Space Plasma Physics

Thomas Wiegelmann, 2012

1. Basic Plasma Physics concepts
2. Overview about solar system plasmas

Plasma Models

3. Single particle motion, Test particle model
4. Statistic description of plasma, BBGKY-Hierarchy and kinetic equations
5. Fluid models, Magneto-Hydro-Dynamics
6. Magneto-Hydro-Statics
7. Stationary MHD and Sequences of Equilibria

Solar system space plasmas

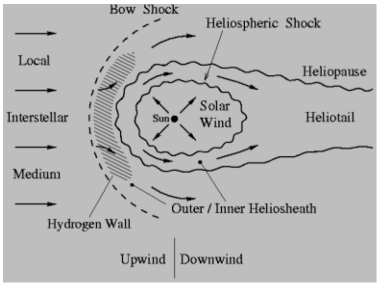
Plasmas differ by their chemical composition and the ionization degree of the ions or molecules (from different sources). Space Plasmas are mostly magnetized (internal and external magnetic fields).

- Solar interior and atmosphere
- Solar corona and wind (heliosphere)
- Planetary magnetospheres (plasma from solar wind)
- Planetary ionospheres (plasma from atmosphere)
- Coma and tail of a comet
- Dusty plasmas in planetary rings

Space plasma

- Space plasma particles are mostly free in the sense that their kinetic exceeds their potential energy, i.e., they are normally hot, T > 1000 K.
- Space plasmas have typically vast dimensions, such that the mean free paths of thermal particles are larger than the typical spatial scales --> they are collisionless.

Structure of the heliosphere



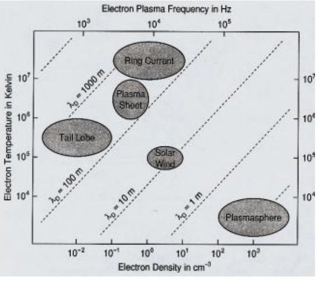
- **Basic plasma motions in the restframe of the Sun**
- **Principal surfaces (wavy lines indicate disturbances)**

Different plasma states

Plasmas differ by the charge, e_j, mass, m_j, temperature, T_j, density, n_j, bulk speed U_j and thermal speed, $V_j=(k_B T_j/m_j)^{1/2}$ of the particles (of species j) by which they are composed.

- Long-range (shielded) Coulomb potential
- Collective behaviour of particles
- Self-consistent electromagnetic fields
- Energy-dependent (often weak) collisions
- Reaction kinetics (ionization, recombination)
- Variable sources (pick-up)

Ranges of electron density and temperature for geophysical plasmas



Some plasmas, like the Sun's chromosphere or Earth's ionosphere are not fully ionized. Collisions between neutrals and charged particles couple the particles together, with a typical collision time, τ_n, say. Behaviour of a gas or fluid as a plasma requires that:

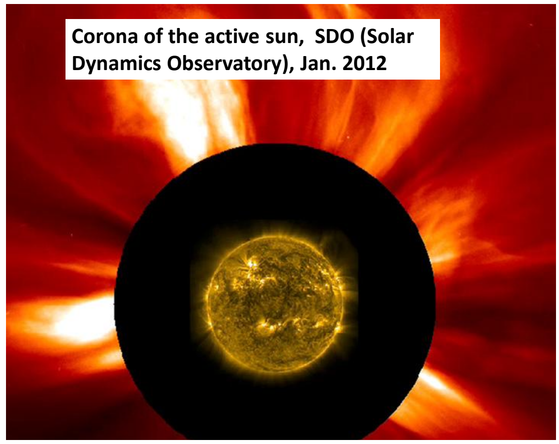
$$\omega_{pe}\tau_n >> 1$$

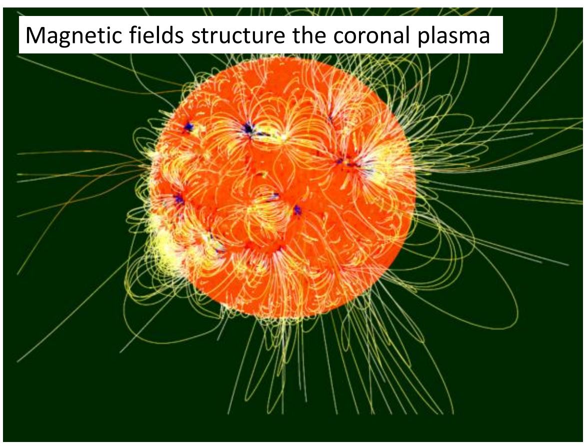
Classification of Magnetic Cosmic Plasmas

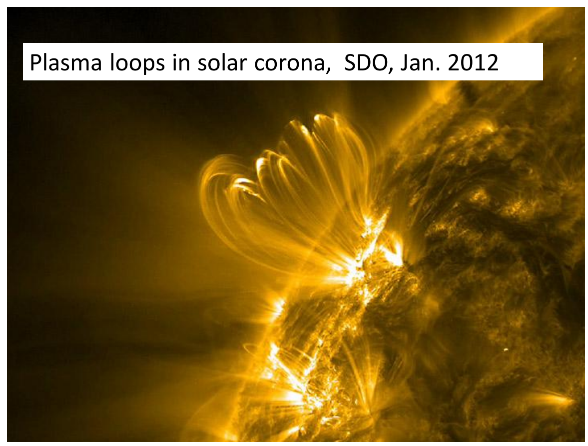
Characteristic	Space plasma density categories (Note that density does not refer to only particle density)			Ideal comparison
	High density	Medium Density	Low Density	
Criterion	$\lambda << \rho$	$\lambda << \rho << l_c$	$l_c << \lambda$	$l_c << \lambda_D$
Examples	Stellar interior Solar photosphere	Solar chromosphere/corona Interstellar/intergalactic space Ionosphere above 70 km	Magnetosphere during magnetic disturbance. Interplanetary space	Single charges in a high vacuum
Diffusion	Isotropic	Anisotropic	Anisotropic and small	No diffusion
Conductivity	Isotropic	Anisotropic	Not defined	Not defined
Electric field parallel to B in completely ionized gas	Small	Small	Any value	Any value
Particle motion in plane perpendicular to B	Almost straight path between collisions	Circle between collisions	Circle	Circle
Path of guiding centre parallel to B	Straight path between collisions	Straight path between collisions	Oscillations (e.g. between mirror points)	Oscillations (e.g. between mirror points)
Debye Distance λ_D	$\lambda_D << l_c$	$\lambda_D << l_c$	$\lambda_D << l_c$	$\lambda_D >> l_c$
Magnetohydrodynamics suitability	Yes	Approximately	No	No

λ=Mean free path. ρ= Larmor radius (gyroradius) of electron. λ_D=Debye length. l_c=Characteristic length

Adapted From *Cosmical Electrodynamics* (2nd Ed. 1952) Alfvén and Fälthammar







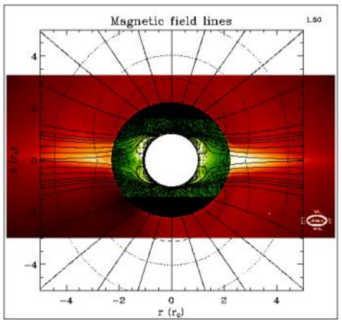
Solar coronal plasma can become unstable
Giant Prominence Erupts - April 16, 2012,
observed with SDO (Solar Dynamics Observatory)

Solar Eruptions

- The solar coronal plasma is frozen into the coronal magnetic field and plasma outlines the magnetic field lines.
- Coronal configurations are most of the time quasistatic and change only slowly.
- Occasionally the configurations become unstable and develop dynamically fast in time, e.g., in coronal mass ejections and flares.

Coronal magnetic field and density

Dipolar, quadrupolar, current sheet contributions



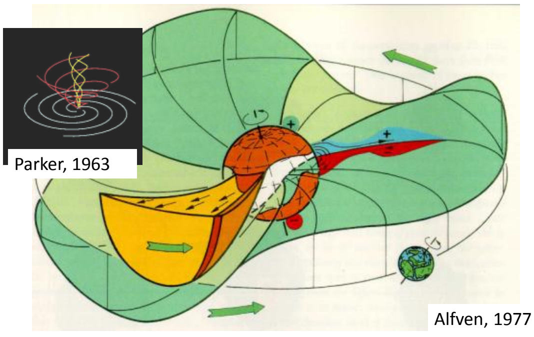
Banaszkiewicz et al., 1998;
Schwenn et al., 1997

Polar field: B = 12 G

Current sheet is a symmetric disc anchored at high latitudes !

LASCO C1/C2 images (SOHO)

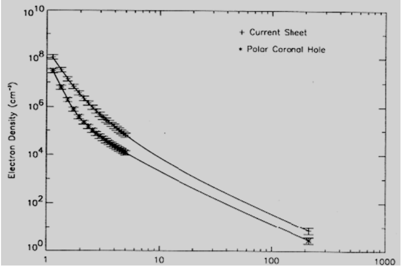
Solar wind stream structure and heliospheric current sheet



Parker, 1963

Alfven, 1977

Electron density in the corona



Heliocentric distance / R_s

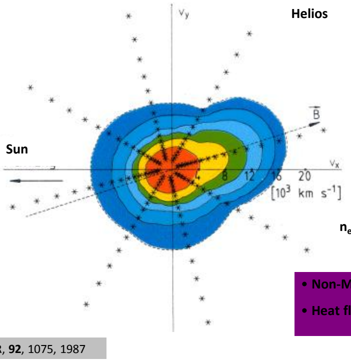
+ Current sheet and streamer belt, closed

• Polar coronal hole, open magnetically

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

Skylab coronagraph/Ulysses in-situ

Measured solar wind electrons

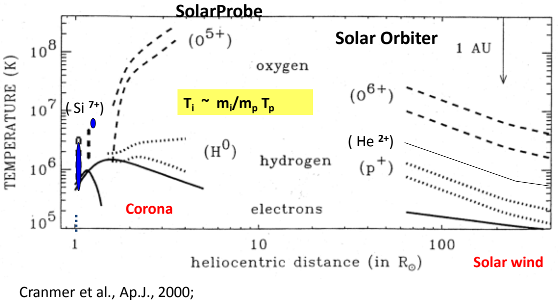


n_e = 3 -10 cm^{-3}

- Non-Maxwellian
- Heat flux tail

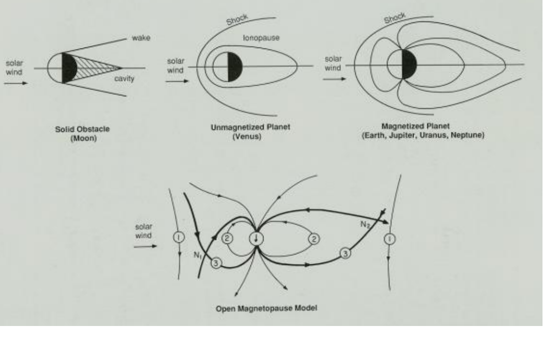
Pilipp et al., JGR, **92**, 1075, 1987

Temperatures in the corona and fast solar wind

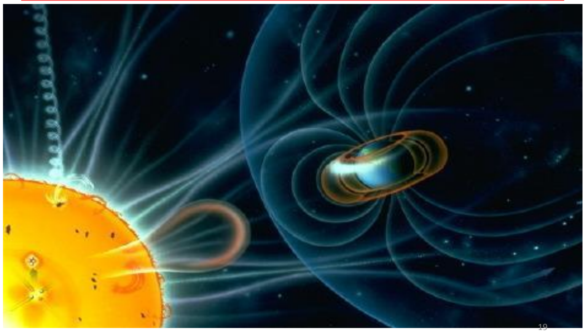


Cranmer et al., Ap.J., 2000;
Marsch, 1991

Boundaries between solar wind and obstacles



Space weather: Instabilities in the solar corona lead to huge eruptions, which can influence the Earth.

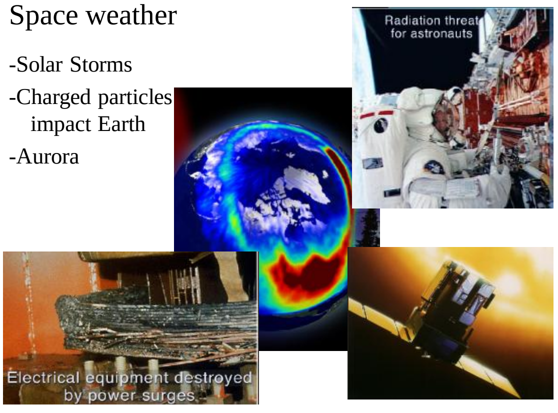


Space weather

-Solar Storms

-Charged particles impact Earth

-Aurora

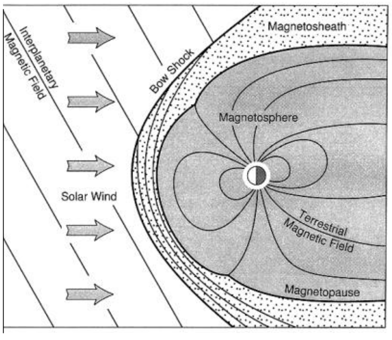


Space weather

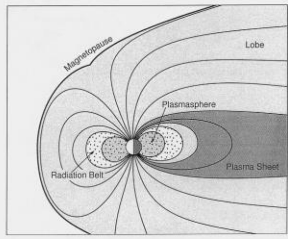
- Solar wind and solar eruptions influence Earth and cause magnetic storms:
- Aurora
- Power cutoffs
- Destroyed satellites
- Harm for astronauts

Movie: Solar wind's effects on Earth
http://www.youtube.com/watch?v=XuD82q4Fxgk

Schematic topography of solar-terrestrial environment



solar wind -> magnetosphere -> iononosphere

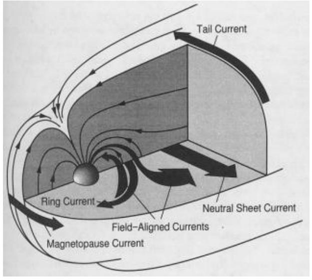


Magnetospheric plasma environment

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 RE thick plasma sheet.
- The plasmasphere inside 4 RE contains cool but dense plasma of ionospheric origin.
- The radiation belt lies on dipolar field lines between 2 to 6 RE.

Magnetospheric current system



The distortion of the Earth's dipole field is accompanied by a current system.

- The currents can be guided by the strong background field, so-called field-aligned currents (like in a wire), which connect the polar cap with the magnetotail regions.
- A tail current flows on the tail surface and as a neutral sheet current in the interior.
- The ring current is carried by radiation belt particles flowing around the Earth in east-west direction.

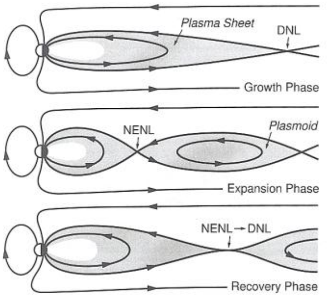
Magnetospheric substorm

Substorm phases:

- Growth
- Onset and expansion
- Recovery

***Magnetic reconnection**:*

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



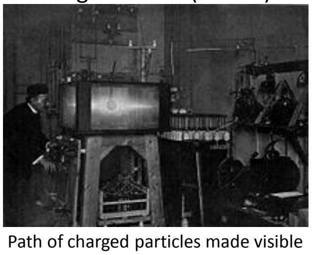
Magnetospheric substorm

- Growth phase: Can be well understood by a sequence of static plasma equilibria and analytic magneto-static models. Plasma is ideal (no resistivity)
- Onset and expansion: The equilibrium becomes unstable and free magnetic energy is set free. Studied with (resistive) MHD-simulations. Cause for resistivity are micro-instabilities (often used ad hoc resistivity models in MHD)
- Recovery phase: Not well studied

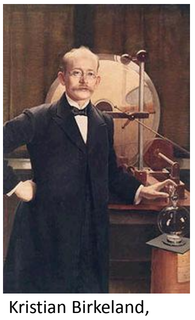
Aurora

Source: Wikipedia

Laboratory experiments, magnetic ball (terella)

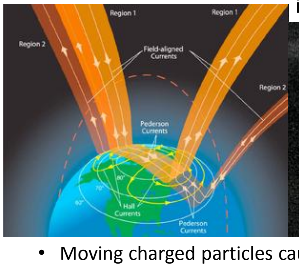


- Path of charged particles made visible in terella, glow in regions around pole.
- Cannot explain why actually in Earth aurora not occur at poles.
- Terellas replace by Computer simulations.

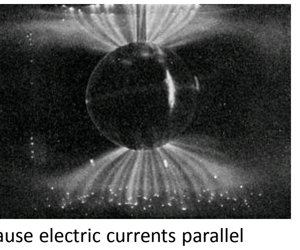


Kristian Birkeland, 1869-1917 first described substorms and investigated Aurora in laboratory.
Source: Wikipedia

Birkeland Currents



Aurora-like Birkeland currents in terella (source:Wikipedia)



- Moving charged particles cause electric currents parallel to the magnetic field lines connecting magnetosphere and ionosphere.
- 100.000 A (quiet times) to 1 million Ampere in disturbed times. => Joule heating of upper atmosphere.

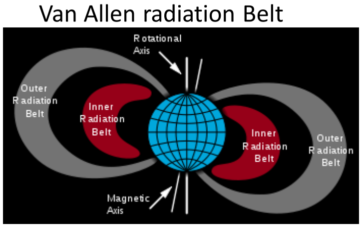
Aurora mechanism

- Atoms become ionized or excited in the Earth's upper atmosphere (above about 80 km) by collision with solar wind and magnetospheric particles accelerated along the Earth's magnetic field lines.
- Returning from ionized or excited states to ground state leads to emissions of photons.
- Ionized nitrogen atoms regaining an electron (blue light) or return to ground based from exited state (red light)
- Oxygen returning from excited state to ground state (red-brownish or green light, depending on absorbed energy in excited states)
- Returning to ground state can also occur by collisions without photon emission => Height dependence of emissions, different colours with height.

Magnetic Storms

- Largest magnetic storm ever measured was in 1859.
- Carrington noticed relation between a white light solar flare and geomagnetic disturbance.
- In 1859 the storm disrupted telegraph communication.
- Such a large storm today could initiate a cascade of destroyed transformators (by induced electric fields) and economic damage of over: 1000 billion Dollar. (source: Moldwin, the coronal current 2010)
- 2005 Hurricane Katrina in USA : 120 billion Dollar. 2011 Earthquake/Tsunami in Japan: 300 billion Dollar.
- Prediction of such storms would help to reduce the damage, e.g., by switching of electric power.

Van Allen radiation Belt



James van Allen
1914-2006
source of pictures: wikipedia

- Contains energetic particles originating from solar wind and cosmic rays.
- Inner belt: protons + electrons
- Outer belt: electrons
- Particles trapped in magnetic field (single particle model sufficient)

Planetary magnetospheres

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

Dynamic equilibrium if ram pressure at magnetopause equals field pressure:

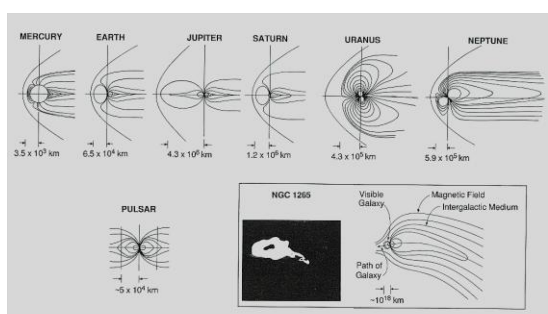
$$\rho_{sw} V_{sw}^2 = B^2/2\mu_0 = B_p^2 (R_p/R_m)^6/2\mu_0$$

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

Planetary parameters and magnetic fields

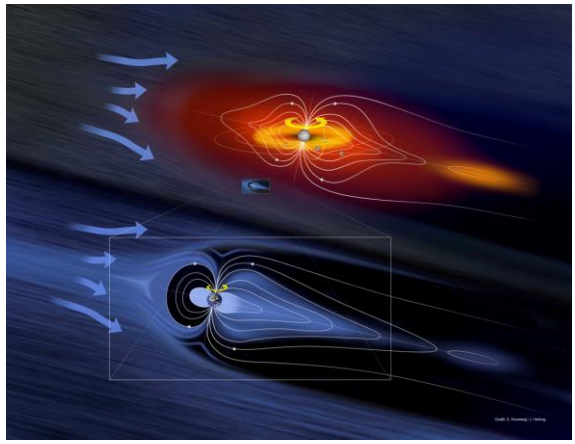
Parameter	Mercury	Earth	Jupiter	Saturn	Sun
Radius [km] (equator)	2425	6378	71492	60268	696000
Rotation period [h]	58.7 d	23.93	9.93	10.66	25-26 d
Dipole field [G] (equator)	340 nT	0.31	4.28	0.22	3-5
Inclination of equator [Degrees]	3	23.45	3.08	26.73	7.12

Magnetospheric configurations



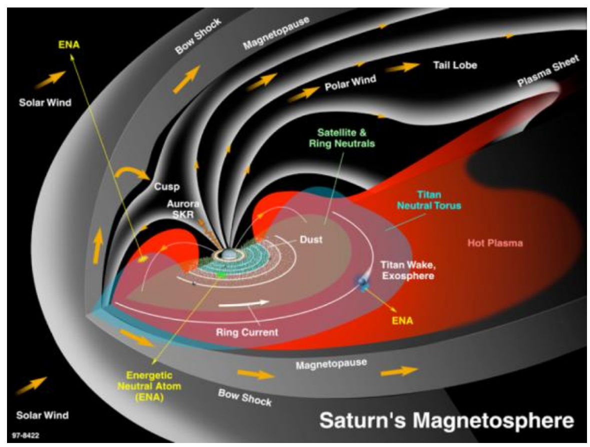
Jovian Magnetosphere

- Jupiter: fast rotation 10 h, mass-loading 1000 kg/s
- Dynamics driven largely by internal sources.
- Planetary rotation coupled with internal plasma loading from the moon Io may lead to additional currents, departure from equilibrium, magnetospheric instabilities and substorm-like processes.
- Regular (periodicity (2.5--4) days) release of mass from the Jovian magnetosphere and changes of the magnetic topology (Kronberg 2007).
- Jovian magnetospheric system is entirely internally driven and impervious to the solar wind (McComas 2007). [Debates are ongoing]



Saturn‘s Magnetosphere

- Saturn's moon Enceladus may be a more significant source of plasma for the Saturn's magnetosphere than Io is for Jovian magnetosphere (Rymer 2010).
- It is important to scale plasma sources, relative to the size of the magnetosphere, to better understand the importance of the internal sources (Vasyliunas 2008).
- At Saturn, auroral features and substorm onset have both been associated with solar wind conditions (Bunce 2005) confirming that both internal loading and the solar wind influence magnetospheric dynamics.



Key phenomena in space plasmas

- Dynamic and structured magnetic fields
- Plasma confinement and flows (solar wind)
- Formation of magnetospheres
- Shocks and turbulence
- Multitude of plasma waves
- Particle heating and acceleration
- Velocity distributions far from thermal equlibrium

Tools needed for space plasma research

- Investigate the motion of charged particles e.g. in radiation belt => Single particle model
- Tools to describe quiet states, where the plasma is in equilibrium (growth phase of magnetic substorms, energy built-up in solar coronal active regions) => Magnetostatics
- Tools to investigate activity (dynamic phase of substorms, coronal eruptions, waves) => MHD
- Cause for change from quiet to active states and tools to investigate energy conversion, reconnection => MHD + kinetic theory