Selected Chapters from Astrophysics

Course on Swift-Stellar Evolutionary Code

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Lecture #1

1. Introductory Remarks

Purpose is to get overview in Swift and its possibilities. Get to know how to use it in evolution models of close binaries.

"sse.f" code developed by Cambridge astronomers in 1998

The code is using simple approximative formulae, not exact figures. Important is that it's following physics even as approximation.

"In the real world, exact formulae don't matter."

2. Overview on "sse.f" code

Authors: Hurley, Pols, Tout (MNRAS 2000) vol. 315

Pols, Eggleton et al. MNRAS

The code covers stellar evolution from MS till relativistic stage (WD/NS/BH).

[Mass range: $0.5 - 50\ M_\odot$; Metalicity range: $0.0001 - 0.03$] + mass loss & ang. momentum loss + restricted bin. system evolution (esp. low mass c.)

plots: H-R, M-L, M-R, L-M_c, etc. ⟺ datafile: L, M, R, M_c, nucl. evol. timescale, special evol. stages, rot. velocities, etc. (for both components)

Rule of thumb: Every 25 years should come completely new approach in astrophysics.

» Not the case of stellar evolution! « ... still the same theory.

Advantages of "sse.f" code: (1) high computational speed (2) high precision (< 5% err. / < 2% in most cases)

Basic formalisms:

pts 1 – MS
pts 2 – GB, CHeB, AGB, HeGB
pts 3 – HG, HeMS

Stellar types:
- 0 - fully convective star
- 1 - MS - star
- 2 - Herzprung gap star
- 3 - RGB - star
- 4 - HB - star
- 5 - 1^{st} AGB star
- 6 - 2^{nd} AGB star
- 7 - MS naked He star
- ...

Mass is given in $M_\odot$

z (metalicity) ~ 0.0001 - 0.03

mflag > 0 => mass-loss

neta - mass-loss rate

pts1, pts2, pts3 => time steps

Elements of stellar evolution:

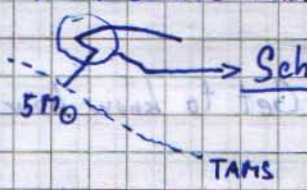
$\varepsilon \approx T^4$ => p-p chain – more important role in case of solar-type stars
$\varepsilon \approx T^{17}$ => CNO cycle

$T \sim 5 \cdot 10^8$ K => triple-α proces (He-burning)

General evolutionary tracs – figure by Iben (1985)

↳ the code can reproduce all the features introduced by this figure despite its approximative form

Intermediate mass stars are in major focus.



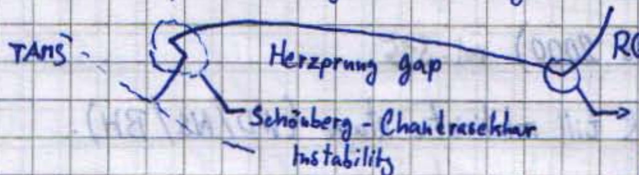
→ Schönberg - Chandrasekhar instability

Star is running out hydrogen in core => $L_c \downarrow$
=> energy is released by gravitational collapse to maintain temperature gradient: $\frac{dT}{dR} = \frac{3 \kappa L \varsigma}{16 \pi a c r^2 T^3}$

=> contraction of core; pressure is inavailable to support outer layers

i. convective core => H is transported to shell source and it's burned to He
ii. radiative core => H stays in core => fossil H

=> expansion of outer layers => $T_{eff} \downarrow$, $L \uparrow$ (in case of $M \gg M_\odot$ stars)



→ bottom of RGB can be calculated by the code as a function of mass and metaliaty (simple power-law approximation). Amazing!

Horizontal ~~Red Giant~~ Branch

He is burning in shell; Most of L is produced by envelope

$T_c > 5 \cdot 10^8$ K => He → C, O => envelope becomes transparent => $T_{eff} \uparrow$

... then follows another gap, AGB ($L \uparrow$), WD sequence ...

The case of Solar-type stars ($\sim 1 M_\odot$)

- 1st dredge-up => convection penetrates core and He can reach external layers
- RGB => almost fully convective; follows Hayashi stage; H burning in core

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AGB Puzzle – Paradox of Stellar Physics

Introduced by Paczynski (died about year ago on brain cancer)

$$\frac{L}{L_\odot} \approx 60{,}000 \left(\frac{M_c}{M_\odot} - 0.5 \right)$$

(empirical equation)

This coresponds both - single and binary star observations.

That's amazing!

The question is: Why? One would expect something like $L \sim \dot{M}_c$, because the core is inert and it cannot contribute to the allover luminosity; however, it seems it does somehow.

=> paradox

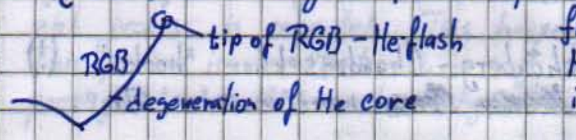
The reason is very simple. The increasing mass of the core is reshaping potentional well and core is collapsing, increasing its density and releasing gravitational energy. It means that core is not actually inert and L should be function of core mass; as shown by observational data.

$$\frac{R}{R_{\odot}} \sim \left(\frac{M}{M_{\odot}}\right)^{-1/3}$$

That explains the paradox.

Red Giant Branch

T_c < He-burning temperature; Starting with small He core. He is falling down from the shell source. After reaching some density, He core degenerates. Gravitational energy is still increasing reaching $M_c = 0.45\, M_{\odot}$



=> Critical core mass; high thermal conductivity of degenerated core leads to runaway triple-α process => He-flash [M_{crit} - Schwarzschild limit]

Significant neutrino loss causes brake in temperature gradient and completely rebuilds structure of star. => break in H-R evolutionary track

- → Horizontal Branch - L is independent on initial mass, $M \sim 0.5\, M_{\odot}$ for all stars
- → Asymptotic Giant Branch - masses are sole => we cannot get evolution from the first principals, thus we are stucked with observations and empirical equat.

Hot Topic ⇐ • far-UV observations of spiral arms => flux increases with λ (!!); Hot Stars cannot be the cause because of their life-time; however, lifetime of AGB stars is quite long, so they are candidates for convenient explanation; maybe effect of binarity; observational effect

Red Giants:

$L > 100 L_{\odot}$; $T_{eff} \sim 4000K$; $R \sim 30 - 100 R_{\odot}$

Illustrations of the code output files

- M_c is the mass of the inert core, thus $M_c = 0$ in MS phase
- phase 6 = thermal pulses => mass of the core drops - 2nd dredge-up
- final phase - $1.28\, M_{\odot}$ WD
- the most massive core-mass-lost is during 3rd dredge-up

Conclusion: "sse.f"-code can produce interesting result with small effort.

Comparison of two codes on stellar evolution:

(1.) Schaller et al 1992 — ⇓ tabular form

i. gives also evolution of abundancies
ii. large timescale convenience

(2.) Pols et al. 1998 — ⇓ graphic form

i. better evolutionary coverage

In practice, both codes should be used. They are complementary.

- Example output: Changes in stellar radius (interesting figure)
- low Z => low opacity => higher L
  => stars with $Z \sim 0.001$ reach AGB earlier than solar metalicity stars; this can be crucial for target selection
- even $M \sim 1.5 M_\odot$ stars are showing Schönberg-Chandrasekhar "hooks" (!) it's not just a feature of the $5 M_\odot$ and more massive stars.

This code is applicable to:

Recapitulation of previous lecture

Lecture #2

$M < 0.08 M_\odot$ BDs
$0.08 < M < 0.5 M_\odot$ Cent. H-burning -> He WD
$0.5 < M < 2 M_\odot$
⋮
$M > 20 M_\odot$ BH

Mixing-length-theory vs. overshooting theory => Small differences in evolutionary tracks

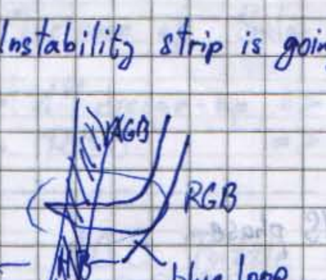
Mixing-length-theory ↓ thin (negligible) boundary layer of convective zone

overshooting theory ↓ transition layer between convective zone and core

Instability strip & blue loops

Convective envelope is becoming transparent; core gives additional continuum and thus star appear actually bluer.

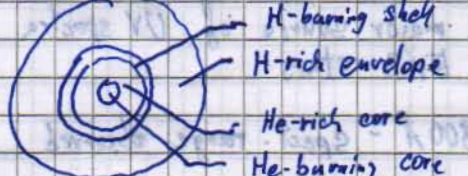
Instability strip is going through region of blue loops



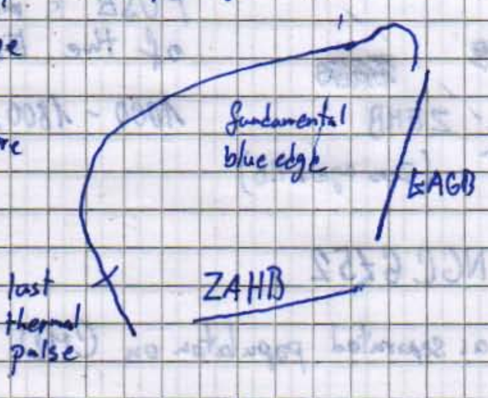
Effect of metallicity

- significant influence on p-p / CNO effectivity

Evolution of star with medium mass



Example of early AGB-star



ZAHB - zero age HB
E-AGB - early AGB

The last thermal pulse occures in 18 000 mil yrs after the first one.

After He-flash, outer layers will expand and temperature goes up in the envelope, high enough to lit on H-burning in outer layers. This ignition initiates thermal pulses. After temperature get lower after H in shell source is depleted, the envelope contracts and process is repeated. This happens several times.
This process is important source of ISM enrichment as far as metals produced are propagated to ISM envelope by stellar wind.

At the end there is just naked core surrounded by expanding envelope -> PN

Mass-loss effect on the trend of stellar evolution on RGB

$$\dot{M} = -\eta \cdot 4 \cdot 10^{-13} \frac{RL}{M}$$ Reimers formula - just a good approx. not exact formula.

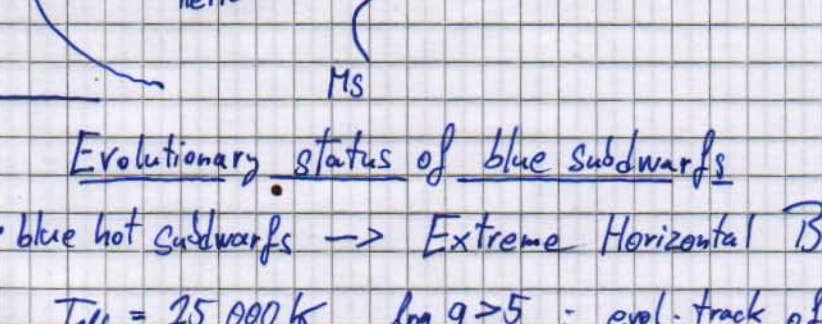
=> for stars on RGB -> depending on η:

I. $\eta = 0.75$ -> CO WD, $M = 0.536\ M_\odot$
II. $\eta = 1.0$ -> CO WD, $M = 0.520\ M_\odot$
III. $\eta = 0.5$ -> He WD, $M = 0.48\ M_\odot$
IV. $\eta = 0.85$ -> completely different route (!)

This may differ by initial mass and metallicity

$\eta = 1$; solar Z, $M = 0.9 M_\odot$; mass-loss twice a Reimers formula prediction => directly to WD sequence from the tip of RGB

$\eta = 0.85$; $Z = 0.001$, $M = 0.9 M_\odot$

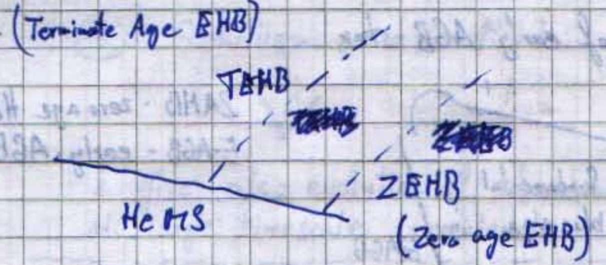


Evolutionary status of blue subdwarfs

- blue hot subdwarfs -> Extreme Horizontal Branch

$T_{eff} = 25\,000$ K $\log g > 5$; evol. track of $0.5 M_\odot$ star, thin envelope $M_{env} < 0.02 M_\odot$

EHB stars are the <u>old object</u> - found in metal poor GCs



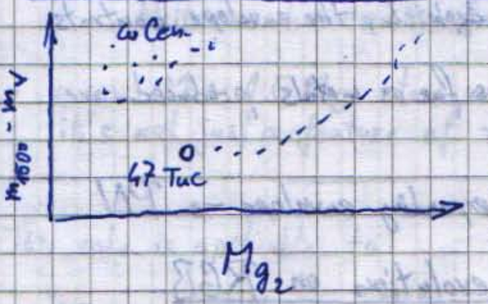
FUSE is major source of UV spectra of the EHB stars

1000 - 1800 Å - Spect. range observed

EHB population NGC 6752

-> EHB shows as separated population on CMD

<u>UV excess in some stellar clusters and ellipticals</u>



$$Mg_2 = \frac{1}{\alpha}\left([Fe/H] + \beta\right)$$

$\alpha = 12.67 \quad \beta = 2.84$

<u>Origin of EHB - The riddle</u>

<u>1996</u> - an idea of enhanced mass-loss on RGB. Degenerated He-core losts almost all surrounding convective envelope close to the RGB tip but core ignit despite the mass-loss -> forms sdB star (EHB)

(D'Cruz et al. 1996; Saffer et al 1994)

This stars were discovered ~5 yrs ago. There is still question of binarity - companion is usually too fait to be shown in spectra. Usually guessed from variation of radial velocities. Evolution in close binaries can be explanation for this sudden mass loss. Investigation is still in progress.