THERMAL INSTABILITY OF HYDROGEN BURNING SHELLS IN VERY MASSIVE STARS

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Stothers and Chin(1972) examined numerically thermal instability of H burning shells in very massive stars. They reported the discovery of the thermal pulses in the shell on a stage of the contracting core just after the core exhaustion. Their results, however, are inconsequential because the pulses are very feeble and the mechanism of such feeble pulses is not well known at the shell burning phases. In this note, we summarize our analytical method and the results on the possibility of such feeble pulses in H burning shells, of which detailed procedure is described in another paper(Tanaka et al., 1980).

Supposing that entropy perturbations are given in a nuclear burning shell, we write, for instance, the deviation of the radial distance of the shell from the equilibrium state as $r'=\{r(M_r,t)-r'_o(M_r)\}/r'_o(M_r)$. Here the suffix 0 means the quantities in equilibrium and t is time. Linearized equations for the deviations are obtained from a set of the fundamental equations of the stellar structure, if we neglect the higher orders of the deviations. In order to solve the linearized equations with the equation of state, we followed the Baker's assumptions in the one-zone model(1966) where he neglected the gradient of the deviations of pressure p' and temperature t' in the shell. Secondly we adopted the geometrical measure introduced by Sackmann(1977). This parameter m_s is defined as a ratio of the percentage thickness change of the shell and the percentage position change. Sackmann introduced m_s for dealing semi-empirically with her numerical results of thermal pulses in He shell in a star with 3 $M_\odot$.

The final equations are as follows;

$$4r'+p'=0 \ , \tag{1}$$
$$r'(m_s+2)+\alpha p'-\delta t'=0 \ , \tag{2}$$
$$\ell' = 4r'-\kappa_p p'-(\kappa_T-4)t' \ , \tag{3}$$
$$ds'/dt=2L_{ro}(k\rho' + nt'-2\ell')/T_o s_o m \ . \tag{4}$$

where ρ', s' and ℓ' mean the deviations of density, entropy and luminosity, respectively, κ is the opacity($\kappa_p=(P/\kappa\cdot\partial\kappa/\partial P)_T$, $\kappa_T=(T/\kappa\cdot\partial\kappa/\partial T)_P$), and $\alpha=(P/\rho\cdot\partial\rho/\partial P)_T$, $\delta=-(T/\rho\cdot\partial\rho/\partial T)_P$. In equation (4), we have approximated

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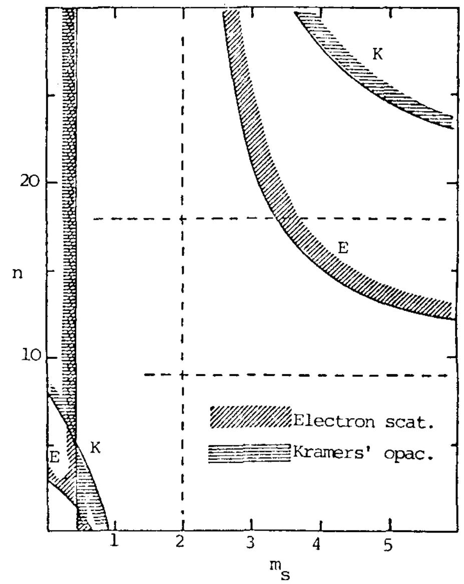

Figure 1. Thermally unstable region for H shell burning. The abscissa is the geometrical measure and the ordinate is the exponent of the temperature in the energy production rate. The unstable regions are hatched.

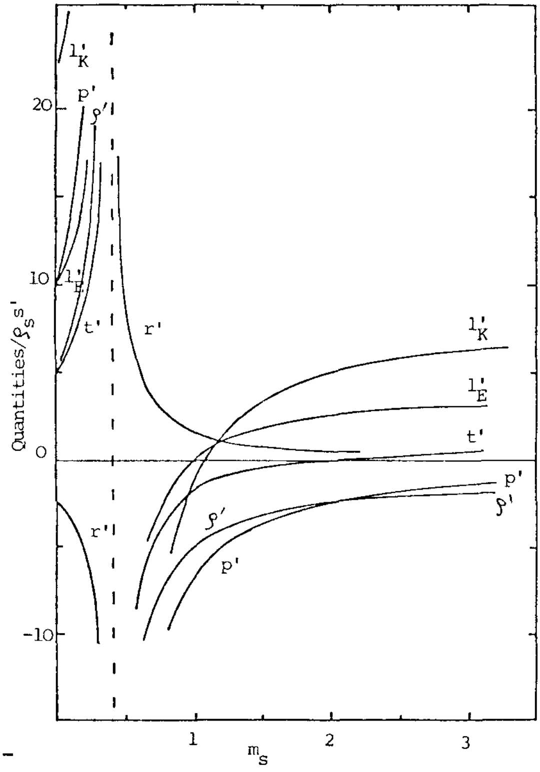

Figure 2. The deviations of physical quantities devided by ρ's' versus the geometrical measure.

the nuclear energy production rate as $\varepsilon=\varepsilon_0\rho^kT^n$ and ignored the core luminosity. The mass of the shell is denoted as m and others have usual meanings.

Substituting equations (1),(2) and (3) into (4), we have an equation from which the conditions of thermal instability were obtained. For simplicity, we assume ideal gas and the ratio of the radiation pressure to the total pressure, 1-β, equal to zero. Then, $\alpha=\delta=1$. If we take simple formulae of opacity, $\kappa_p=1$ and $\kappa_T=-4.5$ for Kramers' opacity and $\kappa_p=\kappa_T=0$ for electron scattering. Thus, the conditions of thermal instability are denoted as a relation between n and m_s. In figure 1, we show the unstable regions in the n-m_s diagram for H burning shell(k=1). There are stable regions between the unstable regions. If we took k=2, we could have a diagram for He burning shell which is very similar to figure 1. We should notice that the value of n for He burning is $\sim$45, while it is $\sim$15 for CNO cycle and $\sim$3 for pp reaction.

Now we ask the role of the unstable region for m_s<0.4. This region may be responsible to excite thermal instability in the shell. Sackmann (1977) showed numerical results of a thermal pulse in He shell in a star with 3 $M_\odot$. It is seen from her figure that m_s seems to be nearly zero just before the beginning of the pulse. Thus it is suggested that the entropy perturbations grow in the unstable region of $m_s<0.4$ enough to jump over the stable region and the growth is accelerated in the unstable region $m_s>2$. Then the thermal pulse will be quenched as shown by Sackmann. If this suggestion on the role of the region $m_s<0.4$ is correct, we may extend this result of He shells to H burning shells. That is, the feeble pulses in H burning shells in very massive stars may be caused by the wide stable region for the value of n for H burning and by insufficiency of the growth to jump over the stable region. It may be also due to no unstable region beyond $m_s>2$. It is noted that the radiation pressure widens the stable regions. When the value of β becomes zero, the unstable region expands from $m_s<0.4$ to $m_s<1$, while the curves in the region $m_s>2$ shift upwards and toward right.

In order to clear the physical meanings of the unstable regions, we illustrated the behaviors of the deviations devided by $\rho_s s'$ in figure 2 where ρ_s is equal to $-(1/\rho \cdot \partial\rho/\partial s)_p$ and $\rho_s s'$ is assumed positive. Here, we have also neglected the effect of the radiation pressure and supposed H burning shells. It is seen for $m_s>2$ that since the increase of s' causes the increase of temperature and the decrease of density, the radius of the shell increases. In the case of $0.4<m_s<2$, a large expansion of the radius and the thickness of the shell causes the cooling of the shell, that is t' is negative. Those relations between s', t', ρ', r' and m_s agree with those shown by Sackmann. We should note that both p' and ρ' are negative for $m_s>0.4$ and s'>0. The situation in the case of $m_s<0.4$ is opposite that both p' and ρ' are positive and p' is greater than ρ'. The increase of p' counterbalances almost always the increase of gravity in the outer region due to the contraction of the core. Finally we note that mass loss around the upper main sequence may not be enhanced by the feeble thermal pulses in a star with a conservative mass, while thermal instability may be enhanced by mass loss in H core burning phase. The discussion on the excitation of the beta Cephei pulsations by the thermal instability is also given in the full text(Tanaka et al., 1980).

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DISCUSSION

BECKER: Over what mass range do you expect these thermal instabilities to occur?

TANAKA: About 15 to 30 $M_\odot$.