Stellar Evolution: Massive Stars

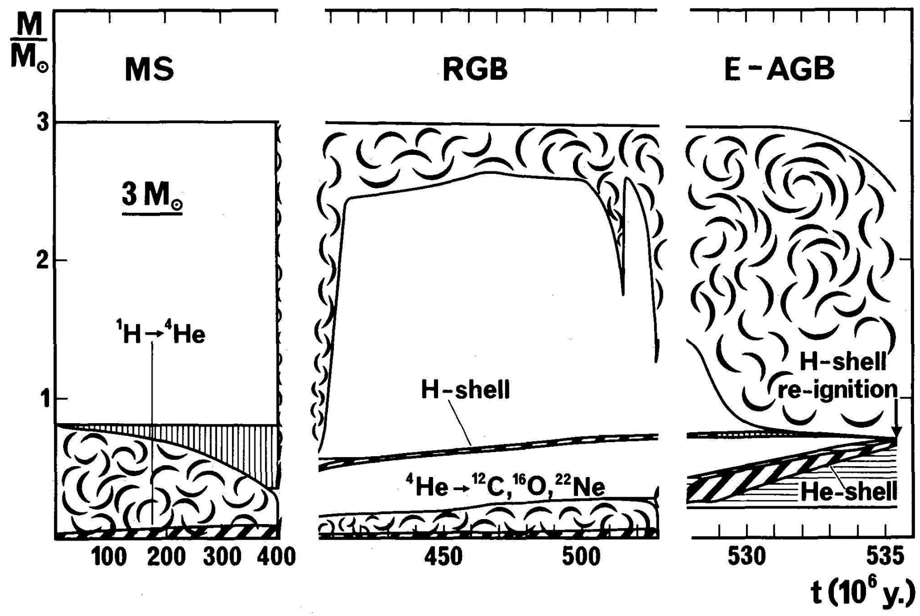
Structure on the Main Sequence: Simulations show existence of two regimes:

lower main sequence : stars have structure similar to Sun:

- energy generation: pp-chain ($\epsilon \propto T^5$)
- inner radiative core
- convective hull

upper main sequence : for central temperatures of 18×10^6 K (1.5 $M_\odot$ stars): pp-chain and CNO-cycle produce equal amounts of energy. Above that: CNO dominates.

- energy generation: CNO-cycle ($\epsilon \propto T^{17}$)
- inner convective core since energy generation from CNO cycle strongly peaked towards center.
- outer radiative hull



Evolution of the structure of a 3 $M_\odot$ star to the early Asymptotic Giant Branch (Maeder & Meynet, 1989).

Stellar Evolution: Massive Stars

Evolution on MS similar, however, faster than for low mass stars.

More massive stars ($\gtrsim$ 1.5 $M_\odot$) reach threshold temperature for 3α before reaching degeneracy

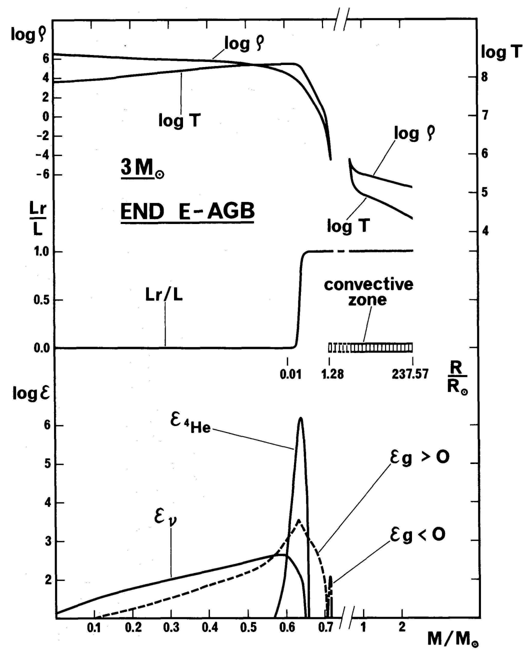
$\Longrightarrow$ He just starts to burn.

In these objects, higher order fusion processes can kick in (but are energetically unimportant): alpha reactions

$$^{12}\text{C} + {}^{4}\text{He} \longrightarrow {}^{16}\text{O} + \gamma$$
$$^{16}\text{O} + {}^{4}\text{He} \longrightarrow {}^{20}\text{Ne} + \gamma$$
$$^{20}\text{Ne} + {}^{4}\text{He} \longrightarrow {}^{24}\text{Mg} + \gamma$$

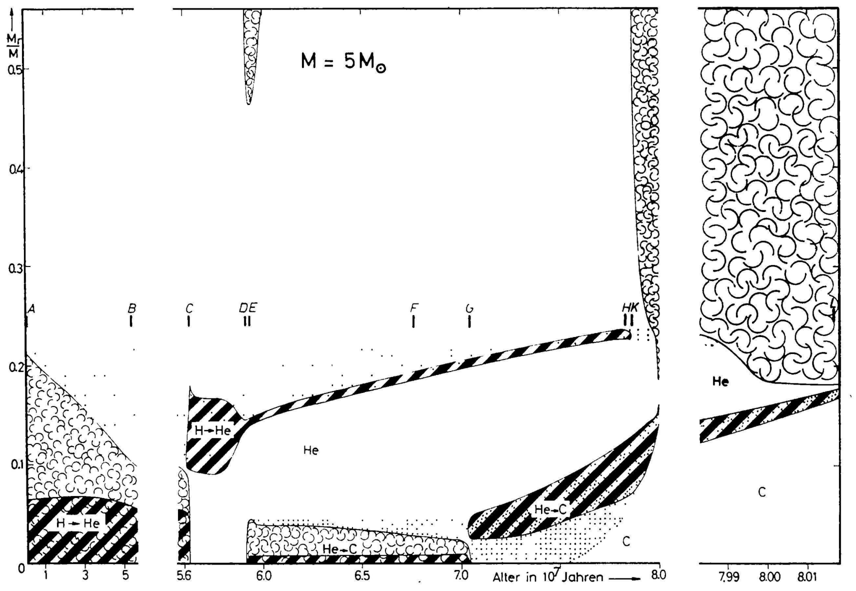
Outer layers continue H shell burning.

During evolution of star on red giant branch: convective hull moves deeper into core, can mix fusion products into outer layers.

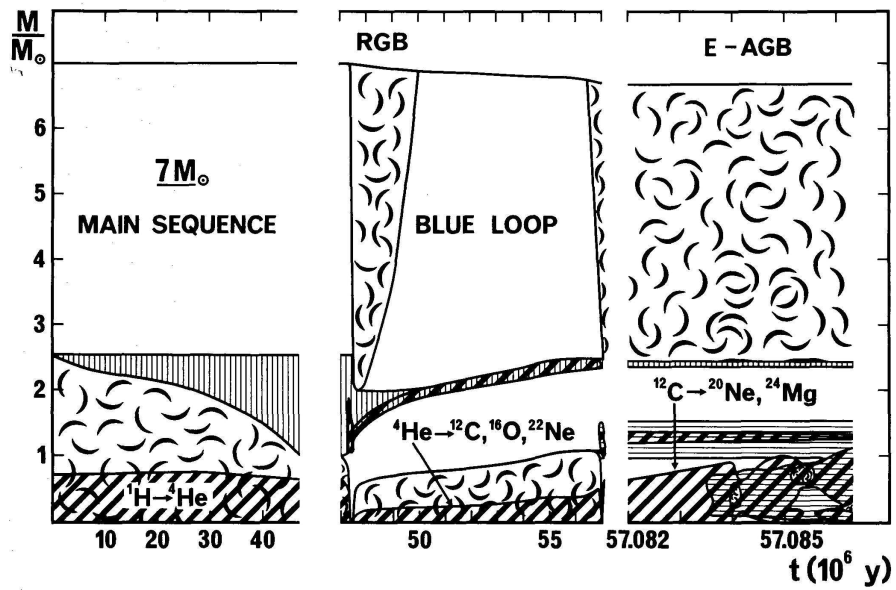


Internal structure of a 3 $M_\odot$ star which has reached the early Asymptotic Giant Branch.

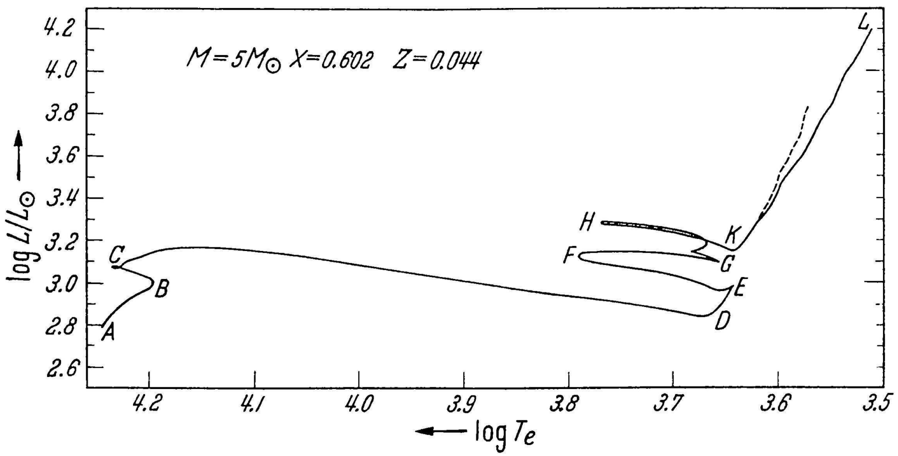
Maeder & Meynet, 1989



Kippenhahn et al. (1965): Evolution of the internal structure of a 5 $M_{\odot}$ star.

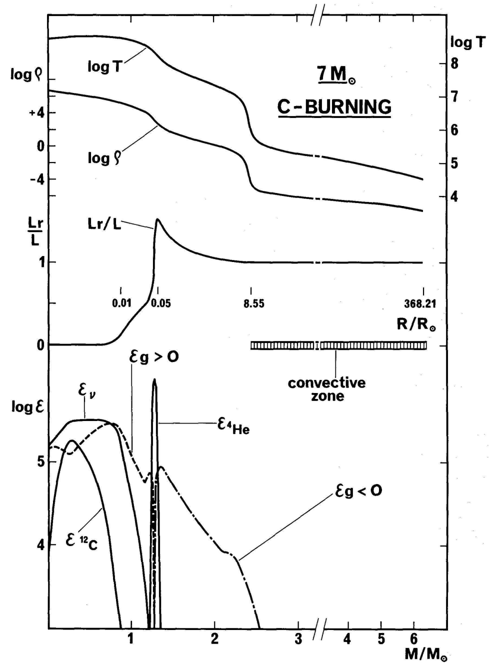


Evolution of the structure of a 7 $M_{\odot}$ star to the carbon burning phase (Maeder & Meynet, 1989).



Kippenhahn et al. (1965)

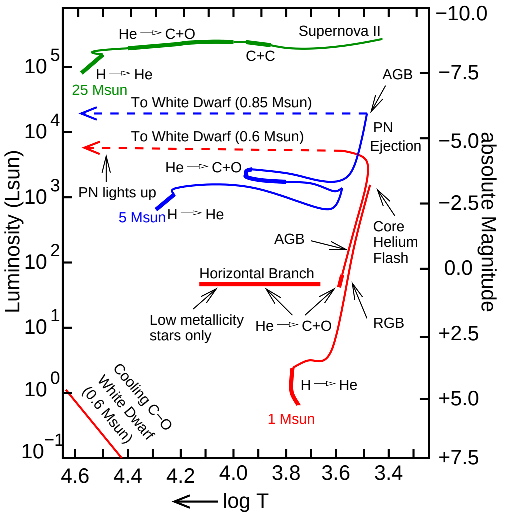
Evolution of a 5 $M_{\odot}$ star in the HRD.



Internal structure of a 7 $M_{\odot}$ star which just starts its carbon burning phase.

Maeder & Meynet, 1989

Stellar Evolution: Massive Stars



after Iben, 1991

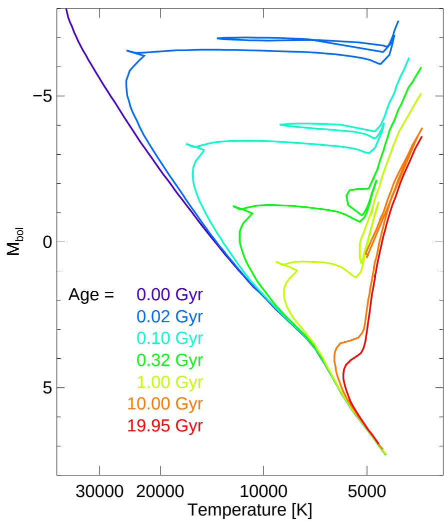
Evolution of stars in the HRD from main sequence to death

Typical timescales (units of 10^6 yr; Schaller et al. 1992):

	$1\,M_\odot$	$5\,M_\odot$	$25\,M_\odot$
H→He	10000	94	6.4
He→C		12	0.6
C+C			0.01
PN	$\lesssim 0.01$	$\lesssim 0.01$	N/A
WD	∞	∞	N/A

Post-H-burning burning: need higher core temperatures (Coulomb barrier!), less energy release $\Longrightarrow$ last much shorter than hydrogen burning.

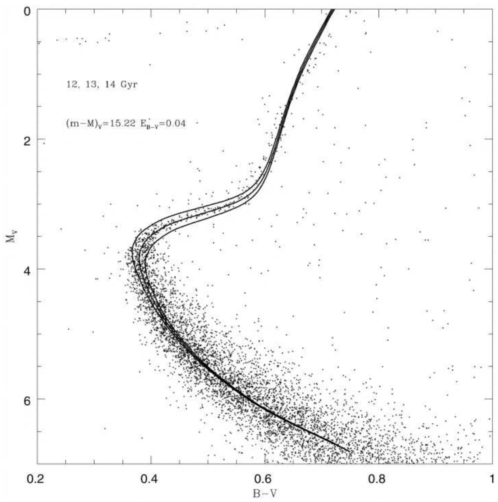
Stellar Evolution: Massive Stars



after Bertelli et al. (1994)

Predicted evolution of HRD from globular clusters can reproduce their HRDs, allows age determination

Stellar Evolution: Massive Stars



(M68; Straniero et al., 1997; Fig. 11)

Predicted evolution of HRD from globular clusters can reproduce their HRDs, allows age determination

Result: ∼12. . . 13 billion years

$\Longrightarrow$ GCs are oldest objects in the universe!