Plan of Lecture
Evolution of Low-Mass Stars

Stellar structure.

Nuclear fusion.

The red giant stage.

Final contraction.

Stellar Structure

Key idea: stars are pretty stable over almost all their lifetimes. Near-equilibrium.

Force from pressure *gradient* balances gravity.

Hydrostatic equilibrium.

All the energy generated in the star must leave.

Energy balance.

Also, how does the energy get out?

Energy transport.

Hydrostatic Equilibrium

Assume that stars are spheres.

Consider a parcel of gas of density $\rho(r)$ and thickness Δr at radius r.

Grav acceleration: $-GM(<r)/r^2$.

Mass per area: $\rho(r)\Delta r$.

Force per area: $-GM(<r)\rho(r)(\Delta r)/r^2$.

What opposes this? Not the pressure but the *change* in pressure ΔP over Δr.

$\Delta P = -GM(<r)\rho(r)(\Delta r)/r^2$.

$dP/dr = -g\rho$.

In star, basically ideal gas pressure: $P = nkT$.

Energy Balance

In equilibrium, energy can't pile up; must go into outward luminosity.

Consider a spherical shell of thickness Δr at radius r.

Volume: $4\pi r^2 \Delta r$.

Mass: $(4\pi r^2 \Delta r)\rho$.

Suppose some process generates an energy per time *per mass* of ϵ.

ΔL**=change in luminosity over** Δr**.**

$\Delta L = (4\pi r^2 \Delta r)\rho\epsilon$.

In main sequence star, energy generated by fusion.

Pre-MS: gravitational contraction.

Energy Transport

Hot cores of stars transport energy to outer regions. How?

Radiation, convection most important for stars.

Radiation.

Energy transported by photons.

Gas is relatively quiet.

Convection.

If rapid energy generation...

...gas bubbles and convects.

Transported by matter motion.

Convection also happens if the gas is very opaque to radiation.

Lots of lines, edges!

The Importance of Mass

Consider a main sequence star in equilibrium.

Mass determines gravity.

Gravity determines pressure.

Pressure determines density/temp.

Density/temp govern fusion.

Fusion rates determine luminosity.

Therefore, mass is a fundamental variable.

Chemical composition (in equilibrium) and mass determine properties of *all* stars.

On MS: mainly mass differences.

Off MS: chemical composition.

Fusion, Part 1

Fusion is the main power source of stars.

Long lasting, efficient, stable.

On the main sequence, 4H$\rightarrow$He.

2 protons convert to 2 neutrons.

Improbable for all 4 to collide!

One way: the proton-proton chain. Several varieties, one of which is:

$^{1}\mathbf{H}+^{1}\mathbf{H}\rightarrow^{2}\mathbf{H}+\mathbf{e}^{+}+\nu_e$.

$^{2}\mathbf{H}+^{1}\mathbf{H}\rightarrow^{3}\mathbf{He}+\gamma$.

$^{3}\mathbf{He}+^{3}\mathbf{He}\rightarrow^{4}\mathbf{He}+^{1}\mathbf{H}+^{1}\mathbf{H}$.

Not important to memorize!

Neutrinos escape immediately; photons and kinetic energy move through star gradually.

Fusion, Part 2

For low-mass stars, or stars without "metals" (>He), only proton-proton chain can fuse H.

But CNO (Carbon, Nitrogen, Oxygen) can also fuse H, in a cycle.

This is a *catalytic* reaction.

CNO not used up!

A little makes a big difference.

At current-day compositions, more important than proton-proton for $M > 1.2\,M_\odot$.

But why isn't it more important all the time?

Temperature Sensitivity

Nuclei have protons, neutrons.

Net charge: positive.

To fuse, nuclei must get to $\sim 10^{-15}$ m!

Electrical barrier.

High T (“running start”) or high ρ (squeeze!).

High temp important for stars.

Highest energy nuclei will fuse.

Slight change in temp increases number of high energy nuclei a lot!

G2: $T_c = 1.5 \times 10^7$ **K,** $L = L_\odot$**.**

B: $T_c = 3.0 \times 10^7$ **K,** $L = 10^4 L_\odot$**!**

CNO have more protons, so more repulsion, more T sensitivity.

Evolution on the Main Sequence

Net result of fusion: 4H$\rightarrow$He.

Number of particles drops.

$P = nkT$**.**

Core shrinks, T and L increase!

Higher luminosity pushes outer layers out, decreasing temperature. Moves up and right in H-R diagram.

Can this continue indefinitely?

No! Core H is depleted.

Helium has greater repulsion, so at MS core temperatures it doesn't burn.

What happens next?

Shell Game

At this stage, H only burns in a shell around the He core.

No core energy source; shrinks, heats up.

Heat increases shell burning.

Luminosity goes up fast!

Pressure increases.

Star expands and cools.

Voila! The *red giant* phase.

Small, dense core.

Enormous diffuse envelope.

Only lasts $\sim 1\%$ of lifetime of star.

Cosmic Flasher

Helium core has nothing but heat to support it.

Shrinks, becomes denser.

For $M < 2.3\,M_\odot$, supported by quantum mechanical “degeneracy” (more when we talk about WD).

Pressure independent of T.

If core $T \to 10^8$ K, helium fuses to carbon (3He→C).

Initially, no expansion.

Rapid increase in L: helium flash!

Eventually, core expands, cools; outer layers contract, heat; “horizontal branch”.

H fuses in shell.

He fuses in core.

Asymptotic Giant Branch

When core helium runs out, we get a recap of the red giant phase.

- **H, He burning in shells.**
- **Contracting inert C/O core.**
- **Huge expansion.**

Low escape velocity, high luminosity means tremendous winds are driven; mass loss.

- **"Planetary nebula".**
- **Sun will lose 40% of its mass.**

In low-mass stars, C/O core never gets hot enough to fuse.

- **Star cools, shrinks.**
- **Ends life as white dwarf.**
- **Not true for high mass stars...**

Summary

Fusion of H to He defines the main sequence.

As core H runs out, core shrinks, star becomes more luminous.

When H shell burning is important, red giant phase.

Recap when helium core burns to carbon.

Low-mass stars end as white dwarfs.

Challenge: what would life be like in orbit around an M star?