CONVECTION IN THE HELIUM FLASH

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Abstract

The evolution of a star through the helium flash depends upon uncertain aspects of convection theory. Observations place some constraints on the theory of convection in stellar cores.

Evolution of Stars in the Mass range 0.6 $M_\odot$ to 1.5 $M_\odot$

When stars finish burning hydrogen to helium in the core, the burning region moves outwards to form a shell source. Matter moves inwards through the burning region into the core which becomes progressively hotter and denser.

As the density of the core increases, the electron gas becomes degenerate. The hydrogen outside the hydrogen-burning shell forms a diffuse convective envelope of low density and great spatial extent (radius ~ 5×10^{10}m). The star is a red giant. Figure 1 shows the structure just before the helium flash.

The site of the Helium Flash

In the core, thermal conduction by degenerate electrons is efficient and there are no heat sources before helium burning starts, so to a first approximation the core is isothermal. However heat is lost from the densest part of the core by the plasmon neutrino process

$$\gamma_{\text{plasmon}} \rightarrow \bar{\nu} + \nu .$$

A slight temperature inversion therefore appears, which causes helium burning to ignite some distance (~ 0.1 $M_\odot$) from the centre. The peak temperature $T_m \sim 10^8$K.

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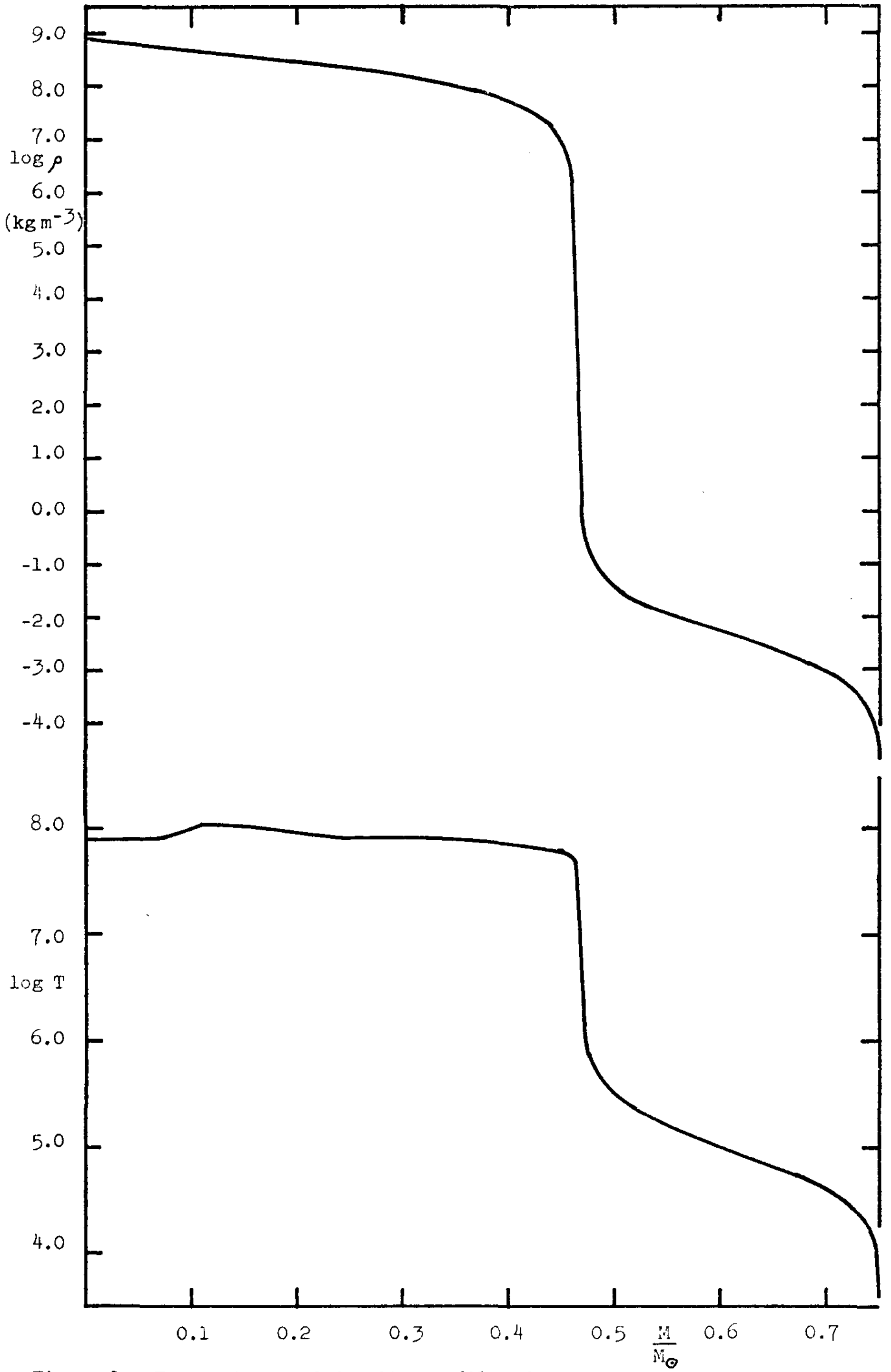

Figure 1. Temperature and density profiles for star of 0.75 $M_\odot$ and zero-age composition X = 0.7, Z = 0.0004 at start of helium flash

The rate of the reaction

$$3\,{}^{4}He \rightarrow {}^{12}C + \gamma$$

(the 3α reaction) is proportional to about the 40th power of the temperature. Since the degenerate electron gas can take up much heat without a large pressure increase, a thermal runaway can occur.

Quasistatic evolution through the Helium Flash

The energy generation rate in the helium-burning shell is great enough to require a convective zone outside it to transport the heat away. The peak temperature rises and the convective zone extends; the rest of the star adjusts its structure adiabatically. When the electron degeneracy is lifted in the burning region, expansion takes over and the peak temperature falls. Figure 2 shows how the structure of the centre of the core changes through the flash.

Calculations with an accurate equation of state (Thomas 1970, Demarque and Mengel 1971, Zimmermann 1970, Wickett 1976) show that if, in the convection zone, the temperature gradient is adiabatic or slightly superadiabatic as prescribed by the standard mixing-length theory and if the convective zone does not reach further towards the centre than the initial helium ignition zone, the burning timescale at the peak of the flash is large compared with the convective timescale. Thus the traditional formulation of convection theory leads to a quasistatic helium flash.

Convective Uncertainties

Edwards (1975) shows however that the traditional convective stability criterion

$$\left(\frac{\partial T}{\partial r}\right)_{\text{star}} < \left(\frac{\partial T}{\partial r}\right)_{\text{adiabatic}} \Rightarrow \text{unstable}$$

is modified in the presence of a very temperature-dependent energy generation rate. Even a positive gradient (temperature rising with radial coordinate) is unstable if, as is the case here, the reaction rate depends sufficiently strongly on the temperature.

It is not clear exactly how this conclusion affects the evolution; however a calculation was performed in which the convective zone was extended to the centre and the temperature gradient was the adiabatic one. The formulation is more fully described in the author's thesis (1976). At the peak of the flash, the burning time

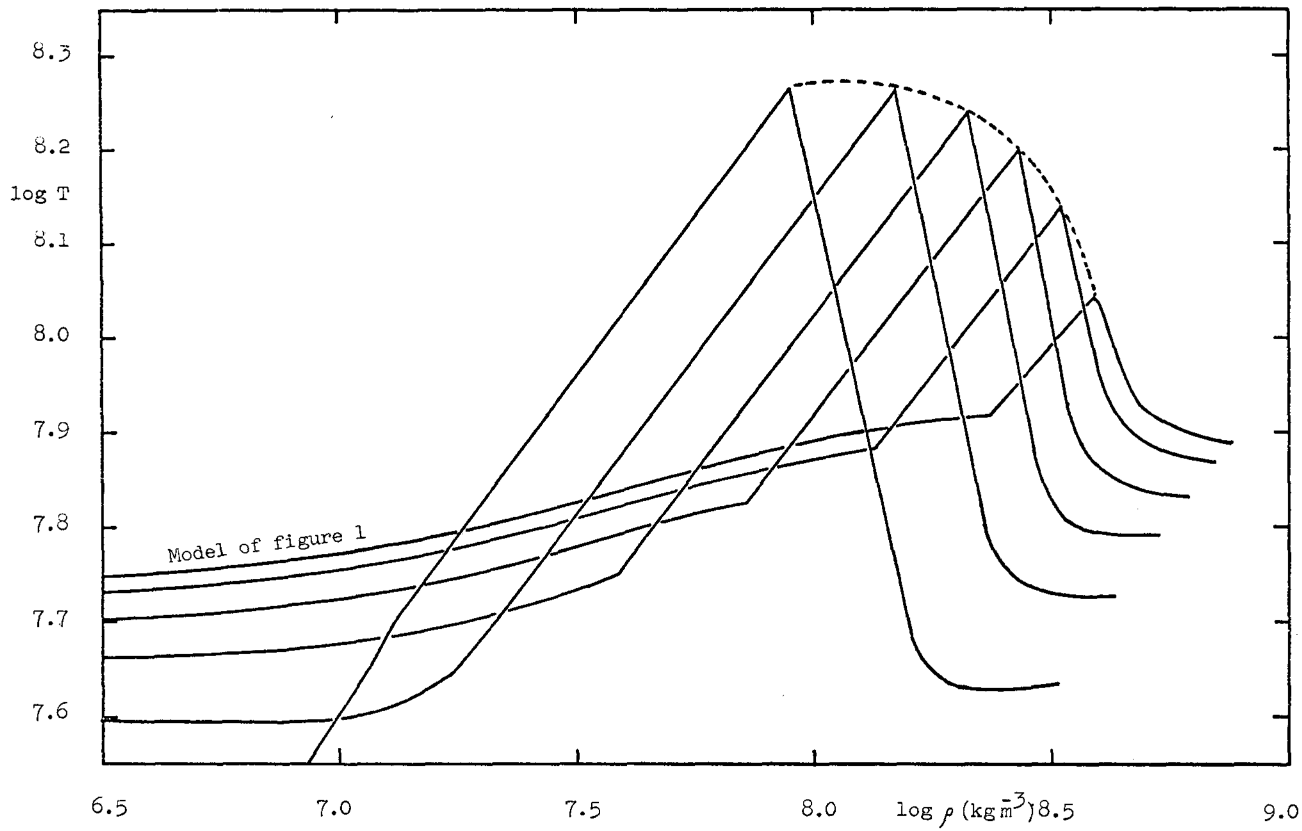

Figure 2. Temperature-density plots for core of star of figure 1 during helium flash

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$$\tau_n = \frac{T}{\dot{T}}$$

for constant density and no heat flow at the hottest point was equal to the convective timescale

$$\tau_c = \frac{l_c}{U_c}.$$

U_c and l_c are the convective speed and mixing length evaluated by the usual theory. The time for thermal runaway is considerably less than τ_n as the burning rate rises sharply with temperature. So convection cannot keep up with the rate of increase of heat production. Thus if this picture of the evolution is correct a thermal runaway and explosion must occur.

Dynamic Calculation

A hydrodynamic code including gravity and nuclear reactions for a spherically symmetric model was used to follow the explosion.

A spherical detonation wave with peak temperatures $\sim 2.5 \times 10^9$K and propagation speed 10 times the sound speed in front and twice that behind passes through the core. Half of the helium burns to neon (or species of similar mass number) releasing $\sim 5 \times 10^{43}$J. The entire star is disrupted with energy typical of a supernova of type I.

Observational Constraints

We assume that the 10^8 Galactic globular sluster stars (Allen 1973) have masses distributed according to Salpeter's (1955) mass function

$$dN \propto M_*^{-1.35} \, d \ln M_*$$

with a lower limit of 0.1 $M_\odot$. The variation of age at helium flash, τ_{hf}, with mass

$$\frac{d \ln \tau_{hf}}{d \ln M_*} = -5.31$$

was calculated using Eggleton's (1971, 1972) code. For age 10^{10} years we are interested in $M_* = 0.92$ $M_\odot$ and find that Galactic globular cluster stars now undergo 5.5×10^{-13} helium flashes per star per year or, 5×10^{-5} per year for the whole Galaxy.

Since one would expect to see a supernova remnant for 10^6 years (Woltjer 1972) and no supernovae remnants or gas of any sort is seen in globular clusters, we conclude that the supernova rate is less than 10^{-14} per star per year. So there is an upper limit of one supernova for 50 helium flashes.

Conclusions

It is not clear how to calculate the temperature gradient or the convective time-scale when the energy generation rate is very temperature-dependent. It is however clear that the traditional prescription does not work.

As to the helium flash supernova model, the observations allow 2% of helium flashes to be that violent. If this is the case then the small fraction might arise either from rather narrow ranges of mass, rotation etc. being favourable or, in some ways more appealingly, from fluctuations in the convection. This implies that the evolution of two stars with the same gross properties may be substantially different because of the random nature of the convective process.

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