Sun and interplanetary space

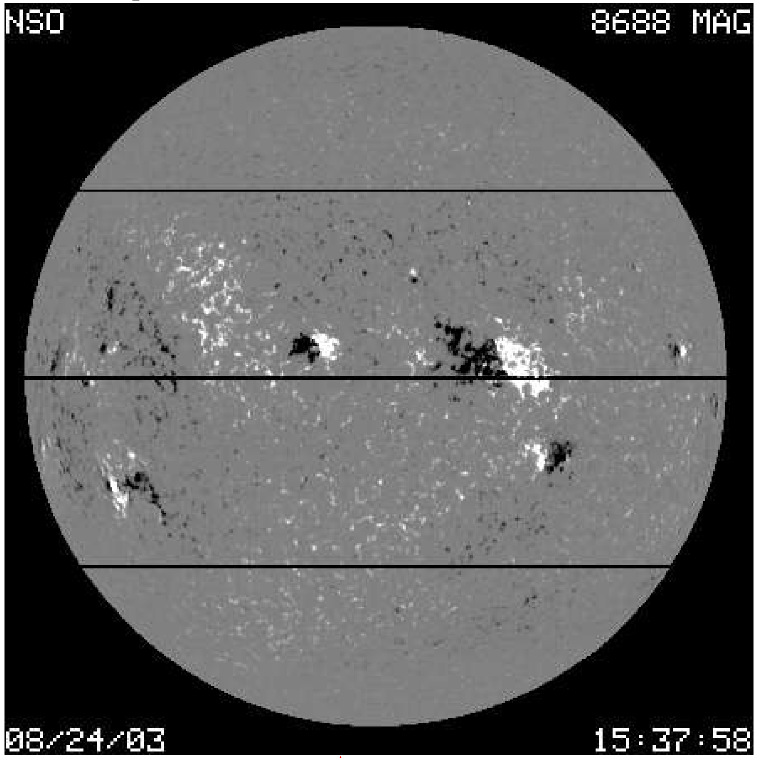
- Overview:
  - The sun as a magnetic star
  - The solar wind
  - The interplanetary medium
  - Waves in interplanetary space
  - The three-dimensional heliosphere
  - The active sun
  - Flares and coronal mass ejections (CMEs)
  - Collisionless shocks

- New concepts:
  - Turbulence and waves
  - Collisionless shocks

Fact sheet sun

Radius	$r_{\odot} = 696\,000$ km
Mass	$M_{\odot} = 1.99 \times 10^{30}$ kg
Average density	$\varrho_{\odot} = 1.91$ g/cm^3
Gravity at the surface	$g_{\odot} = 274$ m/s^2
Escape velocity at the surface	$v_{\text{esc}} = 618$ km/s
Luminosity	$L_{\odot} = 3.86 \times 10^{23}$ kW
Magnetic field	
polar	1 G
general	some G
protuberance	10–100 G
sunspot	3 000 G
Temperature	
core	15 million K
photosphere	5780 K
sunspot (typical)	4200 K
chromosphere	4400–10 000 K
transition region	10 000–800 000 K
corona	2 million K
Sidereal rotation	
equator	26.8 d
30° latitude	28.2 d
60° latitude	30.8 d
75° latitude	31.8 d

The sun as a mgnetic star

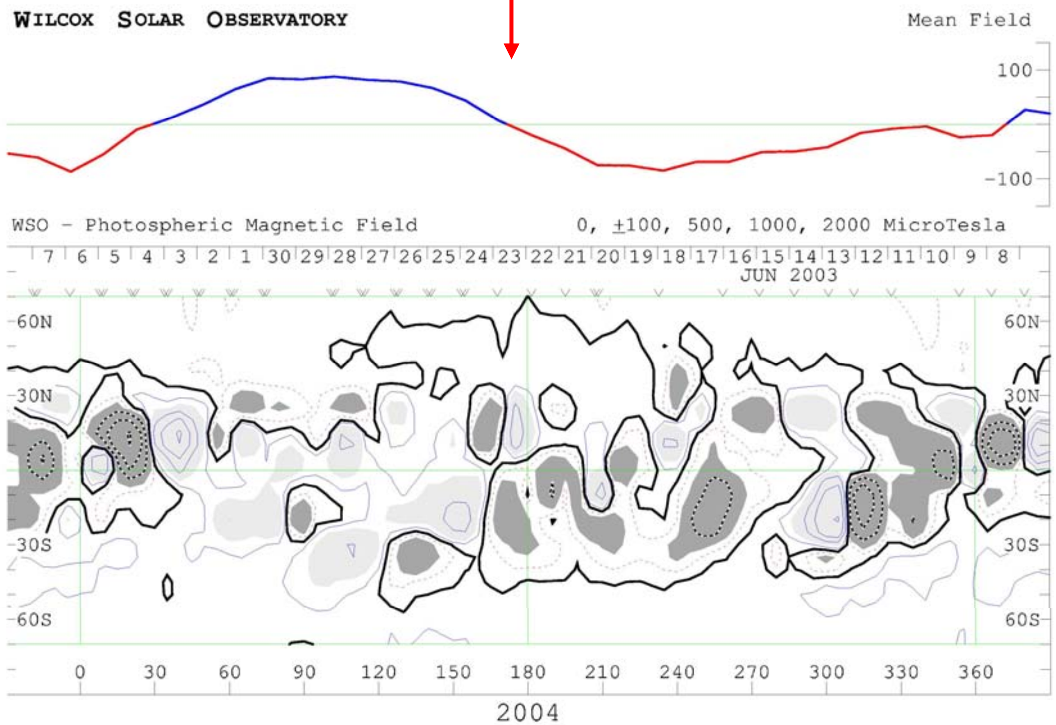


Magnetogram as snap shot of the photospheric magnetic field; National Solar Observatory NSO

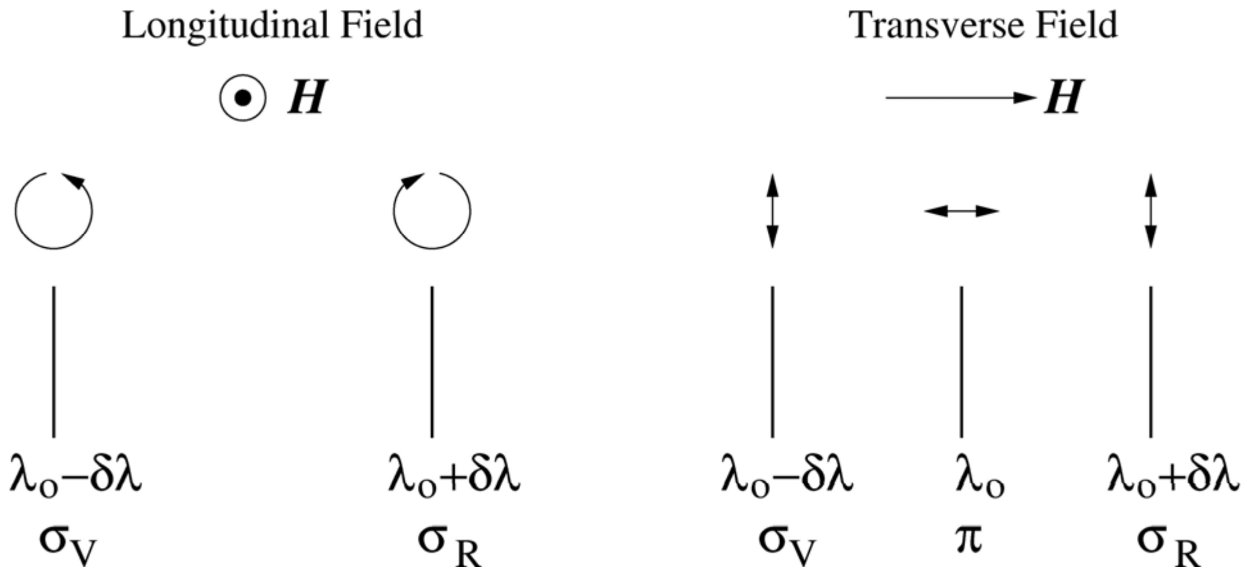
www.nso.noao.edu/synoptic/

Reconstructed photospheric magnetic field for one Carrington rotation (Carrington: frame of reference rotating with the sun; defined by the time the zero meridian crosses the Sun-Earth line)

www.stanford.edu/synoptic.html



Excursion: magnetic field measurement



- Zeeman-Effect: splitting of spectral lines in a magnetic field:

$$\delta\lambda = \frac{\pi e}{m_e} \frac{\lambda_o^2 g B}{c} = 4.7 \times 10^{-13} \lambda_o^2 g B$$

  - distance $\delta\lambda$ is a function of magnetic flux density,
  - polarization is a function of the magnetic field direction!

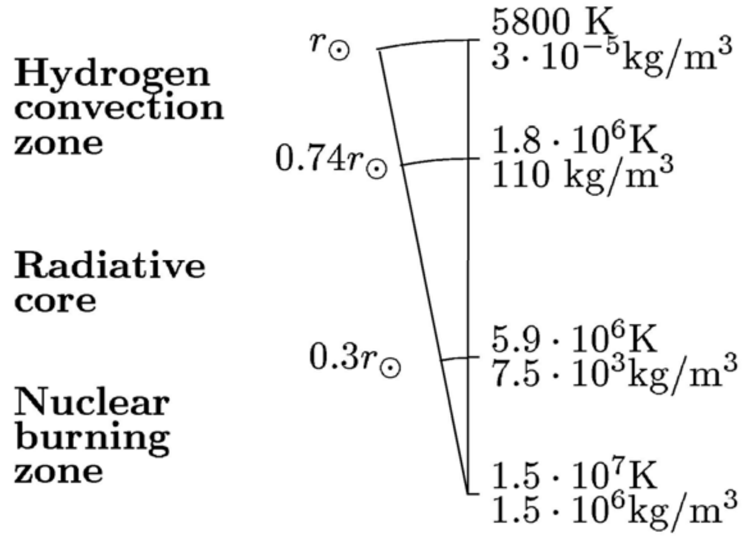
Nuclear fusion as energy source

- Generation of energy by to nuclear fusion: 4 H $\rightarrow$ He + ΔE
- PPI-cycle:

$$^{1}\mathrm{H}(\mathrm{p},\mathrm{e}^{+}\nu_{\mathrm{e}})^{2}\mathrm{D}(\mathrm{p},\gamma)^{3}\mathrm{He}(^{3}\mathrm{He},2\mathrm{p}\gamma)^{4}\mathrm{He}+26.2\ \mathrm{MeV}$$

10E10 years seconds 10E6 years

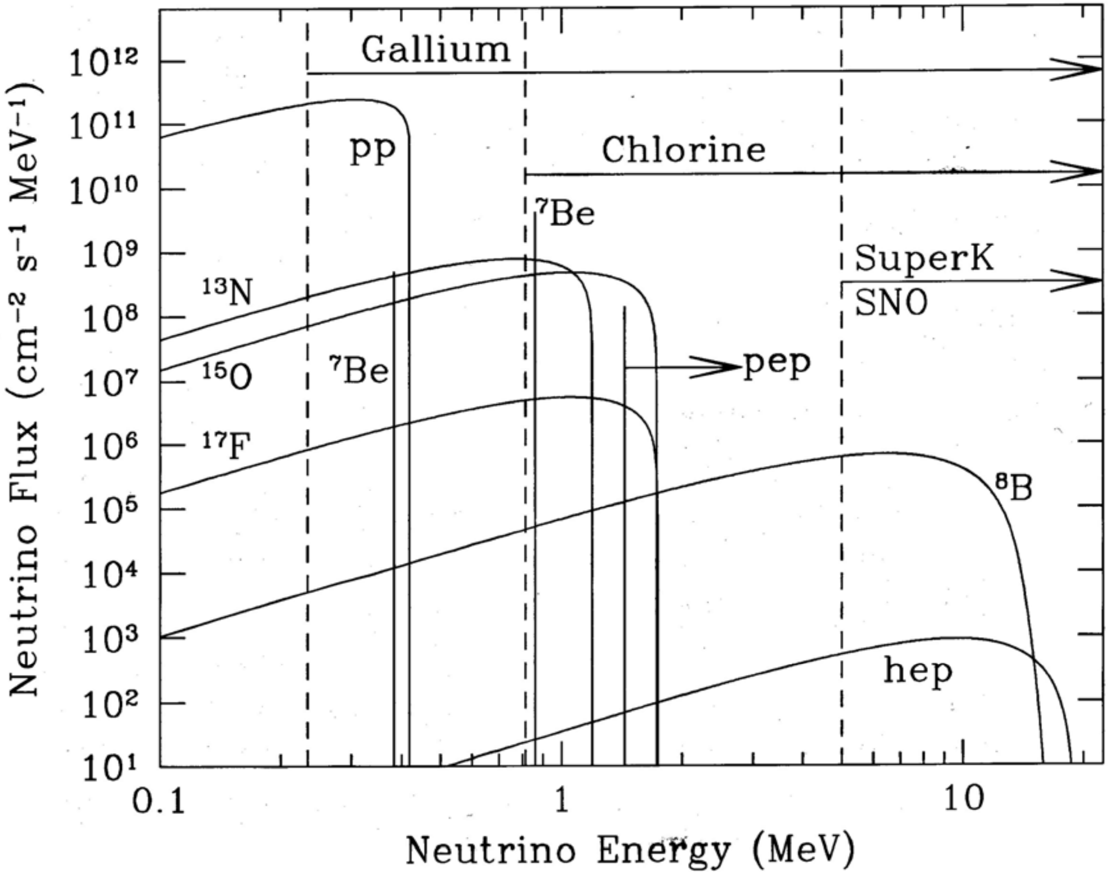
- Alternatively:
  - PPII-cycle $^{3}\mathrm{He}(\alpha,\gamma)^{7}\mathrm{Be}(\mathrm{e}^{-},\nu_{\mathrm{e}})^{7}\mathrm{Li}(\mathrm{p},\gamma)^{8}\mathrm{Be}(\alpha)^{4}\mathrm{He}+25.9\mathrm{MeV}$
  - PPIII-cycle $^{3}\mathrm{He}(\alpha,\gamma)^{7}\mathrm{Be}(\mathrm{p},\gamma)^{8}\mathrm{Be}(\mathrm{e}^{+}\nu_{\mathrm{e}})^{8*}\mathrm{Be}(\alpha)^{4}\mathrm{He}+19.5\mathrm{MeV}$



- Besides from energy all cycles produce neutrinos ν, although with different energies.

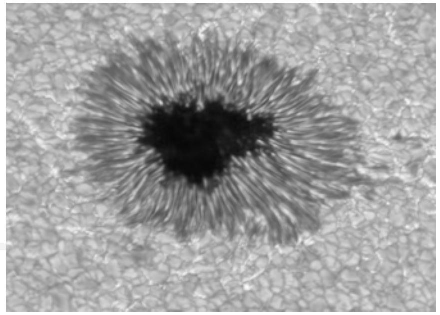
Solar neutrinos: problems

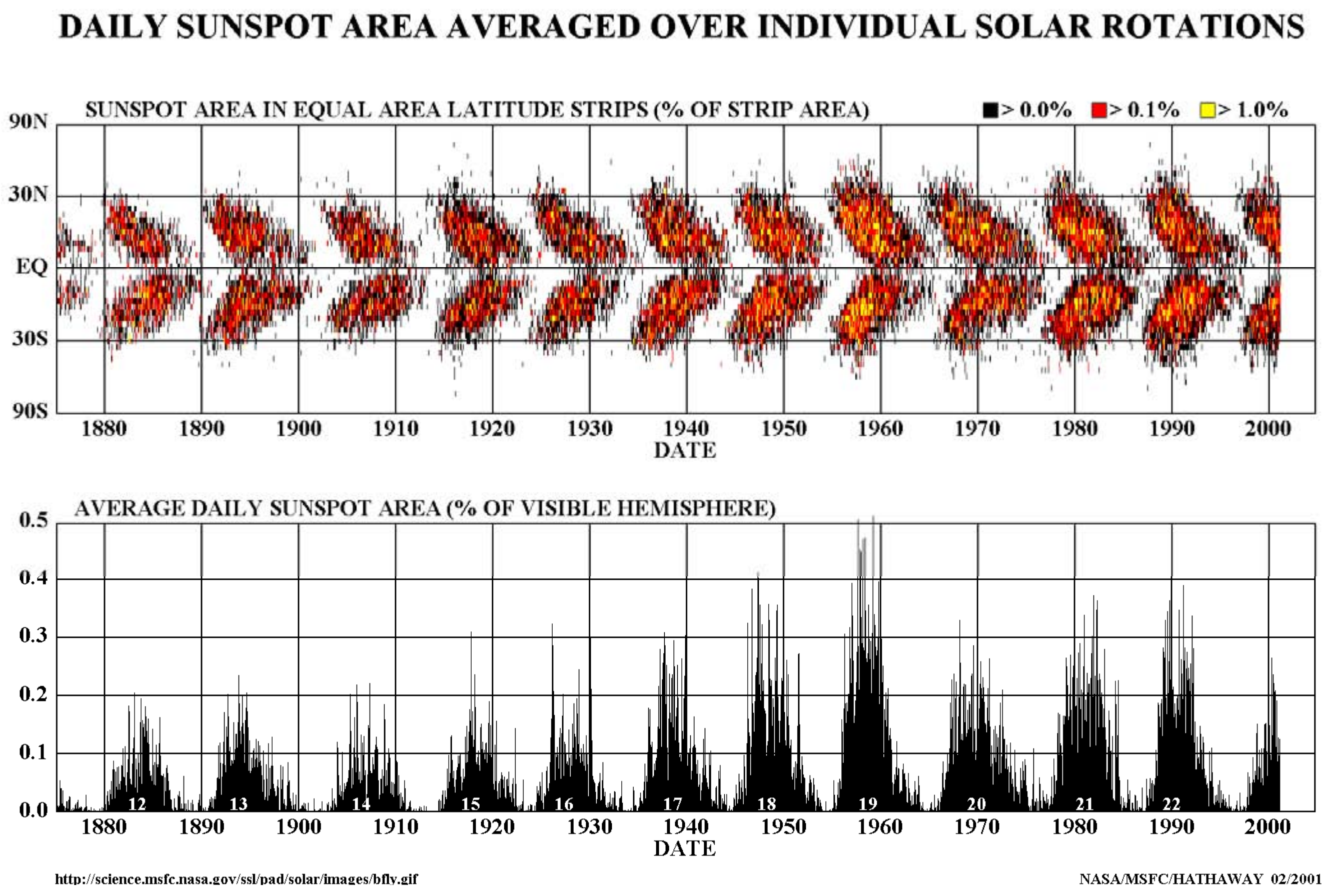
- "Solar neutrino problem": observations give less ν than expected from the standard model of the sun.
- Possible explanations:
  - Observational problem,
  - Fault in the standard model
  - Wrong ideas about neutrinos?
- Neutrinos have a mass and can oscillate between different types!



Chitre, 2003, in Antia et al., Lecture Notes in Phys 619, Springer

Solar cycle I

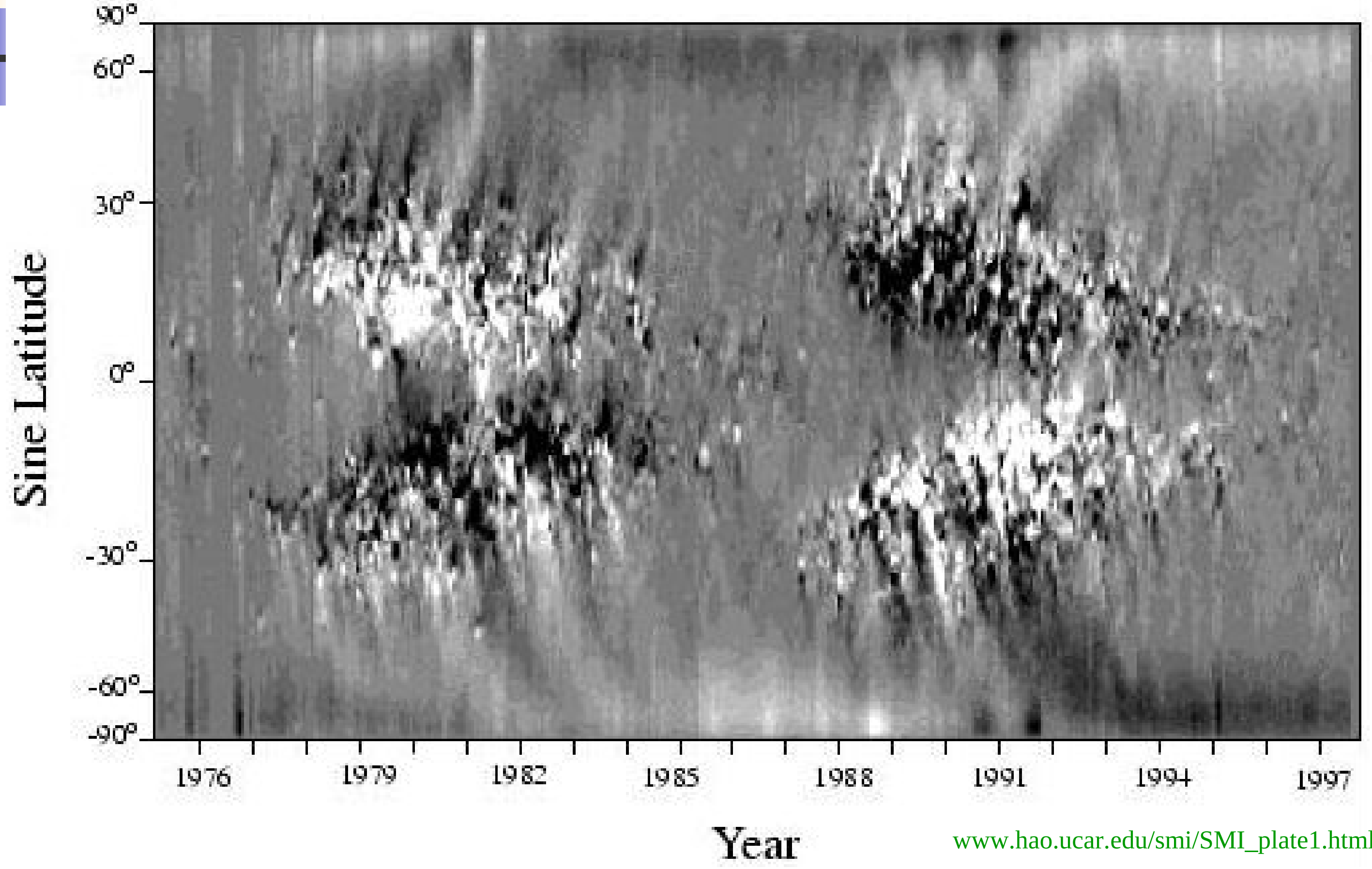




http://science.msfc.nasa.gov/ssl/pad/solar/images/bfly.gif

- Indicator: sun spots.
- Duration: on average 11 years with 11 being everything from 7 to 18.
- Sun spot number highly variable from cycle to cycle and from maximum to maximum.
- „Spotless“ periods: Maunder minimum, Dalton minimum.

Solar cycle II



www.hao.ucar.edu/smi/SMI_plate1.html

- Butterfly diagram of magnetic flux,
- Polarity patterns opposite in both hemispheres,
- Polarity patterns reverse from one solar cycle to the next.

Solar cycle: laws

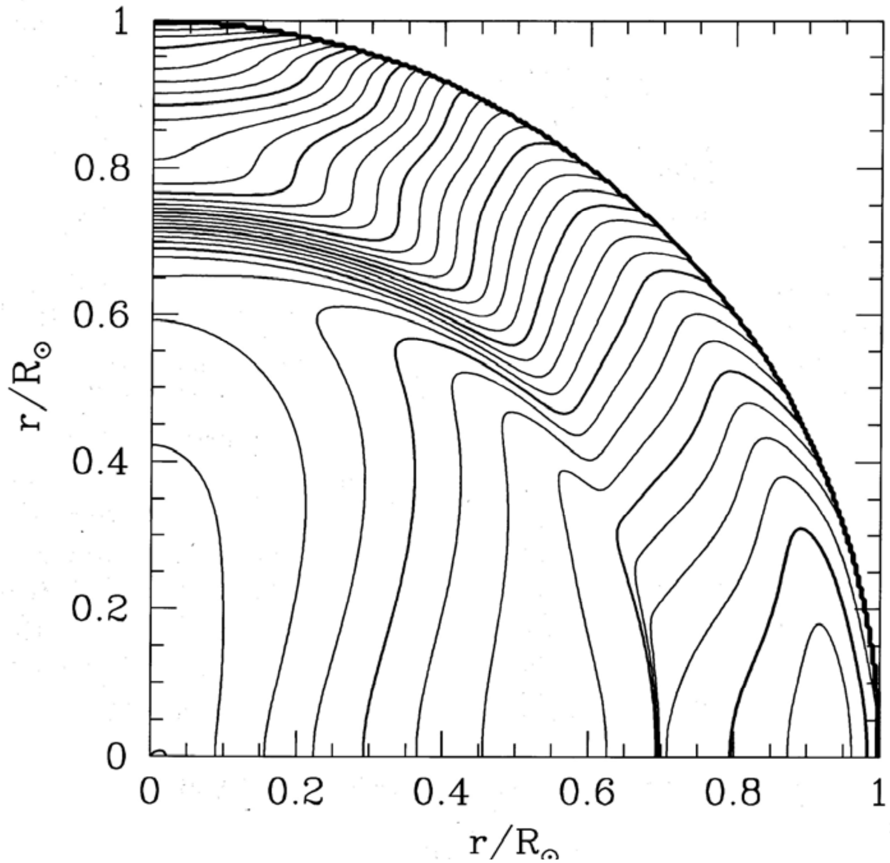
- Observations:
  - Spörer´s law: sunspots emerge at relatively high latitudes and move towards the equator. During the solar cycle the latitude of emergence also moves towards the equator.
  - Hale´s polarity law: sunspots are observed in bipolar groups with the leading spot (in the direction of apparent motion and closest to the equator) having the same polarity as the hemisphere it appeared in. The bipolar groups in opposite hemispheres have opposite magnetic orientation and this orientation reverses with every new cycle.
  - Joy´s law: the tilt angle of the active regions is proportional to latitude.
- These laws have to be obeyed by dynamo models.

Solar cycle and solar dynamo

- Site of the dynamo: bottom of the convection zone.

- Ingredients:
  - differential rotation Ω (left),
  - α-effect (stochastic motion plus Coriolis force creates a poloidal field out of a toroidal one).

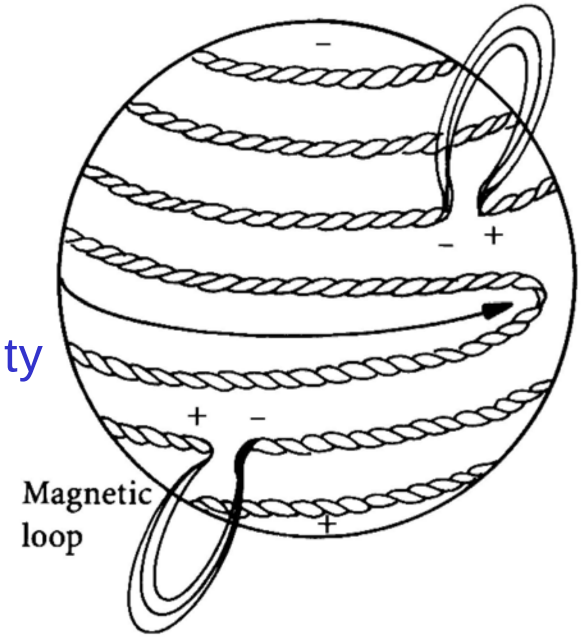
- Dissipation
  - β-effect (stochastic motion reduces spatial scales of the field and thus also time constant for dissipation),
  - Important for the reversal!



Antia, 2003, in Antia et al., Lecture Notes in Phys. 619, Springer

Emerging flux: sunspots

- Rising phase of the solar cycle:
  - Differential rotation creates toroidal field.
  - Increase of magnetic flux.
  - Increase of magnetic pressure.
  - Magnetic buoyancy.
  - Flux tubes rise above the photosphere: bipolar groups of spots in agreement with Hale's polarity law,



- Reversal (declining phase):
  - α-effect (twisted flux tubes).
  - Merging of leading spots.
  - Polward propagation of following spots.

Solar dynamo: details 1

- Emerging flux: pressure equilibrium as in sunspots: $p_\mathrm{i} + \frac{B^2}{2\mu_\mathrm{o}} = p_\mathrm{e}$
- Rewriting using gas law $\varrho_\mathrm{i} RT + \frac{B^2}{2\mu_\mathrm{o}} = \varrho_\mathrm{e} RT$ yields: $\frac{\varrho_\mathrm{e} - \varrho_\mathrm{i}}{\varrho_\mathrm{e}} = \frac{B^2}{2\mu_\mathrm{o} p_\mathrm{e}}$

  for the magnetic buoyancy.

- Parker´s solution:
  - All quantities are averages
  - Combination of Ohm´s and Ampere´s law (see reconnection):

$$\vec{E} = \frac{\vec{j}}{\sigma} - \vec{u} \times \vec{B} = \frac{\nabla \times \vec{B}}{\mu_\mathrm{o} \sigma} - \vec{u} \times \vec{B} = \vec{u}_\mathrm{o} \times \vec{B}_\mathrm{o}$$

  yields together with the correlation function the dynamo equation

$$\frac{\partial \vec{B}}{\partial t} = \nabla \times (\vec{u} \times \vec{v}) + \nabla \times (\alpha \vec{B}) + \beta \nabla^2 \vec{B}$$

Solar dynamo: details 2

- Cartesian reference frame rotating with the Sun (right):

toroidal field　　soleonidal field

$$\vec{B} = B_y(x,z)\vec{e}_y + \nabla \times [A(x,z)\vec{e}_y]$$

- Insert into dynamo equation

Evolution of a toroidal field out of differential rotation and turbulence

$$\frac{\partial B_y}{\partial t} = GB_x - \alpha\nabla^2 A + \beta\nabla^2 B_y$$

with G=∂v_y/∂x being the shear in v

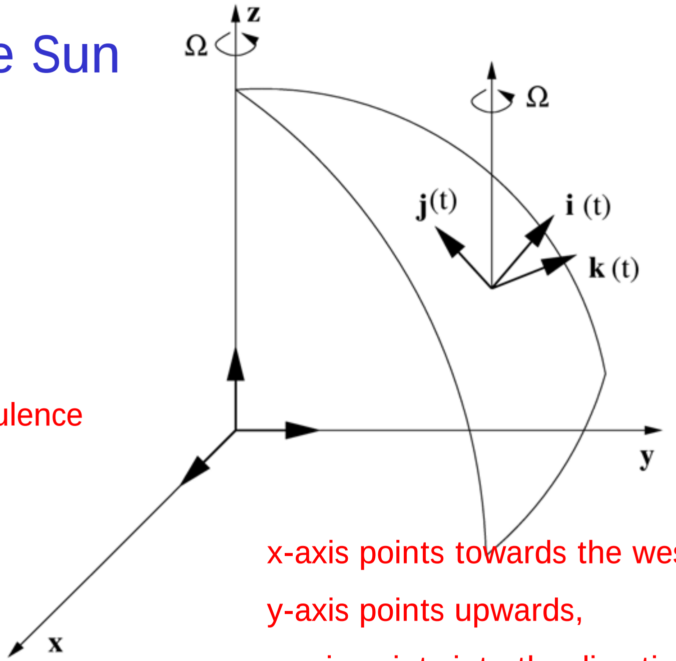
- xz-components can be reduced to

$$\nabla \times \left(\frac{\partial A}{\partial t}\vec{e}_y - \alpha B_y\vec{e}_y - \beta\nabla^2 A\vec{e}_y\right) = 0$$

- Solution

$$\frac{\partial A}{\partial t} = \alpha B_y + \beta\nabla^2 A$$

Evolution poloidal field out of the α-effect



x-axis points towards the west,

y-axis points upwards,

z-axis points into the direction of increasing latitude

Solar dynamo: details 3

- Strong differential rotation: equation for the toroidal field is reduced to the equation for the $\alpha\Omega$-dynamo:

$$\frac{\partial B_y}{\partial t} = G\,\frac{\partial A}{\partial z} + \beta \nabla^2 B_y$$

- Ansatz: wave function

$$A = A_\mathrm{o} \exp(\omega t + \mathrm{i}kz) \quad \text{and} \quad B_y = B_\mathrm{o} \exp(\omega t + \mathrm{i}kz)$$

- Insert, solve PDE, limit to real part, solution

$$\omega = -\beta k^2 + \sqrt{\frac{k\alpha G}{2}} - \mathrm{i}\sqrt{\frac{k\alpha G}{2}} \quad \text{or} \quad \Re(\omega) = -\beta k^2 + \sqrt{\frac{k\alpha G}{2}}$$

- Definition of a dynamo parameter:

$$N_\mathrm{d} = \frac{|\alpha G|}{\beta^2 k^3}$$

Solar dynamo: details 4

- Dynamo-increase for Nd ≥ 2, corresponding to $\Re(\omega) \geq 0$.

- Eigenmodes marginally stable (Nd=2), dynamo with $\alpha G>0$

$$A, B_y \sim \exp\left\{-\mathrm{i}\sqrt{\frac{k\alpha G}{2}}\,t + \mathrm{i}kz\right\}$$

  corresponds to a wave propagating polwards.

- For $\alpha G<0$ it is

$$\omega = -\beta k^2 + \sqrt{\frac{k|\alpha G|}{2}} - \mathrm{i}\sqrt{\frac{k|\alpha G|}{2}} \quad \text{or} \quad \Re(\omega) = -\beta k^2 + \sqrt{\frac{k|\alpha G|}{2}}$$

  and marginally stable solutions

$$A, B_y \sim \exp\left\{\mathrm{i}\sqrt{\frac{k|\alpha G|}{2}}\,t + \mathrm{i}kz\right\}$$

  correspond to waves propagating equatorwards.

Stellar dynamos

- Sun:
  - Due to close proximity small scales aspects of solar activity such as spots, filaments and flares can be identified.
  - The CaII lini give a general measure for magnetic activity.

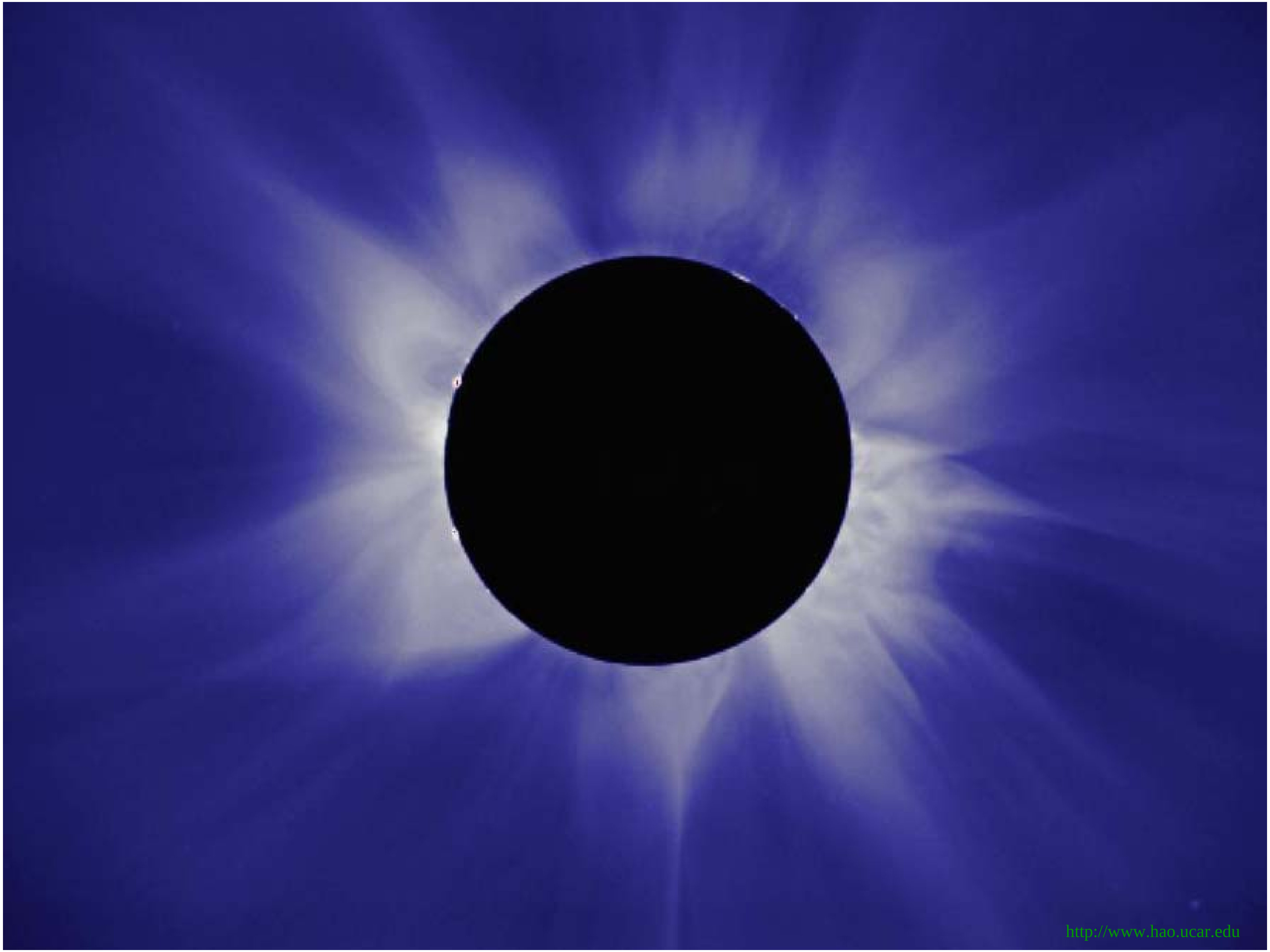
- Other stars (inferred from the CaII-line):
  - Magnetic activity much stronger,
  - Stellar cycles can be markedly shorter than the solar cycle,
  - Similarities to the solar cycle:
    - Stochastic variations in cycle length,
    - Variations in the level of magnetic activity from cycle to cycle.

Solar dynamo: summary

- The solar dynamo is shaped by an interplay between
  - Differential rotation which creates a toroidal magnetic field out of a poloidal one, and
  - Turbulent motion with a systematic twist due to the Coriolis force (α-effect) to create a poloidal field out of a toroidal one.
  - Turbulence (β-effect) also is required for the dissipation of the field (reversal).

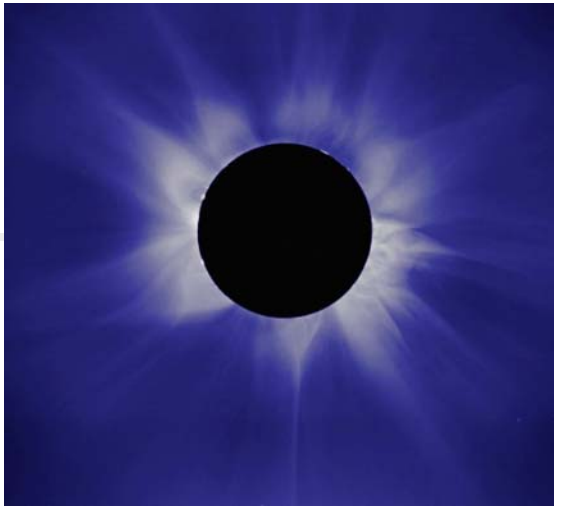
- Magnetic buoyancy explains the obvious properties of solar activity such as bipolar groups and the motion of the sunspots.

- Main problem: reversal with realistic parameters.


http://www.hao.ucar.edu

Solar wind and the interplanetary madium

The corona extends as solar wind into the interplanetary medium.



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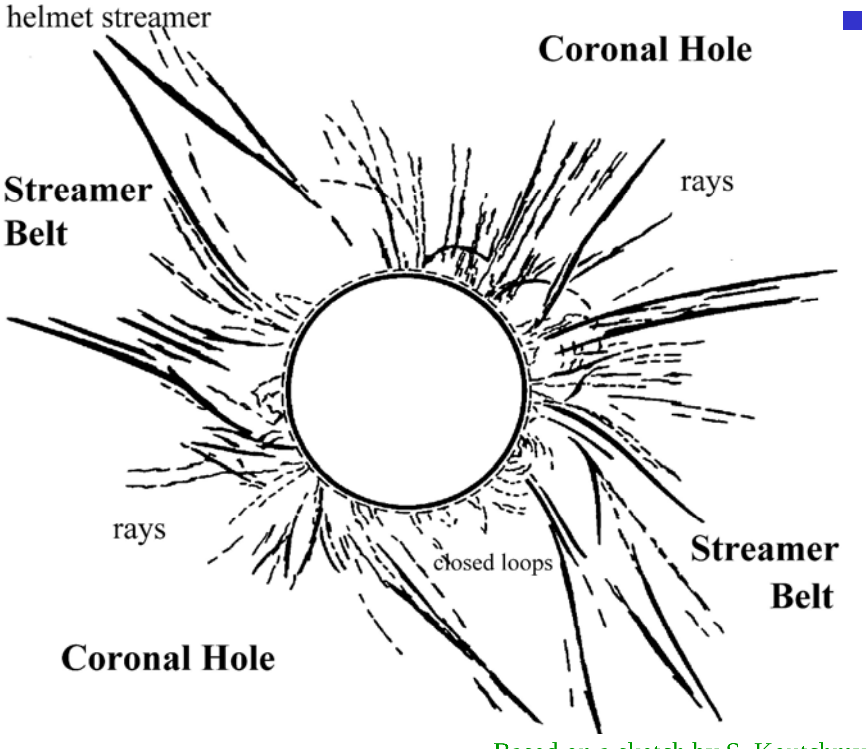


Based on a sketch by S. Koutchmy

- The interplanetary medium is structured by the properties of the corona:
  - Fast solar wind originates in coronal holes
  - Slow solar wind originates in the Streamer Belt
  - Corotating interaction regions form where both meet
  - Coronal structures define the heliospheric current sheet and the source surface

Excursion: radiation

- A black body emits radiation according to Planck´s law:

$$B_\lambda(T) = \frac{2hc^2}{\lambda^5}\frac{1}{e^{\frac{hc^2}{k\lambda T}} - 1} \quad \text{oder} \quad B_\nu(T) = \frac{2h\nu^3}{c^2}\frac{1}{e^{\frac{h\nu}{kT}} - 1}$$

- Integration yields the total flux of radiation (Stefan-Boltzmann's law):

$$q = \pi F = \pi \int_0^\infty B_\lambda(T)\,\mathrm{d}\lambda = \sigma T^4$$

- Differentiation yields the wavelength of maximum emission (Wien´s law):

$$\lambda(\max)\,T = \mathrm{const} = 2884\mu\mathrm{m\,K}$$

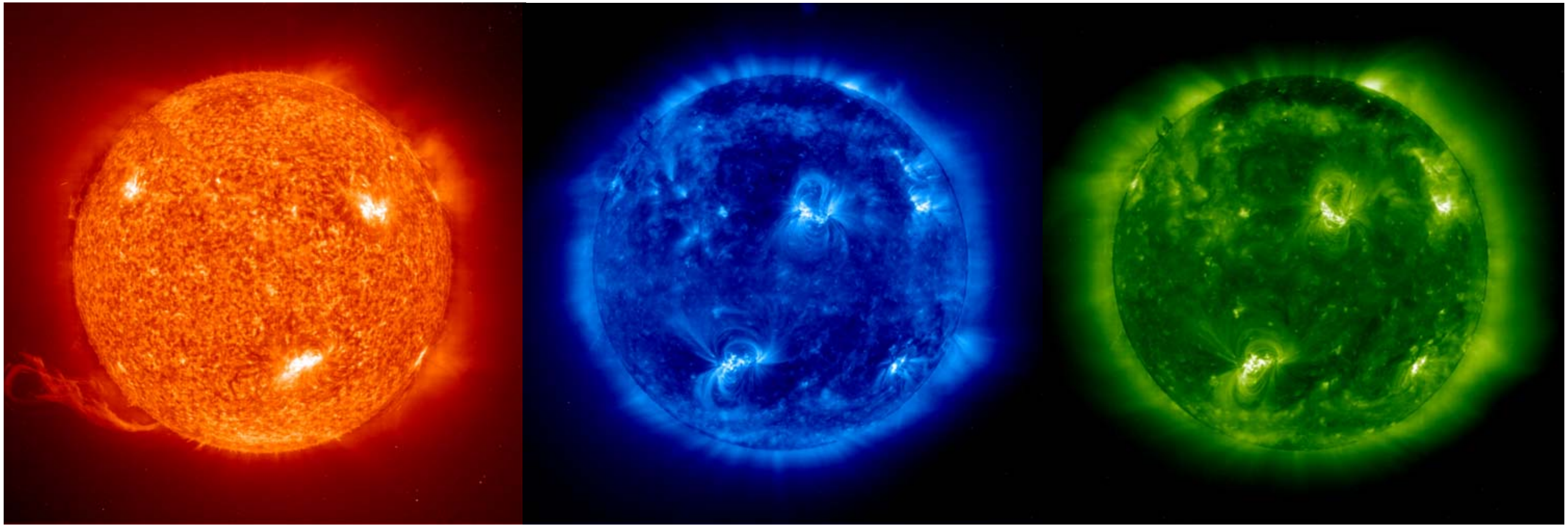
Coronal emission

- Photosphere: radiates like a black body with T ≈ 5800 K

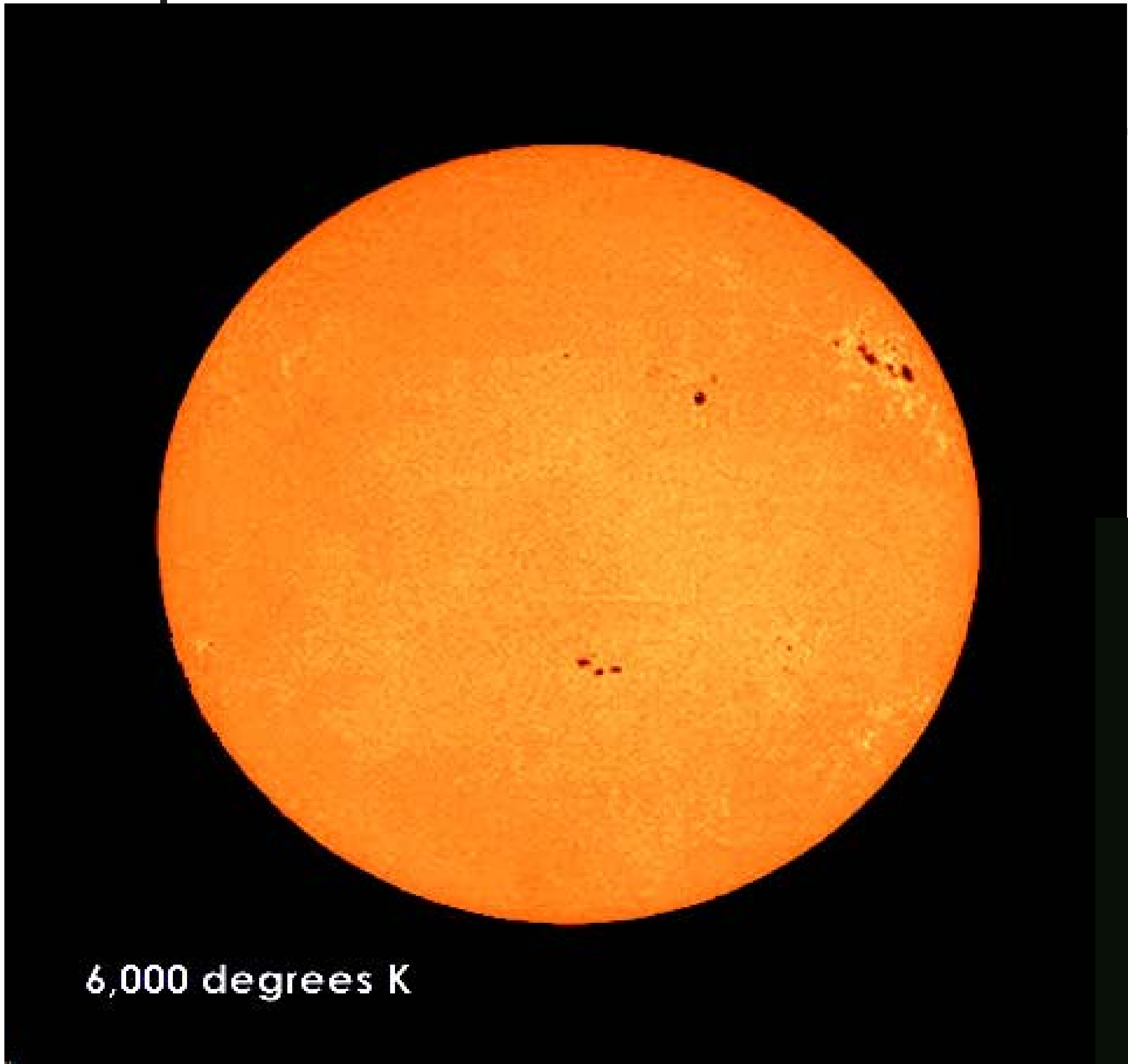
- Corona:
  - Emission lines (E-corona): highly ionized ions (Ca XV, Fe XIV) ⇒ temperature measurement.
  - Continuum corona (K-corona): this is not emission!
    - Visible corona
    - Photospheric light scattered from electrons ⇒ density measurement.
    - Linearly polarized, because electrons orientate by the coronal magnetic field.
    - Electrons are guided by the magnetic field ⇒ Density distribution also reflects the structure of the coronal magnetic field
  - Fraunhofer-Corona (F-Corona): scattering at dust particles with small velocities, extends into interplanetary space (Zodiacal light)

Corona: height structure

- Solar soft X-rays are thermal emission.
- Different wave length are emitted from different temperature ranges/layers in the corona.
- Different spectral lines correspond to different heights.

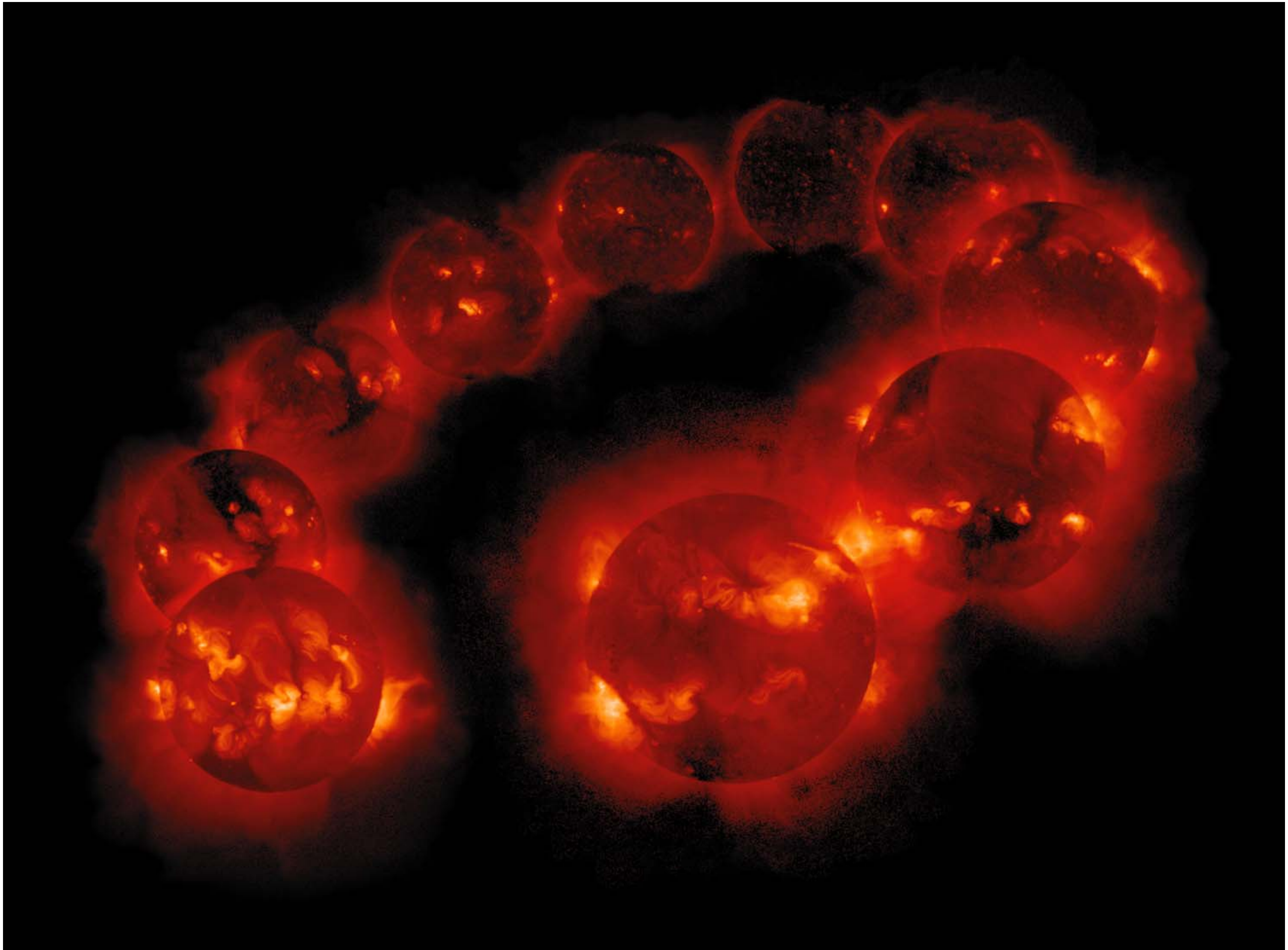


Hα Fe IX/X Fe XII



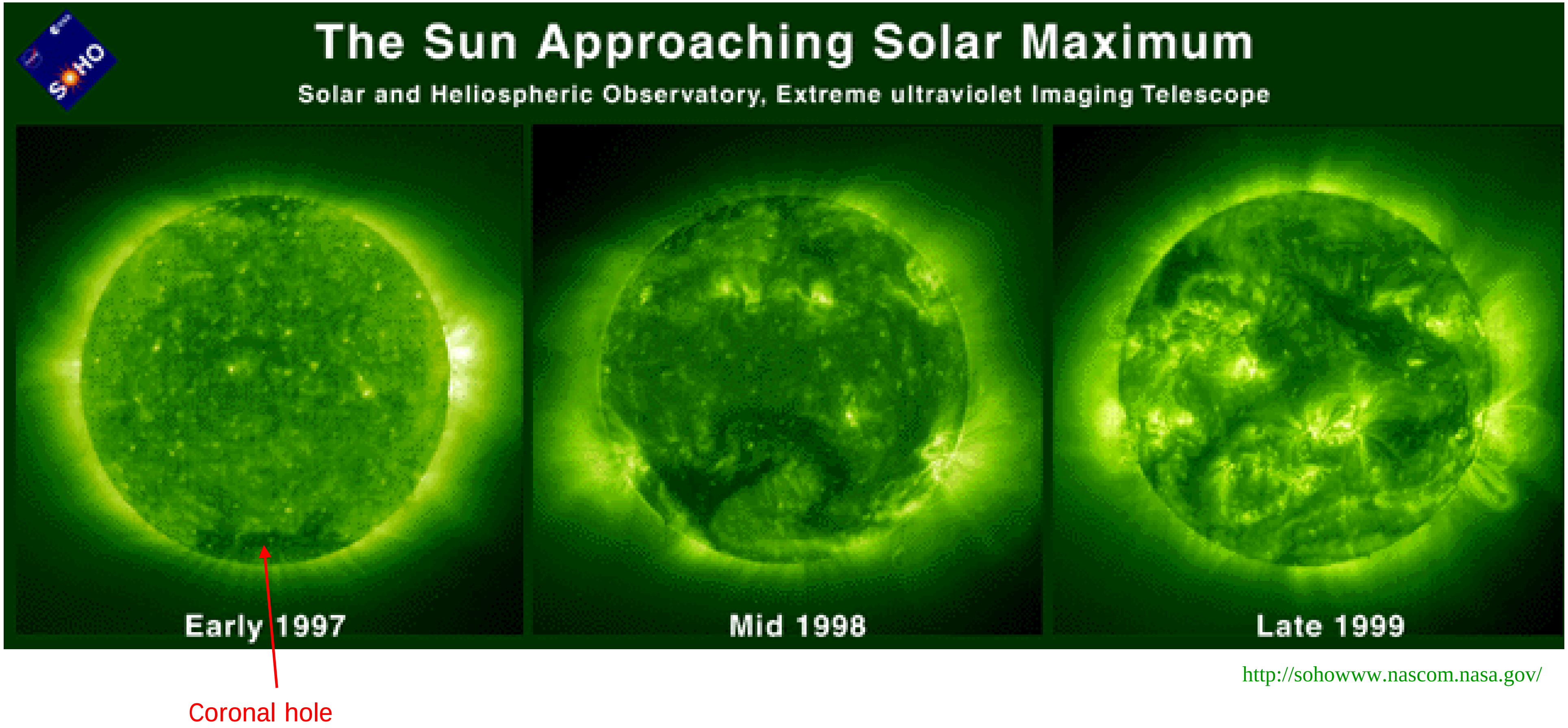
http://sohowww.nascom.nasa.gov/

http://vestige.lmsal.com/TRACE/POD/TRACEpodoverview.html



http://solar.physics.montana.edu/mckenzie/Images/The_Solar_Cycle_XRay_hi.tiff

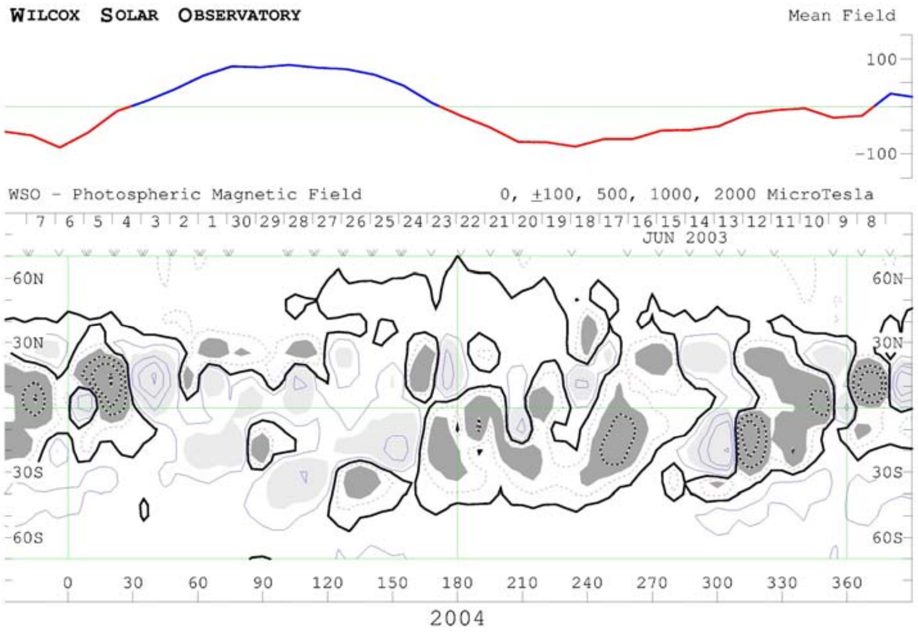
Corona during the solar cycle

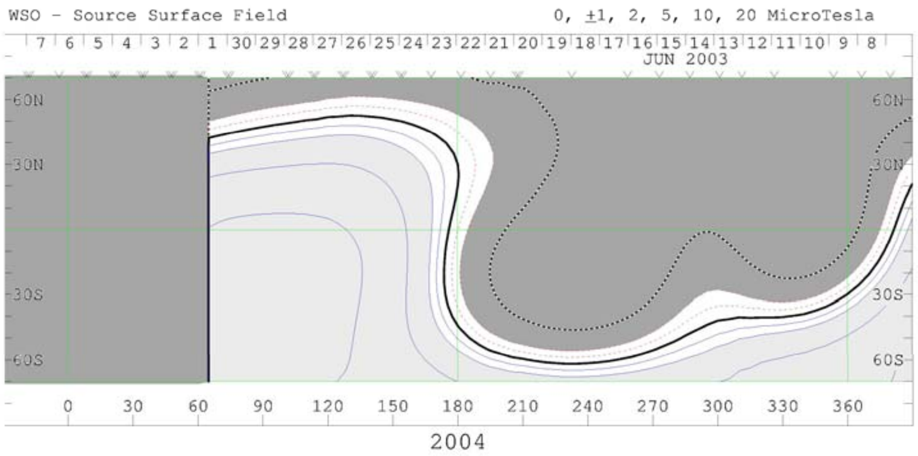


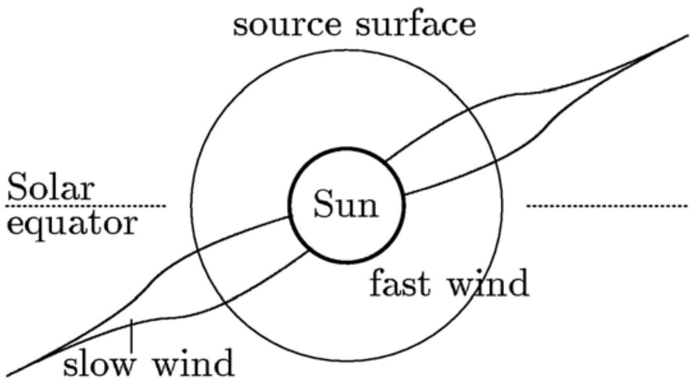
http://sohowww.nascom.nasa.gov/

Source Surface

- Fictitious separation between the small-scale coronal and large-scale interplanetary field:
  - All lines of force are perpendicular to the source surface.
  - Magnetic field structures connected by arcs lie below the source surface.
  - The polarity pattern of the source surface is observed in ipl. space.

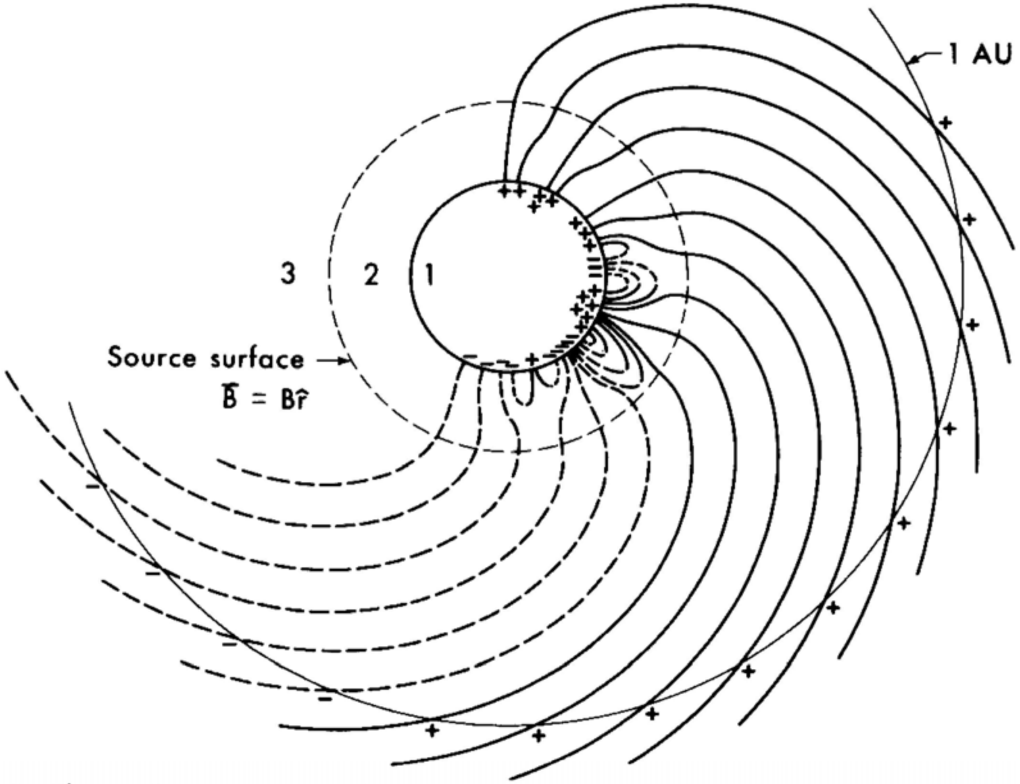






Sectors und Source Surface

- The source surface can be determined from potential theory.
- Polarity patterns of the source surface are carried into interplanetary space.
- The interplanetary magnetic field shows a pattern of sectors, depending on the poalarity pattern on the source surface.

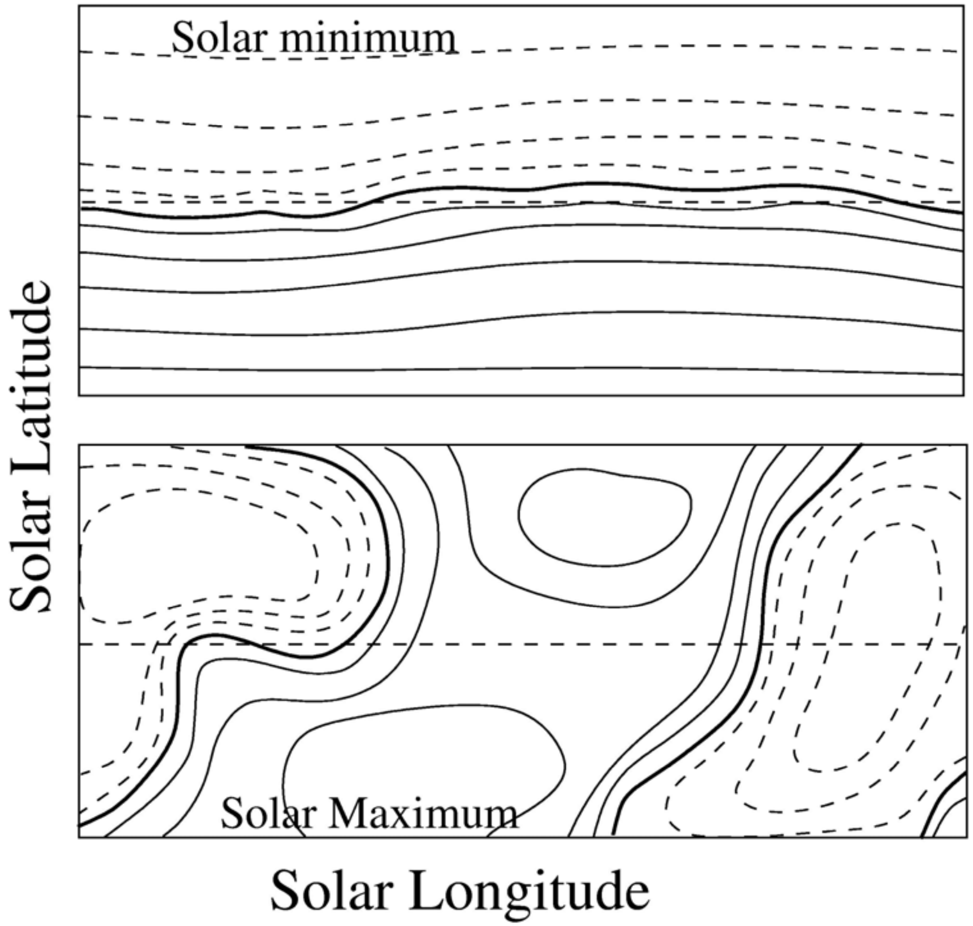


1. Photospheric magnetic field
2. Magnetic field calculated from potential theory $\nabla^2\phi = 0$
3. Magnetic field transported by solar wind (observed by spacecraft at 1 AU) $\frac{d\vec{B}}{dt} = -\vec{B}(\nabla\cdot\vec{V}) + (\vec{B}\cdot\nabla)\vec{V}$

Schatten, 1969, Solar Physics 6, 442

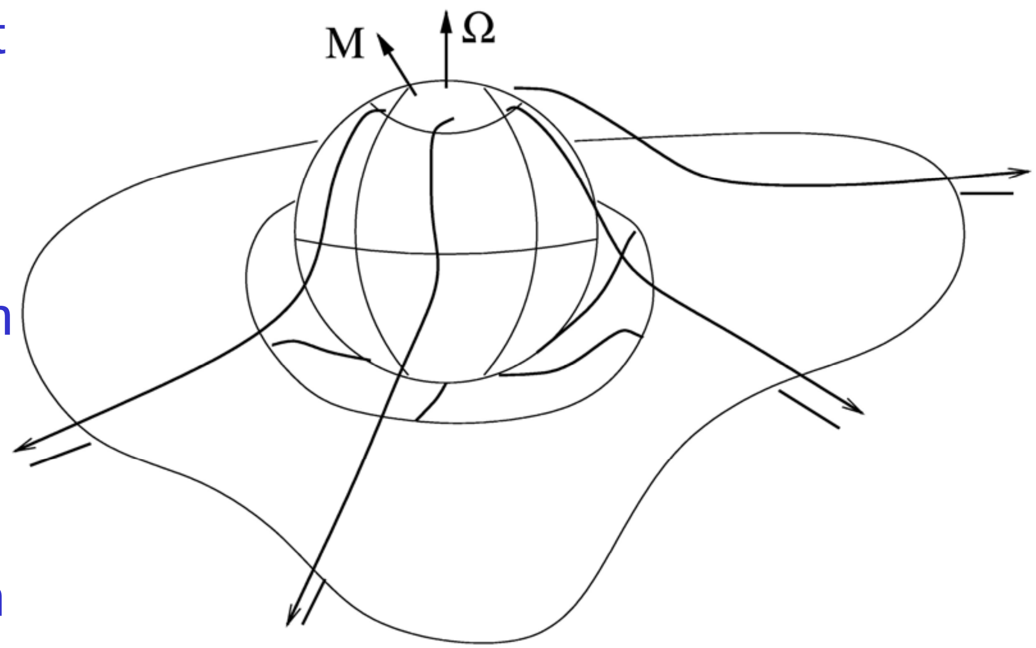
Source Surface during the solar cycle

- Minimum: neutral line roughly parallel to the equator.
- Maximum: strong deflection of the neutral line.
- Maximum deflection described by the tilt angle.
- Neutral line continues into ipl. Space as heliospheric current sheet.
- The tilt also extends into ipl. space.



Ballerina-Model (Alfven)

- Neutral line extends into ipl. Space as heliospheric current sheet.
- Wavyness depends on the position of the neutral line on the source surface.
- Minimum: wavyness is determined by the inclination of the magnetic moment relative to the axis of rotation.

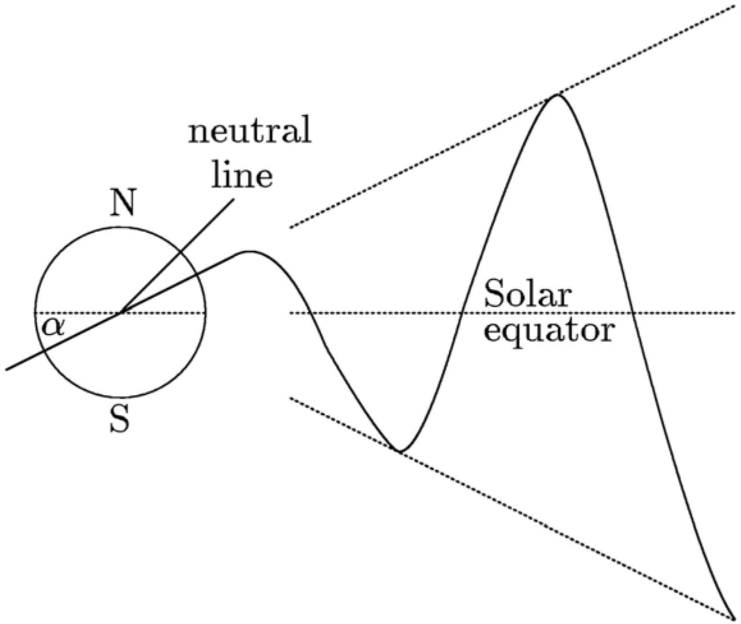


Figue apllicable during solar minimum only!

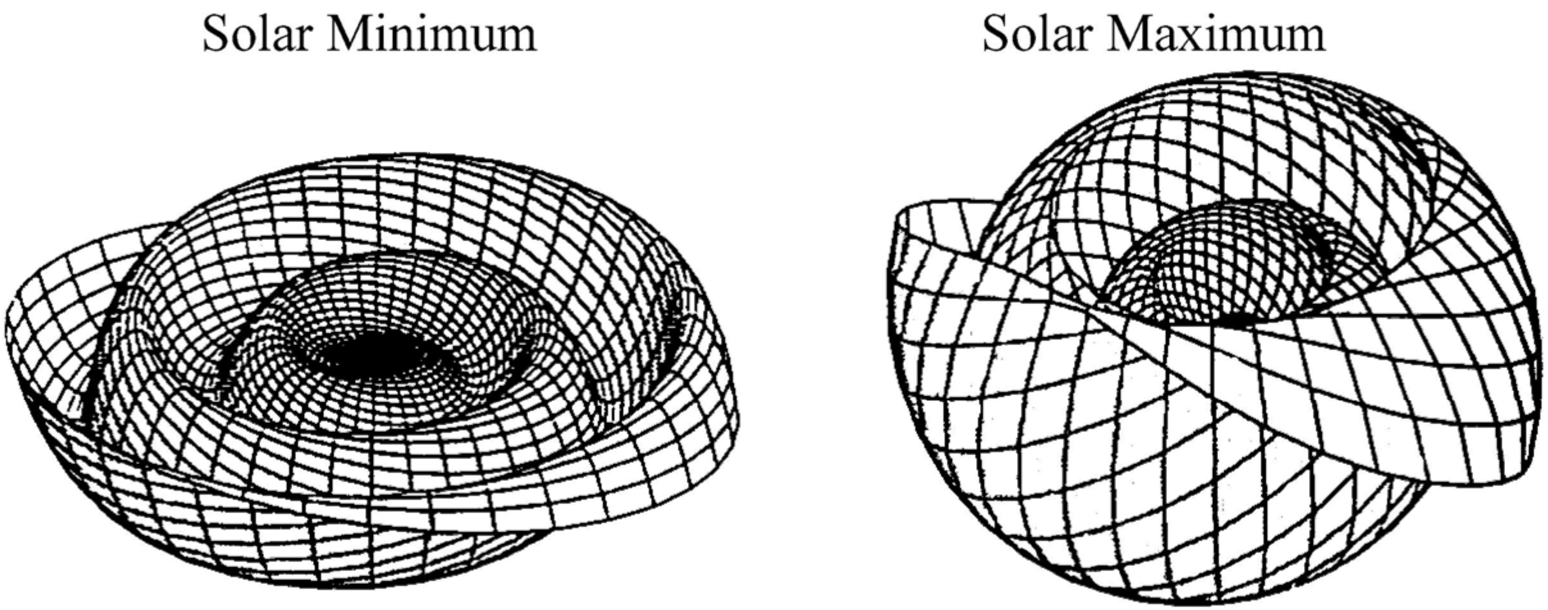
Overexpansion of field lines from the coronal hole?

Heliospheric current sheet (HCS)

- Superposition of
  - Radial propagation of the solar wind,
  - Rotation of the sun.
- The excursion of he heliospheric current sheet is determined by the tilt angle.



HCS during the solar cycle



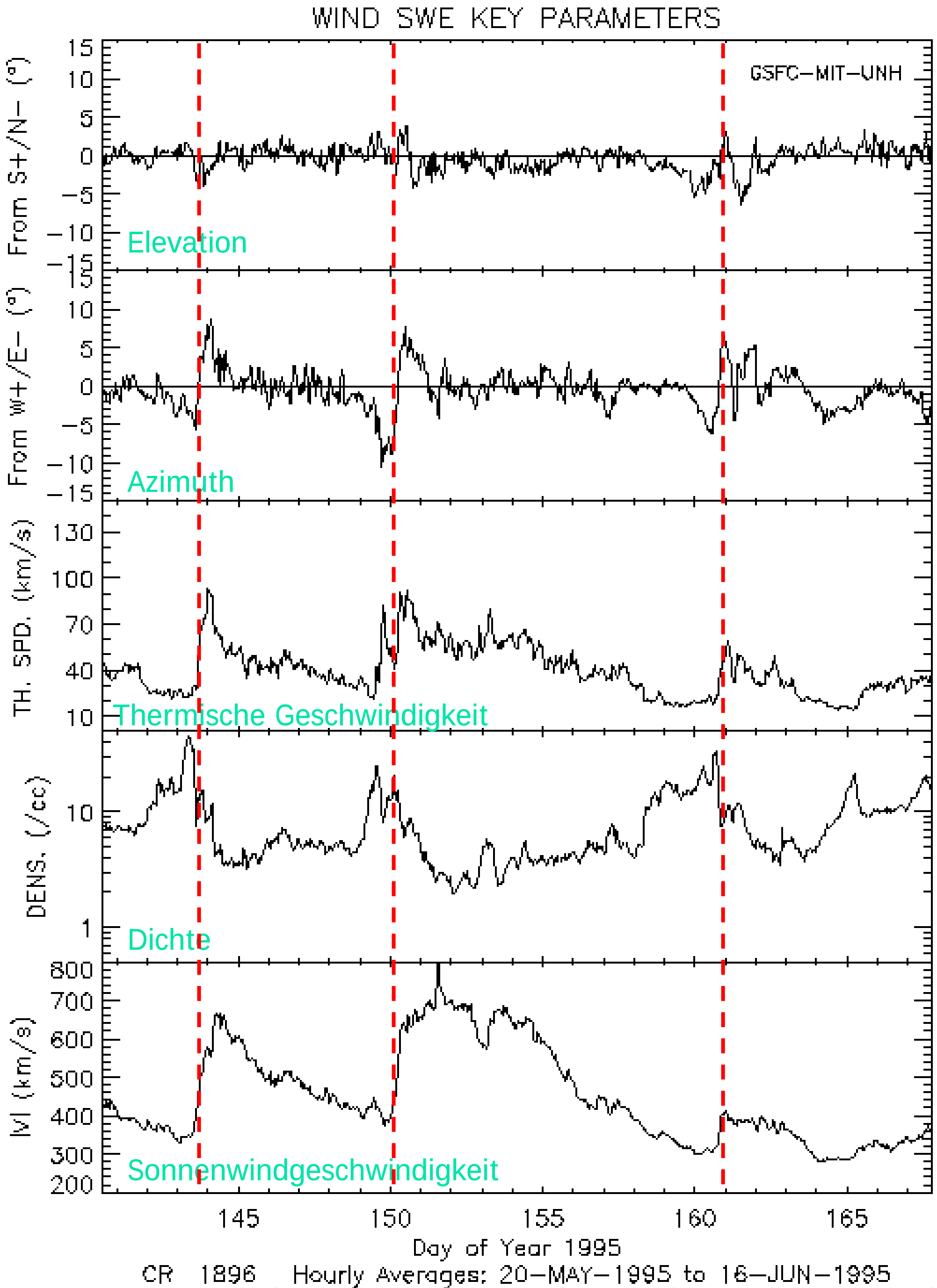
- Heliospheric current sheet relevant for:
  - Fast particle drift (special case of gradient drfit)
  - Dynamic phenomena (reconnection)
- Determines the spatial range over which the ipl. Field can reverse polarity during the rotation of the Sun.

Interplanetary space

- Large-scale structure:
  - Radially flowing solar wind (super-sonic),
  - Frozen-in magnetic field,
  - Termination shock
- Meso-scale structure:
  - Corotating interaction regions (CIRs),
  - Merged interaction regions (MIR)
- Small-scale structure:
  - Waves and/or turbulence
- Transient disturbances, e.g. coronal mass ejections (CMEs)

Solar wind

- Super-sonic flow
- Speed 250-800 km/s
- Density a few particles/cm^3
- Temperature:
  - Protons 2x10E5 K
  - Electrons 1X10E5 K
- Distinction between fast and slow solar wind



http://web.mit.edu/afs/athena/org/s/space/www/wind/wind_figures/wind_95may20.gif

Chapman´s hydrostatic corona

- Similar to earth's atmosphere: static layering

$$\frac{\mathrm{d}p}{\mathrm{d}r} = -\varrho \frac{GM_\odot}{r^2}$$

- Variation of density and temperature with scale height Ho

$$\frac{n}{n_o} = \frac{r^{2/7}}{r_o} \exp\left\{-\frac{7r_o}{5H_o}\left[1 - \left(\frac{r}{r_o}\right)^{-5/7}\right]\right\}$$

$$T = T_o \left(\frac{r}{r_o}\right)^{2/7} \quad \text{mit} \quad H_o = \frac{2k_B T_o}{mM_\odot G/r^2}$$

- Consequenz: earth inside the corona (100 000 k)

… the coronal gas surrounding the Earth may be expected to have a temperature of order of 100 000 K. This is …. consistent with my main inference – that the Earth is surrounded by a very hot coronal gas, which greatly distends our outer atmosphere and that heat must flow from it by conduction into our atmosphere. (Chapman, 1957)

Parker´s hydrodynamic corona

- Problem: comet's tails
- Heat conduction also to gas flow
- Simple ansatz: protons only, because they carry all the momentum (larger mass)
- In addition, inertia term in the equation of motion yields for a spherical symmetric corona

$$u_r \frac{\mathrm{d}u_r}{\mathrm{d}r} = \frac{1}{nm}\frac{\mathrm{d}}{\mathrm{d}r}(2nk_B T) - \frac{GM_\odot}{r^2}$$

Factor of 2 considers that both electron and protons contribute to the pressure

Parker´s Corona II

- Rewrite using the equation of continuity

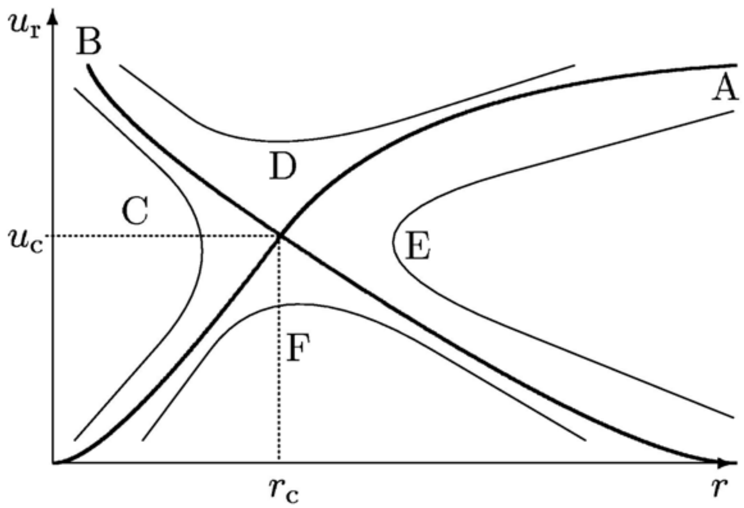
$$\frac{\mathrm{d}u_\mathrm{r}}{\mathrm{d}r}\left[u_\mathrm{r} - \frac{2k_\mathrm{B}T}{mv_\mathrm{r}}\right] = \frac{2k_\mathrm{B}r^2}{m}\frac{\mathrm{d}}{\mathrm{d}r}\frac{T}{r^2} - \frac{GM_\odot}{r^2}$$

- Solutions with critical point rc (transition to super-sonic flow)

$$r_\mathrm{c} = \frac{GM_\odot m}{4k_\mathrm{B}T} \quad \text{and} \quad u_\mathrm{c} = \sqrt{\frac{2k_\mathrm{B}T_\mathrm{o}}{m}}$$

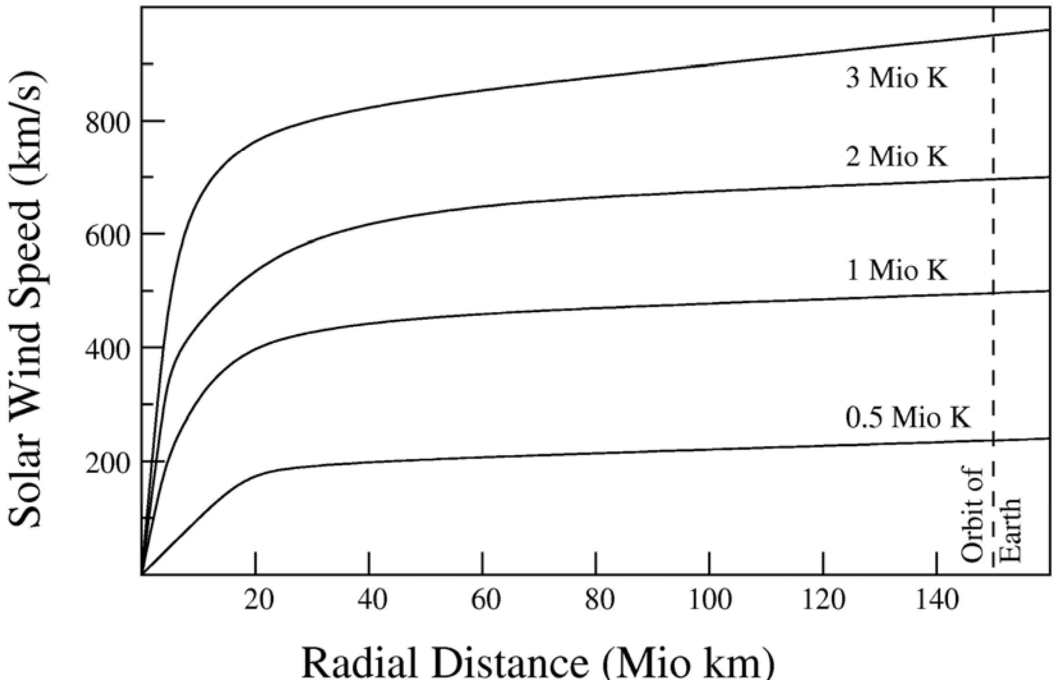
$$\frac{u_\mathrm{r}^2}{u_\mathrm{c}^2} - \ln\frac{u_\mathrm{r}^2}{u_\mathrm{c}^2} = -3 + 4\ln\frac{2u_\mathrm{c}^2 r}{wr_\mathrm{o}} + \frac{2w^2 r_\mathrm{o}}{u_\mathrm{c}^2 r}$$

- Solutions:
  - A Solar wind
  - B „Solar breeze“
  - C captured wind
  - D always super-sonic
  - E no solar origin
  - F „Solar breeze“



Consequence solar wind

- Critical point at 6 solar radii
- Acceleration up to 40 solar radii (0.2 AU)
- Roughly constant speed at larger distances

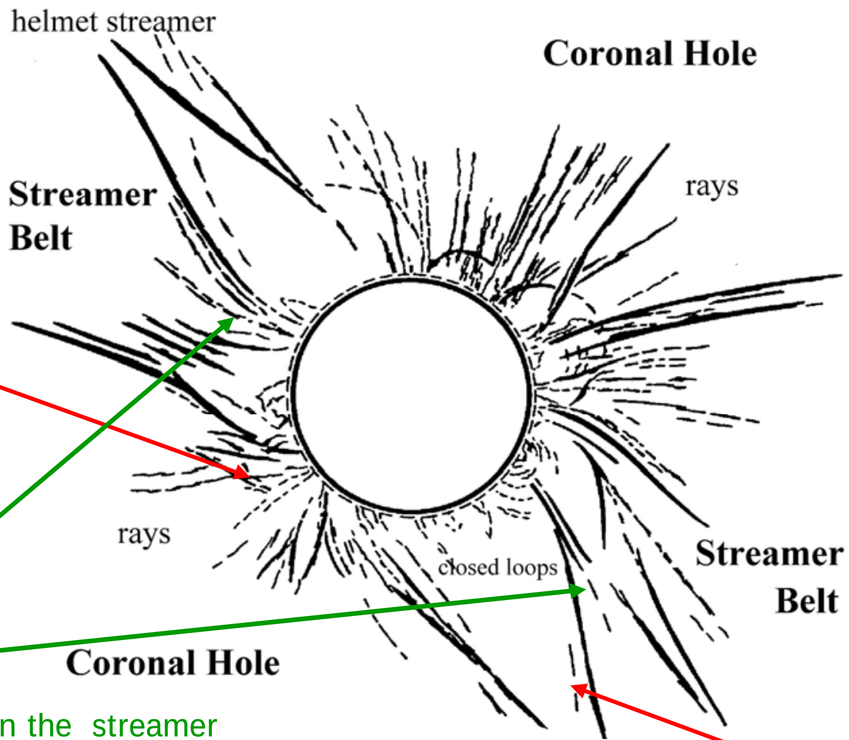


- Decrease in energy density as $r^2 \Rightarrow$ transition to the interstellar medium (termination shock?)
- Model describes properties of the slow wind although it assumes origin of the solar wind on open field lines!!!

Overexpansion

Open field lines:

- fast solar wind
- direct escape



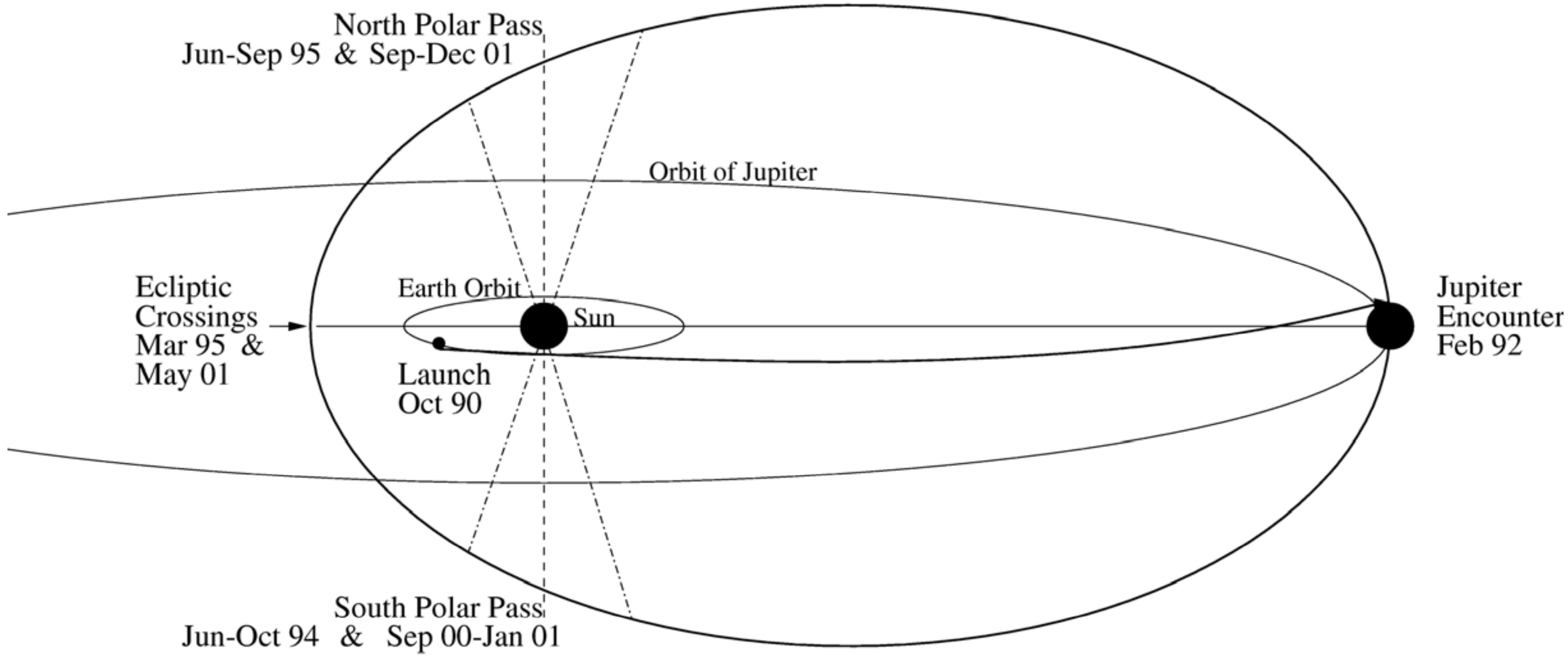
Overexpansion:

Solar wind from open field lines in the streamer belt expands more the solar wind from opoen field lines in high latitudes and fills the area above closed loops (carrying the frozen-in magnetic field with it).

Closed field lines:

- slow solar wind
- is escape possible?

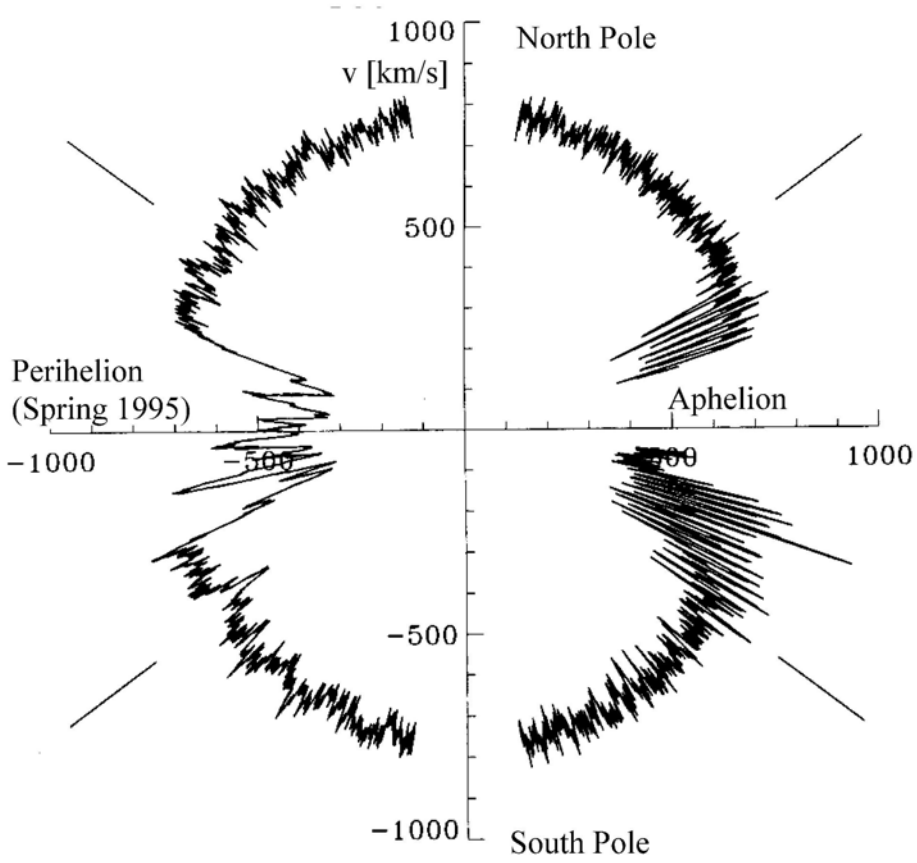
Three-dimensional heliosphere



- Information inferred from observations by
  - Ulysses (elliptical orbit around the Sun extending to Jupiter's orbit, inclination 80°)
  - Pioneer & Voyager (inclination up to 18°, searching for the termination shock)

Solar wind in 3D

- In high latitudes fast solar wind only
- In low latitudes (streamer belt) alternating fast and slow wind
  $\Rightarrow$ corotating interaction regions
- Composition: ions resemble chromospheric composition more closely than coronal one!



McComas et al., 1998, J. Geophys. Res. 103

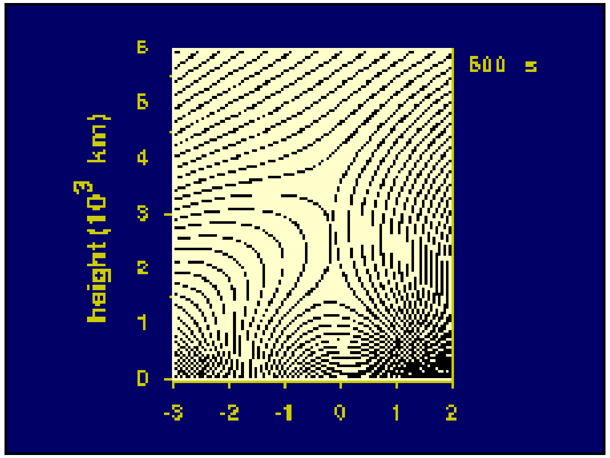
Problem: heating of the corona

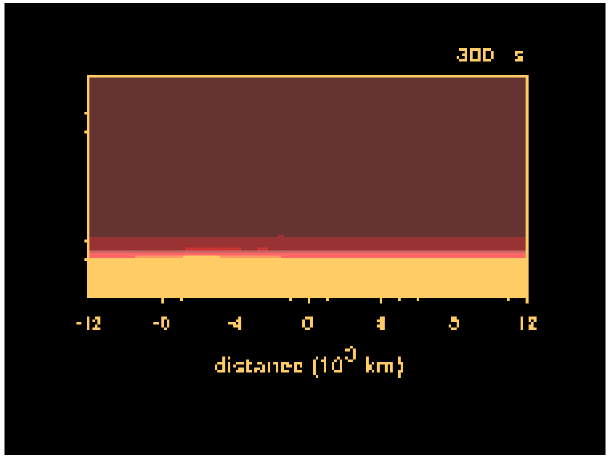
- Problem:
  - Chromosphere about 5000-10000K,
  - Transition region 10 000 – 800 000 K,
  - Corona 1 Mio K

http://vestige.lmsal.com/TRACE/POD/TRACEpodoverview.html

- Heating:
  - magneto-acoustic waves (Landau-damping); observational evidence: non-thermal line broadening as indicator for turbulence
  - impulsive energy release (reconnection):
    - Idea: turbulent motion in the convection zone shuffles field lines around and yields field configurations suitable for reconnection.
    - **Observations:** X-ray bright points
    - **More recent observations:** colliding and merging loops (TRACE)
  - Nano-flares

Reconnection in the corona





http://solartheory.nrl.navy.mil/solartheory/chromo.html

- Assumption: shear flow between two magnetic arcades
- Top: magnetic close to the X-point
- Bottom: density in the corona

Interplanetary magnetic field I

- Frozen-in field:
  - Energy density small compared to plasma's e.d. (above source surface),
  - High conductivity.

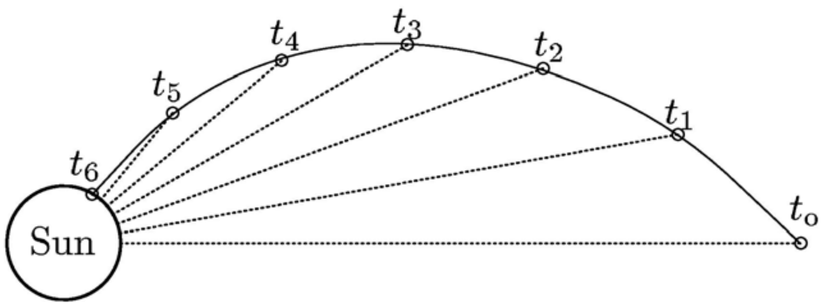
- Can be inferred from the definition of the archimedian spiral:

$$r = u_{\mathrm{sowi}} \frac{\varphi - \varphi_o}{\omega_\odot} + r_o$$

- Spiral length:

$$s = \frac{1}{2} \frac{u_{\mathrm{sowi}}}{\omega_\odot} \left(\psi \sqrt{\psi^2 + 1} + \ln \left\{ \psi + \sqrt{\psi^2 + 1} \right\} \right)$$

with $\tan\Psi = \omega r/u$.



Archimedian spirale: results from the superposition of the motion with constant speed v along a line which rotates with constant angular speed.

Interplanetary magnetic field II

- Gauss´s law for the magnetic field in the equatorial plane (spherical coordinates):

$$\nabla \cdot \vec{B} = \frac{1}{r^2}\frac{\partial}{\partial r}(r^2 B_r) = 0 \qquad B_r = B_o \left(\frac{r_o}{r}\right)^2$$

- Frozen-in magnetic fields:

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\left(u_\varphi B_r - u_r B_\varphi\right)\right) = 0$$

- With ro being the source surface:

$$r u_\varphi B_r - r u_r B_\varphi = r_o u_{\varphi_o} B_o = r_o^2 \omega_\odot B_o$$

- Azimuthal and radial component:

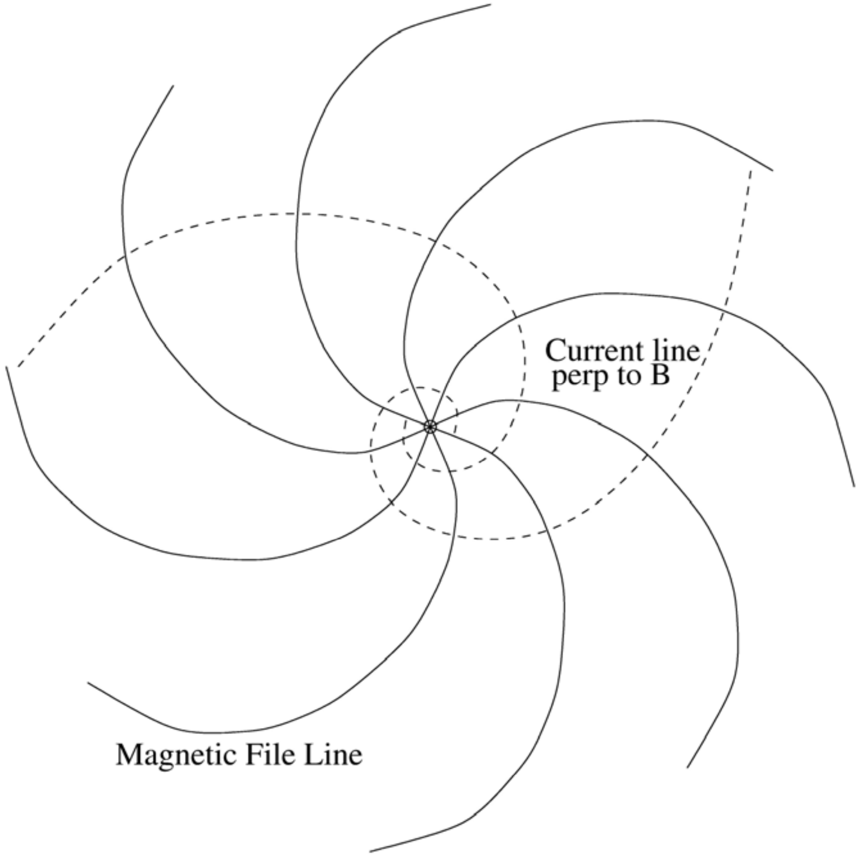
$$B_\varphi = \frac{r u_\varphi B_o - r_o^2 \omega_\odot B_o}{r u_r} = \frac{u_\varphi - r\omega_\odot}{u_r} B_r \qquad B(r) = \frac{B_o r_o}{r^2}\sqrt{1 + \left(\frac{\omega_\odot r}{u_r}\right)^2}$$

Heliospheric current sheet

Ampere´s law:

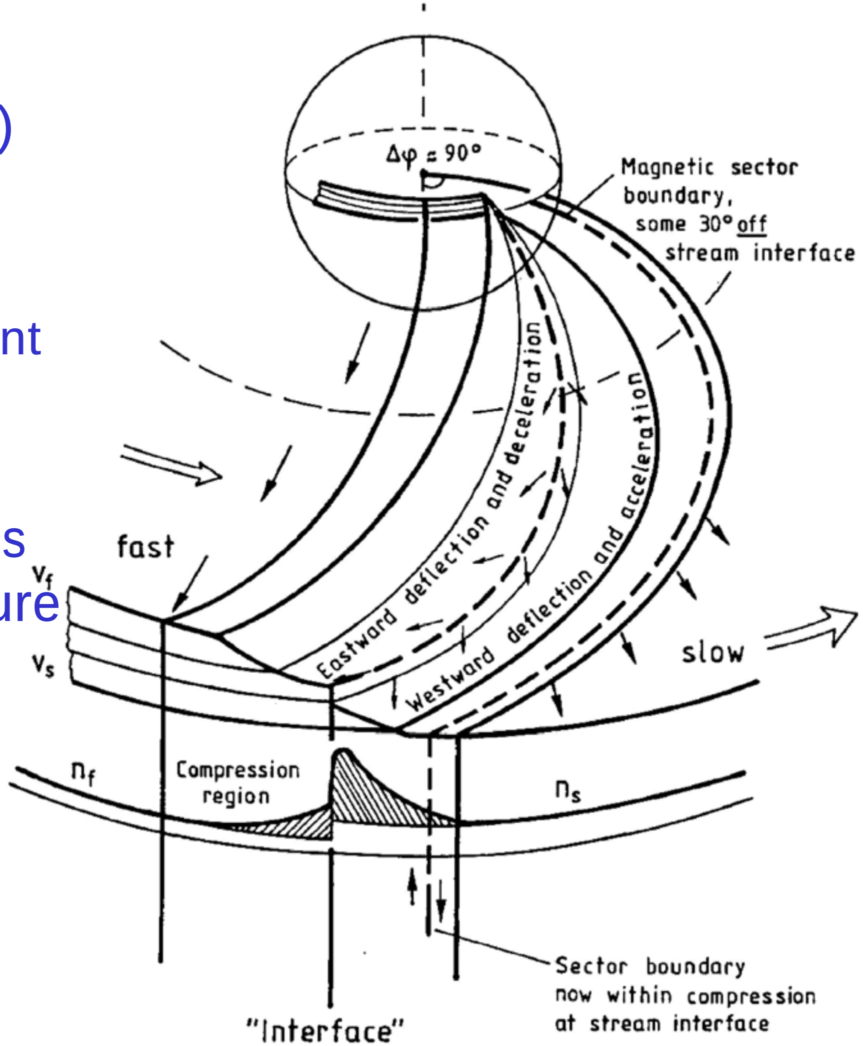
To maintain the magnetic field configuration an electric current in the equatorial plane is required:

$$j_r = j_o \cdot \frac{r_o}{r} \quad \text{and} \quad j_\varphi = \frac{B_\varphi}{B_r} j_r = j_o \frac{B_\varphi}{B_r} \frac{r_o}{r}$$



Corotating interaction regions (CIRs)

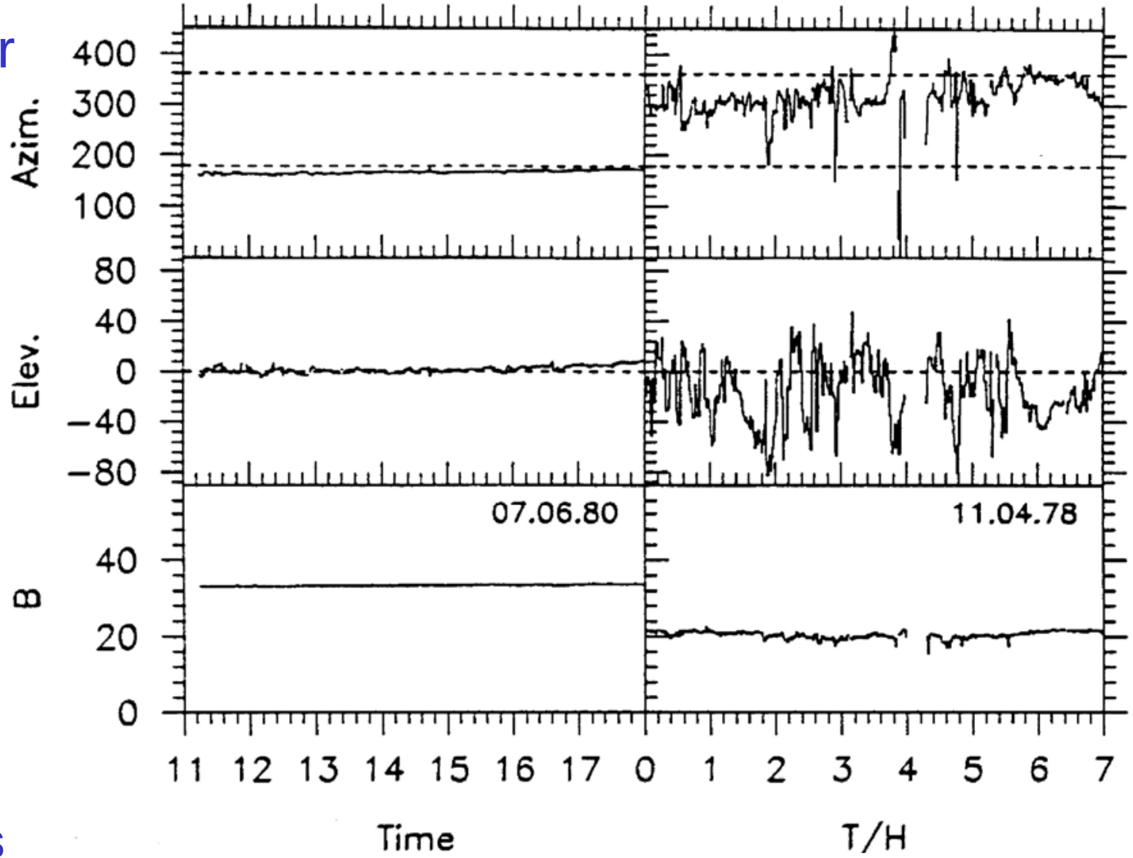
- Source: two adjacent streams of fast and slow solar wind (slow to the west)
- Stronger curvature of the field line in the slow stream ⇒ interaction
  - compression (increased density) in front of the fast stream (see also slide 33),
  - Shock waves.
- Corotating, because the source regions on the Sun rotate and thus the structure reappears with the Sun's rotation.
- More frequent during solar minimum; during solar maximum transient disturbances and the more complex structure of the HCS disturb the CIR pattern.



Schwenn, 1991, in Physics of the inner heliosphere, Springer

Fluctuations in interplanetary space

- Large-scale variations (solar wind streams)
- Small-scale fluctuations (waves or turbulence)
  - Quiet and turbulent times
  - Intermittency (fast alternation between quiet and turbulent)
  - Fluctuations in direction and flux of the magnetic field
  - Accompanying fluctuations in solar wind parameters



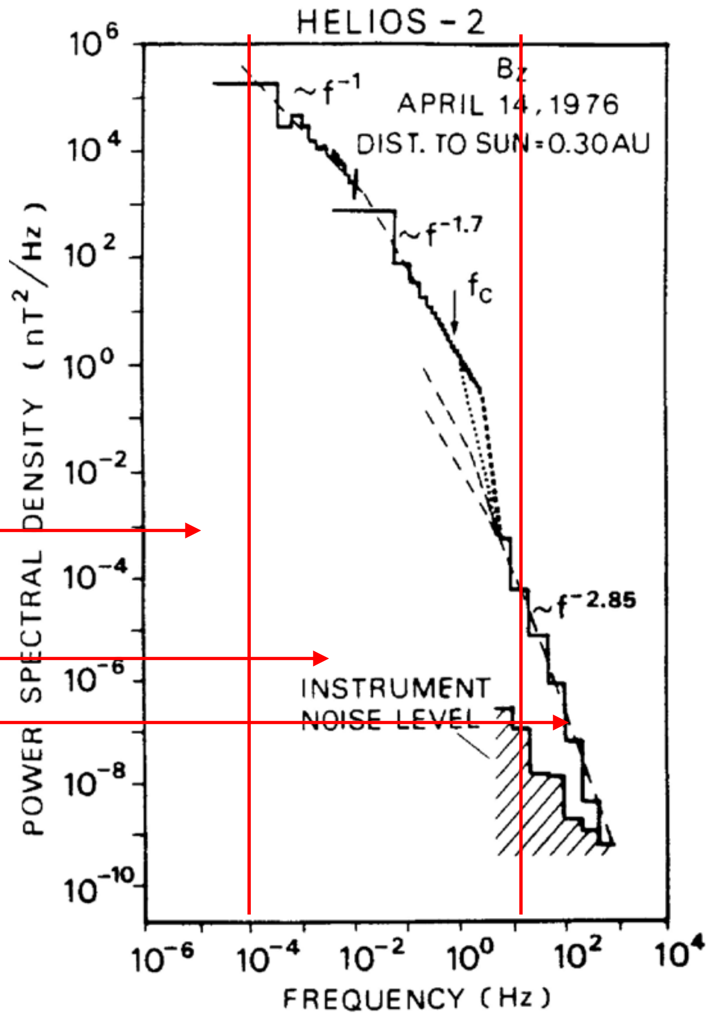
Power density spectrum

- Formal description:

$$f(k_{\parallel}) = C \cdot k_{\parallel}^{-q}$$

- Regimes in the spectrum:
  - large scale: rotation, solar wind streams
  - meso-scale: flux tubes, supergranulation
  - inertial range: Alfven waves
  - dissipation range

- Inertial range important for the scattering of energetic particles.



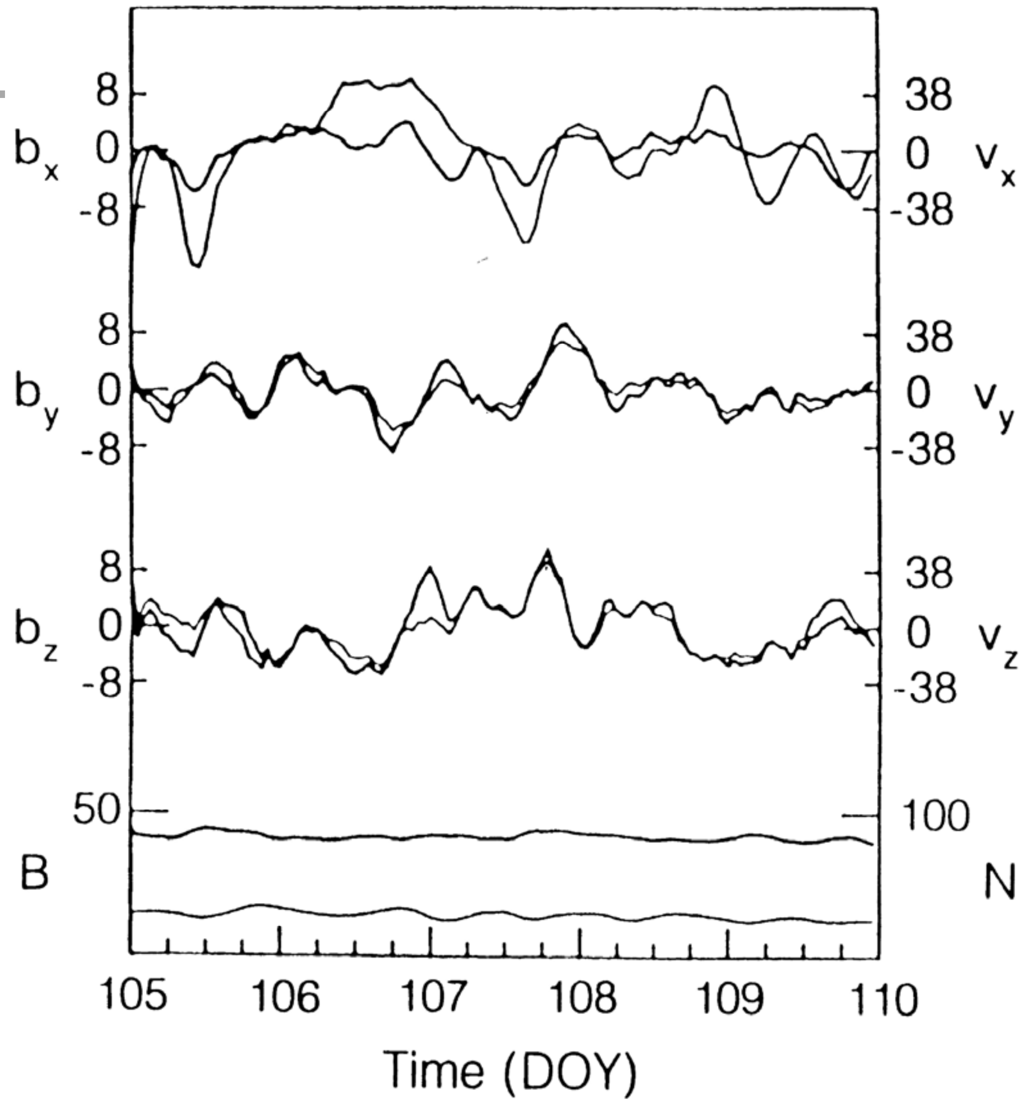
Denskat et al., 1983, J. Geophys Res., 87, 2215

Alfvenicity

- Problem in data interpretation: 1-point-measurement of δs in a moving medium varying in space and time
  - waves?
  - turbulence?

- Alfvenicity in association to the Alfven wave:

$$\delta\vec{u}_{\mathrm{sowi}} = \pm\frac{\delta\vec{B}}{\sqrt{\mu_o\varrho}}$$



Bruno et al., 1985, J. Geophys. Res. 90, 4373

Summary interplanetary space

- Large-scale structure due to:
  - Magnetic field on the source surface (polarity, tilt angle),
  - Magnetic field in the corona (open or closed regions),
  - Type of solar wind (fast or slow).
  - Basic concept: frozen-in magnetic field.
  - Interaction between different solar wind streams.

- Fundamental problems:
  - Heating of the corona.
  - Source of the solar wind.
  - Interpretation of magnetic field fluctuations because measurement is limited to 1 point in space and time.

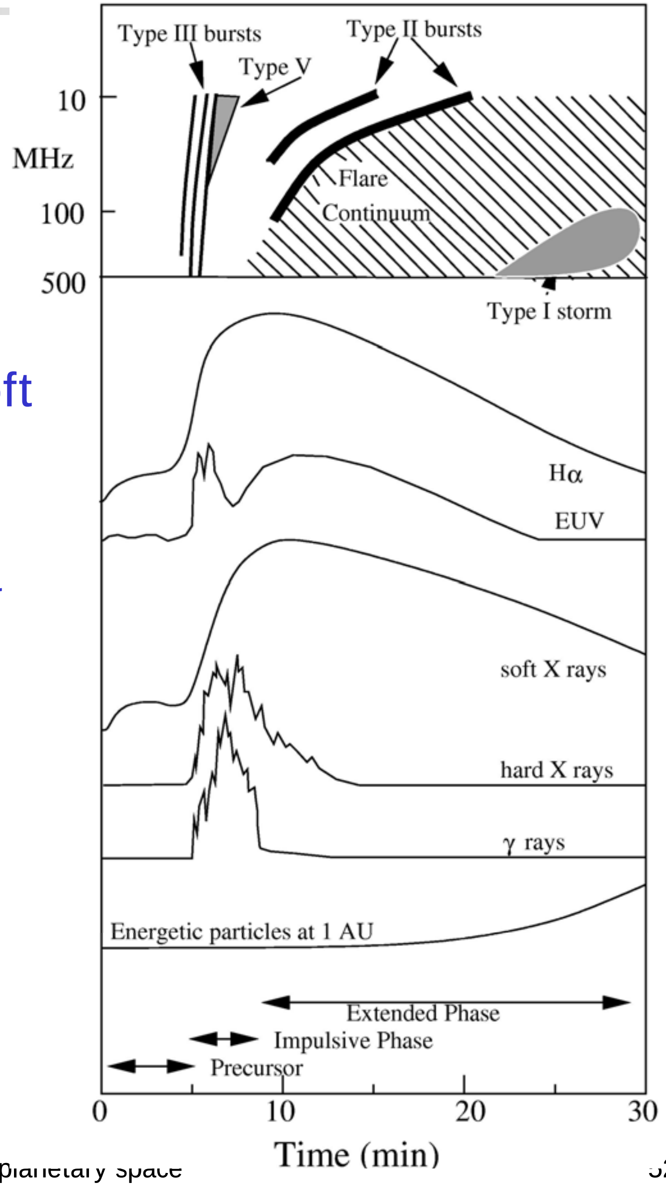
Flares and coronal mass ejections (CMEs)

- Solar activity
  - Flares
    - Electromagnetic radiation over a wider range of frequencies
    - Energetic particles ($\rightarrow$ next chapter)
  - Coronal mass ejections
    - Plasma clouds
    - Magnetic clouds
    - Collisionless shocks
    - Energetic particles

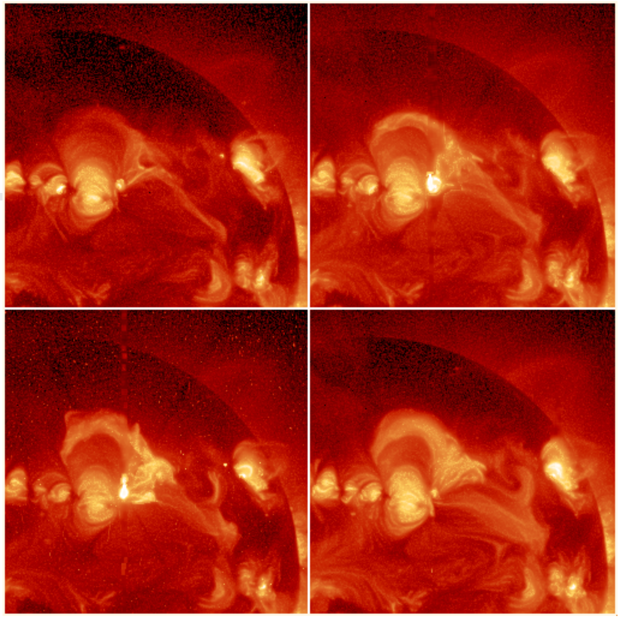
- Explanation: restructuring of the magnetic field
  - Release of magnetic field energy (reconnection)
    - Heating
    - Acceleration of plasma
    - Collisionless shocks
  - Hen or egg problem (Solar Flare Myth) irrelevant

Flares – overview elmag radiation

- Flare defined by the electromagnetic radiation!
- Distinction of phases in temporal development:
  - Precursor: lasts a few minutes, brightening in soft X-rays and Hα, heating of the flaring region;
  - Impulsive phase: fast energy conversion, in particular hard electromagnetic radiation, lasts a few minutes;
  - Gradual phase: can last up to some hours, emission of soft elmags continues.
- Only the largest flares exhibit all three phases!



Soft X-rays



Yohkoh Soft X-rays

- Main part of the electromagnetic radiation emitted by the flare.
- Wave length between 0.1 and 10 nm.
- Thermal emission of a plasma with temperature of about 1E7 K, fast onset due to heating of the flaring region up to 5E7 K.
- Mainly continuum emission, also lines of highly ionized O, Ca and Fe.
- Hα follows the same rules.

Hard X-rays

- Photons with energies from some 10 to a few 100 keV.
- Source: bremsstrahlung generated by electrons with higher energies.
- Only about 1E-5 of the photon's energy is converted to hard X-rays.
- While soft X-rays indicate the heating of the flaring region, hard X-rays indicate the presence of energetic electrons.
- During the impulsive phase elementary bursts (fragmented energy release).

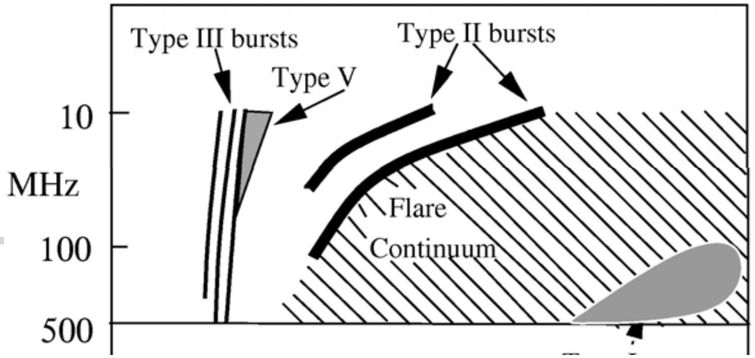
Mikrowaves

- Source: same electron population as in hard X-rays (similarities in fine structures in time profiles).
- Gyro-synchroton radiation of electrons with energies between some 10 and some 100 keV.
- Emitted frequency about 10 to 100 times the gyration frequency, depending on the source height (problem: fixed frequency is generated by electrons with different energies in different heights).
- Impulsive phase: elementary bursts (fragmented energy release).

γ-Emission

- Evidence for energetic particles!
- Continuum due to bremsstrahlung of relativistic electrons and Doppler broadening of closely spaced γ-line. Above 25 MeV continuum due to pion decay.
- Lines between 4 and 7 MeV due to excited CNO-nuclei (incident particles must have energies above 25 MeV).
- Line spectrum gives hints on the composition of the incident particles!

Radio emission



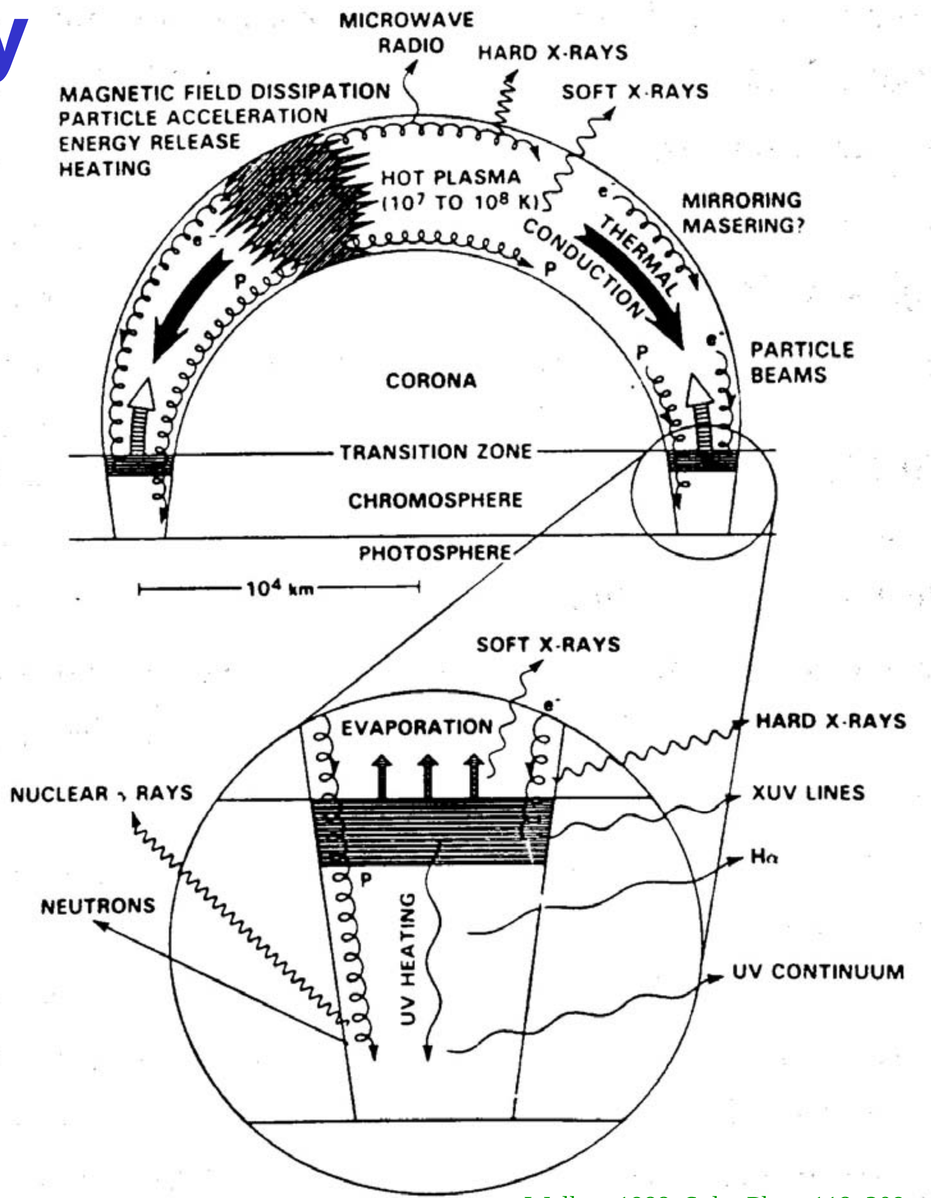
- Source: Langmuir oscillations generated by electron beams streaming through the plasma.

- Classification in bursts:
  - Type I: continuum, background radiation, increased during a flare.
  - Type II: slowly drifting burst, often herrigbone structure (type III bursts branch off the type II burst like fishbones), indicates a shock.
  - Type III: fast drifting burst generated by electrons with c/3; special case: U-burst:, electrons captured in a loop.
  - Type IV: continuum behind type II, gyro-synchrotron radiation, non-drifting parts due to confined electrons.
  - Type V: continuum similar to type IV but following a type III.

- Metric bursts on the Sun, kilometric ones in interplanetary space.

Elmags spatiallly

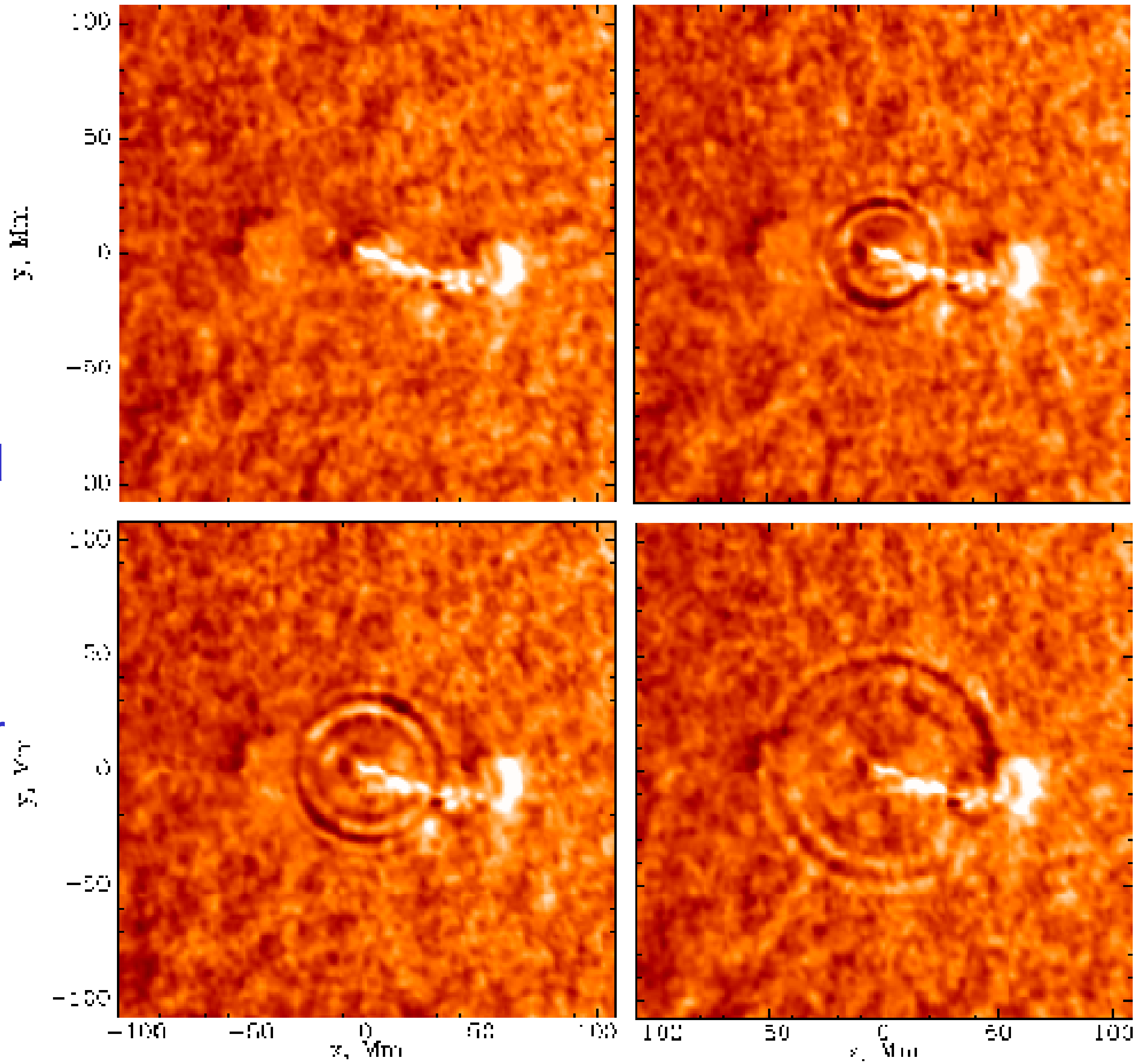
- Reconnection inside a magnetic loop:
  - Heating (soft X-rays, Hα)
  - Energetic particles
- Energetic particles give
  - Radio emission (top and footpoints of the loop; frquency drift depending on density of the ambient medium)
  - Hard X-rays
    - Thin target inside the loop
    - Thick target at the footpoints
  - Gammas (at the footpoints)



Walker, 1988, Solar Phys. 118, 209

Solar Quakes

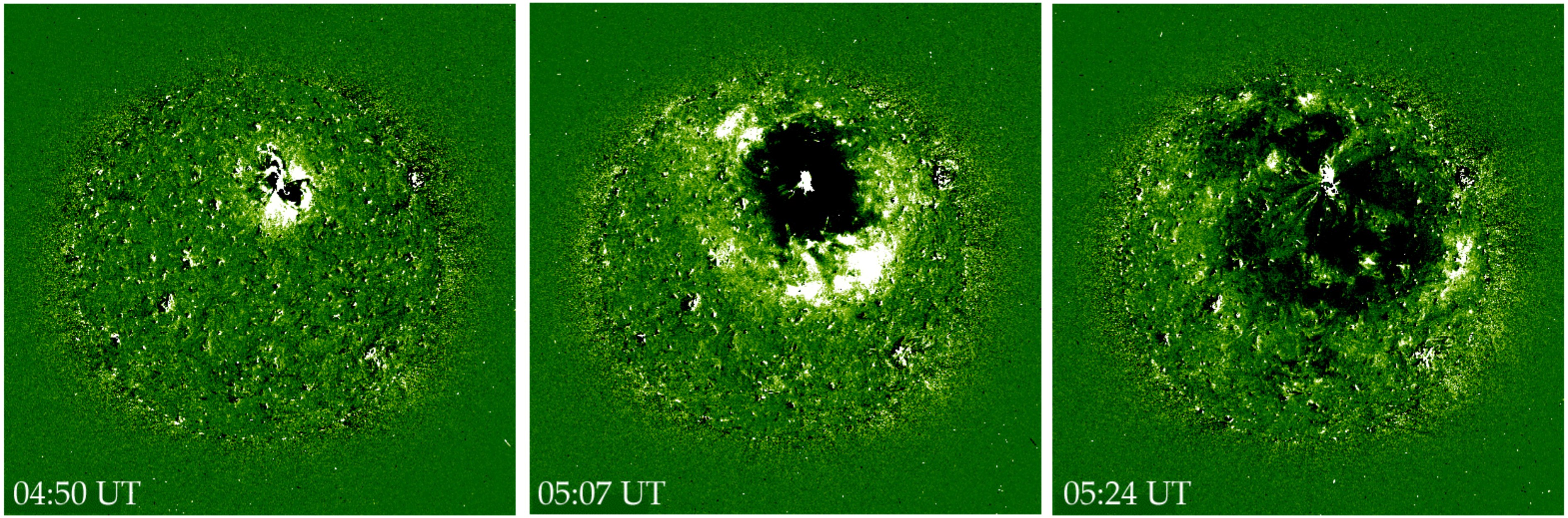
- Magneto-acoustic Wave, analogous earthquakes, ripples on a pond.
- Acceleration; starts with about 10 km/s, final speed about 115 km/s.
- Energy contend about 4 orders of magnitude larger than in the 1906 San Francisco quake



http://pwg.gsfc.nasa.gov/istp/outreach/images/Solar/Events/squake.jpg

Moreton waves

http://umbra.nascom.nasa.gov/eit/



SOHO-Extreme ultraviolet Imaging Telescope (EIT)
observations of Moreton wave expanding from coronal mass ejection (CME) initiation site
1997 May 12
First differences in Fe XII 195 Å (1.5 MK)

- Chromospheric wave around a fast mode shock
- Propagation speed about 1000 km/s

Classes of flares

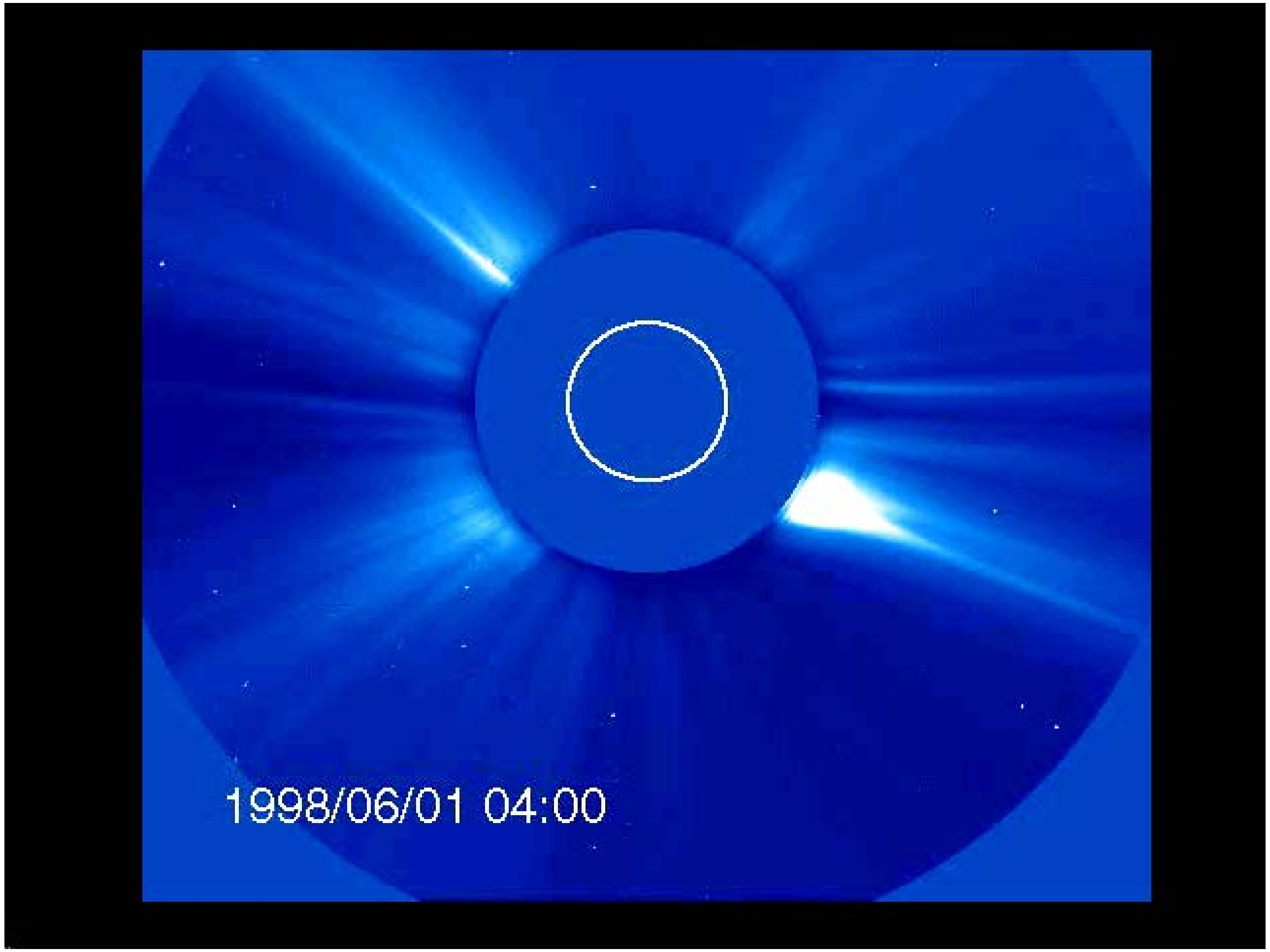
	Impulsive	Gradual
Duration of soft X-rays	< 1 h	>1 h
Decay constant of soft X-rays	< 10 min	>10 min
Height in corona	$\leq 10^4$ km	$\sim 5 \cdot 10^4$ km
Volume	$10^{26} - 10^{27}$ cm^3	$10^{28} - 10^{29}$ cm^3
Energy density	high	low
Size in Hα	small	large
Duration of hard X-rays	<10 min	>10 min
Duration of microwaves	<5 min	>5 min
Metric type II burst	75%	always
Metric type III burst	always	50%
Metric type IV burst	rare	always
Coronal mass ejection	rare	always

- Caution: don’t confuse phases and classes of a flare!

Problems classification scheme

- Phenomenological classification (temporal and spatial scales in soft X-rays):
  - Classification scheme modified with more sensitive instrumentation;
  - Classification does not necessarily have any physical meaning;
  - Two physically distinct classes do no necessarily lead to a bi-modal distribution of event properties;
  - Distinct classes or classes as end points of a continuum?.
- Classification scheme not unambiguous (a flare might be impulsive in soft X-rays but gradual in hard X-rays)
- A classification scheme is helpful to sort data – but only to sort data, it does not imply any differences in underlying physics!!
- Related problem: what is a large solar event?

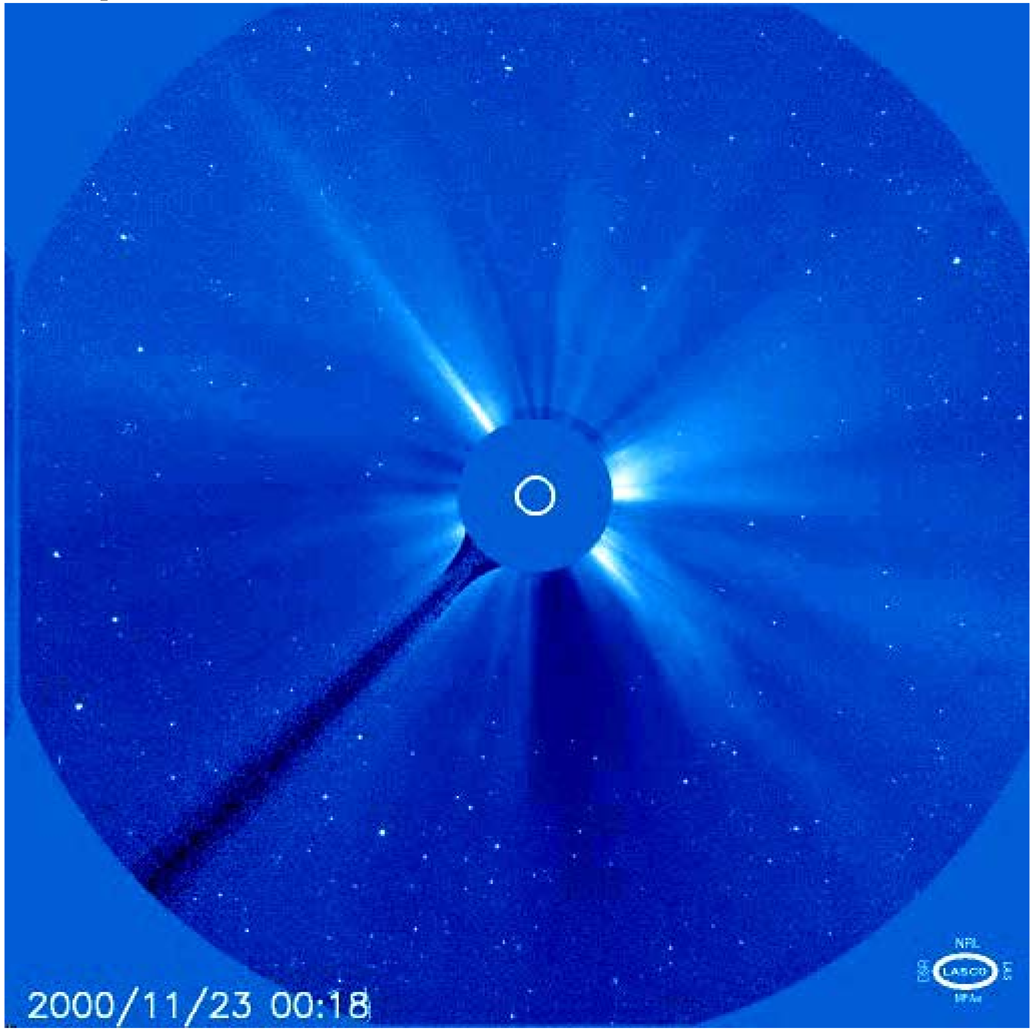
Coronal mass ejections (CMEs)



http://sohowww.nascom.nasa.gov

- Rate of occurrence varies with solar cycle
- Speeds between <10 km/s and >2000 km/s
- CMEs can propagate at constant speed, decelerate or accelerate.
- Mass: 2E14 to 4E16 g
- Energy: 1E22 to 6E24 J

Coronal mass ejections II

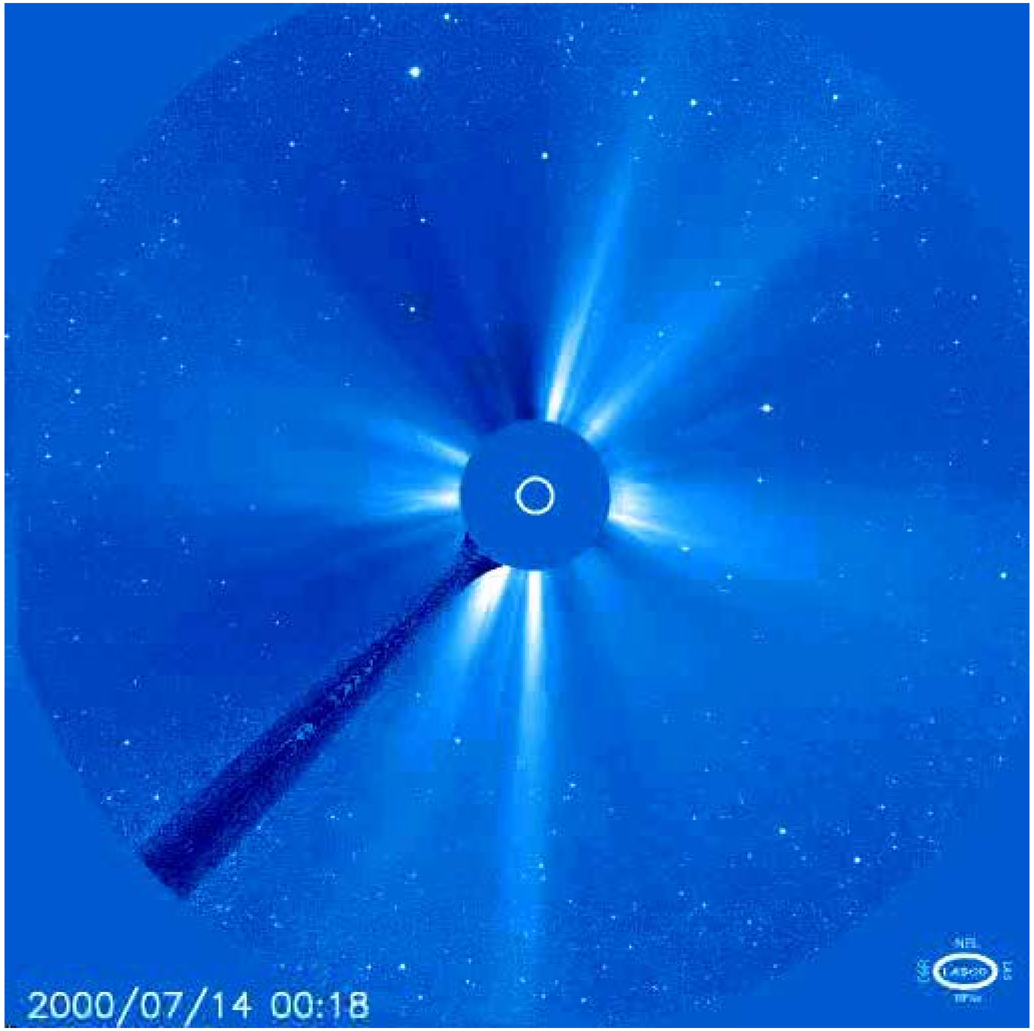


http://sohowww.nascom.nasa.gov

- Apparent geometry, because projection into a plane:
  - Halo-CMEs
  - viewed perpendicular to or along the filament?
- Geometry not always loop; also spikes, fans, streamer blow outs and others
- Latitudinal distribution:
  - Minimum within ± 10° around equator.
  - Maximum within ± 30°.
- Width: from <20° to >60°; median at 42°, maximum >120°

Coronal mass ejections III

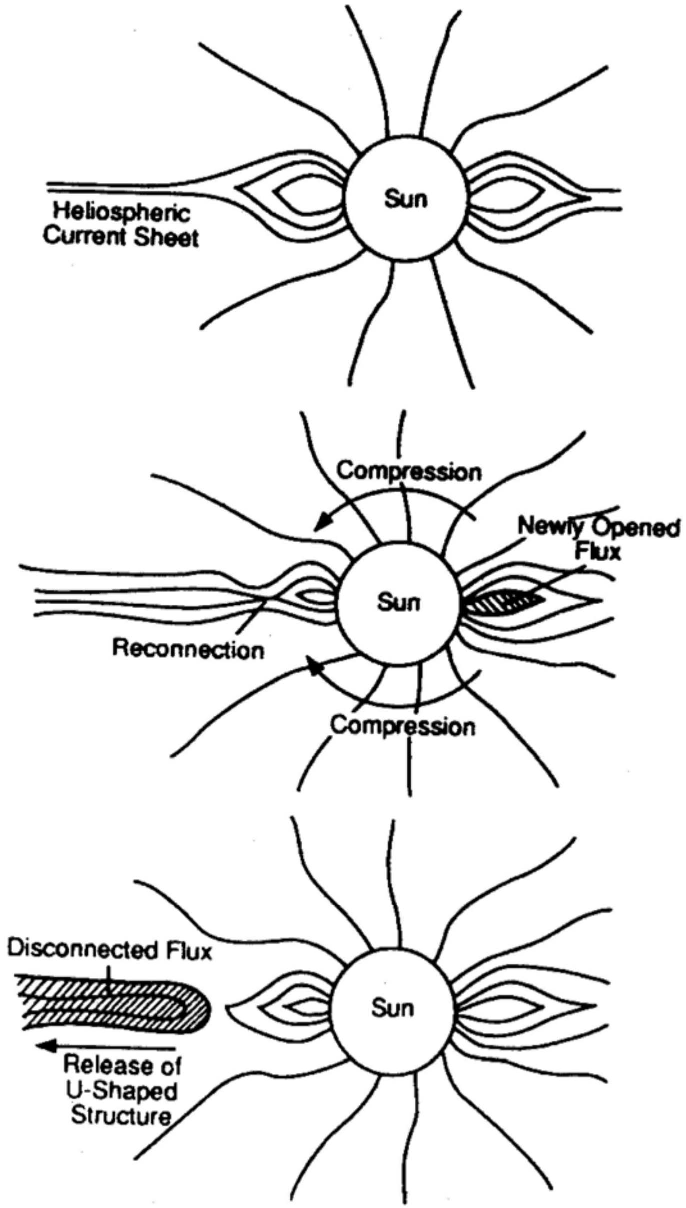
- Example Bastille-Day Event
- Halo-CME
- White noise due to the impact of energetic particles on the coronograph's CCD



http://sohowww.nascom.nasa.gov

Disconnection event

- Example for a non-loop CME.
- Example for a global instability (at the western limb new magnetic flux emerges while on the eastern limb plasma is ejected)
  $\Rightarrow$ sympathetic CMEs.
- Contribution to the solar wind originating in the streamer belt?
- In interplanetary space blobs of rather dense plasma.



McComas et al., 1991, Geophys. Res. Lett. 18, 73

Special flares/CMEs

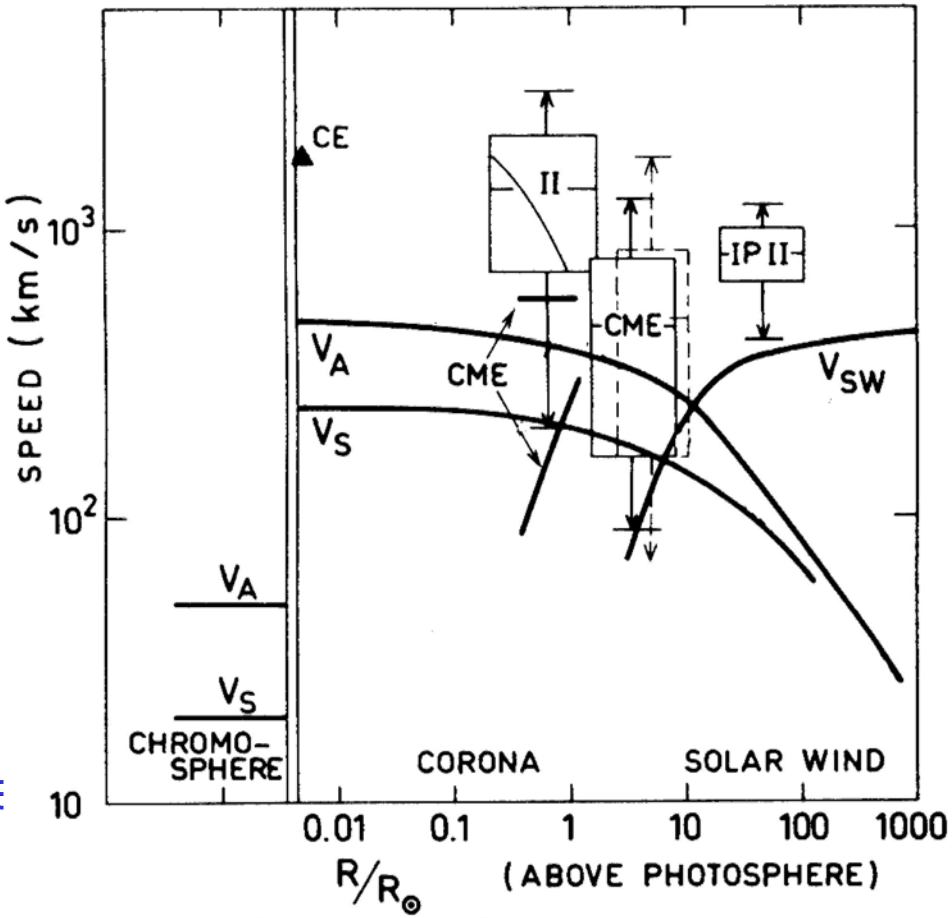
- sympathetic flares: a large flare can trigger another flare in its vicinity or even at entirely different places on the Sun (trigger of pre-existing instabilities).

- sympathetic CMEs: similar, see disconnection event.

- Homologous flares: repeated flaring activity in the same active region with very similar spatial and temporal patterns in energy release. Magnetic energy is released but the large-scale field configuration remains basically unchanged $\Rightarrow$ activation of a filament.

CMEs and shocks?

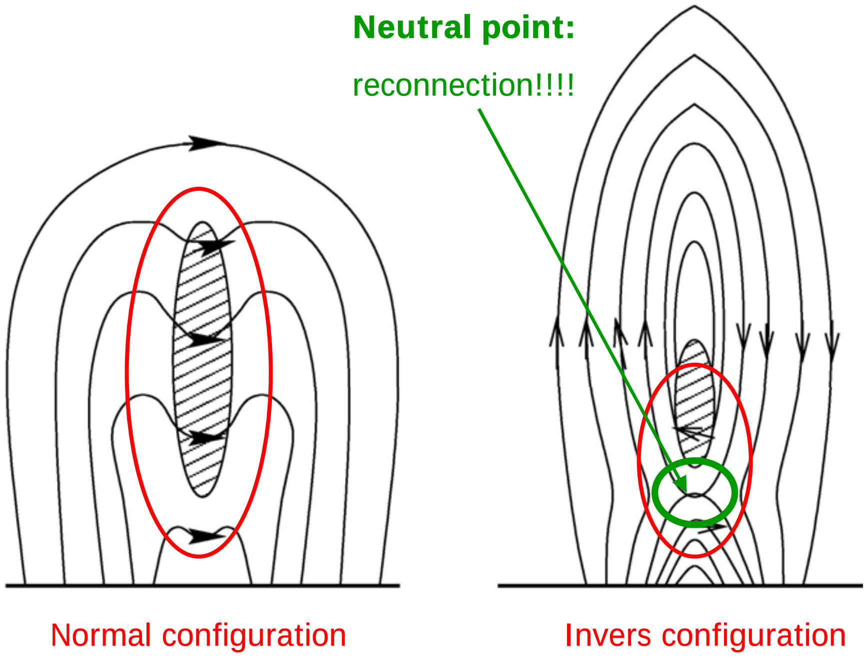
- CME speeds can exceed the signal speed in the medium.
- Consequence: shock formation in front of the CME.
- About 1/3 of the CMEs is fast enough to drive a shock.
- All traveling interplanetary shocks are driven by a CME identified by the magnetic signatures behind the shock front.



Bougeret, 1985, in Collisionless shocks in the heliosphere: reviews of current research, eds. B.T. Tsurutani & G. Stone, AGU Mono 35

Filamen: field configuration

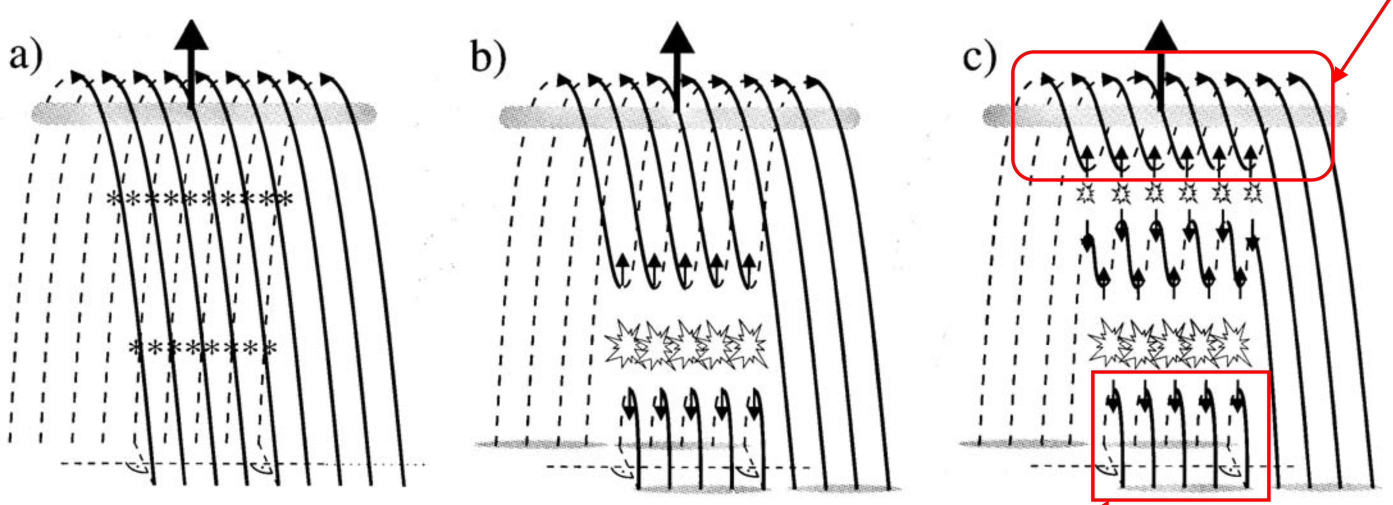
- CME is an erupting filament.
- Eruption requires:
  - Disconnection of anchoring field lines,
  - Energy to overcome the gravitational attraction.
- Field configurations:
  - normal (Kippenhahn-Schlüter),
  - invers (Raadu-Kuperus).



3D-Reconnection below the filament

Helical magnetic field:

Surrounds the filament, can be observed in ipl. Space as part of the magnetic cloud



Vrsnak, 2003, in Klein, Lecture Notes in Phys. 612, Springer

Post-Flare Loops:

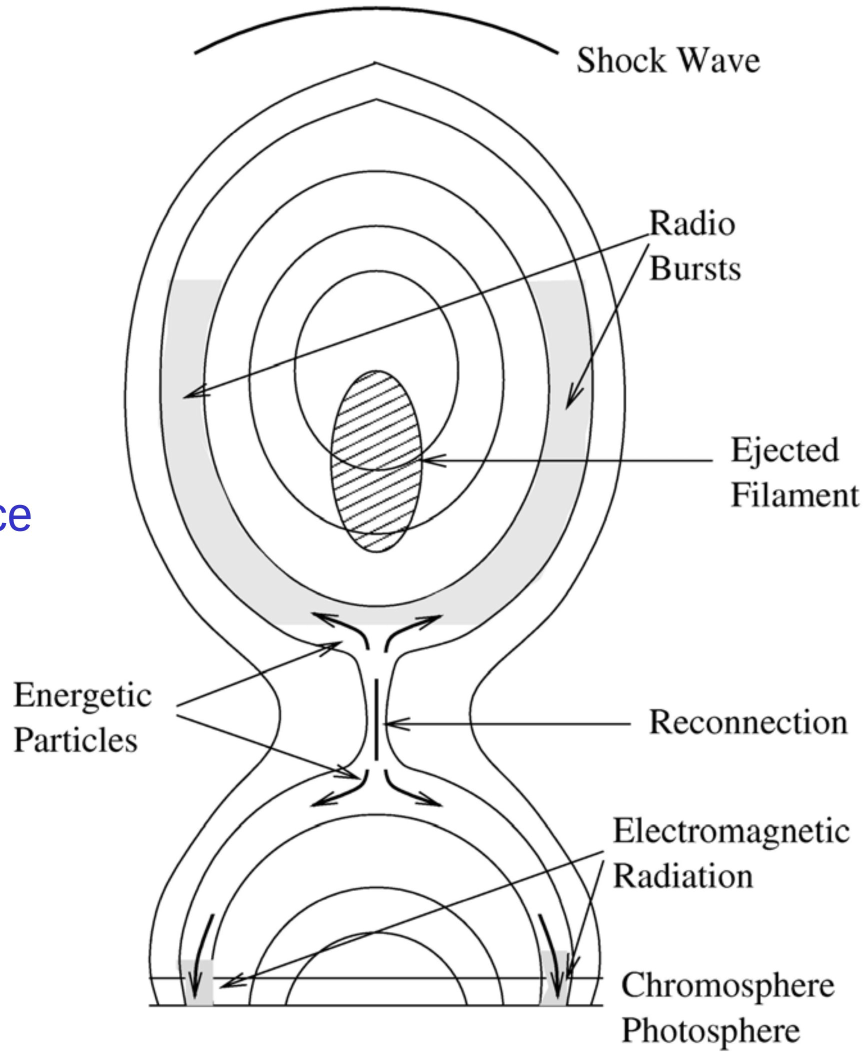
Arcs in Hα in the gradual phase of a flare and later

Model of a gradual flare

- Magnetic instability leads to reconnection.

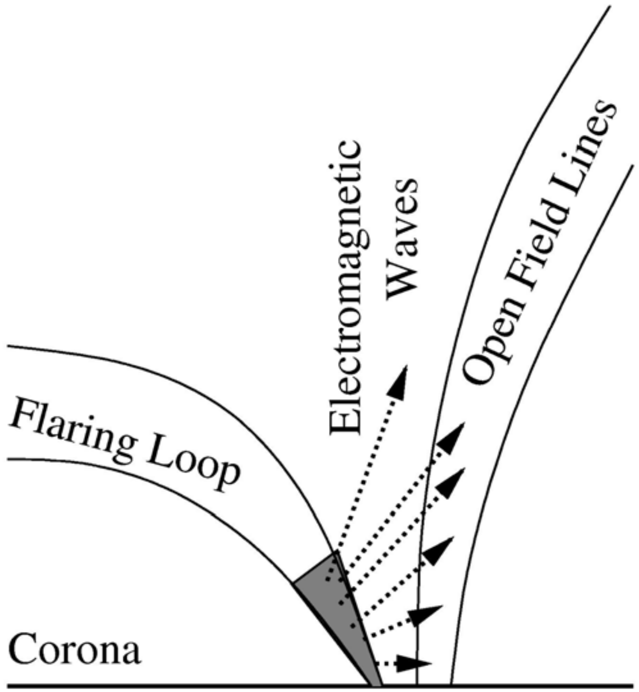
- Energy release:
  - Release and acceleration of the filament ⇒ CME.
  - Acceleration of energetic particles ⇒ energetic particles in interplanetary space and hard elmags.

- Solar Flare Myth:
  - Academic discussion about cause and effect: is the flare a by-product of the CME or vice versa?
  - More important: for terrestrial consequences CME and shock are more relevant.

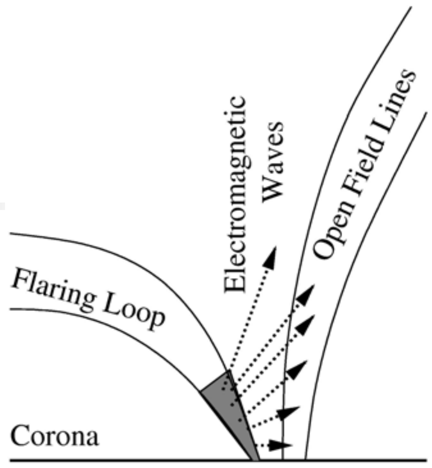


Model of an impulsive flares

- Reconnection/energy release within a closed magnetic loop.
- Energetic particles excite elmags.
- No field restructuring.
- No energetic particles on open field lines, but: particles excite waves that propagate across field lines and accelerated particles on open field lines with a particular composition (selective heating).



Selective Heating

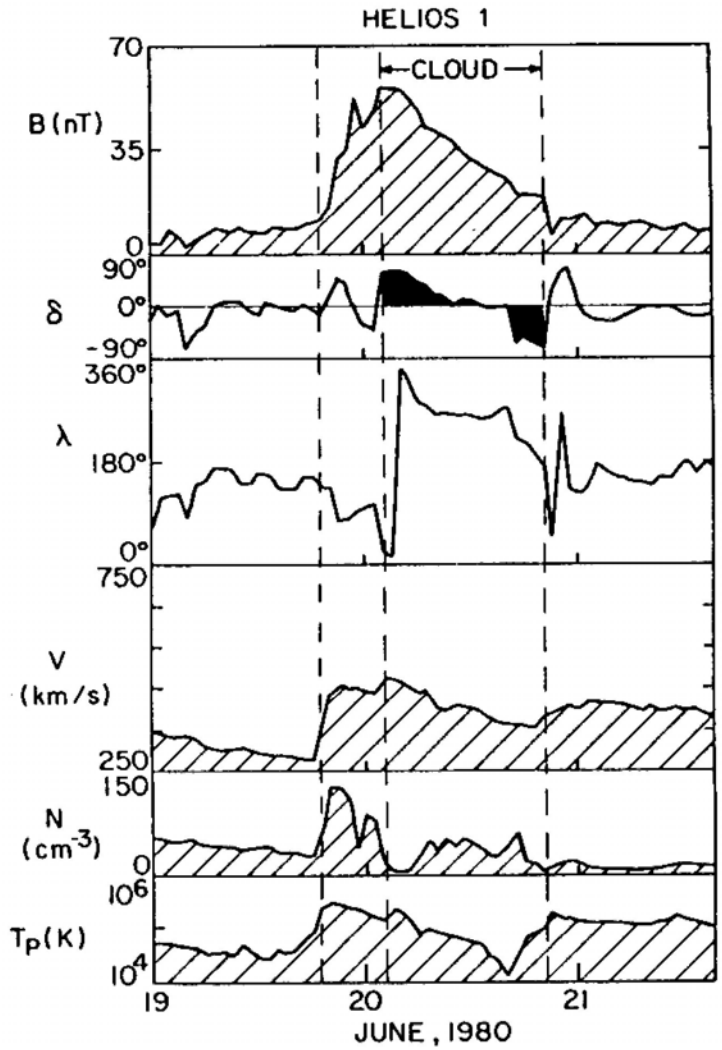


- Explanation for anomalies in composition:
  - Enrichment in heavy nuclei compared to corona
  - Charge states (indicate high temperatures)

- Escaping particles are accelerated not at the flare site but on open field lines:
  - Particles accelerated inside the loop generate electromagnetic ion cyclotron waves (EMICs) that propagate oblique to the loop,
  - The waves are absorbed outside the loop, their energy is converted to particle energy (minor species because waves interacting resonantly with the dominant species already are absorbed inside the loop),
  - Waves cascade down into large-amplitude long-wave Alfven waves,
  - Sequence of acceleration: Fe $\rightarrow$ Si, Mg, Ne $\rightarrow$ O, C$\rightarrow$ He $\rightarrow$ H.

Magnetic clouds: CMEs in ipl. space

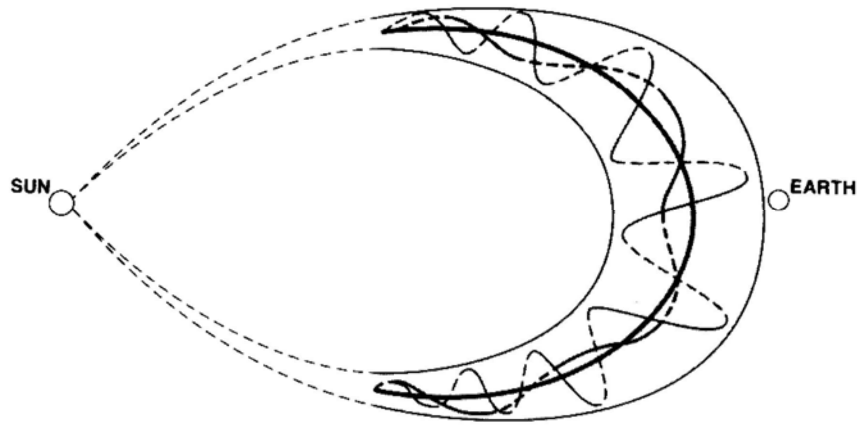
- Plasma and field properties distinct from the ambient medium:
  - Decrease of magnetic field inside the cloud,
  - Rotation of the magnetic field vector, in particular the elevation,
  - Decrease in
    - Plasma density,
    - Plasma temperature,
    - Plasma speed,
    - And thus also in plasma-β.
  - Bi-directional supra-thermal electron streams along the cloud's axis.
- Interpretation: magnetic flux rope with helical structure.



Burlaga, 1990, in Physics of the inner heliosphere, Springer

Magnetic clouds graphically

- Questions:
  - Is the cloud still connected to the Sun?
  - Which part of a CME corresponds to which part of the cloud?



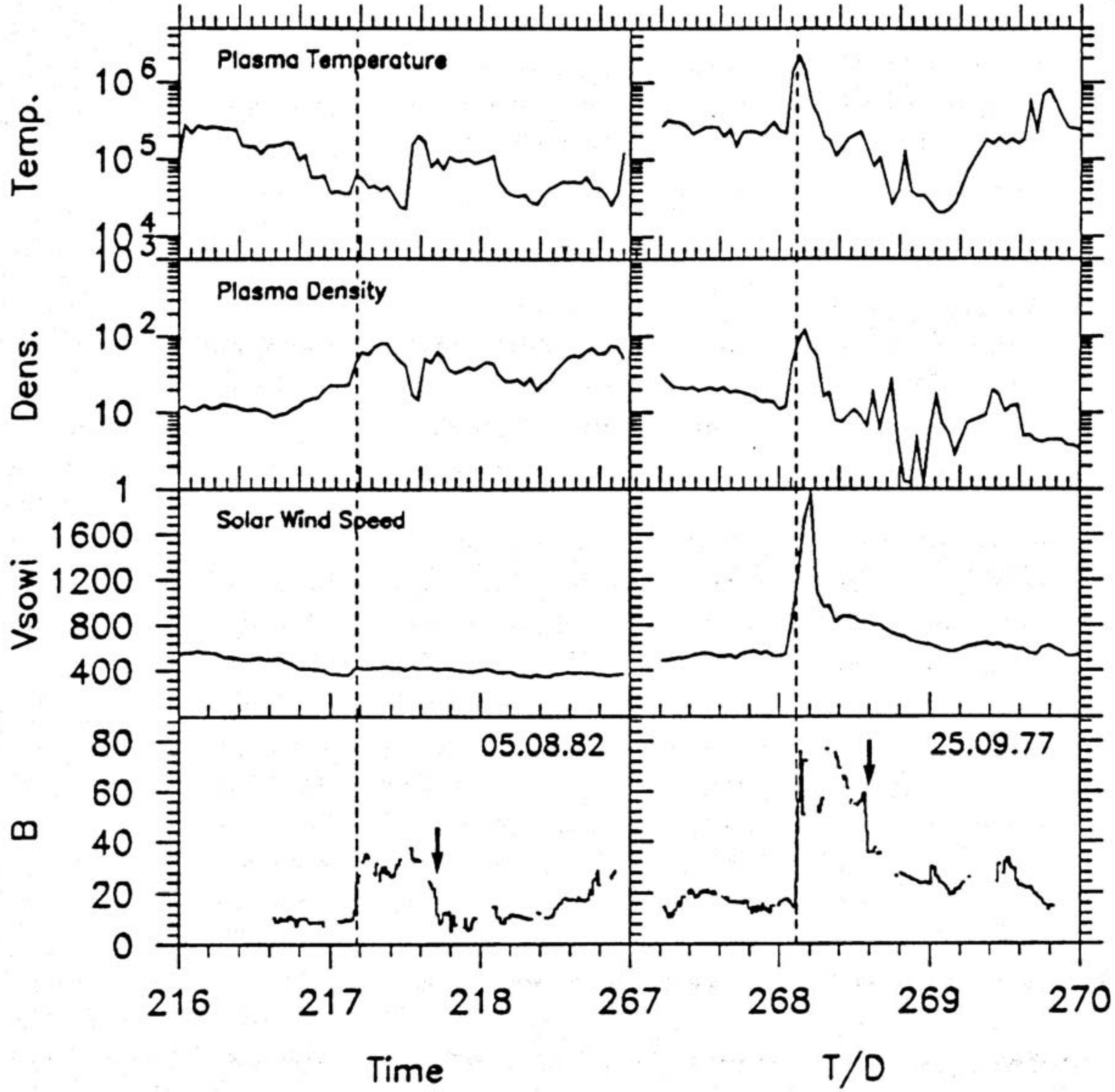
Burlaga, 1990, in Physics of the inner heliosphere, Springer

- The polarity of the cloud corresponds to the polarity of the parent filament.
- Magnetic clouds can be drivers of ipl. shocks.
- Shocks in ipl. Space are always accompanied by a cloud.
- On hitting the terrestrial magnetosphere, magnetic clouds can cause geomagnetic activity and aurora.

CMEs and shocks in ipl. space I

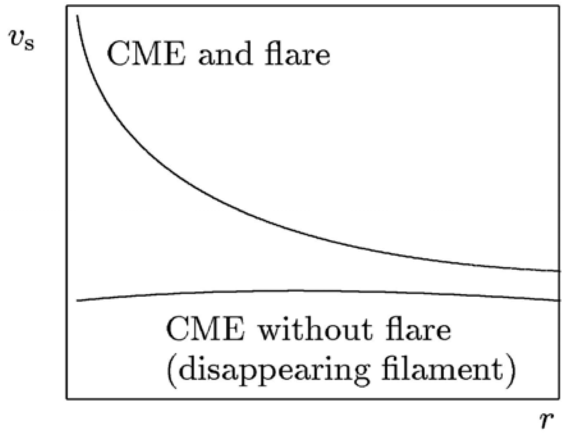
- Abrupt change in plasma and field parameters:
  - Plasma density ↑
  - Plasma speed ↑
  - Plasma temperature ↑
  - Magnetic field ↑

- reverse shock at the transition from the disturbed to the undisturbed medium possible.



CMEs and shocks in ipl. space II

- Properties of ipl. shocks
  - Compression ratio 1…8, ∅≈2,
  - Magnetic compression 1…7, ∅≈1.9,
  - Speed 300…2000 km/s, ∅≈600 km/s,
  - Alfven Mach number 1…13, ∅≈1.7,
  - Angular extend a few 10…>180°.



- Fast shocks in ipl. Space are
  - already fast in the corona and decelerate,
  - accompanied by strong flares.

Different modes of energy release!

- Slow shocks in ipl. Space are
  - slow in the corona, sometimes even accelerate,
  - connected to disappearing filaments or weak flares.

Summary solar activity

- Simple quantitative criterion: sunspot number.
- Physically more important: magnetic field configuration globally (dynamo) and locally (activity).
- Energy release due to reconnection:
  - Expulsion of magnetic flux (important for the polarity reversal of the dynamo),
  - Flares, shocks, CMEs and energetic particles on the Sun,
  - Energetic particles, magnetic clouds and shocks in ipl. space.

Collisionless shocks

- Shock:
  - Discontinuity that separates two regimes in a continuous medium.
  - Motion faster than the signal speed of the medium.
  - Only the relative speed is relevant: standing and traveling shocks follow the same rules.

- Collisionless shock:
  - Conventional hydrodynamic shock: momentum transport and thus propagation of information due to collisions between molecules → sound speed is the signal speed
  - Collisionless shocks: densities to low to allow for collisions. Momentum and information transport due to the plasma's collective behavior as organized by the magnetic field.

Defintion of a shock

- The disturbance propagates with a speed larger than the signal speed.
  - Hydrodynamic: sound speed,
  - Magnetohydrodynamic: Alfven speed or magnetosonic speed.

- Properties of the medium change abruptly at the shock
  - Hydrodynamic: pressure and density,
  - Magnetohydrodynamic: magnetic field and density.

- Behind the shock a transition to the undisturbed medium occurs:
  - Hydrodynamic: decrease in pressure and density,
  - Magnetohydrodynamic: decrease in magnetic field and density.

Comments shock

- Shock: non-linear wave of permanent form (soliton) propagating faster than the signal speed $\Rightarrow$ the upstream medium does not get any information about the approaching disturbance.

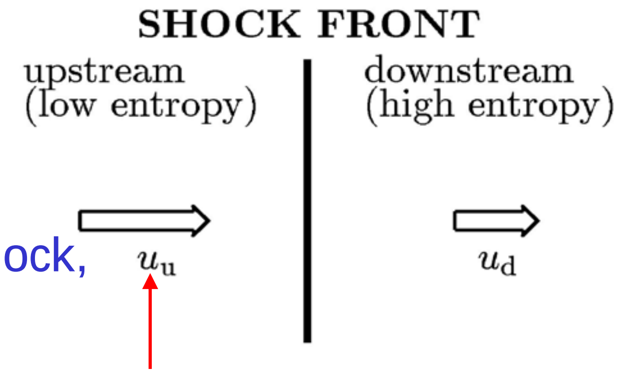
- The signal speed in the medium determines the information horizon $\Rightarrow$ shock outside of the information horizon!

- Development of the shock can be understood from the following questions:
  - Can information propagate faster than with the signal speed?
  - How does sound propagate in front of a disturbance moving faster than with sound speed (Mach´s cone)?
  - What are the particularities of large-amplitude disturbances (blast waves)?

Frames of reference (gas dynamic)

- Rest frame of the shock.

- Upstream medium:
  - Super-sonic medium propagates towards the shock,
  - No information about the shock,
  - Entropy small.



Definition of a Mach number MA:

Flow speed in the upstream medium divided by signal speed

- Shock front:
  - irreversible processes, compression, changes in speed,
  - conservation laws (Rankine-Hugoniot equations).

- Downstream medium:
  - Subsonic medium propagating away from the shock,
  - Entropy large.

Conservation laws (gas dynamic)

- Rankine-Hugoniot equations for a hydrodynamic shock

  - conservation of mass:

$$[m u_\mathrm{n}] = [\varrho u_\mathrm{n}] = 0 \, ;$$

  - conservation of momentum normal to the shock:

$$\left[\varrho u_\mathrm{n}^2 + p\right] = 0 \, ;$$

  - conservation of momentum tangential to the shock:

$$[\varrho u_\mathrm{n} u_\mathrm{t}] = 0 \, ;$$

  - conservation of energy normal to the shock:

$$\left[\left(\frac{\varrho u^2}{2} + \frac{\gamma_\mathrm{a}}{\gamma_\mathrm{a} - 1} p\right) u_\mathrm{n}\right] = 0 \, .$$

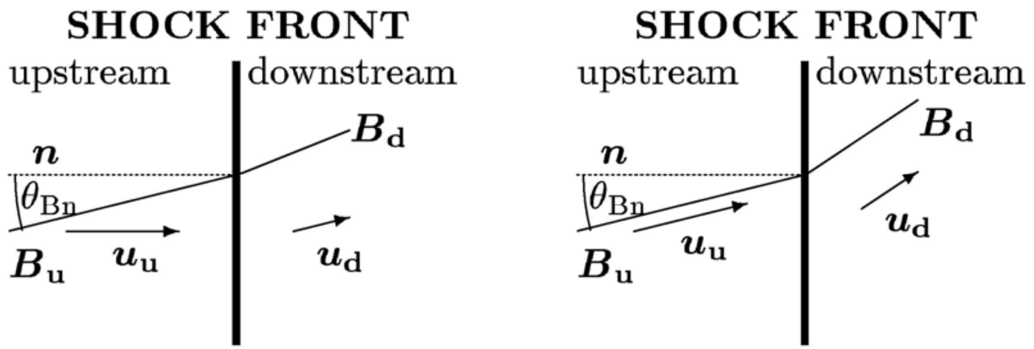
Definition [X]:

Difference of a quantity X in the upstream and downstream media:
[X] = Xu - Xd

- Application shock speed:

$$v_\mathrm{s} = \frac{\varrho_\mathrm{d} u_\mathrm{n,d} - \varrho_\mathrm{u} u_\mathrm{n,u}}{\varrho_\mathrm{d} - \varrho_\mathrm{u}} \, .$$

Frames of reference (MHD)



- Rest frame of the shock:
  - normal incidence frame (left): upstream plasma flow ⊥ shock
  - de Hoffmann-Teller frame (right): plasma flow on both sides ∥ B
    ⇒ electric induction field uxB vanishes!

- Difference hydrodynamic shock: magnetic field
  - B perpendicular to the shock: same as hydrodynamic shock
  - B oblique to the shock: refraction of B away from the shock normal at fast shocks.

- Quasi-perpendicular and quasi-parallel shocks.

Conservation laws (MHD)

- the mass balance, which is the same as for the ordinary shock,

$$[\varrho\vec{u}\cdot\vec{n}] = 0\ ; \tag{6}$$

- momentum balance, where the additional terms describe the magnetic pressure perpendicular and normal to the shock front,

$$\left[\varrho\vec{u}\,(\vec{u}\cdot\vec{n}) + \left(p + \frac{\vec{B}^2}{2\mu_\mathrm{o}}\right)\vec{n} - \frac{(\vec{B}\cdot\vec{n})\vec{B}}{\mu_\mathrm{o}}\right] = 0\ ; \tag{7}$$

- energy balance, where the additional terms describe the electromagnetic energy flux $\vec{E}\times\vec{B}/\mu_\mathrm{o}$ with the electric field expressed by $\vec{E} = -\vec{v}\times\vec{B}$,

$$\left[\vec{u}\cdot\vec{n}\left(\frac{\varrho\vec{u}}{2} + \frac{\gamma}{\gamma-1}p + \frac{\vec{B}^2}{\mu_\mathrm{o}}\right) - \frac{(\vec{B}\cdot\vec{n})\,(\vec{B}\cdot\vec{u})}{\mu_\mathrm{o}}\right] = 0\ ; \tag{8}$$

- Maxwell's equations

$$\left[\vec{B}\cdot\vec{n}\right] = 0\ , \tag{9}$$

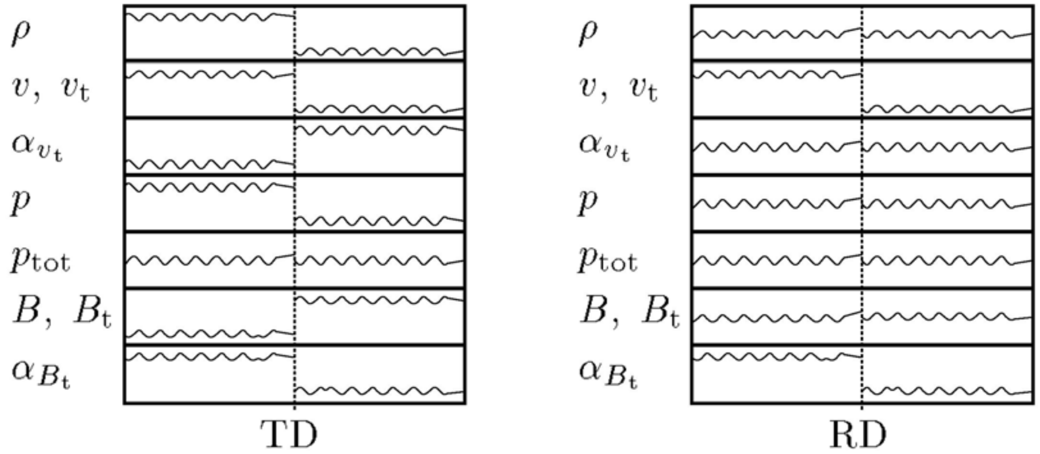
which follows from $\nabla\vec{B} = 0$, and states that the normal component of the magnetic field is continuous ($B_\mathrm{n} = \mathrm{const}$), and

$$\left[\vec{n}\times(\vec{u}\times\vec{B})\right] = 0\ , \tag{10}$$

which states that the tangential component of the electric field must be continuous.

Diskontinuities

- Rankine-Hugoniot describe conservation laws at discontinuities; a shock is one special solution only!



Tangential discontinuity TD:

• both plasma are separated completely,

• all quantities vary arbitrarily,

• the static pressure is constant: [p+B^2/2μ] = 0.

Rotational discontinuity RD:

• field and plasma change direction but not magnitude,

• pressure balance according to eq. (7),

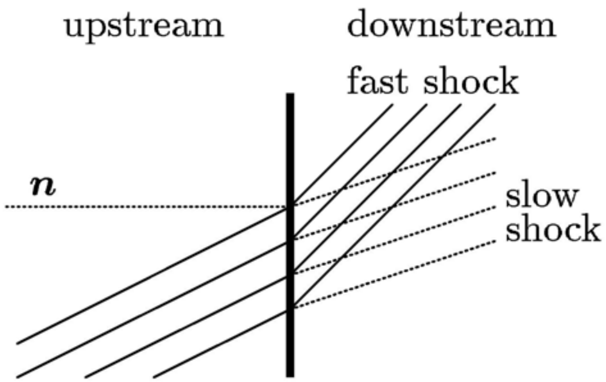
• transport of magnetic signals across the discontinuity.

Contact discontinuity:

• no plasma flow across the discontinuity, [X] in all other quantities arbitrarily,

• both sides are coupled by the normal component of B, tangential speeds the same.

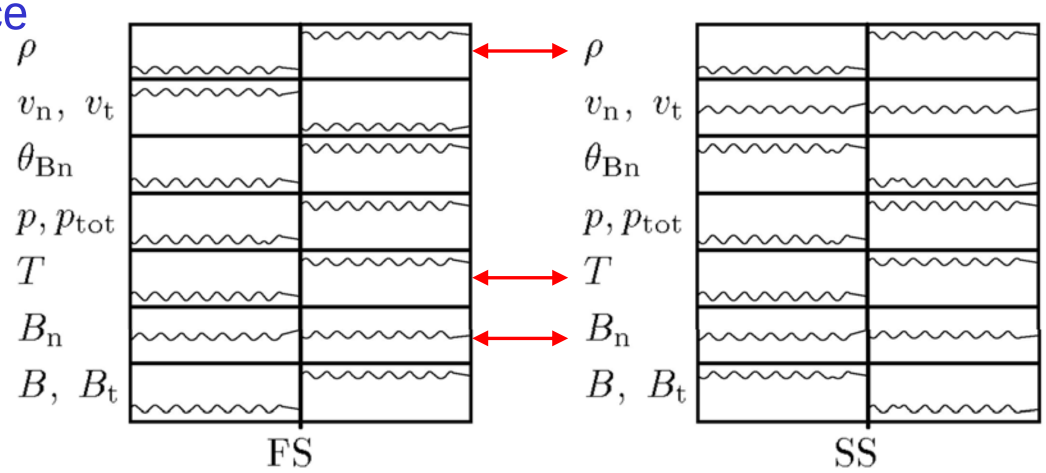
Slow and fast shocks



- Shock: v > signal speed.
  What defines the signal speed in a plasma?
- Candidates:
  - Alfven speed?
  - Slow and fast magnetosonic waves? $u^4 - (v_A^2 + v_s^2)u^2 + v_A^2 v_s^2 \cos^2\theta = 0$

$$2v_{\text{fast,slow}}^2 = (v_s^2 + v_A^2) \pm \sqrt{(v_s^2 + v_A^2)^2 - 4v_s^2 v_A^2 \cos^2\theta}$$

- Fast shock: standard in ipl. space
- Slow shocks in the corona??
- Ordering by Mach numbers:
  - Alfven Mach number,
  - Sonic Mach number,
  - Slow Mach number,
  - Fast Mach number.



Koplanarity

- Assumption: Shock normal and B in a plane in both upstream and downstream medium (already used above):

$$\vec{n} \cdot (\vec{B}_{\mathrm{d}} \times \vec{B}_{\mathrm{u}}) = 0$$

- Start from Rankine Hugoniot; tangential momentum balance

$$\left[\varrho u_{\mathrm{n}} \vec{u}_{\mathrm{t}} - \frac{B_{\mathrm{n}}}{2\mu_{\mathrm{o}}} \vec{B}_{\mathrm{t}}\right] = 0 \; .$$

- Rewrite: $(u_{\mathrm{n,u}} - u_{\mathrm{n,d}})(\vec{B}_{\mathrm{t,u}} \times \vec{B}_{\mathrm{t,d}}) = 0 \; .$

- [u_n] $\neq 0 \Rightarrow$ upstream and downstream tangential components of B are parallel.

$\Rightarrow$ Flow across the shock has a 2D-geometry !!!

Shock normal and speed

- Application coplanarity theorem: shock normal
  - Important for our understanding of shock formation,
  - Important for particle acceleration.

$$\vec{n} = \frac{(\vec{B}_\mathrm{u} \times \vec{B}_\mathrm{d}) \times (\vec{B}_\mathrm{u} - \vec{B}_\mathrm{d})}{|(\vec{B}_\mathrm{u} \times \vec{B}_\mathrm{d}) \times (\vec{B}_\mathrm{u} - \vec{B}_\mathrm{d})|} \,.$$

- Application: shock speed

$$v_\mathrm{s} = \frac{\varrho_\mathrm{d}\vec{u}_\mathrm{d} - \varrho_\mathrm{u}\vec{u}_\mathrm{u}}{\varrho_\mathrm{d} - \varrho_\mathrm{u}} \cdot \vec{n} \,.$$

Summary shocks

- Discontinuity propagating faster than the signal speed (information horizon!).
- Abrupt change in plasma and field properties.
- Frame of reference: rest frame of the shock.
- Conservation laws given by Rankine-Hugoniot.
  - Rankine-Hugoniot also describe discontinuities.
- Definition of different Mach numbers and shocks depending on signal speed.