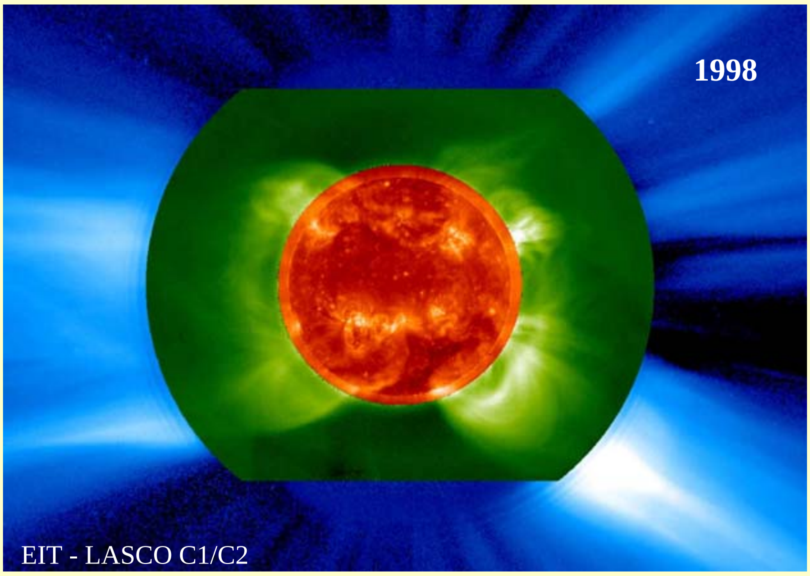
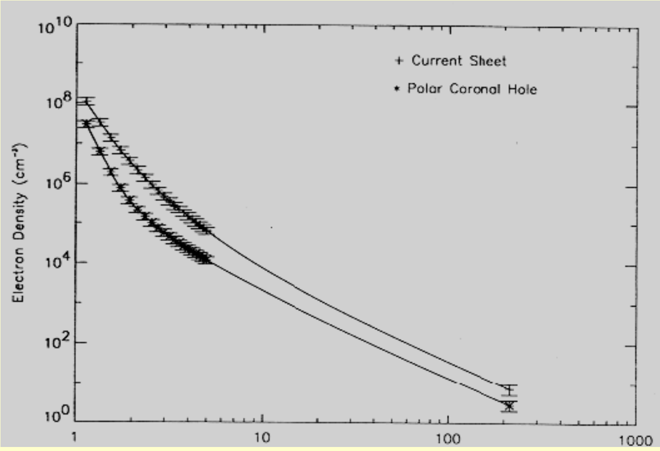
Space plasmas, examples and phenomenology

- Solar interior and atmosphere
- Solar corona and wind
- Heliosphere and energetic particles
- Earth‘s magnetosphere
- Planetary magnetospheres
- The Earth‘s bow shock
- Cometary plasmas

Corona of the active sun



Electron density in the corona



Heliocentric distance / R_s

+ Current sheet and streamer belt, closed

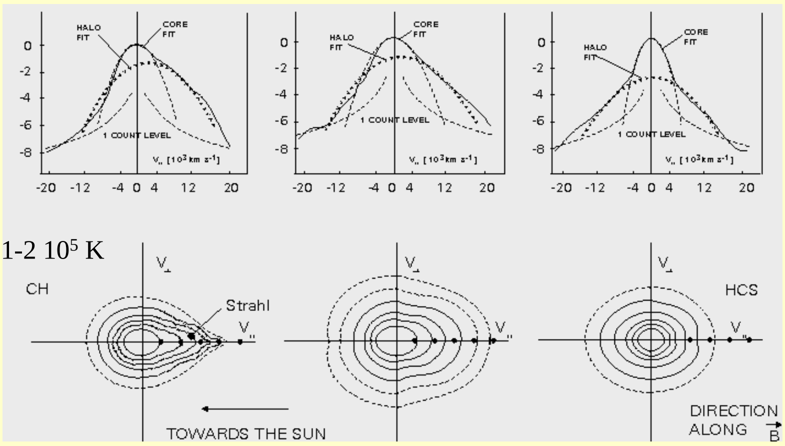
• Polar coronal hole, open magnetically

Guhathakurta and Sittler, 1999, Ap.J., **523**, 812

Skylab coronagraph/Ulysses in-situ

Solar wind electron velocity distributions

T_e = 1-2 10^5 K

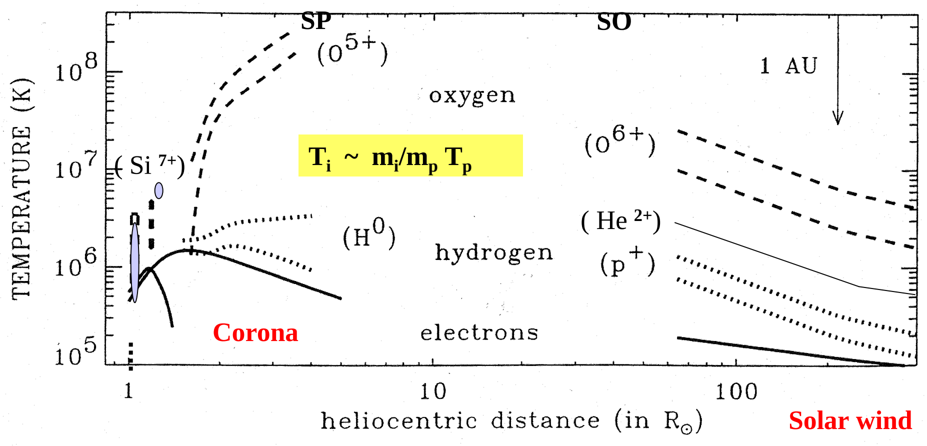


high intermediate speed low

Pilipp et al., JGR, **92**, 1075, 1987

Core (96%), halo (4%) electrons, and „strahl"

Temperatures in the corona and fast solar wind

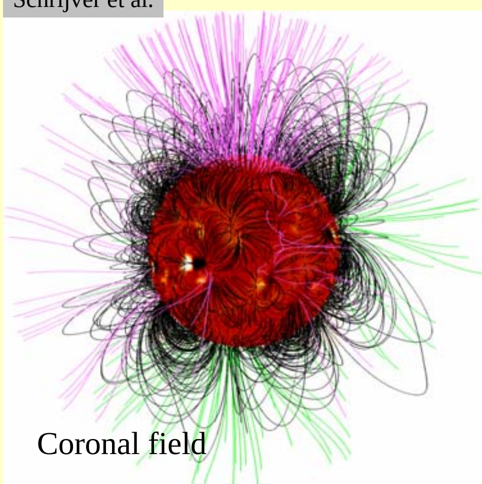


Cranmer et al., Ap.J., 2000; Marsch, 1991

The elusive coronal magnetic field

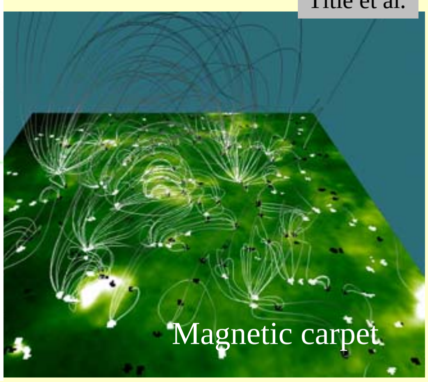
Modelling by extrapolation

Schrijver et al.

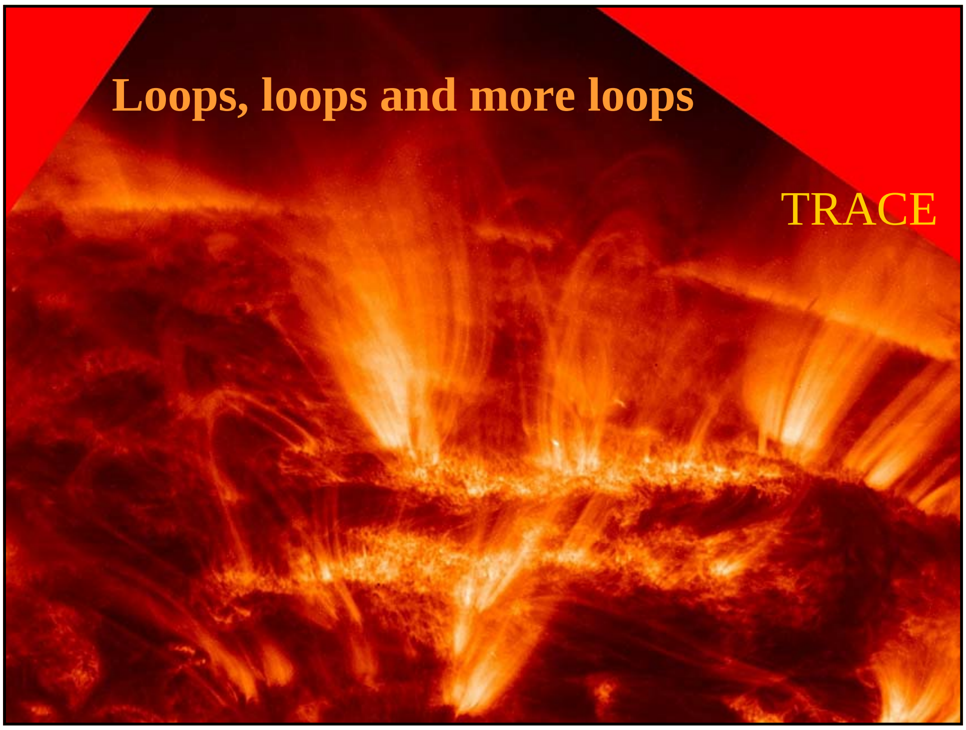


- **Closed loops and streamers**
- **Coronal funnels and holes**
- **Magnetic transition region (network)**

Title et al.

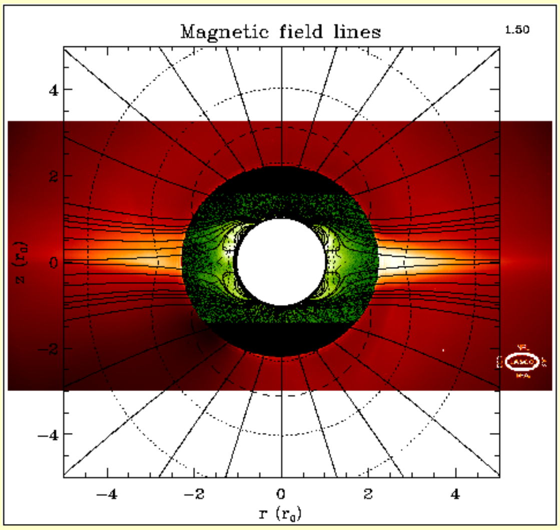


Loops, loops and more loops



Coronal magnetic field and density

Dipolar, quadrupolar, current sheet contributions



Polar field:
B = 12 G

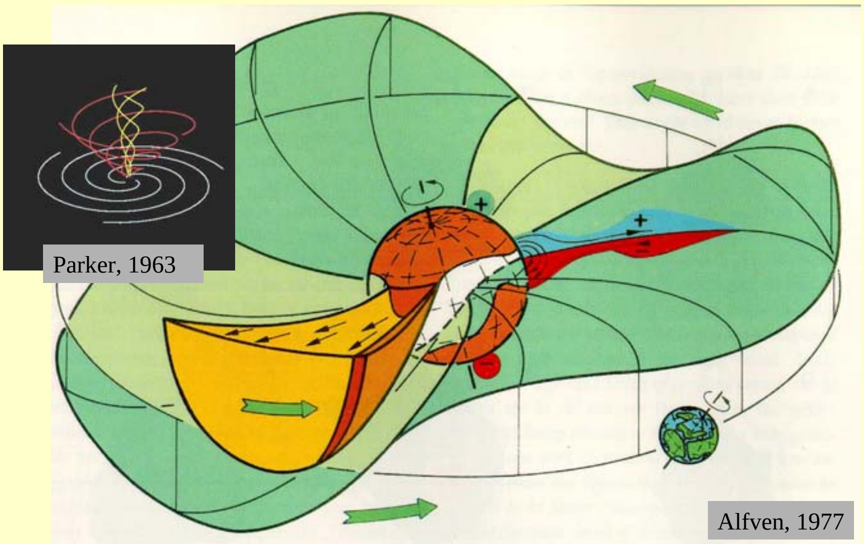
Current sheet is a symmetric disc anchored at high latitudes !

LASCO C1/C2 images (SOHO)

Banaszkiewicz et al., 1998;

Schwenn et al., 1997

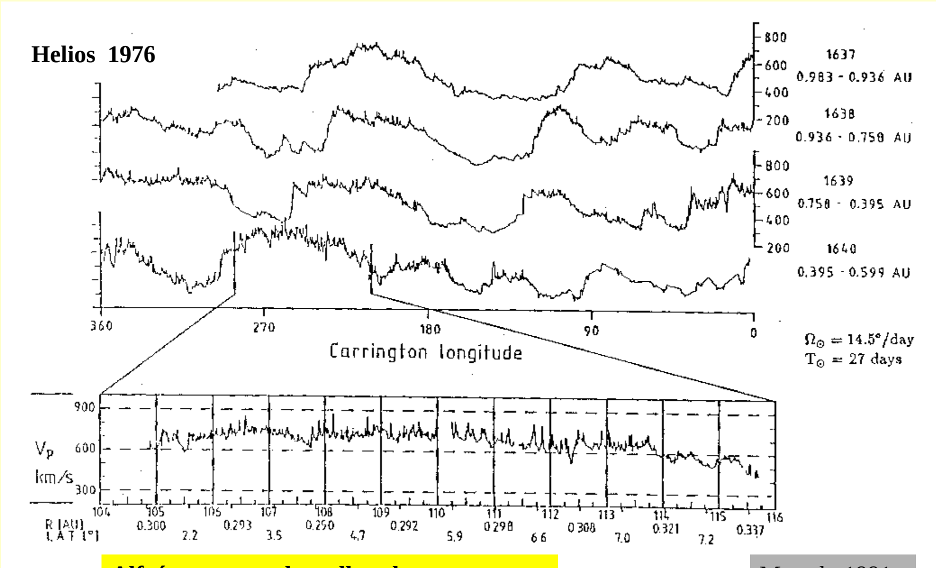
Solar wind stream structure and heliospheric current sheet



Parker, 1963

Alfven, 1977

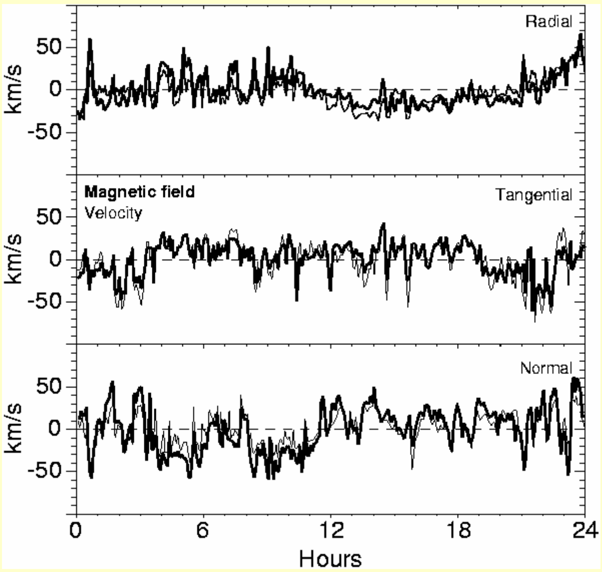
Solar wind fast and slow streams



Alfvén waves and small-scale structures

Marsch, 1991

Alfvénic fluctuations (Ulysses)



Elsässer variables:

$\mathbf{Z}^{\pm} = \mathbf{V} \pm \mathbf{V}_{\mathbf{A}}$

Turbulence energy:

$e^{\pm} = 1/2\,(\mathbf{Z}^{\pm})^2$

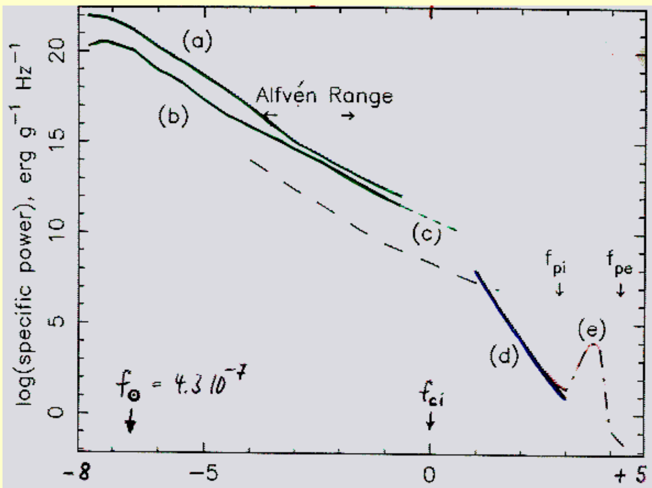
Cross helicity:

$\sigma_c = (e^+ - e^-)/(e^+ + e^-)$

Horbury & Tsurutani, 2001

Schematic power spectrum of fluctuations

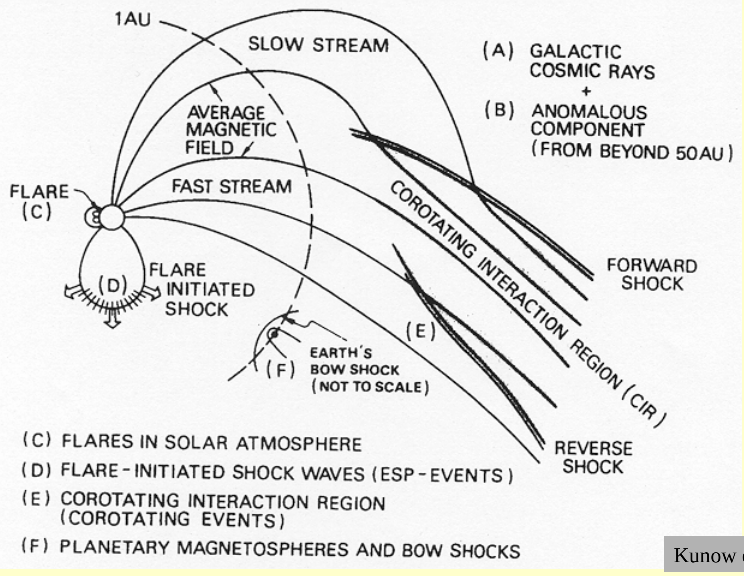
(a) Alfvén waves
(b) Slow and fast magnetosonic
(c) Ion-cyclotron
(d) Whistler mode
(e) Ion acoustic, Langmuir waves



Log(frequency /Hz)

Mangeney et al., 1991

Energetic particles in the heliosphere



Kunow et al., 1991

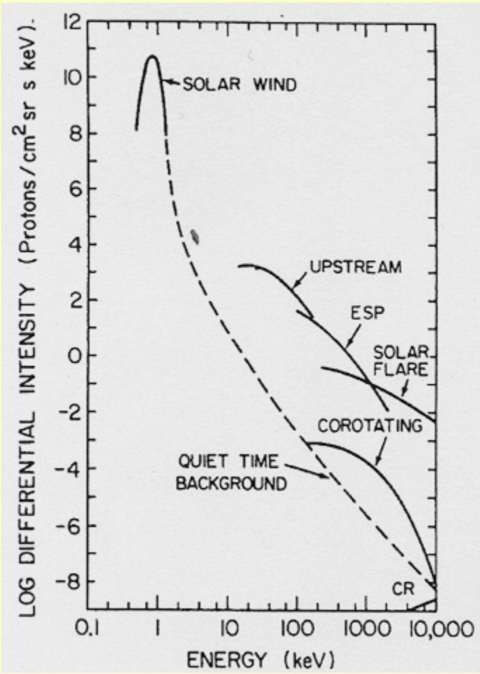
Energy spectra of heliospheric ion populations

- How are they accelerated?
- What is their composition?
- How do they propagate?
- What are the source spectra?

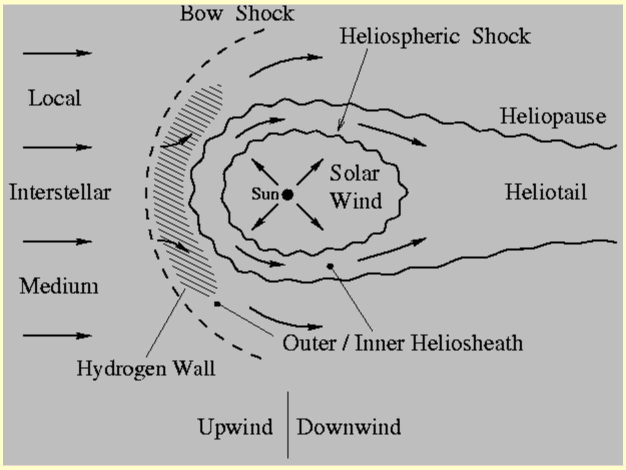
Energies: 1 keV - 100 MeV

Sources: Mainly shock acceleration at flares/CMEs and CIRs

Gloeckler, Adv. Space. Res. **4**, 127, 1984

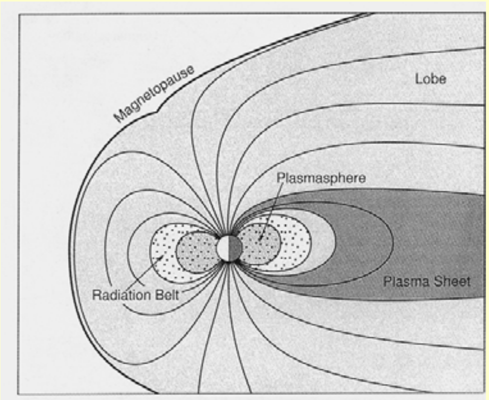


Structure of the heliosphere



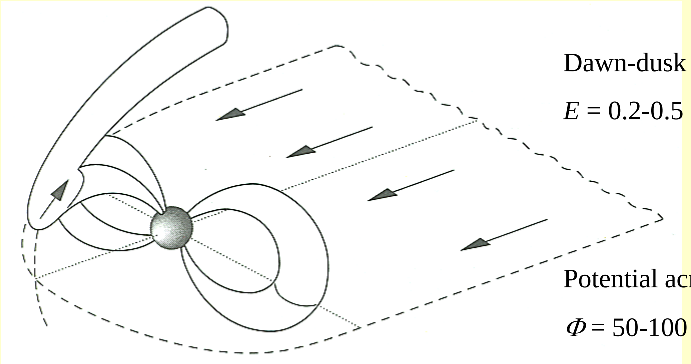
- **Basic plasma motions in the restframe of the Sun**
- **Principal surfaces (wavy lines indicate disturbances)**

Plasma structure of the Earth‘s magnetosphere



The boundary separating the subsonic (after bow shock) *solar wind* from the cavity generated by the Earth‘s magnetic field, the *magnetosphere,* is called the *magnetopause*. The solar wind compresses the field on the dayside and stretches it into the *magnetotail* (far beyond lunar orbit) on the nightside. The magnetotail is concentrated in the 10 R_E thick *plasma sheet*. The *plasmasphere* inside 4 R_E contains cool but dense plasma of ionospheric origin. The *radiation belt* lies on dipolar field lines between 2 to 6 R_E.

Flux tube (plasma) convection in the magnetosphere



Dawn-dusk electric field:

E = 0.2-0.5 mV/m

Potential across polar cap:

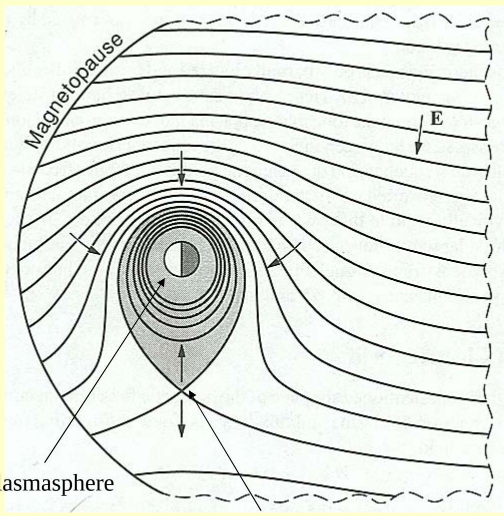
Φ = 50-100 kV

The circulation of magnetic field lines (flux tube) caused by the solar wind is also experienced by the particles gyrating about them.

-> Tailward plasma flow on open polar field lines and in the magnetospheric lobes.

-> Earth-ward flow (drift) in the plasma sheet near the equatorial plane.

Electric equipotential contours in equatorial plane



The Earth rotates at a 24 h period. This gives Ω_E = 7.27 10^{-5} rad/s. An inertial observer finds the ***corotation electric field***:

$$\mathbf{E}_{cr} = -(\mathbf{\Omega}_E \times \mathbf{r}) \times \mathbf{B}$$

This corotation electric field $\mathbf{E}_{cr}$ is directed radially inward and decreases with the square of the radial distance. The associated potential is about 100 kV.

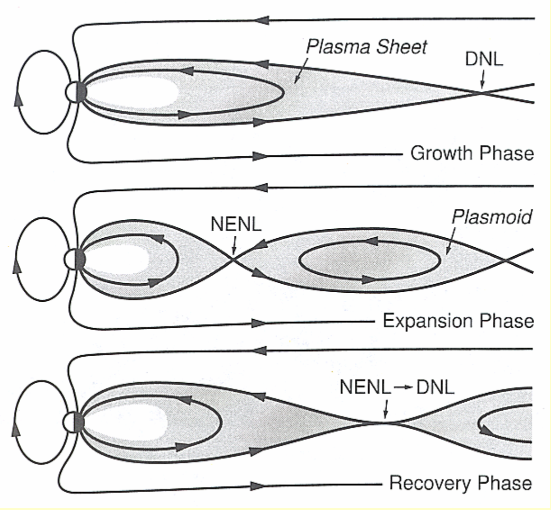
Magnetospheric substorm

Substorm phases:

- Growth
- Onset and expansion
- Recovery

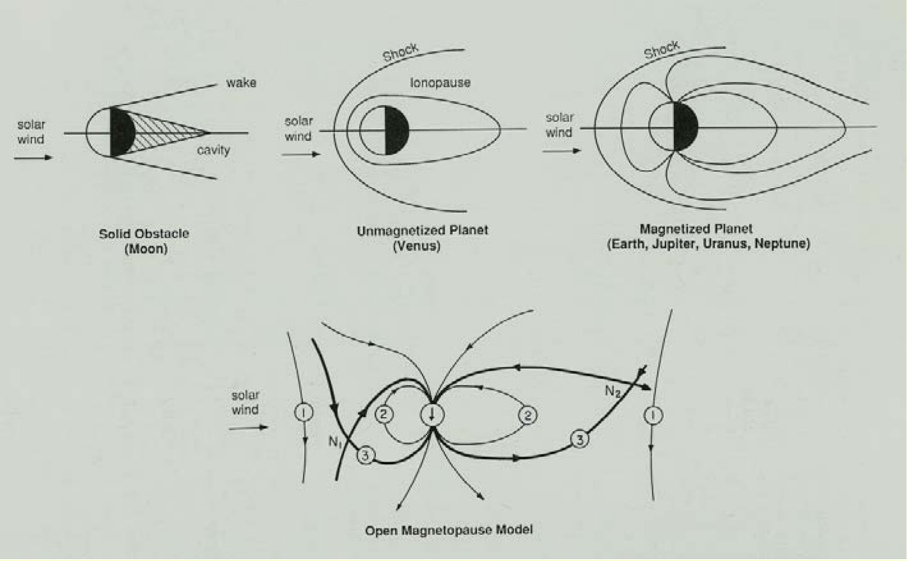
***Conditions for merging**:*

- Southward solar wind magnetic field
- Perturbations in solar wind flow (streams, waves, CMEs)



***Associated effects:** Aurora (particle precipitation) and induced magnetospheric currents.*

Boundaries between solar wind and obstacles



Planetary parameters and magnetic fields

Parameter	Mercury	Earth	Jupiter	Saturn	Sun
Radius [km] (equator)	2425	6378	71492	60268	696000
Rotation period [h]	58.7 d	23.93	9.93	10.66	25-26 d
Dipole field [G] (equator)	340 nT	0.31	4.28	0.22	3-5
Inclination of equator [Degrees]	3	23.45	3.08	26.73	7.12

Planetary magnetospheres

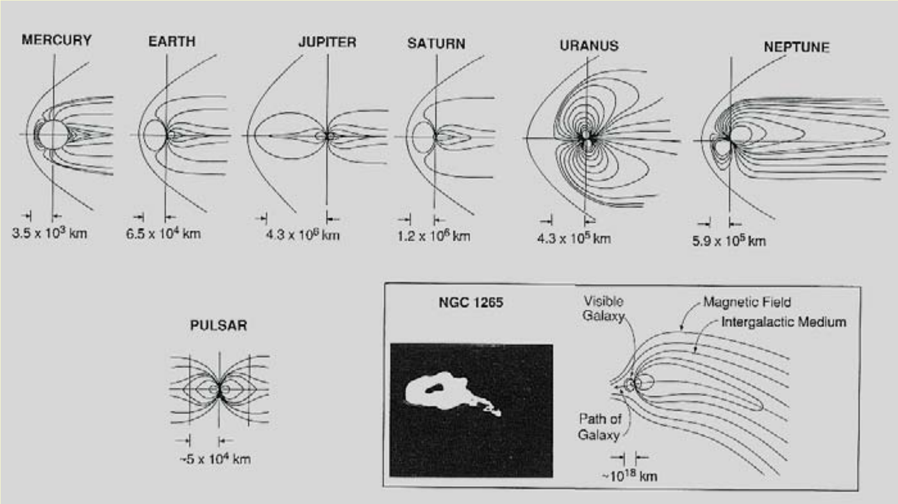
- Rotation, size, mass, ...
- Magnetic field (moment) of planet (object) and its inclination
- Inner/outer plasma sources (atmosphere, surface, moons, rings)
- Boundary layer of planet (object) and its conductivity
- Solar wind ram pressure (variable)

Dynamic equilibrium if ram pressure at magnetopause equals field pressure:

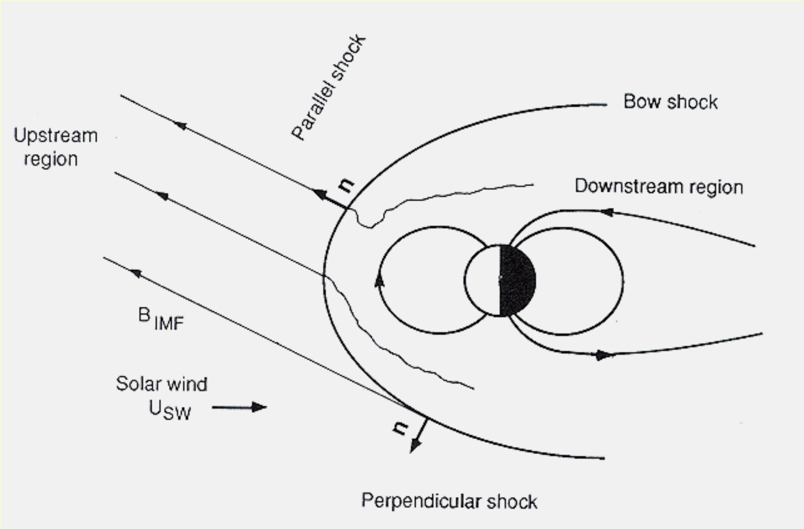
$$\rho_{sw} V_{sw}^2 = B^2/2\mu_0 = B_p^2 (R_p/R_m)^6/2\mu_0$$

Stand-off distances: R_m/R_p = 1.6, 11, 50, 40 for M, E, J, S.

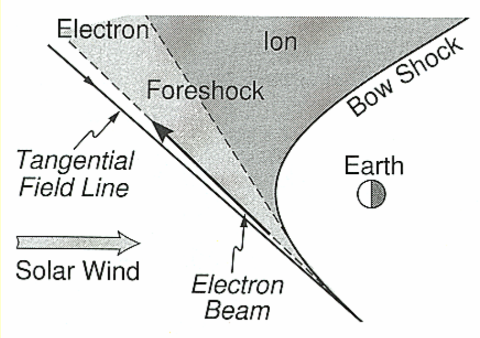
Magnetospheric configurations



Schematic of the Earth‘s bow shock geometry



Electron and ion foreshock geometries

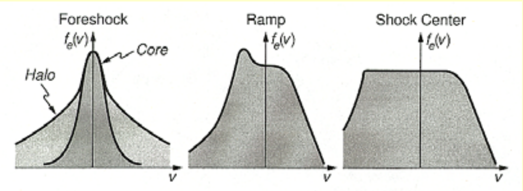


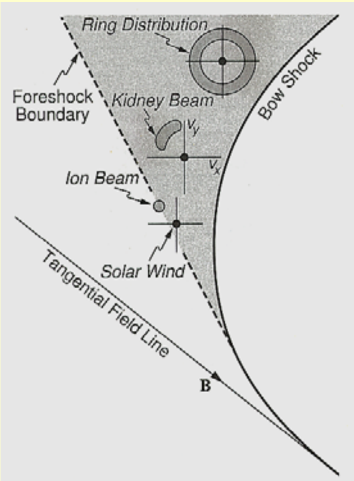
In the de Hoffman-Teller frame one moves parallel to the schock surface with a velocity v_{HT}, which transforms the upstream solar wind inflow velocity into a velocity that is entirely parallel to the upstream magnetic field. This velocity can be expressed by the shock normal unit vector, **n.**

$$\mathbf{v}_{sw} = \mathbf{v}_{HT} + \mathbf{v}_{sw\|}$$

$$\mathbf{v}_{HT} = \hat{\mathbf{n}} \times (\mathbf{v}_{sw} \times \mathbf{B}_{sw}) / \hat{\mathbf{n}} \cdot \mathbf{B}_{sw}$$

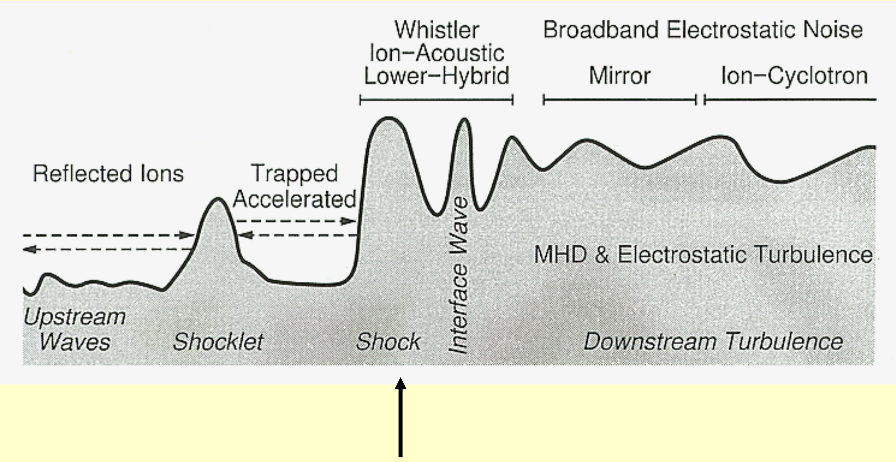
Electron and ion velocity distribution functions



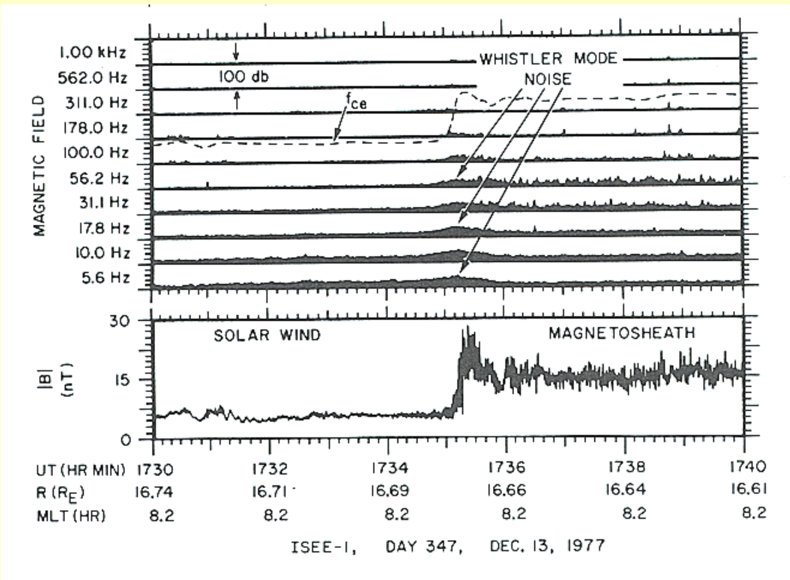


The electron VDF changes from the typical core-halo shape into a broad heated one, which is due to acceleration in the potential of the shock ramp. The ion VDF change from the cold solar wind one by specular reflection and pitch-angle diffusion into a kidney-shaped beam and ring-type VDF in the foreshock region.

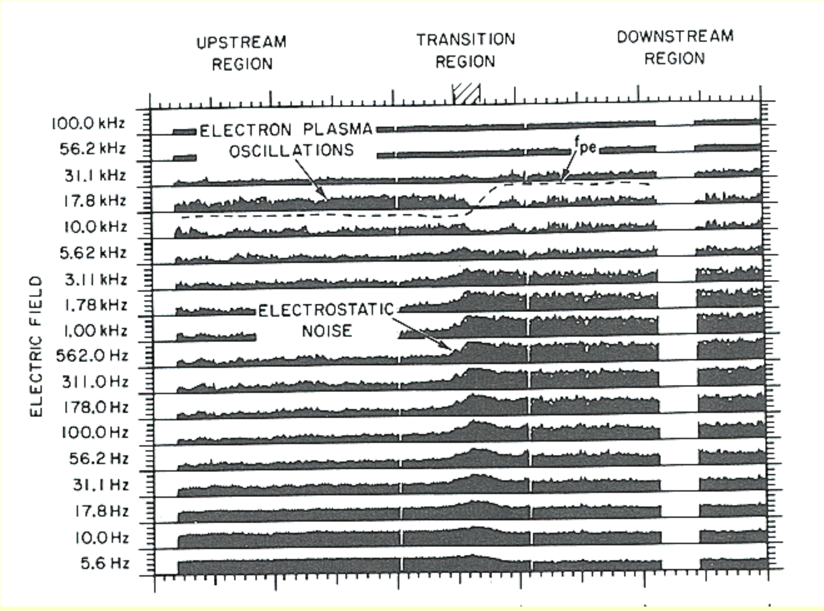
Turbulence and small-scale substructures at the quasiparallel Earth‘s bow shock



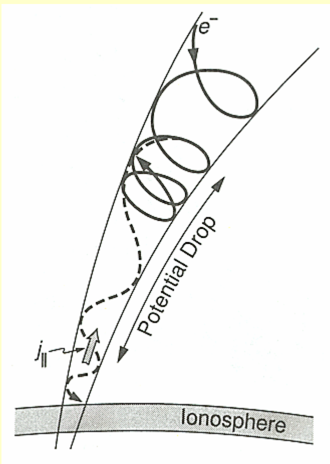
Electromagnetic waves in the vicinity of the bow shock



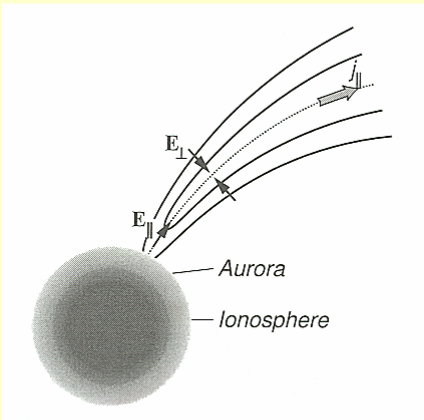
Electrostatic waves in the vicinity of the bow shock



Acceleration of auroral electrons



Mirror impedance due to a field-aligned electric potential drop



Acceleration of auroral electrons by a V-shaped electric potential

Key phenomena in space plasmas

- Dynamic magnetic fields
- Plasma confinement and flows (wind)
- Formation of magnetospheres
- Magnetohydrodynamic waves
- Shocks and turbulence
- Multitude of plasma waves
- Particle heating and acceleration

Complexity in space plasmas

- Highly structured nonuniform magnetic fields
- Multi-component plasmas from various sources
- Velocity distributions far from thermal equlibrium
- Multi-scale spatial and temporal processes
- Sharp but dynamic boundaries and interfaces
- Waves and turbulences everywhere
- Ubiquitous energetic particles