overflow. Theoretical studies on the acceleration mechanisms are briefly reviewed. Finally, I present theoretical light curves for U Sco based on the steady wind approach.

1. INTRODUCTION

Nova is caused by thermonuclear runaway on a white dwarf which accretes hydrogen-rich material. The nuclear energy generation par unit mass of hydrogen is ten times larger than the gravitational energy of the white dwarf. Therefore, we can expect that large part of the envelope mass will be blown off.

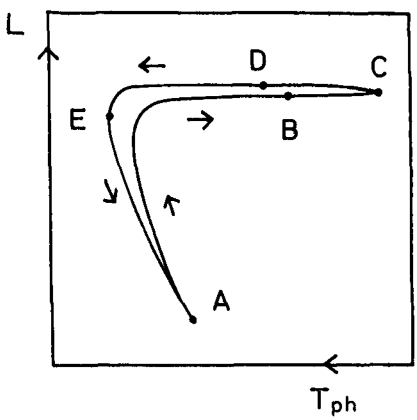

Figure 1: A schematic H-R diagram for an evolutional course of a nova. A:before the onset of hydrogen shell flash, B:mass loss starts, C:the minimum temperature, D: mass loss stops, E: nuclear burning ceases.

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Figure 1 shows a schematic diagram of the evolutional course of a nova outburst. Nova is triggered by unstable hydrogen burning in an envelope of an accreting white dwarf (point A). In the early stage of nova outburst energy is transported by convection, therefore the star brightens up at first and then goes redward. During the stage of radius expansion, mass loss occurs at point B. The envelope reaches a thermal equilibrium around point C. After the temperature minimum (point C), photospheric radius decreases as the envelope mass decreases. Then the star goes blueward. Hydrogen burning extinguishes at point E and then the star gradually cools down to point A.

The mass loss is caused by the wind and the binary's gravitational torque. In the wind mass loss, the acceleration is mainly due to the radiation pressure gradient which is effective inside of the photosphere. In the latter case the gaseous matter outside of the Roche lobe is accelerated by the gravitational torque of the binary.

Many theoretical works have been presented so far about mass ejection during nova outbursts, most of them are classified into three categories: static, steady state, and time-dependent approaches. The static approach is to construct some sequences of static solutions of less massive envelope around a white dwarf. In the steady state approach a sequence is constructed of static and steady state solutions. In both approaches a set of solutions represents the development of a nova outburst. On the other hand, time-dependent calculations follow directly the evolution of a nova outburst. Each method has merits and some difficulties which are characteristic of their assumptions and numerical techniques as will be mentioned below. Therefore what is the best method depends on what we are interested in.

2. ROCHE LOBE OVERFLOW

If the Roche lobe is small enough, matter extended beyond the Roche lobe will be accelerated by the gravitational torque of the binary. This type of acceleration has been directly investigated by the hydrodynamic calculation for gas flows around contact binary systems (Sawada, Hachisu, and Matsuda 1984, see references therein for restricted 3-body problem). Figure 2 shows a flow pattern around a contact binary system (Sawada, Hachisu and Matsuda 1984). The left

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star ejects matter at the surface of the Roche lobe. The outward component of the velocity increases outward within several orbital period. This results, however, is not directly applied to nova ejecta because of the deference of the equation of state, but we can see that the matter is quickly accelerated. Therefore we can conclude that the binary acceleration is effective when the wind velocity is lower than the orbital velocity. Therefore the Roche lobe overflow is effective in the decay phase of nova outbursts where the wind velocity reduces to comparable or less than the orbital velocity.

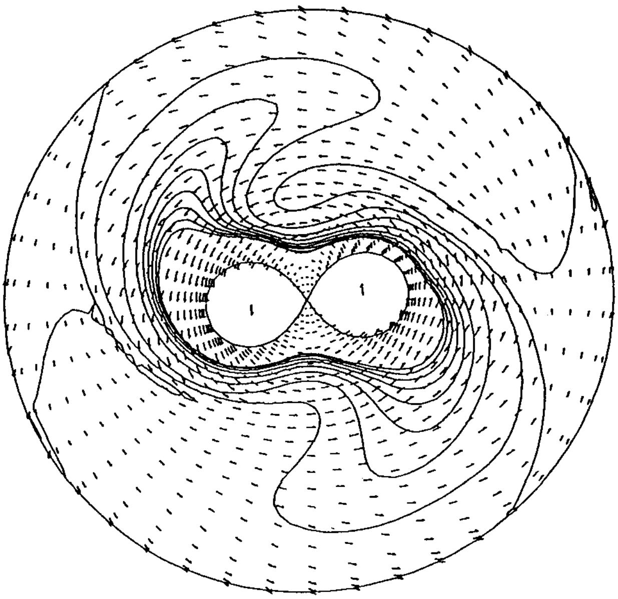

Figure 2: Density contours for a binary with mass ratio 1:1. The arrows represent the velocity vector seen in the inertial frame.

Some theoretical works on novae have taken into account the effect of the Roche lobe overflow (MacDonald, Fujimoto, and Truran 1985, in static approach, Kato and Hachisu 1988, 1989 in steady state approach, Kato, Saio, and Hachisu 1989 in time-dependent calculation), typically in a way to assume the rapid mass stripping at some radius. The decay time scale of novae becomes much shorter, because a large part of the envelope mass is quickly blown off.

The presence of the Roche lobe increases the amount of mass escaping form the binary system. If the Roche lobe is as small as $1R_{\odot}$, more than 2/3 of the envelope mass is ejected even in a weak shell flash in which no mass loss is expected (Kato and Hachisu 1989).

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3. WIND MASS LOSS

The wind mass loss has been mainly studied by the steady state and the time-dependent approach. The steady winds have been investigated in various problems (Finzi and Wolf 1971 for planetary nebulae formation, Ruggles and Bath 1979; Kato 1983b; Kato and Hachisu 1988, 1989 for nova outbursts, Żytkow 1972, 1973 for yellow giants, Kato 1983a,1986; Paczýnski 1983; Quinn and Paczýnski 1985 for X-ray bursts, Kato 1985 for surface boundary condition), and we have now an established way to make sequences for various phenomena. This approach is excellent when we want to know the accurate mass loss rates and light curves, and accurate value of the mass remained after one cycle of a nova outburst (Kato and Hachisu 1988, 1989). This method, however, is limited to only when the steady state is a good assumption such as in the decay phase of novae. On the other hand, the time-dependent approach can follow through a complete nova cycle (Sparks, Starrfield, and Truran 1978; Prialnik, Shara, and Shaviv 1979; Nariai, Nomoto, and Sugimoto 1980; Prialnik 1986, and reviews by Prialnik of this conference). This method, however, is not always free from numerical difficulties which brings ambiguity in the photospheric values. Therefore these two methods are complementary to each other, the combination of them for the same phenomena will yield quite accurate knowledge of the wind mass loss (e.g., Kato, Saio and Hachisu 1989 for helium nova). As some of the results of the time-dependent approach are reviewed in other papers of this proceedings, our attention will be paid here on the steady state approach.

Figure 3 depicts evolutional tracks for the decay phases obtained from the steady state approach. Mass loss solutions are discretely plotted by the dots, the crosses or by the other symbols. Short vertical bars denote the points at which the steady wind terminates. In the left side of these points no wind solution exist and static solutions exist instead. This figure shows that the wind mass loss is the main mechanism to blow off the envelope mass when the Roche lobe is very large, or the white dwarf mass is very massive.

Figure 4 shows the change in the diffusive energy flux of a solution for $1.3M_\odot$ white dwarf (Kato 1983b). The diffusive luminosity L_r decreases outward, because it is consumed to push the envelope matter up against the gravity. The Eddington luminosity $L_{Edd}=4\pi cGM/\kappa$ has dips at the ionization zones of helium and hydrogen where the opacity becomes large. The luminosity is super-Eddington there but

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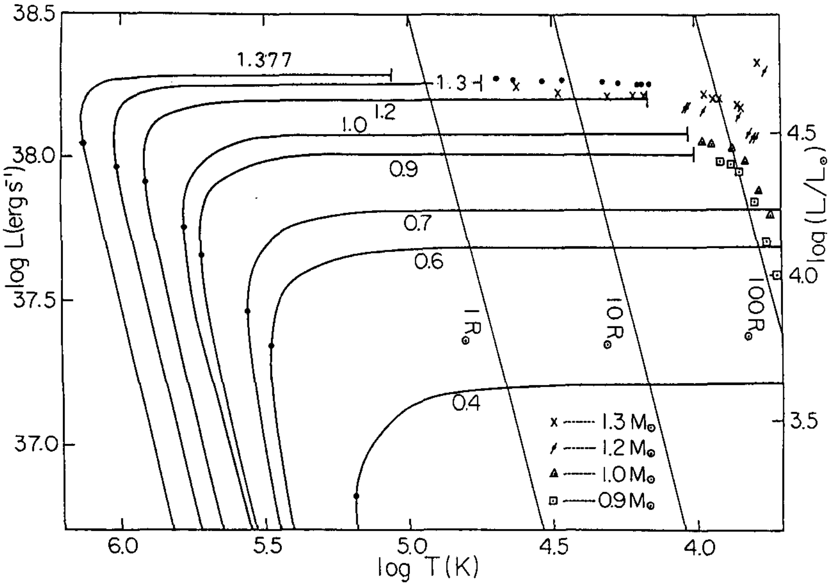

Figure 3: Evolutional courses of novae after the maximum expansion of the photospheric radius. The solutions of optically thick winds are discretely denoted by the filled circles (for 1.377$M_\odot$), the crosses, or the other symbols. The static solutions are plotted by thick solid lines. Short vertical bars denote the solutions at which the wind just stops. The extinction point of hydrogen burning is denoted by filled circles. The constant radius lines are denoted by thin solid lines.

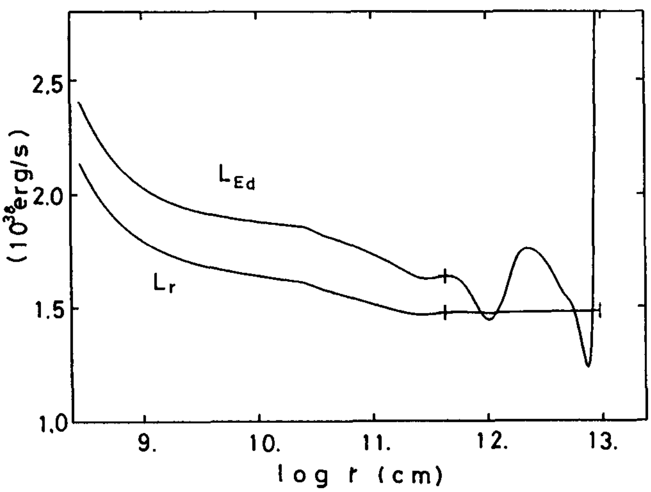

Fig. 4: Distribution of the energy flux by diffusion and the Eddington luminosity vs. radial coordinate.

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sub-Eddington at the photosphere. Matter is accelerated below and around the critical point, which appears near the ionization zone of helium in this case. The mass loss rate is uniquely obtained for each solution as an eigen value of the boundary-value problem. In the decay sequence shown in figure 3, the mass loss rate is large for lower surface temperature and decreases as the star goes blueward.

4. APPLICATION OF THE STEADY WIND MODEL TO U SCO

Let us now apply the steady wind model to a recurrent nova, U Sco. The recurrence interval of this object is very short (1863, 1906, 1936, 1979, and 1987) and its visual light curve develops extremely

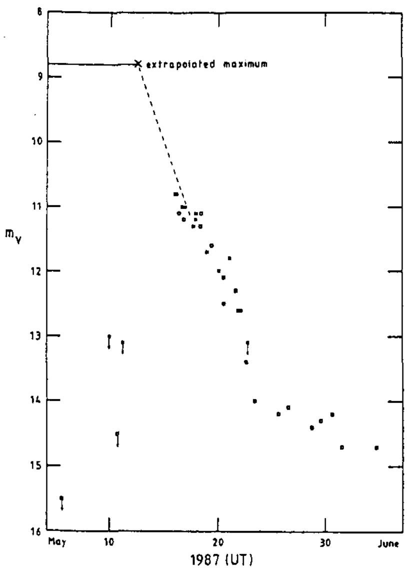

Figure 5: The visual light curve of U Sco during its 1987 outburst (Sekiguchi et al.1988).

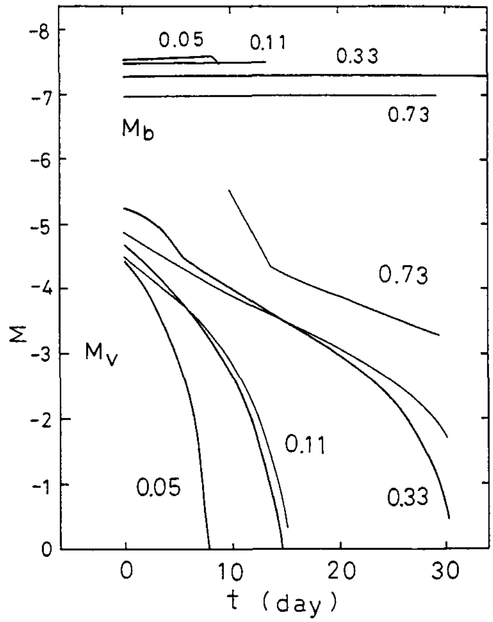

Figure 6: The theoretical light curves for a 1.377$M_\odot$ white dwarf. Numbers attached are the chemical composition of hydrogen with Z=0.02 (thin) and 0.03 (thick).

rapid as shown in figure 5. In 1979 outburst high helium abundance (He/H=2, by number) is observed (Barlow et al. 1981, Williams et al. 1981). From the theoretical point of view, the nature of the outbursts has been interpreted on the bases of the thermonuclear runaway model on a extremely massive white dwarf (Nariai and Nomoto 1979, Starrfield, Sparks, and Truran 1985, Webbink et al. 1987, Starrfield, Sparks and Shaviv 1988, Truran et al. 1988 and references therein). As the Roche lobe overflow may not be effective, we can follow the development of the light curve by the sequence of the steady wind solutions.

On these theoretical bases, sequences of steady wind solutions have been constructed for a $1.377M_{\odot}$ white dwarf. The envelope is assumed to have a uniform chemical composition, with X=0.73, 0.33, 0.11, 0.05 and Z=0.02, 0.03, for hydrogen and heavy element, respectively. The sequences are constructed only for the decay phase, because the steady state assumption may not be good in the initial rising phase. Figure 6 shows theoretical light curves obtained from this wind models.

To fit the theoretical models with the visual light curve observed, we can conclude as follows:

(1) The rapid decay in the light curve observed is reproduced using our steady state method. This rapid decay is caused by the rapid mass decreasing rate due to the hydrogen burning ($\sim 1\times10^{-5}M_{\odot}$ yr^{-1}) as well as the large mass loss rate of the wind ($1-6 \times 10^{-6}M_{\odot}$ yr^{-1})

(2) Observed chemical composition, i.e., helium enrichment and solar abundance of heavy elements, is consistent with our model. The theoretical curves with X=0.11 (observed value) and 0.05 are in good agreement with the observational data.

(3) The envelope mass of our models is consistent with those in other theoretical works based on thermonuclear runaway. The ignition mass for $1.38M_{\odot}$ white dwarf is $(6.5-7.5)\times10^{-7}M_{\odot}$ for X=0.49-0.11 (Truran et al.1988) , and $(3-5)\times10^{-7}$ $M_{\odot}$ for solar composition with high accretion rate $(1-10)\times10^{-8}M_{\odot}$ yr^{-1} (Nariai and Nomoto 1979). Our envelope mass, 4×10^{-7} $M_{\odot}$ for X=0.11 is consistent with these value, if we take into account the small differences of input parameters and the possible mass ejection in the initial phase.

(4) Distance to U Sco is obtained from fitting our theoretical light curves to the apparent visual magnitude observed. The bolometric correction is found to be as large as 2 mag even at the peak in the optical light curve. Then we get a short distance, 5.5 kpc, if we fit the curve X=0.11, and 8.3 kpc for X=0.05, where the extinction A_V=0.6 mag is assumed.

(5) This wind model is based on the thermonuclear runaway model. The excellent agreement of our light curve with the observed one indicates that this outburst is caused by the hydrogen shell flash in a helium rich envelope on a very massive white dwarf.

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