Our Star, the Sun

Chapter Eighteen
Guiding Questions

1. What is the source of the Sun’s energy?
2. What is the internal structure of the Sun?
3. How can astronomers measure the properties of the Sun’s interior?
4. How can we be sure that thermonuclear reactions are happening in the Sun’s core?
5. Does the Sun have a solid surface?
6. Since the Sun is so bright, how is it possible to see its dim outer atmosphere?
7. Where does the solar wind come from?
8. What are sunspots? Why do they appear dark?
9. What is the connection between sunspots and the Sun’s magnetic field?
10. What causes eruptions in the Sun’s atmosphere?
An Overview of the Details

table 18-1 | Sun Data

Distance from the Earth: Mean: 1 AU = 149,598,000 km
Maximum: 152,000,000 km
Minimum: 147,000,000 km

Light travel time to the Earth: 8.32 min
Mean angular diameter: 32 arcmin

Radius: 696,000 km = 109 Earth radii
Mass: $1.9891 \times 10^{30}$ kg = $3.33 \times 10^5$ Earth masses

Composition (by mass): 74% hydrogen, 25% helium,
1% other elements

Composition (by number of atoms): 92.1% hydrogen, 7.8% helium,
0.1% other elements

Mean density: 1410 kg/m$^3$

Mean temperatures: Surface: 5800 K; Center: $1.55 \times 10^7$ K

Luminosity: $3.86 \times 10^{26}$ W

Distance from center of Galaxy: 8000 pc = 26,000 ly

Orbital period around center of Galaxy: 220 million years

Orbital speed around center of Galaxy: 220 km/s
The Sun’s energy is generated by thermonuclear reactions in its core

- The energy released in a nuclear reaction corresponds to a slight reduction of mass according to Einstein’s equation $E = mc^2$.
- Thermonuclear fusion occurs only at very high temperatures; for example, hydrogen fusion occurs only at temperatures in excess of about $10^7$ K.
- In the Sun, fusion occurs only in the dense, hot core.
The Sun’s energy is produced by hydrogen fusion, not in a single step, but in a sequence of thermonuclear reactions in which four hydrogen nuclei combine to produce a single helium nucleus.

(a) Step 1:
- Two protons (hydrogen nuclei, $^1\text{H}$) collide.
- One of the protons changes into a neutron (shown in blue), a neutral, nearly massless neutrino ($\nu$), and a positively charged electron, or positron ($e^+$).
- The proton and neutron form a hydrogen isotope ($^2\text{H}$).
- The positron encounters an ordinary electron ($e^-$), annihilating both particles and converting them into gamma-ray photons ($\gamma$).

(b) Step 2:
- The $^2\text{H}$ nucleus from the first step collides with a third proton.
- A helium isotope ($^3\text{He}$) is formed and another gamma-ray photon is released.

(c) Step 3:
- Two $^3\text{He}$ nuclei collide.
- A different helium isotope with two protons and two neutrons ($^4\text{He}$) is formed and two protons are released.
Step 1:

- Two protons (hydrogen nuclei, \(^1\text{H}\)) collide.
- One of the protons changes into a neutron (shown in blue), a neutral, nearly massless neutrino (\(\nu\)), and a positively charged electron, or positron (\(e^+\)).
- The proton and neutron form a hydrogen isotope (\(^2\text{H}\)).
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Step 2:

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Step 3:

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A theoretical model of the Sun shows how energy gets from its center to its surface

- Hydrogen fusion takes place in a core extending from the Sun’s center to about 0.25 solar radius
- The core is surrounded by a radiative zone extending to about 0.71 solar radius
  - In this zone, energy travels outward through radiative diffusion
- The radiative zone is surrounded by a rather opaque convective zone of gas at relatively low temperature and pressure
  - In this zone, energy travels outward primarily through convection
## Solar Model Results

### Table 18-2: A Theoretical Model of the Sun

<table>
<thead>
<tr>
<th>Distance from the Sun’s center (solar radii)</th>
<th>Fraction of luminosity</th>
<th>Fraction of mass</th>
<th>Temperature ($\times 10^6$ K)</th>
<th>Density (kg/m$^3$)</th>
<th>Pressure (relative to pressure at center)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>0.00</td>
<td>0.00</td>
<td>15.5</td>
<td>160,000</td>
<td>1.00</td>
</tr>
<tr>
<td>0.1</td>
<td>0.42</td>
<td>0.07</td>
<td>13.0</td>
<td>90,000</td>
<td>0.46</td>
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<tr>
<td>0.2</td>
<td>0.94</td>
<td>0.35</td>
<td>9.5</td>
<td>40,000</td>
<td>0.15</td>
</tr>
<tr>
<td>0.3</td>
<td>1.00</td>
<td>0.64</td>
<td>6.7</td>
<td>13,000</td>
<td>0.04</td>
</tr>
<tr>
<td>0.4</td>
<td>1.00</td>
<td>0.85</td>
<td>4.8</td>
<td>4,000</td>
<td>0.007</td>
</tr>
<tr>
<td>0.5</td>
<td>1.00</td>
<td>0.94</td>
<td>3.4</td>
<td>1,000</td>
<td>0.001</td>
</tr>
<tr>
<td>0.6</td>
<td>1.00</td>
<td>0.98</td>
<td>2.2</td>
<td>400</td>
<td>0.0003</td>
</tr>
<tr>
<td>0.7</td>
<td>1.00</td>
<td>0.99</td>
<td>1.2</td>
<td>80</td>
<td>$4 \times 10^{-5}$</td>
</tr>
<tr>
<td>0.8</td>
<td>1.00</td>
<td>1.00</td>
<td>0.7</td>
<td>20</td>
<td>$5 \times 10^{-6}$</td>
</tr>
<tr>
<td>0.9</td>
<td>1.00</td>
<td>1.00</td>
<td>0.3</td>
<td>2</td>
<td>$3 \times 10^{-7}$</td>
</tr>
<tr>
<td>1.0</td>
<td>1.00</td>
<td>1.00</td>
<td>0.006</td>
<td>0.00030</td>
<td>$4 \times 10^{-13}$</td>
</tr>
</tbody>
</table>

Note: The distance from the Sun’s center is expressed as a fraction of the Sun’s radius ($R_\odot$). Thus, 0.0 is at the center of the Sun and 1.0 is at the surface. The fraction of luminosity is that portion of the Sun’s total luminosity produced within each distance from the center; this is equal to 1.00 for distances of 0.25 $R_\odot$ or more, which means that all of the Sun’s nuclear reactions occur within 0.25 solar radius from the Sun’s center. The fraction of mass is that portion of the Sun’s total mass lying within each distance from the Sun’s center. The pressure is expressed as a fraction of the pressure at the center of the Sun.
Understanding Hydrostatic Equilibrium

A fish floating in water is in hydrostatic equilibrium, so forces balance.

Pressure from water above the fish

Weight of the fish

Pressure from water beneath the fish
Understanding Hydrostatic Equilibrium II

Material inside the sun is in hydrostatic equilibrium, so forces balance.
How do we know about the solar interior?

By using the Sun’s own vibrations

- Helioseismology is the study of how the Sun vibrates
- These vibrations have been used to infer pressures, densities, chemical compositions, and rotation rates within the Sun
More Model Results

![Graph showing the relationship between distance from the Sun's center and luminosity and mass.](image)
A Subatomic Interlude

Structure within the Atom

- Quark: Size $< 10^{-18}$ m
- Electron: Size $< 10^{-18}$ m
- Nucleus: Size $= 10^{-14}$ m
- Atom: Size $= 10^{-10}$ m
- Neutron and Proton: Size $= 10^{-15}$ m

If this picture were drawn to the scale given by the protons and neutrons, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.
A Subatomic Interlude II

Scale in m:
10^{-10} m
10^{-14} m
10^{-15} m
\leq 10^{-18} m

atom
nucleus
proton
quark

Scale in 10^{-18} m:
100,000,000
10,000
1,000
\leq 1

electron
A Subatomic Interlude III

Leptons | Quarks
--------|--------

<table>
<thead>
<tr>
<th>Leptons</th>
<th>Quarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\nu_e)</td>
<td>(u)</td>
</tr>
<tr>
<td>(\nu_\mu)</td>
<td>(c)</td>
</tr>
<tr>
<td>(\nu_\tau)</td>
<td>(t)</td>
</tr>
<tr>
<td>e-</td>
<td>charm</td>
</tr>
<tr>
<td>(\mu)</td>
<td>strange</td>
</tr>
<tr>
<td>(\tau)</td>
<td>bottom</td>
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<tr>
<td>electron</td>
<td>up</td>
</tr>
<tr>
<td>muon</td>
<td>charm</td>
</tr>
<tr>
<td>tau</td>
<td>top</td>
</tr>
</tbody>
</table>

Three Generations of Matter
A Subatomic Interlude IIII

<table>
<thead>
<tr>
<th>Flavor</th>
<th>Mass GeV/c^2</th>
<th>Electric charge</th>
<th>Flavor</th>
<th>Approx. Mass GeV/c^2</th>
<th>Electric charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_e$</td>
<td>&lt; 7 x 10^{-9}</td>
<td>0</td>
<td>$u$ up</td>
<td>0.005</td>
<td>2/3</td>
</tr>
<tr>
<td>$e$ electron</td>
<td>0.000511</td>
<td>-1</td>
<td>$d$ down</td>
<td>0.01</td>
<td>-1/3</td>
</tr>
<tr>
<td>$\nu_\mu$</td>
<td>&lt; 0.0003</td>
<td>0</td>
<td>$c$ charm</td>
<td>1.5</td>
<td>2/3</td>
</tr>
<tr>
<td>$\mu$ muon</td>
<td>0.106</td>
<td>-1</td>
<td>$S$ strange</td>
<td>0.2</td>
<td>-1/3</td>
</tr>
<tr>
<td>$\nu_\tau$</td>
<td>&lt; 0.03</td>
<td>0</td>
<td>$t$ top</td>
<td>170</td>
<td>2/3</td>
</tr>
<tr>
<td>$\tau$ tau</td>
<td>1.7771</td>
<td>-1</td>
<td>$b$ bottom</td>
<td>4.7</td>
<td>-1/3</td>
</tr>
</tbody>
</table>

**FERMIIONS**  

**Leptons** spin = 1/2  

<table>
<thead>
<tr>
<th>Flavor</th>
<th>Spin</th>
<th>Mass GeV/c^2</th>
<th>Electric charge</th>
</tr>
</thead>
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<tr>
<td>$e$ electron</td>
<td>spin = 1/2</td>
<td>0.000511</td>
<td>-1</td>
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<tr>
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<td></td>
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**Quarks** spin = 1/2  

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<td>-1/3</td>
</tr>
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<td>2/3</td>
</tr>
<tr>
<td>$S$ strange</td>
<td>0.2</td>
<td>-1/3</td>
</tr>
<tr>
<td>$t$ top</td>
<td>170</td>
<td>2/3</td>
</tr>
</tbody>
</table>

**matter constituents** spin = 1/2, 3/2, 5/2, ...
A Subatomic Interlude V

- Neutrinos are produced in the “Weak Interaction”, for example
  - Neutrinos from the earth
    - natural radioactivity
  - “Man-made” neutrinos
    - accelerators, nuclear power plants.
  - Astrophysical neutrinos
    - Solar neutrinos
    - Atmospheric neutrinos
    - Relic neutrinos
      - left over from the big bang.
Detecting neutrinos requires a different kind of a detector.
Neutrino Factoids

• The earth receives about 40 billion neutrinos per second per cm$^2$ from the sun.
  – About 100 times that amount are passing through us from the big bang.
    • This works out to about 330 neutrinos in every cm$^3$ of the universe!
    • By comparison there are about 0.0000005 protons per cm$^3$ in the universe.

• Our body emits about 340 million neutrinos per day from $^{40}$K.
• Neutrinos don’t do much when passing through matter.
• Remember, it is very difficult to observe neutrinos.
Neutrino Detection II

- The neutrino is observed by detecting the product of its interaction with matter.

$\nu_e$  
Electron

$\nu_\mu$  
Muon

(neutrino, electron, proton, neutron, atom)
Neutrinos reveal information about the Sun’s core—and have surprises of their own

- Neutrinos emitted in thermonuclear reactions in the Sun’s core have been detected, but in smaller numbers than expected
- Recent neutrino experiments explain why this is so
The Photosphere -
the lowest of three main layers in the Sun’s atmosphere

- The Sun’s atmosphere has three main layers
  - the photosphere
  - the chromosphere
  - the corona
- Everything below the solar atmosphere is called the solar interior
- The visible surface of the Sun, the photosphere, is the lowest layer in the solar atmosphere

The spectrum of the photosphere is similar to that of a blackbody at a temperature of 5800 K
The Sun is a sphere, although it appears as a disk. This leads to a phenomenon known as limb darkening.
Convection in the photosphere produces granules.
More Convection

Blue: areas of rising gas
Red: areas of sinking gas
The Chromosphere - characterized by spikes of rising gas

- Above the photosphere is a layer of less dense but higher temperature gases called the chromosphere.
- Spicules extend upward from the photosphere into the chromosphere along the boundaries of supergranules.
The Corona –
outermost layer of the solar atmosphere, made of very high-
temperature gases at extremely low density

- The solar corona blends into the solar wind at great distances from the Sun
The corona ejects mass into space to form the solar wind
Activity in the corona includes coronal mass ejections and coronal holes.
Sunspots -
low-temperature regions in the photosphere
Sunspot Cycle - Sunspots on the move
Near sunspot maximum
Near sunspot minimum
Sunspots are produced by a 22-year cycle in the Sun’s magnetic field.
• The Sun’s surface features vary in an 11-year cycle – the sunspot cycle
• The average number of sunspots increases and decreases in a regular cycle of approximately 11 years, with reversed magnetic polarities from one 11-year cycle to the next
• This is related to a 22-year cycle (the solar cycle) in which the surface magnetic field increases, decreases, and then increases again with the opposite polarity
• Two sunspot cycles make up one 22-year solar cycle
The magnetic-dynamo model suggests that many features of the solar cycle are due to changes in the Sun’s magnetic field
The solar magnetic changes are caused by convection and the Sun’s differential rotation.
(a) A coronal mass ejection

(b) Two to four days later
Bright areas lie on top of sunspot groups
(a) A sunspot

Outside the sunspot, the magnetic field is low and this iron absorption line is single.

Within the sunspot, the magnetic field is strong and this iron absorption line splits into three.

(b) The spectrum in and around the sunspot
The Sun’s magnetic field also produces other forms of solar activity

- A solar flare is a brief eruption of hot, ionized gases from a sunspot group
- A coronal mass ejection is a much larger eruption that involves immense amounts of gas from the corona
Key Words

- 22-year solar cycle
- chromosphere
- CNO cycle
- conduction
- convection
- convective zone
- corona
- coronal hole
- coronal mass ejection
- differential rotation
- filament
- granulation
- granule
- helioseismology
- hydrogen fusion
- hydrostatic equilibrium
- limb darkening
- luminosity (of the Sun)
- magnetic-dynamo model
- magnetogram
- magnetic reconnection
- negative hydrogen ion
- neutrino
- neutrino oscillation
- photosphere
- plage
- plasma
- positron
- prominence