Today

- Stars
- Stellar Lifetimes
- Life cycles of stars
- Star Clusters

Exam II next time
Nuclear fusion in stars

IN
4 protons

OUT
$^4$He nucleus
2 gamma rays
2 positrons
2 neutrinos

$E = mc^2$

Total mass is 0.7% lower.
In addition to the proton-proton chain (see previous lecture):

**CNO Cycle**

- High-mass main-sequence stars fuse H to He at a higher rate using carbon, nitrogen, and oxygen as catalysts.

- Net result the same: 4 protons in; one helium nucleus out.
Fusing $^1\text{H}$ into $^4\text{He}$

• Proton-proton chain
  – more effective in low mass stars (lower T)
    \[ M < 1.5M_{\text{sun}} \]

• CNO cycle
  – more effective in high mass stars (higher T)
    \[ M > 1.5M_{\text{sun}} \]

Sun is about 90% proton-proton; 10% CNO cycle.
Main Sequence Stars

• Obey scaling relations

• Mass-Radius relation
  – more massive stars are bigger

• Mass-Luminosity relation
  – more massive stars are brighter

Main-sequence stars (to scale)
Mass-Luminosity Relation

The mass-luminosity relation for stars, as determined from binary systems, in which the individual masses can be found.

- Detached eclipsing systems B6-M
- OB eclipsing systems
- Resolved spectroscopic binaries
- Visual binaries
Mass-Luminosity Relation

\[ L \propto M^4 \]

- more massive stars much brighter
- use their fuel much faster
  - Mass: fuel supply \( (E = mc^2) \)
  - Luminosity: rate of fuel usage

Mass is finite - the stars don’t shine forever!
**Mass and Lifetime**

\[ \text{lifetime} \propto \frac{\text{energy}(mc^2)}{\text{power}(L)} \]

\[ t \propto \frac{M}{L} \]

- fuel
- rate of fuel use
Mass and Lifetime: \[ t \propto \frac{M}{L} \]

Mass-Luminosity Relation: \[ L \propto M^4 \]

\[ t \propto \frac{M}{L} \propto \frac{M}{M^4} \propto M^{-3} \]

So as mass increases, the main sequence lifetime decreases.
Mass and Lifetime

Sun’s life expectancy: 10 billion years

Life expectancy of a 10 $M_{\text{Sun}}$ star:

10 times as much fuel, but uses it 10,000 times faster

\[ \text{lifetime} \propto \frac{\text{energy} (mc^2)}{\text{power} (L)} \]

\[ \text{lifetime} (10 \ M_{\text{Sun}}) \approx \left( \frac{10 \ M_{\text{Sun}}}{10^4 \ L_{\text{Sun}}} \right) 10 \text{ billion years} \approx 10 \text{ million years} \]
For Main-Sequence Stars:

High-mass:
- High luminosity
- Short-lived
- Large radius
- Blue

Low-mass:
- Low luminosity
- Long-lived
- Small radius
- Red
Hydrostatic Equilibrium

Pressure and gravity in balance

Stars attempt to maintain equilibrium by striking a balance between the gravity of their enormous mass and the pressure produced by the energy of fusion reactions.

A main sequence star is in equilibrium as Hydrogen burning supports it against gravitational collapse.

What happens as the hydrogen runs out?
Off the Main Sequence

• Stellar properties depend on both mass and age: those that have finished fusing H to He in their cores are no longer on the main sequence.

• All stars become larger and redder after exhausting their core hydrogen: giants and supergiants.

• Most stars end up small and dim after fusion has ceased: white dwarfs.
Main-sequence stars (to scale)

Giants, supergiants, white dwarfs
The various branches of stars in the HR diagram

White dwarfs

Giants

Supergiants
Much of this learned from studying Star Clusters

Physically associated groups of stars
All the same age, the same distance away

Open cluster

Globular cluster
**Open cluster:** A few thousand loosely packed stars
**Globular cluster:** Millions of stars in a dense ball bound together by gravity
Measuring the age of a star cluster
Pleiades now has no stars with life expectancy less than around 100 million years.
The main-sequence turnoff point of a cluster tells us its age.
Detailed modeling of the oldest globular clusters reveals that they are about 13 billion years old.
The life stages of a low-mass star
Life Track After Main Sequence

- Observations of star clusters show that a star becomes larger, redder, and more luminous after its time on the main sequence is over.

- At the end of their main sequence lifetime - when hydrogen in the core is exhausted - stars ascend the red giant branch.
After hydrogen fuel is spent

- Without further fusion, the core contracts. H begins fusing to He in a shell around the core.

- As the core contracts, temperature increases, nuclear reaction rates increase (in the shell), and the Luminosity increases.