

Notes: 1. Extremely massive stars

- Radiation pressure → **mass loss** by stellar wind during m-s phase at rates of $10^{-5} - 10^{-7} M_{\text{Sun}} / \text{yr}$

i.e. several M_{Sun} during m-s phase.

- Outer layers (H + He) lost to the star so that products of CNO cycle (N, He) become **exposed** at surface.

- Shell source regions removed so may **not** become red-giants.
- will become the **Wolf-Rayet** stars which have abnormal abundancies of N, O, or C in their atmospheres (hence WN, WO or WC stars); plus **dense stellar winds** with mass loss $\sim 10^{-5} M_{\text{Sun}} / \text{yr}$

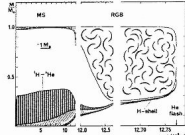


Fig. 7. Evolution of the internal structure of stars of $1 M_{\odot}$ up to the helium flash. Cloudy regions represent convective zones, bold contours hatched regions are zones where the nuclear energy rates are between 1 and $10 \text{ erg g}^{-1} \text{ s}^{-1}$. Diagrams indicate regions of mass $> 10 \text{ erg g}^{-1} \text{ s}^{-1}$. The abscissa scales of the star is indicated: 100 depicts main sequence and flash and giant branch.

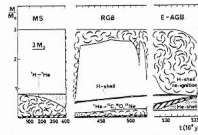


Fig. 8. Stars in Fig. 7 for the $1 M_{\odot}$ model up to the end of the core helium phase. Bold contours indicate regions where the nuclear energy rates are larger than $10 \text{ erg g}^{-1} \text{ s}^{-1}$. The vertically hatched regions are zones of variable hydrogen and helium contents and the horizontally hatched areas represent zones of variable ^{12}C , ^{13}C , and ^{16}O contents.

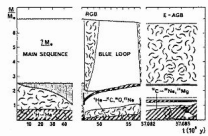


Fig. 9. Stars in Fig. 8 for the $1 M_{\odot}$ model up to the beginning of the C-burning phase.

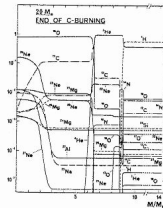
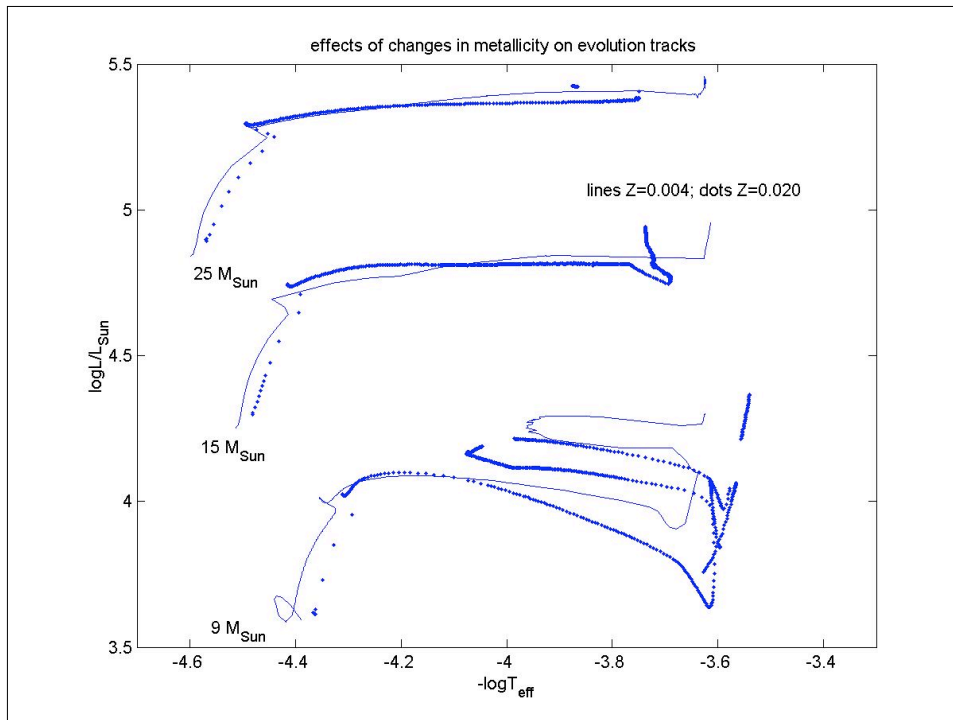


Fig. 10. Composition profiles within the $10 M_{\odot}$ model at the end of the C-burning phase, when it is ^{12}C at the center + ^{13}C and ^{16}O . Above, the top part then coordinate: ordinate, the mass fraction.

2. Evolution for metal-deficient stars

- Evolution tracks for pop II stars similar in overall appearance to those for pop I.
- The p-p chain is used for $\text{H} \rightarrow \text{He}$ fusion since $Z \sim 0.001 - 0.0001$.
- All the more massive pop II stars in the MW Galaxy have evolved to their end states ($> 10^{10}$ yrs) - but young metal-deficient stars of all masses seen in LMC / SMC .



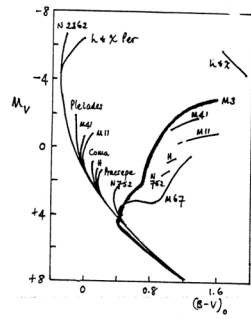
- **Obvious difference in evolution tracks is at core He fusion stage:**
 pop II clusters show an extended horizontal branch (h-b).
- **Mass loss at r-g stage (for ALL stars) reduces total mass. For low mass stars the core mass $\sim 0.6 M_{\text{Sun}}$, and the envelope mass determines the location on the h-b.**

• **Thin** envelopes (ie smaller radius for same luminosity) at **blue** end of h-b, **thick** envelopes at **red** end.

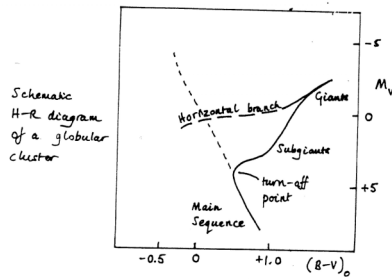
• So....extent of h-b in globular clusters reflects differences in **mass-loss rates** for individual stars at the r-g stage.

3. Colour - magnitude diagrams of star clusters

- Stars in cluster formed from same gas cloud at approx. same time.
- Hence appearance of C-M diagram reflects age of cluster
- e.g after 10^8 yrs,
 - $M > 8 M_{\text{Sun}}$ stars evolved to end states
 - $M \sim 5 M_{\text{Sun}}$ stars are core He fusion red / yellow supergiants (Classical Cepheid variables)
 - $M < 5 M_{\text{Sun}}$ stars still on m-s



Composite H-R diagram for open clusters (with globular cluster M3 for comparison.)



Schematic H-R diagram of a globular cluster

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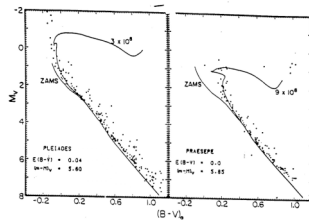


FIG. 7 - Comparison on the theoretical plane of selected isochrones (solid curves) as obtained in this study, with published observations (filled circles) of the Pleiades and Praesepe star clusters. The source of the observations are given in Table 4. In each case, the cluster name and the adopted reddening and apparent distance modulus are specified in the lower left-hand corner. Isochrone ages in years $\times 10^6$ are indicated near the base of the top curve.

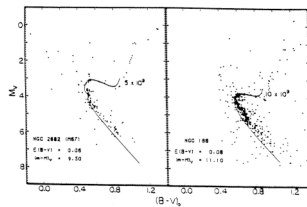
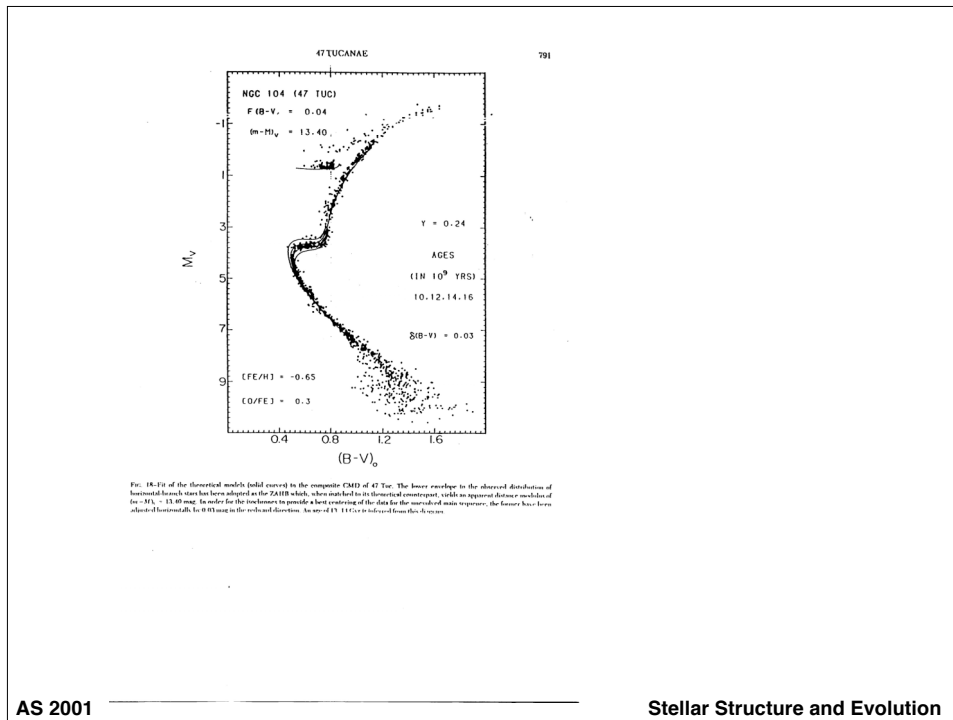


FIG. 8 - Additional comparison to those given in Fig. 7. In this case the theoretical isochrones are compared with published data for NGC 2062 (M87).

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- **Age of cluster determined by matching ISOCHRONE lines to C-M diagrams**
- NB:** isochrone line - locus of evolution stages of stars of **different masses** at a **given time**.
- e.g.

Pleiades	~ 3×10^8 yr
Praesepe	~ 9×10^8 yr
M67	~ 5×10^9 yr
globular clusters	~ 15×10^9 yr
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End states of stars

- Stars lose significant amounts of mass via stellar-wind processes at various stages:
 - low-mass stars: r-g and p-n stages
 - high mass stars: m-s and r-g stages
- Hence majority of stars end as white dwarfs with C + O cores + He - rich envelopes; more massive stars produce O - Ne - Mg cores .

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WHITE DWARFS

Observations

- $M \sim 0.6 M_{\text{Sun}}$
- $R \sim 0.01 R_{\text{Sun}}$
- $M_V \sim +10$ to $+15$
- Sp. type B0 to M

Physics

- escape velocity = $(2GM / R)^{1/2} \sim 10^7 \text{ ms}^{-1}$ (!)
- mass density $\sim 10^9 \text{ kgm}^{-3}$
- **electron-degeneracy pressure**
(remember....indep of temp, dep on density) helps support the star against own gravity

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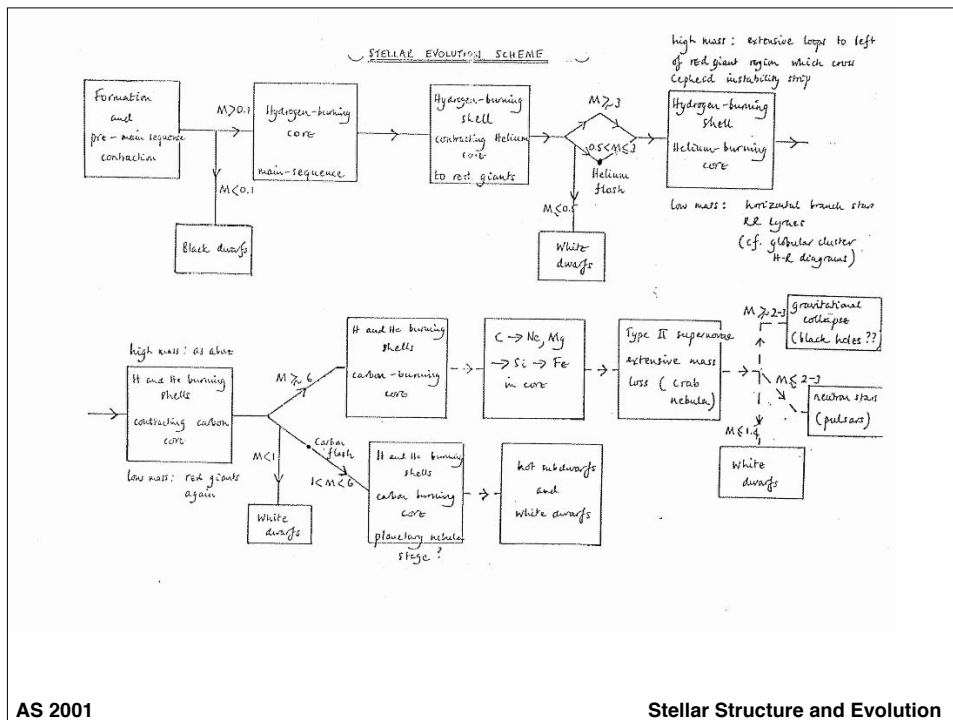
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Size

- W-D cools by emission of radiation, and stays at **constant radius**; cooling time $\sim 10^9$ yrs
 - theoretical models give good agreement with observations and find that $R \propto M^{-1/3}$
 - i.e. a more **massive** WD has a **smaller radius**
- \therefore upper limit to W-D mass of $1.4 M_{\text{Sun}}$ - the **Chandrasekhar limit** - i.e. upper limit to mass of WD that can be supported by electron degeneracy pressure.

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