THE SUN, OUR STAR

Profile of the Sun

Diameter:	1.4×10^9 m (110 Earth's diameter) (3.5 x Earth-Moon distance)
Mass:	2.0×10^{30} kg (3.3×10^5 x mass of Earth)
Average Density	1.4 gm / cm^3 (Density of water =1 gm / cm^3)
Effective Temperature:	5780K
Rotation period:	25.4 days (at Equator)
Luminosity:	3.8×10^{26} Watts (joules/s)
Age:	5×10^9 years
Spectral Type:	G2V
Surface Composition:	70% by mass is Hydrogen 28% by mass is Helium 1% by mass is Oxygen 0.4% by mass is Carbon 0.6% is other elements
Distance from the galactic center::	8kpc

We divide the Sun into 3 broad regions in which different physical processes dominate. These are further divided into subcomponents.

1. The Solar (or Stellar) Interior.

Core (Where the energy is generated)

Radiative zone (includes core)

Convective zone (outermost region of interior)

2. The Solar (or Stellar) Atmosphere.

Photosphere (where the light we see comes from)

Chromosphere

Corona (seen during a Solar eclipse)

In addition to these global zones, there are many local phenomenon:

(i) granulation caused by convection

(ii) coronal holes

(iii) sunspots

(iv) flares

(v) plages

(vi) filaments

(vii) prominences.

3. The Solar (or Stellar) Wind.

This `wind' extends out in to the Solar System and affects the Earth, the tails of comets, etc.

Energy Transport

In stars energy is generally transported in one of three ways:

1. Radiation.

Occurs when electromagnetic radiation moves from one place to another. Energy transport is by radiation in the Sun's core and inner 70% (in radius) of its interior.

Earthly examples:

When the Sun's light warms the ground or our skin;

When we are warmed by a fire;

When a microwave cooks something;

When we broil something in an oven there is partial radiative heating.

For radiation to transport energy from the core of the star to the surface a temperature gradient must exist. Temperature in central region must be higher than surface temperature. Energy **diffuses** to the surface.

2. Convection

Occurs when matter moves energy from one place to another. Energy transport occurs by convection in the outer 30% (in radius) of the Sun's interior.

Earthly examples:

When hot air rises;

When there is forced air heating in a house;

When a shady region outdoors gets warm.

3. Conduction

Occurs when energetic atoms (or particles) communicate their agitation to nearby cooler atoms by collisions. In very dense stars (like white dwarfs) energy transport is by conduction.

Examples:

When a metal spoon placed in a hot liquid heats up;

When any solid heats up.

The Solar Atmosphere

The Sun's atmosphere is divided into 3 zones whose properties are very different from those of the planets.

The Photosphere

The layer that we see is called the photosphere, and is considered to be the inner most part of the atmosphere. It lies next to the convective zone. As radiation from the Sun's interior makes its way toward the surface, ***it is absorbed for the last time in the photosphere and then emitted into space.***

Observations of the Sun therefore primarily reveal information about the photosphere.

e.g.

Temperature

Total energy emitted

Composition through the analysis of the strength of absorption lines.

Density structure through the analysis of the strength (and shape) of absorption lines.

The photosphere is very thin! Approximately 350 kilometers thick, or only 0.05% of the Sun's radius. It has an average temperature of **5,800K.** In the uppermost layers it falls to 4000K.

The photosphere radiates the spectrum of a G type main sequence star (Ch 19).

Granulation:

High spatial resolution observations of the Sun show a highly textured surface which is called granulation. The granules represent material bubbling up from the convective zone (ie convection) carrying energy into the photosphere.

Granules have a typical size of 1000km (approximately 1arcsec) and hence are difficult to study from the Earth.

The granular appearance arises because the rising and falling material have different temperatures (Application of Stefan Boltzmann Law). They differ by only a few hundred degrees.

Doppler measurements show that the bright inner region of the granules are rising upward, while the darker material at the boundaries is descending.

The Chromosphere

The chromosphere is a thin region 10,000 kilometers (10^4 km) thick which lies above the photosphere. It is best seen in the light of Hα [transition 3 to 2 in the Balmer series of Hydrogen].

It is not a shell which encloses the Sun (like the photosphere) but is a series of jets 700 km across and 7,000 km long which rise up off the photosphere at speds of approximately 20km/s. These jets are called ***spicules*** and they have lifetimes of 5 to 15 minutes. The spicules cover only 1 to 3% of the Sun's surface.

Organized convective cells which are rising and falling in the chromosphere can be seen in chromospheric light. Their motions can be studied spectroscopically by observing Doppler shifts. The convective cells are called ***supergranulation cells*** (30,000 km across) and they contain hundreds of smaller cells called ***granules***. Spicules tend to concentrate at the edges of supergranules.

Chromospheric matter has a temperature of about 15,000 degrees Kelvin, *but* it does not contain much "heat" energy because it is so tenuous.

The Corona

The corona is the outermost part of the Sun's atmosphere and it extends into the solar wind throughout the solar system. It is very inhomogeneous and tenuous (an excellent vacuum on Earth)!

Gas in parts of the corona has a temperature of 2 million degrees Kelvin (2×10^6 K) but because it is very tenuous it contains little heat energy. **The hot parts of the corona emit X-rays,** while the cooler parts (called coronal holes) do not. Emission lines of highly ionized species (eg Iron which has lost 13 electrons) are seen.

The Corona can be directly observed in the visible spectral region during a total Solar eclipse, or using a coronograph.

3. The Solar Wind

The Solar corona, and ions associated with flares, expand out into space to form the solar wind. It is an extremely low density wind --- near Earth it has only about 5 particles per cubic cm. Its average velocity near the Earth is 500km/s.

The presence of the Solar wind is known from observations of comets' tails. Since the Solar wind emanates from the Sun, a comet's tail is seen to always point away from the Sun because the Solar wind is pushing the tail in that direction.

The Solar wind has a pronounced effect on the Earth, *especially* when the Sun *is in an active state.*

Charged particles (ions) from flares reach the Earth in a few hours and cause the aurora (borealis and australis). The charged particles excite atmospheric molecules which emit visible light when they fall back to their ground state.

Extremely energetic flares may cause disruptions in radio transmission and even power black outs.

Plasma

A hot mixture of electrically charged particles.

Because of the charge particles, a plasma interacts strongly with magnetic fields.

Most of the matter in the Universe is in the form of a plasma.

Solar Activity

Most of the rich surface activity seen on the Sun's surface is associated with magnetic fields.

Some of the local phenomenon affected by magnetic fields are:

sunspots

plages

flares

filaments and prominences.

When the Sun's magnetic field activity is strong the Sun is said to be active.

Solar Cycle

The magnetic fields vary in strength with an 11 year cycle (the cycle is actually 22 years if the reverse in polarity of the magnetic field is considered). Many local phenomenon on the Sun grow stronger then weaker over this same time period.

The best way to observe the Sun's 11 year magnetic field cycle is to count the number of sunspots. **When there are more sunspots, magnetic activity is stronger.**

Note:

Observations show that the 11 year Sunspot cycle is far from regular. The period varies from 7 to 15 years, and the number of sunspots varies from one cycle to the next.

Sunspots.

Sunspots are magnetic storms on the Sun. Magnetic field in the sunspot can be 1000 times greater than in quiet sun. Sunspots generally occur in pairs - one is magnetic North, the other magnetic South (sometimes in large groups).

Size:

Typically 10,000km, about the diameter of the Earth.

Lifetimes:

1 to 100 days (typically 50 days for large group)

Umbra:

Dark central region of sunspot. Its temperature is around 4500K (Normal photosphere has T=5800K)

Penumbra

Grayer area around the umbra, with a temperature a few hundred degrees lower than the surrounding photosphere.

The lower temperatures explain why the sunspots look dark -- *they emit less energy than the surrounding regions* (the Stefan-Boltzmann Law--- Ch. 11).

By studying the motion of sunspots on the Sun we find that the Sun rotates once every 25 days at the equator, but once every 30 days at its poles. This **differential rotation** helps create the Solar magnetic fields.

The differential rotation is also a key ingredient in generating the Solar Cycle. The differential rotation "winds" up the magnetic field below the sun's surface. Kinks in the windings appear as Sunspot pairs. When the winding/kinking becomes too large, the Magnetic field collapses and a new cycle begins.

At the beginning of an active cycle, sunspots tend to originate at moderate latitudes. At later times in the cycle they originate closer to the equator. Gives rise to **Butterfly Diagram**.

Flares.

A rapid brightening of a small area of the surface of the Sun, generally in the neighborhood of a sunspot.

Typical lifetime is 20 minutes.

Very energetic events which can affect radio reception on Earth, and cause “the Northern Lights”.

Temperatures can reach 10^8 K

It is associated with visible emission lines, x-ray emission, and radio emission. Can dominate radio emission (by factor of 1000)

Plages.

Plages are bright regions near sunspots which emit strong hydrogen spectral lines. They tend to compensate for the lower energy output of the Sun spots in the photosphere.

Filaments and Prominences.

Filaments are string-like structures that may extend up to 100,000 km (8 Earth diameters) across the surface of the Sun. In spectral lines of hydrogen they are seen as dark features because they absorb the light from the background photosphere.

When we see a filament protrude off the edge of the Sun it is called a prominence. Emission lines are then observed.

The Solar Interior

In the stellar core, energy is generated by nuclear reactions. Because the energy (in the form of electromagnetic radiation) is absorbed and emitted by the Sun's matter *MANY MANY TIMES* it takes the energy **nearly 1million years** to make its way to the Sun's surface (photosphere).

During this absorption and emission, the wavelengths of the radiation are changed. *Gamma rays,* generated in the Sun's very hot core, eventually become *visible photons* emitted from the cooler material in the photosphere.

Because the properties of the radiation coming from the Sun's interior are altered by absorption and emission, it is very difficult to directly study what is going on in the Sun's interior.

Consequently, **most** of our knowledge of the Sun's interior structure comes from theoretical calculations.

e.g.

Models show that the *density*, *temperature*, and *pressur*e of the Sun's matter all *increase* as one moves from the Sun's surface toward its core

There are two methods of making observations which tell us about the Sun's interior structure:

(a) We observe Solar neutrinos generated in nuclear reactions.

(b) We observe Solar oscillations (`Solar seismology') (see below).

In summary the Sun's interior consists of 3 parts:

1. The Core

Encompasses 30% of the Sun's interior. Nuclear energy is generated only in the core. Energy transport is by radiation.

2. Radiative Zone.

Encompasses 70% (in radius) of the Sun's interior and includes the core. **Energy transport is by radiation**.

3. Convective Zone.

Encompasses the remaining outer 30% (in radius) of the Sun's interior. *No energy is generated* here, and **energy transport is by convection**.

Pressure

Pressure in a gas arises from the random motion of the molecules that make up the gas. For an ``ideal'' gas

Pressure = Density x Temperature x a constant

$$P = nkT$$

where n = particles per unit volume

k= Boltzmann's constant

Pressure can be thought of as a ***force per unit area***.

Consider a box of gas particles.

Every time a molecule hits a wall both it and the wall experience a force.

Clearly the force acting on the wall will be higher if more particles collide with the wall in a given time --- i.e. if the density of gas is higher or if the particles are moving faster.

The force will also be higher if the particles have more energy --- i.e. if the temperature is higher.

NB: Temperature and Heat energy are not the same.

The temperature of a gas refers to how fast the atoms, ions, or molecules that make up the gas are moving. (Referring only to random motions - not systematic)

It is possible for a gas to have a very high temperature (because its parts are moving randomly very quickly) but to have very little heat energy (if the gas is tenuous, i.e. not dense).

Hydrostatic Equilibrium

The Sun is in equilibrium --- it is not collapsing or expanding.

The inward gravitational forces are exactly balanced by the outward forces of gas pressure --- a balance called hydrostatic equilibrium.

In the Sun, the Pressure in its core must be great enough to counteract the gravitational attraction. The **high pressure** is generated by **high temperatures.**

Knowing only the Mass and Radius of the Sun it can be shown that

$$P > 4.5 \times 10^8 \text{ Earth Atmospheres}$$

where P is the pressure at the center of the Sun. Result requires no knowledge of Sun's composition, or its state.

Definitions:

Proton (^1H)

Simply a hydrogen nucleus.

Alpha particle (^4He)

Helium nucleus (2 protons plus 2 neutrons).

Positron (e^+)

Form of antimatter.

It is the "anti-particle" of the electron.

When positrons are created they immediately meet electrons and annihilate each other, creating gamma rays.

Neutrinos (ν)

Almost invisible particles that carry a tiny amount of energy and angular momentum. A neutrino escapes the interior of the Sun immediately (2 sec) after it is created, because the Sun's matter is transparent to neutrinos.

Stellar Energy Generation

The Sun is losing energy. This energy must be replaced, otherwise the Sun will cool, causing the pressure to drop. If the pressure drops the Sun will begin to collapse, since the pressure forces will no longer be large enough to counteract gravity.

NB

If the Sun generated energy by burning coal, it would last only a few thousand years.

If the Sun was collapsing (ie not in hydrostatic equilibrium) the gravitational energy released in the collapse would allow the Sun to shine for 10^6 years.

But Sun is at least 4.5 billion years old (Age of Earth)

Only possible energy source is **Nuclear Fusion.**

In Nuclear Fusion, mass is (effectively) converted into energy. If 1gm of material were converted to energy, it would release 20 kilotons of energy [a small nuclear weapon).

Equation relating mass (m) and energy (E) is

$$E = m c^2$$

where c is the speed of light (Einstein's equation) .

Nuclear Fusion

The joining of 2 elements of low atomic number (eg Hydrogen) to make a heavier element. The mass of the new element is LESS than the combined mass of its constituents. In the process energy is liberated.

(NB. In Nuclear Fission an atom of high atomic number, like Uranium, is split into 2 lighter atoms liberating energy. The 2 new atoms have LESS mass than the initial atom.)

In the Sun the main energy producing nuclear reaction is

$$4\ {}^1H \text{ gives } {}^4He + \text{energy}$$

Much of the energy produced is in the form of Gamma-Rays (very high energy electromagnetic radiation). The gamma rays are responsible for heating a star's core.

Note:

Mass of $4\ {}^1H$ atoms $= 6.6943 \times 10^{-24}$ gm

Mass of $1\ {}^4He$ atom $= 6.6466 \times 10^{-24}$ gm

The reaction does not occur directly, but instead occurs in a series of steps. In the Sun, these steps (3 in all) are called the ***Proton-Proton Chain***.

Nuclear Fusion can only occur at very high temperatures, hence it can only occur in the inner core of the Sun.

First step in proton-proton chain are

$$^1H + {}^1H \rightarrow {}^2H + e^+ + \nu$$

This reaction can only occur at high temperature, due to the repulsive force between the protons. The protons need to travel extremely fast so that when they collide they can get very close together. If they are close enough, the repulsive force is overwhelmed by the **STRONG NUCLEAR FORCE**.

The STRONG NUCLEAR FORCE is the force that holds nuclei together --- it only acts on scales the size of nuclei.

Subsequent steps are:

$$^1H + {}^2H \rightarrow {}^3He + \gamma$$

$$^3He + {}^3He \rightarrow {}^4He + {}^1H + {}^1H$$

During each step energy is liberated.

The Solar Neutrino Experiment

One way to check theoretical calculations of the Sun's core is to count the number of neutrinos coming from the core of the Sun.

An experiment to observe **neutrinos** has been set up 1.5 km underground in the Homestake gold mine in South Dakota. 100,000 gallons of liquid cleaning fluid (perchloroethylene, C_2Cl_4) have been placed in a tank in this mine. Theoretically, in a tank this size, a neutrino should interact with a chlorine isotope to form a radioactive argon atom once each day.

However, only about one radioactive argon atom is produced every three days.

This has led to a number of suggestions:

(a) particle theory is wrong or

(b) the experimental techniques are wrong or

(c) models of the Sun are incorrect.

New, more sensitive, neutrino detection experiments are being performed, and will (hopefully) supply the answer in a few years.

Helioseismology (Solar Seismology)

The study of solar oscillations to determine constraints on the Sun's structure.

In the 1960's it was discovered that the Sun vibrates like a complex set of bells. These vibrations are the result of internal pressure (sound) waves "trapped" in the stellar interior.

From the nature of the surface vibrations (oscillations) it is possible to study conditions far below the Sun's surface. eg.

Size of the convective zone.

Rotation rate below surface.

The oscillation is known as the "5 minute oscillation" but is not a single frequency, but the supersition (ie addition) of millions of individual patterns of vibration. Periods range from minutes to hours.

Observations are best made from the south pole in summer -- get long runs uninterrupted by night. Alternatively, use many telescopes at different locations (GONG project).

Summary of Sun's Layers

Layer	**% Mass**	**Radii (R_{sun})**	**T (K)**	**Density (gm/cm^3)**
core	40	0 to 0.28	1.5×10^7	160
R.E.	59	0.28 to 0.72	4×10^6	2
C.E.	1	0.72 to 1.0	1×10^6	0.01
Phot.	-	1.0	5780	10^{-9}
Chrom.	-	-	10,000	low

NB.

Values refer to center of core, and at the midway point in the outer layers.

T = Temperature

R.E. = Radiative Envelope

C.E. = Convective Envelope

Photosphere has a height of only a few hundred km (less than 0.05% of the solar radius)

Chromosphere has a thickness of approximately 1.5% of the radius of the sun.