“The glorious lamp of heaven, the sun.”

Robert Herrick
What We Will Learn Today

• How does the Sun shine?

• What do we know about the Sun?

• What are the layers of the Sun?

• What is solar activity?
How Does the Sun Shine?

• Review
  – Gravitational collapse of solar nebula heated the core
  – Hydrogen fusion ignited the Sun
    • $E = mc^2$

• Details of energy production
  – $M \left( ^1H \right) = 6.690 \times 10^{-27} \text{ kg}$
  – $M \left( ^4\text{He} \right) = 6.643 \times 10^{-27} \text{ kg}$
  – Mass converted into Energy
    = $0.047 \times 10^{-27} \text{ kg}$
  – Efficiency = $0.047/6.690 = 0.7\%$
  – Energy = $0.047 \times 10^{-27} \text{ kg} \times c^2$
    = $4.23 \times 10^{-12} \text{ J}$

• Sun’s shining power
  – $L = 3.8 \times 10^{26} \text{ J/s or Watts (W)}$

The Sun consumes 600 million tons ($6 \times 10^{11} \text{ kg}$) of Hydrogen *per second*
How Long Can the Sun Shine?

- Mass of the Sun = $2 \times 10^{30}$ kg
- Rate of Hydrogen use = $6 \times 10^{11}$ kg / s
- Fuel exhaustion time $\approx 3.3 \times 10^{18}$ s
  $\approx 10^{11}$ y
- That’s 100 billion years!
- The Sun will spend $\sim 10$ billion years in the MS
- It has used only $\sim 5\%$ of its fuel so far!
- It will only use 10% of its fuel in its lifetime
  - The bulk is ejected into the beautiful planetary nebula
Sun’s Regulated Fusion

- A slight drop in core temperature...
- A slight rise in core temperature...
- That raises the core pressure...
- That lowers the core pressure...
- Leads to a large decrease in the fusion rate...
- Leads to a large increase in the fusion rate...

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Light’s Journey Through the Sun

• “Random walk”
  – Photon moves in a straight line until it interacts with an electron
  – In the dense core, it travels only a millimeter or so before the next interaction
  – Each interaction redirects the photon in a random direction

• The photon can take hundreds of thousands of years to exit the Sun!
- Random walk through the radiation zone
- Temperature drops in convection zone, enough to cause absorption
- Surface bubbles due to convection
  - Hot gas rises
  - Cool gas sinks
Learning About the Interior

- **Mathematical Models**
  - Prediction of radius, surface temperature and other observables are very good

- **Helioseismology**
  - Measure vibrations on the surface via Doppler shifts and correlate to structure of the interior

- **Solar neutrinos**
  - Trillions pass through your body every second!
  - Rarely interact with matter
  - Produced as a byproduct of fusion
  - Solving the solar neutrino “problem” was a major victory
The Core

- 200,000 km radius
- Highest density (~ 160 g/cc)
- Highest temperature (15 million K)
- Where all the fusion occurs
The Radiation Zone

- 300,000 km thick
- Temperature ~ 7 million K
- Light makes its way out via random walk
- Neutrinos stream through with little interaction
The Convection Zone

- 200,000 km thick
- Temperature drops to ~ 2 million K
- Convective cells bubble energy up

Fig 14.10
The Photosphere

- The “surface” of the Sun
  - 500 km thin
- Temperature = 5800 K
- See sun spots and granulation (convection cells)
- The Earth would fit inside a typical sunspot!
What Causes Sunspots?

- Differential rotation
- Twisting magnetic field lines
- Magnetic lines penetrate surface, ejecting material into space
  - Some falls back: prominences
  - Other are blown away: flares
- 11 year sunspot cycle observed
The Chromosphere

• About 4500 K
• Seen in Hydrogen-alpha filter
• Shows spicules (jets of gas shooting out), and filaments (cooler areas)

Sun, viewed through H-alpha filter

Spicules
The Corona

- Visible during a solar eclipse
- Outermost layer of the Sun
  - Extends 100,000s km beyond the surface
- Much higher temperature than other layers (millions of K)!
The Solar Wind

- Stream of particles blown away by the Sun
- Extends out to Jupiter and beyond
- Causes Aurora Borealis
  - Charged particles accelerated by Earth’s magnetic field interact with atmosphere
Coronal Mass Ejection

• Very large flares blow a lot of mass into space
  – Occur a couple of times a week
  – If directed at Earth, can disrupt satellite communication, electrical grids
  – And they can blow off comet tails!

Fig 14.18  
NASA movie
Basic Properties of the Sun

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radius ($R_{\text{Sun}}$)</td>
<td>696,000 km (about 109 times the radius of Earth)</td>
</tr>
<tr>
<td>Mass ($M_{\text{Sun}}$)</td>
<td>$2 \times 10^{30}$ kg (about 300,000 times the mass of Earth)</td>
</tr>
<tr>
<td>Luminosity ($L_{\text{Sun}}$)</td>
<td>$3.8 \times 10^{26}$ watts</td>
</tr>
<tr>
<td>Composition (by percentage of mass)</td>
<td>70% hydrogen, 28% helium, 2% heavier elements</td>
</tr>
<tr>
<td>Rotation rate</td>
<td>25 days (equator) to 30 days (poles)</td>
</tr>
<tr>
<td>Surface temperature</td>
<td>5,800 K (average); 4,000 K (sunspots)</td>
</tr>
<tr>
<td>Core temperature</td>
<td>15 million K</td>
</tr>
</tbody>
</table>

- **Average** density = 1.4 g/cc (¼ of Earth’s)
- Gravity = 274 m/s² (28 times Earth’s)