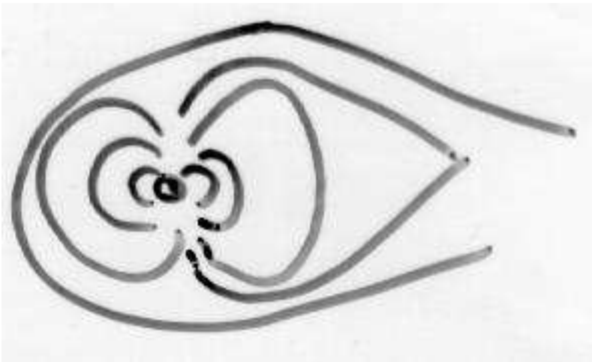
3. The Solar Wind - Interaction with Solar System Bodies

The Earth's Magnetosphere

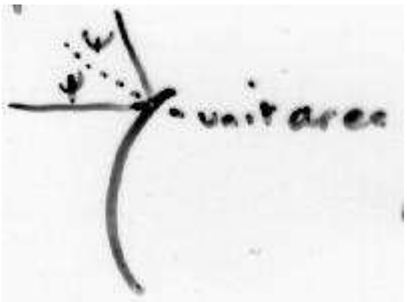
The solar wind impinges upon an Earth which is "protected" by its magnetic field. To a first approximation we can consider this a dipole field - angled slightly to the Earth's spin axis and somewhat offset from centre:

The charged particles of the solar wind are deflected by this magnetic field, so that the earth's field effectively forms a barrier, and we can say that the Earth is insulated from the particles of the solar wind by this protective barrier. The outer limit of the Earth's field influence is known as the "magnetopause". The volume within, where the earth's field dominates, is the "magnetosphere":



We can calculate the stand-off distance of the sun-side magnetopause by considering the balance of forces there. Note that it is generally true that the "stand-off" point which is the nearest point the solar wind and IMF get to a planet will in general be determined by the balance of forces between the solar wind environment and the planet's environment. Thus, if the planet has no atmosphere and no magnetic field, the balance will just be that the solar wind is shat the solar wind is stopped by the planet's surface. If it has either a magnetic field or an atmosphere, however, there will be a balance where the pressures in the two environments cancel each other out. Both solar wind and planet in general will have a particle pressure (atmospheric pressure or momentum pressure in the case of the solar wind) and a "magnetic pressure" $B^2/2[mu]_0$, where $[mu]_0$ is the permeability of free space. Thus for any planet we find the balance point or stand-off point by calculating the point where magnetic plus gas pressure from the two environments balance.

If we calculate the momentum pressure and magnetic pressure in the solar wind we find that, at 1AU from the sun, the particle pressure dominates. Obviously at the surface of the earth this is also true, but gas pressure falls off much faster than magnetic pressure from the earth's surface, and a little working out will show that the magnetic pressure dominates above the thermosphere. Thus, to find the stand-off point for the earth we equate particle momentum "pressure" due to the solar wind, with magnetic field pressure due to the earth. Thus we can treat this by looking at a particle "reflected" off the magnetopause:



The change of momentum of a single particle will be given by 2mvcos[psi], and the number of reflections per unit surface ions per unit surface area of solar wind particles will be vN/sec[psi] or vNcos[psi]. {m and v are mass and velocity of solar wind particle, N the particle density - no. per cubic meter - and [psi] the angle shown in the diagram.}

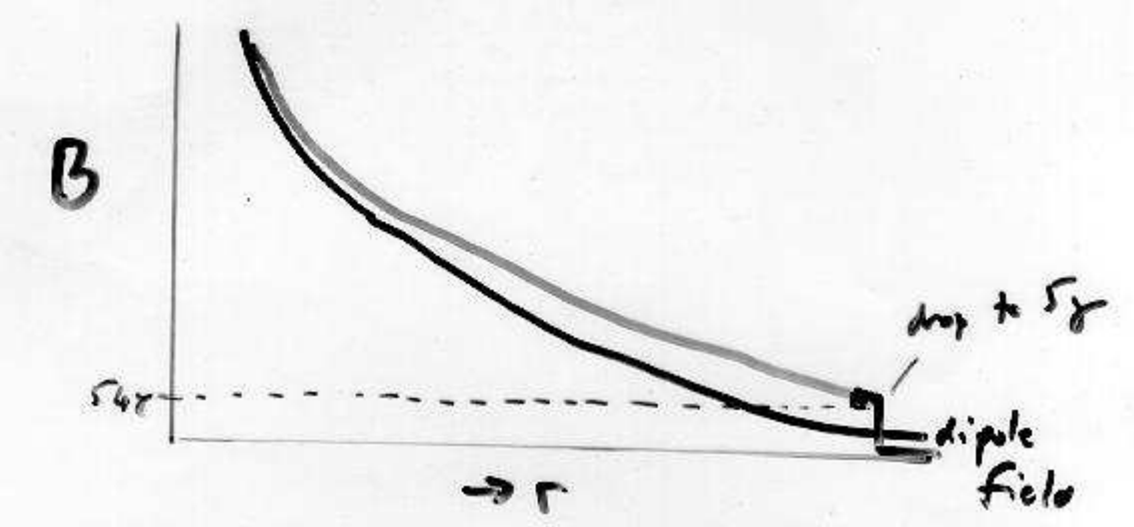
This gives an equation from which we can find the magnetic field strength at the boundary:

$$\frac{B^2}{2\mu_0} = 2mv^2 N \cos^2\psi$$

$$\psi = 0 \text{ (subsolar point)} \qquad B \approx 54\gamma$$

From the magnetic field strength at the boundary we can calculate how far out the stand-off point will be from the earth, since we know that a dipole field falls off as distance-cubed (B prop. to $1/R^3$).

There is one complication, that the Earth's field is compressed by the solar wind flow and so we do not get a dipole fall-off as $1/R^3$, but rather a faster fall off of B from the earth, followed by a sudden drop to the value in interplanetary space (the IMF) at the magnetopause:



The field magnitude at the boundary is actually twice what it would be without the compression, and so we are at a position where the dipole field would, without compression, be 27 nT (gamma). Thus:

$$27\gamma = B_E \Big/ \left(\frac{R_M}{R_E}\right)^3 \rightarrow \frac{R_M}{R_E} = \left(\frac{B_E}{B_M}\right)^{\frac{1}{3}} = \left(\frac{B_E}{27\, 10^{-9}}\right)^{\frac{1}{3}}$$

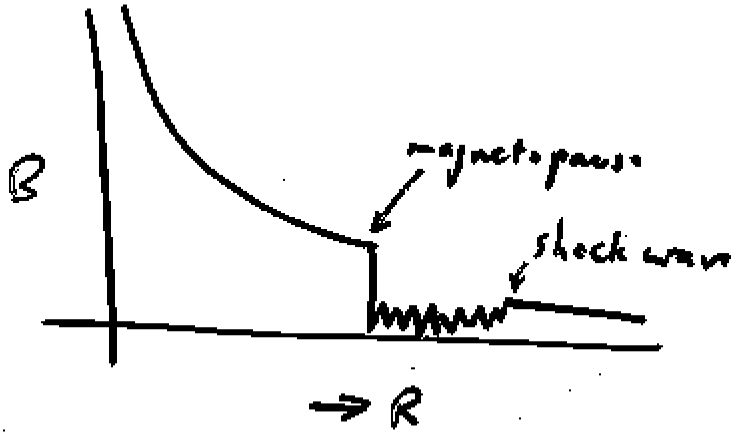
where R_M and B_M are the distance (radial) to, and magnetic field at, the Magnetopause, and R_e and B_E the distance to and magnetic field at, the earth's surface at the same latituh's surface at the same latitude. For an equatorial position (i.e. [psi]=0), B_E is the equatorial field strength.

Putting in the relevant values gives a stand-off distance on this simple calculation of about $11R_E$.

In general we have:

$$\frac{R_M}{R_E} = \frac{B_E^{1/3}}{(4\mu_0 m v^2 N)^{1/6}}$$

A further complication is that the flow of solar wind is supersonic, and so there is a shock wave produced (the "bow shock") in front of the magnetopause, and a region of shocked flow between them:



That the interaction is supersonic can be seen if we consider first the sound speed in a plasma. This is similar to that in a non-ionised gas: you just need to take account of the fact the protons and electrons may have different temperatures, and you will need to use the ratio of specific heats for ionised Hydrogen (=5/3). The sound speed is given by:

$$c_s = \left\{ \frac{\gamma p}{\rho} \right\}^{\frac{1}{2}} = \left\{ \frac{\gamma k}{m_p + m_e} (T_p + T_e) \right\}^{\frac{1}{2}}$$

where gamma is the ratio of specific heats, T_p and T_e the proton and electron temperatures, m_p and m_e their masses, p the pressure, [ro] the density and k Boltzmann's constant. Substituting in the appropriate numbers we find c_s is about 60km s^{-1}, much less than the solar wind speed.

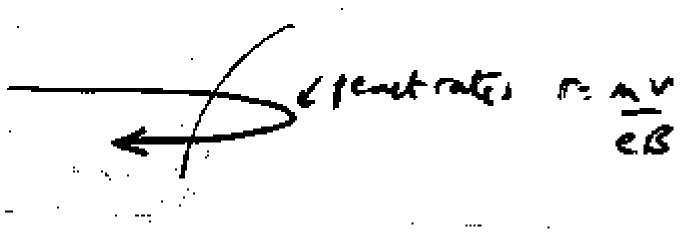
Actually, in the case of a plasma we should look at the other wave modes to do this properly.e modes to do this properly. In plasmas the electromagnetic forces change the response of the system to wave propagation and we can study these by looking at the MHD (Magneto-Hydrodynamic) equations. We solve for travelling waves of the type exp(wt-**k.x**), but the dispersion relation (the relation between k and w) is modified from the simple neutral gas case by the extra electromagnetic forces.

It turns out that a warm MHD plasma like the solar wind has three wave solutions. Two of these are compressional waves, carrying changes of plasma and magnetic pressure and changes of plasma density. The third mode, though, is more relevant to our consideration of how fast information is carried forward in the medium. This is the shear Alfven wave, which acts as the field lines bend in a wave motion (like the transverse wave moving along a string). The Alfven wave propagates with a velocity v_A given by:

$$V_A = \frac{B}{(\mu_0 \rho)^{\frac{1}{2}}}$$

It turns out, though, that this is not a lot different from the sound speed calculated above: so we are still left with the conclusion that the interaction of the solar wind with the magnetopause is a supersonic one.

The solar wind penetrates into the magnetosphere only one Larmor radius before being turned back, so this is a good approximation for the thickness of the boundary layer (the magnetosheath):



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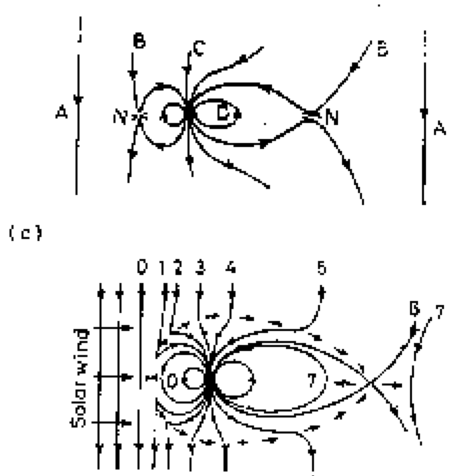
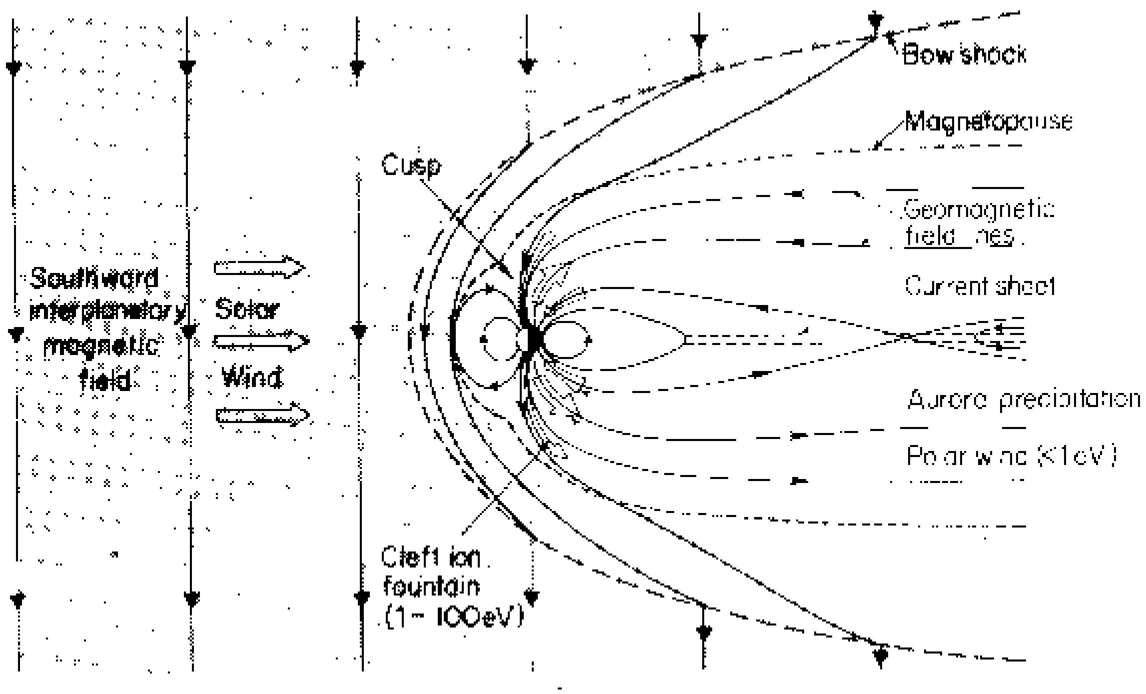
Merging and Reconnection

One consequence of the solar wind having an embedded interplanetary magnetic field (IMF) is that it can interact with the earth's magnetic field. It is believed, indeed, that when the IMF is southward, it can merge with the earth's field at the subsolar magnetopause. The solar wind then carries these field lines over the poles to the tail of the magnetosphere where they can reconnect and return. at lower latitudes, to the sunward side of the magnetosphere (to start the process again).

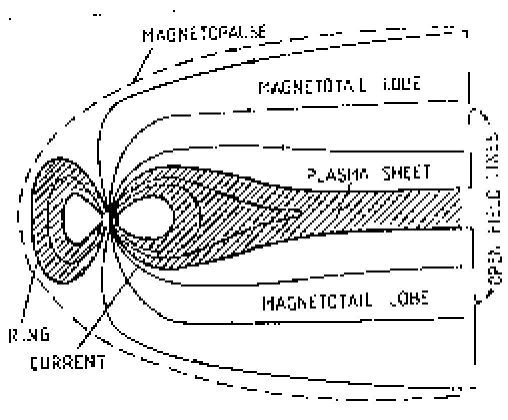


Particles can be accelerated at the dayside merging region, and they can then travel along the field lines earthwards, leading to the dayside cusp or cleft aurorae. Even greater acceleration can take place in the tail where reconnection takes place, and these particles can also travel along the field lines earthwards; nightside aurorae can be very energetic. Note that because of the geometry of this configuration the auroral zone forms a ring around the magnetic poles - that is the auroral zone is some way south of the poles, not at the poles. The area "inside" the auroral zone - ie the area around the magnetic pole bounded by the aurorae, is called the Polar Cap.

Overall then, we can have a complex picture of the solar-wind / magnetosphere interaction when we look at it in detail:



We see that the "tear-drop" shape of the magnetosphere is distended anti-sunward so that the magnetotail is virtually cylindrical for a great distance from the earth. It probably stretches much more than 50-100 R_E. These field lines threading the outer reaches of the magnetosphere from the merging to the reconnection regions are "open" field lines - that is they are connected to interplanetary space, as opposed to the "closed" field lines which co-rotate with the earth at low latitudes (and start and end at the earth). All the open field lines originate in the polar cap, and so the total field threading the top or bottom halves of the magnetotail (the tail lobes) equals the total field flux exiting from the polar cap. To maintain the oppositely directed ("outwards" and "inwards") field lines near the equatorial plane of the megnetotail there must be currents flowing across the neutral sheet which divides the northern from southern lobes.



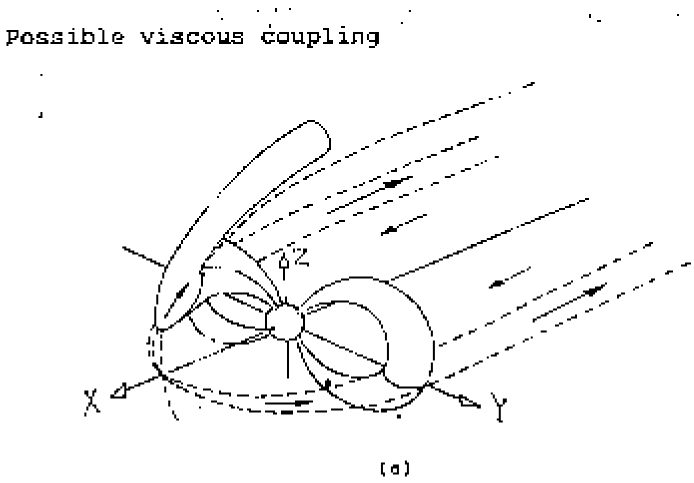
We can see from the diagrams above that there are a lot more complications in the details of the magnetospheric structure; these complications will keep physicists employed for some years yet! One of the features we have not yet considered is the radiation belts which we shall look at below.

Note that, in the general case, the magnetosphere is e, the magnetosphere is pretty well closed so unless there is a source of particles inside, the magnetosphere will contain far less ionised particles than outside. There will be some leakage at the cusp/cleft and at the tail, but otherwise we might expect it to be fairly empty. We are considering here magnetospheres in general, not just the earth's. Things which might contribute to putting particles into the magnetosphere include the exosphere of the planet ("outgassing" from the atmosphere), gases given off from the surfaces or exospheres of bodies like satellites which are enclosed by the magetosphere, and cosmic ray "sputtering (n --> p + e) from the atmosphere or body of the primary body or any satellites. In the case of the earth the moon does pass through the magnetotail occasionally but does not spend a great deal of time there (why??).

The consideration of the loss v gain processes in any specific magnetosphere can be very complex. "Leakage" can be via auroral substorms, diffusion across the magnetopause, discharge from the tail, and adsorption onto bodies inside the magnetosphere.

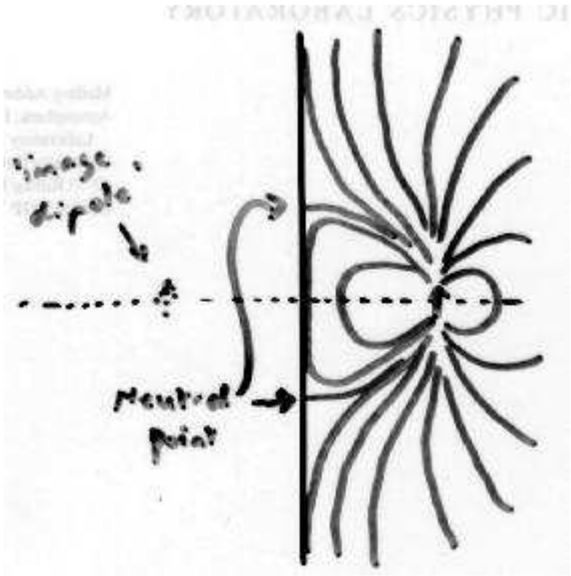
"Viscous" Interaction

Besides the merging-reconnection interaction of the solar wind plasma with the magnetosphere, there is believed also to be a "viscous" interaction setting up a vortex motion in the magnetosphere even when no merging is occurring. This interaction is due to drag on the outside of the flux tubes threof the flux tubes threading the magnetopause, caused by the solar wind passage along the flanks of the magnetosphere:



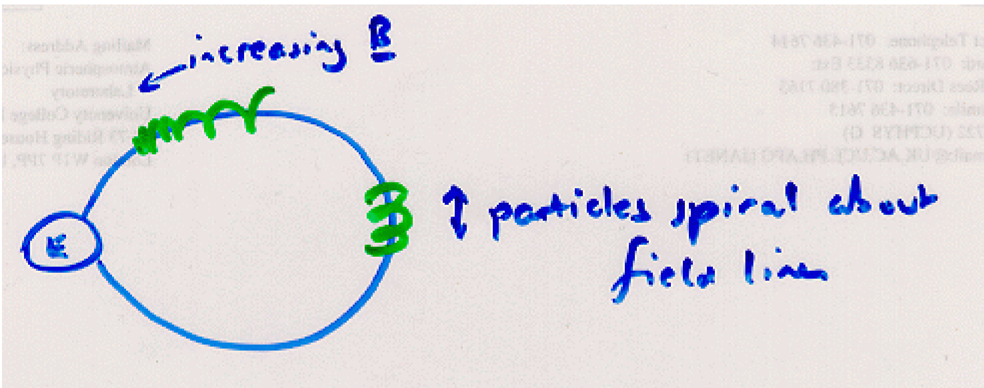
The image dipole analogy

In passing we can mention that another way of looking at the field shape within the magnetosphere is to consider it like the classical representation of what happens when a magnetic field is brought up to an infinitely conducting sheet; this acts as if an "image dipole" were created:



Radiation Belts

We looked previously at the motion of a charged particle in a magnetic field when we studied the IMF. The same **v**x**B** force will cause particles to spiral around the earth's magnetic field lines. motion along the field line is unimpeded and so they move in a helix alongthe field. We can show that for small deviations of the field line from a straight line the particles will tend to follow the field line as a guiding centre. As they approach the earth, the field lines get closer together (i.e the field strength increases) and this leads to a force on the particle tending to slow its motion along the field line (this is the same effect that we see in the "magnetic bottle" or "magnetic confinement" used in fusion reactors). Eventually, where the field becomes strong enough, the particles will "bounce off" and start moving ounce off" and start moving back along the field line in the opposite direction:



Thus particles can become "trapped" in the earth's magnetic field. This leads to the formation of the radiation belts, regions of high densities of charged particles, first detected by Explorer 1 in 1958. (The experiment - basically a Geiger Counter - which made the first detection, was built by van Allen and his team - hence the belts are often known as the **van Allen belts**.)

There are two main belts, an inner and an outer:

The Inner Belt has protons mainly spread from 1.5-2.5R_E, with up to 10^8 particles m^{-2} s^{-1} at energies greater than 30MeV. The electrons are concentrated from 2-6 R_E, again up to 10^8 particles m^{-2} s^{-1} at energies greater than 1.6MeV. The particles are believed to be produced from neutrons in the atmosphere following cosmic ray impact, that is:

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n --> p + e
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The Outer Belt has protons 3-10 R_E, with a maximum at 5R_E, and energies between 0.1 and 5MeV, and electrons 2.5-11R_E, maximum at 5 R_E and energies greater than 40keV.

The inner belt particles are fairly long lived - once created there are very few once created there are very few mechanisms which could remove them (which is why the belts have become so well-populated despite the obvious low creation rate of the cosmic ray mechanism). The outer belt, however, is constantly being disrupted by geomagnetic substorms. These "compress" the field lines and precipitate particles down into the atmosphere at the auroral zones. There must therefore be a mechanism for continual replenishment of the outer belt, and the full details of this are not yet understood. The outer belt could be from in-situ acceleration of (previously low-energy) background particles: but even then we are unsure what might accelerate them.

Note that high fluxes (around 10^{12} $m^{-2}s$) are seen in the outer belt but this is mainly due to the high velocities rather than high densities. The concentration is around 10^2 m^{-3}.

Drift motions of the radiation belt particles

Besides the "bounce" motion of the radiation belt particles they also drift due to various mechanisms:

- Electric fields cause a drift perpendicular to both **E** and **B**, that is:
  $v_0 = (\mathbf{E} \times \mathbf{B})/B^2$
- radial Decrease of **B**:

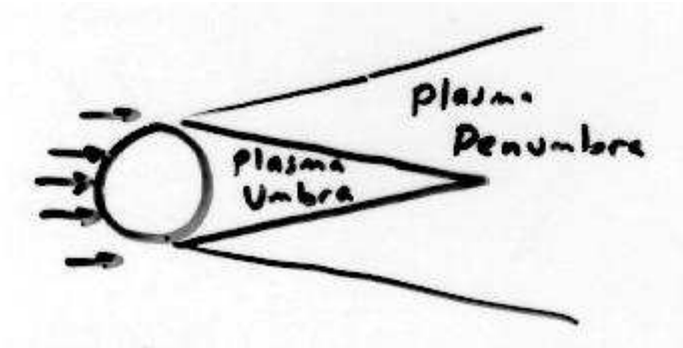
- Curvature of the field lines: This gives a westward drift for protons and an eastward drift for electronsan eastward drift for electrons

Interaction of the solar wind with bodies with no magnetic field:

We can divide this into two types of interaction, depending on whether or not the body encountered has an atmosphere:

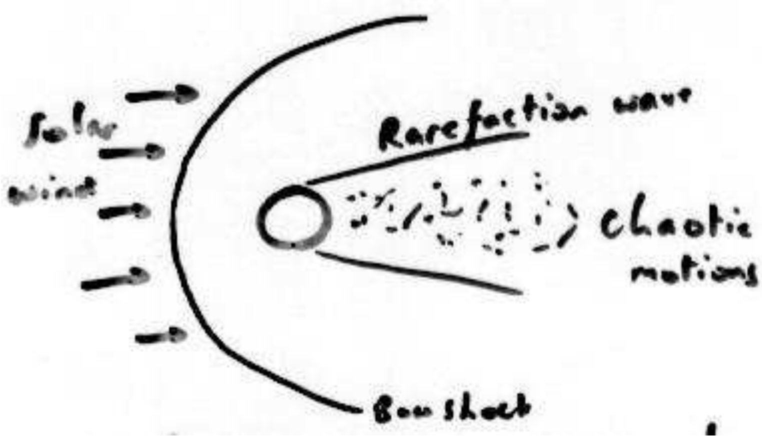
i. No field, no atmosphere

Here we get the interaction we mentioned above: that is, the solar wind particles just encounter the surface off the body and are absorbed or "bounce off". If the body is at all conductive, it "shorts out" the fields. Some particles diffuse around it and so the total particle "shadow" just anti-sunward of the body will be surrounded by a penumbra, and the "wake" will be gradually filled in with solar wind particles a long way downstream.

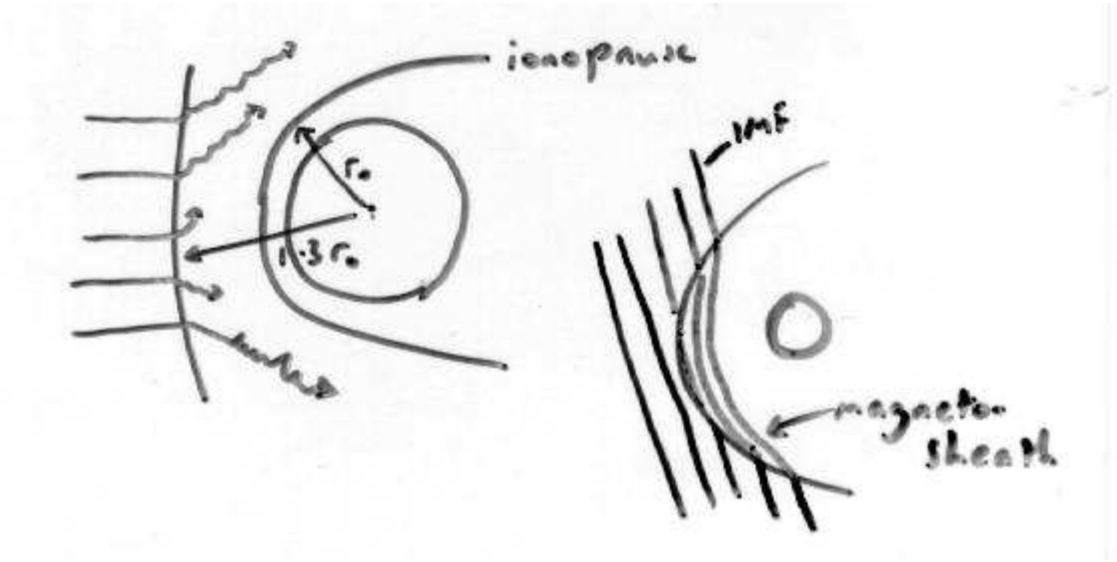


ii. No field, but atmosphere present

Going back to our general comment above in the introduction to the magnetospheric interaction, we again have to consider the balance of pressures at the interface between solar wind and planetary environments. In the absence of a planetary magnetic field, the balance is now between particle pressures alone. (That is, we assume p is greater than $B^2/2[mu]_0$ on both sides of the boundary.) We will get an Ionopause or Anemopause ("where the wind stops") where $p_1=p_2$, p_1 being the pressure in the solar wind, p_2 the presar wind, p_2 the pressure of the planetary atmosphere at the point of balance.



This is believed to be the situation at Venus and Mars, neither of which has a significant magnetic field. We are gradually learning more about this type of interaction as we send more space probes to these bodies, but much of the detail of this type of interaction is still largely conjectural. The interaction is still supersonic so a bow shock is set up, with a boundary layer of turbulent particle flows. The IMF penetrates the bow shock but is distorted in the boundary layer as it is in the magnetosheath of a magnetised planet, and is carried around the planet by the diverted solar wind flow. The details are far from clear though.



In the atmosphere:

$$p_2 = p_0 \exp\{-(r-r_H)/H\} = nkT$$

p_0 being the surface pressure on a planet of radius r_H and H being the scale height (see the lectures on planetary atmospheres).

The static pressure of the solar wind is given by:

$$p_1 = kNmv^2\cos^2[psi]$$

where [psi] is the angle on the ionopause defined as in the magnetopause case above. k is a constant depending on the interaction, and in the case of Mars and Venus is thought to be aboutars and Venus is thought to be about 0.9.

Venus

$N = 3.10^6\ m^{-3}$

$v = 500\ km\ s^{-1}$

$T = 700K$

$r_0 = 6300\ km$

$n_1 = n_e = n/2 = c.\ 6.10^{10}\ m^{-3}$

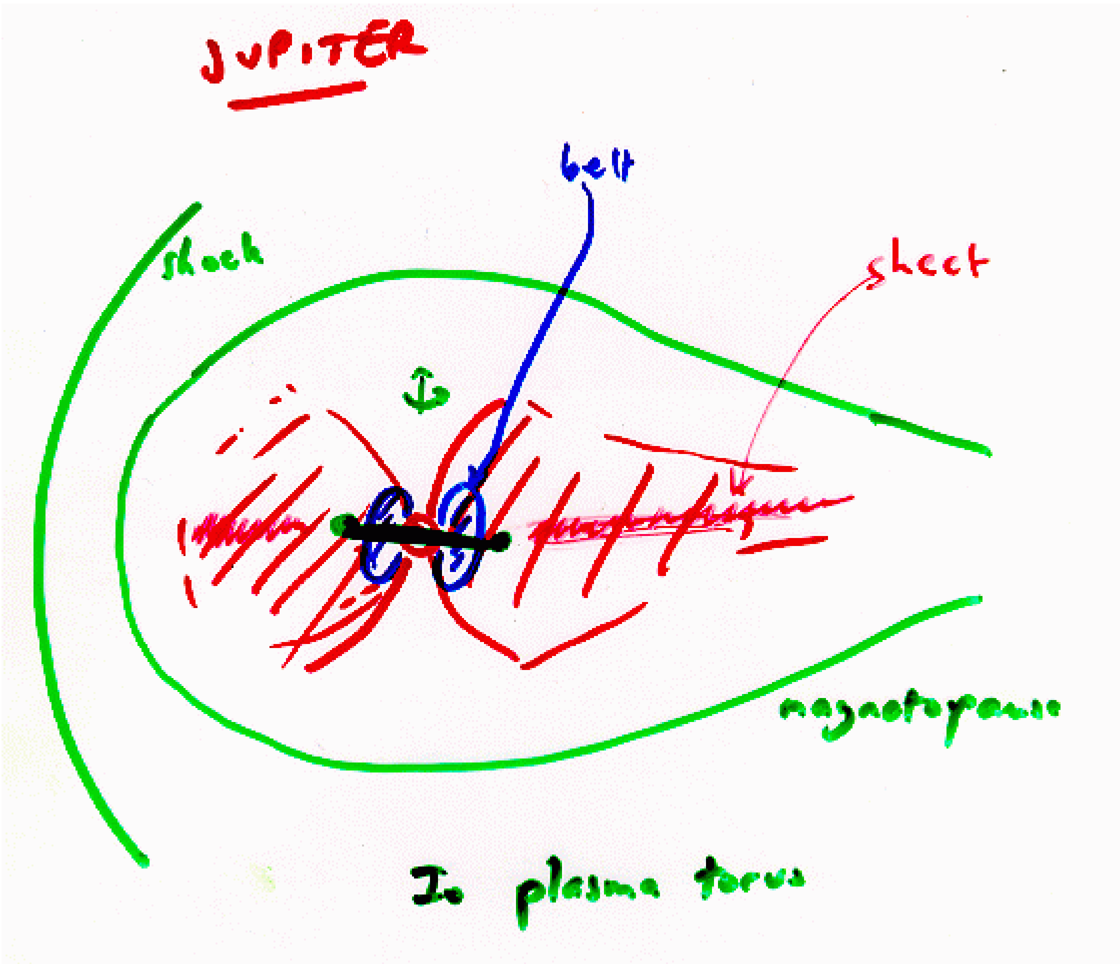
The observed value of r_0 is actually c. 6500km, which is a fairly large discrepancy given the height of about 450km above the ground.

Mars

$N = 1.10^6\ m^{-3}$
$v = 330 km\ s^{-1}$
$T = 200\ K$
$n = 3.10^{10}\ m^{-3}$
r_0 = 155-175 km above the ground (i.e. it is so small it could reach the surface. (R_M = 3393 km)

OTHER PLANETS WITH MAGNETOSPHERES: the GAS GIANTS
The Jovian system

Once we get out beyond the asteroids we are back again to planets which have magnetospheres, like the Earth. Jupiter, indeed, has an enormous magnetosphere because of the very strong magnetic field it possesses. It can be interesting to "compare and contrast" its magnetosphere with that of Earth:



The stand-off distance up-wind is around $100R_J$, which is much greater than the Sun's radius, making Jupiter and its magnetosphere the largest object in the solar system. The tail goes out beyond Saturn's orbit. The very strong Jovian nd Saturn's orbit. The very strong Jovian **B** field is 19,000 times the earth's in dipole strength, 15 times its field density. The dipole is 10.8 degrees inclined to the spin axis and 0.1 R_J off the centre of mass. The particles in the magnetosphere are mainly concentrated in the belts, torus and plasmasheet.

Jupiter's plasma environment motions are complex because of the "floppy" nature of the magnetotail - that is the way it flaps up and down as the inclined magnetic equatorial plane rotates around the spin axis.

The emissions of large amounts of SO_2 from Io, the innermost Galilean moon complicates the plasma environment. It creates a torus about the planet of O+, S+ and S^{2+}. There is a neutral cloud of Na, K and Mg around Ion caused by sputtering. (Note only the ions form the torus as they are constrained by the Jovian field: the neutral species which are ionised to form them tend to move with Io). The Io torus has its sink in the Jovian atmosphere, to which it is connected by field lines. There are active aurora on Jupiter which seem to be linked to the particles from Io.

The belts co-rotate with Jupiter. Beyond the point of Keplerian orbit of co-rotation these move out and form the plasma sheet. The magnetic confinement is weakest at the equator which is the plane in which the plasma sheet lies. Jupiter is a radio-emitter because of the energetic processes in tgetic processes in the magnetosphere. (Wave-particle interactions.)

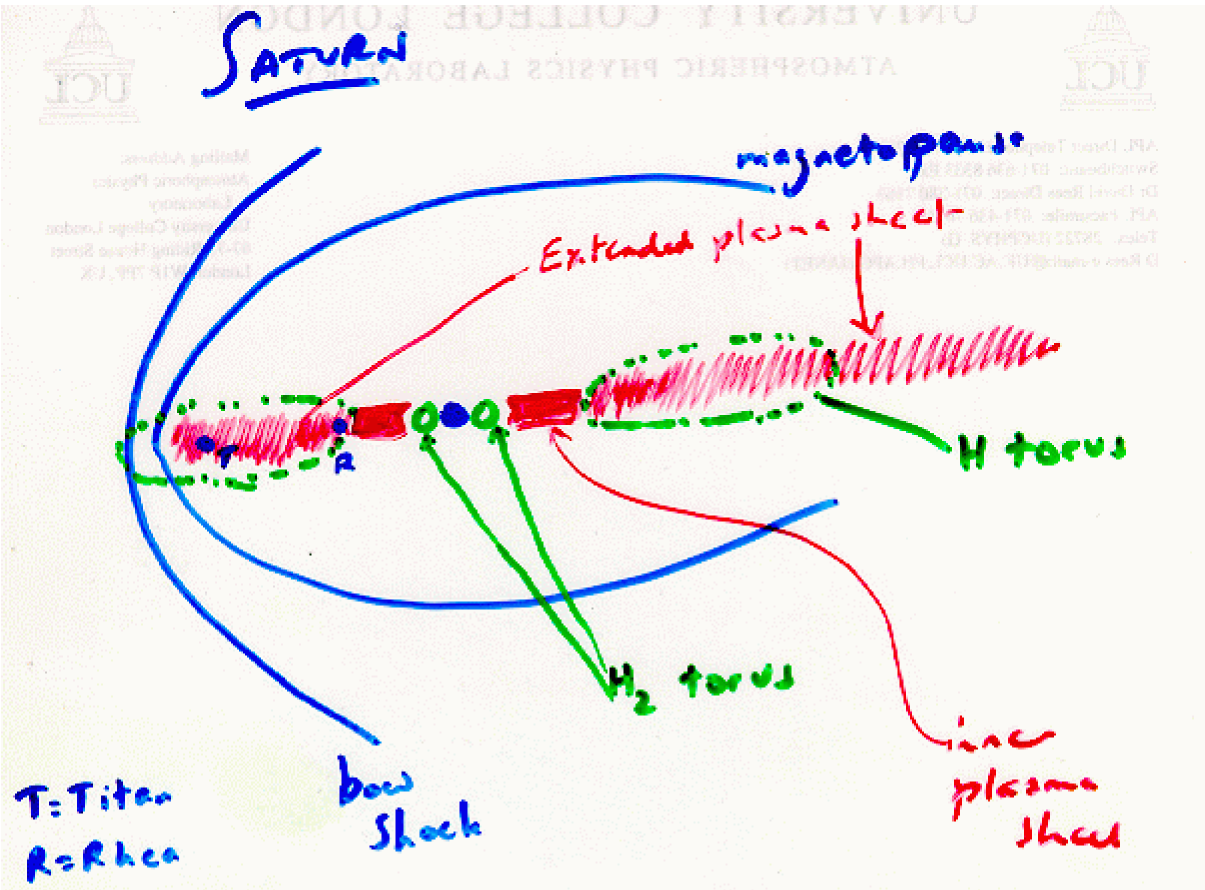
Saturn's magnetosphere

We can again compare and contrast Saturn's magnetosphere with those of earth and Jupiter. We have the familiar magnetospheric cavity bounded by the magnetopause, and a bow shock. Saturn's magnetic field, however, is symmetric about the spin axis and very near the centre of mass, giving a very symmetric magnetosphere, which does not "flap about" like Jupiter's.

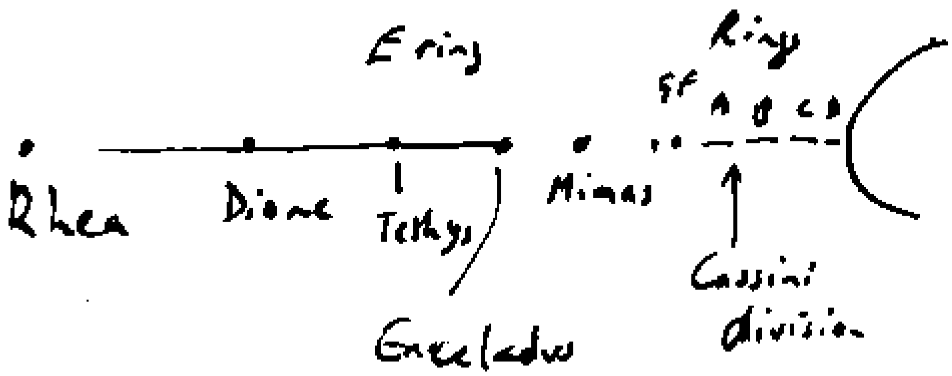
The fact that the magnetic field dipole seems to be aligned along Saturn's spin axis is itself very interesting since theories of magnetic dipole formation normally produce the off-axis morphology. Th fact it is so symmetric suggests that Saturn's field could be decaying or in the process of reversing!

The dipole strength is about 35 times less than Jupiter's (20 x less field density).

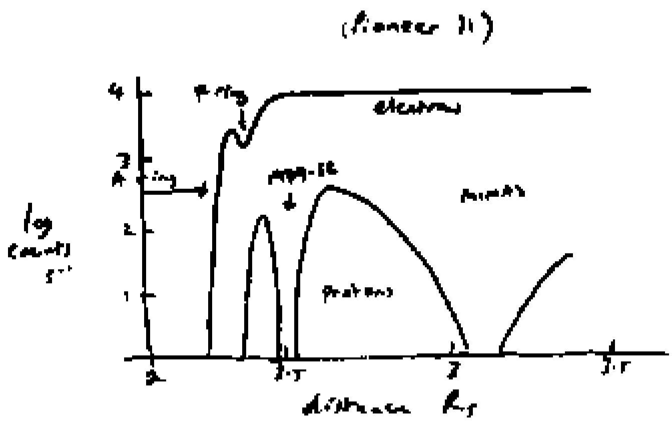
The atomic hydrogen torus seems to come from Titan, which is also a source of Nitrogen. The H_2 torus is probably from water ice in the rings. The plasmasheet is produced by plasma leakage from the belts which are not shown on the figure.



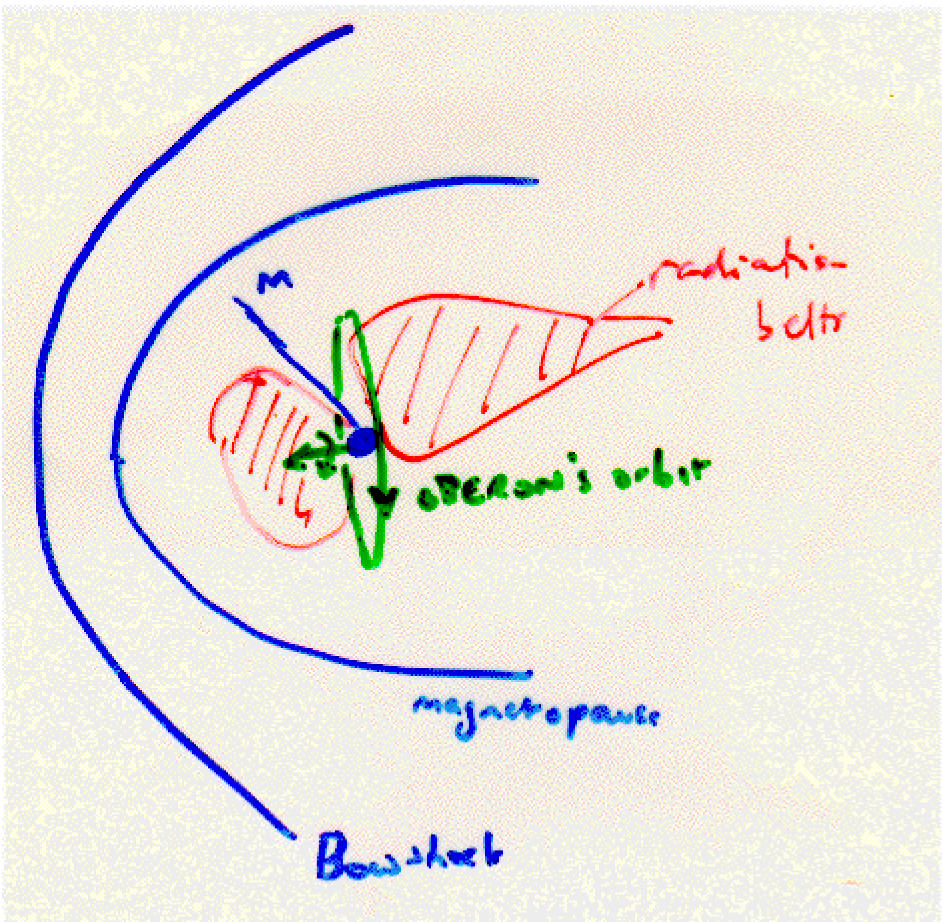
In the inner part of the system the charged particle distribution is controlled by the presence of the rings and the inner satellites:



From Rhea to Mimas the protons arem Rhea to Mimas the protons are soaked up but the electrons continue to diffuse across if drifting at the satellite orbital rates or a harmonic. Inside the orbit of Mimas nearly all the particles have energies around 1.6MeV. Around and inside ring A there are no particles at all since they are all absorbed.



The Uranian System
The Uranian system has its own peculiarities due to the large inclination of Uranus' spin axis. This is combined with a large separation between the spin axis and Uranian magnetic dipole:



The magnetic moment is about 1/10 of Saturn's. The dipole axis **M** is aligned 58.6 degrees from the rotational axis, which is itself near the planet's orbital plane. (The satellites on the whole are in the planet's equatorial plane and so also move in orbits cutting the ecliptic virtually at right angles.) This peculiar set-up obviously means the field configuration "flaps around" a lot, complicating the trapping of the particles. Absorption of particles on the satellites further complicates this picture.

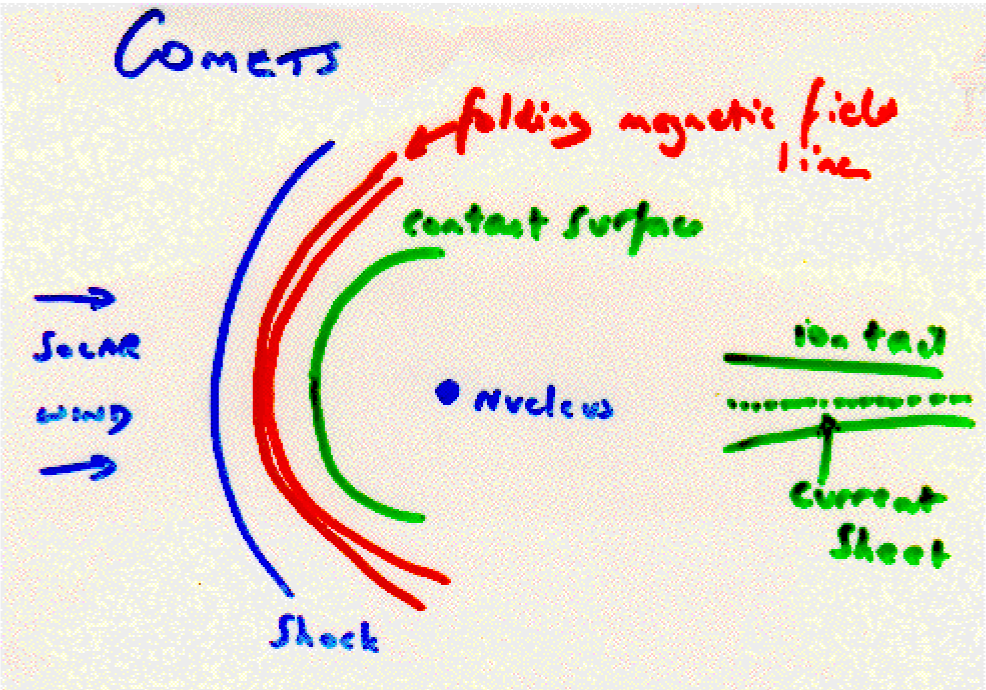
Uranus is also a radio-emitter like Jupiter and Saturn, so there are energetic wave-particle interactions taking place in the magnetosphere.

Neptune

Neptune also has a large magnetosphere, though the fact the planet's spin plane is more conventionally neane is more conventionally near the ecliptic means it is nothing like as exotic as Uranus, with far less surprising features.

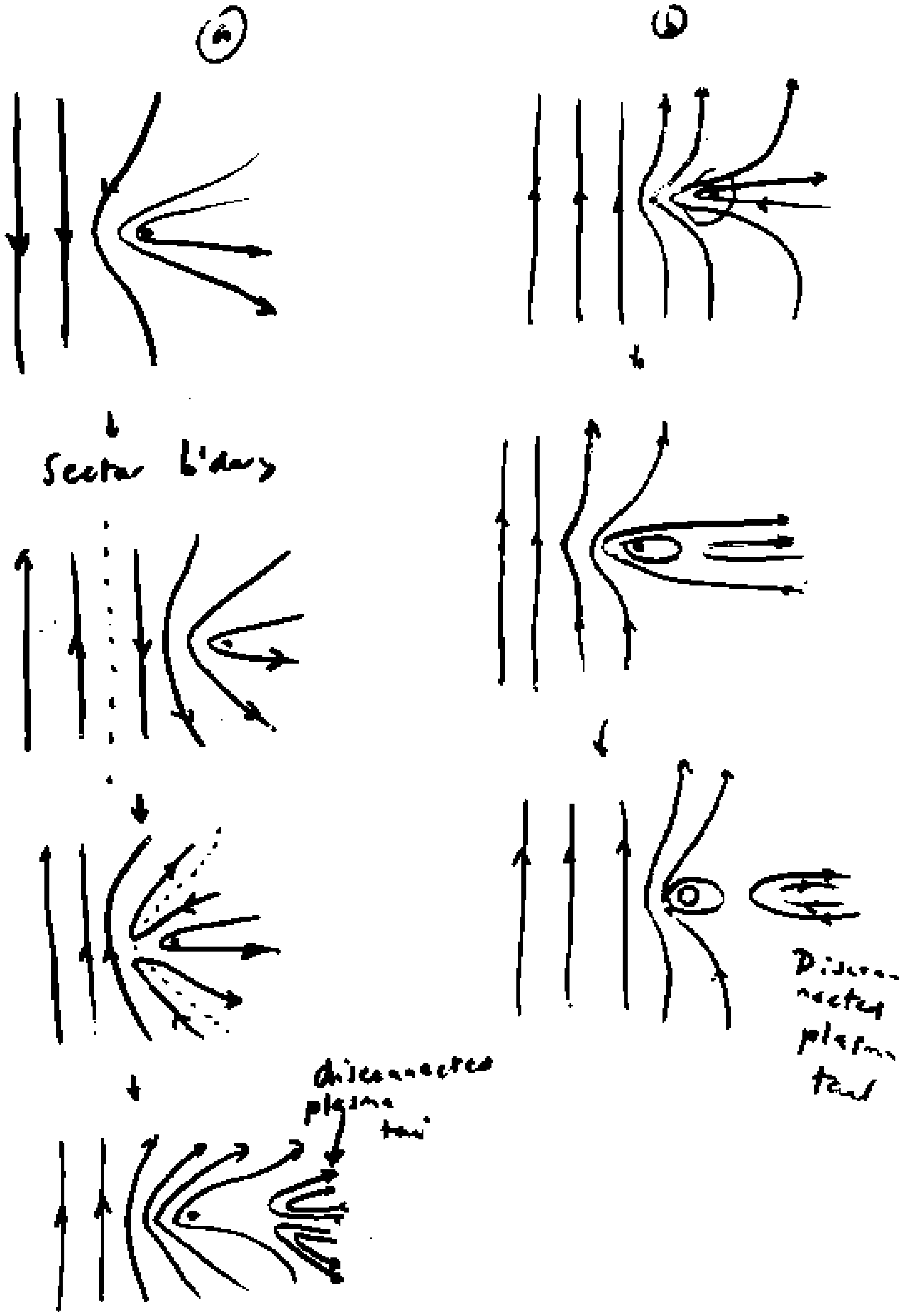
Comets

Since comets have a large ionised environment that accompanies them - at least close in near the Sun, they have a complex, magnetosphere-like interaction with the solar wind:



We have already looked at the comet's ionised tail when discussing the solar wind. More detail on comets' morphology is given in a later section on comets and asteroids.

There has been a lot of work on the effectson the IMF as a comet passes through it. In particular the way that the IMF field lines "wrap"themselves around a comet is still not entirely worked out:



Postscript

We may have, for future lectures, to add another section to this part of the course, as data from Galileo are evaluated. Following measurements by the Jovian probe recently, it now seems that at least two (Galileo and Europa) and maybe three (Io?) of the Jovian satellites themselves have magnetic fields, sufficiently strong to form their own magnetospheres. We now have the strange prospect of having to describe magnetospheres within magnetospheres!