Astro 404
Lecture 30
Nov. 5, 2021

Announcements:

- **PS9 due today**
- **PS10 due next Friday**
- **Exams Graded at last!** scores posted on Canvas

Last time (Monday):
finished through intermediate-mass stars

Q: main distinction between $M < 0.08 M_\odot$ *and more massive?*

Recap: Stars Through Intermediate Masses

very low mass: $M \lesssim 0.08 M_{\odot}$
core degenerate at birth, *no H burning: brown dwarf*

low-mass: $0.08 M_{\odot} \lesssim M \lesssim 2 M_{\odot}$
H burning → red giant → He flash → AGB
→ C+O *white dwarf + planetary nebula*

intermediate mass: $2 M_{\odot} \lesssim M \lesssim 8 M_{\odot}$
H burning → red giant → no He flash → AGB
→ O+Ne+Mg *white dwarf and planetary nebula*

Onward to massive stars!

Massive Star Demographics

in our context, massive: $M \gtrsim 8 - 10 M_\odot$
that is: destined to become core-collapse supernovae

PS10: study initial mass function
distribution of star birth masses

- massive stars are $\sim$ 0.5% by *number* of all stars born
- but comprise $\sim$ 10% of *mass* going into stars

  Q: how can these both be true?

lesson: massive stars are rare but spectacular
celebrities of the cosmos

Massive Stars: Radiation Pressure

Massive stars: interior fully ionized = electrons roam free!
radiation force on electron with cross section σ_e (PS9):

$$F_{\text{rad}} = P_{\text{rad}}\sigma_e = \frac{L\sigma}{4\pi r^2 c} \tag{1}$$

inverse square law! same as gravity but repulsive!

radiation force balances gravity on $e+p$ pair when

$$L = L_{\text{Edd}} = \frac{4\pi G M m_p c}{\sigma} \tag{2}$$

Eddington luminosity

Q: what if $L > L_{\text{Edd}}$?

Massive Stars and the Eddington Luminosity

Eddington luminosity: $F_{\rm rad} = F_{\rm grav}$ when

$$L = L_{\rm Edd} = \frac{4\pi G M m_p c}{\sigma} \tag{3}$$

if $L > L_{\rm Edd}$: radiation pressure stronger than gravity!
star pushes its own atmosphere away
→ Eddington gives *maximum stable luminosity*

massive stars have L very near $L_{\rm Edd}$!

- near the edge of stability!
- drive strong winds even during main sequence
- mass loss important (and uncertain) over entire star life

Q: consequences of strong mass loss?

The Highest(?) Masses: Wolf-Rayet Stars

for the very *highest masses*: $M \gtrsim 30 M_\odot$?
and with solar composition

★ *mass loss very strong* even in main sequence
★ *reduces star mass* → converge to $30 M_\odot$?
★ hydrogen envelope can be completely removed
and *helium core exposed* (and sometimes deeper)
★ wind material shows nucleosynthesis products
e.g., CNO cycle abundance pattern: nitrogen rich

observed at *Wolf-Rayet* stars
`www: Wolf-Rayet wind`

- eta Carinae: initially $120 M_\odot$? now $\sim 100 M_\odot$
`www: eta Carinae`

iClicker Poll: Massive Stars on the HR Diagram

evolution drives $L \to L_{\mathrm{Edd}} \propto M$

Implications for a given mass on HR diagram?

A HR evolution nearly horizontal

B HR evolution nearly vertical

C HR evolution keeps L/T_{eff} fixed

Massive Stars on the HR Diagram

evolution drives $L \to L_{\mathrm{Edd}} \propto M$

also recall: main sequence is sequence in mass
so on main sequence, for all stars: L grows with mass

and for massive stars:
$L \to L_{\mathrm{Edd}}$ fixed by mass (roughly) on MS and beyond

so *post-main-sequence evolution changes* T_{eff} *but not* L
→ **motion on HR diagram is horizontal**

∞ `www: MESA simulation massive star HR diagram`

Massive Stars: Core Conditions

As seen in PS9: for ideal gas stars, at center

$$\rho_c \propto \frac{T_c^3}{M^2} \tag{4}$$

at fixed T_c, stars with large mass M have low ρ_c

counter-intuitive: *more mass* → **less** *dense core!*
perhaps easier to understand as $T_C \propto \rho_c^{1/3} M^{2/3}$
more mass means hotter, Virial say same: $kT \sim GMm_{\mathrm{g}}/R$

Lessons:

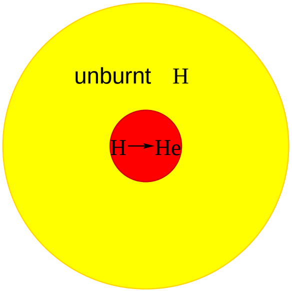
- massive star cores are hot!
- massive star cores avoid degeneracy...until the end

  `www:  MESA simulation plot of` (ρ_c, T_c) `for massive stars`

Massive Stars: Burning Phases

Main sequence: hydrogen burning

- convective core → fuel circulation
- $T_c \gtrsim 2\times$ hotter than Sun
- burn $p \to {}^4\mathrm{He}$ via CNO cycle
  avoid Weak $pp \to de\nu$: goes much faster



when core hydrogen exhausted:

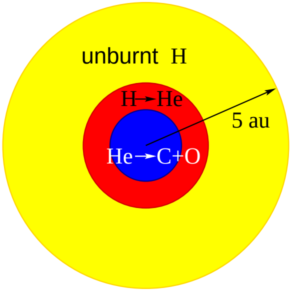
core contracts, smoothly begins burning helium

non-degenerate, no helium flash

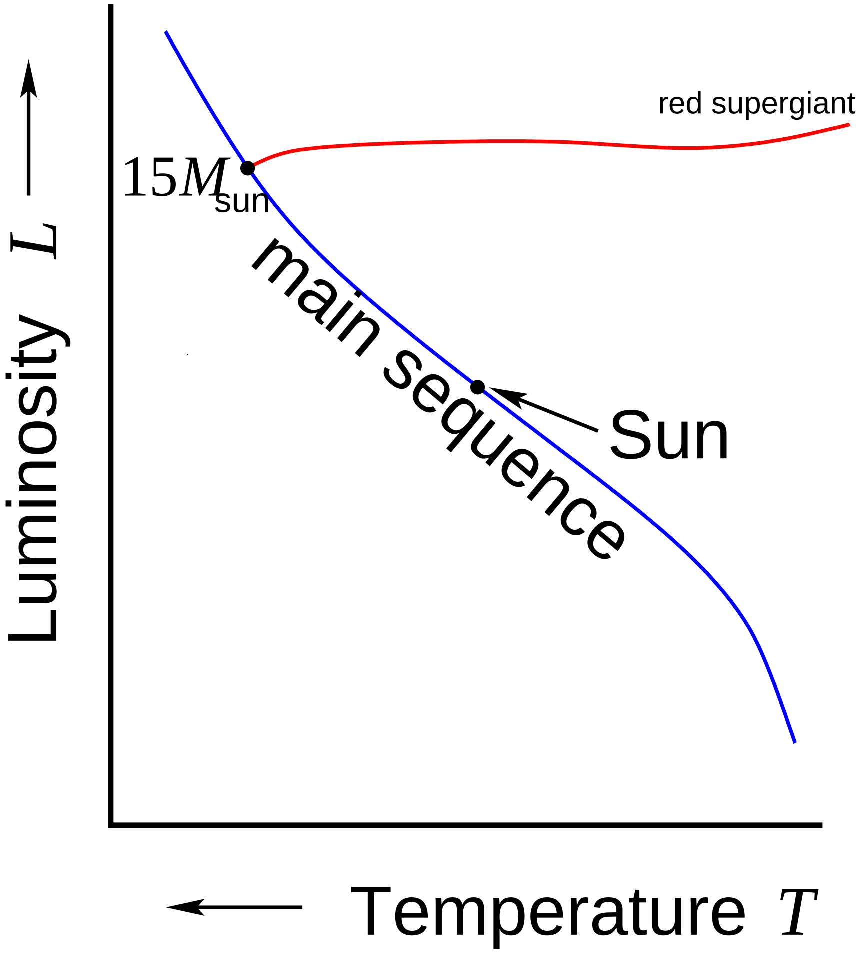
with hydrogen burning in shell

star becomes a supergiant

`www: Betelgeuse imaged`



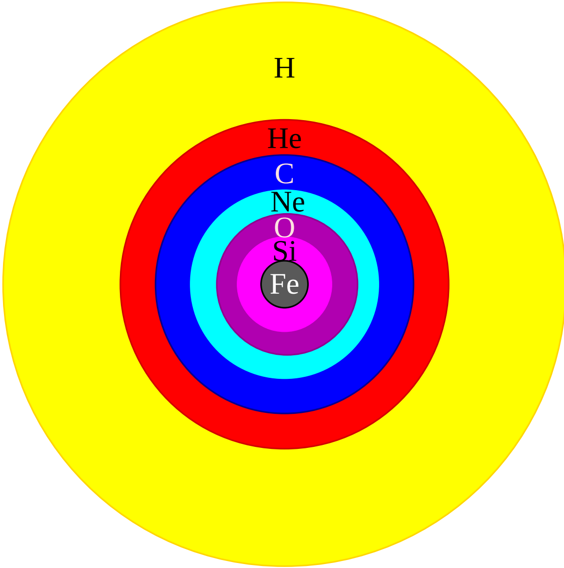
Massive Stars on the HR Diagram: Supergiants



When core He exhausted, begin cycles:

- contract
- ignite new shell burning
- ignite ash → fuel in core
- burn core to exhaustion

repeat…



develop "onion skin" structure: `www: pre-SN`

favors "α-elements" : tightly bound

C burning:	$^{12}\mathrm{C} + {}^{12}\mathrm{C}$	$\rightarrow$	$^{20}\mathrm{Ne} + \alpha$
Ne burning:	$^{20}\mathrm{Ne} + \gamma$	$\rightarrow$	$^{16}\mathrm{O} + \alpha$
	$^{20}\mathrm{Ne} + \alpha$	$\rightarrow$	$m_{\mathrm{g}}24 + \gamma$
	$m_{\mathrm{g}}24 + \alpha$	$\rightarrow$	$^{28}\mathrm{Si} + \gamma$
O burning:	$^{16}\mathrm{O} + {}^{16}\mathrm{O}$	$\rightarrow$	$^{28}\mathrm{Si} + \alpha$
		$\rightarrow$	$^{32}\mathrm{S} + \gamma$

Neutrino Cooling

At $T \gtrsim 5 \times 10^8$ K (C burn):
neutrinos produced via $e^+e^- \to \nu\bar{\nu}$
much slower than $e^+e^- \to \gamma\gamma$ yet still crucial
Q: why?

neutrino production rate per volume:

$$q_\nu = \langle \sigma v n_e^2 \rangle \sim T^2 \times (T^3)^2 \sim T^8 \tag{5}$$

ν escape → dominate E loss: **neutrino cooling**

neutrino E loss rate per vol: $\varepsilon_\nu = E_\nu q \sim T^9$
equilibrium: $\varepsilon_{\text{emit},\nu} = \varepsilon_{\text{released,nuc}}$
$\to L_\nu \sim (1-10^6) L_\gamma$ for C thru Si burning: **neutrino star!**

iClicker Poll: Effect of Neutrino Losses

when neutrino emission dominates total luminosity:

What is effect on burning phases?

A neutrino star burning phases last a *longer* time than if no neutrinos emitted

B neutrino star burning phases last a *shorter* time than if no neutrinos emitted

C neutrino star burning phases last the *same* time than if no neutrinos emitted

Si Burning

neutrino emission removes energy from core
"steals" nuclear energy now unavailable to heat star
shortens burning phases–final stages: months, days

$T \sim 4 \times 10^9$ K → photon energy density $\epsilon_\gamma \sim T^4$ large
photodisintegration $^{28}\mathrm{Si} + \gamma \rightarrow p, n, \alpha$

1. γs take p, n, α from weakly bound nuclei
2. these recombine with all nuclei
3. flow → more tightly bound

Net effect: redistribute to most tightly bound nuclei

Binding Energy Patterns

recall: binding energy B_i is
energy required to tear nucleus to protons and neutrons

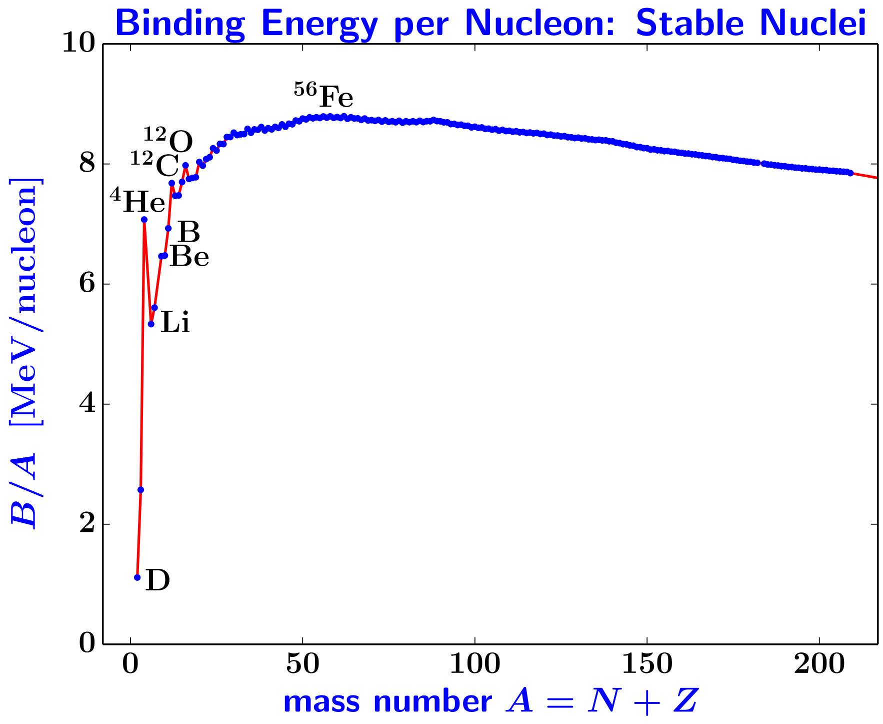
note that larger nuclei have large B_i,
but shared among more nucleons

consider: **binding energy per nucleon** B/A
Q: what does this represent physically?

Nuclear Stability: Binding Energy

For stable nuclei:

- sharp rise in B_i/A_i at low A
- local max at ^{4}He
- *no stable nuclei at $A = 5, 8$*
- lowest B/A for D, LiBeB
- *max B/A for middle masses:*
- **peak at** ^{56}Fe



Nuclear Equilibrium

nuclear reactions drive core to **equilibrium**
dominated by most stable nuclei possible
→ most tightly bound

max abundance → largest nuclear binding: "iron peak"

core dominated by iron and nickel

An now the end is imminent. *Q: why?*

Iron Core Evolution

can't burn Fe → degenerate core

support: e degeneracy pressure–core is iron white dwarf!

first time a massive star core is degenerate

stable briefly, but...

do burn Si in overlying shell

→ increase Fe core mass

when $M_{\rm core} > M_{\rm Chandra}$ → core unstable

begins to collapse

Core Collapse

upon collapse: *iron core disintegrated by photons*
e.g., $^{56}\text{Fe}\to 13\alpha + 4n$

huge density: electrons have high Fermi energy
→ favorable to get rid of them!

electrons capture onto protons $e^- + p \to n + \nu_e$
and onto nuclei $e^- + Z_A \to Z-1_A + \nu_e$
"neutronization" or "deleptonization"

removes e and so reduces degeneracy pressure!
- accelerates collapse (positive feedback)
- also: releases ν_e

Collapse Dynamics

Freefall timescale for material with density ρ (PS4):

$$\tau_{\rm ff} \sim \frac{1}{\sqrt{G\rho}} \sim 446 \text{ s}\sqrt{\frac{1 \text{ g/cm}^3}{\rho_{\rm cgs}}} \lesssim 1 \text{ sec}$$

but pre-supernova star very non-uniform density

Q: what does this mean for collapse?

inner core: homologous collapse $v \propto r$

outer core: quickly becomes supersonic $v > c_{\rm s}$

outer envelope: unaware of collapse

Q: what (if anything) stops collapse?

Bounce and Explosion

core collapses until $\rho_{\text{core}} > \rho_{\text{nuc}} \sim 3 \times 10^{14}$ g/cm^3

repulsive sort-range nuclear force dominates: *"incompressible"*

details depend on equation of state of nuke matter

1. *core bounce* → proto neutron star born
2. *shock wave* launched
3. a miracle occurs
4. outer layers *accelerated*

   Demo: AstroBlaster$^{\text{TM}}$
5. successful *explosion* observed

   $\rightarrow v_{\text{ej}} \sim 15,000$ km/s $\sim c/20$!

Why step 3? What's the miracle?

"prompt shock" fails:

do launch shock, but

- overlying layers infalling

→ ram pressure $P = \rho v_{\rm in}^2$

- dissociate Fe → lose energy

shock motion stalls → "accretion shock"

"prompt explosion" mechanism fails

Q: what needed to revive explosion?

Delayed Explosion Mechanisms

"delayed explosion" to revive:
neutrinos, 3-D hydro/instability, rotation effects?
some models not work, but controversial

Energetics:
$E_{\rm ejecta} \sim M_{\rm ej} v^2 \sim (10 M_\odot)(c/20)^2 \sim 10^{51}$ erg $\equiv 1$ foe
but must release gravitational binding energy

$$\begin{aligned} \Delta E &\sim -GM_\star^2/R_\star - (-GM_{\rm NS}^2/R_{\rm NS}) \\ &\simeq GM_{\rm NS}^2/R_{\rm NS} \sim 3 \times 10^{53}\ {\rm erg} = 300\ {\rm foe} \end{aligned}$$

Q: Where does the rest go?
⇒ SN calculations must be good to ~ 1%
to see the minor optical fireworks