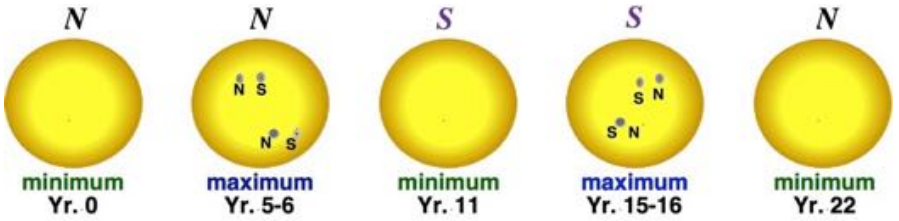
Reading: Chapter 16 (next week: Chapter 17)
Exam 1: This Thursday, February 9 - bring a #2 pencil!
ESSAY, Review Sheet and Practice Exam Posted

Brief review of last time: **Our Sun**

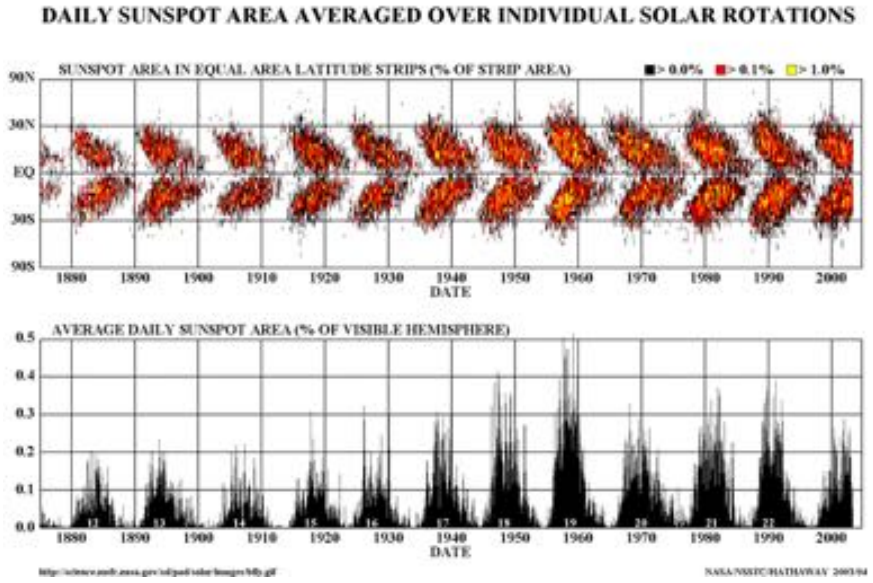
- Vital Statistics
- The Photosphere - the visible surface
  - granulation
  - sunspots
- The Chromsphere
  - prominences
  - flares
- The Corona - hot outer atmosphere
- Magnetic fields and the Solar Cycle
  - 11 year sunspot cycle, but 22 year magnetic cycle
  - the butterfly diagram

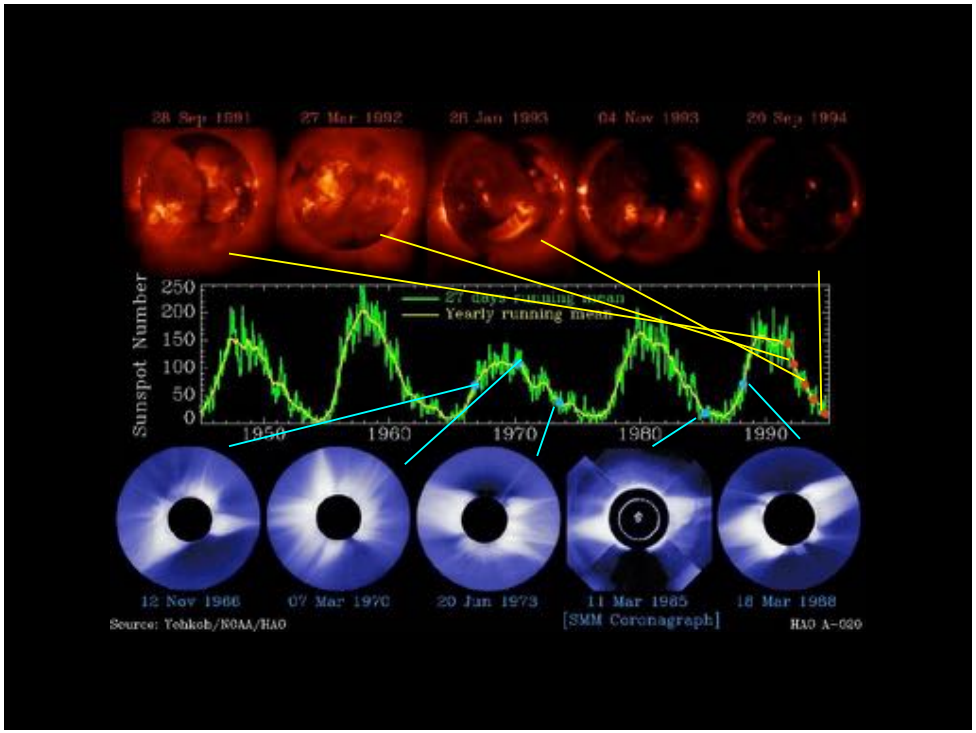
The Solar Cycle

- number of spots changes over 11 year cycle
- magnetic polarity (N/S) of spots flips every 11 years
- —> whole pattern repeats every 22 years

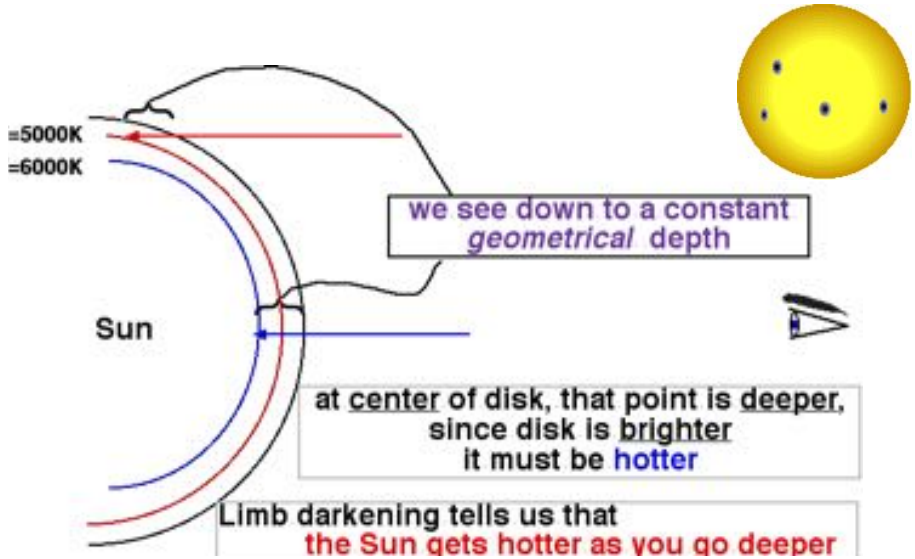


The Butterfly Diagram





Limb Darkening:



inside the sun

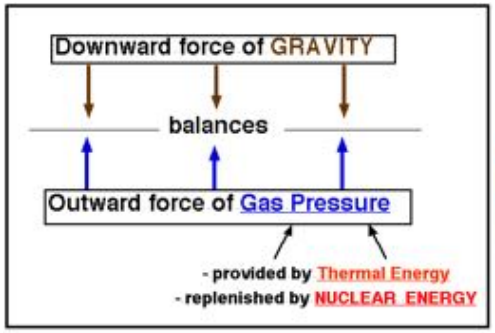
The Inside of the Sun:

- What keeps the Sun shining?
- What keeps the Sun from collapsing?

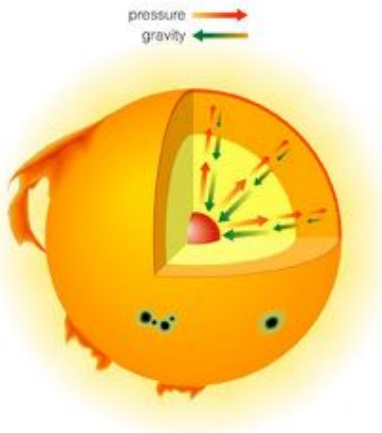
- Mechanical Structure
  - balance between gravity and gas pressure
- Thermal Structure
  - production, flow, and escape of radiant energy
- Energy Source

Mechanical Structure

- Gravity versus Pressure



HYDROSTATIC EQUILIBRIUM

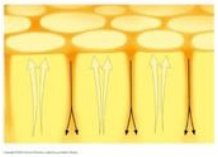


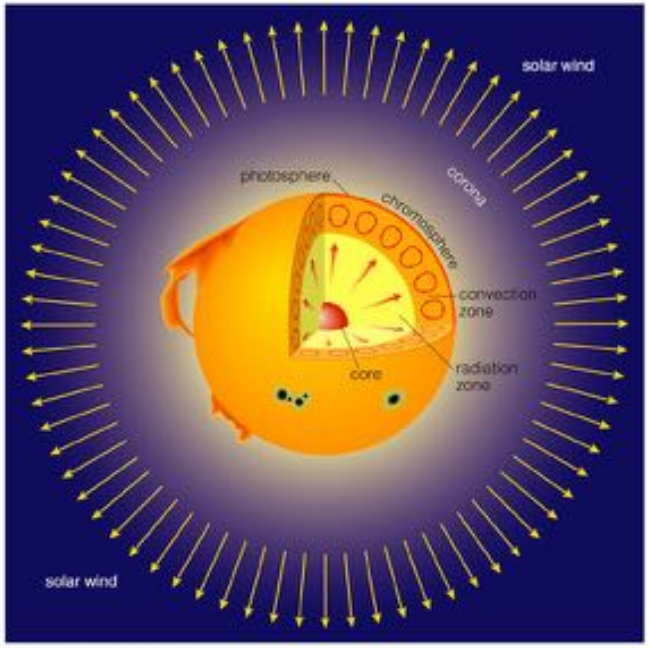
- punishment is swift for violation
- **Pressure increases with depth**

Thermal Equilibrium

- Energy in = energy out
  - globally: energy produced = energy lost
  - locally: flow in bottom = flow out top

- Heat Transport Processes
  1. **conduction** - direct contact
  2. **convection**
     1. bulk motion of matter
     2. occurs when temperature changes rapidly with depth
  3. **radiation**
     - transport by photons
     - transparent stuff -- rapid transport
     - opaque stuff -- slow transport
     - 1 million years for energy to flow out from center!

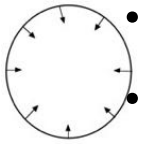




Energy Source for the Sun

- **Combustion?**
  - 1 kg of coal per square meter per second!
  - whole Sun consumed in 10,000 years! . . .nope
- **Gravitational Contraction?**

  Kelvin and Helmholtz, 1871



  - falling objects acquire energy that can be converted to heat
  - slow contraction can provide heat energy to keep the Sun shining
  - contraction by 20 meters each year can keep the Sun shining
  - K-H contraction can provide energy for

    100 million years!

BUT

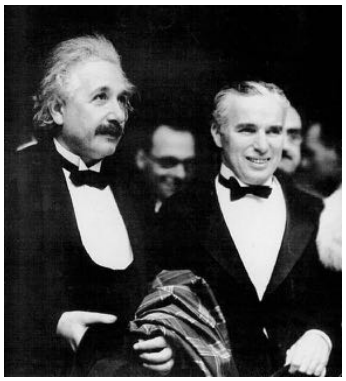
various evidence shows that the Sun has been shining for at least

4.6 billion years!

Where does this energy come from?

(a hint: E= m c^2)

Answer: NUCLEAR FUSION



"They cheer for me because they all understand me and they cheer for you because nobody understands you."

Atomic Structure

- Atom = nucleus and electrons
  (+ charge) (- charge)

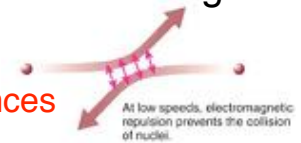
  nucleus = protons and neutrons
- Chemical element
  - all atoms w/ same number of protons

Element	# protons	#	symbol
Hydrogen	1	0	H
Helium	2	2	He
Carbon	6	6	C
Oxygen	8	8	O
Iron	26	30	Fe

Relevant Forces

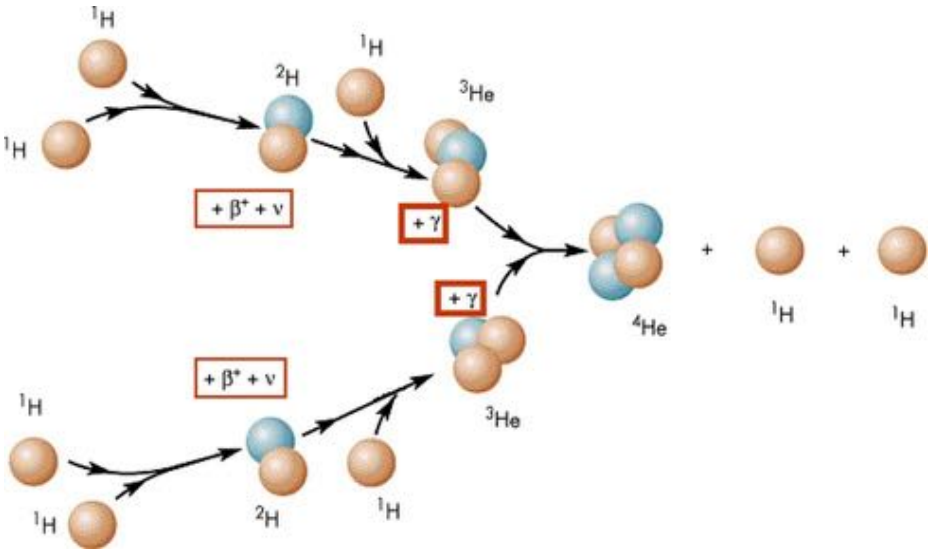
- Electromagnetism: repulsive *and* long-range

- Strong Nuclear Force: attractive but short range
  - binds protons together in nucleus
  - stronger than EM at very small distances



- At 10,000,000 K
  - nuclei move quickly
  - (+) nuclei get very close in collision
  - strong nuclear force can take over

- **Nuclei stick together --- FUSION!**



$4\ H^1 \rightarrow He^4 + photons + neutrinos$

- mass of H^1 = 1.0078 AM
- mass of 4 x H^1 = 4.0312 AMU
- BUT: mass of He^4 = 4.0026 AMU . . .

  0.0286 AMU

  disappears in p-p chain!
  - **converted into energy via $E=mc^2$**
- **0.7% of H is converted into energy**
- **E = 0.007 x c^2 ergs per gram of H-> He**
- **E = 6 x 10^{18} ergs per gram of H -> He**

Hans Bethe - Nobel Prize in Physics
for work published in 1939

To supply the solar luminosity (4×10^{33} ergs/second) the Sun must consume

6.4×10^{14} grams of hydrogen every second!

How long can this go on?

$M_{sun} = 2\times10^{33}$ grams

rate of consumption = 6.4×10^{14} grams/second

$$\text{lifetime} = \frac{2\times10^{33}\ \text{grams}}{6.4\times10^{14}\ \text{grams/second}} \times 0.1$$

$$= 3.1\times10^{17}\ \text{seconds}$$

= 10 billion years!

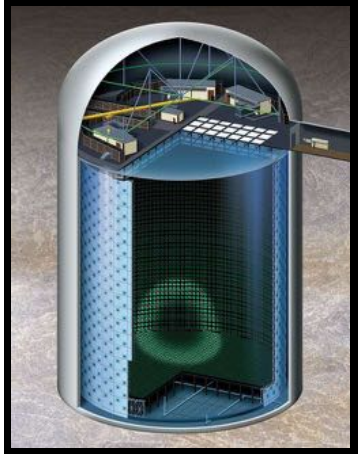
...but the "solar neutrino 'problem'" lurks

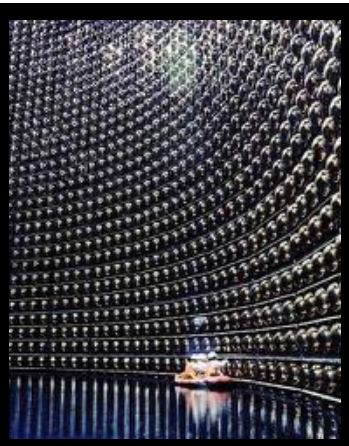
- Neutrinos
  - massless particles
  - travel at the speed of light
  - rarely interact with matter
  - produced in center of Sun during fusion
- Experiments to detect solar neutrinos
  - Chemical method: find ***rare*** changed atom in big sample
    - **Ray Davis** - 100,000 gallons of C_2Cl_4 in Homestake Mine
    - SAGE/GALLEX - gallium neutrino detector
  - Photodetectors: detect ***rare*** recoil of affected particles
    - **Kamiokande II** - neutrino flashes in huge water tank
    - Sudbury Neutrino Observatory (SNO) - heavy water
- ALL show ~50% of expected neutrino rate! uh oh

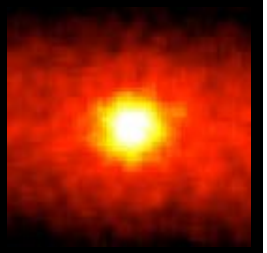
2002 Nobel Prize in Physics

Ray Davis - Homestake Neutrino Experiment

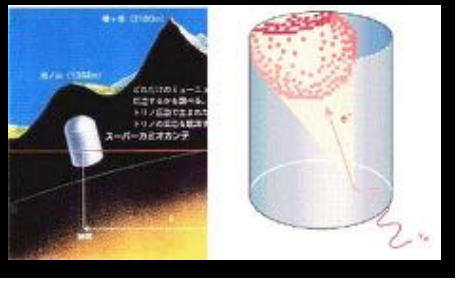
Kamiokande II - Water Scintillation







a neutrino "picture" of the Sun



Sudbury Neutrino Observatory: Heavy Water Scintillation