SPACE WEATHER INTRODUCTORY COURSE

SWIC

Collaboration of

Solar-Terrestrial Centre of Excellence

Koninklijke luchtmacht

Koninklijk Nederlands
Meteorologisch Instituut
Ministerie van Infrastructuur en Milieu

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THE MAGNETOSPHERE

Space Weather physics and instrumentation

Johan De Keyser (BIRA-IASB)

This part of the SWIC course deals with the magnetosphere, the magnetized plasma envelope surrounding Earth.

OVERVIEW

- Principles of plasma physics
- Solar wind – magnetosphere interaction
- The magnetosphere at high latitudes
- The magnetosphere at low latitudes
- Quantifying the state of the magnetosphere

We will first briefly review some of the principles of plasma physics to the extent that they are important to this session. We then describe the most important features of the magnetosphere in view of their relevance for space weather. That includes the solar wind – magnetosphere interaction. It is impossible to speak about the magnetosphere without at the same time addressing the ionosphere, since there is a tight coupling between both. We describe this coupling both for high and low magnetic latitudes. More details about ionospheric physics will be provided in a later session. To end, we cursorily describe how the state of the magnetosphere can be quantified.

PRINCIPLES OF PLASMA PHYSICS

Principles of plasma physics

ELECTROMAGNETIC FIELDS

- Electric force
  - Individual particle behaviour
  - Collective behaviour
- Magnetic force
- Interplay between electric and magnetic field and velocity

The magnetosphere is essentially filled with a fully ionized, collisionless, magnetized plasma – as is the solar wind – consisting of charged particles (ions and electrons). As one descends down into the ionosphere, the neutral component becomes important and the plasma becomes collisional. In a collisionless plasma the only forces on the particles are the electric and magnetic fields (gravity is often unimportant). So let us have a brief look at the forces due to the electromagnetic fields.

ELECTRIC FORCE

A particle with charge q in a uniform electric field $\boldsymbol{E}$ experiences a force $\boldsymbol{F} = q\boldsymbol{E}$. Consequently, the particle will be accelerated in the direction of the electric force.

Rule of thumb: A plasma in space must necessarily be quasi-neutral – if not, the plasma would completely rearrange itself.

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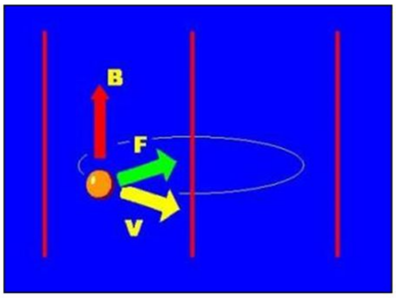
A particle with charge q in a uniform electric field $\boldsymbol{E}$ experiences a force $\boldsymbol{F} = q\boldsymbol{E}$. Consequently, the particle will be accelerated in the direction of the electric force.

An immediate consequence of this is that a plasma must be quasi-neutral. That means that the net charge density (sum of all positive charges minus sum of all negative charges in a given volume) must be very small (typically < 1e-6). If not, very strong electric fields would be created that would immediately force the particles to rearrange themselves.

MAGNETIC FORCES

A particle with charge q and speed $\boldsymbol{v}$ in a uniform magnetic field $\boldsymbol{B}$ experiences a force $\boldsymbol{F} = q\,(\boldsymbol{v} \times \boldsymbol{B})$. Consequently, the particle will make a helical orbit along the magnetic field lines.

Rule of thumb: charged particles follow magnetic field lines.



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We now turn our attention to the role of the magnetic field. A particle with charge q and speed $\boldsymbol{v}$ in a uniform magnetic field $\boldsymbol{B}$ experiences a Lorentz force $\boldsymbol{F} = q\,(\boldsymbol{v} \times \boldsymbol{B})$. This is a force that always is perpendicular to the particle speed and to the magnetic field vector. Consequently, the particle will make a helical orbit along the magnetic field lines with a gyroradius $\varrho = \frac{\sqrt{2mk_BT}}{ZeB}$. An important consequence therefore is that charged particles tend to follow the magnetic field lines, at least as long as the magnetic field is uniform (with respect to the gyroradius scale); the particle speed and gyroradius do not change. Magnetic field gradients or curvature, as well as the presence of an electric field, modify that simple behaviour.

MAGNETIC MOMENT OF A GYRATING PARTICLE

A charged particle that gyrates constitutes a current and thus creates a magnetic field. The magnetic moment of a gyrating particle is

$$\mu = \frac{k_B T_\perp}{B} = \frac{m v_\perp^2}{2B}$$

This is an "adiabatic invariant" since it is exactly conserved during the gyrating motion, and approximately conserved if B changes slowly along the particle trajectory.

Another invariant is the particle energy.

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An example of that is a charged particle that gyrates in a field that slowly varies in strength along the field line.
A charged particle that gyrates constitutes a current and thus creates a magnetic field, that is, it has a magnetic moment $\mu = \frac{k_B T_\perp}{B} = \frac{m v_\perp^2}{2B}$.
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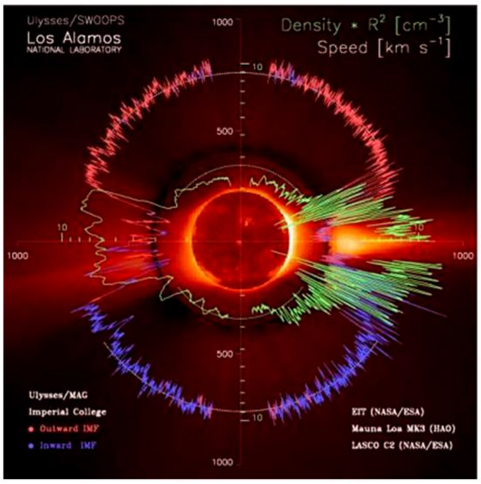
Another invariant is the particle energy.

SOLAR WIND – MAGNETOSPHERE INTERACTION

Solar wind – magnetosphere interaction

THE SOLAR WIND



The solar wind carries the interplanetary magnetic field.

Slow wind:
- V = 300-400 km/s
- 10 /cm3 (1 AU)
- coronal hole edges

Fast wind:
- V = 1000 km/s
- 1-3 /cm3 (1 AU)
- coronal holes

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The Sun is spewing out material into space continuously. This is a magnetized plasma, called the solar wind. The solar wind is pervaded by the interplanetary magnetic field (IMF).

As discovered by the Ulysses space probe, the solar wind has two distinct regimes, which is most evident during solar activity minimum:

Slow wind:

V = 300-400 km/s
10 particles/cm3 (1 AU)
Source: opening of closed loops (at lower latitudes)

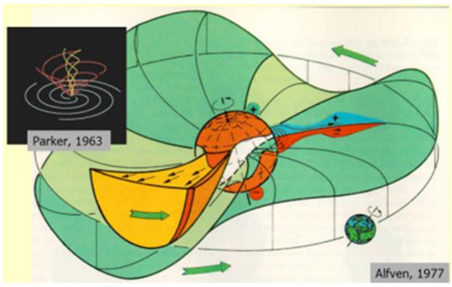
Fast wind:

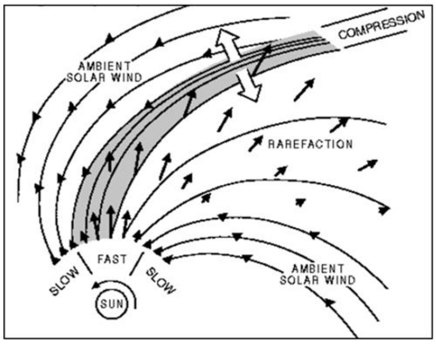
V = 1000 km/s
1-3 particles/cm3 (1 AU)
Source: coronal holes

SECTOR BOUNDARIES

Magnetic sector boundaries are passages of Earth through the (curved) heliospheric neutral surface. They separate alternating sectors of N and S polarity.

When fast wind overtakes slow wind, a co-rotating interaction zone with compressed plasma is formed, that may be encountered on successive solar rotations.





There are two kinds of structures in the solar wind that merit extra attention in view of Space Weather. The first are the so-called sector boundaries or stream interaction regions.

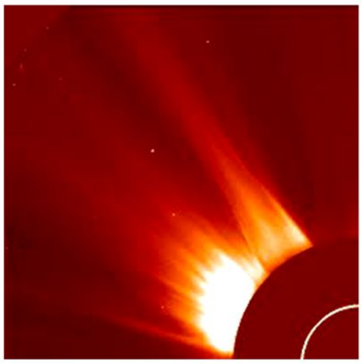
The plane of the Earth's orbit around the Sun (the ecliptic) does not coincide with the (curved) heliospheric neutral surface. Therefore, assuming the magnetic configuration of the solar corona changes rather slowly per solar rotation (~27 days) we observe alternately sectors of N and S magnetic polarity. If the undulations of the heliospheric current sheet have limited amplitude, we simply observe slow wind with alternating polarities. When the amplitudes are larger, however, fast wind overtakes slow wind, thus the Parker spiral angle changes and a corotating interaction zone with compressed plasma (and possibly forward and reverse shocks) is formed. Such a zone may be encountered repeatedly on successive solar rotations.

CORONAL MASS EJECTION

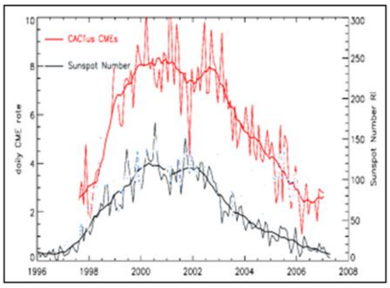
Gas is ejected from the solar corona during a coronal magnetic reconfiguration.

This typically creates a magnetized magnetic cloud. In front of such plasma clouds a shock wave is formed, where the ejected mass is pushing the ambient solar wind aside.

Travel time to Earth (at 1 AU) is 1 to 4 days.



SOHO
LASCO 2



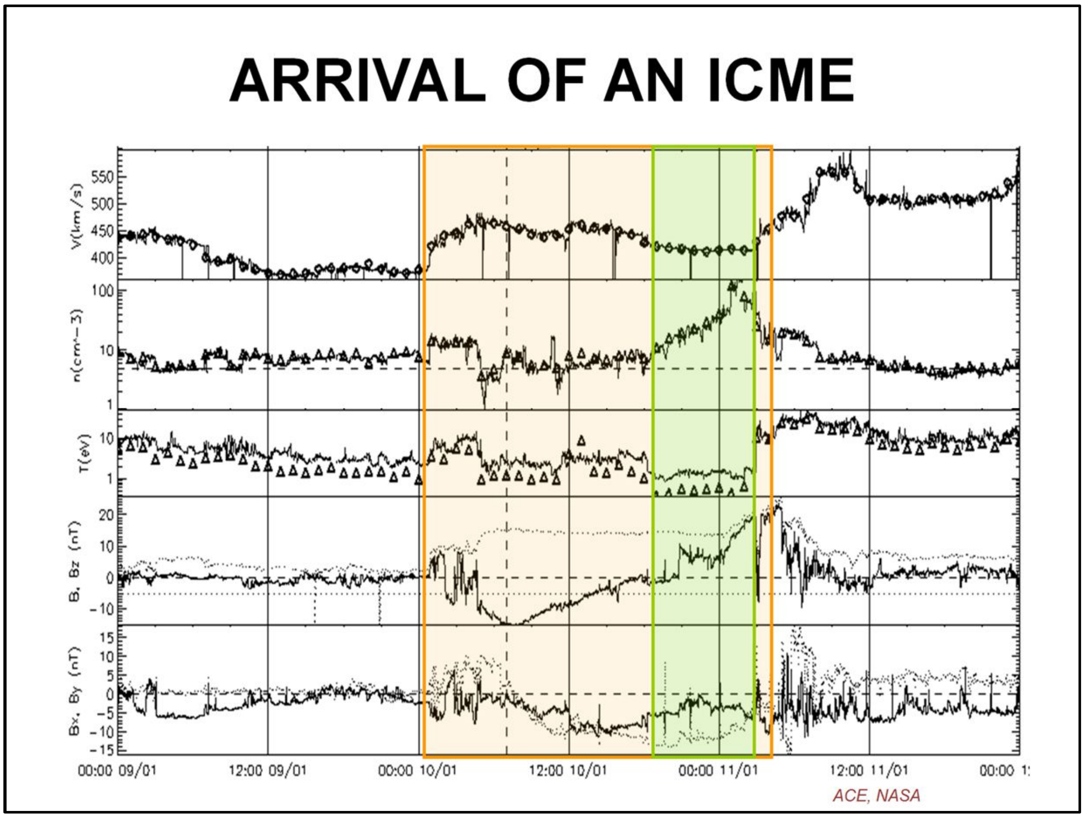
A second type of major events in the solar wind that are important for Space Weather are coronal mass ejections (CMEs).

During such events, gas is ejected from the solar corona. The magnetic structure is largely retained: it forms one big magnetic loop or flux rope, containing twisted field lines, often with dense cold plasma at its core, and with a shock and compression zone in front of it. The gas may have high speed (1000-2000 km/s), but often it may simply have more normal solar wind speeds. In front of such plasma clouds a shock wave is formed, where the ejected mass is pushing the ambient solar wind aside. Travel time to Earth (at 1 AU) is 1 to 4 days.

Frequency of occurrence

1 per day during solar activity minimum

8 per day during solar activity maximum

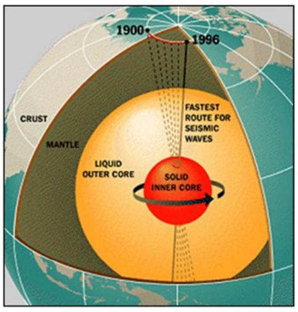


We can observe these magnetic clouds in space as they pass the Sun-Earth L1 Langrangian point, at least if we have a solar wind monitoring spacecraft there. Depending on what part of the cloud passes across the spacecraft, we might get a slightly different picture. Typically we see first an interplanetary shock, then a region with compressed plasma (higher density and temperature), then the actual gas in the cloud with a smoothly rotating magnetic field reflecting the flux rope structure (twisted magnetic field) in the cloud, possibly with the ejected cold, high density coronal plasma at the core of the cloud, and then the end of the cloud.

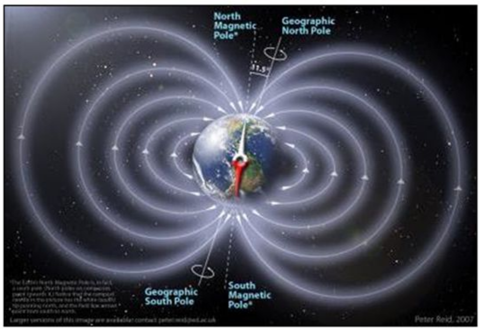
Such observations remain of crucial importance. Although such measurements are made not long before the cloud hits the magnetosphere, these in situ measurements often are the only ones that tell us the magnetic field orientation – which turns out to play a decisive role for the "geo-effectiveness" of the event, that is, how strongly it can interact with the magnetosphere.

THE GEOMAGNETIC FIELD

The Earth has an internal magnetic field. That field is produced in the Earth's interior. It is changing slowly.



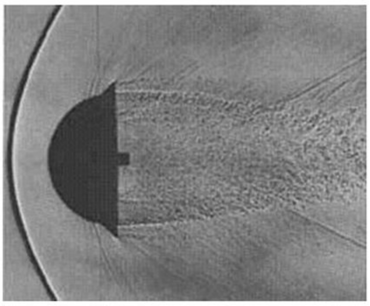
The magnetosphere is the region around Earth that is dominated by the geomagnetic field. It is filled mainly with material from the Earth's atmosphere.



The solar wind is a magnetized plasma. It encounters the environment of the Earth, which also turns out to be a magnetized plasma. Indeed, the Earth has an internal magnetic field. That field is produced in the Earth's interior. It is changing slowly. (The magnetic poles move with a speed of about 10 km/year.) The magnetosphere is the region around Earth that is dominated by the geomagnetic field. The magnetospheric plasma originates in part in the ionosphere; the rest is captured solar wind material.

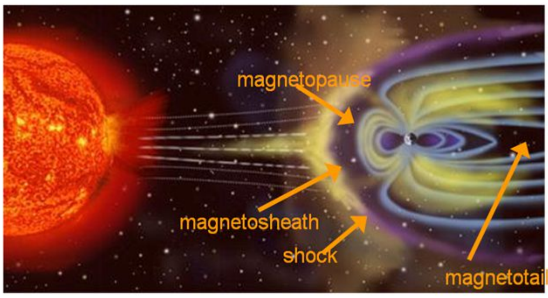
SUPERSONIC FLOW AROUND AN IMPERMEABLE OBJECT

A blunt body fired from a gun against a supersonic flow in a wind tunnel, producing a bow shock, behind which the flow becomes subsonic and is forced around the body.



Since the solar wind consists of particles that follow the IMF field lines, and the magnetosphere consists of particles that follow the geomagnetic field lines, the two do not easily mix. That is, the magnetosphere is like a (soft) impermeable body for the solar wind. Moreover, the solar wind flow is essentially supersonic, so you obtain the same features as when firing a bullet through air, or when flying a supersonic jet through the wall of sound: a shock front forms, behind which the flow is subsonic. A wake is formed behind the object.

MAGNETOSPHERIC REGIONS



The dayside of the magnetosphere is compressed by the solar wind. A bow shock is created. Behind the bow shock is the magnetosheath where the solar wind is deviated so as to flow around the magnetosphere. The boundary between magnetosheath and magnetosphere is the magnetopause. On the night side, a long magnetotail is formed.

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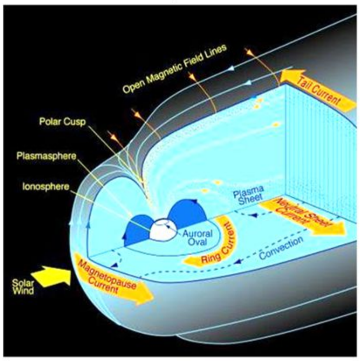
The dayside of the magnetosphere is compressed by the solar wind. Because the wind is supersonic, a bow shock is created. Behind the bow shock is the magnetosheath where the solar wind is deviated so as to flow around the magnetosphere. The boundary between magnetosheath and magnetosphere is the magnetopause. On the night side, a long magnetotail is formed. Dimensions: depends on the solar wind pressure; the subsolar magnetopause is found typically at ~11 Earth radii, the tail stretches over > 100 Earth radii.

MAGNETOSPHERE AND IONOSPHERE

Field lines connect magnetosphere and ionosphere.

- Magnetopause ↔ footpoints of the cusps
- Tail lobes ↔ polar caps
- Plasma sheet ↔ auroral oval
- Plasmasphere ↔ ionosphere at low latitude



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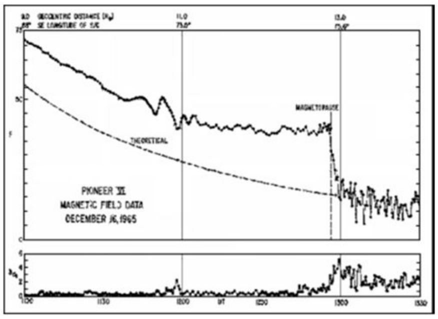
Charged particles can move rather freely along field lines and therefore are good electric conductors. Electric currents flow along the field lines and connect magnetosphere and ionosphere. Therefore every electric feature in the magnetosphere has an “image” in the ionosphere, and conversely. We identify the following regions:

Magnetopause ↔ footpoints of the cusps
Tail lobes ↔ polar caps
Plasma sheet ↔ auroral oval
Plasmasphere ↔ ionosphere at low latitude

Between field lines there can always be changes in field strength or direction. Consequently, electric currents flow there:

Magnetopause current
Neutral sheet current
Ring current

THE MAGNETOPAUSE



Ness et al., JGR, 1966

The first spacecraft that left the magnetosphere already detected the transition between the geomagnetic field and the interplanetary field: That transition is often very sharp as the interplanetary magnetic field (IMF) tends to be weaker, more variable, and has a different orientation.

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The magnetopause is the surface where the shocked solar wind in the magnetosheath comes in contact with the magnetospheric plasma.

One of the first spacecraft that ever left the magnetosphere was Pioneer 6. Upon moving outward from the magnetosphere, it detected the transition between the geomagnetic field and the interplanetary field: That transition is often very sharp as the interplanetary magnetic field (IMF) tends to be weaker, more variable, and has a different orientation. As the magnetopause interfaces two regions with different magnetic field, it must be a current sheet : it carries the magnetopause current responsible for the change in magnetic field.

MAGNETOPAUSE CURRENT

The magnetopause interfaces two regions with different magnetic field. It therefore must be a current sheet : it carries the magnetopause current responsible for the change in magnetic field.

The shocked IMF in the magnetosheath is
- Variable with time (in strength and orientation)
- << than the geomagnetic field.

The stand-off distance of the subsolar magnetopause is typically 10-12 Earth radii but widely varying with solar wind pressure.

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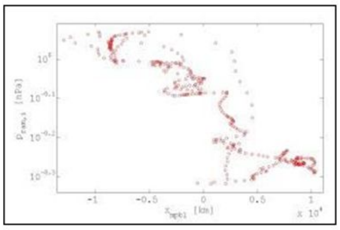
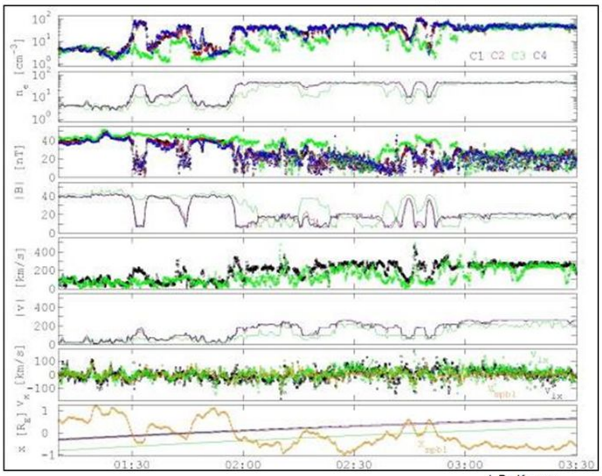
MAGNETOPAUSE OBSERVATION

A spacecraft usually moves slowly along its orbit, much slower than the back-and-forth MP motion. It therefore often detects the MP several times during a pass. That can be seen very well in measurements of the 4 Cluster spacecraft.

ESA



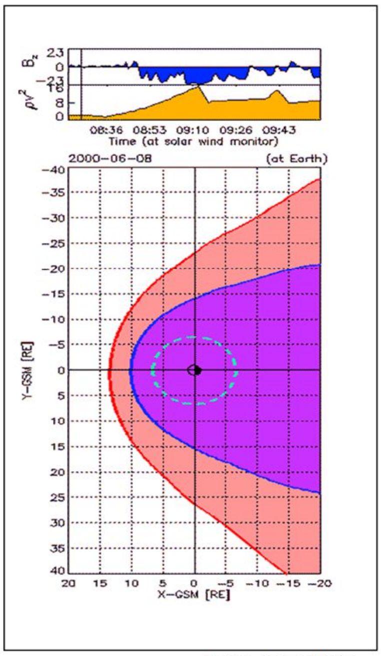


J. De Keyser

A spacecraft usually moves slowly along its orbit (a few km/s), much slower than the back-and-forth MP motion. It therefore often detects the MP several times (multiple crossings) during a pass. That can be seen very well in measurements of the 4 Cluster spacecraft.

MP SURFACE WAVES

Changes in solar wind pressure (mainly the dynamic pressure) cause the magnetopause to move. Together with the tailward solar wind flow in the magnetosheath this produces propagating surface waves.



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Petrinec – Lockheed Martin

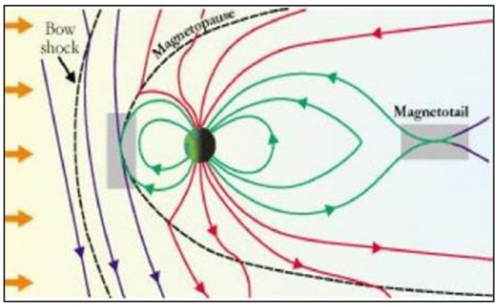
Changes in solar wind pressure (mainly the dynamic pressure) cause the magnetopause to move. Together with the tailward solar wind flow in the magnetosheath this produces propagating surface waves.

Occasionally the magnetosphere can be compressed such that the MP stand-off distance is < 6.6 R_E, i.e. the solar wind can push the MP within geostationary orbit. That implies that telecommunications satellites that typically reside in that orbit are subject to the solar wind environment, which at such times tends to be disturbed and may deliver energetic particles, which is an obvious risk.

THE MAGNETOSPHERE AT HIGH LATITUDES

The magnetosphere at high latitudes

MAGNETIC RECONNECTION



Ch. Day & Physics Today

An (open) field line in the solar wind passes the shock.

A closed field line has foot points in the ionosphere.

Reconnection occurs at the dayside between antiparallel geomagnetic and interplanetary field lines.

Half-open field lines have their far end moving tailward with the solar wind, and accumulate in the middle of the tail.

Reconnection at the night side closes half-open field lines, part of them forced Earthward, part of them tailward.

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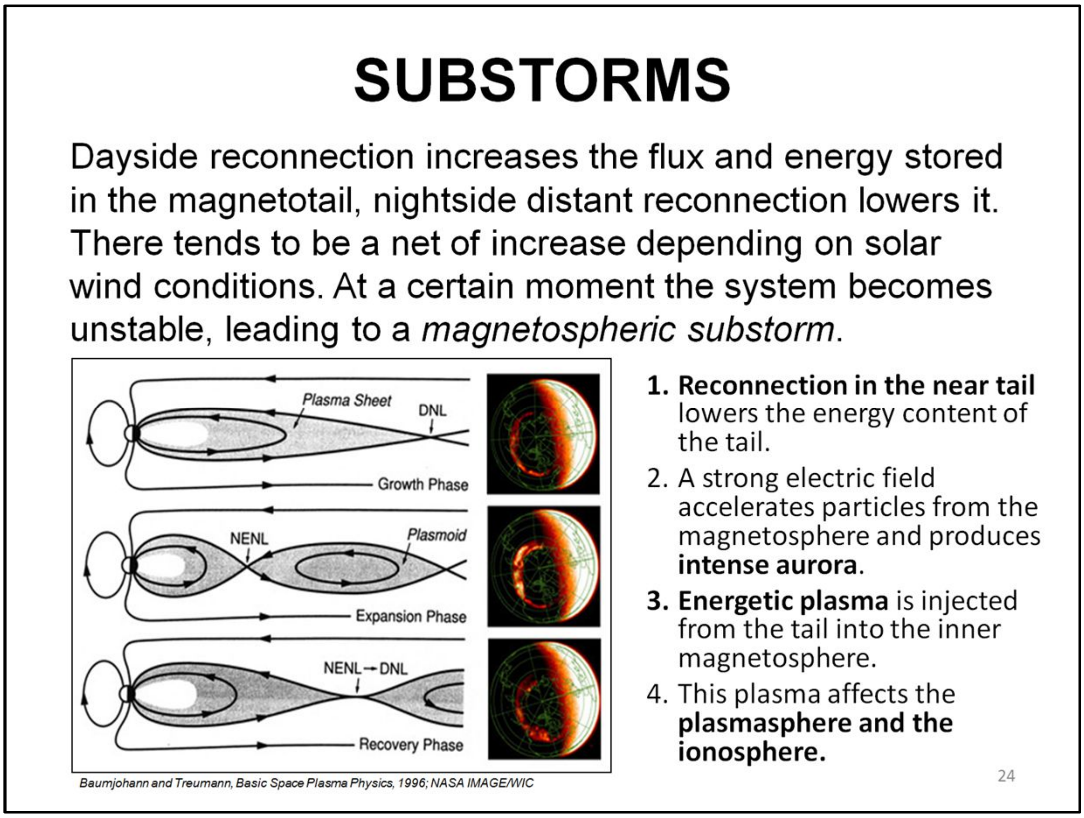
The process of magnetic reconnection plays an important role. While the physical details of this process are still only partially understood, it can be imagined as a process in which magnetic field lines with opposite sense “reconnect” with each other. For the Earth’s magnetosphere, this leads to the so-called Dungey cycle:

- blue: an (open) field line in the solar wind passes the shock.
- green : a closed geomagnetic field line has its foot points in the ionosphere.
- reconnection between antiparallel geomagnetic and interplanetary field lines.
- red : half-open field lines; their far end moves tailward with the solar wind, so that the lines accumulate in the middle of the tail (which creates the dawn-dusk electric field); particles from the solar wind “rain down” on the ionosphere, while ionospheric ions can escape.
- reconnection at the night side closes half-open field lines, which are forced towards Earth, but it also creates open field lines that carry plasma downtail.

This process has its effect on the convection (winds) in the ionosphere.

Note: the process essentially is the same for all IMF clock angles, except when the IMF points roughly northward (in that case, there can be high latitude reconnection leading to a modified scenario)



The Dungey cycle as described above assumes that the reconnection rate at the dayside and at the nightside balance each other exactly. In general, this does not really happen; both reconnection rates depend on the local circumstances.

What typically happens is that dayside reconnection adds magnetic flux and energy to the tail, while reconnection in the distant tail offloads a small fraction of this energy, but such that there is a net rate of increase that depends on IMF and on solar wind speed. After a while, there is just too much energy stored in the tail. The system becomes unstable. Reconnection in the near tail then offloads the excess flux and energy. This initiates a sequence of events known as a “magnetospheric substorm”: a reorganization of the magnetosphere. Below, a simplified picture is sketched:

1. Reconnection in the near tail lowers the energy content of the tail.
2. A strong electric field accelerates particles from the magnetosphere and produces intense aurora.
3. Energetic plasma is injected from the tail into the inner magnetosphere.
4. This plasma affects the plasmasphere and the ionosphere.

Note that this is a quasi-periodic cycle that the magnetosphere goes through every few days.

GEOMAGNETIC STORMS

We have seen how a – relatively minor – change in the solar wind can trigger changes in the magnetosphere: a substorm.

When a major solar wind perturbation occurs, such as when a geoeffective magnetic cloud produced by a CME reaches Earth, or when the Earth encounters a strong corotating interaction region, the same series of events takes place as during a substorm, but in a more intense fashion, plus some additional phenomena. We then speak of a *geomagnetic storm*.

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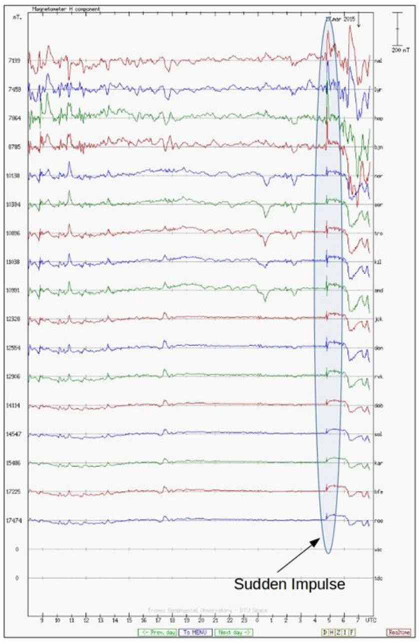
MAGNETIC SIGNATURE

When a (CME or CIR) shock hits the magnetosphere, this leads to a sudden magnetic field change recorded on the ground as a Sudden Impulse (SI).

Whether a full geomagnetic storm develops, depends on the IMF orientation. If so, we also speak of Storm Sudden Commencement (SSC).



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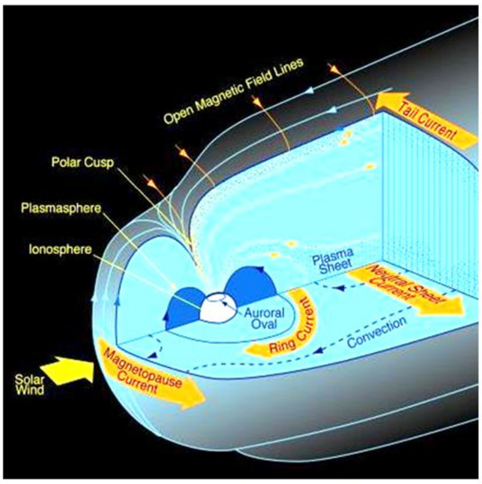
Whether a full geomagnetic storm develops, depends on the IMF orientation. If so, we also speak of Storm Sudden Commencement (SSC). Strictly speaking, Storm Sudden Commencements are defined by an abrupt increase or decrease in the northward component of the geomagnetic field, which marks the beginning of a geomagnetic storm or an increase in activity lasting at least one hour.

PLASMA SHEET

The above discussion of reconnection and the substorm cycle highlights the importance of the plasma sheet.

The lobes are quite empty, the plasma sheet is rather dense.

All this can be understood in terms of the reconnection cycle.



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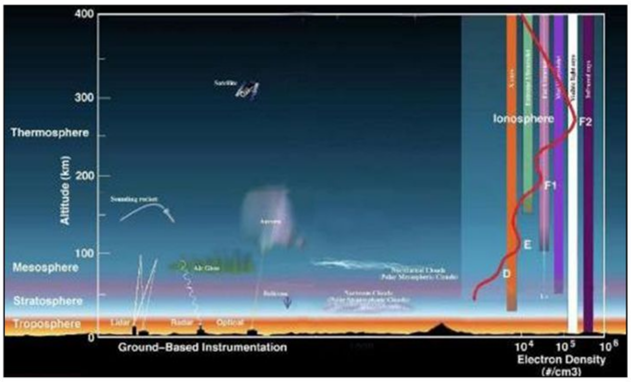
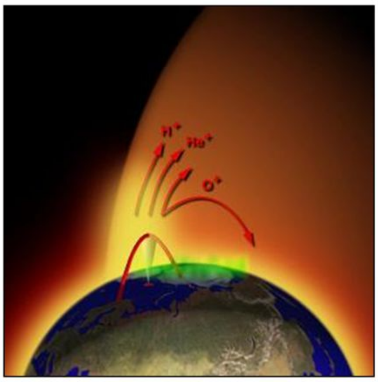
The above discussion of reconnection and the substorm cycle highlights the importance of the plasma sheet. While the magnetospheric lobes are quite empty, this region is rather dense. All this can be understood in terms of the reconnection cycle.

Density gradients in the plasma sheet, in particular at the plasma sheet boundary layer, are prime candidates for the sources of auroras.

IONOSPHERIC OUTFLOW AND THE PLASMA SHEET





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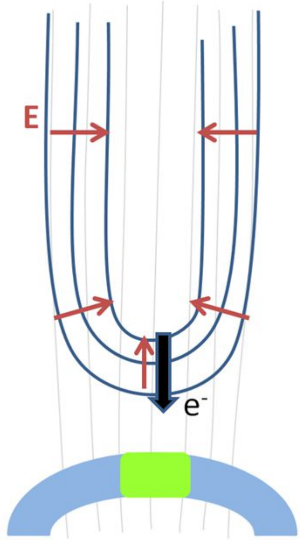
The ionosphere is the partially ionized upper atmosphere. One of the main sources of ionization is solar ultraviolet light. Absorption by specific atmospheric constituents at different altitudes leads to a vertical structure of ionization. Charged particles can move up and flow out of the ionosphere along the field lines into the magnetosphere, mostly H+, He+, O+. In particular those particles that travel along (half-)open field lines can escape directly; those that get trapped in the plasma sheet can return to Earth or escape to space. Additional ionization may be created in auroras, leading to more localized outflows.

Note that magnetospheric particles may also move down and be deposited in the ionosphere, e.g. polar rain, auroral electrons, … So there is two-way exchange, but escape dominates.

AURORAL CURRENT CIRCUIT

During storms and substorms, reconnection and flows in the magnetosphere create potential differences between field lines.

These drive an electric current circuit with currents flowing along field lines and closing in the (conducting) ionosphere. From current continuity, one can understand that this must create parallel electric fields. These accelerate particles – most easily electrons – which bombard the atmosphere and create aurora.



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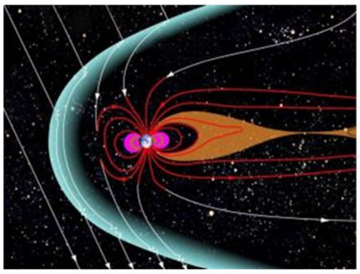
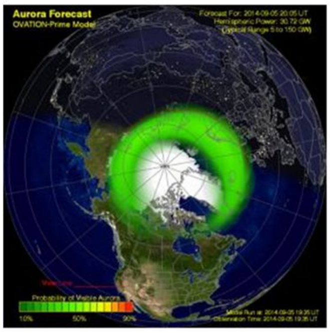
AURORAL OVAL

Low altitude: The Auroral Oval is the ionospheric part of a coupled system. It is the place where the aurora occurs.

High altitude: Particles from the magnetosphere follow the magnetic field lines and bombard the auroral ionosphere. The field lines corresponding to the auroral oval map to the plasma sheet boundary or to the central plasma sheet.



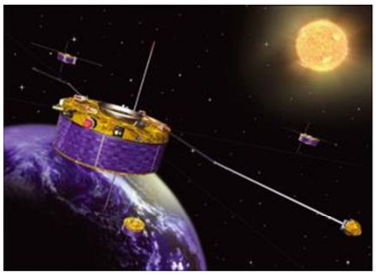


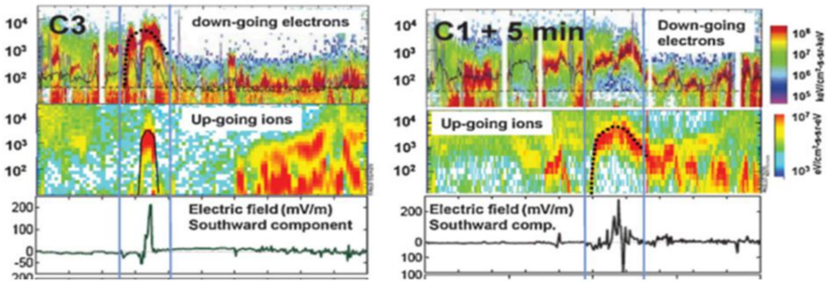
Low altitude: The Auroral Oval is the ionospheric part of a coupled system. It forms an oval around the geomagnetic poles, in which the Aurora Borealis (and Australis) occurs.

High altitude: Particles coming from the magnetosphere follow the magnetic field lines and bombard the auroral ionosphere. The field lines corresponding to the auroral oval map to the plasma sheet boundary layer and/or adjacent layers in the lobe or embedded in the central plasma sheet.

CLUSTER OBSERVATIONS

With Cluster it has been possible to fly through the AAR. One then sees both downgoing electrons, partially accelerated, and upgoing ions, partially accelerated.





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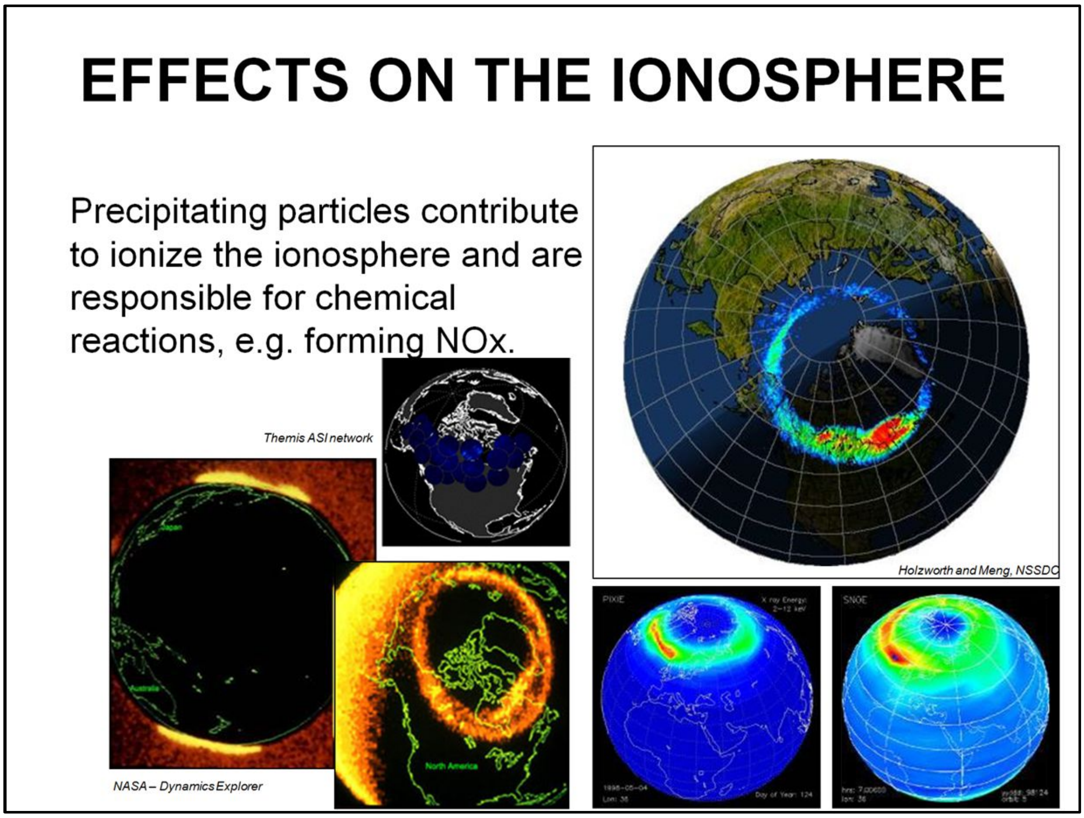
The Cluster satellites have provided valuable insights into the functioning of auroras, but there still are a lot of unknown features. Satellites typically fly below the auroral acceleration region (AAR), for instance in low Earth orbit. They can then detect the precipitating electrons. Other satellites fly high above the AAR and see upflowing ions. With Cluster it has been possible to fly through the AAR. One then sees both downgoing electrons, partially accelerated, and upgoing ions, partially accelerated. Adding up the electrostatic acceleration potentials of ions and electrons gives a total parallel potential differences that matches the value inferred from electric field measurements.



Precipitating particles contribute to ionize the ionosphere and are responsible for chemical reactions, e.g. forming NOx.

VARIABILITY

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Y. Takasaka – Blue Moon

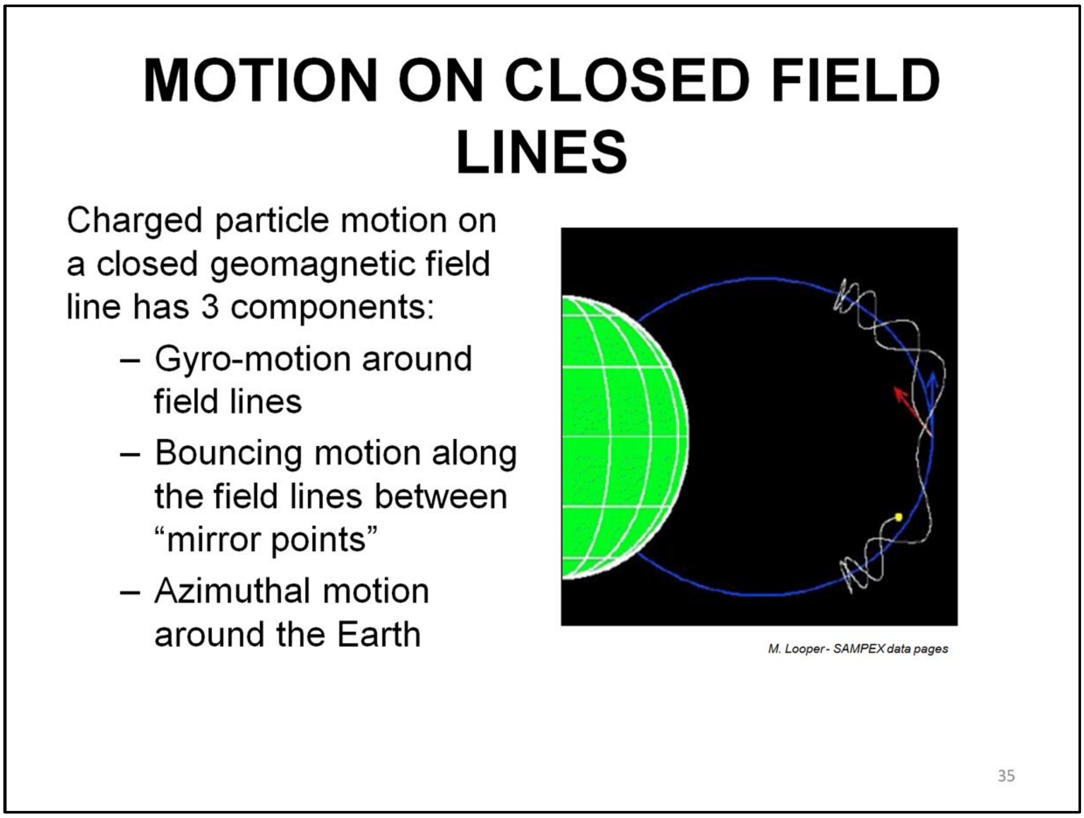
The visual aspect of auroras depends on the viewing geometry, on the energy and flux of the precipitating particles, and on the state of the ionosphere. Auroral forms occur over a wide range of length scales. From the ground, the most important scale is that of auroral curtains or arcs, typically 1-5 km thick but tens of kilometers long. There is also the more diffuse aurora over thickness scales of tens of kilometers. From space, one often has insufficient resolution to distinguish all the spatial details.

This movie nicely illustrates the dynamics of auroral curtains. The speedup of the time scale can be estimated from the speed at which the clouds drift by or the airplanes cross the sky.

During a substorm the auroral ovals widen. Aurora can the be observed at lower latitude, sometimes also in Belgium. You would need a very dark spot, without light pollution (difficult to find these days), the Moon should not interfere, and the weather should cooperate.

THE MAGNETOSPHERE AT LOW LATITUDES

The magnetosphere at low latitudes



Let us now look more closely to what happens at low magnetic latitude. Ionospheric particles that escape onto closed magnetic field lines (or magnetospheric particles that get trapped on such field lines) in principle bounce back and forth between two mirror points (as follows from conservation of energy and of magnetic moment).

Charged particle motion on a closed geomagnetic field line has 3 components:

Gyro-motion around field lines
Bouncing motion along the field lines between “mirror points”
Azimuthal motion around the Earth

Conservation of energy in the absence of an electric field is simply

$$v^2 = v_\perp^2 + v_\parallel^2 = constant$$

Conservation of the magnetic moment requires

$$\frac{mv_\perp^2}{2B} = constant$$

With θ the pitch angle at the equator, and $\pm 90°$ pitch angle at the mirror point, one finds in a dipole field

$$B_{mirror} = \frac{B_0}{L^3 \sin^2\theta} = B(L, \lambda_{mirror}) = \frac{B_0\sqrt{1 + 3\sin^2\lambda_{mirror}}}{L^3 \ \cos^6\lambda_{mirror}}$$

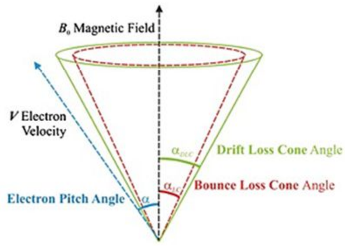
which is independent of particle energy.

LOSS CONE

The mirror point depends on the pitch angle θ of the particle at the equator (not on its energy).

Particles moving almost parallel to the magnetic field mirror at low altitude: they likely collide in the atmosphere before being able to bounce back, thus creating a loss cone.

Pitch-angle diffusion in the magnetosphere slowly brings particles in the loss cone, from which they then are lost.



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The mirror point depends on the pitch angle θ of the particle at the equator (not on its energy). From

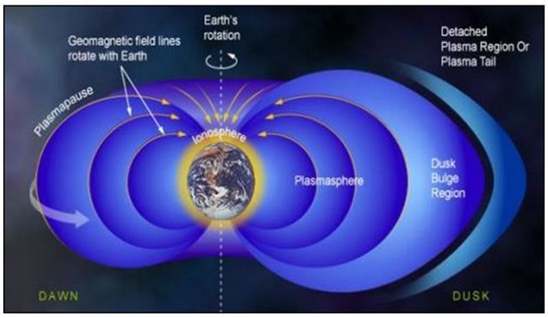
$$\frac{1}{\sin^2\theta} = \frac{\sqrt{1+3\sin^2\lambda_{mirror}}}{\cos^6\lambda_{mirror}}$$

and taking $\lambda_{mirror} = \Lambda$ (ignoring the atmospheric height), one can relate Λ and θ. Indeed, with $A = \cos^2\Lambda$, this can be solved iteratively ($A \leftarrow \sqrt[12]{\sin^4\theta\ (4-3A)}$, start from $A = 0$). For $\theta = 1°$ we find $A\ =\ 0{,}285$ or $\Lambda = 58°$. That means that on field lines with $\Lambda \leq 58°$ all particles with $\theta \leq 1°$ are in the loss cone : those particles likely collide in the atmosphere before being able to bounce back. Pitch-angle diffusion in the magnetosphere slowly brings particles in the loss cone, from which they then are lost.

THE PLASMASPHERE

At low latitudes the loss cone is small, so that the particles are captured in a “magnetic bottle”.

Ionospheric particles that are ionized during the day can move up along the field lines and fill the plasmasphere. During the night those particles sink back, making sure that the ionosphere remains ionized also at night.



Windows to the Universe

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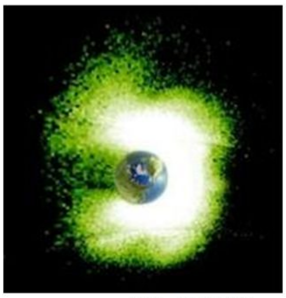
From the above, we can conclude that at low latitudes the loss cone is small, so that the particles are captured in a “magnetic bottle”.

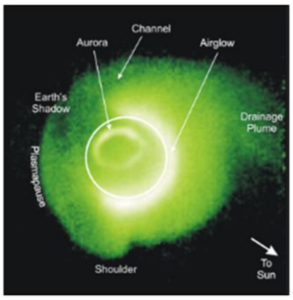
During the day, solar UV ionizes atoms and molecules in the ionosphere. These particles can move upwards along the field lines, and fill the plasmasphere. During the night those particles sink back, making sure that the ionosphere remains ionized also at night, in spite of the recombination that goes on. The plasma in the plasmasphere is roughly in corotation with Earth (except at the edges).

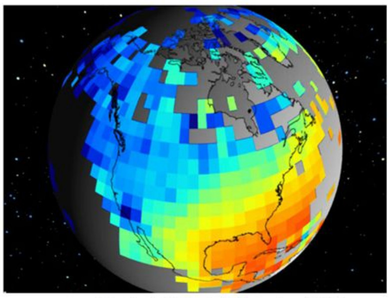
SUBSTORMS AND THE PLASMASPHERE

During a substorm the outer layers of the plasmasphere are eroded and form “plasmaspheric plumes”. These plumes have their counterpart in the ionosphere: tongues of higher ionization (“storm enhanced density”).

In the days following the substorm, the plasmasphere is progressively refilled with ionospheric material.







NASA – IMAGE/EUV team

J. Foster – MIT/Haystack Observatory - GSFC

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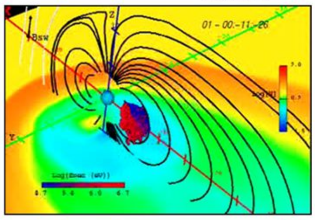
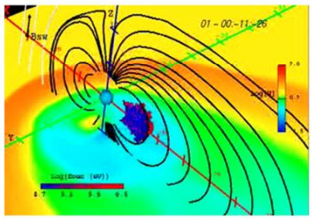
The solar wind – magnetosphere interaction during a substorm modifies the convection electric field in the magnetosphere (the dawn-dusk electric field that is typically present, is intensified; one may also have inductive electric fields). In combination with the corotation electric field, the net effect is that the outer layers of the plasmasphere are eroded and form “plasmaspheric plumes”. These plumes have their counterpart in the ionosphere: tongues of higher ionization (“storm enhanced density”). In the days following the substorm, the plasmasphere is progressively refilled with ionospheric material.

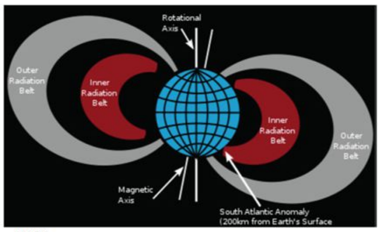
THE RADIATION BELTS

NASA GSFC



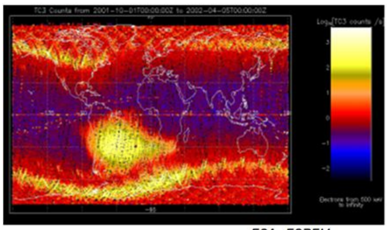


When a CME hits, the magnetosphere is compressed. Charged particles in the magnetosphere get an additional acceleration. These high-energy particles form the radiation belts (van Allen belts).



NASA

These particles remain trapped for a long time and disappear on a time scale of weeks to months.



ESA - ESREM

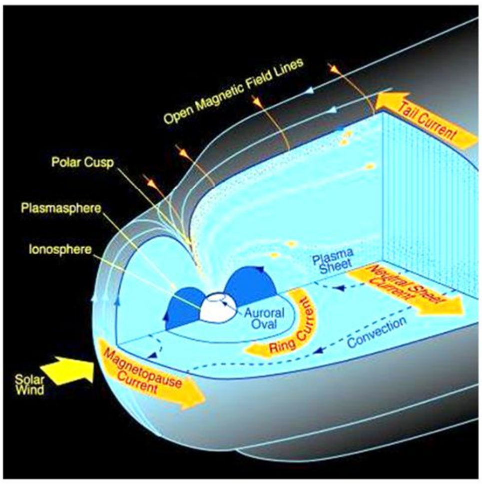
When a CME hits, the magnetosphere is compressed. As a consequence, charged particles in the magnetosphere are additionally accelerated. So, these high-energy particles during geomagnetic storms feed into the radiation belts (van Allen belts). These particles remain present in the radiation belts for a long time; they are trapped in the magnetic field and disappear on a time scale of weeks to months. They behave fairly similarly to the plasmasphere particles in the sense that they are also trapped on the closed dipolar field lines, although because of their high energies their drifts are much larger.

Note that the location of the radiation belts (partly) overlaps with the plasmasphere; both refer to different particle energy ranges.

RING CURRENT

The differential drift of energetic electrons and ions in the inner magnetosphere leads to a net current, which is called the “ring current”.

Such a circulating ring current induces a magnetic field – it has an overall effect on the magnetic field in the inner magnetosphere and at the Earth’s surface, measured by the Dst index.



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The Dst index (and in particular negative excursions of that index) is therefore a sensitive global indicator of geomagnetic storm activity and the presence of high energy particles in the inner magnetosphere.

QUANTIFYING THE STATE OF THE MAGNETOSPHERE

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Quantifying the state of the magnetosphere

SPACECRAFT ORBITS

LEO : low Earth orbit

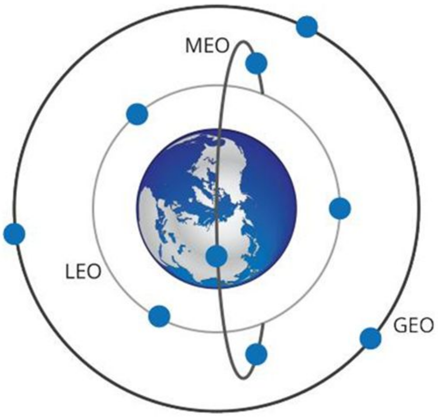
MEO : medium Earth orbit

GEO : geostationary orbit

GTO : geostationary transfer orbit

Sun-Earth L1 halo orbit

Other



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Spacecraft subject to the solar wind – magnetosphere – ionosphere interactions can be found on different orbits.

Low Earth Orbit (LEO):
- Typical altitude ~500 km, cf ISS
- Close to Earth with high spatial resolution for remote sensing
- Short communication path
- Rapid revisit times
- Special cases such as high-inclination or sun-synchronous orbits

Medium Earth Orbit (MEO):
- Altitudes 700-2000 km
- Often constellations with high inclination, on different orbital planes
- Useful for GNSS, Earth observation, …

Geostationary Orbit (GEO) :
- Altitude 36000 km, geocentric distance 6.6 Earth radii
- Fixed longitude slots, corotating with Earth
- Useful for telecommunications, ground stations with fixed antenna
- Not necessarily in equatorial plane
- Graveyard strategies

GTO : geostationary transfer orbit
- Intermediate to go from LEO to GEO

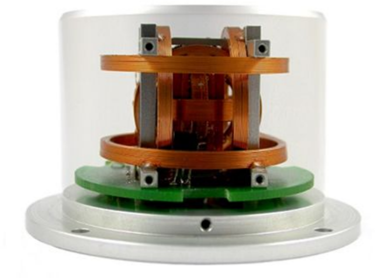
- Brief transit through radiation belts

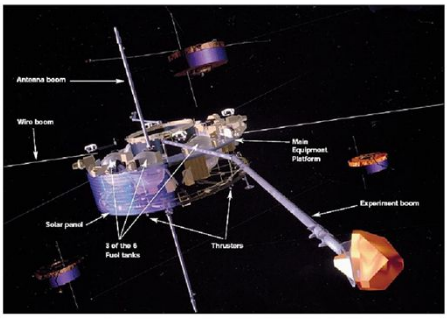
Sun-Earth L1 halo orbit
- Ideal to monitor the solar wind coming towards Earth

Other
- High apogee orbits that take spacecraft out of the magnetosphere
- Interplanetary trajectories

MAGNETIC FIELD

Magnetometers in space are often fluxgate instruments. They are light, provide high cadence measurements, but require booms, magnetic cleanliness, special calibration tricks.





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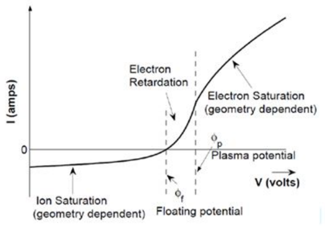
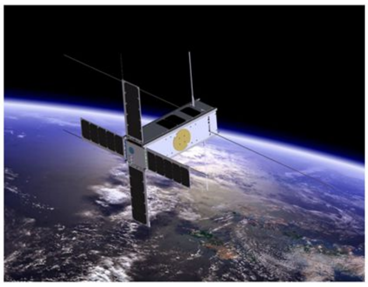
Magnetometers in space are often fluxgate instruments. They are light, provide high cadence measurements, but require booms, magnetic cleanliness, special calibration tricks.

ELECTRIC FIELD

Electric probes allow to

- Determine the j(V) from which one can obtain electron density and temperature, and spacecraft potential.
- Determine the floating potential, then subtract the measurements from two probes divided by the separation distance to get the electric field.





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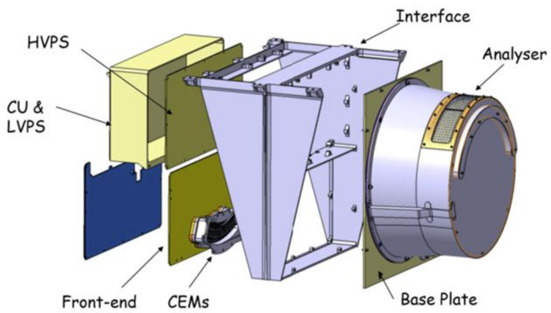
Electric probes allow to
-Determine the j(V) from which one can obtain electron density and temperature, and spacecraft potential.
-Determine the floating potential, then subtract the measurements from two probes divided by the separation distance to get the electric field.

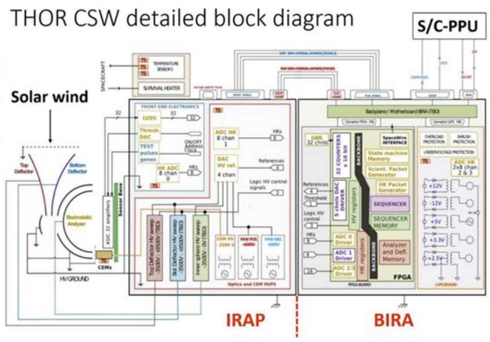
Sometimes these probes are placed on wire booms (e.g. on Cluster 2 x 50 meter long), at least if the spacecraft are spin-stabilized. That is the only way to get a very long baseline and thus a really accurate electric field measurement.

PLASMA SPECTROMETERS

The goal of a plasma spectrometer is to obtain 3D velocity distribution functions of ions or electrons. This is done by

- Selecting the energy: potential on hemispherical analyzer
- Selecting elevation: either by potentials on electrostatic deflector plates, or by scanning during satellite rotation
- Selecting azimuth: by multiple detectors in focal plane





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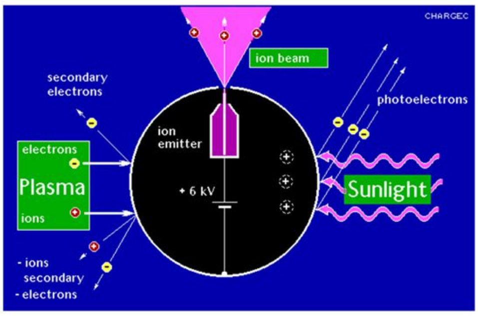
-Selecting the energy: potential on hemispherical analyzer
-Selecting elevation: either by potentials on electrostatic deflector plates, or by scanning during satellite rotation
-Selecting azimuth: by multiple detectors in focal plane
This is not trivial if you want to achieve high energy, angular, and time resolution. Such instruments must be properly calibrated and one has to account for aging of the detectors.

Plasma spectrometers sort particles on m/Z. Sometimes more advanced versions are used in which the spectrometer is followed by a time-of-flight section to have mass resolution as well.

SURFACE CHARGING

Solar UV photons create a cloud of photo-electrons around a satellite, thus producing an electric potential difference between the spacecraft and the space surrounding it. The ambient plasma environment also affects this potential. This potential may represent a barrier for cold ions/electrons, so one cannot measure them, unless if one has spacecraft potential control.



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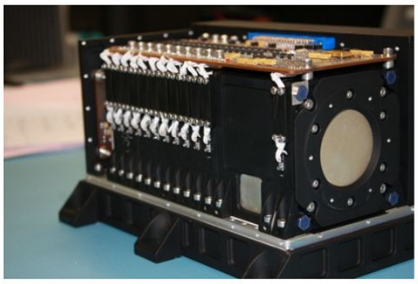
ENERGETIC PARTICLE DETECTORS

Energetic particle detectors typically consist of a number of absorbers, forming a detection stack.

By measuring how deep a particle penetrates into the stack, one can determine its energy. Such detectors therefore are able to provide energy spectra; in some cases they can distinguish electrons from various ion species.



EPT consortium

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Energetic particle detectors typically consist of a number of absorbers, forming a detection stack.
By measuring how deep a particle penetrates into the stack, one can determine its energy. Such detectors therefore are able to provide energy spectra; in some cases they can distinguish electrons from various ion species.

A 3D view of the energetic particle distribution can be obtained by a set of such instruments with different look directions. It is very hard to get a decent angular resolution.

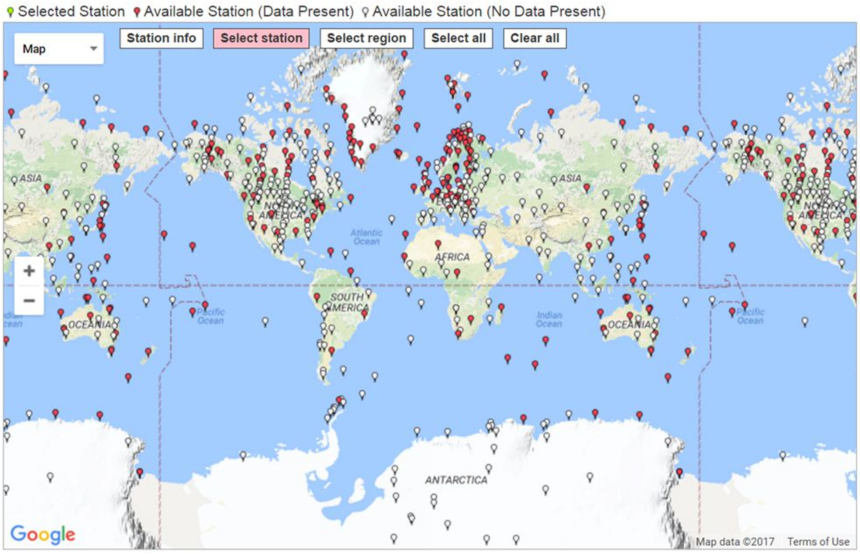
AURORAL CAMERAS

Ground camera networks have been put in place, using wide angle or all-sky cameras. From space, visual and UV cameras are used, the latter being able to see auroras also in daylight.

A major problem is that ground- and space-based cameras have very different spatial resolution: relating images from both is difficult.

Ground camera networks have been put in place, using wide angle or all-sky cameras. From space, visual and UV cameras are used, the latter being able to see auroras also in daylight. A major problem is that ground- and space-based cameras have very different spatial resolution: relating images from both is difficult. All such imaging instruments require very good calibration (dark current, flat-fielding, stray light removal, …).

MAGNETOMETER NETWORK



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Magnetometer networks cover the entire planet. They measure the variations in the magnetic field, which are due to the IMF changes (especially above the polar cap) and due to changes in the magnetosphere (magnetic field induced by the ring current) and in the ionosphere (magnetic fields induced by currents flowing in the auroral ionosphere).

GEOMAGNETIC INDICES

The state of the magnetosphere is complex. Therefore, some characteristic indices are being used:

Overall geomagnetic activity: K and Kp, ap, Ap, aa

Ring current: Dst and Sym-H

Auroral ionosphere: AE

Polar cap ionosphere: PC

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Characteristic indices reflect the state of the magnetosphere

Dst
The Dst (Disturbance Storm Time) index is an index of magnetic activity derived from a network of near-equatorial geomagnetic observatories that measures the intensity of the globally symmetrical equatorial electrojet (the "ring current").
This magnetic disturbance index is derived from hourly low-latitude horizontal magnetic variation records. It shows the effect of the globally symmetrical westward flowing ring current, which causes the "main phase" depression worldwide in the H-component of the magnetic field during large magnetic storms.

Sym-H
The longitudinally symmetric disturbance index describes geomagnetic disturbance fields in mid-latitudes with high-time (1 minute) resolution , and is effectively the same as the hourly D_{st} index, even though it uses 1-minute values from different sets of stations and a slightly different coordinate system.

K and Kp
The K-index is a quasi-logarithmic local index on a 3-hour interval of the magnetic activity relative to an assumed quiet-day curve for a single geomagnetic observatory site. The planetary 3-hour-range index K_p is the mean standardized K-index from 13 geomagnetic observatories. The scale runs from 0 to 9 expressed in thirds of a unit, e.g. 5- is 4 2/3, 5o is 5 and 5+ is 5 1/3. This

planetary index is designed to measure the geomagnetic effects of solar particle radiation.

ap and Ap

The ap index is a translation of Kp onto a different scale; it is the magnetic field perturbation amplitude measured as a multiple of 2 nT. Ap is the daily average of this ap index. So these indices also quantify the geomagnetic effects of solar particle radiation.

aa

The aa index is 3-hour index of geomagnetic activity determined from the K-indices at two antipodal subauroral stations. The contributions from both stations are weighted to account for the small differences in the latitudes of the two stations, or for the slight changes in the very place of the observatory. The unit for the aa index is nT, and it represents the activity level at an invariant magnetic latitude of about 50 degrees.

AE

The Auroral Electrojet Index, AE, provides a global measure of auroral zone magnetic activity produced by enhanced ionospheric currents flowing below and within the auroral oval. In principle, it represents the deviation from quiet day values of the horizontal magnetic field around the auroral oval. It is instantaneous.

PC

The PC-index measures magnetic activity in the Polar Cap. It is based on data from a single near-polar station (Thule N and Wostok S).

END

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SUPPLEMENTARY MATERIAL

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THE DIPOLE FIELD

The geomagnetic field can be approximated by a magnetic dipole. In the far field, it can be written as

$$B(r,\lambda) = \frac{m\mu_0}{4\pi r^3}\sqrt{1+3\sin^2\lambda}$$

where r is geocentric distance and λ geomagnetic latitude, and m is the dipole moment. With $R = r/R_E$, this is

$$B(R,\lambda) = \frac{B_0}{R^3}\sqrt{1+3\sin^2\lambda}$$

where $B_0 = B(R_E, 0) = 35000\ nT$ is the field at the equator and $R_E = 6370\ km$.

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The geomagnetic field can roughly be approximated by a magnetic dipole. We give here some formulae that describe the dipolar field to introduce the related terminology.

In the far field, the dipolar field strength can be written as

$$B(r,\lambda) = \frac{m\mu_0}{4\pi r^3}\sqrt{1+3\sin^2\lambda}$$

Where r is the geocentric distance and λ the geomagnetic latitude, and m is the dipole moment. With $R = r/R_E$, one can write this as

$$B(R,\lambda) = \frac{B_0}{R^3}\sqrt{1+3\sin^2\lambda}$$

where $B_0 = B(R_E, 0) = 35000\ nT$ is the field at the equator and $R_E = 6370\ km$.

DIPOLE FIELD LINES

The equation of a field line is $R = L\cos^2\lambda$, where L is the geocentric distance of the field line at the equator.

The latitude at which the field line reaches the surface is the invariant latitude $\mathit{\Lambda}$.

$$1 = L\cos^2\mathit{\Lambda}$$

The field strength along a field line is then

$$B(L,\lambda) = \frac{B_0\sqrt{1+3\sin^2\lambda}}{L^3\ \ \cos^6\lambda}$$

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$$R = L\cos^2\lambda,$$

where L is the geocentric distance of the field line at the equator.
The latitude at which the field line reaches the surface is the invariant latitude Λ, that is,

$$1 = L\cos^2\mathit{\Lambda}.$$

The field strength along a field line is then

$$B(L,\lambda) = \frac{B_0\sqrt{1+3\sin^2\lambda}}{L^3\ \ \cos^6\lambda}$$

PRESSURE BALANCE

Pressure balance at the magnetopause (MP)

$$P_{total} = P_{ram} + P_{th} + P_{mag} = \rho v_{\perp n}^2 + \sum_i N_i k_B T_{\perp i} + \frac{B^2}{2\mu_0} = cnst$$

On the solar wind side:

$$P_{ram} = \rho v_{sw}^2 \text{ , } P_{th} = 0 \text{ , } P_{mag} = 0$$

On the magnetospheric side:

$$P_{ram} = 0,\ P_{th} = 0,\ P_{mag} = \frac{{B_{msph}}^2}{2\mu_0} \text{ , with } B_{msph}(R) = \frac{2B_0}{R^3}$$

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At the magnetopause (MP), the total pressure of the solar wind must be balanced by the pressure from the magnetosphere. This is expressed by the pressure balance condition, fundamental for space weather:

$$P_{total} = P_{ram} + P_{th} + P_{mag} = \rho v_{\perp n}^2 + \sum_i N_i k_B T_{\perp i} + \frac{B^2}{2\mu_0} = constant$$

The pressure from the solar wind is dominated by ram pressure

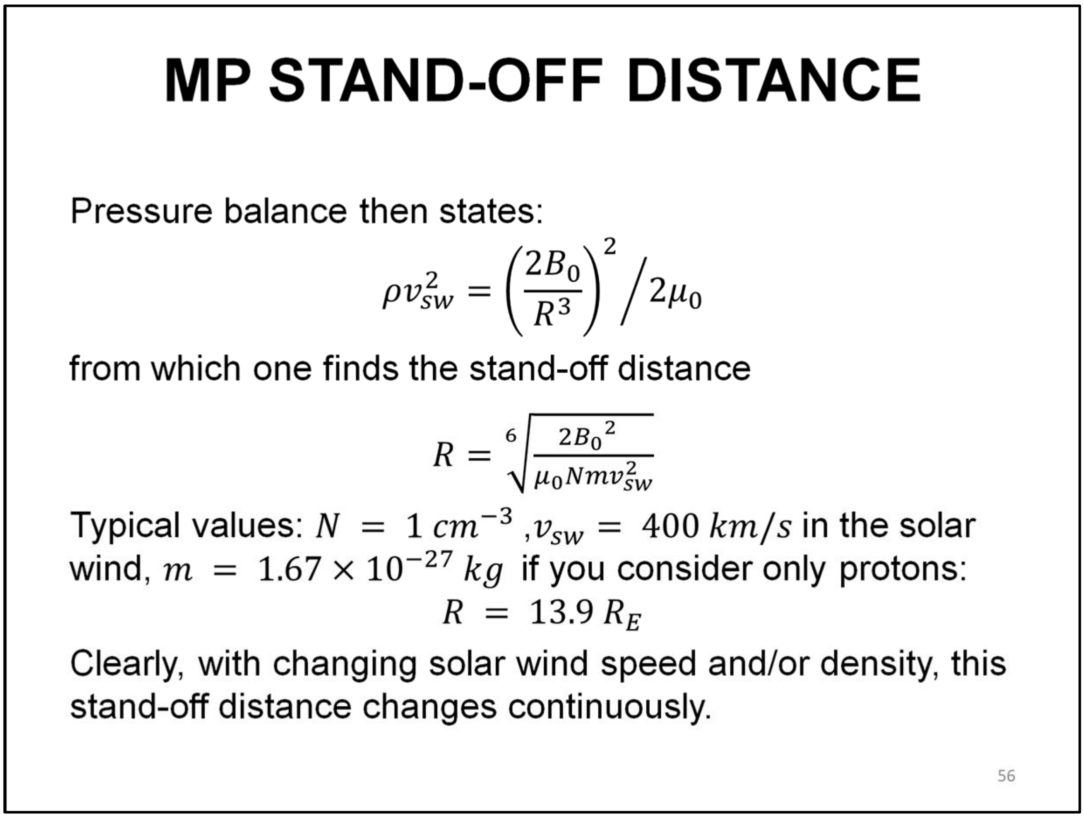
$$P_{ram} = \rho v_{sw}^2$$

The pressure from the magnetosphere is dominated by magnetic pressure. The dipole field strength at the equator is (ignoring tilt)

$$B(R) = \frac{B_0}{R^3}$$

Since the MP current essentially nulls the field outside the MP, it will double the field just inward of the MP, so that

$$B_{msph}(R) = \frac{2B_0}{R^3}$$



Pressure balance then states:

$$P_{total,sw} = P_{total,msph}$$

or

$$\rho v_{sw}^2 = \left(\frac{2B_0}{R^3}\right)^2 \Big/ 2\mu_0$$

from which one finds the stand-off distance

$$R = \sqrt[6]{\frac{2{B_0}^2}{\mu_0 N m v_{sw}^2}}$$

so that we obtain the magnetopause stand-off distance.
Typical values: $N = 1\ cm^{-3}$,$v_{sw} = 400\ km/s$ in the solar wind, $m = 1.67 \times 10^{-27}\ kg$ if you consider only protons; then one finds

$$R = 13.9\ R_E$$

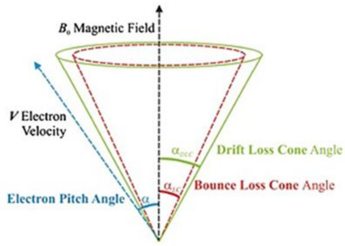
Clearly, with changing solar wind speed and/or density, this stand-off distance changes continuously.

LOSS CONE

The mirror point depends on the pitch angle θ of the particle at the equator (not on its energy). From

$$\frac{1}{\sin^2\theta} = \frac{\sqrt{1 + 3\sin^2\lambda_{mirror}}}{\cos^6\lambda_{mirror}}$$

and taking $\lambda_{mirror} = \Lambda$ (ignoring the atmospheric height), one finds for instance that on field lines with $\Lambda \leq 58°$ all particles with $\theta \leq 1°$ are in the loss cone : those particles likely collide in the atmosphere before being able to bounce back.



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The mirror point depends on the pitch angle θ of the particle at the equator (not on its energy). From

$$\frac{1}{\sin^2\theta} = \frac{\sqrt{1 + 3\sin^2\lambda_{mirror}}}{\cos^6\lambda_{mirror}}$$

and taking $\lambda_{mirror} = \Lambda$ (ignoring the atmospheric height), one can relate Λ and θ. Indeed, with $A = \cos^2\Lambda$, this can be solved iteratively ($A \leftarrow \sqrt[12]{\sin^4\theta\ (4 - 3A)}$, start from $A = 0$). For $\theta = 1°$ we find $A\ =\ 0{,}285$ or $\Lambda = 58°$. That means that on field lines with $\Lambda \leq 58°$ all particles with $\theta \leq 1°$ are in the loss cone : those particles likely collide in the atmosphere before being able to bounce back. Pitch-angle diffusion in the magnetosphere slowly brings particles in the loss cone, from which they then are lost.