2. The Solar Wind

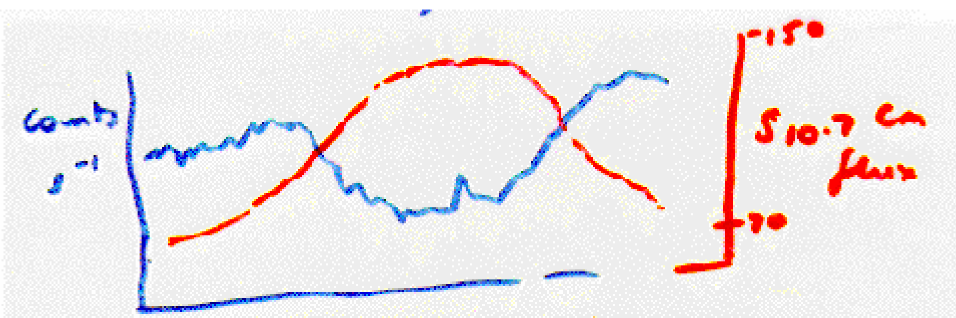
Early evidence of the Solar Wind

Before the satellite age and the ability to measure the interplanetary medium directly there were two pieces of evidence that some sort of solar wind existed. (The solar wind in this case would be a tenuous atmosphere of the sun that permeated the spaces between the planets, and moving outwards from the sun.) The first piece of evidence came from Cosmic Rays.

Cosmic Ray Modulation

In 1912 Victor Hess discovered a "weak but penetrating" radiation which increased with height. It was soon realised this came from outside the Earth, and the term "cosmic rays" coined to describe it. It was also soon realised it comprised of high-energy particle injection, where the particles were mainly protons, electrons and neutrons, with energies from 10's of MeV to many GeV. It has further been discovered that these comprise two types - particles of solar origin (generally the lower energy ones) and those of "galactic" origin - i.e from outside the solar system. What we see at ground level are not generally the primary particles but secondaries - often cascades of particles caused when the primary particles collide with the atmosphere.

If the strength of the galactic cosmic ray influx is measured over a period os measured over a period of time we find that it varies with the solar cycle, only with the opposite phase to solar radiation fluxes like the 10.7 cm flux:



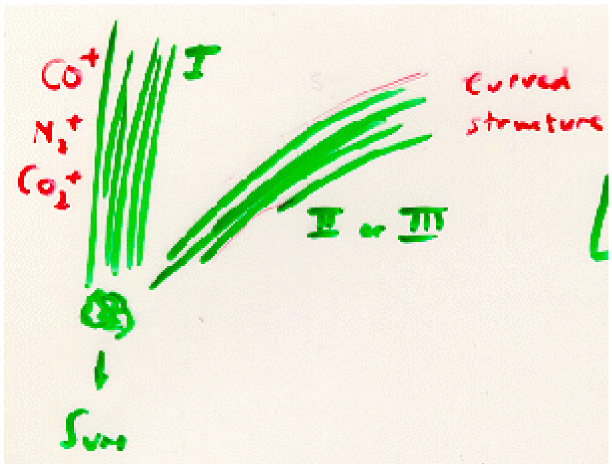
This decrease of the cosmic ray flux at solar maximum is known as the "Forbush Decrease" after its discoverer. It is seen to be more marked with altitude. It is believed this is due to the modulation of galactic cosmic rays by the solar wind and Interplanetary Magnetic Field as they diffuse inwards from the heliopause. The stronger the solar wind/IMF, the more the particles diffuse and effectively deflected away from the inner solar system.

This effect is so marked that it is thought that cosmic ray detection on the Pioneer spacecraft might have been a better way of detecting the heliopause than direct measurement of the organisation of the solar wind particles.

Comets' tails

The other piece of pre-space exploration indirect evidence for the solar wind came from the study of comets' tails. Much of this work is due to Biermann (1951-7).

It had long been known that comet's sometimes had two tails, and that comets' tails were of two or even three types. Type I tails were straight, and pointed more or less radially away from the Sun. Type II and type III were curved, angled to the sun-comet direction, and were known to be dust (< 1 micron pieces) from the fact their spectrum was that of scatterum was that of scattered sunlight. (Where types II and III were taken to be distinct, II was where large lumps of matter seemed to be given off, and III a more "uniform" flow.) Tail I is ionised, mainly CO^+, with some N_2^+ and CO_2^+ (see later in the course).



The Type II tail could be explained by the pressure of sunlight moving small dust particles radially away from the sun. (Accelerations are of the order of solar gravity - about 0.6 10^{-2} m s^{-1} at 1 AU.) Applying radiation pressure to the type I tail, however, showed it to be too small by a factor of 10^3 - one could see the speed with which the particles in the tail moved by tracking discontinuities in it (type I tails display filaments, kinks and knots at times).

Biermann postulated that the motion of the ions was due to their being entrained in a flow of particles being given off by the sun and moving radially outwards. There would be momentum transfer from the proton/electron stream which accelerated the cometary ions according to:

$$\frac{dV_i}{dt} \simeq \frac{e^2 N_e v_e m_e}{\sigma m_i} \simeq 10^{-4.3} \frac{m_e N_e v_e}{m_i}$$

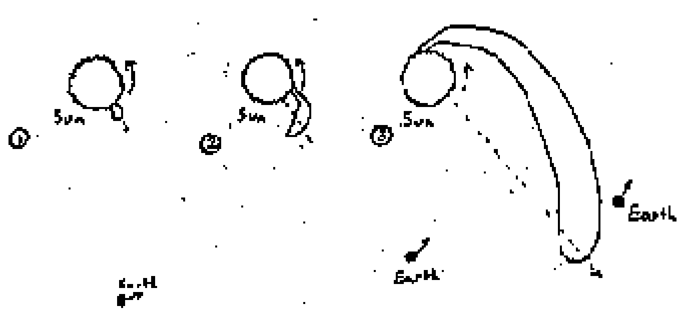
where sigma, the conductivity, is evaluated approximately, and N_e is the electron density on the "wind" stream. By looking at the motions in the tail we can get an estimate for v_e of about 10^3 km s^{-1},P> km s^{-1}, and this gives an estimate of the solar wind density of about 600 electrons per cubic meter. This is too large, but the error is due to our having ignored the "frozen-in" magnetic field (which we shall return to below).

SOLAR WIND

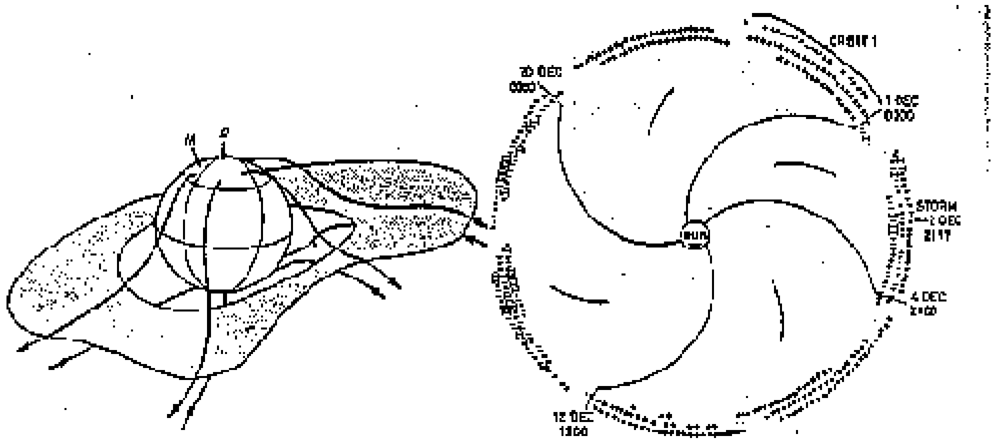
We now know that the solar wind comprises a stream of particles from the Sun moving at speeds of 450km s^{-1} (slow stream) or 700 km s^{-1} (fast stream) more or less radially outwards. The high-speed wind originates from predominantly open field areas in coronal holes. The low-speed wind originates from the predominantly closed field areas near the equator. The solar wind has a variable temperature and composition. On average it has around 5 particles per cc ($5\ 10^{-6}\ m^{-3}$), mainly electrons and protons, though there are some heavier ions. This is an almost completely dissociated **plasma** of effectively infinite conductivity, at a temperature of around 100,000K. It is known to get out to at least 100 AU, though at some point it must meet the interstellar medium at the *heliopause* and be randomised there.

with solar flares/CMEs causing denser and faster outburst. The Ulysses spacecraft has been the first to fly sufficiently far outside the solar ecliptic to be able to confirm the presence of the solar wind at all solar latitudes. This, and work on interplis, and work on interplanetary scintillations, has confirmed the presence of the two types of solar wind flow - fast and slow stream - and the latitudinal distribution of these described above. These two particular speeds seem to be fairly unique, with others (not even intermediate values) being rare. Where fast streams overtake slow streams one sees a shock front.

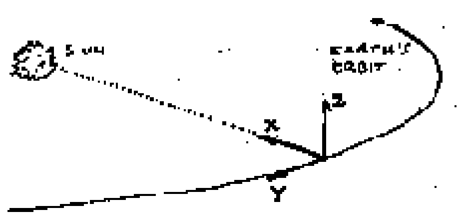
Inside 30 solar radii the solar wind co-rotates with the Sun (bound in with the magnetic field). Outside 30 R_S the magnetic field weakens and the solar wind becomes radial. The magnetic field is then "trapped" in the plasma because of its infinite conductivity (the so-called "frozen-in" field) and so is carried outwards with it. It is then known as the IMF - the Interplanetary magnetic Field - and willbe seen wherever the solar wind is. Because the sun spins beneath the radial flow carrying the IMF, the field pattern going out from the sun resembles an Archimedean spiral (called here the "Parker Spiral"):



This is stretched out mainly in the ecliptic plane of the sun, where currents flow to support the outwards and inwards pointing field lines above and below this plane. The "neutral" plane or sheet will not be completely flat but wrinkled like a popadum, and as the earth orbits around the sun it will pass sometimes above and sometimes below the dividing sheet. Sometimes it will therefore see outwardrefore see outward pointing magnetic field (the "away sector") and sometimes it will see field pointing towards the sun (the "towards sector"):



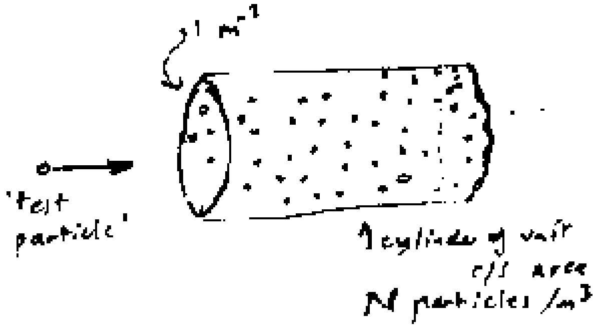
We discuss the IMF often in terms of its component parts, B_z in]the direction north from the ecliptic plane, B_x towards the sun and B_y in the opposite direction to the earth's orbital motion vector. These components are important (especially B_z and B_y) when considering interactions of bodies with the solar wind and IMF.



The solar wind as a fluid

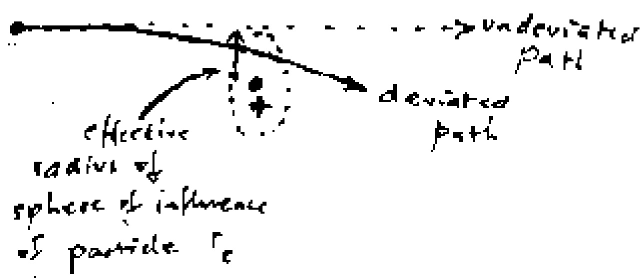
It is important when looking at the behaviour of the solar wind to know whether we have to treat it as individual particles, or whether we can treat it as a fluid (which makes calculations of its bulk behaviour much simpler). To decide on this we need to know on what scale sizes the particles interact. Here the concept of the "effective mean free path" is important. A particle entering a group of others must be affected if we are to assume it acts as a fluid - seen from far away its properties are altered: this is the concept of LOCALIZATION.

From standard gas theory you will remember that the mean free path of a particle is the average distance it goes between collisions. As a very rough approximatin we can say that at distance scales over this we can consider this we can consider the particles as a fluid, since they interact by collisions and this "spreads" effects between them at scales larger than those in which they collide. At scale sizes below the mean free path we have to deal with individual particles. For a hard-body collision where the cross-section of the body is A, we can easily calculate f, the mean free path, since it is the distance one body will travel into the gas with which we are measuring the collision rate before there is roughly 100% chance it will have collided. Taking a 1 square meter tube penetrating into the target:



After 1 meter, the chances of the test particle colliding is equal to the total cross-sectional areas of all the particles in that cubic meter compared to the surface area of the tube (1 sq. m). Thus, probability of collision = NA where N is the number of particles per cubic meter. f is then the distance the test particle will have to travel to have a "100%" probability of collision - i.e. in simple terms 1/NA.
We can apply this idea to particles in the solar wind to calculate how far a solar wind particle must travel before it collides with another. Putting in the numbers above we see the mean free path is much larger than the solar system! (This is a very crude approximation but we are only interested in an order of magnitude calculation.) So we can definitely say that as far as hard-body car as hard-body collisions go the solar wind is not a fluid on planetary scales.

However, if the solar wind were "organised" by other forces in some way, it may have an effective collision cross-section between particles that is larger (and therefore an effective shorter mean free path, f_e). One candidate might be Coulomb forces. The parameter that defines how significant Coulomb forces are in comparison with the thermal energy acting to separate them, is the *Landau Length*, L. We define L as the mean free path derived assuming a collision cross-section given by the deflection of particles due to Coulomb collisions:



Here we see the deflection produced by Coulomb attraction as a charged particle passes close to another (assumed for simplicity here to be so large it doesn't move itself). We can see that the deflecting particle now has an effective cross-sectional area given by the radius r_e, and we can find this approximately by assuming it is the distance scale at which the Coulomb potential energy is approximately equal to the kinetic energy (ie the thermal energy). Thus:

$$\frac{e^2}{4\pi\epsilon_0 r_e} = kT \longrightarrow r_e = \frac{1.67\ 10^{-5}}{T}\ m$$

We define a *close binary collision* if the separation in the absence of the interaction is r_e. The cross-section for close collision is therefore (pi)r_e^2, and if N is t/SUP>, and if N is the number density of particles, by the same argument as above about the relationship between c/s and mean-free path we have L = 1/N(pi)r_e^2

Substituting for (pi) and r_e we have:

$$L = 0.75\ 10^8\ T^2/N\ m$$

Drawing up a table of these values:

	N m^{-2}	T (K)	L(m)
Solar atmosphere	10^{18}	10^4	10^{-1}
Solar Corona	10^{13}	10^6	10^8
Solar Wind	5.10^6	10^5	10^{12}

10^{12}m is about 1 AU, so this again shows that Coulomb interaction does not allow us to treat the solar wind as a fluid on planetary scales.

However, this ignores the magnetic field **B**.

The IMF, as we have said above, is "frozen in" to the solar wind by its infinite conductivity. As it moves out from the sun the expansion of the solar wind means that the strength of **B** must fall off with radial distance from the Sun,adial distance from the Sun, but still at 1AU it has a strength of a few nT. The presence of the magnetic field will cause the charged particles to circle the magnetic field with the appropriate Larmor radius.

If we plug in the appropriate numbers we see that for protons, this radius is of the order of $<10^3$ km. Thus the particles are ordered on this sort of spatial scale. This means that we CAN treat it as a hydrodynamic fluid on spatial scales greater than this -i.e on planetary scales the solar wind acts like a fluid. This is important for the work below where we deal with the interaction with the planetary bodies.

(Note thatthe 10^3 km comes from assuming 400km s^{-1} for the solar wind speed to put into the Larmor radius calculation. One might argue that since this is the radial speed moving out from the Sun, and this bulk flow is what is trapping **B**, so it is moving with the flow, that it is not this but the "thermal" speed of the ions which should be used instead. If you use that one gets a Larmor radius of 100km. Soour argument is still valid. If one considers this problem in full detail and does the calculation "properly" one gets a radius which is intermediate between these two.)

Debye Length

A parameter which is important when one considers plasma is the scale size within the plasma over which a particle "los which a particle "loses its identity". We call this scale size the Debye length. Below this scale size we see the individual particles (with a probing radar, for example), but above this the particles are seen as an interacting "whole" - a fluid or as wave motions in the plasma. Another way of looking at it is that the Debye length:

$$\lambda_D = \sqrt{\frac{\varepsilon_0 kT}{n_e e^2}}$$

is analogous to the free mean path above, so if we take a box

$$\lambda \times \lambda \times \lambda$$

this has a statistical variation in N_e (the electron density) comparable to (N_e-N_+), which is the more formal definition.

Using the identity scale size argument, however,we can see how to get something approaching the derivation of the Debye length. (To do this properly takes more work than we need to put in here: we are just trying to get a feel for its meaning and rough size.)

For an "unshielded" charge (or close to one in a plasma) the electric field falls off as:

$$E \propto \frac{1}{r}$$

but where it is "shielded" by other charges in a plasma we might expect there to be an exponential fall off with a scale size given by the Debye length:

$$E \propto \frac{1}{r} e^{-r/\lambda} \qquad \lambda = \text{Debye Length}$$

Taking a volume within that Debye length:

$$\frac{4}{3}\pi \lambda^3$$

This contains charge:

$$\frac{4}{3}\pi\lambda^3 n_e e$$

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And we have a potential energy here (at

$$r = \lambda$$

of:

$$\frac{Q}{4\pi\epsilon_0\lambda} e \left\{\exp(-1)\right\}$$

where Q is the charge contained in the volume, given above, hence the potential energy is:

$$\frac{4}{3}\pi\frac{\lambda^3}{4\pi\epsilon_0\lambda} n_e e^2 \exp(-1)$$

We can set take it that if this potential energy equals the kinetic energy of a particle passing this point that anything outside this distance can "escape" the central charge. Thus the point at which the potential energy balances the kinetic energy is a sort of "sphere of influence" of the central charge. The Kinetic energy of a particle is given by 3kT/2, so setting this equal to the p.e. above and rearranging, we have:

$$\lambda = \sqrt{\frac{3}{2}kT \cdot \frac{3\epsilon_0}{n_e e^2} \cdot \exp(+1)}$$

This is the same as the "proper" equation for the Debye Length given above apart from a numerical factor.

Typical Debye Lengths

Typical values of Debye Length under different conditions we might encounter are given in the following table:

Plasma Type	Density m^{-3}	Temperature(eV)	Debye Length (m)
Interstellar	10^6	10^{-1}	1
Solar Wind	10^7	10	10
Solar Corona	10^{12}	10^2	10^{-1}
Solar atmos	10^{20}	1	10^{-6}
Magnetosphere	1		
Magnetosphere	10^7	10^3	10^2
Ionosphere	10^{12}	10^{-1}	10^{-3}