GENERAL THEORY FOR SHELL FLAŚH AND NOVA EXPLOSION OF ACCRETING WHITE DWARFS

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I. INTRODUCTION

It is now well known that an accreting white dwarf experiences a shell flash near its suface. Such phenomena are related with rekindling of white dwarfs, slow and fast nova explosions etc. depending on its strength. Though many authors computed evolution through such shell flashes, they treated them only under specific conditions.

Since the shell flashes are involved in a wide variety of applications to the evolution of binary stars, it is desirable to advance a theory on the basis of more general ground. As for the development of the shell flash Sugimoto and Fujimoto (1978) advanced an analytical theory that its peak strength is determined by two parameters $\underline{M}$ and ΔM_H, i.e., by the mass of the accreting white dwarf and the mass lying above the hydrogen-burning shell, respectively. Though they treated mainly the helium shell-flash, the same theory is applicable to the hydrogen shell-flash as will be done in the present paper. Our analytical results will be compared with existing numerical computations.

In practical problems, however, the rate of mass accretion dM/dt determines the value of ΔM_H. We will discuss general concepts for the effect of finite accretion rate. Then some numerical results will be given in order to illustrate how the accretion rate affects ΔM_H and the development of the shell flash.

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II. MAXIMUM TEMPERATURE THROUGH THE FLASH

According to Sugimoto and Fujimoto (1978), the progress of the shell flash is described by the proper pressure P^* and the proper potential Ω^*. They are related with our parameters by

$$P^* = \frac{GM\Delta M_H}{4\pi r_H^{*4}} \quad , \quad \Omega^* = \frac{GM}{r_H^*} \quad , \tag{1}$$

where we neglected the difference between the total mass of the star $\underline{M}$ and the core mass $M - \Delta M_H$. Here, the radius of the hydrogen burning-shell r_H^* is well approximated by the radius of the white dwarf of corresponding mass so that r_H^* is determined only by $\underline{M}$. As the nuclear energy is released, the specific entropy $\underline{s}$ in the hydrogen-burning shell increases and the pressure decreases as a result of expansion. The change in the pressure is described by $P = fP^*$. Here $\underline{f}$ is the flatness parameter defined by Sugimoto and Fujimoto (1978) and is expressed analytically as a function of the polytropic index and the ratio of r_H^* to the scale height of pressure which is described also by the pressure and the specific entropy. Therefore, the gravothermal specific heat c_{gr}, in which the effect of expansion/

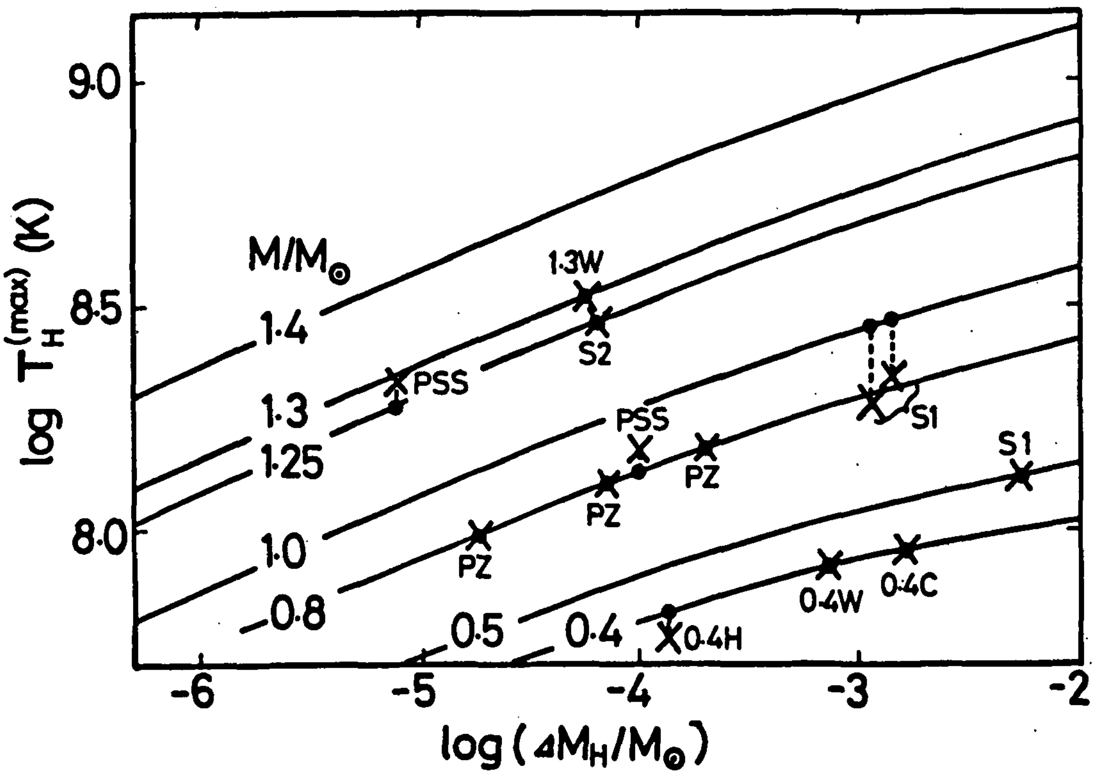

Fig. 1. - Maximum temperature attained in the course of the hydrogen shell-flash. Theoretical values are shown by curves labelled with the mass of the white dwarfs. Results of numerical computations are plotted by X-marks. References are as follows: S1 (Starrfield et al. 1974a, b), S2 (Sparks et al. 1978), PSS (Prialnik et al. 1978 , 1979), PZ (Paczyński and Żytkow 1978), 1.3W and 0.4W (Nariai et al. 1979), 0.4H (Nomoto et al. 1979) and 0.4C (new computation).

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TABLE 1

Accretion onto $0.4M_\odot$ White Dwarfs and Resultant Mass of the Hydrogen-rich Envelopes

model of accretion	case*	dM/dt ($M_\odot$ yr^{-1})	$\Delta M_H^{(ig)}$ ($M_\odot$)	$\Delta M_H^{(max)}$ ($M_\odot$)	$\Delta M_{pk}^{(max)}$ ($M_\odot$)
cold	0.4C	1×10^{-13}	2.05×10^{-3}	2.15×10^{-3}	1.66×10^{-3}
warm	0.4W	1×10^{-8}	7.40×10^{-4}	8.44×10^{-4}	7.40×10^{-4}
hot	0.4H	2×10^{-5}	7.80×10^{-5}	1.52×10^{-4}	1.35×10^{-4}

* See Figure 1 for references

contraction is taken into account, can be computed by

$$\frac{1}{c_{gr}} = \frac{d \ln T}{ds} = \left(\frac{d \ln T}{d \ln P}\right)_s \frac{d \ln f}{ds} + \frac{1}{c_p} \quad , \tag{2}$$

where c_p is the usual specific heat at constant pressure. Integration of equation (2) gives the progress of the flash and, in particular, the condition $c_{gr} = \infty$ gives the peak temperature of the shell-flash.

Results of such analytical computations are shown in Figure 1, where each curve labelled with the value of mass gives a relation between the maximum temperature through the flash $T_H^{(max)}$ and the mass lying above the hydrogen burning shell. Results of some numerical computations are plotted by X-mark together with the corresponding theoretical predictions by dot. Both of them are in excellent agreement except for some cases where some discrepancies are apparent. Though a coarse zoning is likely to be responsible for such discrepancies, the true reason is not clear until we learn more about their details.

III. THERMAL HISTORY OF ACCRETION AND MASS OF HYDROGEN-RICH ENVELOPE

The excellent agreement discussed in the preceding section implies the following fact. Once a value of ΔM_H is given, the value of $T_H^{(max)}$ is determined almost independently from thermal history of accretion. However, it is the thermal history itself that determines the value of ΔM_H. It is best demonstrated by showing numerical examples of accreting white dwarfs of mass $0.4M_\odot$. Three typical cases are compared in Table 1 and Figure 2, to which the initial conditions at the onset of accretion are common but for which the accretion rates differ greatly.

For the accretion rate there are two critical rates dividing physical situations. One is related with the timescale of heat transport t_K over unit scale height of pressure at the bottom of the accreted hydrogen-rich envelope, i.e.,

$$(dM/dt)_K \equiv \Delta M_H/t_K \quad . \tag{3}$$

The other is related with the rate of core growth if the white dwarf were immersed deep in the hydrogen-rich envelope of a red giant, i.e.,

$$(dM/dt)_N \equiv L_H / X_e E_H \ , \qquad (4)$$

where X_e and E_H are the concentration of hydrogen and the nuclear energy release from unit mass of hydrogen, respectively. Here 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 our total mass of the white dwarf.

According to values of the actual accretion rate, the accretion is classified into three categories as seen in Table 1. When the accretion rate is lower than $(dM/dt)_K$, we call it cold accretion, because the specific entropy of the accreted matter is well radiated away and the hydrogen-rich envelope is thermally well relaxed. When the accretion rate is higher than $(dM/dt)_N$, we call it hot accretion. In this case the accretion is so rapid that the accreted matter can not be processed by nuclear burning. When the accretion rate is intermediate between $(dM/dt)_K$ and $(dM/dt)_N$, we call it warm accretion, because the specific entropy of the accreted matter is partly retained in the envelope and partly radiated away.

In our example of $0.4M_\odot$ star, we have $(dM/dt)_K \simeq 5 \times 10^{-9} M_\odot yr^{-1}$ for a typical case of $\Delta M_H = 7.4 \times 10^{-4} M_\odot$, and $(dM/dt)_N \simeq 1.6 \times 10^{-8} M_\odot yr^{-1}$ so that the cases 0.4C, 0.4W, and 0.4H correspond to cold, warm and hot accretion, respectively. From Table 1 and Figure 2 we see the

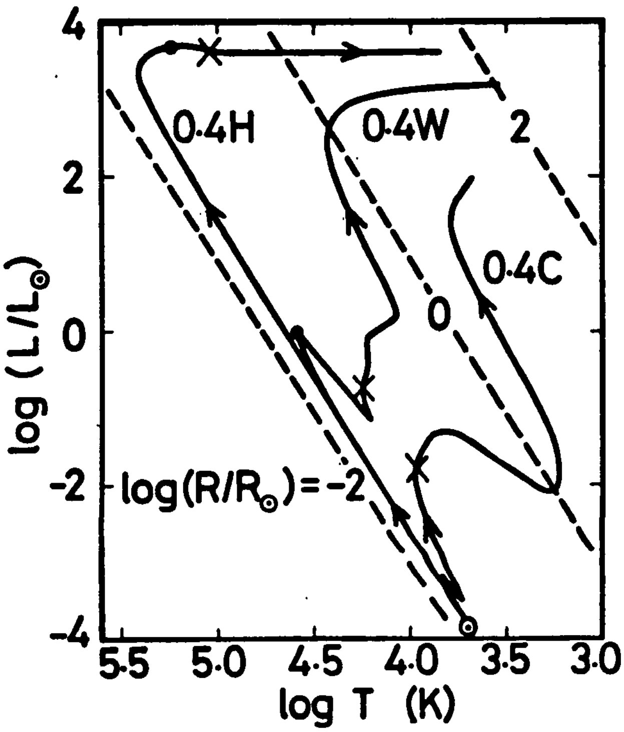

Fig. 2. - Evolution of accreting white dwarfs of $0.4M_\odot$ for different accretion rates as summarized in Table 1. Circled dot, dots and X-marks indicate the points of the initial model, the ignition, and the peak of the temperature, respectively. In the case of 0.4C the star cools first along a line of constant radius. Then the ignition takes place where log $L/L_\odot$ = -4.5.

following. The mass of the hydrogen-rich envelope which has been formed at the ignition stage $\Delta M_H^{(ig)}$ differs among them by a factor as much as 30. Therefore, as seen in Figures 1 and 2, the maximum temperatures and the evolutionary tracks in HR diagram are also different very much among these cases.

The hydrogen shell-burning is not strongest in the layers lying in the bottom of the envelope, because such layers are cooled by heat conduction into the core. Even after the stage of ignition the mass continues to accrete. At the stage of the maximum temperature, the mass of the hydrogen-rich envelope is $\Delta M_H^{(max)}$, but the mass lying above the hydrogen-burning shell is $\Delta M_{pk}^{(max)}$. Their values are also listed in Table 1. It is the value of $\Delta M_{pk}^{(max)}$ that is to be substituted into ΔM_H of equation (1).

IV. CONCLUSION

From the discussions in the preceding sections the shell flash in accreting white dwarfs is understood to be separable into two problems. One is to determine ΔM_H by studying thermal history of accretion, and the other is to find the peak energy generation for a given value of ΔM_H. These two problems hardly interfere each other. In many of existing computations, their authors chose some values of ΔM_H without computing the thermal history of accretion. For the initial model they assumed a structure in thermal equilibrium. Such structure corresponds to one with infinitely slow accretion, and should be classified as <u>frigid</u> accretion. However, their computational results are valid as far as the peak of the flash is concerned, if we imagine that appropriate accretion rate has been assigned to their models.

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