FORMATION OF LUMINOUS CONTACT BINARIES BY RAPID ACCRETION ONTO WHITE DWARFS

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1. INTRODUCTION

During the evolution of a close binary system, there is a phase of mass exchange between its component stars. When the mass-losing star is an evolved star off the main sequence, the mass exchange is very rapid. Its rate may well exceed the critical accretion rate corresponding to the Eddington limit of the mass accreting star. Effects of such a rapid accretion were studied for the mass-accreting main-sequence stars (Flannery and Ulrich 1977; Kippenhahn and Mayer-Hofmeister 1977; Neo et al. 1977). The mass-accreting stars become quickly overluminous and their radii increase even to a red-giant size as mass is accumulated. Then the both component stars will fill their Roche lobes to form a contact binary system.

In some cases, the mass-accreting star is a white dwarf. The accreting white dwarf will be rekindled. Though such a rekindling was studied by several authors, they considered only the cases of slow accretion (Giannone and Weigert 1967; Taam and Faulkner 1975). The rekindled hydrogen shell-burning is unstable to develop a shell flash or even to grow into a nova-like explosion.

It will be interesting to investigate what happens in the case of extremely rapid accretion onto a white dwarf. Which is a more important effect, the rapid mass accumulation or the shell flash? Will it become a red giant star? We have computed the whole processes of mass accretion starting from its onset through the shell flash and further mass accumulation. Throughout our computation the effect of gravitational energy release has been correctly taken into account.

The initial model was chosen to be a helium white dwarf, whose mass, luminosity and radius are 0.4 $M_\odot$, 1.7 x $10^{-4} L_\odot$, and 1.6 x $10^{-2} R_\odot$, respectively. The mass accretion rate dM/dt was assumed to be 2 x 10^{-5} $M_\odot yr^{-1}$, which is the critical accretion rate for the initial radius of the model. Assumptions and more details of the results are given by Nomoto et al. (1979).

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2. NUMERICAL RESULTS

The evolutionary stages will be characterized by the mass ΔM_H contained in the hydrogen-rich envelope. In our case of rapid accretion, ΔM_H is practically equal to the amount of mass that has been accreted since the onset of the accretion. It is related with the evolutionary time by $t = 5 \times (\Delta M_H/10^{-4}M_\odot)$ yr. We have found the following sequence of events takes place.

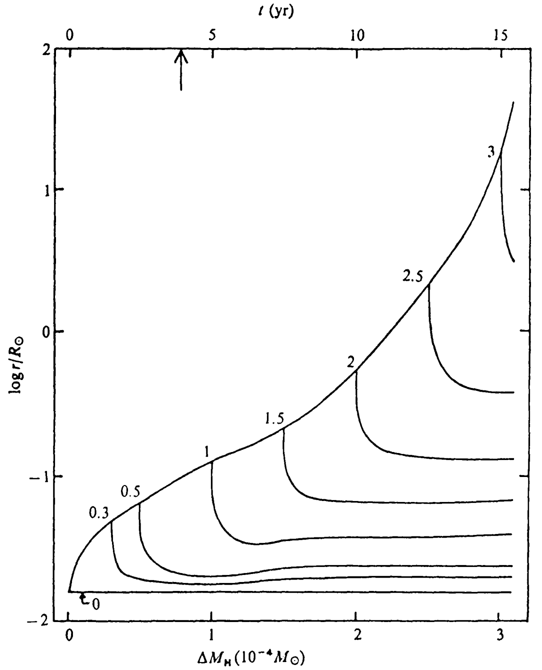

Fig. 1

a) Increase in Luminosity

Figure 1 shows evolutionary changes in the radial distance $\underline{r}$ of Lagrangian shells against ΔM_H or t. (For each shell attached is the value of $M_r-0.4M_\odot$ in units of $10^{-4}M_\odot$.) As the weight of the overlying layers increases, the accreted matter contracts and releases the gravitational energy. In the deep layers of the envelope, the contraction is almost adiabatic because the time scale of contraction is shorter than that of the heat transport In the relatively outer layers, on the contrary, an appreciable fraction of the gravitational energy release is radiated away. Figure 2 shows evolutionary path in the HR diagram. (The values of ΔM_H in units of

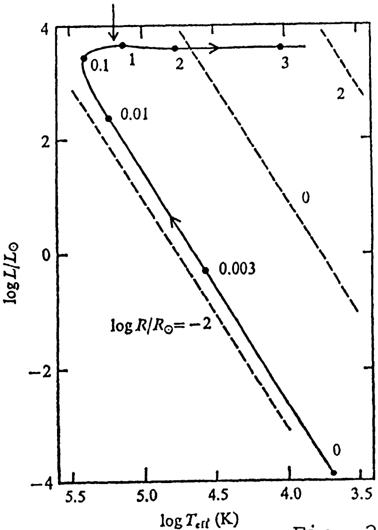

Fig. 2

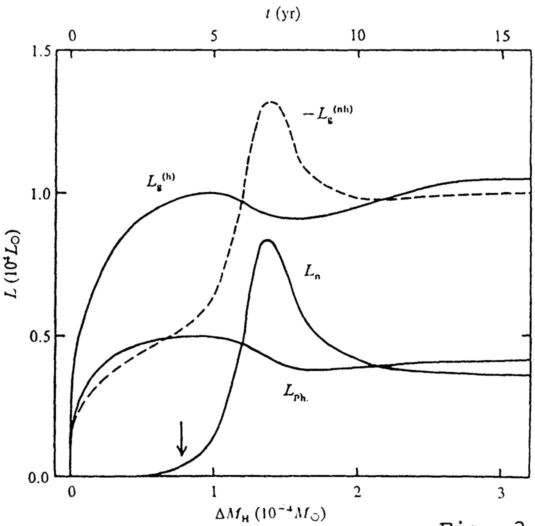

Fig. 3

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$10^{-4}M_{\odot}$ are attached.) The luminosity of the white dwarf increases quickly in 0.2yr, though the stellar radius increases only slightly during these initial stages. Afterwards, the radius increases as matter is accumulated.

Changes in the luminosity L_{ph}, the rate of the so-called gravitational energy release L_g, and the nuclear energy generation rate L_n are shown in Figure 3. Here, L_g is divided into two terms, one ascribed to a homologous contraction $L_g^{(h)}$ and the other ascribed to non-homologous contraction $L_g^{(nh)}$ (see Nomoto et al. 1979). We find that $L_g^{(h)} \simeq 2L_{ph}$ and $-L_g^{(nh)} \simeq L_{ph}$ before the ignition of the flash. This implies that much entropy is brought into the star. The resultant non-homologous change in the stellar structure is important to increase the stellar radius as will be described below.

Though dM/dt is just equal to the critical rate at the initial stage of accretion, L_{ph} reaches only $5 \times 10^3 L_{\odot}$, i.e., 0.3 times the Eddington limit. This is explained by the fact that the contraction of the lower layers is suppressed as seen in Figure 1 because of the trapped entropy within the star.

b) Hydrogen Shell-Flash

As ΔM_H increases, the bottom of the hydrogen-rich envelope is compressed. When ΔM_H becomes $7.8 \times 10^{-5} M_{\odot}$, the hydrogen shell-burning is ignited. In Figures 1-3, the ignition time is indicated by the arrow. The shell burning is thermally unstable and makes a relatively weak shell flash as seen in Figure 3. The peak energy generation rate amounts only to $L_n = 8.3 \times 10^3 L_{\odot}$.

The reason why the shell flash is so weak can be understood as follows. The shell flash is stronger when the pressure of the shell is higher at the stage of the ignition, i.e., the value of ΔM_H and/or the mass of the white dwarf are larger (Sugimoto et al. 1979). Since the accretion is very rapid in our case, much entropy is retained in the accreted mass element. Consequently, the hydrogen burning is ignited at a relatively smaller ΔM_H, which is only 3.8% of that for much slower accretion onto the same 0.4 $M_{\odot}$ white dwarf with $dM/dt = 1 \times 10^{-13} M_{\odot} yr^{-1}$ (Sugimoto et al. 1979).

c) Formation of a Supergiant-like Envelope

The mass accreted during the flash and its decaying phase is comparable to the mass which was contained in the envelope at the time of the ignition. However, the contraction of the accreted matter is halted in relatively inner layers because of the heat generated by the hydrogen shell-burning as well as the entropy brought into the star with the accreted matter. The accreted matter is piled up simply on the stellar surface, which makes the stellar radius increase (Figure 1).

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Thus the gravitational contraction takes place only in the relatively outer layers of large radial distance $\underline{r}$ so that the gravitational energy release $L_g = L_g^{(h)} + L_g^{(nh)}$ is small as compared with L_{ph}. This fact implies also that the matter is accumulated almost adiabatically in the relatively inner layers. In other words, the small L_g implies that $L_g^{(h)} \simeq - L_g^{(nh)}$. Such non-homologous changes of the outer layers are the main cause of the formation of a supergiant-like envelope (Neo et al. 1977).

3. DISCUSSION

As a result of further mass accumulation, the envelope of our accreting white dwarf will become of a red giant size. Such formation of a red giant-like envelope takes place when the accretion rate is higher than the critical one $(dM/dt)_N$. This is the rate of core growth if the white dwarf were immersed deep in the hydrogen-rich envelope of a red giant star, and is given by

$$(dM/dt)_N = L_H \,/\, X_e \cdot E_H \simeq (2 \times 10^{-8} - 6 \times 10^{-7}) M_\odot yr^{-1}, \quad (1)$$

for $M = (0.4 - 1.4) M_\odot$. Here X_e and E_H are the concentration of hydrogen and the nuclear energy release from unit mass of hydrogen, respectively, and the value of the hydrogen burning rate L_H is taken to be that of the corresponding red giant star which has the same core mass as the mass of the white dwarf. When $dM/dt > (dM/dt)_N$, all of the accreted matter can not be processed into helium. Then the accreting gas is piled up to form an extended envelope of a red giant size.

In a close binary system, the radius of such an accreting envelope exceeds its Roche lobe to form a contact system. After that the mass overflowing from the companion star will not be swallowed any more but eventually escape from the binary system. The following sequence of events is very likely. The escaping mass carries away the angular momenta, the separation between the stars becomes smaller and smaller, and finally the white dwarf falls into the companion star.

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DISCUSSION FOLLOWING NOMOTO, NARIAI AND SUGIMOTO

Friedjung: Can you relate your theoretical predictions with a class of observed objects?

Nomoto: I would like to know the candidates.

Smith: How would your results be affected by including the angular momentum of the accreted material?

Nomoto: Since the stellar radius is very large, effects of angular momentum are small in this case.

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