12. Evolution off the Main Sequence

12.1 Role of electron degeneracy

- onset of degeneracy provides pressure support that allows stability at (almost) any temperature
- when degeneracy occurs, temperature "decouples" from hydrostatic balance
- first we need to consider electron degeneracy, only for very compact objects (when e^- are "pushed into" p^+, to give n^0) we need to also take neutrons degeneracy into account (neutron stars)

- recall: Fermi energy $E_F \approx \frac{p_F^2}{2m_e}$

[to estimate p_F: electron density: $n_e = \frac{\rho}{m_p} \stackrel{!}{=} \frac{8\pi}{3h^3} p_F^3$

$\Rightarrow$ $p_F^3 = \frac{3h^3 \rho}{8\pi m_p}$ fully ionized $\Rightarrow n_e = n_p = n = \frac{\rho}{m_p}$]

- critical temperature when $E_F \approx E_{thermal}$

$$\frac{p_F^2}{2m_e} \approx kT$$

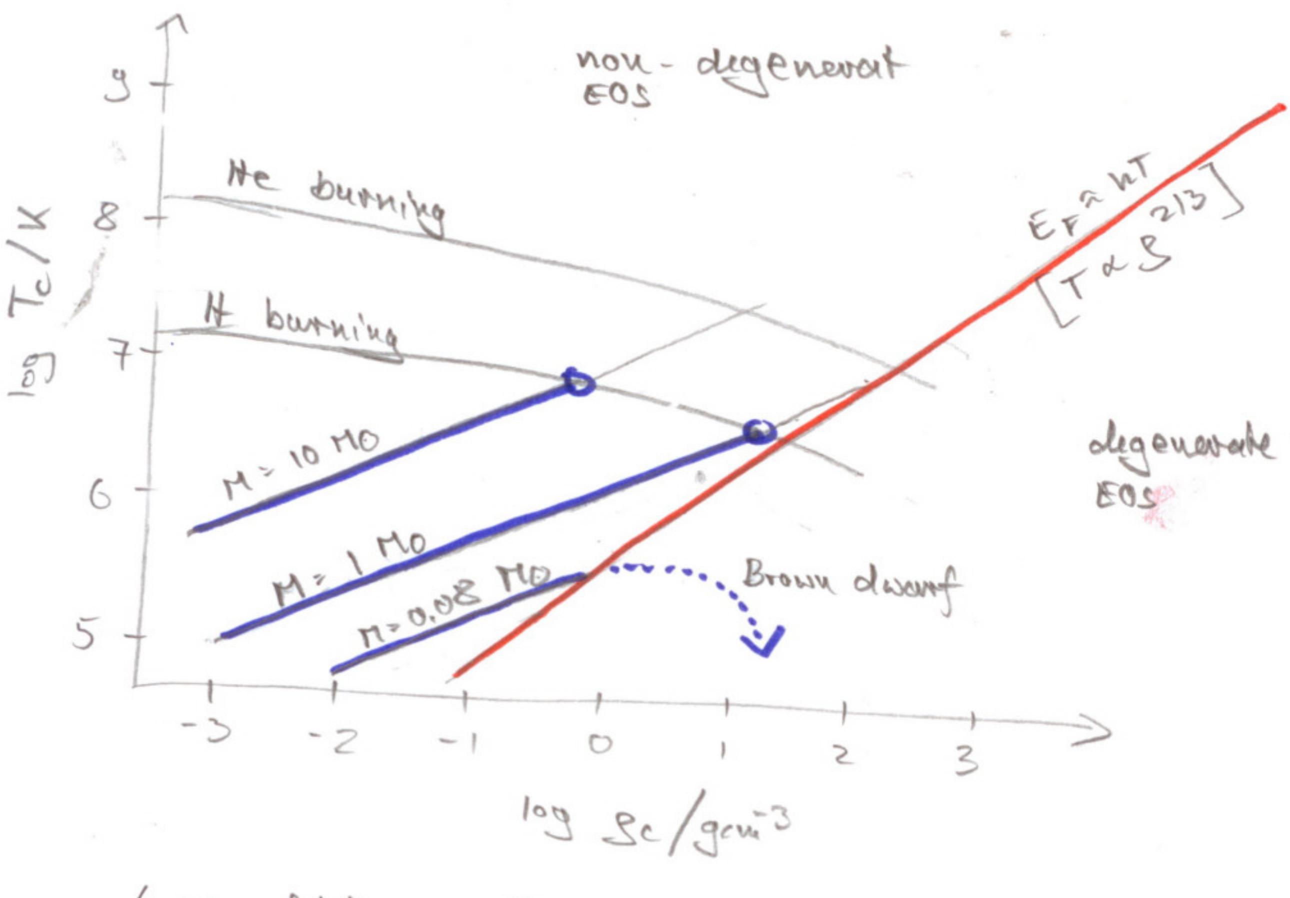
$$\Rightarrow kT \approx \left(\frac{3h^3}{8\pi m_p}\right)^{2/3} \frac{1}{2m_e} \cdot \rho^{2/3}$$

→ critical temp: $T_c \approx 3 \cdot 10^5\,K \cdot \left(\frac{\rho}{1\,g/cm^3}\right)^{2/3}$

↳ recall for hydrostatic balance:

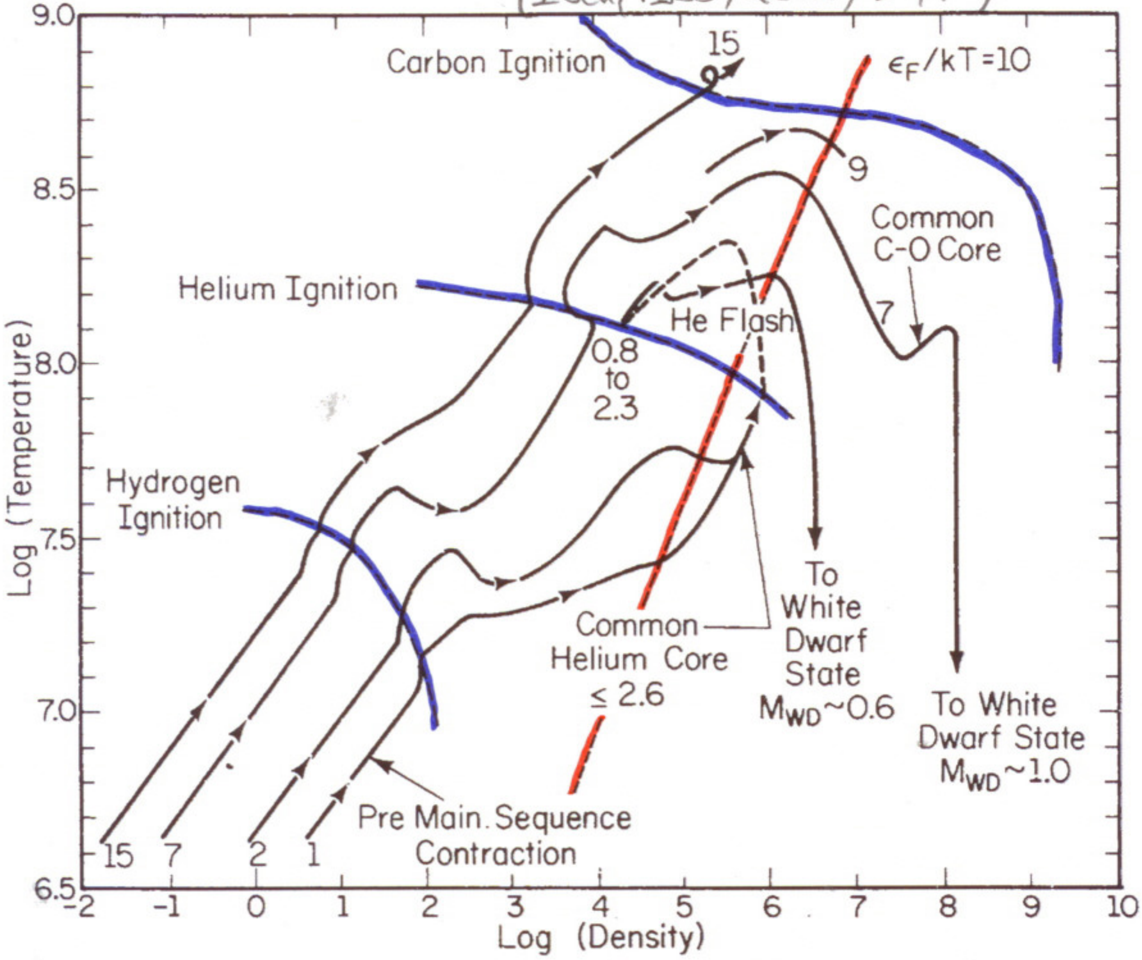
$$T_c \approx 2 \cdot 10^6\,K \left(\frac{M}{1 M_\odot}\right)^{2/3} \left(\frac{\rho}{1\,g/cm^3}\right)^{1/3}$$

- so star contracts until either degeneracy is reached, or nuclear burning occurs:



(more details, e.g., Iben 1985, QRAS, 26, 1-39)

(Iben, 1985, QRAS, 26, 1)



- stars with initial mass below ≈ 10 $M_\odot$ will turn into white Dwarfes after heavy mass loss.

- low-mass *'s develop e^--degenerate core before He burning (He burning then may occur in degenerate phase)

- low- to intermediate-mass *'s can burn He and develop e^--degenerate core made of carbon and oxygen (C,O core)

- recall evolution <u>ON</u> main sequence:

  for $M \gtrsim 1 M_\odot$: CNO cycle produces energy

  $$L \propto M^3 \mu^4$$

  ↳ as H burns into He, the mean molecular weight μ increases, as $M \approx$ const ⟶ $\boxed{\mu \uparrow \Rightarrow L \uparrow}$

  ↳ because $L_{CNO} \propto T^{20}$ the central temperature increases only slightly to match the growing demand in luminosity.

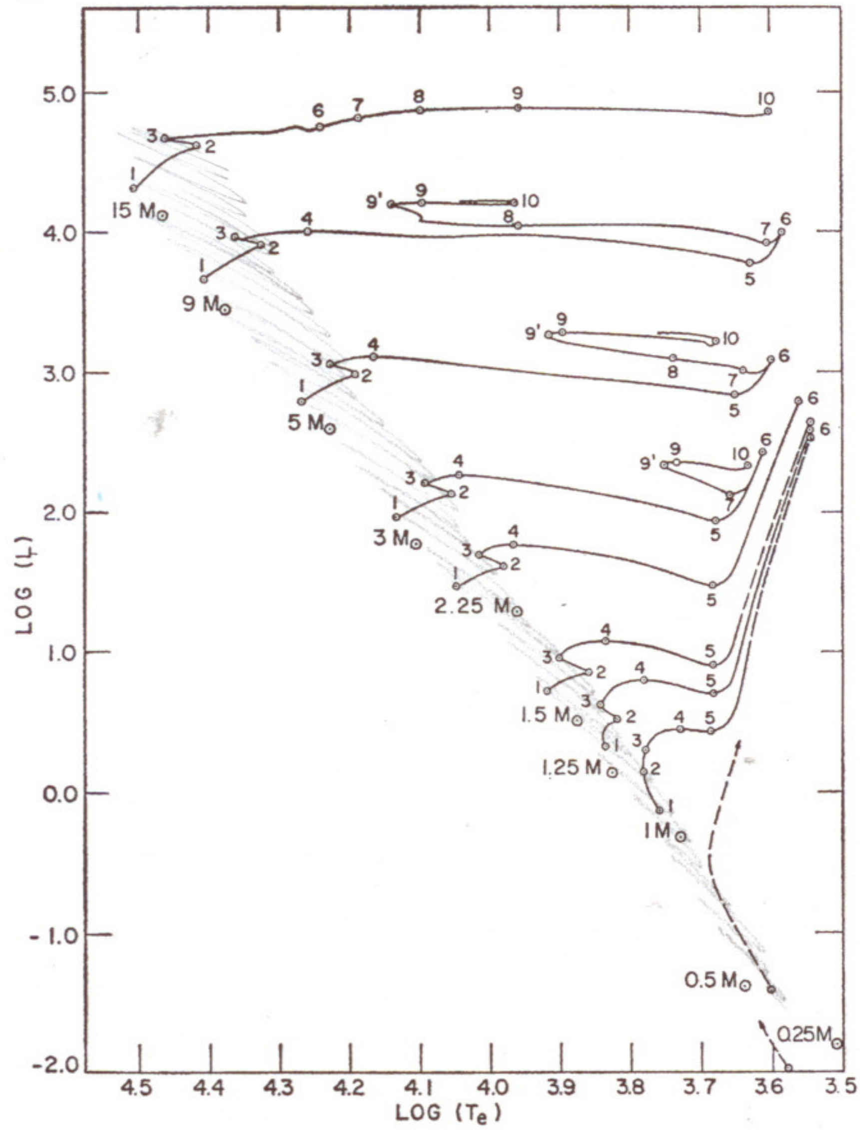
  ⟶ $T \approx$ const.

- <u>evolution OFF main sequence</u>

  as H is depleted, star contracts and heats up, further evolution again mass dependent

  - low masses: e^- degeneracy kicks in before onset of He burning
  - intermediate masses: He burning
  - higher masses: C/O burning
  - up to Fe & SN

• past main-sequence evolution is very diverse, depending on initial stellar mass:



Iben (1967, ARAA, 5, 571)

FIG. 3. Paths in the H-R diagram for metal-rich stars of mass $(M/M_{\odot})=15$, 9, 5, 3, 2.25, 1.5, 1.25, 1, 0.5, 0.25. Units of luminosity and surface temperature are the same as in Figure 1. Traversal times between labeled points are given in Tables III and IV. Dashed portions of evolutionary paths are estimates.

TABLE III

STELLAR LIFETIMES (yr)[a]

Mass ($M_{\odot}$) \ Interval $(i-j)$	(1–2)	(2–3)	(3–4)	(4–5)	(5–6)
15	1.010 (7)	2.270 (5)		7.55 (4)	
9	2.144 (7)	6.053 (5)	9.113 (4)	1.477 (5)	6.552 (4)
5	6.547 (7)	2.173 (6)	1.372 (6)	7.532 (5)	4.857 (5)
3	2.212 (8)	1.042 (7)	1.033 (7)	4.505 (6)	4.238 (6)
2.25	4.802 (8)	1.647 (7)	3.696 (7)	1.310 (7)	3.829 (7)
1.5	1.553 (9)	8.10 (7)	3.490 (8)	1.049 (8)	≥2 (8)
1.25	2.803 (9)	1.824 (8)	1.045 (9)	1.463 (8)	≥4 (8)
1.0	7 (9)	2 (9)	1.20 (9)	1.57 (8)	≥1 (9)

[a] Numbers in parentheses beside each entry give the power of ten to which that entry is to be raised.

phase 1-2 : corresponds to H burning phase = main sequence

phase 2-3 : rapid phase: contraction of stellar core as H is rapidly depleted

phases 3-6: correspond to RED GIANT BRANCH:

- continuous expansion of envelope
- reddening of surface to cooler temperatures

(A) Lower - MS Stars

example: 2,25 $M_\odot$ star (Iben, 1985, QRAS)

- core completely convective → is always well mixed → H burning stops when ≈ 0,2 $M_\odot$ He has been produced
- now: He core contracts

↳ T_c increases and H ignites in SHELL around core

↳ Star moves up red giant branch

• He flash ignites (off center)

↳ this is an almost explosive event
(He ignition under electron degenerate conditions)

↳ released energy goes into heat
T increases, but because of e^- degeneracy
the pressure is not increased!
↳ star cannot cool by expansion!

↳ as T increases rapidly, the energy production in 3α process increases dramatically

(eventually the outer convective zone deepens and begins to transport away the energy released) ⊛

↳ He core burns quietly
star expands dramatically (and reddens) (∗∗)

↳ **Red giant phase**

⊛ also He is transported outwards
↳ first dredge up

(∗∗) also H burning shell expands → gets cooler
→ L decreases!

- while He burns (quietly) in core
  C&O build up & eventually He burning ceases.

  ↳ He shell burning still continues

  ↳ Asymptotic Giant BRANCH (He shell dominates)

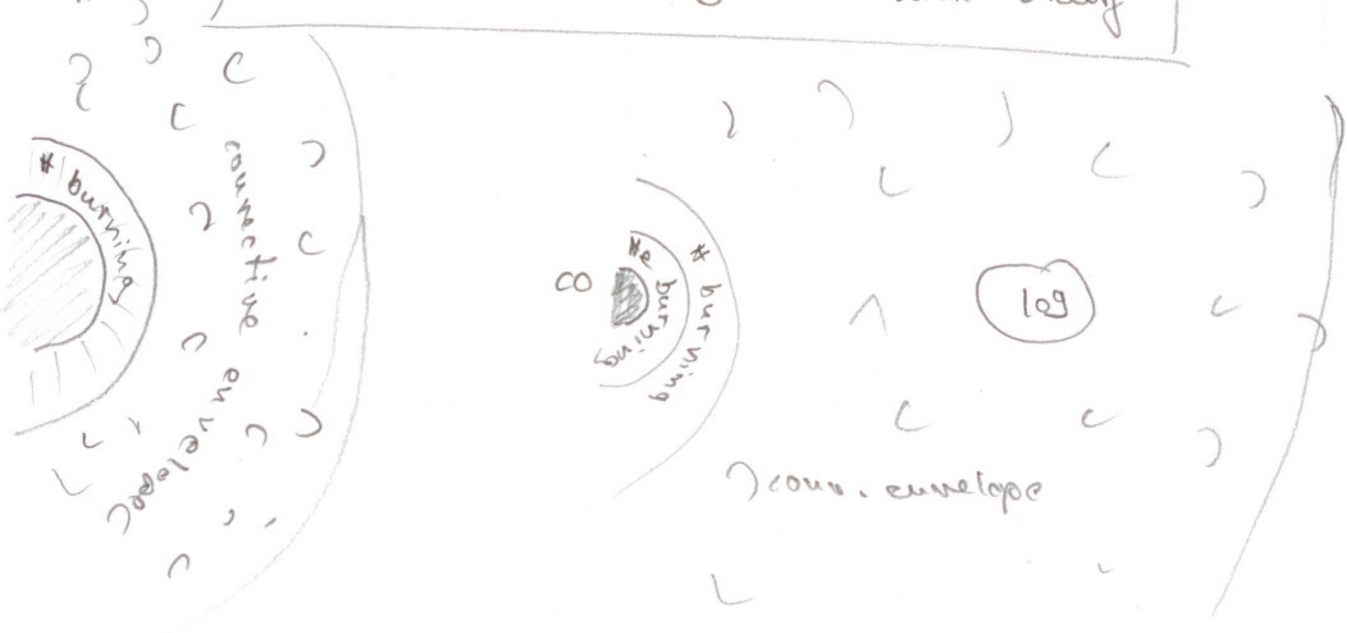
- there is the possibility for He shell flashes (and additional dredge ups)

  & for higher mass objects: thermal pulses that can revitalize H burning outer shells.

- now heavy mass loss in post-AGB phase (line driven winds)

  ↳ formation of planetary nebulae

  ↳ remnant ≈ 0,6 $M_\odot$ CO white dwarf



Iben (1985, QRAS, 26, 1)

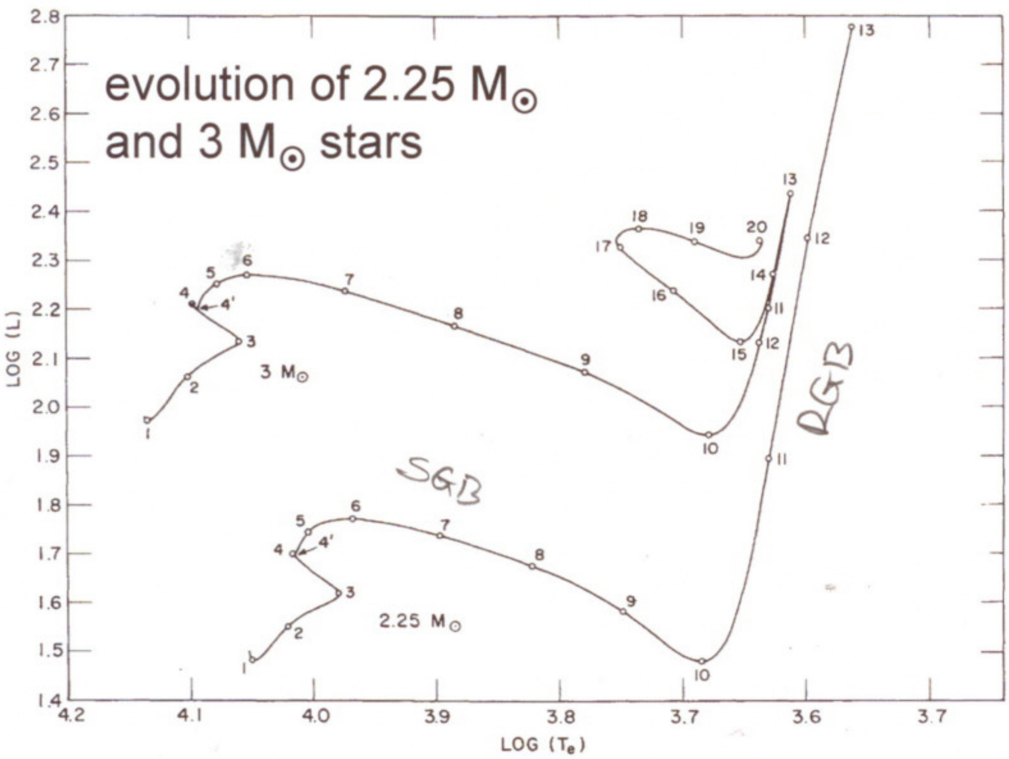


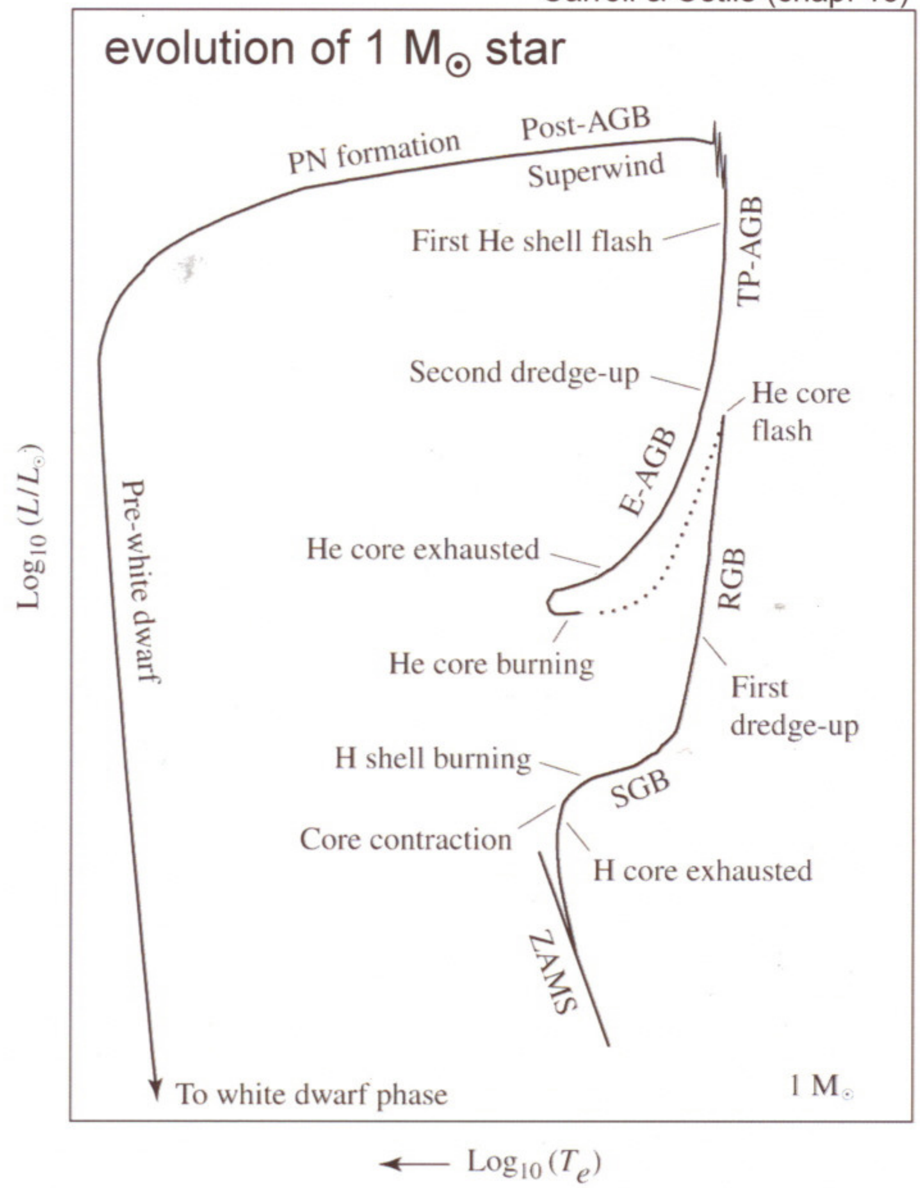
FIG. 1. Evolutionary tracks in the Hertzsprung–Russell diagram for model stars of mass 2·25 and 3 $M_\odot$. Luminosity L is in solar units, $L_\odot = 3{\cdot}86 \times 10^{33}$ erg s^{-1}, and surface temperature T_e is in degrees Kelvin. The model of mass 2·25 $M_\odot$ develops an electron-degenerate core and evolves to a higher luminosity than does the 3 $M_\odot$ model before helium burning reactions are ignited in the core. The times taken by the 2·25 $M_\odot$ model to reach labelled points along its evolutionary track are (in 10^8 yr): (1) 0·05855, (2) 2·7989, (3) 4·8503, (4) 5·0150, (4′) 5·0174, (5) 5·2018, (6) 5·3847, (7) 5·4460, (8) 5·4737, (9) 5·4947, (10) 5·5157, (11) 5·6167, (12) 5·7774, (13) 5·8986. For the 3 $M_\odot$ model, times to reach equivalent points are (in 10^8 yr): (1) 0·02459, (2) 1·3892, (3) 2·2367, (4) 2·3409, (4′) 2·3422, (5) 2·4012, (6) 2·4442, (7) 2·4700, (8) 2·4787, (9) 2·4843, (10) 2·4893, (11) 2·4982, (12) 2·5073, (13) 2·5316. From Iben, I. (Jr), 1967. *Astrophys. J.*, **147**, 624.

RGB = red giant phase

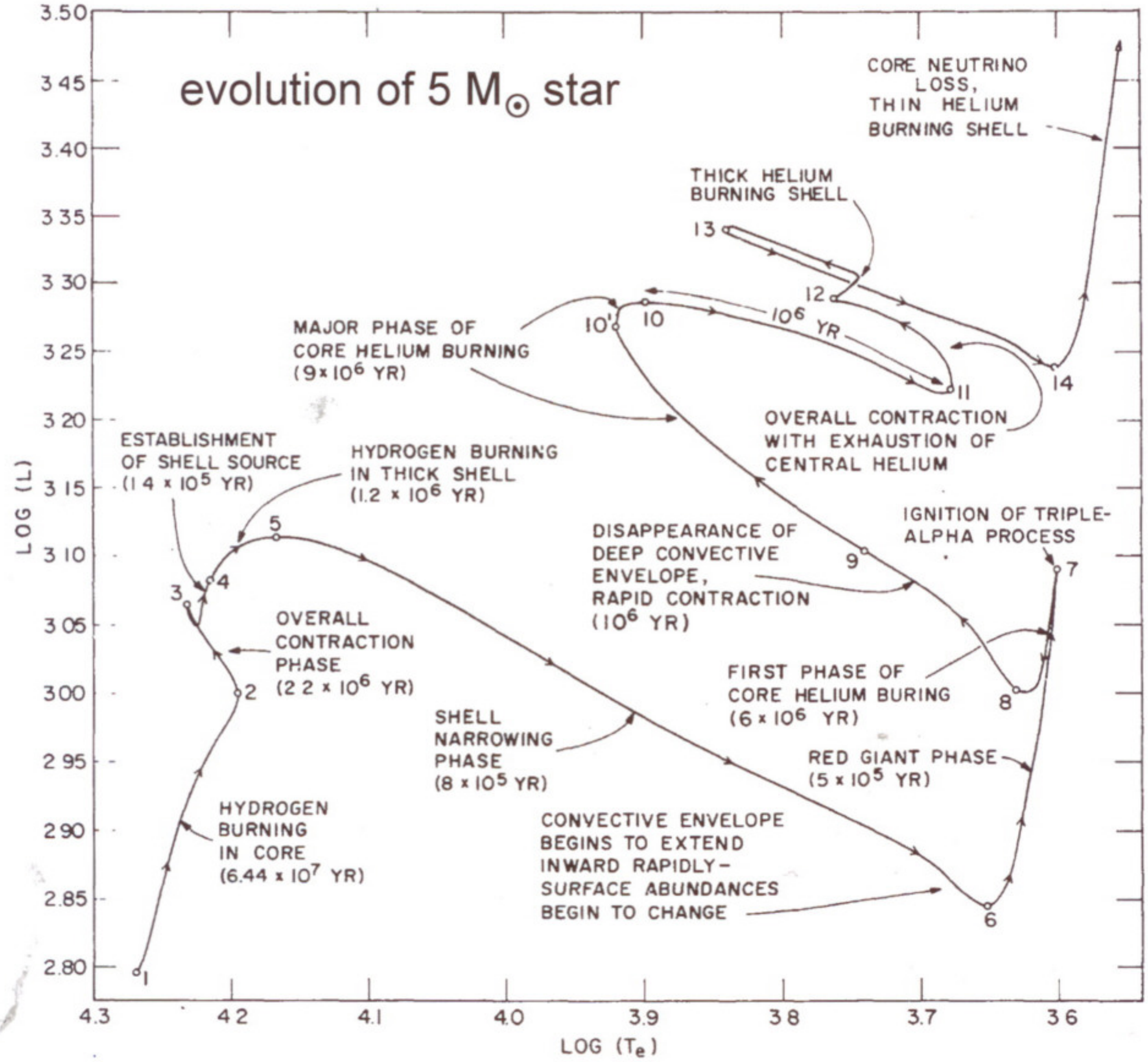
SGB = sub giant phase

* very similar: Evolution of 1 $M_\odot$ Star

Carroll & Ostlie (chap. 13)



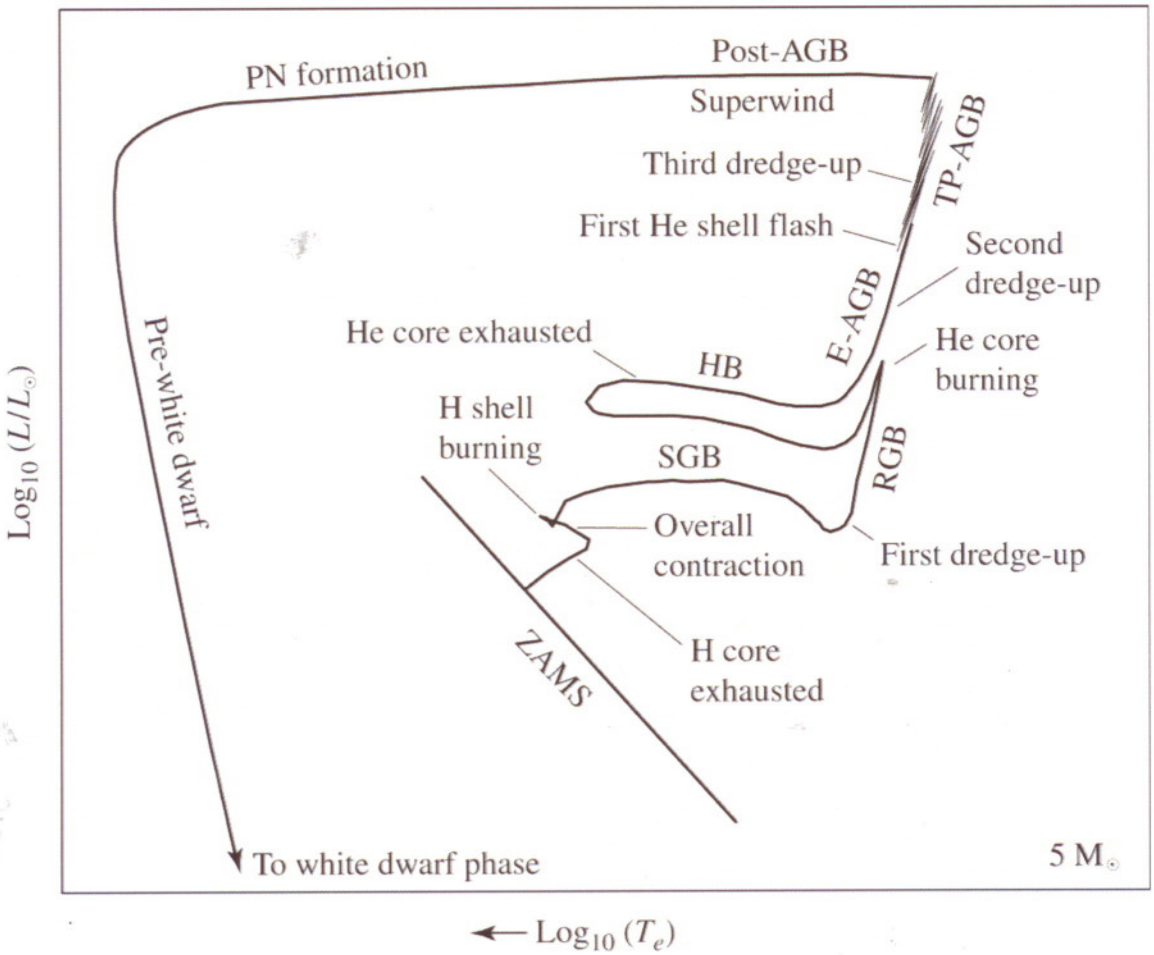
Iben (1985, QRAS, 26, 1)



* evolution of a 5 $M_\odot$ star
(after Iben, 1985) (see also Carroll & Ostlie, Fig 13.5)

similar to the $1 M_\odot$ star, but now a well-established <u>HORIZONTAL - BRANCH</u> phase occurs.

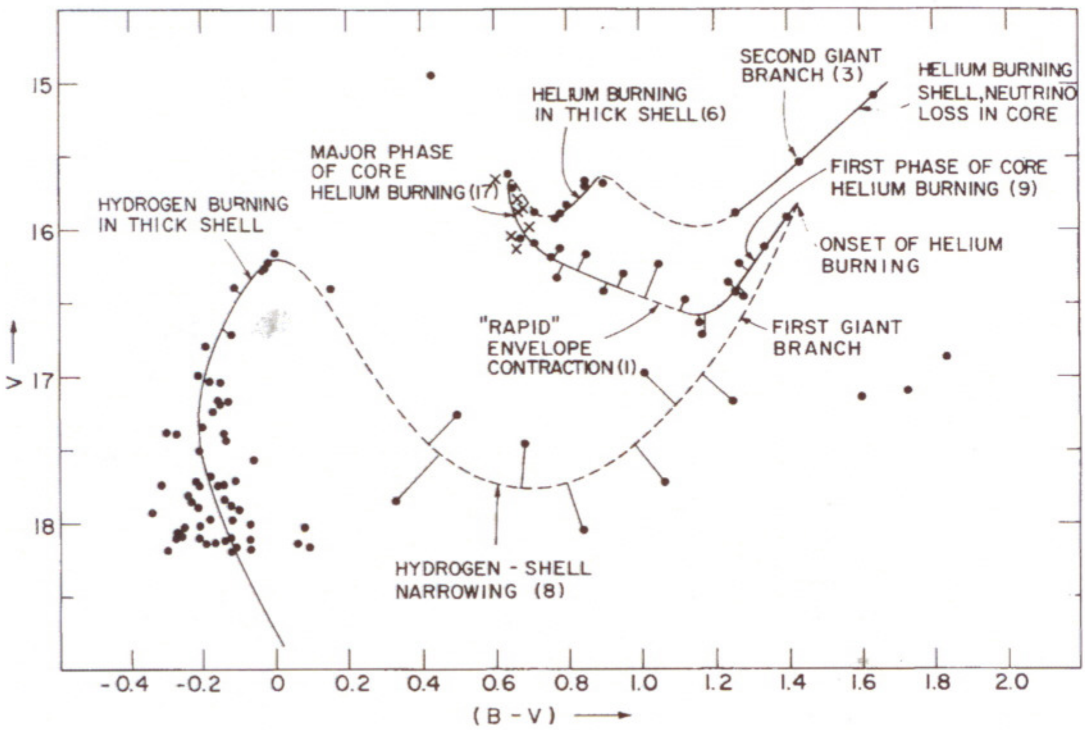
Carroll & Ostlie (chap. 13)



The HB occurs when He burns in the core which becomes convective (no longer e^- degenerate).

↳ HB is the analogon to the fully convective CNO H-burning cores of upper-main sequence stars.

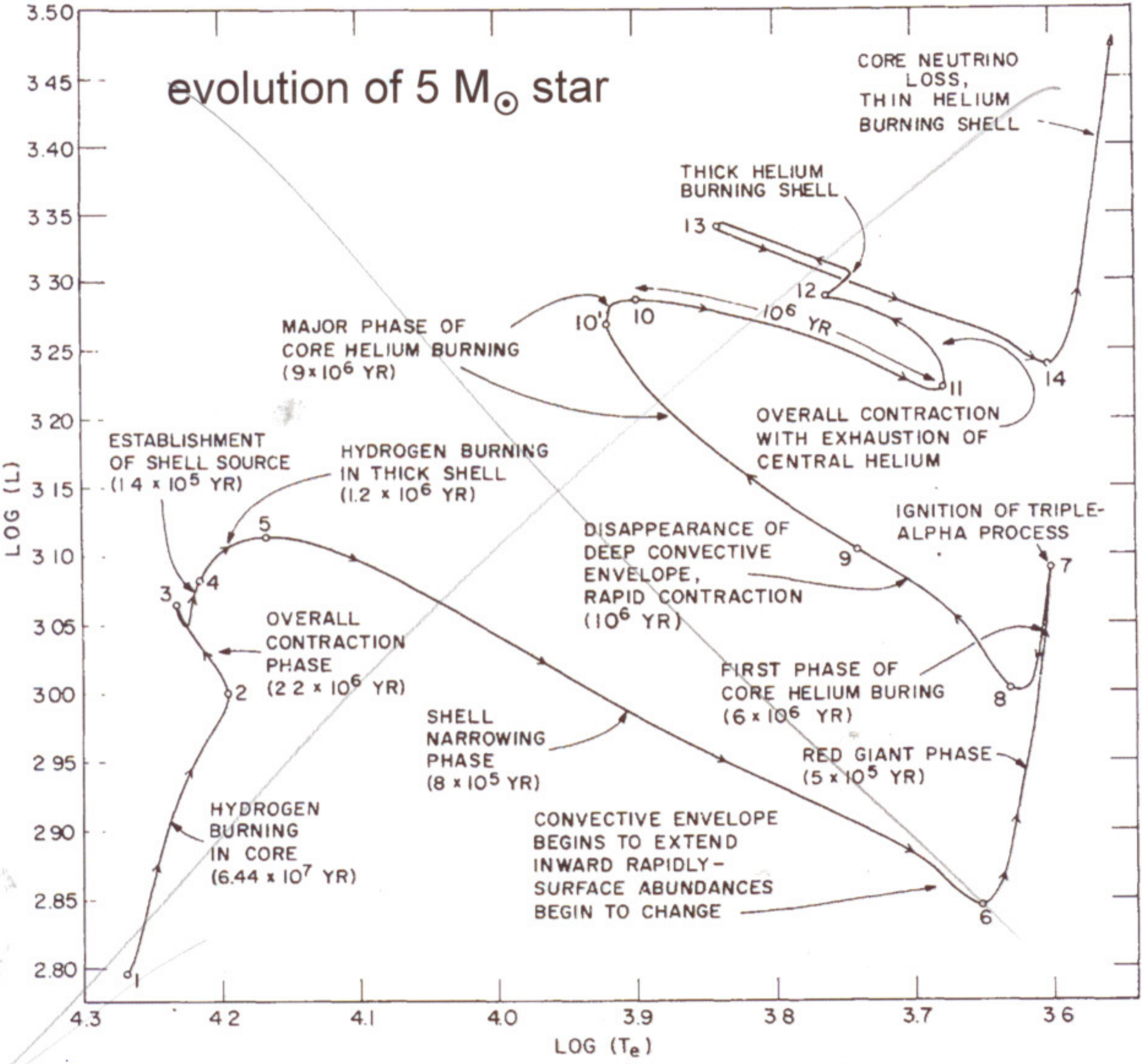
Iben (1985, QRAS, 26, 1)



Eye fit to the data. The fit is similar to the 5 $M_{\odot}$ track on the previous page.

- when the evolution of the star reaches the blueward point of the HD, then μ has changed (dominated by C & O) so that the core needs to contract again to produce required luminosity
  ↳ envelope expands & cools
  ↳ star moves redwards.

Iben (1985, QRAS, 26, 1)



- in red part of HB core helium is exhausted

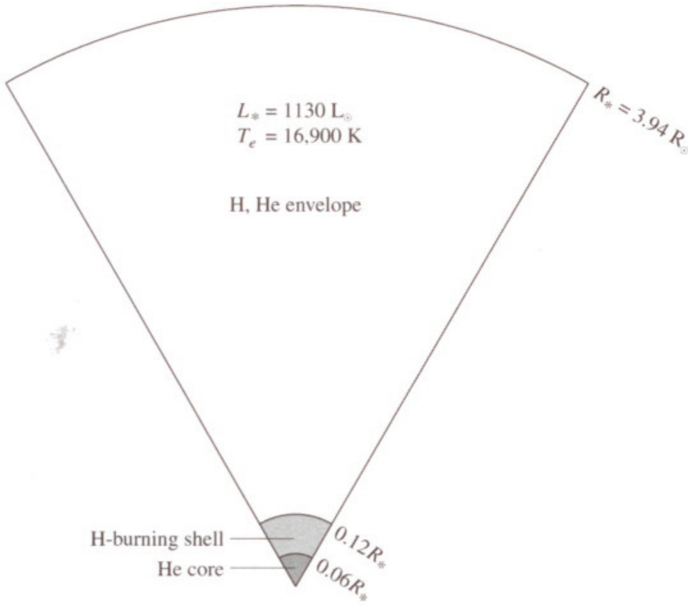
  ↳ core contracts (just like in sub giant phase: SGB)

  ↳ as stars move through HB, instabilities & pulsation may occur

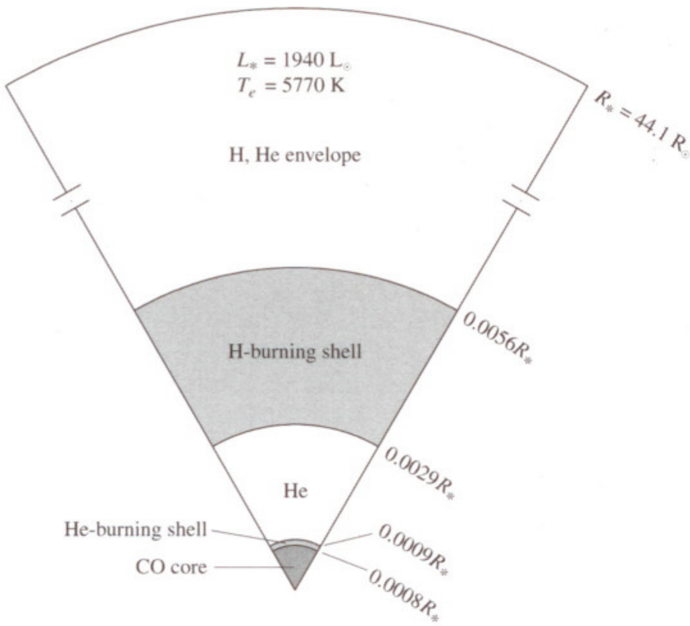
- then the (early) AGB comes, where the luminosity is generated by He shell burning (similar to H shell burning at RGB).

- intermediate-mass stars then may go through thermal pulses: narrow He shell may turn on and off:
  - as * contracts, dormant H shell wakes up.
  - H shell produces He ashes that rain down on He shell
  - as mass of He shell increases it may become slightly degenerate
  - then, when the temperature at the base of the shell increases sufficiently, He may ignite again and a He flash occurs (analogous to the earlier He flash of low-mass *'s)
  - eventually He burning ceises and H burning recovers and the process repeats.

- structure of star during RGB, shortly after H-burning shell ignited



- structure of star during He flash



• thermal pulses at end of AGB phase:

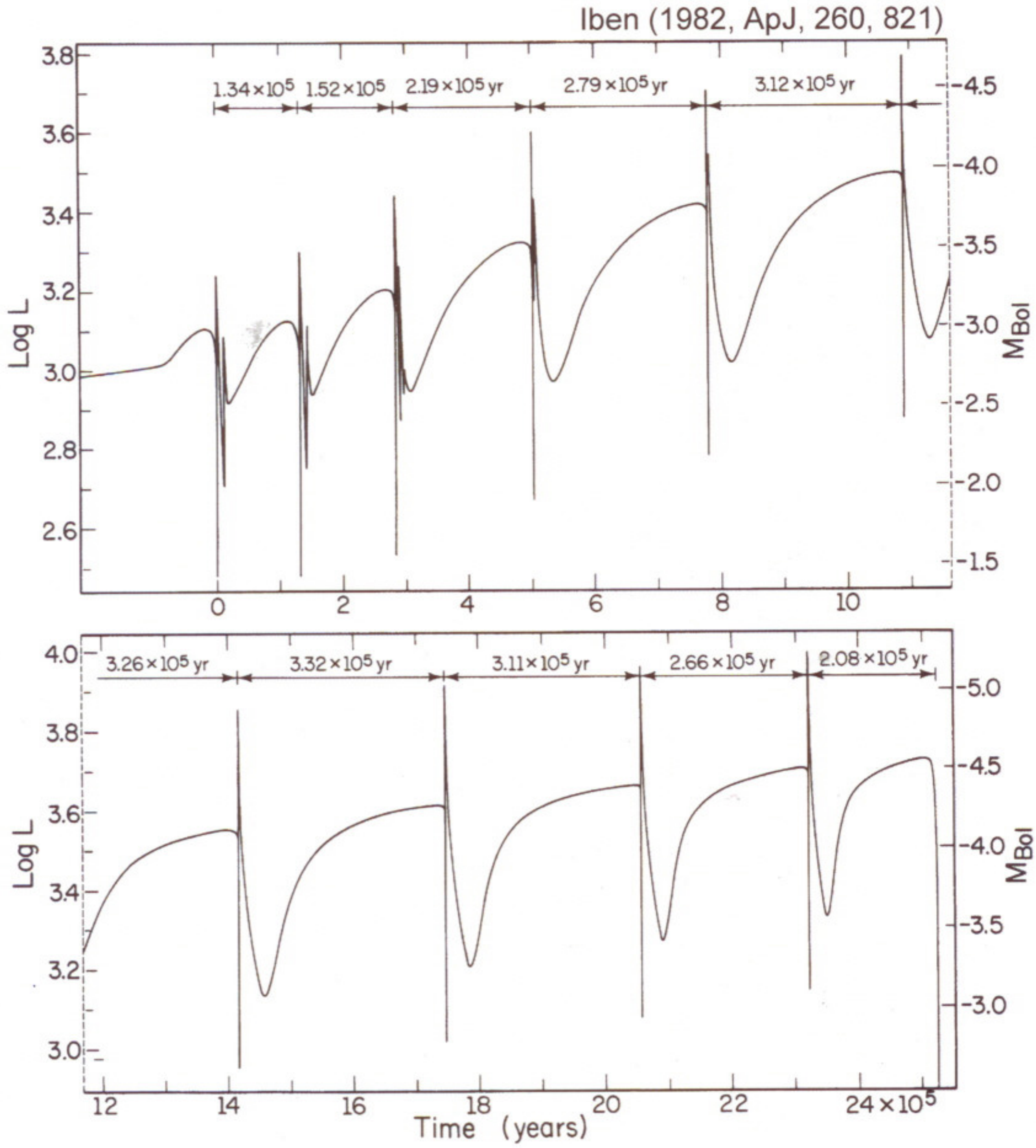


FIG. 2.—Time dependence of luminosity and bolometric magnitude during the thermally pulsing phase for a model of mass 0.6 $M_\odot$

• during He flashes, a convection zone occurs between He & H burning shell; this zone may merge with the convection zone of the envelope

↳ carbon may be mixed up all the way to the stellar surface

- this is the "third dredge up" which leads to carbon-rich giants (C spectral type)

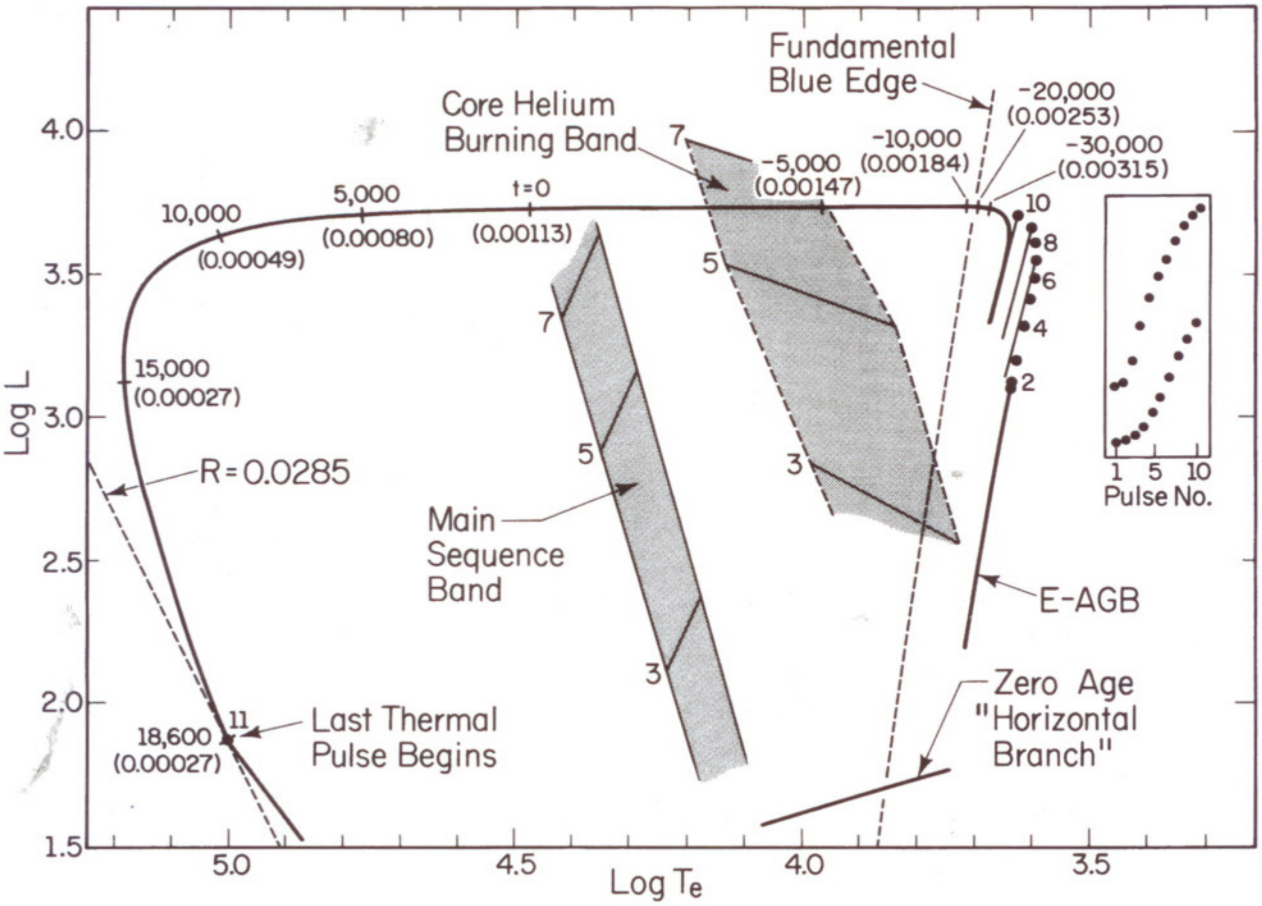


FIG. 3.—Evolutionary track in the H-R diagram of an 0.6 $M_\odot$ model with a carbon-oxygen core. Details are given in the text.

- AGB stars are known to lose mass at high rate (up to $\dot{M} \approx 10^{-4}$ $M_\odot$/yr)

$T_{surface} \approx 3000$ K they are quite cool

↳ dust can form: - silicates in O-rich environment
- graphite in C-rich stars

- this dust may couple to radiation and this radiation may drive the large mass loss

(not well understood, maybe thermal pulses)

- as the envelope expands, it eventually becomes opt. thin → thus exposing the central star, which typically shows spectrum of F or G-type supergiant

the evolutionary track moves more or less horizontally to the blue

- eventually expelled envelope + central white dwarf make up a <u>planetary nebula</u> (PN)

* Post main sequence evolution of
very-massive stars

- stars initially more massive than ~ 8 ... 10 $M_\odot$ end their lifes in supernova explosions.

- before that, they go through several higher-element nuclear burning phases and severe mass-loss phases

  - luminous blue variables (LBVs)
    * have surface temperatures $T \simeq$ 15.000 - 30.000 K and luminosities $L \gtrsim 10^6 L_\odot$ & masses $M \geq 85 M_\odot$
      ↳ sit in upper left of H-R diagram.
    * ↳ these stars have huge mass loss rates and they are rapid rotators

  - Wolf-Rayet stars (WR)
    * are closely related to LBVs
    * there are ~ 1000 - 2000 WRs in the Galaxy
    * have $T_{eff} \simeq$ 25.000 - 100.000 K and show very strong emission lines
    * have huge mass loss rate $10^{-5} M_\odot/yr$ with wind speeds $\gtrsim$ 800 km/s
    * have masses ~ 20 $M_\odot$
    * three classes: WC have emission lines of C & He (no N & H)
      WN have N & He
      WO have strong O lines.

- there are also <u>blue super giants</u> (BSG), <u>red super giants</u> (RSG), and <u>Of stars</u> (O super giants with pronounced emission lines)

- the general evolutionary sequence is as follows:

$10 < M/M_\odot < 20$: O → RSG → BSG → **SN**

$20 < M/M_\odot < 25$: O → RSG → WN → **SN**

$25 < M/M_\odot < 40$: O → RSG → WN → WC → **SN**

$40 < M/M_\odot < 85$: O → Of → WN → WC → **SN**

$85 < M/M_\odot$: O → Of → LBV → WN → WC → **SN**

- <u>supernovae</u>

- supernovae describe the explosive, sudden mass loss (very-) massive stars experience at the end of their lives.

- there are two classes of SN:

  Type I : no hydrogen lines

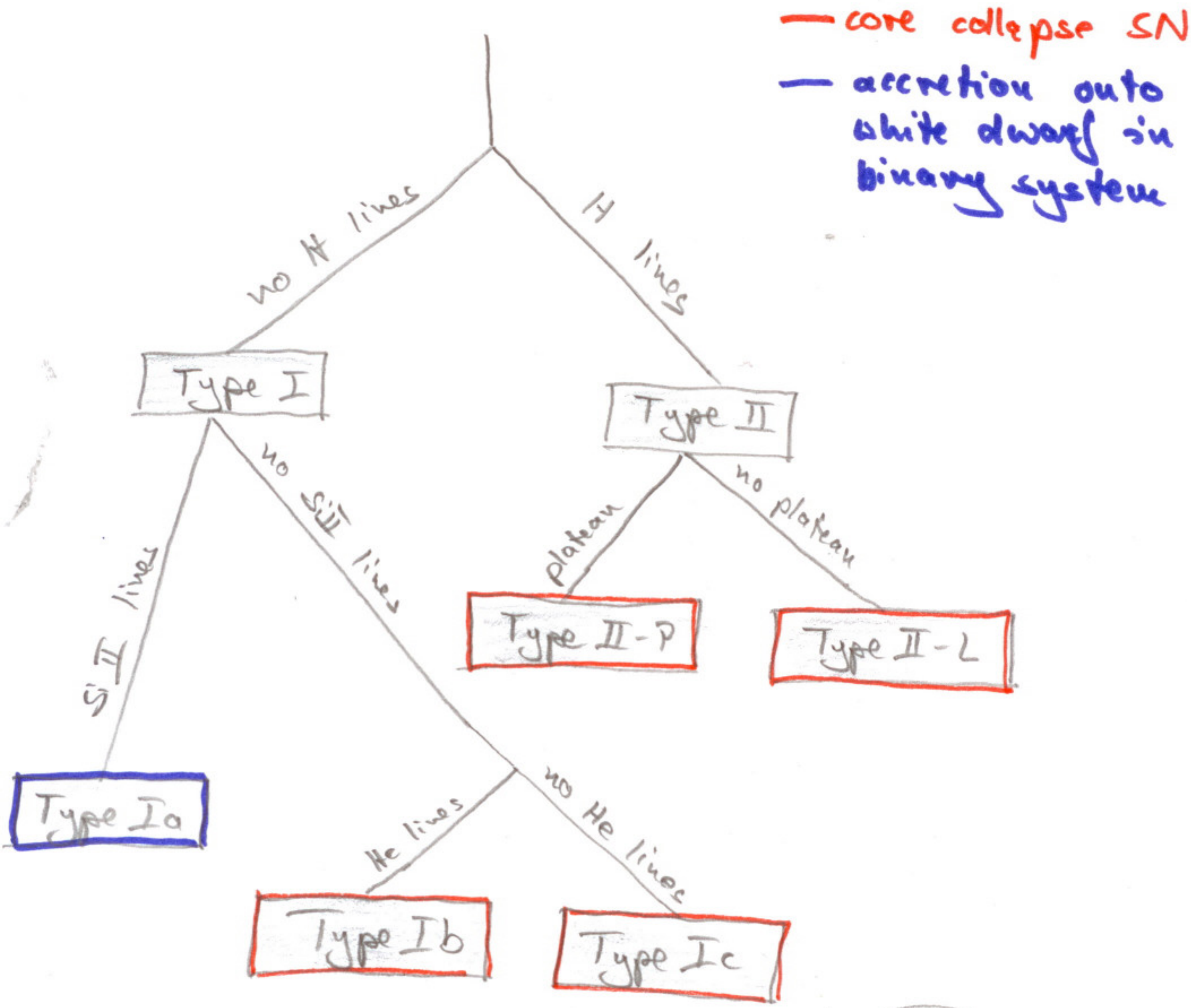
  Type II : strong H lines

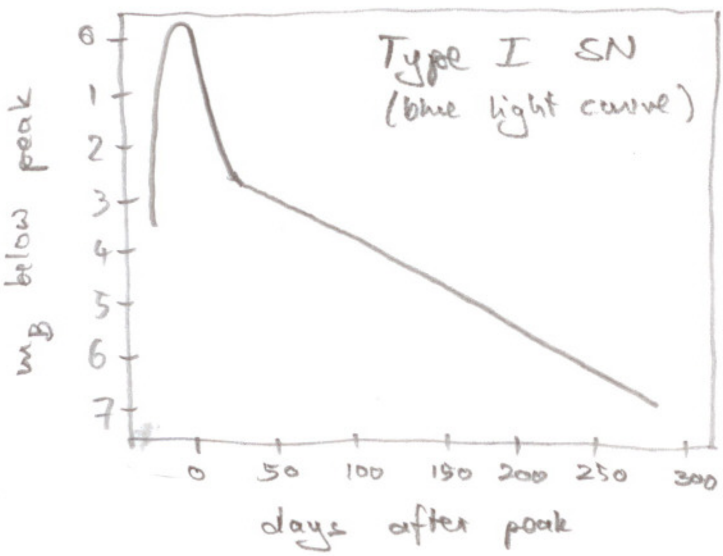
Type I's are subclassified according to other spectral features:

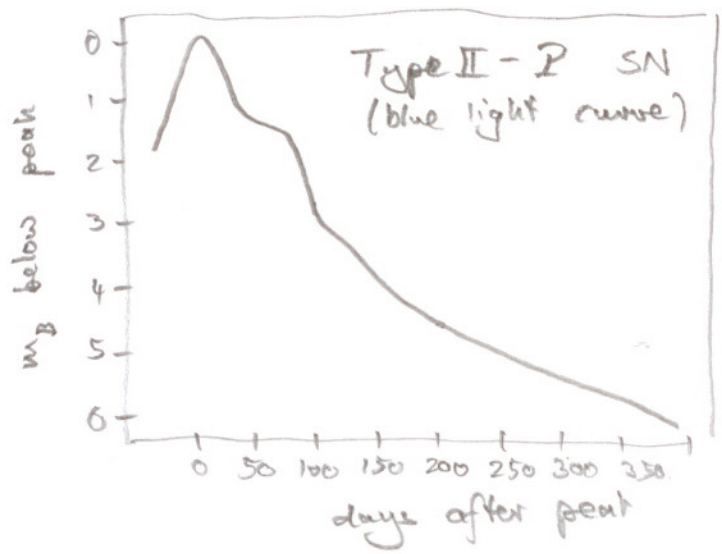
Type Ia: strong Si II line (615 nm)

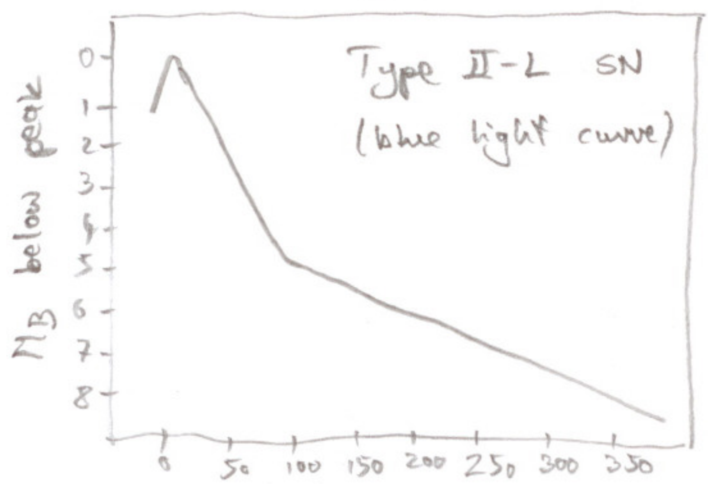
Type Ib: strong He I line

Type Ic: no He I line




Type I SN
(blue light curve)
m_B below peak
0
1
2
3
4
5
6
7
0
50
100
150
200
250
300
days after peak


Type II - P SN
(blue light curve)
m_B below peak
0
1
2
3
4
5
6
0
50
100
150
200
250
300
350
days after peak


Type II-L SN
(blue light curve)
M_B below peak
0
1
2
3
4
5
6
7
8
0
50
100
150
200
250
300
350

- a typical Type II SN releases 10^{53} erg energy: ~99% in neutrinos
  ~1% in kinetic energy of ejecta
  ~0,01% in radiation

similar values for Type Ib and Ic.

- Type II and Types Ib and Ic are core collapse supernovae

Type Ia occur in binary system, when mass transfer onto white dwarf causes ignition of degenerate He and sends a shock wave into CO core which ignites carbon & oxygen burning as well. The WD gets completely disrupted, leaving the binary companion "alone".

- core collapse SN:

this type of SN occurs in shell-burning massive stars.

He-shell adds C & O ashes to CO core, as the core continues to contract (not degenerate!) it ignites C burning, generating elements like $^{16}_{8}O$, $^{20}_{10}Ne$, $^{23}_{11}Na$, $^{23}_{12}Mg$, $^{24}_{12}Mg$

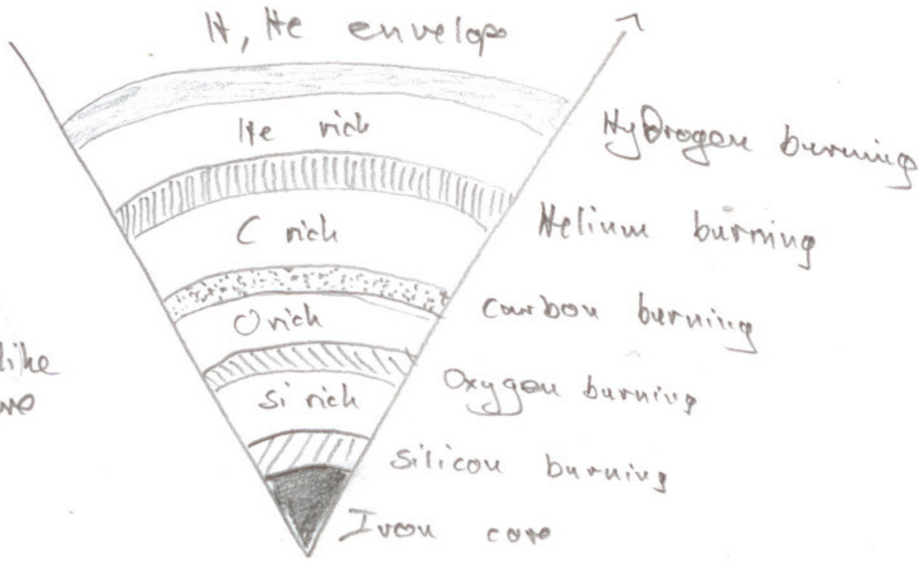
this triggers a variety of further burning processes: Ne-O core will burn to Si then:

$$^{28}_{14}Si + ^{4}_{2}He \rightleftharpoons ^{32}_{16}S + \gamma$$

$$^{32}_{16}S + ^{4}_{2}He \rightleftharpoons ^{36}_{18}Ar + \gamma$$

$$^{52}_{24}Cr + ^{4}_{2}He \rightleftharpoons ^{56}_{28}Ni + \gamma$$

eventually an iron-rich core builds up



Onion like structure

- at very high temperatures in the core <u>photodisintegration</u> of heavy elements occurs:

$$^{56}_{26}Fe + \gamma \rightarrow 13\ ^{4}_{2}He + 4n$$

$$^{4}_{2}He + \gamma \rightarrow 2p^{+} + 2n$$

$(T_c = 8 \cdot 10^{9}\,K$ & $\rho_c \approx 10^{10}\,g\,cm^{-3})$

now, the free electrons that had assisted in supporting the star against further collapse (by degeneracy pressure) are captured by protons:

$$p^+ + e^- \longrightarrow n + \nu_e$$

there is a gigantic burst of neutrino emission, the neutrino luminosity is orders of magnitude larger than nuclear burning luminosity

↳ degeneracy pressure is gone + enormous energy loss by ν_e emission

↳ core collapses extremely rapidly.

depending on mass a neutron star remnant builds up in center (for $*$'s with $M_{ZAMS} \doteq 25\, M_\odot$)

↳ reverse shock expels outer layers

for stars with $M_{ZAMS} \gtrsim 25\, M_\odot$ the remnant is too heavy and cannot be stabilized by n degeneracy ⟶ collapse to black hole!

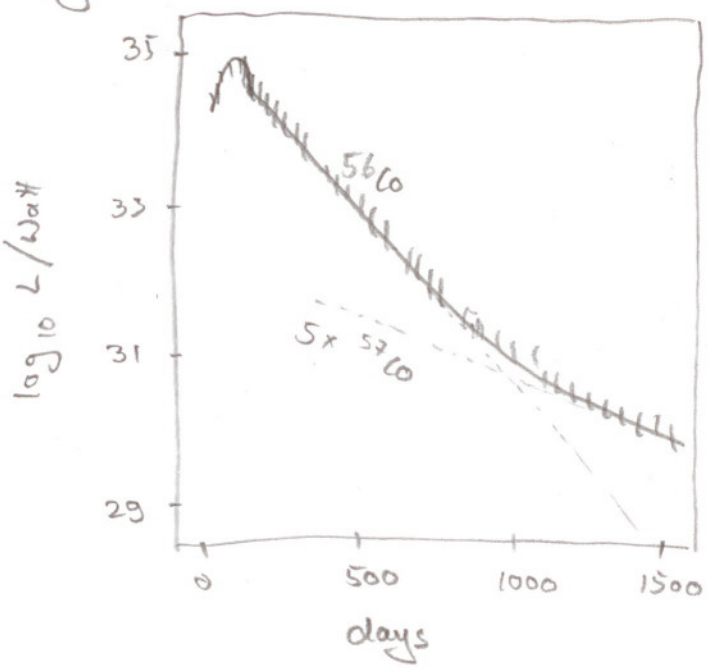
still a reverse shock expells material just like with neutron star.

- the energy in the light curve comes from radioactive decay of expelled material.

$$^{56}_{28}Ni \longrightarrow {}^{56}_{27}Co + e^+ + \nu_e + \gamma$$
$(\tau = 6{,}1 \text{ days})$

$$^{56}_{27}Co \longrightarrow {}^{56}_{26}Fe + e^+ + \nu_e + \gamma$$
$(\tau = 77{,}7 \text{ days})$

- typical light curve:



• summary of post-main sequence evolution:

Iben (1985, QRAS, 26, 1)