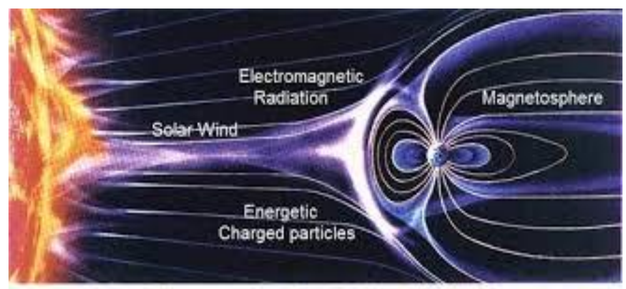
Chapter Four

The solar wind and the magnetosphere



Magnetosphere Squished by Solar Wind

Chapter Four
The solar wind and the magnetosphere

Introduction

1. <u>The magnetosphere is the region of the terrestrial environment where the geomagnetic field exerts the dominating influence. Generally, the energy density of the magnetic field exceeds that of the plasma:</u>

$$B^2/2\mu_o > nkT \qquad (1)$$

(In SI units) where B is the magnetic flux density, k is Boltzmann's constant, and the plasma contains n particles per cubic metre at temperature T.
2. There is no sharp boundary and the traditional separation between magnetosphere and ionosphere owes more to semantics (دلالات الالفاظ) than to physics. The outer boundary of the magnetosphere is determined by its interaction with the solar wind. The magnetosphere can thus be regarded as the outermost part of the Earth.
3. Since solar activity is continually varying, the magnetosphere also changes from day to day, and from hour to hour. We therefore begin our account at the Sun.

Solar radiations
The Sun

mass	$m = M_\odot$	=	1.989×10^{30} kg
radius	$R = R_\odot$	=	6.960×10^{8} m
mean density	$\bar{\rho}$	=	1409 kg/m^3
central density	ρ_c	=	1.6×10^{5} kg/m^3
luminosity	$L = L_\odot$	=	3.9×10^{26} W
effective temperature	T_e	=	5785 K
central temperature	T_c	=	1.5×10^{7} K
absolute bolometric magnitude	M_{bol}	=	4.72
absolute visual magnitude	M_V	=	4.79
spectral class			G2 V
colour indices	$B - V$	=	0.62
	$U - B$	=	0.10
surface chemical composition	X	=	0.71
	Y	=	0.27
	Z	=	0.02
rotational period			
at the equator			25 d
at latitude 60°			29 d

1. The Sun is a typical star, emitting electromagnetic radiation over a wide spectral range, a continuous stream of plasma, and bursts of energetic particles.
2. The solar atmosphere is divided into the *photosphere* and the *chromosphere*. Outside the actual atmosphere, the *corona* extends much further outwards.

❖ **The Photosphere.** The innermost layer of the atmosphere is the photosphere, which is only about 300–500 km thick. The photosphere is the visible surface of the Sun, where the density rapidly increases inwards, hiding the interior from sight. The temperature at the inner boundary of the photosphere is 8000 K and at the outer boundary 4500 K.

- **The Chromosphere.** Outside the photosphere there is a layer, perhaps about 500 km thick, where the temperature increases from 4500 K to about 6000 K, the chromosphere. Outside this layer, there is a transition region of a few thousand kilometers, where the chromosphere gradually goes over into the corona. In the outer parts of the transition region, the kinetic temperature is already about 10^6 K. Normally the chromosphere is not visible, because its radiation is so much weaker than that of the photosphere.
- **The Corona.** The chromosphere gradually goes over into the corona. The corona is also best seen during total solar eclipses (Fig. 2). It then appears as a halo of light extending out to a few solar radii. See figure (1). The entire corona has to have a temperature of about a million degrees. A continuous supply of energy is needed in order to maintain the high temperature of the corona. According to earlier theories, the energy came in the form of acoustic or magneto hydrodynamic MHD shock waves generated at the solar surface by the convection. The interaction between a plasma and a magnetic field can be modeled according to the principles of magneto-hydrodynamics (MHD), in which the plasma can be treated as a continuous medium. The equations of MHD unify the equations of slow electromagnetism and fluid mechanics.
- In spite of its high temperature the coronal gas is so diffuse that the total energy stored in it is small. It is constantly streaming outwards, gradually becoming a *solar wind*, which carries a flux of particles away from the Sun. The gas lost in this way is replaced with new material from the chromosphere.

3. The rotation of the Sun on its axis is important in relation to geophysical phenomena because the Sun's active regions are not uniformly distributed. The rotation period increases with latitude from 25.4 days at the equator to 33 days at latitude 75°. The intensity of certain of the emissions received at Earth therefore varies with the solar rotation, a typical average period for geophysical purposes being 27 days.

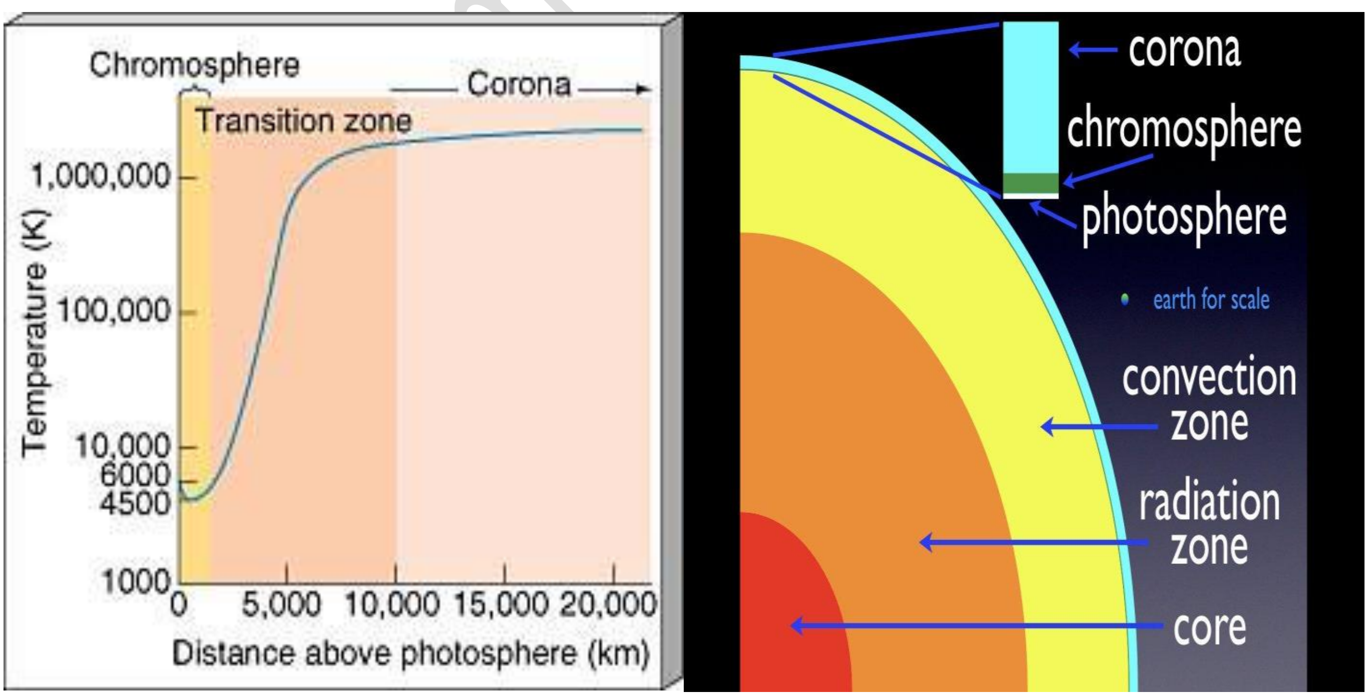


Figure (2.1) the solar interior and atmosphere

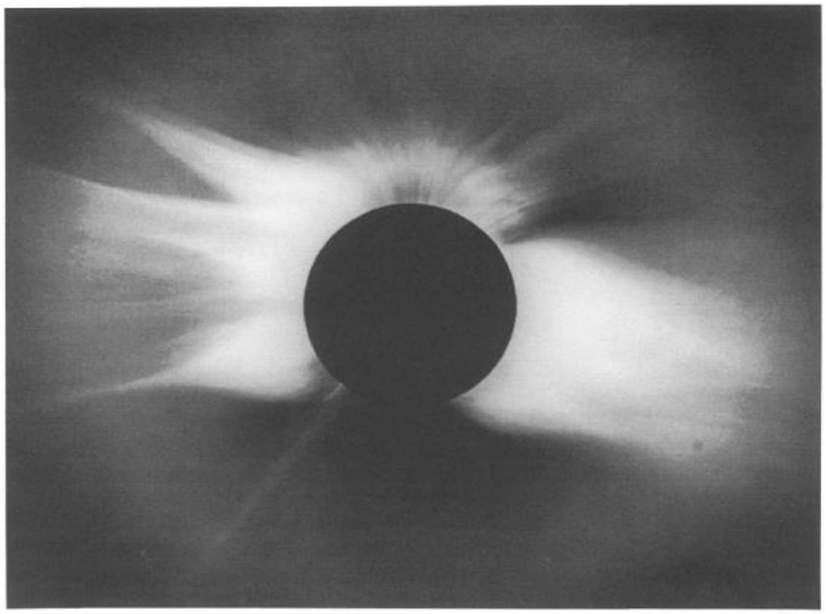


Figure (2.2) the solar eclipse showing the corona

Solar electromagnetic radiation

1. The Sun emits 4x 10^{26} W of electromagnetic radiation, irradiating the Earth with almost 1.4 kW/m^2.
2. Corresponding to its black body temperature, the spectrum peaks in the visible and the intensity falls away both at shorter wavelengths (ultra-violet, X-rays and y-rays) and at the long wavelength end (infra-red and radio).
3. The variations of solar emissions are remarkably constant in the visible, to within 1 % except for the local brightening called solar flares.
4. In addition to a continuum of radiation there are some strong discrete lines. This part of the spectrum is more variable than the visible, particularly at the short-wave end. The region of greatest concern to us will be that below 100 nm (1000 A, 0.1 μm), which is far to the short-wave side of the peak. See figure (3).

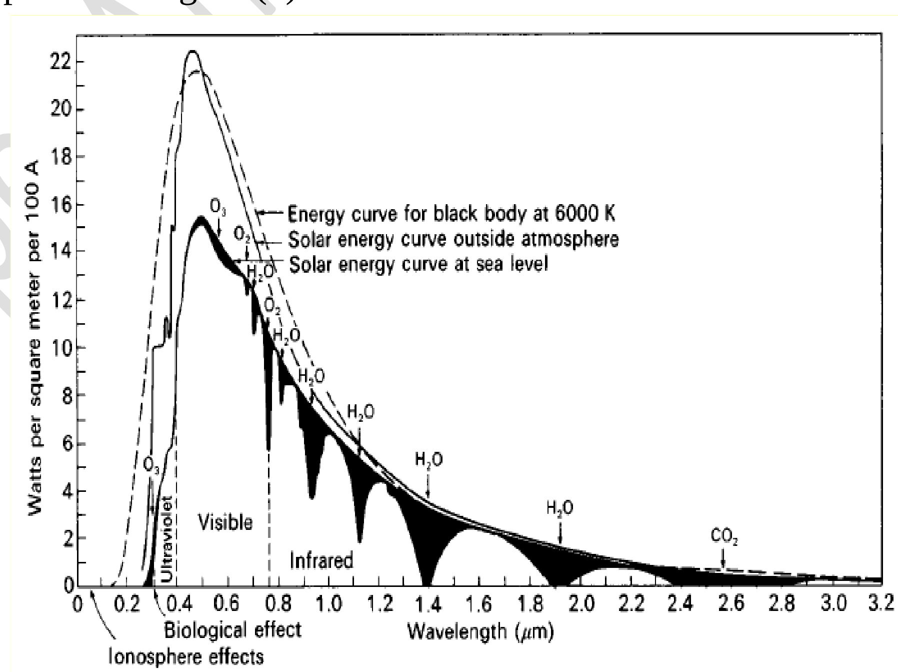


Fig. 3 The spectrum of solar electromagnetic radiation reaching the Earth's surface (including the effects of major absorbing species), and outside the atmosphere. The 6000 K black body curve is shown for comparison. The principal ionospheric effects are below 0.1μm.

Example: Assume that the Sun converts 0.8% of its mass into energy. Find an upper limit for the age of the Sun, assuming that its luminosity has remained constant.

Solution //

The total amount of energy released is

$$E = mc^2 = 0.008\ M*c^2 = 0.008*2*10^{30}\ \text{kg}*(3*10^8\ \text{ms}^{-1})^2 = 1.4\times10^{45}\ \text{J}$$

The time needed to radiate this energy is

$$t = E/L = 1.4\times10^{45}\ \text{J}/3.9\times10^{26}\ \text{W} = 3.6\times10^{18}\ \text{s} \approx 10^{11}\ \text{years}$$

Solar activity

Sunspots.

1. The clearest visible sign of solar activity are the *sunspots*. The existence of sunspots has been known for long (Fig. 4), since the largest ones can be seen with the naked eye by looking at the Sun.
2. A sunspot looks like a ragged hole in the solar surface. In the interior of the spot there is a dark *umbra* and around it, a less dark *penumbra*. By looking at spots near the edge of the solar disc, it can be seen that the spots are slightly depressed with respect to the rest of the surface. The surface temperature in a sunspot is about 1500 K below that of its surroundings, which explains the dark colour of the spots.
3. The diameter of a typical sunspot is about 10,000 km and its lifetime is from a few days to several months, depending on its size. The larger spots are more likely to be long-lived. Sunspots often occur in pairs or in larger groups.
4. The variations in the number of sunspots have been followed for almost 250 years. The frequency of spots is described by the **<u>Zurich sunspot number *Z*</u>**:

$$Z = C(S+10\ G) \qquad (2)$$

Where S is the number of spots and G the number of spot groups visible at a particular time. C is a constant depending on the observer and the conditions of observation.

5. In Fig. 5, the variations in the Zurich sunspot number between the 18th century and the present are shown. Evidently the number of spots varies with an average period of about 11 years. The actual period may be between 7 and 17 years. In the past decades, it has been about 10.5 years. Usually the activity rises to its maximum in about 3–4 years, and then falls off slightly more slowly. The period was first noted by *Samuel Heinrich Schwabe* in 1843.
6. The magnetic fields in sunspots are measured on the basis of the Zeeman Effect, and may be as large as 0.45 tesla. (The magnetic field of the Earth is 0.03 mT) The strong magnetic field inhibits convective energy transport, which explains the lower temperature of the spots.
7. Sunspots often occur in pairs where the components have opposite polarity. The structure of such *bipolar groups* can be understood if the field rises into a loop above the solar surface, connecting the components of the pair. If gas is streaming along such a loop, it becomes visible as a *loop prominence* (Fig. 6).
8. At the beginning of a new activity cycle spots first begin to appear at latitudes of about ±40°. As the cycle advances, the spots move closer to the equator.

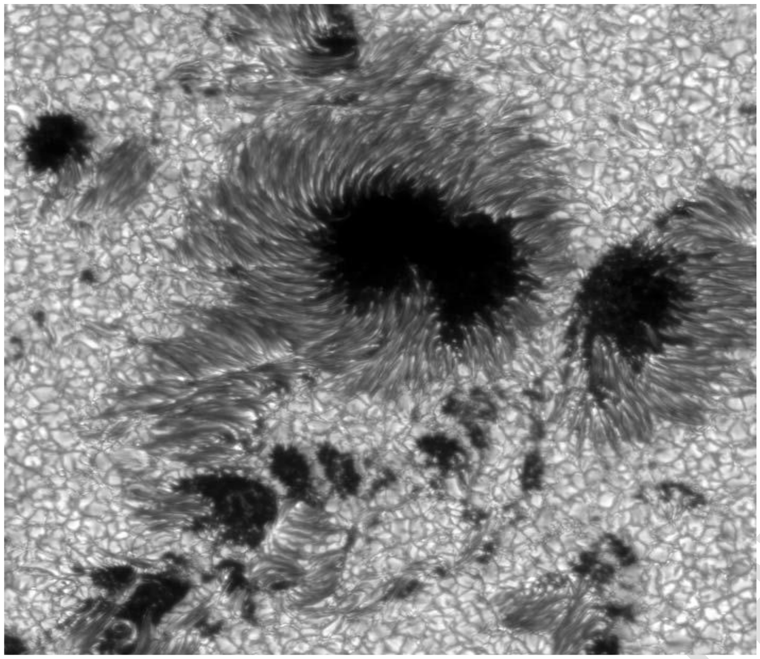


Fig. 4 the sunspots are the form of solar activity that has been known for the longest time. The photograph was taken with the Swedish 1-meter Solar Telescope in July 2002. (Photograph Royal Swedish Academy of Sciences)

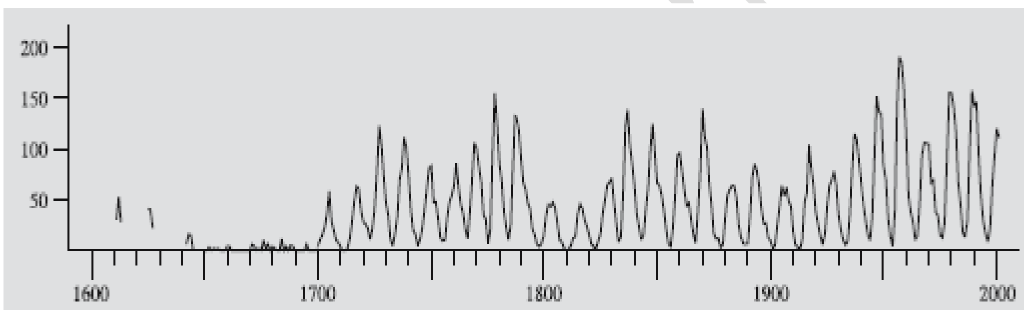


Fig. 5 The Zurich sunspot number from 1700 to 2001

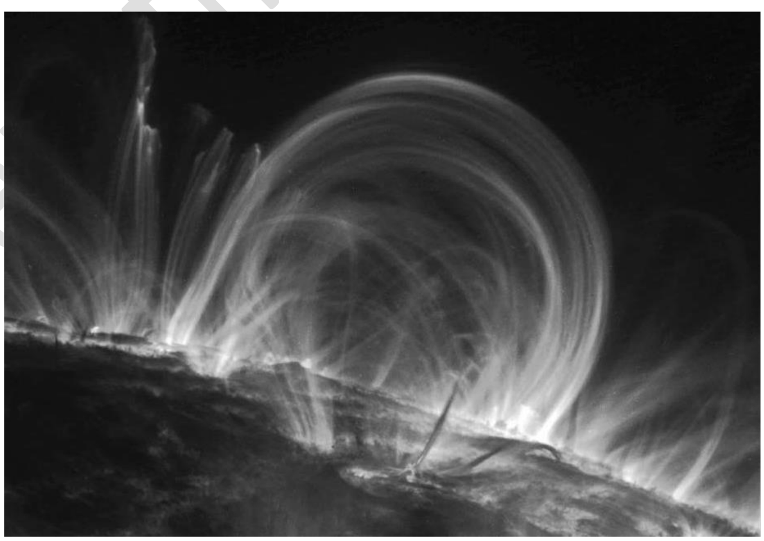


Fig. 2.6 Pairs of sunspots the magnetic field lines form a loop outside the solar surface. Material streaming along the field lines may form loop prominences. Loops of different size can be seen in this image

Solar Flares

1. The flare outbursts are among the most violent forms of solar activity (Fig. 7).
2. They appear as bright flashes, lasting from one second to just under an hour.
3. In the flares a large amount of energy stored in the magnetic field is suddenly released. The detailed mechanism is not yet known.
4. Flares can be observed at all wavelengths. The hard X-ray emission of the Sun may increase hundredfold during a flare. Several different types of flares are observed at radio wavelengths (Fig. 8). The emission of solar cosmic ray particles also rises.
5. The flares give rise to disturbances on the Earth. The X-rays cause changes in the ionosphere, which affect short-wave radio communications. The flare particles give rise to strong auroras when they enter the Earth's magnetic field a few days after the outburst.

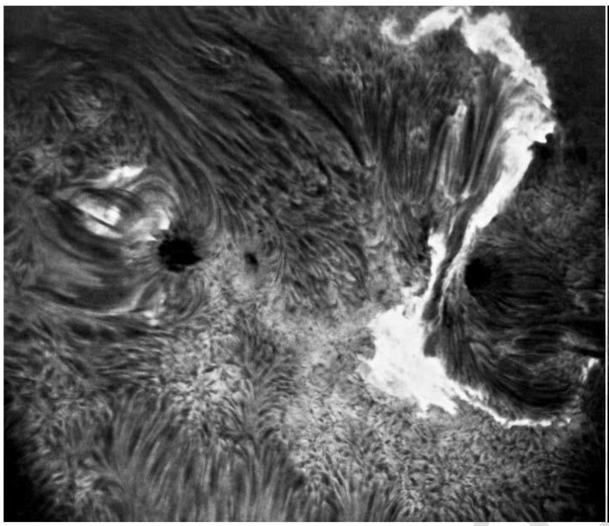


Fig. 7 A violent flare near some small sunspots

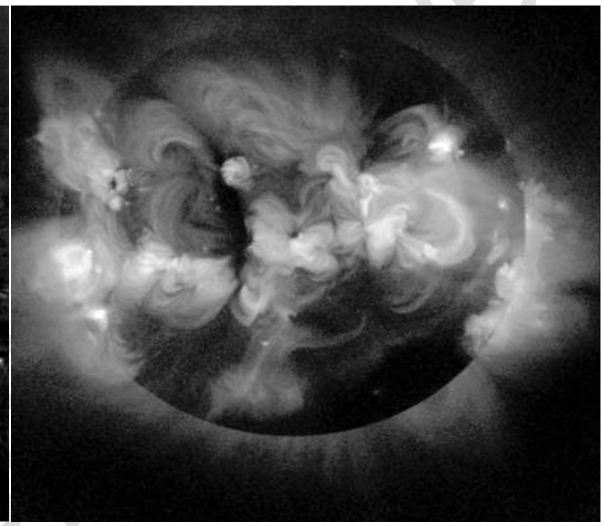


Fig. 8 An X-ray picture of the active Sun, around the last maximum of sunspot activity

Solar Radio Emission.

1. The Sun is the strongest radio source in the sky and has been observed since the 1940's. The 10 cm emission originates in the upper layers of the chromosphere and the 1 m emission, in the corona.
2. The radio emission of the Sun is constantly changing according to solar activity. During large storms the total emission may be 100,000 times higher than normal.

The solar wind

Discovery

1. Chapman and Ferraro suggested in 1931 that they are caused by streams of corpuscles ejected from the Sun, to reach the Earth about a day later. There, unable to penetrate the geomagnetic field, it would be deflected around and, at the same time, cause some compression of the field, which would be detectable at the ground.
2. Theoretical studies by Chapman and by E. N. Parker subsequently proved that, unlike the Earth's atmosphere, the solar corona is not in hydrostatic equilibrium but expands continuously, with matter leaving the Sun and streaming out into space. Parker called this flow the **solar wind**.

Theory of the solar wind

1. It is possible, from optical measurements, to estimate the electron density in the solar corona at various distances from the Sun.
2. If it is assumed that the material of the corona is moving outward, the velocity can then be calculated from the **conservation of flux**. That is, for particle density (n) and velocity (v) at distance (r), then nr^2v is constant.
3. From this, the outward acceleration can be calculated. It is found that beyond 15 or 20 solar radii the convective acceleration, acting outward, exceeds the gravitational acceleration acting inward. Matter therefore leaves the Sun continuously beyond a certain distance.
4. The solar wind carries with it the Sun's magnetic field. Therefore, the solar wind is a magnetized plasma.

Properties of the solar wind

1. There have been many observations of the solar wind since its discovery in the early 1960s. Measurements of the positive ions using plasma probes find that the flux of particles with energy exceeding 25 eV is between 2×10^{12} and 7×10^{12} particles/m^2.s.
2. Although most ions are protons (H^+) there is α-particle (He^{++}) component, heavier atoms total perhaps 0.5%, and, in contrast to the light ions, these are not fully ionized.
3. The number density of positive ions varies between 3×10^6 and 10^7 m^{-3}, and there is a similar number of electrons for bulk neutrality.
4. The mean mass of solar wind particles is therefore almost half that of the proton, about 10^{-27} kg.
5. At the distance of the Earth's orbit the speed of the solar wind is usually between 200 and 700 or 800 km/s (Figure 9), on which is superimposed a random component of temperature 10^5 K.
6. The energy is more directed than random. The energy carried is about 10^{-4} W/m^2.
7. The variability in the density and speed of the solar wind is shown over one solar rotation in Figure 2.10. There is a degree of anticorrelation between density and speed.
8. The solar wind is the principal medium by which the activity of the Sun is communicated to the vicinity of the Earth, and it is extremely important in **solar-terrestrial relations**.

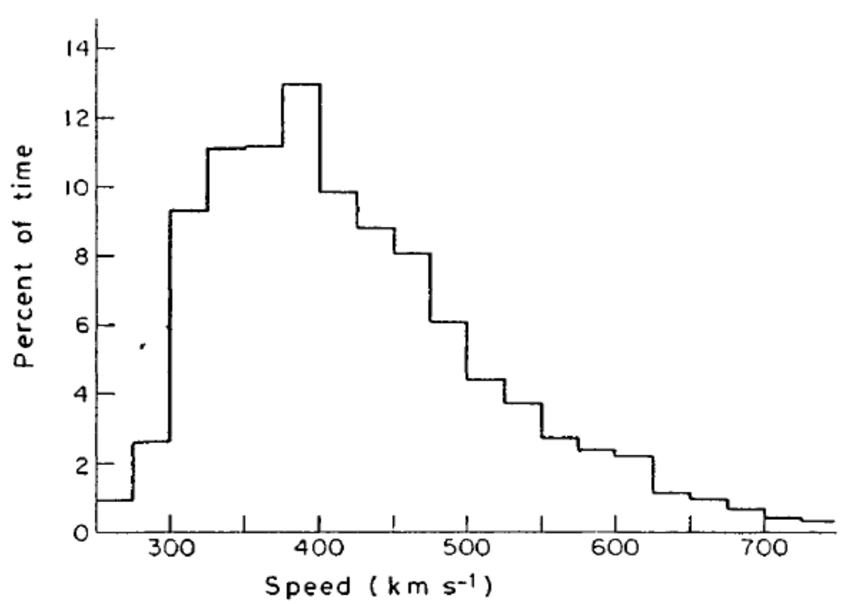


Figure (9) Speed of solar wind: a histogram of measurments between 1962 and 1970

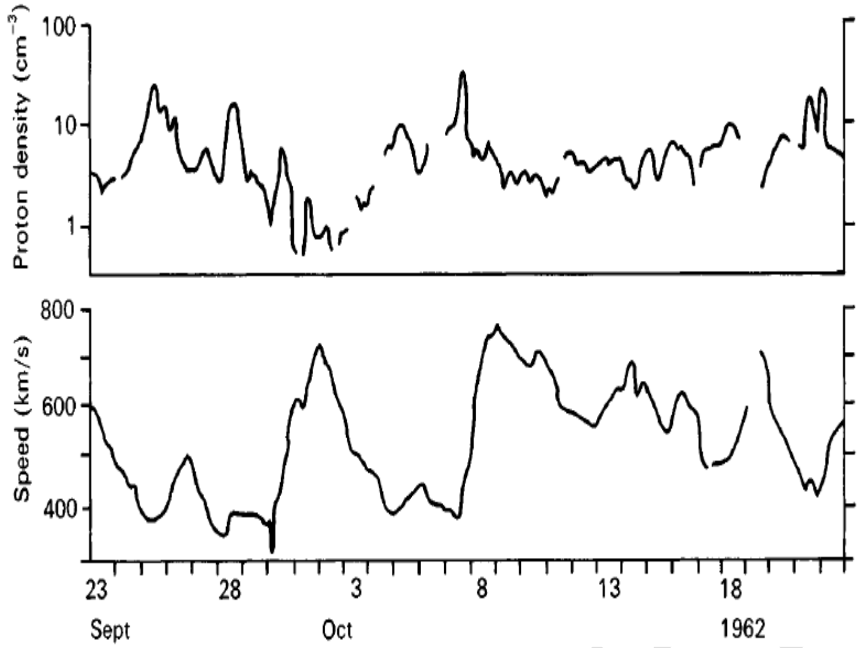


Figure (10) Density and speed of the solar wind over one solar rotation.

Earth's space environment

Introduction

1. At approximately 100 km (or about 60 miles) above Earth's surface, the amount of ionized gas becomes appreciable. Because ionized gas is electrically charged, it feels the effect of Earth's magnetic field, which plays an important role in guiding the motion of charged particles in near-Earth space.
2. Through its interaction with the magnetized solar wind, Earth's magnetic field is intimately involved in coupling or transferring of energy and momentum from the Sun into our space environment.
3. This section describes the magnetic field region surrounding Earth called the magnetosphere. The connection of the magnetosphere with the Sun is at the heart of space weather.

Dipole magnetic field

1. Magnetic fields are force fields around magnets, electric currents, or moving charged particles that exert a force on other magnets, electric currents, or moving charged particles.
2. Like the magnetic field in sunspot pairs or magnets, Earth's magnetic field emerges from one hemisphere with a certain direction and points towards the opposite hemisphere.
3. Imagine a magnet inside Earth with the north magnetic pole pointing south and the south magnetic pole pointing north (see Figure 11).
4. Earth's magnetic poles are not located in the same place as the geographic north and south poles, which are defined by Earth's spin axis. The magnetic dipole axis is tilted by about 11^{o} with respect to the spin axis.
5. In Figure 11, the direction of each field line is indicated; the spacing between the lines represents the strength of the field. Note that the field is stronger at the poles than at the equator. The strength of a dipole magnetic field is two times greater at the magnetic pole than at the equator and falls off very quickly with distance; the strength of the field at the equator decreases as the cube of the distance:

$$|B| \propto \frac{1}{r^3} \qquad \text{..........(3)}$$

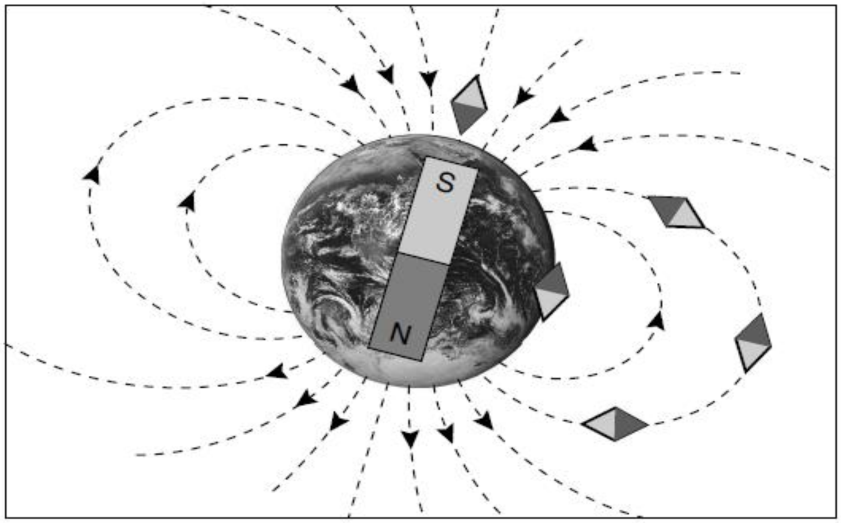


Figure (11) Earth has a dipole magnetic field with the same shape as that of a regular magnet.

Structure of the inner magnetosphere

1. Figure 12 shows a cross section of the magnetosphere in the noon–midnight meridian, with north at the top and the Sun on the left.
2. The regions of the magnetosphere are labeled. Note that the magnetic field resembles a dipole close to Earth. The dipole region of Earth's magnetosphere is called the inner magnetosphere. On the nightside at about geosynchronous orbit (6.6 Earth radii (R_E) from the center of Earth), the magnetic field lines become stretched into a long, tail-like configuration.
3. The interaction of Earth's magnetic field with the solar wind is responsible for the distortion of its dipole field. The non-dipolar regions are called the outer magnetosphere.
4. Immediately surrounding Earth is a region of cold (about 1 electronvolt, eV), dense (tens to thousands of particles per cm^{-3}) plasma that essentially co-rotates with Earth. This region is called the plasmasphere.
5. An eV is a measure of kinetic energy. For a proton, 1 eV corresponds to a velocity of about 14 $km.s^{-1}$. Prove?

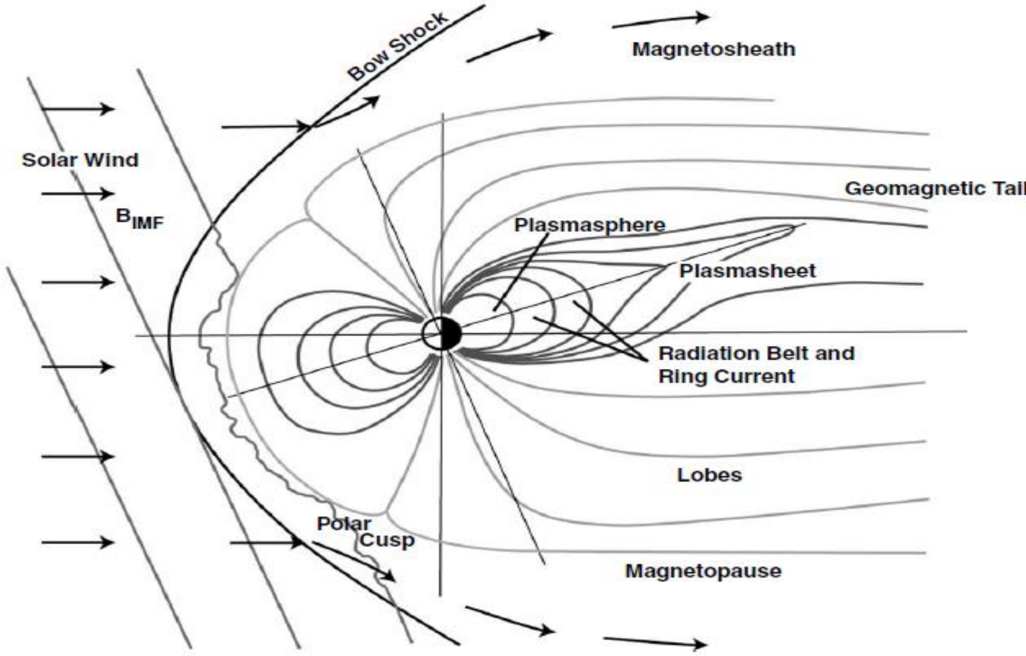


Figure (12) A noon–midnight cross section of Earth's magnetosphere. Note the dipole shape of the inner magnetosphere. The Sun (hence noon) is to the left and north is up.

6. The plasmasphere consists mostly of hydrogen and helium, but also an appreciable amount of oxygen, that have just enough energy to escape from Earth's ionosphere.
7. As plasma drifts up the magnetic field line from below (plasmasphere), it becomes trapped and co-rotates with Earth. There is often a very sharp boundary to the dense plasmasphere called the plasmapause.
8. Often overlapping with the plasmasphere are the Van Allen radiation belts and the ring current. These two regions are characterized by high-energy particles that are trapped in Earth's magnetosphere.
9. The ring current is made up of particles with a peak energy of about 200 Kev, while the radiation belts consist of particles with energies extending into the relativistic regime. Relativistic particles have velocities near the speed of light and carry tremendous amounts of kinetic energy. The ring current is so named because its charged particles produce an electric current that encircles Earth.

Figure 13 is a schematic of the magnetosphere showing both the noon–midnight meridian and the equatorial plane.

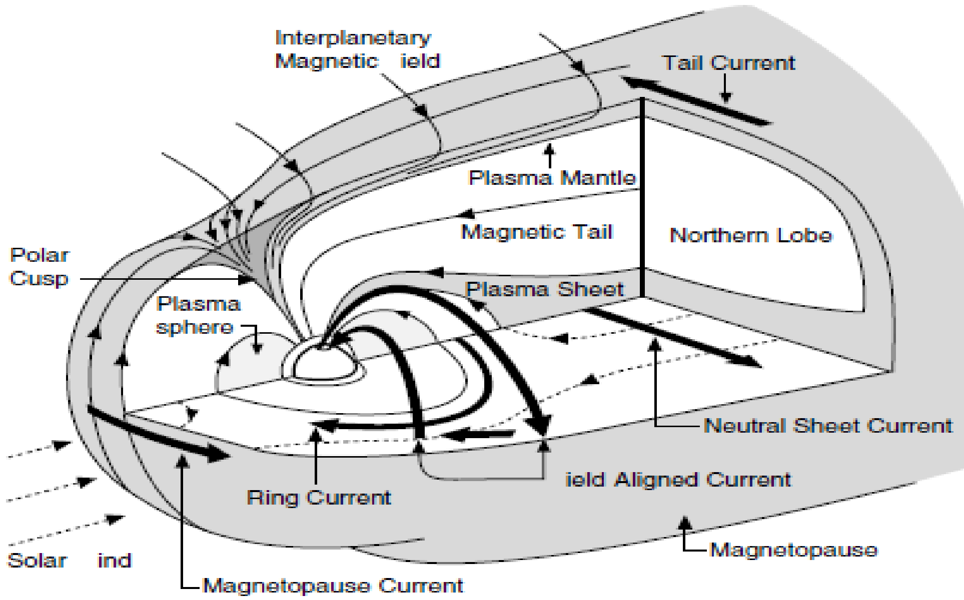


Figure (13) A schematic of Earth's magnetosphere showing the equatorial and noon–midnight meridional planes. The electric currents flowing in the magnetosphere are shown as dark arrows.

10. The solid arrows indicate the directions of the different currents flowing in the magnetosphere.
11. Because of the shape and strength of Earth's dipole magnetic field region, energetic ions flow from midnight to the dusk side, and energetic electrons flow in the opposite direction. This difference in flow directions of positively charged ions and negatively charged electrons gives rise to an electric current, a ring current that circles Earth.
12. This ring current in turn gives rise to a magnetic field that points in the opposite direction to the dipole field at Earth's surface. Therefore, the ring current decreases the strength of Earth's magnetic field as measured on the surface.
13. A magnetic index, called the Disturbed Storm Time Index (or Dst), measures the deviation or change in Earth's magnetic field from its normal quiet time value, the strength of Earth's internal magnetic field. When this index goes negative (indicating a decrease in Earth's field), it is due to intensification or increase in the strength of the ring current.
14. Note that in Figure 13 there are other currents, called field-aligned currents that connect the ring current and plasma sheet to the ionosphere. These currents play a major role in aurora and other space weather phenomena.
15. The radiation belts, named after their discoverer James Van Allen, consist of two distinct regions of energetic particles. The outer belt, composed mostly of energetic electrons, has its inner edge around 3 R_E and its highly variable outer edge usually just beyond geosynchronous orbit. The inner belt, which consists of energetic electrons and protons, extends out to about 2.5 R_E.
16. The radiation belts contain intense radiation that can kill astronauts and damage or destroy sensitive electronics on spacecraft. Understanding this region is one of the main efforts of space weather since many important satellites have their orbits in or through the radiation belts.

Interaction of the solar wind and magnetosphere

1. Within the magnetosphere the dynamics of charged particles (the plasma) are determined by the configuration of Earth's magnetic field.
2. The interaction of Earth's magnetic field with the magnetized solar wind is similar to that of a rock in a stream. The solar wind (stream) encounters Earth's magnetosphere (rock) as an obstacle and moves around it, leaving a wake behind.
3. In the case of Earth and the solar wind, the interaction produces a long magnetotail.
4. Figure 14 is a schematic of Earth's magnetosphere.

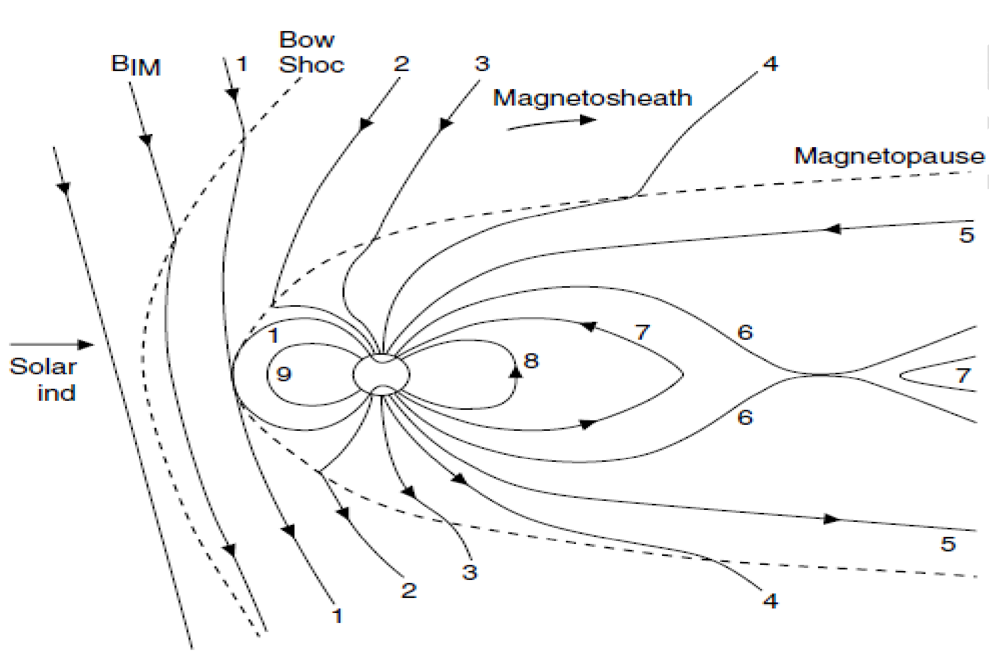


Figure (14) A two-dimensional noon–midnight meridional cross section of Earth's magnetosphere showing magnetic reconnection on the dayside and in the magnetotail.

5. Because the solar wind is supersonic, a shock wave is formed upstream or on the dayside of the magnetosphere.
6. This shock wave is called the bow shock. The bow shock slows the solar wind and begins to divert it around the magnetosphere. The region between the bow shock and the magnetosphere is called the magnetosheath.
7. The magnetopause is the boundary of the magnetosphere. The position of this boundary depends on the strength of the solar wind pressure, which is primarily due to solar wind density and velocity.
8. As solar wind pressure increases, it moves the magnetopause earthward. When solar wind pressure decreases, the entire magnetosphere expands.
9. The location of the magnetopause is determined by a balance between the solar wind pressure and the magnetic pressure of the magnetosphere.

Problems

1. Estimate the time required for a parcel of solar wind with a speed of 800 km s^{-1} to travel from the surface of the Sun to Earth?
2. How long does it take electromagnetic radiation moving at the speed of light to reach Earth from the Sun?
3. If a parcel of solar wind were radially accelerated at 10 km s^{-1} from rest, how long would it take to be going faster than the escape velocity of the Sun?
4. The solar constant, i. e. the flux density of the solar radiation at the distance of the Earth is $1370 Wm^{-2}$.
   (a) Find the flux density on the surface of the Sun, when the apparent diameter of the Sun is $32''$
   (b) How many square meters of solar surface is needed to produce 1000 megawatts?
5. Define 1. Zurich sunspot number *Z*.
   2. Solar Flares
   3. Zeeman Effect,
   4. The Magnetosphere
   5. Differential rotation
6. The corona has high temperature than the photosphere (the surface of the Sun). Explain.
7. The rotation of the Sun on its axis is important in relation to geophysical phenomena. How?
8. What are the main effects of solar flares on the upper atmosphere?