ASTR 113
Lecture 1

with Prof. M. Opher

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What do I work with?

- Interaction of the Solar System with the Galaxy
- Space Weather (effect of the Sun on Earth)
- Jets

www.physics.gmu.edu/~mopher
Active Sun
Space Weather

Major solar energetic particles (SEP) events: GeV/nucleon

Events can:
- interrupt satellite communications;
- disrupt ground based power grids;
- threaten the safety of astronauts

Crucial for missions to Moon; Mars!
Introduction

• Syllabus
  – Online, but a printed copy is available, the first lecture only, in class
    www.physics.gmu.edu/~mopher/astr113

  Check the dates of the classes!

• Grading
  There will be 3 one-hour in-class (regular class dates/times) examinations and one 3-hour comprehensive final. NO MAKEUP EXAMS

  2/3 In class one-hour examinations (30% each) 60%
  1  Comprehensive Final      40 %====100%

  • Exams and final – calculators, pencils, scantron (bring your own) and ID only – follow posted rules or “F”

  – NO MAKE-UP EXAMINATIONS
  – NO EXTRA CREDIT WORK SUBSTITUTIONS
• Web notes
  – Will be updated routinely; check back often
• Observing Sessions (H. Geller)
  – Offered on campus for your enjoyment
How to Study Astronomy

• For the main ideas
• Let facts fall into place
• How do you know a main idea when you see it? Ask,
  • "What is the instructor (or textbook) talking about here?"
  • "Put it in your own words, but keep your answer to a single sentence. "Today we talked about..."
  • "This section explains how..." In a science course main ideas are usually theories, methods, or processes
• ....check more on www.physics.gmu.edu/~mopher/astr113
Today - Chapter 18: Our Star, the Sun

• Solar energy generation and fusion (18.1)
• Modeling the Sun (18.2)
• Determining the solar interior (18.3)
• Probing the Sun with neutrinos (18.4)
• The photosphere as the surface we "see" (18.5)
### An Overview of the Details

#### Table 18-1: Sun Data

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance from the Earth</td>
<td>Mean: 1 AU = 149,598,000 km</td>
</tr>
<tr>
<td></td>
<td>Maximum: 152,000,000 km</td>
</tr>
<tr>
<td></td>
<td>Minimum: 147,000,000 km</td>
</tr>
<tr>
<td>Light travel time to the Earth</td>
<td>8.32 min</td>
</tr>
<tr>
<td>Mean angular diameter</td>
<td>32 arcmin</td>
</tr>
<tr>
<td>Radius</td>
<td>696,000 km = 109 Earth radii</td>
</tr>
<tr>
<td>Mass</td>
<td>$1.9891 \times 10^{30}$ kg = $3.33 \times 10^5$ Earth masses</td>
</tr>
<tr>
<td>Composition (by mass)</td>
<td>74% hydrogen, 25% helium, 1% other elements</td>
</tr>
<tr>
<td>Composition (by number of atoms)</td>
<td>92.1% hydrogen, 7.8% helium, 0.1% other elements</td>
</tr>
<tr>
<td>Mean density</td>
<td>1410 kg/m$^3$</td>
</tr>
<tr>
<td>Mean temperatures</td>
<td>Surface: 5800 K; Center: $1.55 \times 10^7$ K</td>
</tr>
<tr>
<td>Luminosity</td>
<td>$3.86 \times 10^{26}$ W</td>
</tr>
<tr>
<td>Distance from center of Galaxy</td>
<td>8000 pc = 26,000 ly</td>
</tr>
<tr>
<td>Orbital period around center of Galaxy</td>
<td>220 million years</td>
</tr>
<tr>
<td>Orbital speed around center of Galaxy</td>
<td>220 km/s</td>
</tr>
</tbody>
</table>
What is the source of energy of the Sun?

• Gravitational Contraction (Kelvin Helmholtz) no!-contracting from the original solar nebula will give an Age of 25 million years much younger that Earth!

• Burning fuel: release $10^{-19}$ joule per atoms
  Counting the number of atoms of the sun the entire Sun will
  • Be consumed in $3 \times 10^{11}$ seconds = $10^4$ years!!!

• Albert Einstein discover the process (in 1905): Energy-mass Equation. -> thermonuclear fusion can only take place in very High temperatures (the nuclei will be moving so fast to overcome Their electric repulsion)
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, $^1$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 ($^2$H).
- The positron encounters an ordinary electron ($e^-$), annihilating both particles and converting them into gamma-ray photons ($\gamma$).

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

(c) 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.
Step 1:

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- One of the protons changes into a neutron (shown in blue), a neutral, nearly massless neutrino ($\nu$), and a positively charged electron, or positron ($e^+$).
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- 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 $^3\text{He}$ nuclei collide.
- A different helium isotope with two protons and two neutrons ($^4\text{He}$) is formed and two protons are released.
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.
It takes 170,000 years for the energy created at the core to escape as sunlight. After escaping the surface, the solar energy takes only 8 minutes to travel from the Sun to Earth!

We are actually looking at the sunlight that was produced in the core hundreds of thousands of years ago!
# 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>
</tr>
<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.*
More Model Results

The graph shows the relationship between distance from the Sun’s center and luminosity and mass. The graph indicates that as you move from the center of the Sun to the surface, the luminosity and mass increase. The y-axis represents the percentage of luminosity and mass, while the x-axis represents the distance from the Sun’s center in solar radii.
Understanding Hydrostatic Equilibrium

Material inside the sun is in hydrostatic equilibrium, so forces balance.
Understanding Hydrostatic Equilibrium II

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.

http://gong.nso.edu/
Neutrino Detection

• The Sun produced $10^{38}$ neutrinos/each second!
• As part of hydrogen fusion neutrinos are produced $->$ if we Will be able to detect them this will be a direct evidence That thermonuclear reactions occur in the Sun.
• Raymond Davis in Brookhaven National Lab (1960’s) built 100,000 gallons of C$_2$Cl$_4$
• They found that only one-third of the neutrino flux predicted By standard model of the sun were observed: solar neutrino problem

Other experiments: GALLEX
http://www.mpi-hd.mpg.de/nuastro/gallex.html

Measuring the direction where the neutrinos are coming
From: http://neutrino.phys.washington.edu/~superk/
Solution?
The core is 10% cooler? No!
Massive Neutrinos and Neutrino Oscillations!

SNO measured and confirmed in early 2004.
Sudbury Neutrino Observatory (SNO): it can measure \textit{any} type of neutrinos!
Questions

• 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?
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.