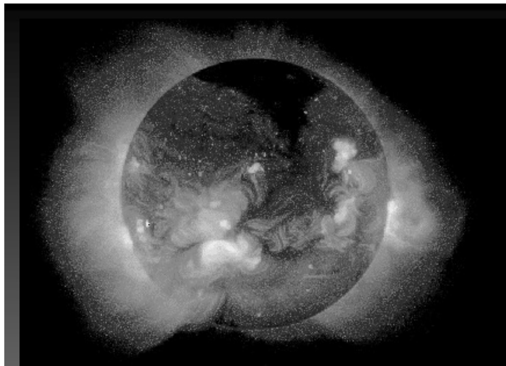


The Sun

Chapter 16

Most important concepts:

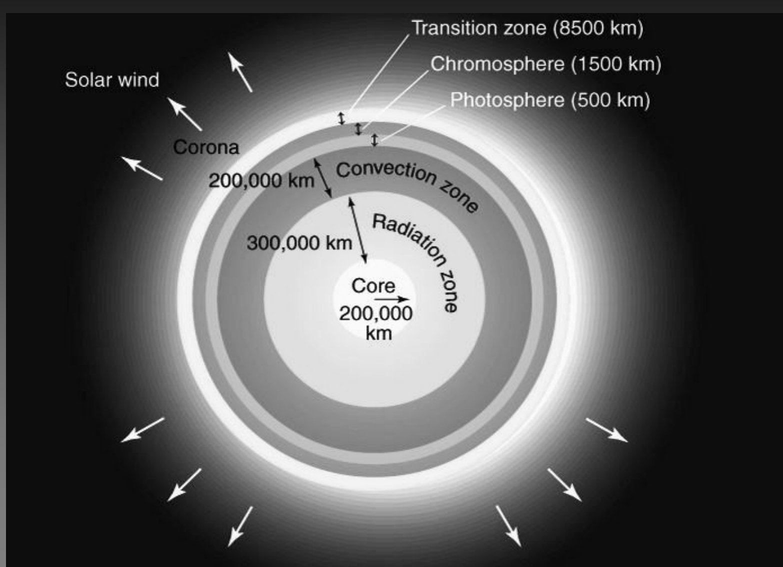
- Energy production
- Stability

Basic data

Diameter	1.4×10^6 km = 109 D_{earth}
Mass	2.0×10^{30} kg = 333,000 M_{earth}
Density	1400 kg/m^3 (160,000 kg/m^3 in center)
Temperature	5800 K (“surface”) to 1.55×10^7 K (ctr)
Luminosity	3.86×10^{26} W
Rotation rate	25 days (equator), 35 days (poles)
Composition (atmos, by mass)	74% H, 25% He, 1% other elements
Orbital period (MW)	220×10^6 years

The Sun is a star: a shining ball of gas powered by fusion

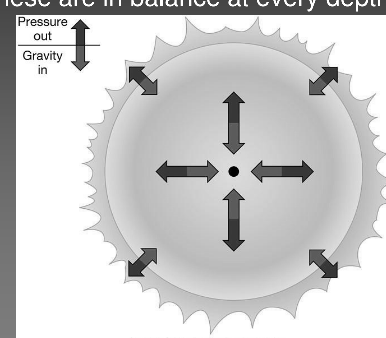
Solar structure



Hydrostatic equilibrium

Why is the Sun stable (not contracting or expanding)? Gravity makes objects want to collapse. Pressure causes objects to expand.

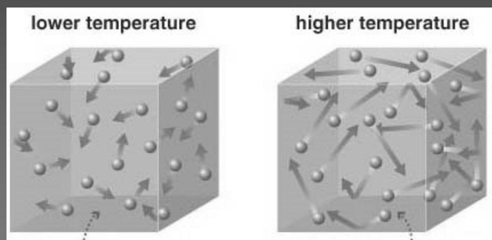
In a star like the Sun, these are in balance at every depth: hydrostatic equilibrium



At early or late times in a star’s life, this balance is not achieved, e.g. contraction during formation, expansion during late stages of evolution. What is pressure and how do we calculate it? And what provides it???

The Ideal Gas Law

- Consider pressure that gas particles in a box exert on the walls (P=F/A).
- Particles in hot gas move faster, and collide with more force than those in a cooler gas => hot gas exerts higher pressure



- However, gas pressure also depends on the number of particles that are colliding with the surface area per sec. So depends on <u>number density</u> n [m^{-3}] as well as temperature.

- This is expressed in the ideal gas law:

$$P = nkT$$

where P is the gas pressure [N/m^2 or Pascals], n the <u>number density</u> [m^{-3}], and k is Boltzmann's constant.

Law works well for most stellar applications (exceptions later).

- Pressure very high at center of Sun, so n and T both very high. What provides this pressure? Thermonuclear fusion in the hot core: H is being fused into He. Only possible because T is so high (high n helps too), as we'll see.

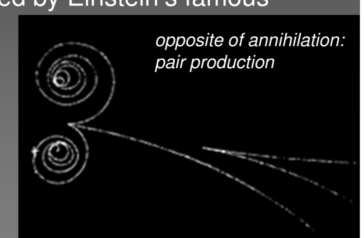
Reminder: elements and isotopes

- Elements: depends on # of protons
- Isotopes: depends on # of neutrons
- Atoms: nuclei with electrons, with charge balance
- Ions: charge imbalance
- Example nuclei: ^{1}H = one proton
  ^{2}H = one proton with one neutron (a.k.a. deuterium)
  ^{3}He = 2p + 1n (light isotope of He)
  ^{4}He = 2p + 2n (common isotope of He)

Antimatter, annihilation and neutrinos

- Antimatter: for every charged particle there is an antiparticle with the opposite charge.
  - Example: positron (e^+) is like the electron except positive charge
- Annihilation: if a particle and its antiparticle collide they completely disappear (explosively) as mass and liberate energy in the form of photons. Mass-energy conversion is governed by Einstein's famous equation:

$$E=mc^2$$



- Neutrinos (ν):
  - Exotic particles with no charge and little mass.
  - Tiny probability of interacting with other particles.

Fundamental forces of nature

Interactions in nature are governed by four fundamental forces:

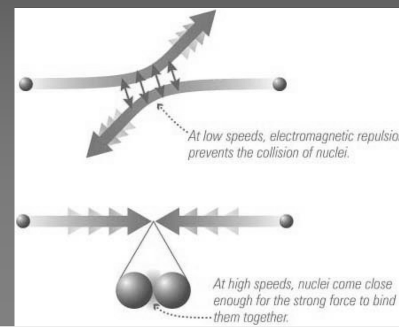
- Gravitational force
- Electromagnetic force
- Weak nuclear force
- Strong nuclear force

- Gravity dominates on largest scales: binds massive objects together, and mediates orbital motions
- Electromagnetism dominates on atomic scale: binds electrons to protons, atoms to atoms
- Strong and weak forces dominate on nuclear scales (~10^{-15} m): strong force binds protons to neutrons, important for fusion. Very strong on this scale but quickly falls off for larger separations. Weak force important for radioactive decay

Hydrogen fusion

Box 16-1 and Cosmic Connections

- Fusion is any event where nuclear particles collide and join together.
- Fusion reactions obey several conservation laws.
- Sun and stars fuse H into He for most of their lives. This <u>creates energy</u>.
- How to fuse 4 ^{1}H (p) into a ^{4}He (2p+2n)?
  - Unlikely 4 protons are colliding at once – need different reaction chain
  - Must turn 2 protons into 2 neutrons
  - Must be > 10^7 K to get protons close enough for fusion

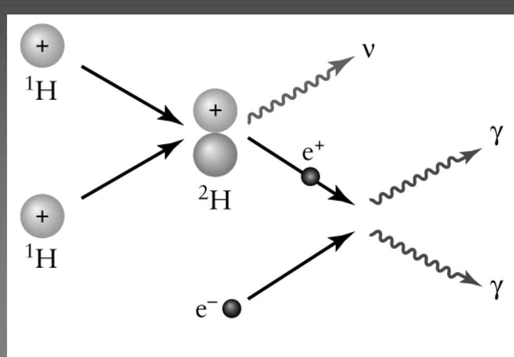


Key: bring nuclei sufficiently close (~10^{-15} m) for the strong force to dominate over the electromagnetic force.

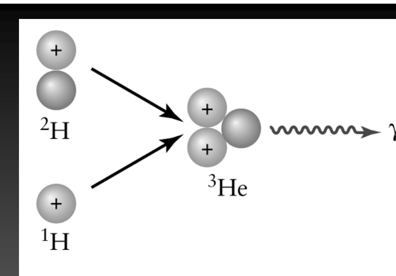
Fusion provides energy to support stars against gravity. Making new elements and shining are "by-products"

The proton-proton chain - in pictures

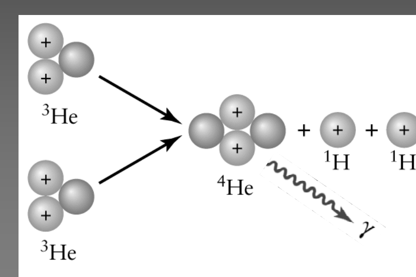
- Starting point: at 1.5x10^7 K, hydrogen in the core of the Sun is completely ionized, thus a mixture of free electrons and protons. Ignore other elements.
- Step 1:



- Step 2:



- Step 3:



Proton-proton chain

$$p + p \rightarrow {}^2H + e^+ + \nu + \gamma \quad \text{(twice)}$$

$$(e^+ + e^- \rightarrow \gamma + \gamma)$$

$$p + {}^2H \rightarrow {}^3He + \gamma \quad \text{(twice)}$$

$$^3He + {}^3He \rightarrow {}^4He + p + p + \gamma$$

Energy Generation

- The 4 protons have 4.8×10^{-29} kg more mass than the He nucleus (0.7% of the total mass has been converted to energy).
- $E=mc^2$ => 4.3×10^{-12} J is released by the formation of a single He nucleus.
- $L_\odot/E = (3.9 \times 10^{26}$ J/s) / (4.3×10^{-12} J) = 9.1×10^{37} conversions per second. Each conversion involves four protons, so (9.1×10^{37}/sec) x ($4m_p$) = 6×10^{11} kg/sec of H is converted to He. About 4×10^9 kg (0.7% of this mass) converted to energy per second (also just $L_\odot/c^2$).

- Sun began with about 1.5×10^{30} kg of H. But only the inner 10% of the Sun [i.e. 10% of its mass] is hot enough for fusion to take place
- => fusion lifetime about 10 Gyrs
- Composition must now be different at core than at the surface!
- How do we know fusion occurs? We detect neutrinos from the Sun.