The Sun

1992 June 07
## Vital Statistics

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotation Period</td>
<td>25.04 days</td>
</tr>
<tr>
<td>Mass</td>
<td>$332,943 , M_\text{E} ,(1.99 \times 10^{30} , \text{kg})$</td>
</tr>
<tr>
<td>Density</td>
<td>$1.41 , \text{g/cm}^3$</td>
</tr>
<tr>
<td>Diameter</td>
<td>$109.3 , D_\text{E} ,(1.391 \times 10^6 , \text{km})$</td>
</tr>
<tr>
<td>Surface Temperature</td>
<td>5800 K</td>
</tr>
<tr>
<td>Core Temperature</td>
<td>$15.5 \times 10^6 , \text{K}$</td>
</tr>
<tr>
<td>Energy Output</td>
<td>$3.9 \times 10^{26} , \text{Watts}$</td>
</tr>
</tbody>
</table>
Stability

Relatively constant both in size and energy output
Forces are balanced at every point in the Sun
Temperature, pressure, and density remain constant
But Sun is active

http://www.flickr.com/photos/gsfc/3442090793/
Solar Vibrations

(a) 

(b)
Hydrostatic Equilibrium

The inward gravitational force is counterbalanced by the outward flow of energy

Radiation Pressure

If energy outflow were to increase, then
- Sun would expand
- Rate of energy production would then decrease
- Allowing the Sun to shrink again

If energy outflow were to decrease, then
- Sun would contract
- Causing an increase in energy production
- Causing the Sun to expand outwards
Energy Transport

Transport of energy can be done in several ways:

**Radiation**

Emission of Electromagnetic waves

**Conduction**

Transfer of energy from one molecule or atom to its neighbor

**Convection**

Actual movement of material from one point to another
Radiation

In the Sun very important

Outward movement not smooth

Absorbed and reradiated many times

Reradiation is at longer and longer wavelengths

Radiative Diffusion

\(~1,000,000\) years for radiation to escape
Conduction

Not appreciable in the Sun

Conditions are not favorable
Convection

Definitely a means of energy transport
Results of convection currents seen in the granulation cells
Gases rise up in the center and then fall over at the edges of the cells
Movement is seen in the Doppler shifting of the emitted spectrum
Structure

1. Core
2. Radiative Zone
3. Convection Zone
4. Photosphere
5. Chromosphere
6. Corona
Core

Region where the energy is generated by fusion reactions
Core temperatures reach $15 \times 10^6$ K
Densities here reach 150 gm/cm$^3$
Contains roughly 1/3 the Sun's mass
Extends from the center to $\sim 0.25 \, R_{\text{Sun}}$
Radiative Zone

Photons generated in core transported outwards by radiative diffusion process
Photons take $\sim 1 \times 10^6$ years to escape Sun
Extends from $0.25 \, R_{\text{Sun}}$ to $0.70 \, R_{\text{Sun}}$
Convection Zone

Energy transport outwards by convection of gaseous materials
Results seen as granulation on the surface
Extends from 0.70 $R_{\text{Sun}}$ to roughly the surface
Photosphere

This is what is seen as the “surface”
Photons finally escape from here
This zone is about 100 km thick
Temperature is about 5800 degrees K
3400 times less dense than Earth's atmosphere
Granules on surface up to 1500 km in diameter
Chromosphere

2000 km to 10,000 km thick
Largely hydrogen gas
Can only be seen during total eclipse
Pinkish in color due to $H_\alpha$ transition
Columns of rising gas, Spicules, are seen
Temperature rises from 4500 K to $4 \times 10^5$ K
Presence of Na, Ca, and Mg detected
Corona

Extends from top of chromosphere to several million km
Can only be seen during eclipses
It is extremely hot $1 - 2 \times 10^6$ K
Source of X-ray emissions
Not very dense and not very uniform
Corona

Structure varies with solar activity
Solar wind escapes through holes in the corona
Solar wind empties 1 million metric tons per second of solar material into space
Solar wind has speeds of $1.45 \times 10^6$ km/hour
Source of Energy

It was realized early on that gravitational contraction could not supply enough energy.

The clue for the Sun's energy came from Einstein's Theory of Special Relativity and the relationship

\[ E = m \, c^2 \]

A small amount of mass can be converted into a large amount of energy.
Source of Energy

The hydrogen fusion reactions convert 1000 grams of hydrogen into only 993 grams of helium.

The remaining 7 grams are converted into energy.

These 7 grams are equivalent to 200 metric tons of coal.
Fusion Reactions

Two basic fusion reactions:

Proton - Proton Chain
  This is for core temperatures < $16 \times 10^6$ K

Carbon-Nitrogen-Oxygen (CNO) Cycle
  This is for core temperatures > $16 \times 10^6$ K

Both processes consume 4 hydrogen atoms and yield one helium atom
Proton – Proton Chain

\[ 4H^1 \rightarrow He^4 + 2e^+ + 2\nu_e + 2\gamma \]
Carbon-Nitrogen-Oxygen (CNO) Cycle

\[ 4H^1 \rightarrow \text{He}^4 + 2e^+ + 2\nu_e + 3\gamma \]
Fusion Reactions

Predominate chain in our Sun is the proton – proton chain

Calculations correctly predict amount of energy being produced

Also predicts number of neutrinos being produced

Measured number does NOT agree
Neutrino Problem

Calculations concerning the proton-proton chain predict the number of neutrinos that should be produced per second. However, the experimentally measured number is lower than the prediction.

Suggestions for this are:

1) Neutrino absorption somewhere in the Sun
2) Neutrino oscillations, that is the neutrinos change their character.
Rotation of the Sun

Rotates differentially

Rotation rate at the polar regions is slower than in the equatorial regions

At the equator \(~25\) days
At the poles \(33 – 35\) days
Sunspots

Dark, Cooler regions on the surface
Temperatures in the range 4000 – 4500 K

Associated with strong magnetic fields
Fields 1000 times stronger than average

Sunspots occur in pairs
Last from a few hours to a few months

Astronomy 1-2  Lecture 16-26
Sunspots

Two regions to a sunspot

Innermost region – Umbra
Temp 4000 – 4500 K
Surrounding region – Penumbra
Temp ~5000 K

Average Size of Sunspot ~twice the size of Earth
Sunspot Cycle

Number of sunspots is not constant
varies with time
Time to go from minimum number of sunspots to maximum number of sunspots is 11 years
Maunder Minimum

Very few sunspots were seen on the Sun from about 1645 to 1715.

This period of solar inactivity also corresponds to a climatic period called the "Little Ice Age" when rivers that are normally ice-free froze and snow fields remained year-round at lower altitudes.

There is evidence that the Sun has had similar periods of inactivity in the more distant past.
Sunspot Cycle

At the beginning of the cycle,
Sunspots appear at latitudes of 30 degrees

As the cycle progresses,
The number of sunspots increase and they migrate towards the solar equator

At the end of the cycle,
The sunspots reach the equatorial region, but with minimal numbers
Sunspots

Linked to the solar magnetic field

The sunspots that occur in pairs are of opposite polarity

The leading sunspot has the same polarity as the hemisphere in which it is located. The trailing sunspot has the opposite polarity

At the end of the cycle of sunspot numbers, the Sun reverses the polarity of its magnetic field

Therefore in the next sunspot cycle, the leading sunspot has the opposite polarity to what it had during the previous cycle

The full sunspot cycle is 22 years
Phenomena Associated with Sunspots

Flares

Plages

Prominences
Solar Flares

Violent eruptions that eject particles and radiation
Track with magnetic field lines
Occur over sunspots
Ejected particles interact with the Earth causing
  Aurorae,
  Interference with radio transmissions,
  Satellites,
  Power Grid,
  Heating of the atmosphere
Plages

Bright cloud-like feature found around sunspots
a region of higher temperature and density within the chromosphere
The focusing of energy into regions of strong magnetic field often above the sunspots
Bright plages may appear before the corresponding sunspot
Prominences

Arching columns of gas

Various types:

- **Quiescent** - Long lasting
- **Eruptive** - Very rapid movement
- **Loop** - Also called filaments when viewed from overhead

Extend hundreds of thousands of kilometers