Today's Learning Goals

- Mini-review: basic properties of stars
- Stellar Structure (The Sun is typical)
- How most stars derive their energies
- **The H-R Diagram** <— IMPORTANT!
  - The Main Sequence (93% of all stars)
  - Red Giants and white dwarfs (7%)
  - Correlations of properties
  - Observational clues for stellar evolution

Review: Define ___

Concept (measurement units??)

- Brightness
- Luminosity
- Color
- Temperature
- Spectrum
- Size
- Mass and density
- Gravity
- 'Hydrostatic Equilibrium'

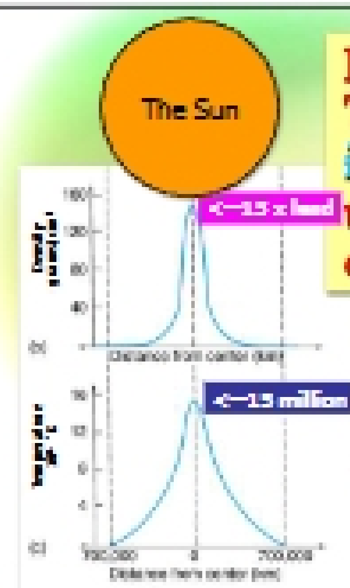
Stellar Structure

The internal structure of the Sun

> What does 'structure' actually mean?

> The Earth's atmosphere is a good starting point

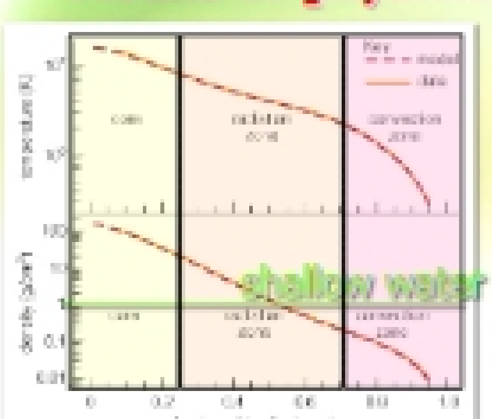
Density & Temperature increase rapidly towards the core of the "bell"



Why? The weight of the layers above compresses and heats the gas.

The weight of the Earth's atmosphere above you pushes on you @ 15.4 pounds per in² at sea level (1/3 less @ 10,000 ft)

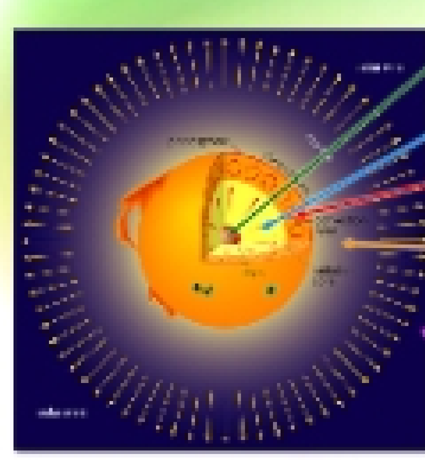
How the Bell Tolls: results of physical models



Fitting the model: Vary the structure in the ringing regions of the model sun until agreement with the patterns of surface oscillations is reached.

Then use the model to predict the density and temperature of the solar core.

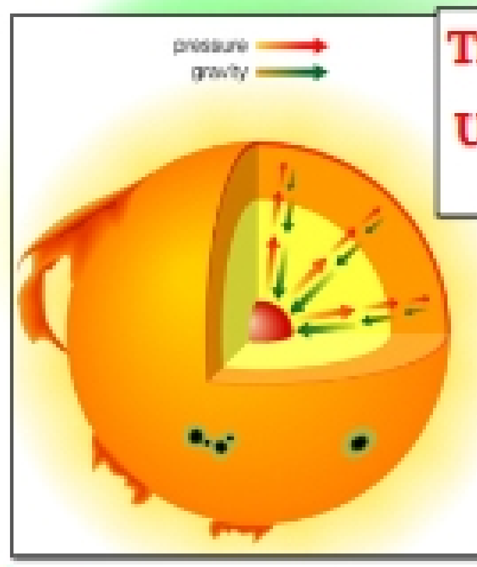
The Sun's major regions



- Core *(remember this!)* dense! 160 gm/cm³, hot! 15 x 10⁶K
- Radiative zone (no circulation)
- Convective zone (vigorous circulation)
- Corona hot plasma @ 10⁶K
- Solar Wind: A weak but steady flow of charged particles from the surface of the Sun punctuated by flares and CMEs

How does the Sun shine?

The Fiery Core is a Star's Ultimate Heat Source



- Density of 160 gm/cm³; ~15 times that of of a lead brick; 160 x water.
- Fully ionized "plasma" - a dense gas of nuclei and their stripped off electrons

What powers the Sun? - Chemical Energy?

Is it on FIRE?

$$\frac{\text{Chemical Energy Content}}{\text{Luminosity}} \sim 10{,}000 \text{ years}$$

NO!
The Sun's chemical energy reserves would be consumed in 10^4 y.

What powers the Sun? - Gravitational Energy?

Is it CONTRACTING?

$$\frac{\text{Gravitational Potential Energy}}{\text{Luminosity}} \sim 25 \text{ million years}$$

NO!
Although gravity compresses and heats the solar interior, light energy emitted at the surface soon sheds this heat, and the Sun would collapse to a black hole in $\approx 10^8$ y.

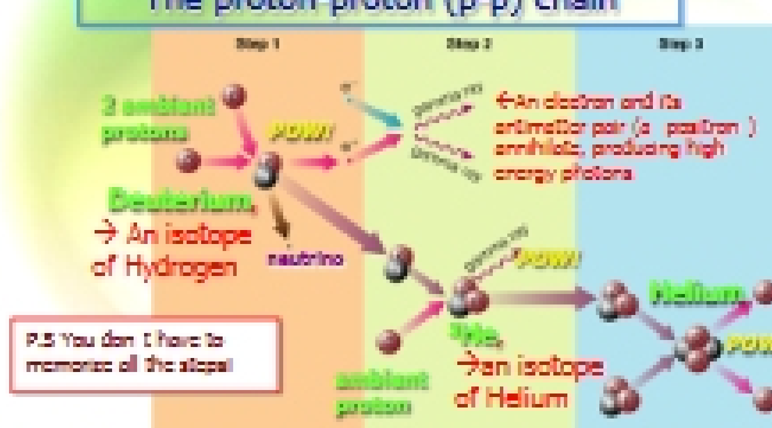
What powers the Sun? — Nuclear Energy?

4 Hydrogen Atoms fuse to make 1 Helium Atom and a bunch of energy.

As we're about to see, the energy reserves will last 10^{10} y. So this looks like a sensible answer!

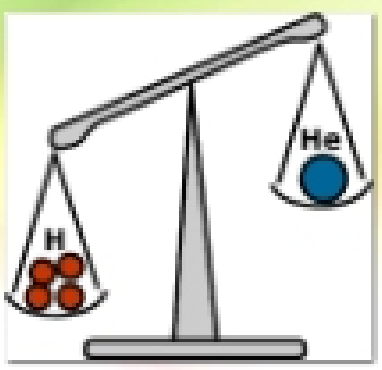
Energy Production in Stars

"The proton-proton (p-p) chain"



Net: In = 6 protons, Out = 1 He⁴ + 2 protons + e⁺ + light

Why extra energy at the end?

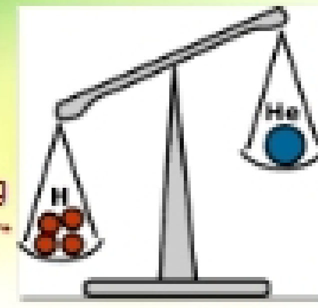


$E = Mc^2$!!

Some mass converts to energy!

How much mass per reaction?

6.690 X 10^{-27} kg



6.643 X 10^{-27} kg

Mass Difference = 0.047 X 10^{-27} kg
(0.7% of the original mass)

Energy released per reaction = mass lost * c^2

How much energy?

Doesn't take much mass!

Two 200-lb jocks converted to pure energy!

Releases 2×10^{28} ergs, which is ~4×10^{12} kW hrs, or $^1/_5$ of the entire US energy consumption per year.

How much energy?

- The fusion process used by the Sun isn't 100% efficient - just 0.7%
  - (99.3% of mass remains after a helium nucleus is produced)
- 10% of the Sun's mass is in the core where combustion occurs

  …so 0.07% of the Sun's mass of hydrogen will ultimately be consumed !

  – Nonetheless, that's lots of energy

- How long will the energy reserves last?
  Answer: ≈10^{10} years … let's do the math

How much mass EVERY SECOND?

1 Solar Luminosity = 3.8 X 10^{26} watts
1 watt = 10^7 "erg" per second

In one second, Sun releases ~4 X 10^{33} erg, so:

Energy released= (mass destroyed) c^2, so:

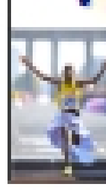
Mass destroyed=(4×10^{33} erg) / (3×10^{10} cm/s)^2

= 4 x 10^{12} grams = 4 million tons is consumed every second!

(1.3 Earth masses since the dinosaurs)

How long will the Fuel last?

- Lifetime = $\frac{\text{energy reserves}}{\text{rate of energy consumption}}$
- *Example: a car with a 10-gallon tank burning 2 gallons/hour can run for 5 hours*
- Sun: energy reserves
  = 0.7% x core mass of hydrogen x c^2
  = 0.007 x [0.1 x 2 x 10^{33} gm] x c^2
  = 1.4 x 10^{30} gm x c^2 = 1.3 x 10^{51} ergs
- Sun: rate of consumption = luminosity
  = 4 x 10^{33} erg/sec



The fuel will last 1.3 x 10^{51} ergs / 4 x 10^{33} erg/sec = 3.1 x 10^{17} sec = 10^{10} years!