The sun and the solar corona

Introduction

The Sun of our solar system is a typical star of intermediate size and luminosity. Its radius is about 696000 km, and it rotates with a period that increases with latitude from 25 days at the equator to 36 days at poles. For practical reasons, the period is often taken to be 27 days. Its mass is about 2×10^{30} kg, consisting mainly of hydrogen (90%) and helium (10%). The Sun emits radio waves, X-rays, and energetic particles in addition to visible light. The total energy output, solar constant, is about 3.8×10^{33} ergs/sec. For further details (and more accurate figures), see the table below.
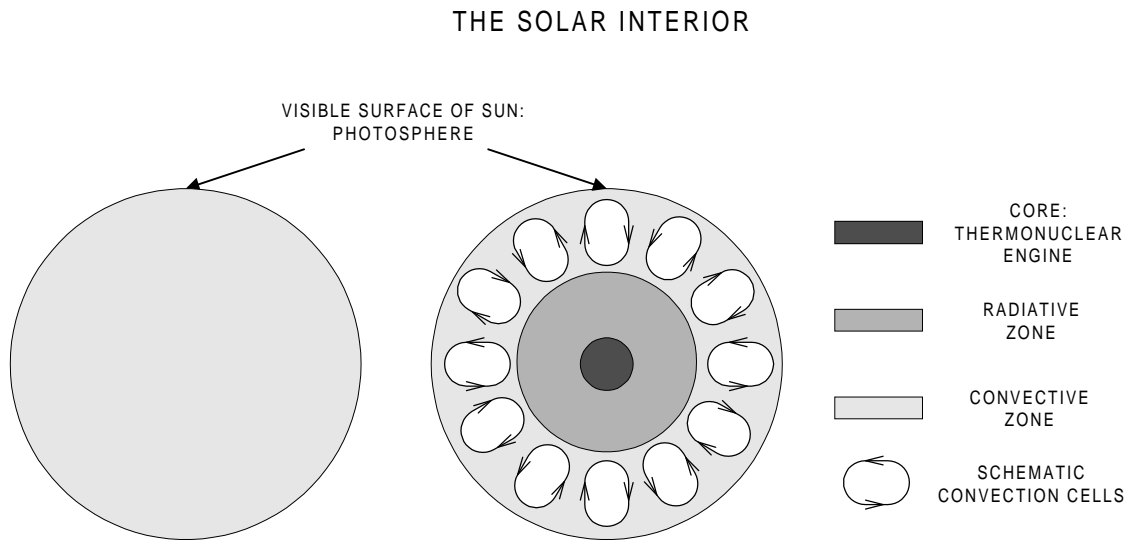.

THE SOLAR INTERIOR

Figure 1: Schematic representation of the regions in the interior of the Sun.

Physical characteristics		Photospheric composition		
Property	**Value**	**Element**	**% mass**	**% number**
Diameter	1,392,530 km	Hydrogen	73.46	92.1
Radius	696,265 km	Helium	24.85	7.8
Volume	1.41×10^{18} m^3	Oxygen	0.77	
Mass	1.9891×10^{30} kg	Carbon	0.29	
Solar radiation (entire Sun)	3.83×10^{23} kW	Iron	0.16	
Solar radiation per unit area on the photosphere	6.29×10^4 kW m^{-2}	Neon	0.12	0.1
Solar radiation at the top of the Earth's atmosphere	1,368 W m^{-2}	Nitrogen	0.09	
Mean distance from Earth	149.60×10^6 km	Silicon	0.07	
Mean distance from Earth (in units of solar radii)	214.86	Magnesium	0.05	

In the interior of the Sun, at the centre, nuclear reactions provide the Sun's energy. The energy escapes by first by radiation, through the radiative zone. At a distance of about 0.7 times the solar radius from the centre, the thermal gradient increases above the value at which convective instability sets in; the heat can only be evacuated to the surface by material motions. A set of complex convective cells are set up, which bring the heat, material and magnetic fields to the Sun's surface, the photosphere.

SPACE PHYSICS ADVANCED STUDY OPTION HANDOUT

The solar interior is separated into four regions by the different processes that occur there. Energy is generated in the core. This energy diffuses outward by radiation (mostly gamma-rays and x-rays) through the radiative zone and by convective fluid flows (boiling motion) through the outermost convection zone. The thin interface layer between the radiative zone and the convection zone is where the Sun's magnetic field is thought to be generated.

The solar interior 1: The core

The Sun's core is the central region where nuclear reactions consume hydrogen to form helium. These reactions release the energy that ultimately leaves the surface as visible light. These reactions are highly sensitive to temperature and density. The individual hydrogen nuclei must collide with enough energy to give a reasonable probability of overcoming the repulsive electrical force between these two positively charged particles. The temperature at the very centre of the Sun is about 15,000,000° C and the density is about 150 g/cm³ (about 10 times the density of gold or lead). Both the temperature and the density decrease as one moves outward from the centre of the Sun. The nuclear burning is almost completely shut off beyond the outer edge of the core (about 25% of the distance to the surface or 175,000 km from the centre). At that point the temperature is only half its central value and the density drops to about 20 g/cm³.

The most important nuclear process generating energy inside the core of the sun is the proton-proton reaction. Three branches are involved, starting with the same chain of two reactions, but then following different paths as shown in the table below.

	$^1H + {}^1H \rightarrow {}^2H + e^+ + \nu_e$
	$^1H + {}^2H \rightarrow {}^3He + \gamma$
Branch I	$^3He + {}^3He \rightarrow {}^4He + {}^1H + {}^1H$
Alternatively, Branches II and III	$^3He + {}^3He \rightarrow {}^7Be + \gamma$
Branch II	$e^- + {}^7Be \rightarrow {}^7Li + \nu_e$
	$^1H + {}^7Li \rightarrow {}^4He + {}^4He$
Branch III	$^1H + {}^7Be \rightarrow {}^8B + \gamma$
	$^8B \rightarrow {}^8Be* + e^+ + \nu_e$
	$^8Be* \rightarrow {}^4He + {}^4He$

In the process of fusing hydrogen to form helium, about 25 MeV energy is generated, the energy equivalent of the mass difference between four protons and a ^4He nucleus. In the Sun, Branch I generates about 85% of the total energy, Branch II about 15%, with Branch III only contributing about 0.02%. (An additional reaction, the carbon-nitrogen cycle, only operates in stars hotter than the Sun.) The timescales for these reaction to take place is interesting. Given the temperature and pressure conditions calculated for the solar core, half of the hydrogen (^1H) in the core is converted into deuterons (^2H) in 10^{10} years, because for the fusion of two protons their mutual distance must be less than the proton radius and then one of the protons must undergo a spontaneous β-emission (emitting an electron to turn it into a neutron). Deuterons, on the other hand, can capture a proton within only a few seconds, to generate a ^3He nucleus. The last step in the Branch I chain, the fusion of two ^3He nuclei, is again long, with a timescale of 10^6 years.

The nuclear reactions also produce neutrinos. Neutrinos pass right through the overlying layers of the Sun and can be detected on Earth, using large and complex detectors. The neutrino flux that has been now quite reliably measured on earth is about 1.6 SNU (1 SNU = 10^{-36} neutrino absorptions/sec/target

atom in the detector) is about a third of what was expected. This problem of the missing neutrinos has been a great mystery of solar models, leading to many conjectures as to the reason for the discrepancy. Finally, it seems that the problem has been resolved by better understanding the life cycle of the different neutrinos: about two thirds of the neutrinos (the missing ones) emitted from the nuclear reactions from the Sun's core turn into different kinds of neutrinos (tau and mu neutrinos) on the way to Earth that would not be detected by the experimental set-ups used.

The solar interior 2: The Radiative Zone

The radiative zone extends outward from the outer edge of the core to the interface layer at the base of the convection zone (from 25% of the distance to the surface to 70% of that distance). The radiative zone is characterised by the method of energy transport - radiation. The energy generated in the core is carried by light (photons) that bounces from particle to particle through the radiative zone. Although the photons travel at the speed of light, they bounce so many times through this dense material that an individual photon takes about a million years to finally reach the interface layer. This can be estimated as follows.

Photons emitted in the nuclear reactions are absorbed and re-emitted or scattered frequently so that their motion can be described as random.

The density drops from 20 g/cm³ (about the density of gold) down to only 0.2 g/cm³ (less than the density of water) from the bottom to the top of the radiative zone. The temperature falls from 7,000,000° C to about 2,000,000° C over the same distance.

The solar interior 3: The tachocline

The tachocline is the interface layer between the radiative zone and the convective zone. The fluid motions found in the convection zone slowly disappear from the top of this layer to its bottom where the conditions match those of the calm radiative zone. This thin layer has become more interesting in recent years as more details have been discovered about it. It is now believed that the Sun's magnetic field is generated by a magnetic dynamo in this layer. The changes in fluid flow velocities across the tachocline (shear flows) stretch the magnetic field lines and increase their strength. The velocity shear arises from the difference between the uniformly (rigidly) rotating Radiative Zone, and the differentially rotating overlying Convection Zone, which rotates slower as the latitude increases (as described for the rotation of the visible Sun below). There also appears to be sudden changes in chemical composition across this layer.

The solar interior 4: The Convection Zone

The convection zone is the outermost layer of the Sun. It extends from a depth of about 200,000 km up to the visible surface, the photosphere. At the base of the convection zone the temperature is about 2,000,000° C. This is "cool" enough for the heavier ions (such as carbon, nitrogen, oxygen, calcium, and iron) to hold onto some of their electrons. This makes the material more opaque so that it is harder for radiation to get through. This traps heat that ultimately makes the fluid unstable and it starts to "boil" or convect. These convective motions carry heat quite rapidly to the surface.

In fact, convection sets in when the radial gradient of the temperature is greater than the adiabatic temperature gradient (this is the Schwartzschild criterion):

$$\left| \frac{dT}{dr} \right| > \left| \left(\frac{dT}{dr} \right)_{ad} \right|$$

This means that heat from below can no longer transmitted towards the surface by radiation alone, and that heat is transported by material motion. But the fluid expands and cools as it rises. At the visible surface (at the photosphere) the temperature has dropped to 5,700° K and the density is only 0.0000002 gm/cm³ (about 1/10,000th the density of air at sea level). The convective motions themselves are visible at the surface as granules and supergranules.

The photosphere

The photosphere is the visible surface layer of the Sun where photons last interact with atoms before escaping from the Sun; the temperature of the photosphere is 5,700 K; its main constituents are given in the table above. The photosphere is covered by granulation, which represents the tops of convective cells rising from the interior. Two or three characteristic cell sizes are distinguished: granules are bright features of order of hundreds to a thousand km across, with lifetimes of about 10 minutes, surrounded by dark edges, representing the downflow of convection cells; supergranules are of order 30,000 km across, with lifetimes of 12 to 24 hours; giant cells, a fraction of the solar radius across, are apparently, occasionally seen, but their existence is still in doubt. The boundaries of supergranules contain a concentration of magnetic fields, swept there by horizontal motions in the supergranule cells. This concentration of magnetic fields gives rise to the chromospheric network in the layer above the photosphere, the chromosphere.
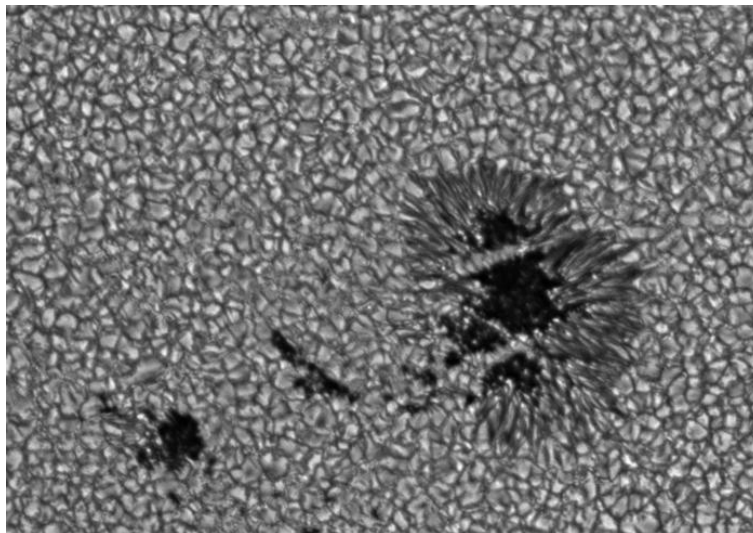

Figure 2. Photograph of a sunspot, showing the dark interior (the umbra) and the less dark surround, with striations (the penumbra). The sunspot is surrounded by photospheric granulation.

Sunspots are sites of very strong magnetic fields (thousands of gauss, or about 0.1 to 0.3 T) that are cooler by about 2000 K than the rest of the photosphere. This is why they appear dark against the photosphere. A medium size sunspot is bigger than the Earth's diameter. Small sunspots (such as the one shown in Fig. 2) may only last days, larger sunspots and sunspot groups may last several months. Sunspots usually come in groups with two sets of spots. One set will have positive or north magnetic field while the other set will have negative or south magnetic field. The field is strongest in the darker parts of the sunspots - the umbra. The field is weaker and more horizontal in the lighter part - the penumbra. Sunspots have been, historically, important manifestation of variable solar activity. The fluctuation in their number with a period of about eleven years provides a record over more than 250 years of the solar cycle (see Fig. 6). We now know that solar activity is a very complex process, involving the whole Sun and its atmosphere, but sunspot numbers retain their value as a simple measure of solar activity.

SPACE PHYSICS ADVANCED STUDY OPTION HANDOUT

The Sun rotates around its axis, but different features on the Sun and its atmosphere rotate at different rates, mainly dependent on heliolatitude. The equatorial photospheric rotation period is taken to be 25.4 days, corresponding to a sidereal rotation rate of 2.86 x 10^{-6} rad s^{-1} or 14.158 º/day. (The sidereal rotation period refers to the time taken by a point on the Sun's equator to rotate 360º around the Sun's rotation axis. As the Earth rotates around the Sun in the same direction as the Sun rotates around its axis, a given point on the Sun's equator takes more than a sidereal rotation period to reach the same point as seen from the Earth; this is the synodic rotation period, about 26.8 days. For information, the Earth's orbital rotation rate is 0.9865 º/day.) A general formula for the differential rotation of the Sun's surface as a function of latitude λ is

$$\Omega = A - B\sin^2\lambda - C\sin^4\lambda \text{ º/day}$$

where Ω is the rotation rate, A, B and C are constants determined by following the motion of different tracers on the Sun. The values determined spectroscopically are A = 14.58, B = 1.70 and C = 2.36. Different tracers give somewhat different values; and some features in the corona, such as coronal holes (see below) are often observed to rotate at the equatorial rate at all latitudes.

Helioseismology and the Sun's interior

How do we know about the Sun's interior? In fact, solar (and consequently) stellar models have been established by purely theoretical considerations, based on the measured energy output (luminosity), radius and mass, using of course all the applicable laws of physics. Making some simplifying assumptions, such as spherical symmetry, no rotation and no magnetic fields, basic models of the Sun's internal structure were developed. Given further assumptions about the chemical composition, solving equations that involve conservation of mass and momentum, as well as the laws of thermodynamics, variations of the key parameters: density, temperature and pressure with radius can be deduced. But unless we find a way to "see" inside the Sun, to verify the calculations, we cannot be certain that the model deduced with its many assumptions is anywhere near correct.

Fortunately, a very powerful way has been found. In the early 1960s, solar observers noticed oscillatory motions on the solar surface; these were explained as the combination of many acoustic standing waves that imparted small amplitude up-down motions of material in the photosphere that could be detected by the minute Doppler shifts in the frequency of spectral lines or even in minute oscillations in luminosity. It was then also recognised, that the acoustic waves that propagated in the solar interior could be used to deduce the properties of the medium through which these waves propagated. This is also the way in which the interior of the Earth is studied, by the analysis of the propagation of waves generated by the shocks produced by Earthquakes. This is why the new science is called helioseismology, or seismology of the Sun.

Since the Sun is a ball of hot gas, its interior transmits sound very well. It is generally believed that convection near the surface gives rise to vigorous turbulent flows that produce a broad spectrum of random acoustical noise. The dominant part of this noise is in the range with periods in a two-octave span centered on five minutes, with frequencies around 3 mHz. Furthermore, since the Sun is essentially spherical, it also forms a spherical acoustical resonator with millions of different normal modes of oscillation. Due to the waves' long life times, destructive interference filters out all but the resonant frequencies, transforming the random convective noise into a very rich line spectrum in the five-minute range. Thus, convection acts rather like a random clapper causing the Sun to ring like a bell. The resulting oscillations are pressure waves or *p*-modes.

The oscillation modes are trapped in spherical-shell cavities starting essentially at the visible surface and extending inward. The outer boundaries are defined by the abrupt change in sound speed associated with the steep temperature gradient in the superadiabatic region just below the surface. The inner boundaries result from the refraction of the waves back toward the surface, caused by the inwardly increasing sound

speed (essentially, temperature). Like any spherical oscillator, the angular component of the wave function of these five-minute oscillations is described by the spherical harmonics, characterized by the degree and azimuthal-order quantum numbers, l and m.

While the outer limits of all of the cavities are confined to a narrow region just below the photosphere, the depth of a given cavity depends on both the oscillation frequency and the spherical-harmonic degree l of the associated mode. Consequently, there are modes whose entire cavities are confined very near the surface, while others extend much deeper, even reaching the centre of the Sun itself. This leads to the very large number of oscillation modes. Depending on the frequency and degree, these modes sample different, but overlapping, regions of the solar interior.

The precise frequency of a particular cavity depends intimately on the thermodynamic, compositional, and dynamic state of the material in the cavity. Consequently, the large number of resonant modes makes it possible to construct extremely narrow probes of the temperature, chemical composition, and motions throughout the interior of the Sun. While the physics is rather different, helioseismology uses acoustic waves to probe the interior of the Sun in a way roughly analogous to medicine using x-rays to do a CAT (Computer-Assisted Tomography) scan of the human body.

Physically and mathematically, one can understand the oscillation modes using spherical harmonics: l, and m, and n values. The spherical harmonic functions provide the nodes of standing wave patterns. The order n is the number of nodes in the radial direction. The harmonic degree, l, indicates the number of node lines on the surface, which is the total number of planes slicing through the Sun. The azimuthal number m, describes the number of planes slicing through the Sun longitudinally.
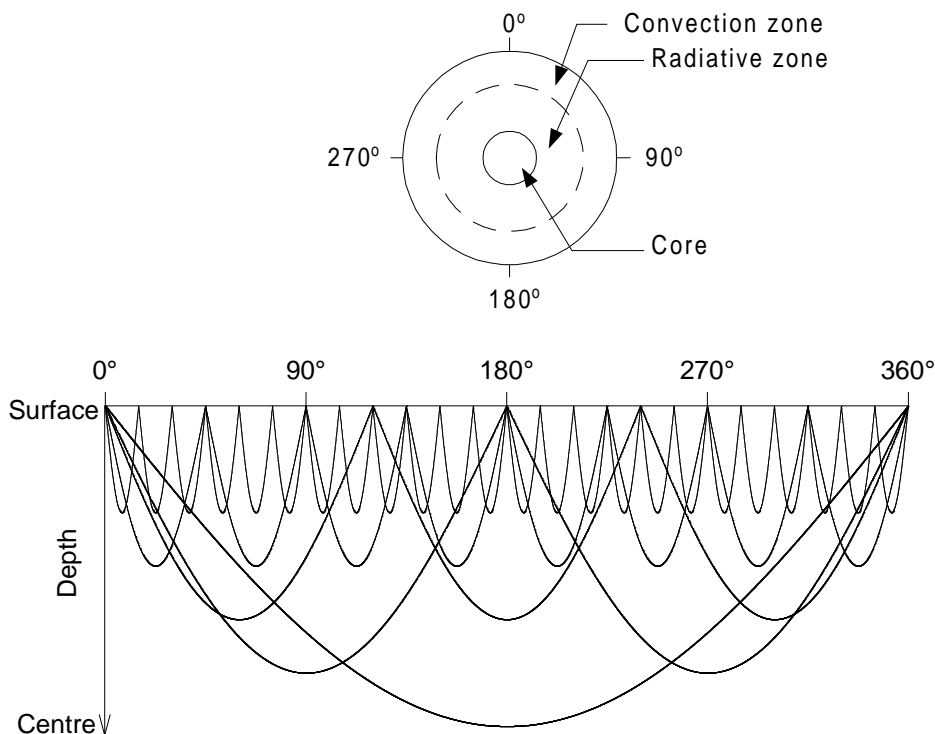

Figure 3. A schematic illustration of the waves that penetrate to different depths in the Sun and whose propagation characteristics provide information on the different regions in the solar interior. The lower part of this figure represents, horizontally, the solar surface.

The solar atmosphere

Above the photosphere, the temperature first falls to about 4,300 K, but then rises through the chromosphere, and then in particular through the transition region, to reach the temperature of the corona which is between 1 and 2 million K. This is illustrated in Fig. 4 below. Note that the thickness of the transition region is only a few hundred km, yet through it the temperature rises from about 10,000 K to in excess of a million K.

The temperature of a 1 eV electron (i.e. the temperature corresponding to its thermal velocity) is 1.1604×10^4 K. This means that the energy of an electron in a 2 million K plasma is 172 eV. (The thermal velocity of an electron is $5.50 \times T^{0.5}$ km s^{-1} .) This is much greater than the ionisation potential for hydrogen (13.6 eV) and for helium (25 eV for the first ionisation, 54 eV for the second). The high temperatures in the corona mean that all hydrogen and helium is completely ionised, and that many of the heavier atoms are at least partially ionised.

The solar atmosphere above the photosphere is highly non-uniform. It consists of a plasma, mostly electrons and protons, with a small percentage of ionised helium and at least partially ionised heavier ions. Its electrical conductivity is very high (it can even taken to be infinity) and it is shaped by the structure of the magnetic fields in the atmosphere. In the chromosphere, there is a network along which spicules (upward shooting jets of plasma) can be observed. The magnetic field is enhanced in the active regions, which are large regions which are hotter than their surroundings.
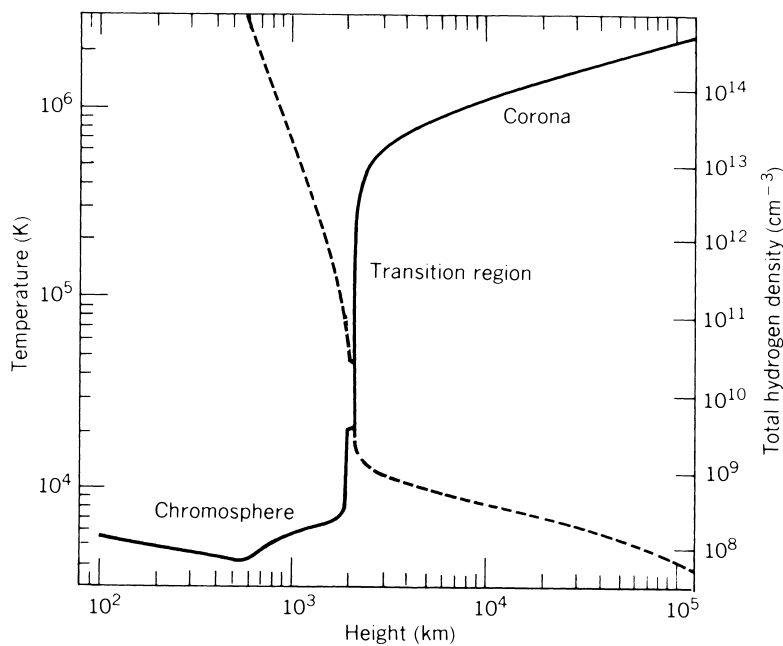

Figure 4. "Average" temperature and electron number density of the solar atmosphere as a function of height above the photosphere.

The solar corona consists of very tenuous plasma. Its structure is determined by the coronal magnetic field which is an extension of the solar surface magnetic fields into the solar atmosphere, as illustrated in the figures in the section below. The hotter and more dense parts of the corona (two million K) are contained in complex magnetic loop structures, with their footpoints anchored in the photosphere. The cooler, less dense parts of the corona, called coronal holes (because they show up as darker regions in x-ray pictures of the corona) have temperatures about 1.2 million K; magnetic field lines in coronal holes are open, they are anchored only at one end in the photosphere, but the magnetic flux - and the field lines - are carried out into interplanetary space by the solar wind.

Features occurring above the Sun's surface (photosphere)	
Chromospheric features	**Coronal features**

Chromospheric Network
  weblike pattern formed by magnetic field lines related to supergranules
Plage
  bright patches surrounding sunspots and associated with concentrations of magnetic field lines
Prominences/Filaments
  dense clouds of material suspended above the surface of the Sun by magnetic field line loops, called prominences when seen on the limb of the Sun, otherwise filaments; can remain quiet for days or weeks, but can also erupt within few minutes
Spicules
  small, jet-like eruptions in the chromospheric network lasting a few minutes only
Solar flares
  huge explosions with time scales of only a few minutes
	Coronal Holes
	  source of high-speed solar wind
	Coronal Loops
	  closed magnetic field line loops around sunspots and active regions; can last for days or weeks if not associated with solar flares
	Coronal Mass Ejections (CMEs)
	  huge bubbles of gas ejected from the Sun over the course of several hours
	Helmet Streamers
	  source of low-speed solar wind; network of magnetic loops with dense plasma connecting the sunspots in active regions, typically occurring above prominences
	Polar Plumes
	  long thin streamers associated with open magnetic field lines at the poles

The solar corona

At times of total eclipse, observations of the corona are possible because radiation from the solar disk is masked by the Moon. What is normally observed is the so-called K-corona. The white light from the corona is due to Thomson scattering of photospheric light by free electrons in the coronal plasma. The intensity ratio of light from the corona (close to the solar surface) to light from the photosphere is less than 10^{-5}, this is why the corona can only be seen when the solar disk is blocked out. The visible structure of the corona during eclipses is due to the variations of the total electron content in the corona, i.e. the integrated electron density along the line-of-sight.

The corona is known to be hot, because it also emits radiation in some spectral lines which were discovered to originate in electronic transitions of highly excited and highly ionized ions of heavy elements, for instance FeX and FeXI (respectively iron atoms from which 9 and 10 electrons have been stripped by ionization). Many of these lines correspond to "forbidden transitions", not following the normal selection rules, due the highly complex interaction of the electronic system in the ions which can only result from the very high temperatures.

Given that many of these spectral lines are in the UV or extreme UV (EUV), where the emission from the photosphere is much reduced, coronal observations can now be made even against the solar disk, with high resolution spectrographs from space.

The corona is characterized by complex plasma and magnetic structures. Essentially, there are two basic structural elements in the corona: magnetically "closed" and magnetically "open". What is meant by this can be illustrated using the magnetic field of a dipole. The field lines are as shown in the illustration here: all field lines "return" to the dipole, they are closed. Maxwell's equation:

$$\nabla \cdot \mathbf{B} = 0 \text{, or alternatively, } \int (\mathbf{B} \cdot \mathbf{n}) dS = 0 \text{ (if integrated over a closed surface } S)$$

expresses the fact that the net magnetic flux through a closed surface is zero. If we consider the surface S around the dipole (see Fig. 5), some of the field lines are "open" on the surface, i.e. they cross the surface, others are completely inside the surface and are therefore "closed". It is in this sense that we describe structures in the corona as open or closed. The difference is that, above the corona, the solar wind drags out the open magnetic field lines into the heliosphere, so close to the sun, the field lines are distorted as shown in Fig. 6.
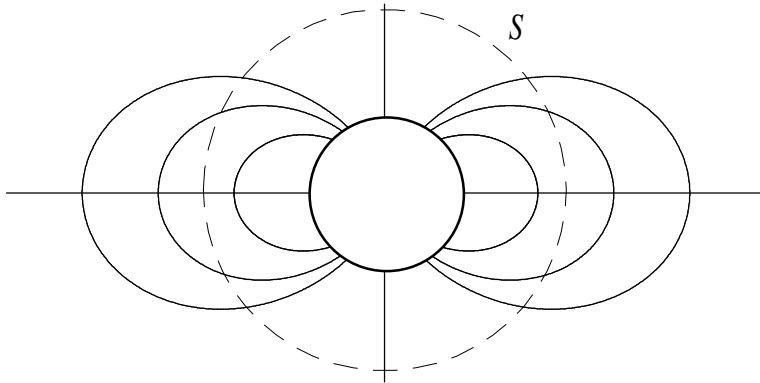

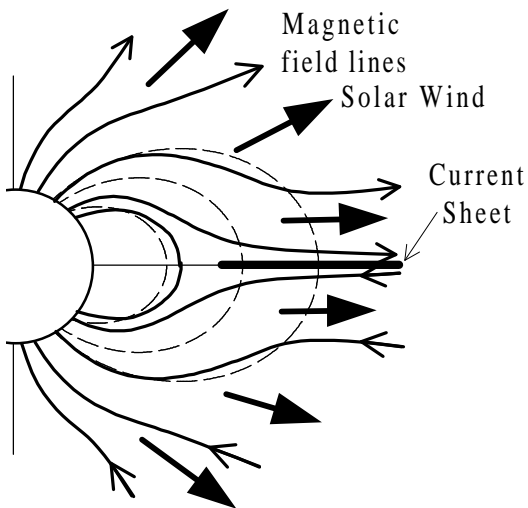Figure 5. Schematic representation of a dipole with a source surface S.

Figure 6. The flow of the solar wind distorts the nominally dipole magnetic field lines as the field is carried away from the corona. Close to the equator, the field lines are stretched out so that opposite polarity field lines are close to each other, separated by a current sheet in the equatorial plane.

There are three concepts that need to be considered here. The first is that the field lines are carried away in the solar wind, because they become "frozen into" the infinitely conducting solar wind plasma. The second is that the field lines generally point away from the Sun in one (northern or southern) hemisphere and point towards the Sun in the other hemisphere. This is the general structure of the corona (and the heliosphere) near solar minimum activity (near sunspot minimum). Around solar maximum, the polarity of the Sun's dipole reverses, so near the next solar activity minimum, the magnetic field lines reverse their direction. This is why the solar magnetic cycle has a period of 22 years, or twice 11-year the sunspot cycle.

The third concept arises from the near-parallel, but oppositely directed magnetic field lines above and below the equatorial plane. When that happens, a current sheet is formed. For the extension of the solar coronal magnetic field into the heliosphere, this sheet becomes the Heliospheric Current Sheet (HCS), one of the most important large-scale structures in the heliosphere.

A very important research tool for coronal structures is the approximate calculation of coronal magnetic fields, given the measurements of the magnetic fields in the photosphere. For these calculations, it is assumed that there are no currents in the corona. This assumption is not really fully valid, but the

calculations still give a usually good approximation to the coronal structures observed. We have in effect, from Maxwell's equation (or Ampere's law):

$$\nabla \times \mathbf{B} = \frac{1}{\mu_0} \mathbf{j}$$

where we neglect the contribution of the displacement current (as the time variations are slow). If there are no currents, $\mathbf{j} = 0$, and the magnetic field is curl-free: $\nabla \times \mathbf{B} = 0$. In this case, as for all scalar functions Φ it is true that $\nabla \times (\nabla \Phi) = 0$, the magnetic field can be derived from a scalar magnetic potential Φ_B, to get $\mathbf{B} = -\nabla \Phi_B$.
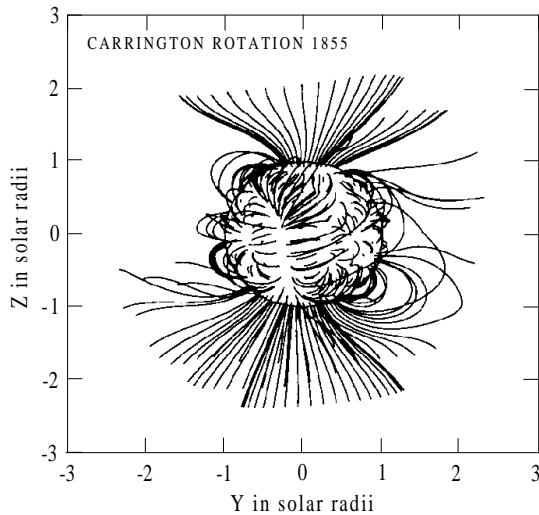

Figure 7. Calculated coronal magnetic field lines at a time in the solar cycle (just before solar minimum) when most of the open magnetic field lines originate near the poles of the Sun and the closed loops are concentrated in the equatorial regions.

Such calculations are routinely made in the following way. The magnetic fields in the photosphere are measured, to high accuracy, but with a relatively low spatial resolution by the Wilcox Solar Observatory, Stanford University, in California. Using these measurements as a boundary condition, together with an outer boundary condition at (usually) 2.5 solar radii, where the magnetic fields that reach this outer boundary (called the source surface) are constrained to be radially oriented, the scalar magnetic potential Φ_B is calculated, using the Laplace equation $\nabla^2 \Phi_B = 0$. From the solution, the magnetic field is computed, together with the geometry of the magnetic field lines. A sample result is shown in Fig. 7. As can be seen in this figure, the magnetic field lines are indeed either "closed" in the form of loop structures, or "open" at the source surface where the solar wind is assumed to take over. These calculations are referred to as the Source Surface Potential magnetic field models.

It has become also possible now, thanks to very fast supercomputers, to perform a more realistic modeling of coronal structures, without assuming that the corona is current free. In this case, the simulation uses an MHD (magnetohydrodynamics) code. The result of one such calculation is shown in Fig. 8. Note that this figure shows the solar corona near solar minimum activity, when the closed magnetic field lines are mostly close to the solar equator.
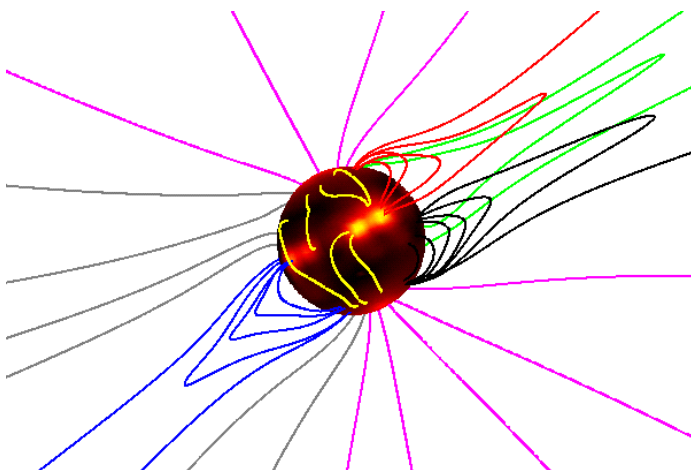

Figure 8. Results of an MHD calculation of coronal magnetic field lines at solar minimum. The open field lines stretch from the polar regions of the corona to lower latitudes, while the near-equatorial loop sustem is stretched out to form the coronal streamers.

These closed field lines often end, at their tops, in extended high density regions which are called the coronal streamers observed at the time of total eclipses. At solar minimum, the closed magnetic loop structures and the coronal streamers are located near the equator. As these structures gird the Sun, they form the so-called streamer belt. The streamer belt is characterized by high temperatures (up to 2 million K) and high densities. The open magnetic field regions, by contrast, are cooler (about 1.2 million K) and less dense. In soft x-ray pictures of the corona, the regions of open magnetic field lines appear to be darker than the closed magnetic regions (because of their lower temperatures and lower densities), and are called coronal holes.

At solar minimum, coronal holes are large, long-lasting regions covering both poles of the Sun. As solar activity increases, coronal holes all but disappear, with only small and changeable coronal holes occasionally appearing on the Sun, as most of the corona is in the form of closed magnetic loops.

Solar activity

An important part of Space Physics is the study of solar activity. Several important solar and coronal phenomena, in particular those related to the transient release of large amounts of energy: Coronal Mass Ejections, solar flares, the output of x-rays and UV radiation vary with a cycle with a period of approximately 11 years. The longest running indicator of solar activity is the number of sunspots, as already indicted above, and illustrated in Fig. 9.

Solar activity is driven by periodic changes in the magnetic field of the sun under the photosphere. The magnetic flux emerges to the solar surface in an uneven manner through the cycle. Sunspots at the beginning of a cycle (near minimum activity) are located at latitudes of $> 25^{o}$, but as the cycle progresses, newer sunspots emerge closer and closer to the equator. When plotted against time, the location of sunspots produces the so-called "butterfly" diagram, as shown in Fig. 10.

At the beginning of a cycle the solar magnetic field resembles a dipole which axis is aligned with Sun's rotation axis. In this configuration the helmet streamers form a continuous belt about the Sun's equator and coronal holes are found near the poles. During the following 2-3 years towards the maximum this nice configuration is totally destroyed, leaving the Sun, magnetically, in a disorganised state with streamers and holes scattered all over different latitudes. During the latter part of the cycle the dipole field is restored. At the beginning the dipole tilt can be large, but as the minimum epoch approaches and the dipole grows in strength, it also orients itself more with the Sun's rotation axis. When a new dipole is reformed, it has an opposite orientation (polarity) than the old one: this creates a 22-year cycle for the Sun, the so-called double-solar-cycle (DSC).

The orientation of the magnetic polarity of sunspot groups also reflects this change. The leading spot of a pair (in the direction of the rotation) in one hemisphere shows the same polarity throughout a cycle, while the leading spot in the other hemisphere has the opposite polarity. This is known as Hale's law, from the name of the American solar observer who first measured the magnetic fields of sunspots around 1910 and who subsequently discovered the regularity in their polarity. At the start of a new 11-year cycle, this polarity rule changes, creating a 22-year cycle.
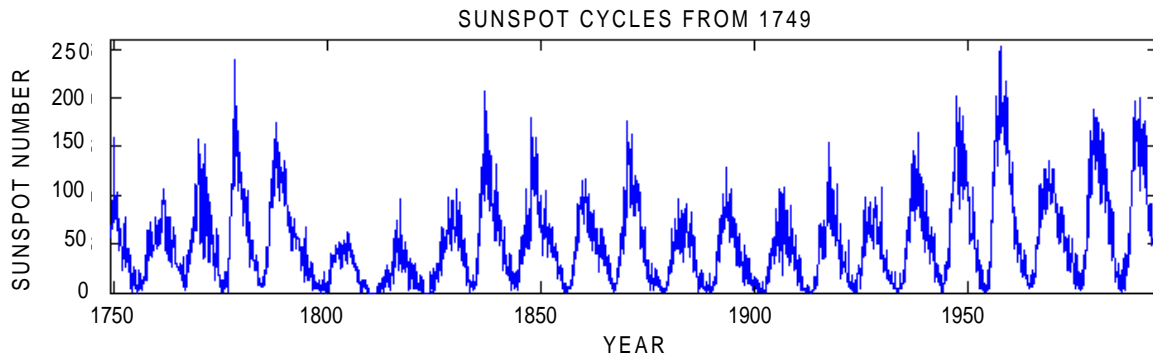
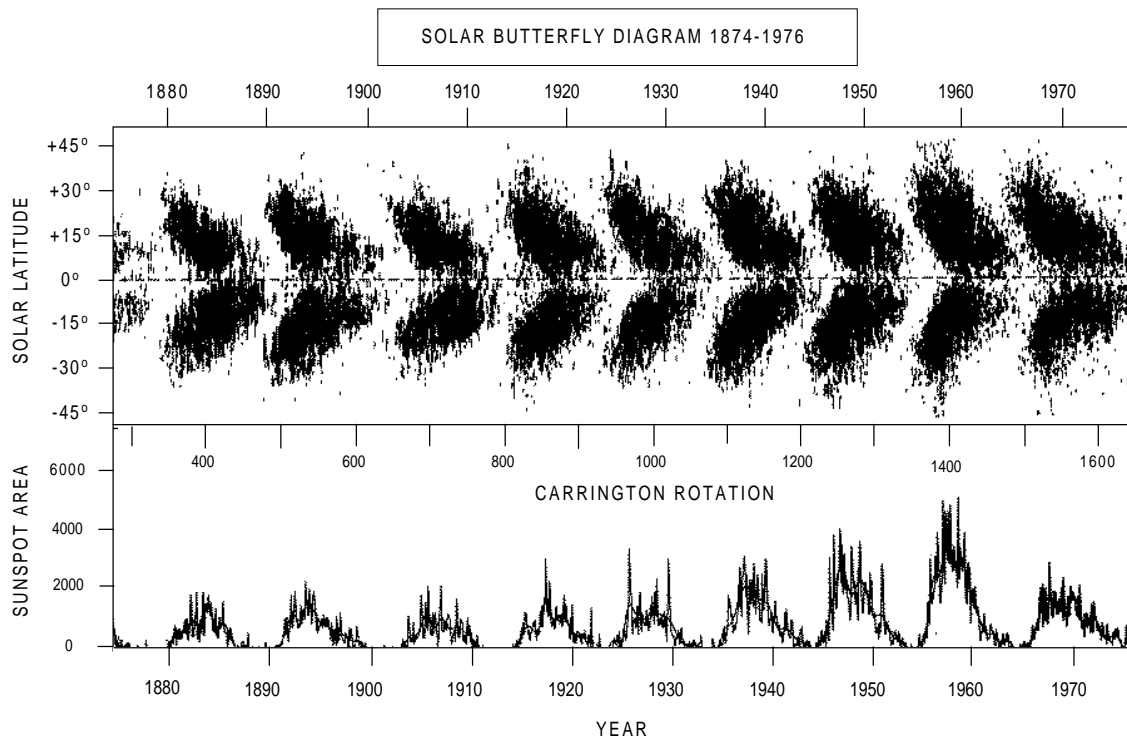*Figure 9. The 11-year periodicity of sunspot numbers*

Figure 10. The top panel shows the latitude distribution of sunspots on the sun as a function time. At the start of each solar cycle, just following minimum activity, the first sunspots of the new cycle appear at mid-latitudes, while some spots from the old cycle remain at low latitudes, close to the equator. As the cycle progresses, sunspots appear at lower and lower latitudes, so that the plot appears to show a series of butterflies; hence the name "butterfly diagram". The lower panel shows, for the same epoch, the area of the solar disk occupied by sunspots. This clearly shows the same activity cycle effect as the number of sunspots in Fig. 9, however, the total area may be a more accurate and direct measurement of solar activity.

Coronal expansion: The solar wind

At the coronal temperatures, the plasma is no longer bound to the Sun by its gravitational potential, but expands into interplanetary space at supersonic speeds. This is the solar wind. In the following, a brief introduction is given to the derivation of the first theory of coronal expansion, due to Eugene Parker in 1958, just four years before the first interplanetary space missions were able to verify the existence of solar wind.

SPACE PHYSICS ADVANCED STUDY OPTION HANDOUT

We start with two basic equations of space plasma physics, the conservation of mass and momentum:

Conservation of mass	ρ	plasma mass density
$\dfrac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{v}) = 0$	$\boldsymbol{v}$	plasma bulk velocity vector
	p	plasma pressure
Conservation of momentum	$\boldsymbol{j} \times \boldsymbol{B}$	force on plasma due to the magnetic field
		$\boldsymbol{B}$, where $\boldsymbol{j}$ is the current density vector
$\rho \dfrac{d\boldsymbol{v}}{dt} = \rho \dfrac{\partial \boldsymbol{v}}{\partial t} + \rho (\boldsymbol{v} \cdot \nabla)\boldsymbol{v} = -\nabla p + \boldsymbol{j} \times \boldsymbol{B} + \boldsymbol{F}_g$	$\boldsymbol{F}_g = -\rho \boldsymbol{g}$	force due to gravity

For the spherically symmetric, time independent case that was first solved by Parker, these equations can be written as

Conservation of mass

$$\frac{1}{r^2}\frac{d}{dr}\rho v r^2 = 0$$

Conservation of momentum

$$\rho v \frac{dv}{dr} = -\frac{dp}{dr} - \rho \frac{GM_s}{r^2}$$

where the density ρ, velocity v and pressure p are dependent only on r, the distance from the Sun; in addition, the electromagnetic force term, $\boldsymbol{j} \times \boldsymbol{B}$ has been neglected for this very simple treatment. The conservation of mass implies that $4\pi r^2 \rho v = 4\pi r^2 nmv = \text{constant}$, in other words, the total mass flux over the surface of any sphere surrounding the Sun is constant.

Using these equations, together with the assumption that the solar wind plasma can be treated as an ideal gas consisting of protons and electrons, so that $p = 2nkT$, and, for the isothermal case treated by Parker we also have $T = \text{constant}$, with the plasma number density n also only a function of distance from the Sun, a differential equation can be derived that gives the velocity v as a function of r:

$$\left(v^2 - \frac{2kT}{m}\right)\frac{1}{v}\frac{dv}{dr} = \frac{4kT}{mr} - \frac{GM_s}{r^2}$$

This differential equation has four general families of solutions. These are shown in Fig. 11. By examining the nature of these solutions, Parker correctly concluded that the only physically possible solution was in fact the singular solution, shown as a thick line in Fig. 11. This solution provides a solar wind with an increasing velocity that becomes supersonic at distances greater from the Sun than a critical radius. It also depends on the temperature of the coronal base of the solar wind as illustrated in Fig. 12.

Although this solution is far too simple to be fully representative of the real solar wind, its basic results have correctly predicted the range of values found by interplanetary spacecraft.

In fact, it is now known that there are two kinds of solar wind. Slow streams originate above and near the closed magnetic field loops and streamers in the corona at about 400 km/sec. Fast streams originate in cooler regions of the corona, with open magnetic field lines, at speeds approaching 800 km/sec. The solar wind needs about 4-5 days to reach Earth, and as many months to attain the outermost planets: its outer limits, the boundary between the space dominated by the Sun and the interstellar medium, is probably more distant still. The space probes Voyager 1 and 2, launched in 1977, are expected to reach that boundary early in the 21st century, and NASA is hopeful that the nuclear batteries which power those spacecraft will last long enough to observe the transition. As the solar wind leaves the corona, it picks up the local magnetic field--contributed by sunspots and by the Sun's magnetic poles--and drags its field lines into space, forming the heliospheric magnetic field (HMF). The HMF is quite weak--at the Earth's orbit, only 1/10,000 of the field at the Earth's surface, but it exerts a significant influence on the Earth's magnetosphere.

$$v_c = \left(\frac{2kT}{m}\right)^{1/2}$$
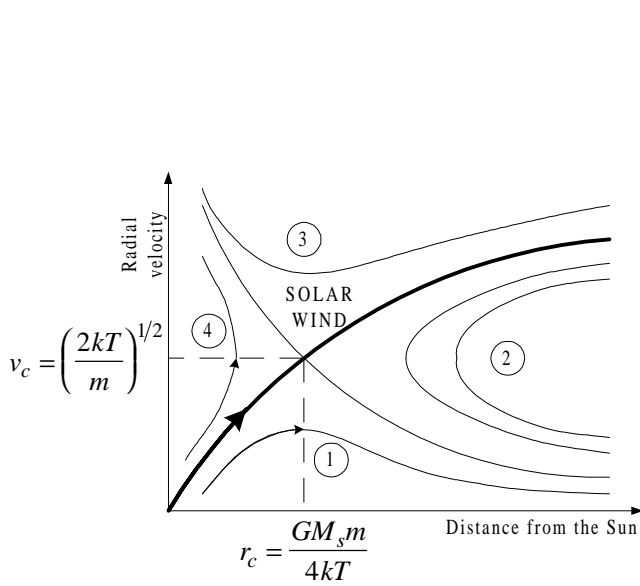
$$r_c = \frac{GM_s m}{4kT}$$

Figure 11. The four families of solutions to the equation of coronal expansion. The correct solution is the thick line, as deduced correctly by Parker.
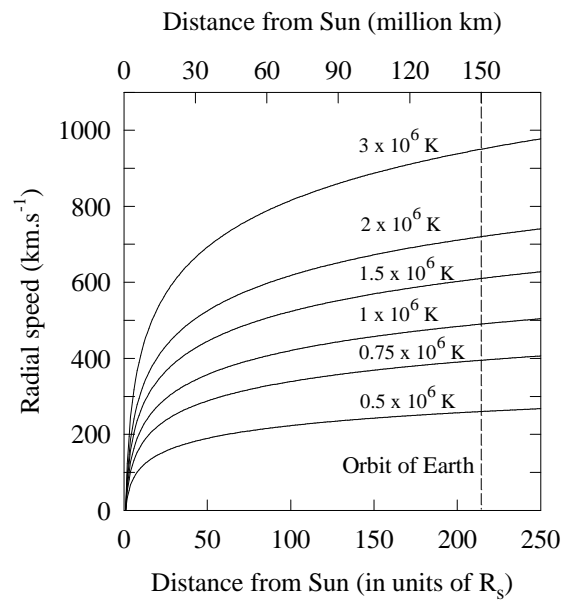

Figure 12. The dependence of the solar wind speed on coronal temperature. This is a very much simplified view, as the solar wind is a much more complex phenomenon than Parker envisaged.

The table below lists the basic solar wind characteristics at the Earth's orbit.

Parameter	Minimum	Average	Maximum
Flux $(cm^{-2}s^{-1})$	1	3	100
Velocity (km/s)	200	400	900
Density (cm^{-3})	0.4	6.5	100
Helium (α-particles) %	0	5	25
Magnetic field magnitude (nT)	0.2	6	80