Solar Energy

Lecture #8
HNRS 228
Energy and the Environment
Chapter 4 Summary

- Energy from the Sun
  - This lecture will focus on this only
- Passive solar systems
- Solar Thermal Systems
  - Electric power generation indirectly
- Photovoltaic systems
  - Making electricity directly
- Solar cooling systems
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>table 18-1</th>
<th>Sun Data</th>
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</thead>
</table>
| 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/m³ |
| 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
iClicker Question

The release of energy from the Sun is accompanied by a very slight

A  increase in the Sun's gravitational attraction on the planets
B  increase in the Sun's rotation rate
C  decrease in the mass of the Sun
D  all of the above are true
E  none of the above are true
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, $^1\text{H}$) 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 ($\gamma$).
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.
Step 3:

- Two $^3$He nuclei collide.
- A different helium isotope with two protons and two neutrons ($^4$He) is formed and two protons are released.
The proton-proton reaction in the core of the sun is a multi-step process in reality, but it can be summarized as which of the following?

- **A**  $1 \times ^4\text{He} \rightarrow 4 \times ^1\text{H} + \text{energy}$
- **B**  $4 \times ^1\text{He} \rightarrow 1 \times ^4\text{H} + \text{energy}$
- **C**  $4 \times ^1\text{H} + \text{energy} \rightarrow 1 \times ^4\text{He}$
- **D**  $4 \times ^1\text{H} \rightarrow 1 \times ^4\text{He} + \text{energy}$
- **E**  all of the above are equivalent.
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
Which of the following is true of Hydrogen conversion into Helium?

- A  It absorbs more energy than it creates.
- B  It only takes place in stars more massive than the Sun.
- C  It takes place throughout the interior of the Sun.
- D  It takes place only in the core of the Sun.
- E  All of the above are true regarding Hydrogen conversion into Helium.
Understanding Hydrostatic Equilibrium

A fish floating in water is in hydrostatic equilibrium, so forces balance.
Material inside the sun is in hydrostatic equilibrium, so forces balance.
Most of the Sun's energy is produced in
A  supergranules
B  the convection zone
C  the photosphere
D  the chromosphere
E  the core
Energy generation in the Sun results from

- A fission of uranium
- B fission of hydrogen
- C gravitational contraction
- D the Sun isn't generating energy; it's just cooling
- E fusion of hydrogen
How do we know about the solar interior?

- 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.
Solar Model Results

The graph shows the variations in luminosity and mass of the Sun as a function of distance from the Sun's center. The luminosity increases significantly from the center to the surface, while the mass is more evenly distributed. The x-axis represents the distance from the Sun's center in solar radii, while the y-axis represents the percentage values for luminosity and mass.
iClicker Question

- The fraction of the Sun that is comprised of hydrogen and helium is roughly
  - A 98%
  - B 90%
  - C 50%
  - D 10%
  - E 2%
A Subatomic Interlude

Structure within the Atom

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

electron

Scale in $10^{-18}$ m:

100,000,000

10,000

1,000

$\leq 1$
### FERMIONS

**Leptons spin = 1/2**

<table>
<thead>
<tr>
<th>Flavor</th>
<th>Mass GeV/c²</th>
<th>Electric charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_e$ electron (neutrino)</td>
<td>$&lt; 7 \times 10^{-9}$</td>
<td>0</td>
</tr>
<tr>
<td>e electron</td>
<td>0.000511</td>
<td>-1</td>
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<tr>
<td>$\nu_\mu$ muon (neutrino)</td>
<td>$&lt; 0.0003$</td>
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<tr>
<td>$\mu$ muon</td>
<td>0.106</td>
<td>-1</td>
</tr>
<tr>
<td>$\nu_\tau$ tau (neutrino)</td>
<td>$&lt; 0.03$</td>
<td>0</td>
</tr>
<tr>
<td>$\tau$ tau</td>
<td>1.7771</td>
<td>-1</td>
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</table>

**Quarks spin = 1/2**

<table>
<thead>
<tr>
<th>Flavor</th>
<th>Approx. Mass GeV/c²</th>
<th>Electric charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>u up</td>
<td>0.005</td>
<td>2/3</td>
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<tr>
<td>d down</td>
<td>0.01</td>
<td>-1/3</td>
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<tr>
<td>c charm</td>
<td>1.5</td>
<td>2/3</td>
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<tr>
<td>s strange</td>
<td>0.2</td>
<td>-1/3</td>
</tr>
<tr>
<td>t top</td>
<td>170 (initial evidence)</td>
<td>2/3</td>
</tr>
<tr>
<td>b bottom</td>
<td>4.7</td>
<td>-1/3</td>
</tr>
</tbody>
</table>
A Subatomic Interlude IV

- 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.
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 cm³ of the universe!
    - By comparison there are about 0.0000005 protons per cm³ in the universe.
- Our body emits about 340 million neutrinos per day from $^{40}\text{K}$.
- 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.

\[ n_e \quad n_m \]

Electron

Muon
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
iClicker Question

Which of the following are most likely to get to Earth from the core of the Sun, before any of the others?

- A protons
- B electrons
- C photons
- D neutrinos
- E all of the above will arrive at about the same time
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.

- Appears orange and dim
- Appears yellow and bright

To observer
iClicker Question

The correct order of the layers of the Sun from innermost to outermost is:

- A core, chromosphere, photosphere
- B core, convective layer, radiative layer
- C radiative layer, convective layer, core
- D convective layer, core, radiative layer
- E core, radiative layer, convective layer
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.
Cross Sectional View of the Solar Atmosphere
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.

In this narrow transition region between the chromosphere and corona, the temperature rises abruptly by about a factor of 100.
The corona ejects mass into space to form the solar wind.
iClicker Question

The highest temperatures found in the Sun’s atmosphere is located in the

- A chromosphere
- B corona
- C photosphere
- D core
- E cytosphere
Activity in the corona includes coronal mass ejections and coronal holes.
The solar wind is mostly composed of

- A  oxygen
- B  dust grains
- C  neutrinos
- D  photons
- E  charged particles

iClicker Question
Sunspots -
low-temperature regions in the photosphere

(a) Penumbra
(b) Umbra
iClicker Question

Sunspots are

- A areas obscured by higher layers of clouds
- B ashes of nuclear burning brought to the surface by convection
- C holes in the photosphere that allow us to see deeper regions
- D regions which are cooler and darker than surrounding material
- E causing global warming
Sunspot Cycle - Sunspots on the move

November 9

November 12

November 14

November 15

November 17

November 19
Sunspots are produced by a 22-year cycle in the Sun’s magnetic field.

(a) Graph showing the average number of sunspots over time from 1750 to 2000.

(b) Near sunspot maximum

(c) Near sunspot minimum
- 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.
During the sunspot cycle the position of new sunspots on the Sun

- A changes from mid-latitudes to the equator
- B changes from mid-latitudes to the poles
- C changes from the equator to the mid-latitudes
- D changes from the equator to the poles
- E does not change in any predictable manner
iClicker Question

Sunspot cycles are, on the average, what length?

• A 22 years
• B 11 years
• C 5.5 years
• D 1 year
• E 3 years
The solar magnetic changes are caused by convection and the Sun’s differential rotation.
iClicker Question

The solar cycle is determined by the change in the

- A solar constant
- B sunspot location and number
- C solar radiance flux measurements
- D solar electric field changes
- E solar magnetic field polarity
During a sunspot cycle

- **A** each sunspot increases in size and then decreases in size
- **B** the material composing a spot makes one complete rotation
- **C** the spots move from one of the Sun's polar regions to the other
- **D** the number of spots rises to maximum and then decreases to a minimum
- **E** the Sun and the spots on it make one complete rotation
(a) A coronal mass ejection

(b) Two to four days later
Coronal mass ejections are

- A large bits of the sun that blow out into interplanetary space
- B charged particles from the sun accelerated/guided by magnetic field lines
- C richer in heavier elements than other mass ejections
- D nothing to be feared by spacecraft and humans in space
- E never going to achieve escape velocity
(a) A sunspot

(b) The spectrum in and around the 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.
Rotation of the Solar Interior
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)
- magnetic-dynamo model
- magnetogram
- magnetic reconnection
- negative hydrogen ion
- neutrino
- neutrino oscillation
- photosphere
- plage
- plasma
- positron
- prominence