Our Star, The Sun

- The source of the Sun's heat and light
- Models of the Sun's interior
- The Sun's vibrations
- Probing the energy generating core
- Why the outer gaseous layers appear to have sharp edges
- Emission spectra of upper regions
- The corona and the solar wind
- Sunspots
- Sunspots and magnetic fields
- Magnetic reconnection power solar eruptions

http://physics.wm.edu/~hancock/171/
The Sun Our Nearby Star

visible

UV
# The Sun

## TABLE 16-1 Sun Data

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance from 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 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 temperature</td>
<td>Surface: 5800 K; Center: 1.55 $\times$ 10$^7$ K</td>
</tr>
<tr>
<td>Luminosity</td>
<td>$3.9 \times 10^{26}$ 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>
The Sun Energy

- Many ancients thought it was literally on fire
- 1800's:
  - chemical burning?
  - gravitational contraction?
  - As the Sun shrinks, gravitational potential energy is converted into radiative energy

- But, neither of these provide enough energy…
  Sun would last only a short time
The Sun Energy

The Sun's energy output is about $3.9 \times 10^{26}$ joules/sec. A chemical reaction provides roughly $10^{-19}$ joules/atom. For the Sun to get its energy from chemical reactions, it would have to react about $3.0 \times 10^{45}$ atoms/sec. Since the Sun contains about $10^{57}$ atoms, the Sun would use all of its energy and go dark in $3 \times 10^{11}$ seconds or about 10,000 years. The solar system has been here for 4.6 billion years.

Gravitational contraction (Kelvin-Helmholtz) could provide some of the Sun's energy? While the math is a little more involved, the number is about 8 million years of energy from gravitational contraction. That is far short of 4.6 billion years.

So where does the Sun get its energy?
The answer: mass is converted to radiative energy!

\[ E = mc^2 \]

This is Einstein's famous relationship that says a small amount of mass \((m)\) multiplied by \(c^2\) can be converted to an enormous amount of energy \((E)\). The actual process deep inside the Sun is nuclear fusion. The Sun converts about 600 million tons /sec into energy.
The Sun

The nuclear fusion process converts 4 protons into energy and one helium nucleus with 2 protons and 2 neutrons. The chain of reactions is known as the proton-proton chain. About 600 million tons of hydrogen are converted to helium each second.
The fusion process takes place deep in the Sun's core where the temperature is $1.5 \times 10^7$ K. The Sun is in both hydrostatic equilibrium and thermal equilibrium. Hydrostatic equilibrium is when the outward (upward) force of the expanding gas (plasma) is balanced by the down gravitational pressure from the material above. While the temperature may be significantly different between the core and the surface, thermal equilibrium means that the temperature is the same at a given depth.
The Solar Thermostat

The rate of fusion is highly sensitive to temperature, thanks to hydrostatic equilibrium.

- Large decrease in rate of fusion
- Slight decrease in core temperature
- Slight rise in core temperature
- Large rise in rate of fusion

Because the energy supply is diminished, gravity starts to overcome thermal pressure.

Gravity compresses the core, heats it up, and restores fusion rate to normal value.

Increased energy output enables thermal pressure to overcome gravity.

Increased thermal pressure causes the core to expand and then cool, which restores fusion rate to normal value.
Energy transport from the Sun's Core

Heat is normally transported by three methods
- Conduction
- Convection
- Radiative diffusion

Conduction is not efficient with a gas (or plasma) even in the Sun. Convection is the circulation of a fluid with the hotter fluid rising and the colder fluid sinking. Radiative diffusion is the process of photons being absorbed by atoms and electrons and being re-emitted. Photons then travel outward by continuously being absorbed and re-emitted.
This table shows a typical solar model. The temperature in the core is $15.5 \times 10^6 \text{ K}$ and the density is $1.6 \times 10^5 \text{ kg/m}^3$ (14 time the density of lead!).
The core that produces energy by fusion is about 0.25 $R_\odot$ ($R_\odot$ the solar radius of 696,000 km). About 94% of the mass of the Sun is found in the inner $\frac{1}{2}R_\odot$. 
The density falls rapidly outside of the energy producing core. The temperature falls more slowly as you move away from the core.
From the center of the Sun out to $0.71 \, R_\odot$, energy is transported by radiative diffusion in a zone called the radiative zone. Beyond $0.71 \, R_\odot$ energy is transported by convection in the convection zone. In the radiative zone the energy travels as photons. The matter in this zone is very dense so the photons are constantly absorbed and re-emitted. It takes 170,000 years for a photon to travel from the core to the surface 696,000 km away. This is a speed of about $\frac{1}{2}$ meter/hour or 20 times slower than a snail!
The Sun vibrates at various frequencies much like a ringing a bell. These vibrations bounce off of the surface and are reflected downward where the higher density and temperature bend the wave upward. The strongest of the wave have a frequency of 0.003 Hz (well below human hearing). These vibrations can be detected by measuring the movement of the Sun’s upper regions using the Doppler shift. The Pattern depends on temperature, density, etc. This method confirms the solar model.
Neutrinos are 'ghostly' particles that have very tiny masses and hardly interact with anything (only via the weak interaction). Most neutrinos pass through the Earth without interacting. Neutrinos are produced in fusion reaction like the reactions that produce energy in the Sun. The neutrinos produced in the core of the Sun escape from the Sun and a very small number can interact with a giant underground particle detectors. This is a giant tank of clean fluid (C$_2$Cl$_4$) that was used by Ray Davis and collaborators for 40 years to detected neutrinos in a deep gold mine. But there was a problem. The number of neutrinos observed was 1/3 of what was predicted by solar model calculations.
Several ideas were proposed to explain the missing solar neutrinos. The problem was not the detector or the theoretical models of how the neutrinos are produced in the Sun. The problem was the neutrinos were changing their identity. There are three 'flavors' of neutrinos (electron, muon and tau). The Sun only produces electron neutrinos. In 1998 Kamiokande II (a tank of 3000 tons of water with 1100 light detectors deep under a mountain) in Japan showed neutrons do oscillate (change flavors). The top image is the Sun in neutrinos. The bottom image is inside the partially drained tank during repairs. Note the small raft.
Solar Neutrinos and the Solar Neutrino Problem

On the way to Earth, some of the electron neutrinos were changing into muon and tau neutrinos leaving only 1/3 of the original solar electron neutrons. This was confirmed by the SNO (Sudbury Neutrino Observatory) in a deep nickel mine in Canada. The detector contained 1000 tons of heavy water.

The fusion reaction model in the core of the Sun has been confirmed by direct observation of neutrinos.
The Photosphere

The Sun appears to have a surface in visible light but this is an illusion. The Sun is a ball of gas (plasma) and does not have a solid surface. All of the visible light comes from a single thin layer (400 km) of gas called the photosphere.
The Photosphere

The photosphere has a density of only $10^{-24} \text{ kg/m}^3$ or 0.01% of Earth's atmosphere. It is very opaque to visible light because of some of the hydrogen is H$^-$ ions (a proton with two electrons). The extra electron is loosely bound and can be detached by a photon of any energy. When the electron attaches back to a hydrogen atom it emits a photon in a random direction. The H$^-$ ions absorb visible light very efficiently making the photosphere opaque and nearly a perfect blackbody spectrum.
Photosphere Limb Darkening

The photosphere looks like a perfect blackbody spectrum at 5800 K. It is heated from below so the photosphere temperature should decrease as you go upward. But superimposed on this blackbody spectrum are many dark absorption lines. These are from the cooler regions of the upper photosphere at 4400 K. Because we don't see as deep into the photosphere around the edges (or limbs) of the photosphere, these regions appear to be orange and darker. This effect is called photosphere limb darkening.
High resolution images of the Sun show blotchy granulated areas. (Never look directly at the Sun with or without a telescope!) These granulations are ~100 km across. These areas are due to raising hot gas and descending cooler gas. Superimposed on the granulations are large convection cells called supergranules. These can be 35,000 km. These supergranules move at 0.4 km/s which is about one tenth the speed of the gases in the smaller granules.
The Chromosphere

When an eclipse blocks out the photosphere, a region called the chromosphere is revealed. This region is only about $10^{-4}$ as dense as the photosphere. Temperature increase with height in the chromosphere. Its spectrum show emission lines of H, He and Ca. The pink color comes from the $\text{H}_\alpha$ line of hydrogen at 656 nm. Helium was discovered in the chromosphere 30 years before it was discovered on Earth.
Spicules in the Chromosphere

Spicules are jets of rising gas that stick out of the chromosphere. Spicules move at 20 km/s and last about 15 minutes. Hundreds of thousands of the spicules exist at any given time. Spicules can extend out to 10,000 km above the photosphere. Spicules appear to be related to the Sun's magnetic field but the details are not understood.
The Corona

The Corona is the region above the chromosphere and the outer most region of the Sun. It is not spherical and the streams change over time. The corona extends out to millions of km. The density of the gas in the corona is very tenuous. Its emission spectra are from atoms that are highly ionized. It has a very high temperature (up to $2 \times 10^6$ K)
The Sun's Atmosphere

This composite image shows the Sun's atmosphere at different temperature. In visible light the 5800 K photosphere is visible. The UV images show features at 1 and 2 million K. Magnetic field lines are superimposed at the right.
The Solar Wind

The Sun's gravity holds the atoms of the photosphere and chromosphere. Because of the high temperature in the corona, some of the atoms and ions are moving at \(~1,000,000\) km/hr. These can escape the Sun's gravity and become the solar wind. The mass ejected as solar wind is about \(10^9\) kg/s. It is mainly electron, hydrogen and helium ions.
The dark areas in this image of the corona are thin low temperature regions known as corona holes. This corona holes are devoid of luminous gas. They offer an escape corridor for the solar wind. The Ulysses spacecraft flew over the north and south poles of the Sun. There are permanent corona holes over the poles. Ulysses measured an increased solar wind at the poles.
The Temperature of the Corona

The high temperature of the corona and chromosphere are not what we would expected. We expect the temperature to decrease as we move further away from the sun. Some recent evidence suggest that part of the heating of the corona is caused by spicules. These spicules are millions of degrees and shoot gas high speed particles 10,000 km into the corona. However this can not be the whole story concerning the heating of the corona. Sunspots also play a role.
The Sunspots

Sunspots are irregularly shaped dark regions on the photosphere. They vary in size but are typically about the size of the Earth. They are an active feature of the Sun. The dark region is called the umbra and the lighter surrounding area is the penumbra. Sunspots are cooler regions of the photosphere with the umbra having a temperature of ~4300K.

The Stefan-Boltzmann law gives a flux of only 30% of the amount of light compared to the surrounding photosphere. The lower image shows a group of sunspots.
Galileo used the motion of sunspots to determine the rotation rate of the Sun. Galileo's measurement was about 4 weeks. Later in the 1800s, sunspots showed that the Sun does not rotate as a rigid body. The equatorial regions rotate faster than the poles. This is the same differential rotation we saw with the Jovian planets. The equator rotates in about 25 days while the poles rotate about one every 35 days.
Sunspots do not appear at a constant rate but the number varies over time. Sunspots vary with a period of about 11 years. Sunspots also vary in location. At a Sunspot minimum the first appear at about $30^\circ$ north and south latitude. As the cycle reached a maximum sunspots appear closer to the equator.
Hale in 1908, showed sunspots are associated with large magnetic fields on the Sun. This spectrum of iron shows the absorption line split into three lines (the Zeeman effect) in the strong magnetic field in the region of a sunspot. This indicates a field 5000 times the magnetic field of the Earth.
The gas in the Sun is actually a plasma where the electrons move independently from the ions. A magnetic field deflects electrical charged particles. On the Sun where the magnetic field is particularly strong, the charged ions of the hot convection plasma are pushed away leaving a cooler region.

By taking images of the Sun at two different wavelengths which are slightly lower and slightly higher than the wavelength of a magnetically split spectral line, an image of the magnetic field can be produced called a magnetogram.
The Sun's Magnetic Cycle and Sunspots

Groups of sunspots look like giant bar magnets with a north and south pole. Hale discovered that there is a regularity in the magnetization of sunspot groups. As the Sun rotates, the first or 'proceeding members' are trailed by 'following members'. Hale compared the northern and southern hemispheres. He found the 'proceeding members' all had the same polarity in one hemisphere and the opposite polarity in the other hemisphere. In the northern hemisphere of the Sun with the north magnetic pole the 'proceeding members' all had a north magnetic polarity and in the southern hemisphere the proceeding members had a south magnetic polarity. Hale and his collaborator discovered the Sun's magnetic field completely reverses every 11 years. The hemisphere that has north proceeding members will reverse every 11 years. The Sun's pattern repeats only during two Sunspot cycles so astronomers call it the 22-year solar cycle.
The magnetic dynamo model uses two basic properties of the photosphere: differential rotation and convection. Differential rotation cause the magnetic field to wrap around the Sun. The field become concentrated at latitudes around the equator. Convection causes kinks that erupt through the photosphere where sunspots appear.
Magnetic Reconnection

Magnetic field lines and plasma move together. When convection pushes up plasma, it pushes up magnetic field lines as well. This explains why the chromosphere and corona is so hot. Observations show magnetic field arches $10^4$ km into the corona. If two arches come close to one another the field lines will re-arrange in a magnetic reconnection. This releases huge amounts of energy which heats the corona and chromosphere.
Prominences, Flares & Coronal Mass Ejections

The chromosphere is shown in this image using the H$_{\alpha}$ line. Plages are bright areas that form before sunspots where magnetic fields push up from the interior. The dark filaments are relatively cool and dense where parts of the chromosphere is pulled along with magnetic field lines as they arch upward. From the side they form prominences. Prominences can extend tens of thousands of km.
Prominences can extend tens of thousands of kilometers into space. Magnetic reconnection also causes violent solar flares. In minutes, the temperature is a small region may reach 5 million K. Vast amounts of radiation and particles are ejected. The most energetic flares can release $10^{30}$ joules of energy.
If a solar flare or coronal mass ejection is pointed at Earth, the plasma of electrons and ions can disrupt satellites and electrical equipment and communication equipment on the ground. Solar flares and coronal ejections are monitored to provide early warning.