Space Physics Handout 1 : The sun and the solar wind

The Sun is a typical star of intermediate size and luminosity, and as stars go is fairly ordinary. However due to its proximity to the Earth, it is of great interest to us and is the source of virtually all of the energy of our solar system. Solar radiation (radio waves, X-rays and energetic particles) heats our atmosphere and also provides the visible light needed to sustain life on Earth. In addition to that the Sun is also the source of space plasmas in the solar system as a whole.

It's physical characteristics are listed in Table 1 below. The most important ones are that is has a radius of 696 000km, rotates with a period that increases with latitude (from 25 days at the equator to 36 days at the poles) with the average period taken to be 27 days. It has a mass of about 2 x 10^{30} kg and this consists mainly of hydrogen (≈90%) and helium (≈10%). These gases are mostly ionised due to the very high temperature of the Sun and there are various other elements such as C, N and O which compose about 0.1% of the solar mass (see Table 2 for more details). The total energy output of the Sun, the solar constant, is about 3.8 x 10^{33} ergs/sec.

Table 1 : Physical Characteristics of the Sun

Diameter	1, 392, 530 km
Radius	696,265 km
Volume	1.41 x 10^{18} m^3
Mass	1.9891 x 10^{30} kg
Solar radiation (entire Sun)	3.83 x 10^{23} kW
Solar radiation per unit area on the photosphere	6.29 x 10^4 kW m^{-2}
Solar radiation at the top of the Earth's atmosphere	1, 368 W m^{-2}
Mean distance from the Earth (in km)	149.60 x 10^6 km ≡ 1 AU
Mean distance from the Earth (in solar radii)	214.86 R_S

The overall structure of the interior and atmosphere of the Sun is shown in Figure 1.

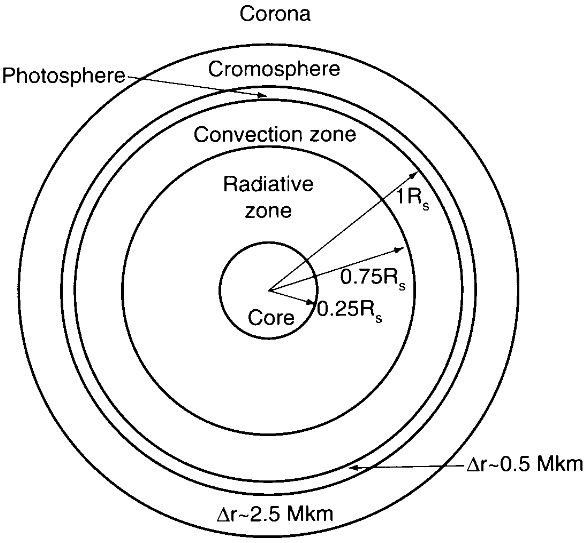

Figure 1: Structure of the solar interior and atmosphere (from Gombosi, 1998)

The core of the Sun is the high density, high temperature gas at the centre of the Sun. It is here where thermonuclear reactions occur by which the Sun's energy is provided. This energy escapes from the centre of the Sun, first through the radiative zone by radiation. Then at about $0.75R_S$ from the centre the thermal gradient increases above the value at which the convective instability sets in and thereafter heat can only be moved to the surface by material motions. A set of convective cells are set up which transport the heat, material and magnetic fields up to the solar surface, the photosphere. Above this is the solar atmosphere; this is the observable region of the Sun from which solar energy is radiated out into space. The density and temperature variation of this region with radial distance is shown in Figure 2.

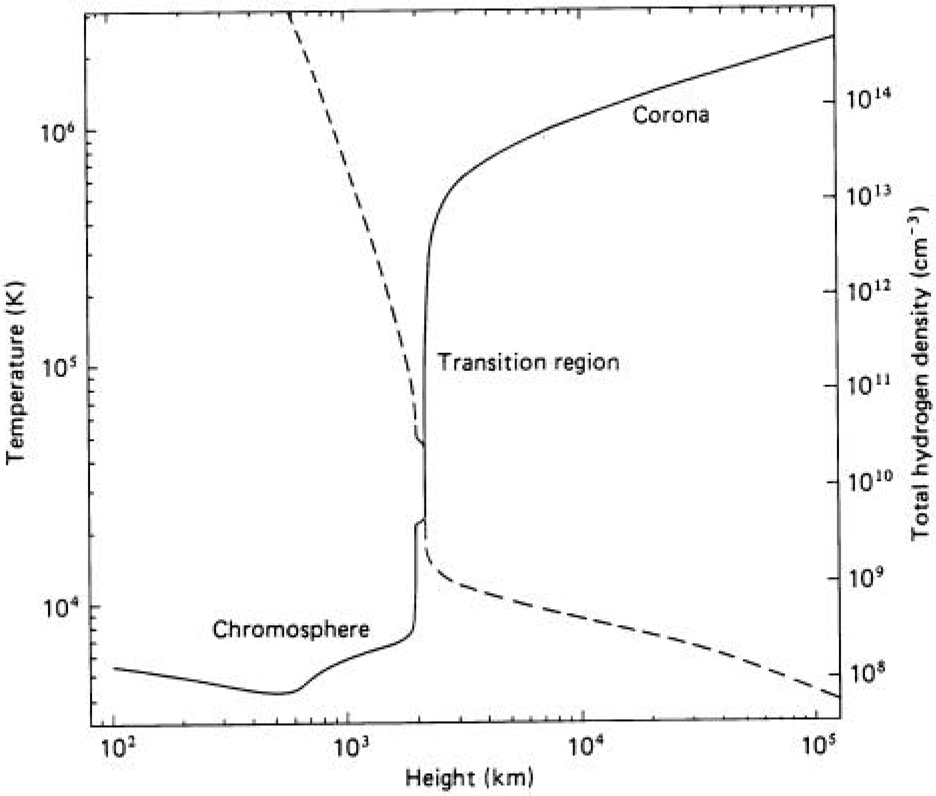

Figure 2: The temperature and density variation of the solar atmosphere as a function of height above the photosphere (from Cravens, 1997).

1) The photosphere

This is the visible surface of the Sun and has a temperature of 5,800K; is only about 500km thick and has a density of 10^{23} m^{-3}. This is where photons last interact with atoms before escaping from the Sun, and the main constituents are shown in the Table 2. The photosphere is covered by granulation, which represents the tops of the convective cells arising from the interior and shown schematically in Figure 3. There are a number of characteristic sizes for these convective cells. Granules are bright features of the order of hundreds to a thousand kms across, with a lifetime of about 10 minutes. These are surrounded by dark edges (representing downflow of convection cells). Supergranules are of the order of 30,000 km across and have lifetimes of 12 to 24 hours. The boundaries of supergranules contain a magnetic field concentration swept there by horizontal motion in the supergranule cells. This concentration of magnetic field gives rise to the chromospheric network in the layer above the photosphere, the chromosphere. There possibly may also be giant cells, which are a fraction of the solar radius across.

Table 2: Photospheric composition

Element	% mass	% number
Hydrogen	73.46	92.1
Helium	24.85	7.8
Oxygen	0.77	0.1
Carbon	0.29	
Iron	0.16	
Neon	0.12	
Nitrogen	0.09	
Silicon	0.07	
Magnesium	0.05	

Sunspots which are observed as dark spots are sites of very strong magnetic fields (thousands of Gauss or about 0.1-0.3 nT) and are cooler by about 2000 K than the rest of the photosphere (hence their darkness). A medium size sunspot is bigger than the diameter of the Earth. Small sunspots may only last a few hours however larger sunspots and sunspot groups may last up to several months. Historically, sunspots have been an important measure of the solar cycle (as will be discussed later in the handout). The solar atmosphere above the photosphere is highly non-uniform. It consists of a plasma, mostly electrons and protons, with a small % of ionised helium and some partially ionised heavier ions. Its electrical conductivity is high (it can be taken to be infinite usually) and it is shaped by the structure of the magnetic fields.

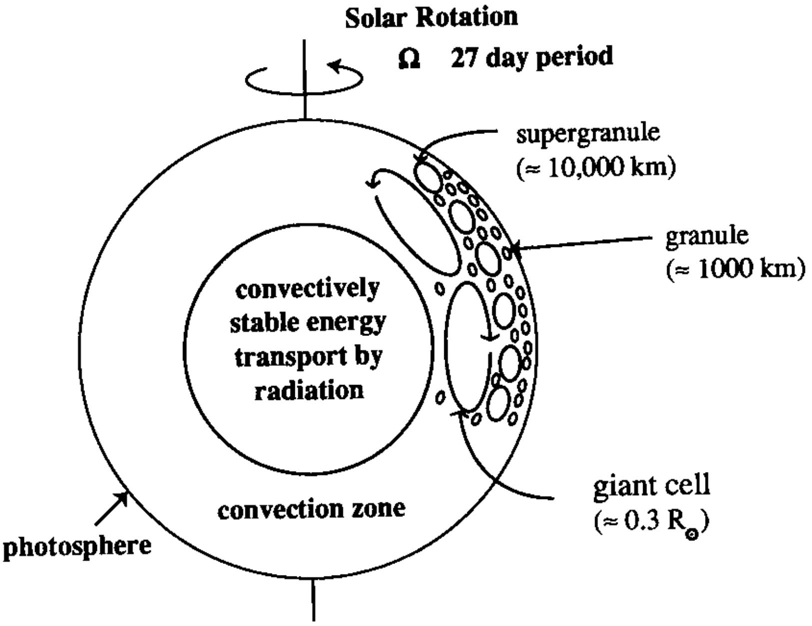

Figure 3: Schematic of the interior of the Sun and convection cells of various sizes (from Cravens, 1997)

2) The chromosphere

Above the photosphere lies the chromosphere which has a thickness of 2,000 – 3,000 km and a density of 10^{17} m^{-3}. The temperature first falls to about 4,300 K and then after that rises through the chromosphere and reaches about 10^4K at the top. A variety of features can be observed in this region which are described in Table 3.

3) The transition region

This layer extends only a few hundred kms above the chromosphere but the temperature increases very rapidly from 10^4 to 10^6 K at the top (or the base of the corona). This rapid rise in temperature can clearly be seen in the Figure 2.

4) The solar corona.

The solar corona is the uppermost region of the solar atmosphere and it extends many solar radii out into space where it gradually becomes the solar wind and interplanetary medium. *The corona is the source of the solar wind.* It consists of a hot and very tenuous plasma which can only be observed in visible light during a full solar eclipse (when the much more intense light from the photosphere is blocked out). The structure of the corona is determined by the coronal magnetic field which is an extension of the solar surface magnetic fields. The hotter and more dense parts of the corona (2 million K) are contained in complex magnetic loop structures, with their footprints anchored firmly in the photosphere. The cooler less dense parts of the corona, called coronal holes, (since they show up as darker regions in X-ray pictures of the corona) have temperatures of about 1.2 million K. The magnetic field lines in coronal holes are open, with one end anchored in the photosphere. The magnetic flux and magnetic field lines however are carried out into interplanetary space by the solar wind.

Table 3: Features occurring above the Sun's surface (photosphere)

Chromospheric features	Coronal features
Chromospheric network weblike pattern formed by magnetic field lines related to supergranules	*Coronal holes* source of high speed solar wind
Plage bright patches surrounding sunspots and associated with concentrations of magnetic field lines	*Coronal loops* closed magnetic field line loops around sunspots and active regions; can last for days or weeks if not associated with solar flares
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	*Coronal Mass Ejections (CME's)* huge bubbles of gas ejected from the Sun over the course of several hours
Spicules Small, jet-like eruptions in the Chromospheric network lasting a few Minutes only	*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
Solar flares Huge explosions with time scales of only a few minutes	*Polar plumes* long thin streamers associated with open magnetic field lines at the poles

The solar wind

The solar wind is a flow of ionised solar plasma and a remnant of the solar magnetic field that pervades interplanetary space. It is a result of the huge difference in gas pressure between the solar corona and interstellar space – which drives the gas outwards despite the restraining influence of solar gravity. At coronal temperatures the plasma is no longer bound to the Sun by its gravitational potential and can expand out into interplanetary space at supersonic speeds. The upper fringes of the coronal plasma flow away in all directions in a constant stream of particles. It was first observed directly by space probes in the mid-1960's.

There are two kinds of solar wind:

1) slow streams which originate above and near the closed magnetic field loops and streamers in the corona at about 400 km/sec
2) and fast streams which originate in the cooler regions of the corona with open magnetic field lines at speeds approaching 800 km/sec.

Embedded in the solar wind plasma is the heliospheric magnetic field which becomes the interplanetary magnetic field (IMF). This magnetic field is quite weak, at the Earth for example, it is only about 1/10,000 of the magnetic field at the surface of the Earth, but as we shall see it exerts an extraordinary influence on the environment of the Earth (known as its magnetosphere). It takes the solar wind about 4-5 days to reach the Earth (the distance from the Earth to the Sun is defined as 1 Astronomical Unit (1 AU)), and many months to reach the outer planets. Table 4 lists the basic solar wind characteristics at 1AU, the Earth's orbit.

The radial outflow of the solar wind from the corona transports the IMF into interplanetary space, while the footprint of the field line remains anchored in the solar atmosphere. This field is transported radially outwards with a constant radial velocity while the Sun rotates and the combination of outflow and rotation results in a magnetic field which becomes bent into an Archimedian spiral (this will be discussed in more detail later in the course). This radial plasma outflow of the solar wind impinges on planetary obstacles and interacts with them (again a topic for later in the course).

Table 4: Solar wind characteristics at 1AU

Parameter	Minimum	Average	Maximum
Flux (cm^{-2} s^{-1})	1	3	100
Velocity(km s^{-1})	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

The outer limits of the solar wind, the boundary between the space dominated by the Sun and by the interstellar medium has not yet been reached, although it is predicted to lie somewhere between 50 – 150 AU. The space probes Voyager 1 and 2, which were launched in 1977, are expected to reach this boundary early this century. Figure 5 shows a schematic of the heliosphere, with the heliopause separating solar wind plasma from plasma of interstellar origin. The heliosphere acts as an obstacle to the flow of the local interstellar medium (within a distance of 2,000AU), which flows around the heliopause. If this plasma is flowing supersonically then a shock wave would form in the flow (a bow shock). We will learn more about bow shocks in the course. It is unclear whether such a shock wave forms because we do not know what the flow speed of the plasma is.

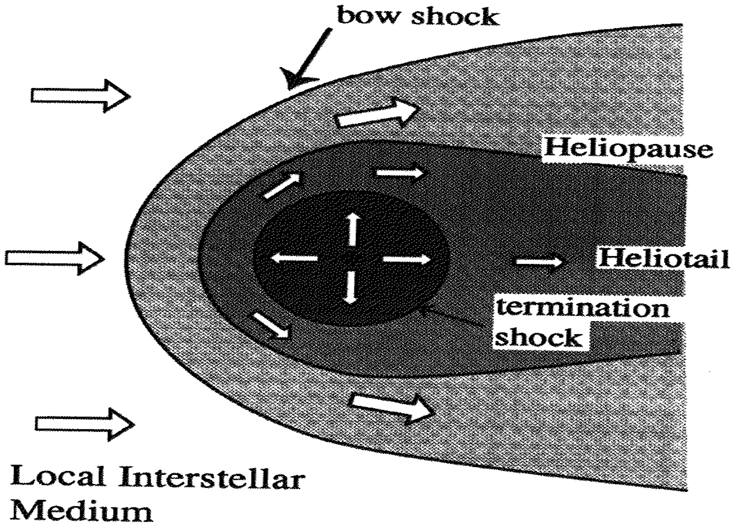

Figure 5: Schematic structure of the heliosphere (taken from Cravens, 1997)

Solar activity

It was mentioned earlier that sunspots are an important manifestation of the variability of the solar cycle. Their number fluctuates with a period of about 11 years (the solar cycle) and this can be clearly seen in Figure 6 which provides a record of the last 250 years. In fact solar activity is a very complicated process which involves the entire Sun and its atmosphere, but sunspot numbers still retain their value as a simple measure of solar activity. The study and understanding of solar activity is a very important part of Space Physics and we will discuss briefly the main aspects. There are several important solar and coronal phenomena (in addition to sunspots) which vary with a period approximately equal to the solar cycle. Coronal Mass Ejections (CME's), solar flares, the output of x-rays and UV radiation all vary with the solar cycle – and all of these are related to the transient release of large amounts of energy from the Sun.

Solar activity is driven by periodic changes in the magnetic field of the Sun under the photosphere, with the magnetic flux emerging to the surface in an uneven manner throughout the solar cycle. During the course of the solar cycle the position of sunspots moves from latitudes of > 25° (at the beginning of the cycle near solar minimum) towards the equator. When plotted against time, the location of sunspots produces a "butterfly" diagram, as can be seen in Figure 7. The top panel shows the latitude distribution of sunspots as a function of time, and the lower panel shows the area of the solar disk occupied by sunspots (which shows the same 11-year cycle as shown in Figure 6).

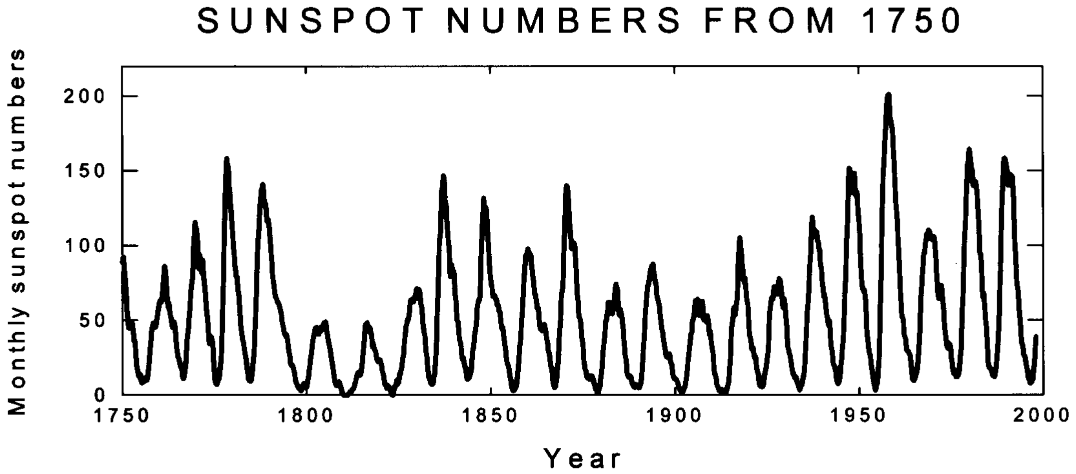

Figure 6: Monthly sunspot numbers from the last 250 years, showing the 11-year periodicity.

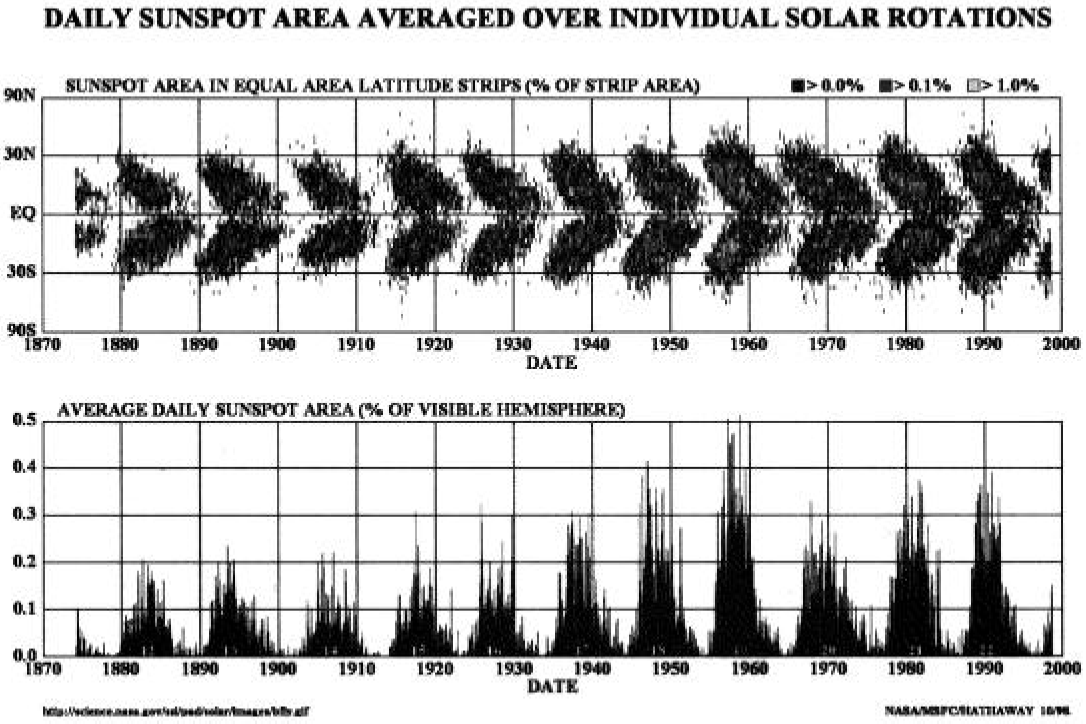

Figure 7: Distribution of sunspots and sunspot area.

At the beginning of a cycle the solar magnetic field resembles a dipole whose axis is aligned with the rotation axis of the Sun. At this time helmet streamers form a continuous belt about the Sun's equator and coronal holes are found near the poles. During the next 5-6 years as the Sun approaches the maximum of its cycle the ordered configuration is totally destroyed and as a result the Sun is magnetically in a disorganised state with streamers and coronal holes scattered all over the surface. During the second half of the cycle from solar maximum towards solar minimum the dipole field is restored. Initially during this time 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 rotation axis of the Sun. When this new dipole has reformed it has an opposite polarity or orientation to the previous one. This then creates a 22-year cycle for the Sun (the double solar cycle – DSC). Sunspot pairs also reflect this change. Sunspot pairs usually have opposite polarity and the leading sunspot (in the direction of rotation) of a pair has opposite polarity in the northern and southern hemispheres – and keeps the polarity during the period of the solar cycle. At the start of the new 11-year cycle this polarity switches – creating a 22-year cycle.