Lecture 18
The Visible Sun

**Radius:**
6.9 x 10^8 m
(109 times Earth)

**Mass:**
2 x 10^{30} kg
(300,000 Earths)

**Luminosity:**
3.8 x 10^{26} watts
Solar wind: A flow of charged particles from the surface of the Sun.
Corona: Outermost layer of solar atmosphere

~1 million K
Chromosphere:
Middle layer of solar atmosphere
\( \sim 10^4 - 10^5 \) K
**Photosphere:**

Visible surface of Sun

\(\sim 6,000 \text{ K}\)
The Solar “Surface”

Bright blobs on photosphere are where hot gas is reaching surface
Convection (rising hot gas) takes energy to surface
The Solar Wind
Solar Activity
Solar activity is like “weather”

• Sunspots
• Solar Flares
• Solar Prominences

• All related to magnetic fields
Charged particles spiral along magnetic field lines.
Solar Rotation and the Solar Magnetic Field
Solar Flares

Approximate size of Earth for comparison
Magnetic activity causes *solar flares* that send bursts of X-rays and charged particles into space.
Loops of bright gas often connect sunspot pairs
Coronal Mass Ejection
Sunspots
Solar Rotation and the Solar Magnetic Field

© 2005 Pearson Education, Inc., publishing as Addison Wesley
Magnetic fields trap gas.

$T \approx 5,800 \, \text{K}$

$T \approx 4,500 \, \text{K}$

Convection cells

Magnetic fields of sunspots suppress convection and prevent surrounding plasma from sliding sideways into sunspot.

Loops trace magnetic field lines
Sunspots

Are cooler than other parts of the Sun’s surface (4000 K)

Are regions with strong magnetic fields
The Sunspot Cycle

DAILY SUNSPOT AREA AVERAGED OVER INDIVIDUAL SOLAR ROTATIONS

SUNSPOT AREA IN EQUAL AREA LATITUDE STRIPS (% OF STRIP AREA)

AVG DAILY SUNSPOT AREA (% OF VISIBLE HEMISPHERE)

http://science.nasa.gov/solwind/solarimages/bfly.gif

NASA/NSSTC/HATHAWAY 2003/04
Sunspots and Solar Activity

The Sun Approaching Solar Maximum
Solar and Heliospheric Observatory, Extreme ultraviolet Imaging Telescope

Early 1997  Mid 1998  Late 1999
• Why is the Sun shining?
  – Not a problem - A sphere of anything with a radius of 700,000km and T=5500K would produce $3.8 \times 10^{26}$ watts. (Blackbody radiation)

• Why has it been shining for >4 billion years
  – A problem. To understand we have to look inside the Sun
**Gravitational equilibrium:**

The outward push of pressure balances the inward pull of gravity.
Weight of upper layers compresses lower layers
Figure 1-2. A standard solar model of the present solar interior:
\[ X = 0.708, \quad Y = 0.272, \quad Z = 0.0020, \]
\[ \rho_c = 158 \text{g cm}^{-3}, \quad T_c = 1.57\times10^7 \text{K}. \]

**Fission**

Big nucleus splits into smaller pieces

(Nuclear power plants)

---

**Fusion**

Small nuclei stick together to make a bigger one

(Sun, stars)
High temperature enables nuclear fusion to happen in the core.

At low speeds, electromagnetic repulsion prevents the collision of nuclei.

At high speeds, nuclei come close enough for the strong force to bind them together.
**Proton-proton chain** is how hydrogen fuses into helium in Sun
IN
4 protons

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

Total mass is
0.7% lower
Sun releases energy by fusing four hydrogen nuclei into one helium nucleus

**Mass:**
2 \times 10^{30} \text{ kg}

**Luminosity:**
3.8 \times 10^{26} \text{ watts}

\[
\frac{\text{Luminosity}}{c^2} = \frac{3.8 \times 10^{26} \text{ Joules} / \text{sec}}{9 \times 10^{16} \text{ m}^2 / \text{sec}^2} \approx 4 \times 10^9 \text{ kg} / \text{sec} \approx 5 \text{ million tons/sec}
\]

\[
\text{Lifetime} = \frac{\text{Mass}}{\text{Burning Rate}} = \frac{2 \times 10^{30} \text{ kg}}{4 \times 10^9 \text{ kg} / \text{sec}} = 5 \times 10^{20} \text{ sec} \approx 10^{13} \text{ years}
\]
Radiation Zone:
• From core to about 0.7 Solar Radii
• Energy diffuses out in form of randomly bouncing photons
• $\tau \cong 10^5$ years
Energy Transport in the Sun: Convection

Convective Zone:
• From 0.7 Solar Radii to Surface
• Cells boil to the surface carrying energy.
• $\tau \approx 2$ weeks
Convection Zone:

Energy transported upward by rising hot gas
Radiation Zone:
Energy transported upward by photons
Core:

Energy generated by nuclear fusion

~ 15 million K
Solar Thermostat

- Temperature Decreases
- Fusion Rate Decreases
- Core compresses
- Temperature Restored
Solar Thermostat

Temperature Increases

Fusion Rate Increases

Core expands

Temperature Restored
We learn about inside of Sun by ...

• Making mathematical models
• Observing sun quakes
• Observing solar neutrinos
Patterns of vibration on surface tell us about what Sun is like inside

Results agree very well with mathematical models of solar interior
Neutrinos created during fusion fly directly through the Sun.

Observations of these solar neutrinos can tell us what’s happening in core.