The Sun
Our Extraordinary Ordinary Star

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>
<thead>
<tr>
<th>The Sun's energy is generated by thermonuclear reactions in its core</th>
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<tr>
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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

- Step 1: Two protons (hydrogen nuclei, $^1H$) collide.
- The nascent helium (nucleus of helium, $^4He$) emits two positrons (charged particles) and two neutrinos (spinless, almost massless particles).
- The positrons and neutrinos are emitted in opposite directions.
- The helium nucleus consists of two protons and two neutrons, which are held together by the strong nuclear force.
- The helium nucleus is the lightest stable nucleus.

The Sun Data

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<tr>
<th>Distance from Earth</th>
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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.

Understanding Hydrostatic Equilibrium:

A fish floating in water 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.
**A Subatomic Interlude**

- 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.

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**A Subatomic Interlude II**

Scale in m: $10^15$ m: 10,000

- $10^{14}$ m
- $10^{15}$ m
- $10^{16}$ m

- Neutrinos from the earth
- “Man-made” neutrinos
- Astrophysical neutrinos
- Relic neutrinos

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**A Subatomic Interlude III**

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<tr>
<th>FERMIONS</th>
<th>leptons spin = 1/2</th>
<th>quarks spin = 1/2</th>
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<tr>
<td>Flavor</td>
<td>Mass (GeV/c²)</td>
<td>Electric charge</td>
</tr>
<tr>
<td>u proton</td>
<td>$\approx 7 \times 10^{-6}$</td>
<td>0</td>
</tr>
<tr>
<td>e electron</td>
<td>0.000511</td>
<td>-1</td>
</tr>
<tr>
<td>ν neutrino</td>
<td>$\approx 0.003$</td>
<td>0</td>
</tr>
<tr>
<td>µ neutrino</td>
<td>0.1</td>
<td>-1</td>
</tr>
<tr>
<td>τ neutrino</td>
<td>$\approx 0.006$</td>
<td>0</td>
</tr>
<tr>
<td>ν_{had}</td>
<td>0.1</td>
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Neutrino Factoids

- The earth receives about 40 billion neutrinos per second per cm² 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 cm² of the universe.
    - By comparison there are about 0.0000005 protons per cm² in the universe.
- Our body emits about 340 million neutrinos per day from 4⁰K.
- Neutrinos don’t do much when passing through matter.
- Remember, it is very difficult to observe neutrinos.

Neutrino Detection

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

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.
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

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.
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

Jargon

- 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)
- magneto-dynamo model
- magnetogram
- magnetic reconnection
- negative hydrogen ion
- neutrino
- neutrino oscillation
- photosphere
- plage
- plasma
- positron
- prominence