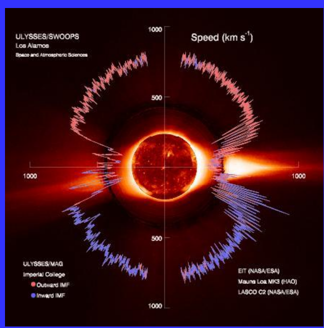
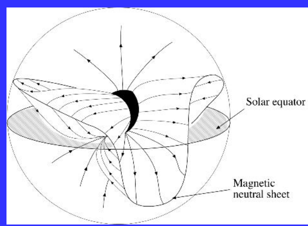
The solar corona and the stream structure of the solar wind

Hannu Koskinen
with special thanks to prof. Rainer Schwenn, MPS, Lindau

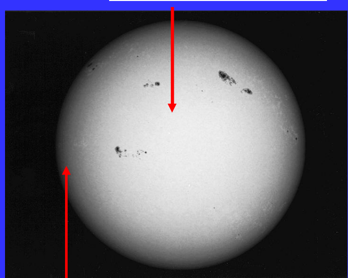


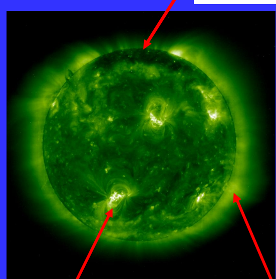


Solar atmosphere

Cool surface
5778 K black body

Coronal hole
source of solar wind

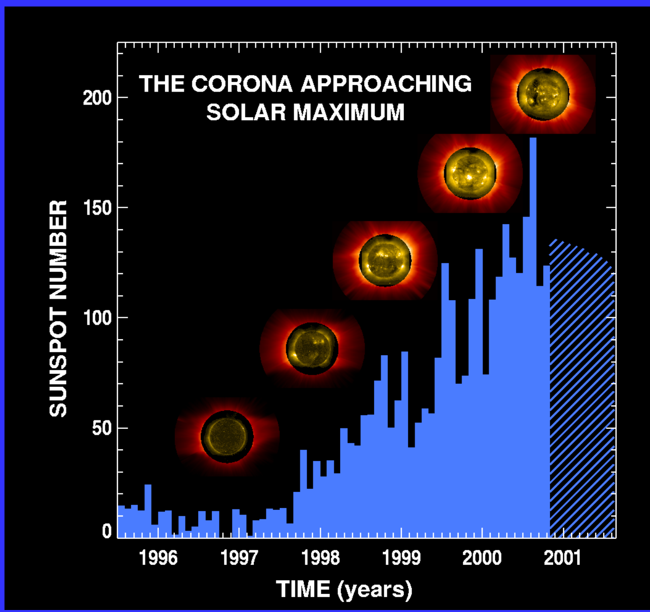




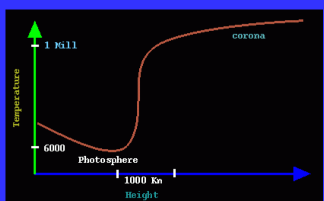
Limb darkening
Sun has an atmosphere

Various types
of activity

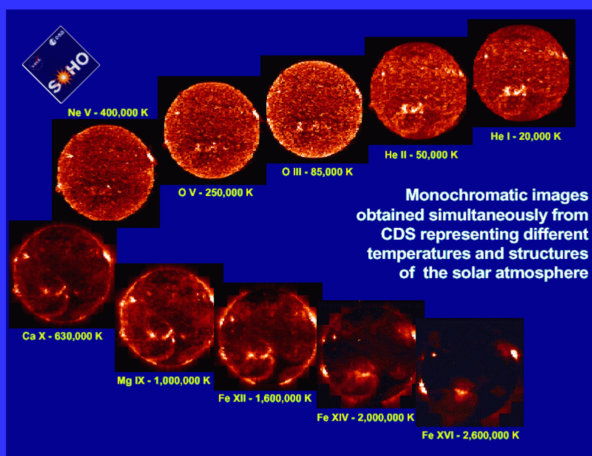
Hot corona
up to 2 MK



Heating of solar corona



A very non-trivial problem !



Why solar wind?

- There must be a mechanism to transfer solar activity to the Earth
  - Chapman 1929: Solar flares emit plasma clouds
  - Chapman and Ferraro ~ 1931: First ideas of magnetic storms
  - Biermann 1951: Cometary tails require a fast corpuscular flow in addition to radiation pressure

Parker's solution:

Isothermal expanding solar wind

Assume a spherically symmetric time-independent outward flow.
Equations of continuity, momentum and state are:

$$4\pi r^2 nv = \mathrm{const}$$

$$nmv\frac{dv}{dr} = -\frac{dp}{dr} - \frac{GM_8 mn}{r^2}$$

$$p = nk_B T$$

Although the solar wind certainly cools when expanding, <u>assume</u> that the expansion is isothermal (T = const.)

Þ $$\left(v - \frac{v_c^2}{v}\right)\frac{dv}{dr} = \frac{2v_c^2}{r} - \frac{GM_8}{r^2}$$

where $v_c = \sqrt{k_B T / m}$ is the isothermal sound speed

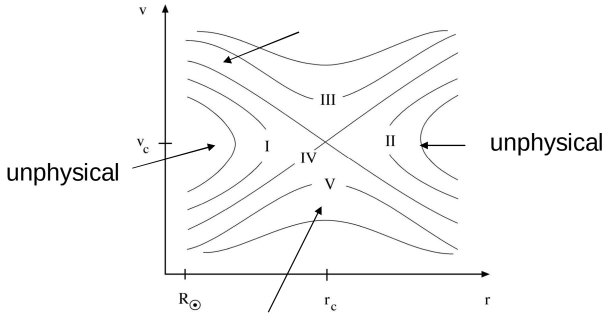
This equation has a critical point: $v = v_c \quad ; \quad r = r_c = GM_8/(2v_c^2)$

Integration gives a family of curves:

$$\left(\frac{v}{v_c^2}\right)^2 - \ln\left(\frac{v}{v_c^2}\right)^2 = 4\ln\frac{r}{r_c} + \frac{2GM_8}{rv_c^2} + C$$

Five regimes of solutions

not consistent
with observations



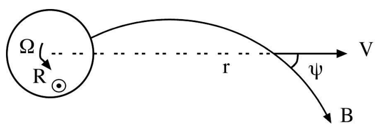
stellar breeze (subsonic: $v < v_c$)

Solution IV through the critical point (Þ C = – 3) is the solar wind:
subsonic near the Sun → supersonic beyond the critical point

The interplanetary magnetic field (IMF)

Close to the Sun:
Flow is radial, **B** is nearly radial
Assume, that flow remains radial

B is frozen-in to the rotation surface
and in the outflowing plasma



Flow speed ^ **B** : $V_\wedge = V \sin$ Y

"Speed of the fl." ^ **r** : W $(r - R_8)$

$$V \sin \Psi = \Omega (r - R_8) \cos \Psi \quad \Rightarrow \quad \tan \Psi = \frac{\Omega (r - R_8)}{V}$$

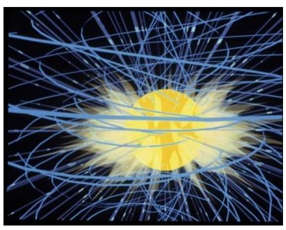
For large r :
Archimedes' spiral

≈ 44º at Earth (1 AU)
≈ 57º at Mars (1.5 AU)
≈ 88º at Neptune (30 AU)

Far from the Sun:

$B \rightarrow r^{-1}$ In the ecliptic (tight spiral)

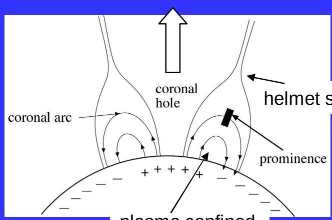
$B \rightarrow r^{-2}$ In the polar directions



Sources of the solar wind:

Coronal holes

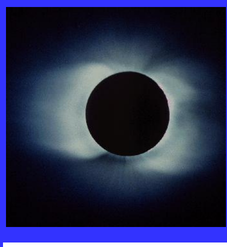
plasma escapes on open flux tubes



helmet streamer

plasma confined by magnetic field

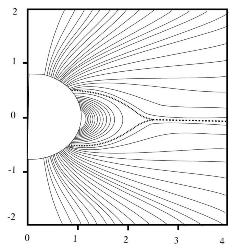
Corona seen during solar eclipses



near solar minimum
- clear polar holes

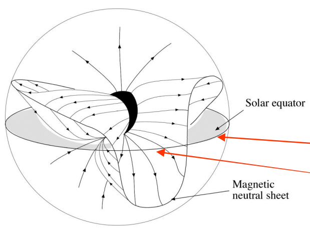
near solar maximum
- holes all over the Sun

How does the real solar wind look like?



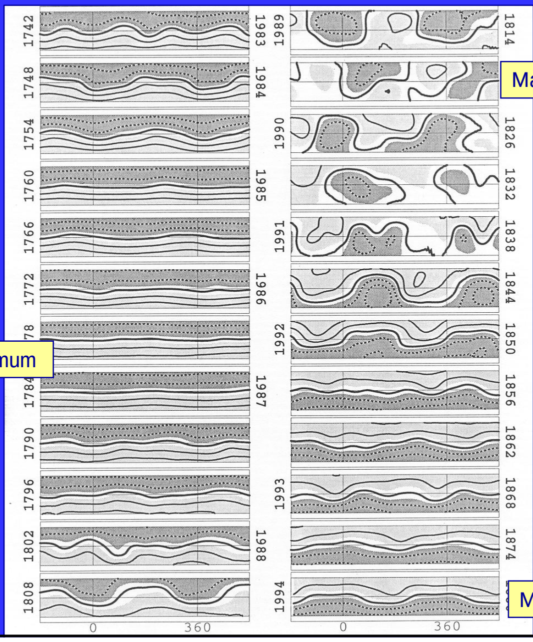
Formation of the heliospheric current sheet
(Pneuman and Knopp)

The real current sheet is curved
"Ballerina skirt"
(Alfvén)



The Earth can be "toward" sector or in "away" sector

The ballerina dancing through the solar cycle

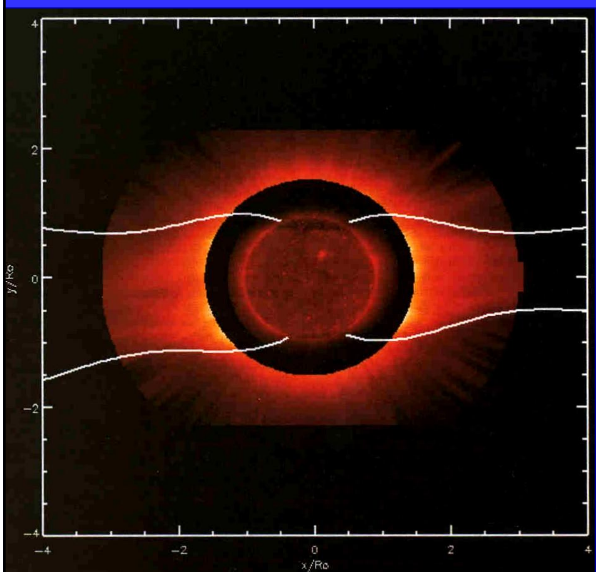


The magnetic topology of the large-scale heliosphere

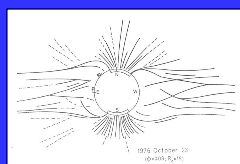
At activity maximum, the ballerina skirt flips over, and the magnetic polarity is then reversed at next minimum. Thus, the magnetic cycle of the sun (the “Hale-cycle”) takes 22 years!

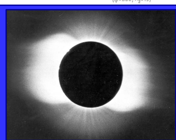
Hoeksema, 1995

The equatorial streamer belt



The boundaries of coronal holes and the streamer belt, as seen by **EIT** and **UVCS** on **SOHO**

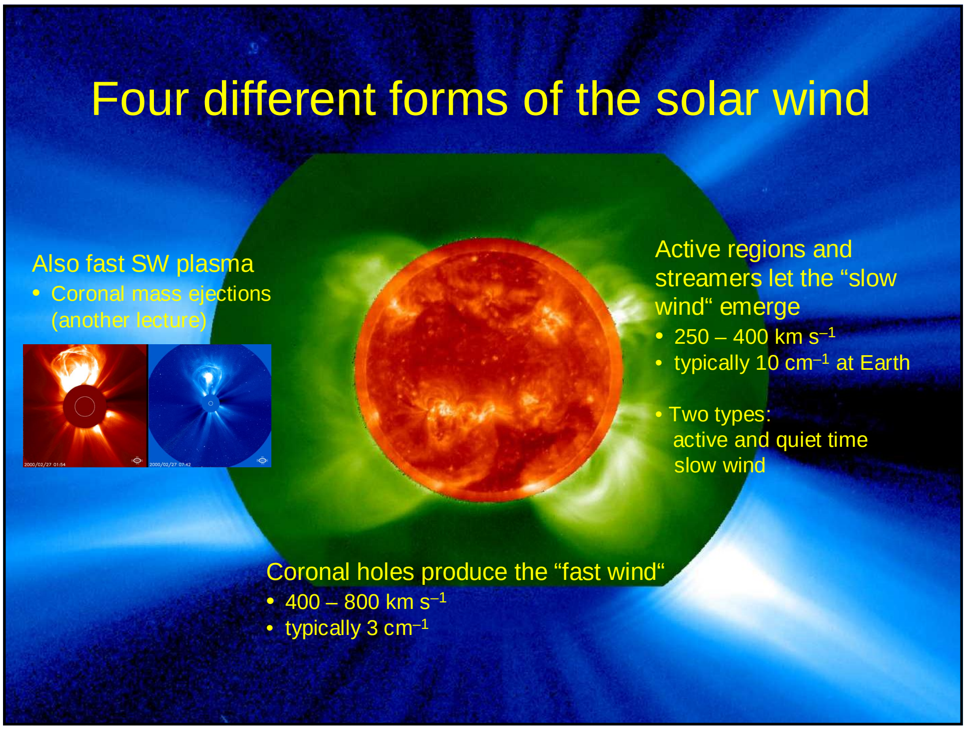




Solar wind at 1 AU

	minimum	average	maximum
v	200 km/s	400 km/s	900 km/s
n	4×10^5 m^{-3}	6.5×10^6 m^{-3}	10^8 m^{-3}
T_e	5×10^3 K	2×10^5 K	10^6 K
T_p	3×10^3 K	5×10^4 K	10^6 K
B	0.2 nT	6 nT	80 nT
v_A	30 km/s	60 km/s	150 km/s

But average is a pretty useless concept here!

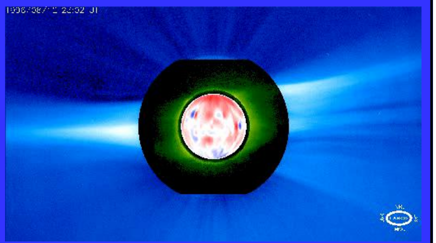


The two basic types of solar wind

<u>1. Fast wind in high speed streams</u>

High speed	400-800 kms^{-1}
Low density	3 cm^{-3}
Low particle flux	2 x 10^8 cm^{-2} s^{-1}
Helium content	3.6%, stationary
Source	coronal holes
Signatures	stationary for long times, all streams are alike, Alfvénic fluctuations

All values with reference to 1 AU



<u>2. Low speed wind of "interstream" type</u>

Low speed	250-400 kms^{-1}
High density	10.7 cm^{-3}
High particle flux	3.7 x 10^8 cm^{-2} s^{-1}
Helium content	below 2%, highly variable
Source	helmet streamers near current sheet, at activity minimum (???)
Signatures	generally very variable, sector boundaries imbedded,

The two basic types of solar wind

Differences and similarities

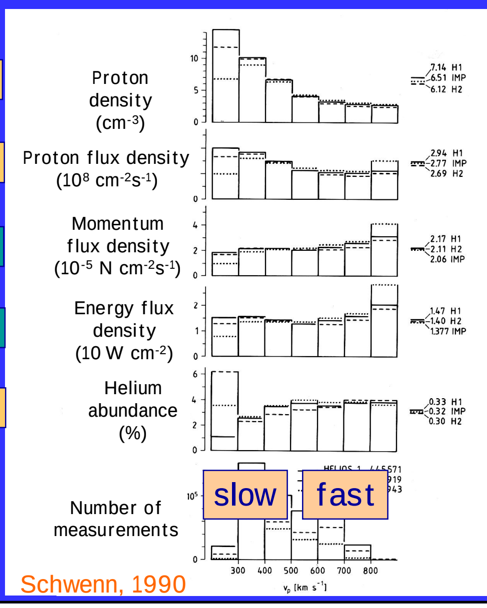
Strongly different

Significantly different!

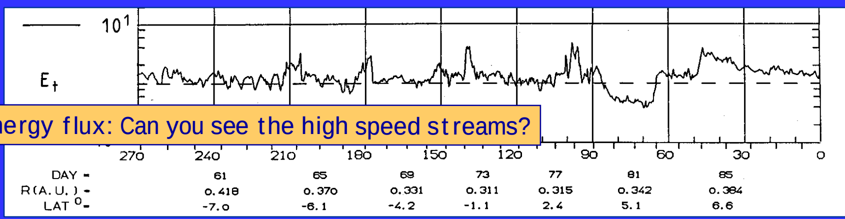
Almost invariant!

Also almost invariant!

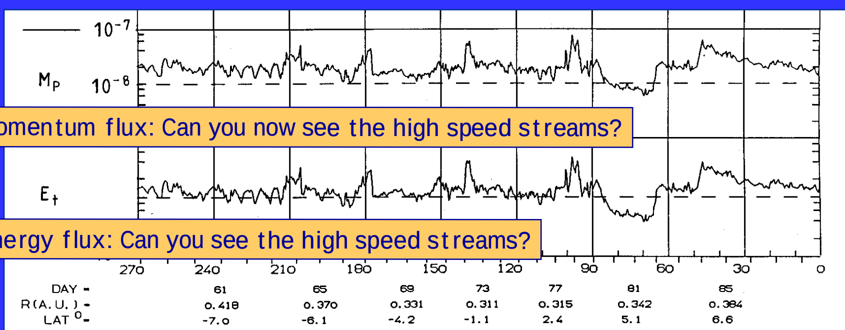
Significantly different!



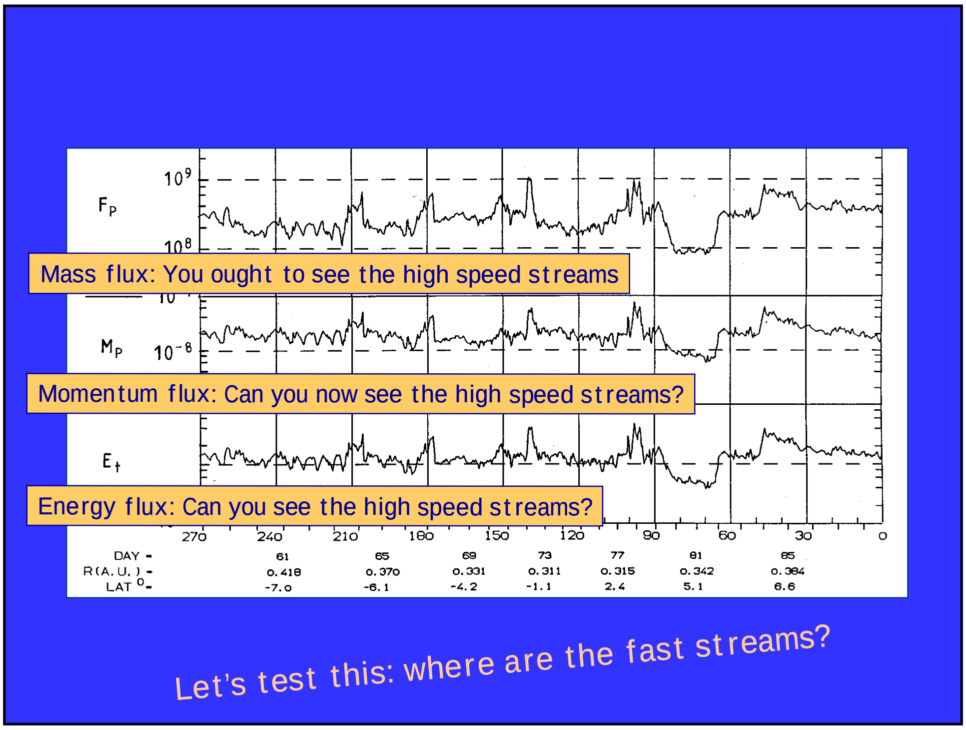
Schwenn, 1990



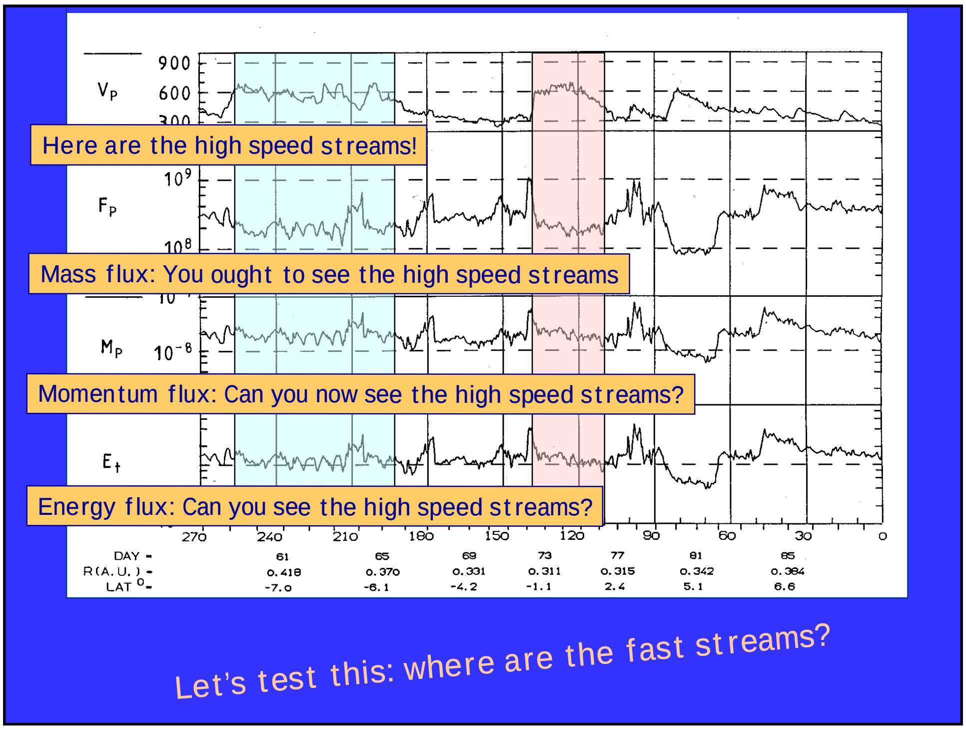
Let's test this: where are the fast streams?



Let's test this: where are the fast streams?



F_p
10^9
10^8
Mass flux: You ought to see the high speed streams
M_p
10^{-8}
Momentum flux: Can you now see the high speed streams?
E_t
Energy flux: Can you see the high speed streams?
270 240 210 180 150 120 90 60 30 0
DAY - 61 65 69 73 77 81 85
R(A.U.) - 0.418 0.370 0.331 0.311 0.315 0.342 0.384
LAT °- -7.0 -6.1 -4.2 -1.1 2.4 5.1 6.6
Let's test this: where are the fast streams?



V_p
900
600
300
Here are the high speed streams!
F_p
10^9
10^8
Mass flux: You ought to see the high speed streams
M_p
10^{-8}
Momentum flux: Can you now see the high speed streams?
E_t
Energy flux: Can you see the high speed streams?
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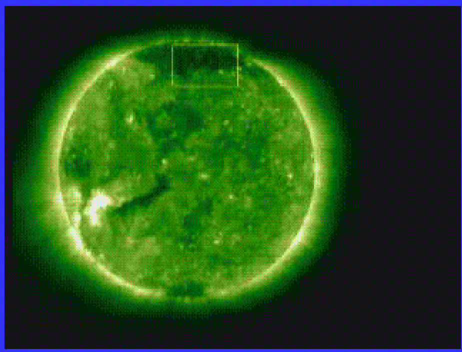
Let's test this: where are the fast streams?

The “fast” solar wind,

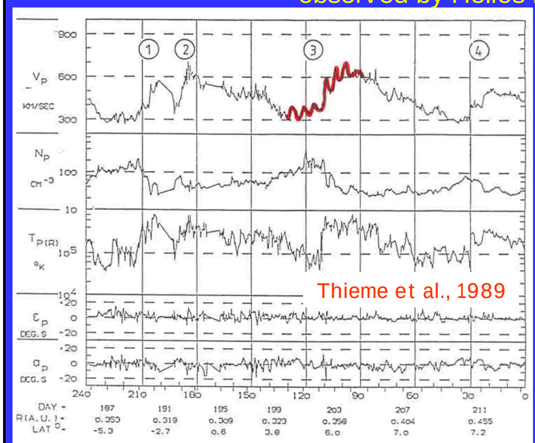
from high latitude coronal holes

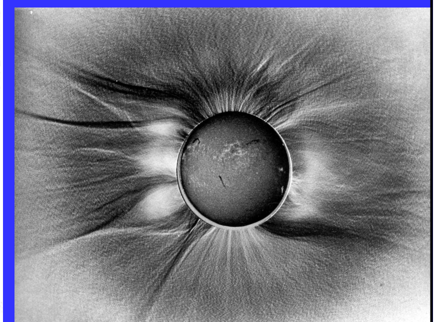


The SOHO instruments have shown, that the fast solar wind from coronal holes emerges from the network boundaries, in particular from their intersections

The filamentary structure of the solar wind

observed by Helios near 0.3 AU



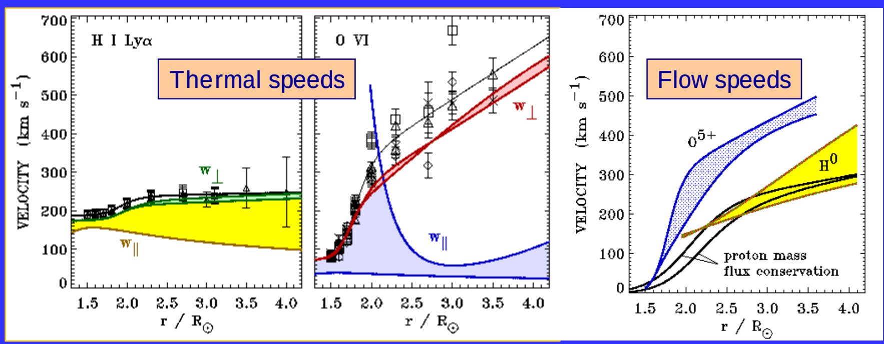


Koutchmy et al., 1978

The angular size of the solar wind flux tubes is ~5^0. It corresponds well to the scale size of the expanded polar plume structure known from eclipses.
At 1 AU these structures are usually flattened out.

The “fast” solar wind,

from high latitude coronal holes

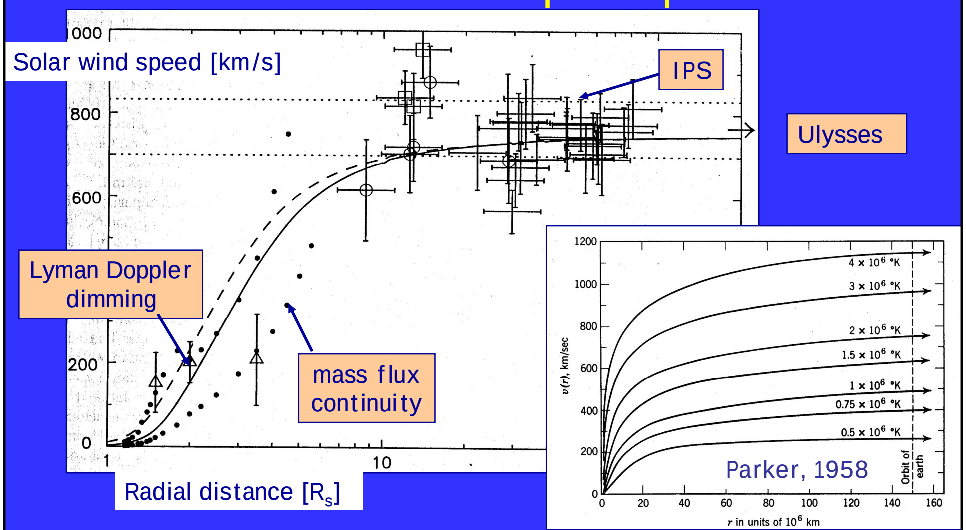


UVCS on SOHO measured the proton and O^{5+} ion thermal speeds in a coronal hole. For reference, the electron thermal speeds are shown as well.

Note the pronounced anisotropy and acceleration of oxygen with respect to the protons, thus indicating ion cyclotron heating.

Note that the fast wind is almost “ready” by 3 R_{s}!

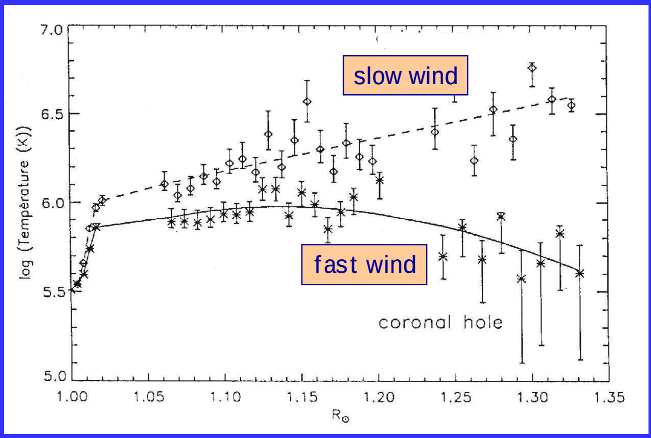
Fast solar wind speed profile



Note: the fast solar wind has substantial speed as low down as 3 R_s and reaches its final speed inside 10 R_s

The fast solar wind,

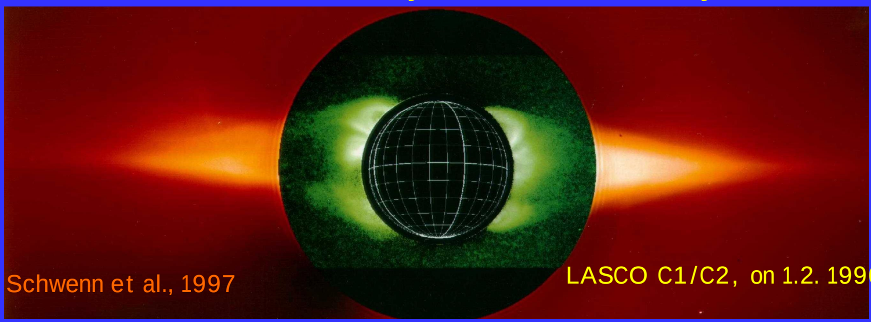
from high latitude coronal holes



CDS/SUMER: profiles of electron temperature from EUV line-ratios

- The electron temperature is generally lower and drops off more rapidly in coronal holes than in streamers!
- In fast wind electrons are cooler than protons!

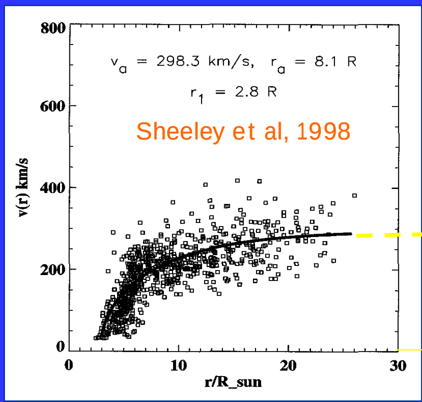
The corona at activity minimum in early 1996

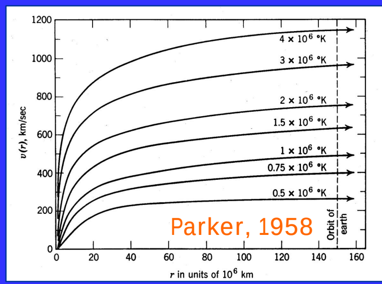


- There are magnetic multipole structures at mid-latitudes, in addition to the general dipole,
- these helmets may involve multiple current sheets,
- the mid latitude loops appear to be very stable in time, i.e., they extend over substantial longitudes as do the underlying photospheric neutral lines,
- the near-equatorial helmets vary strongly and are often absent.

The streamer sheet (only 30 deg wide in interplanetary space!) and the HCS imbedded in it are products of the mid-latitude streamers close to the Sun, NOT of the activity belt near the equator!

Slow solar wind speed profile





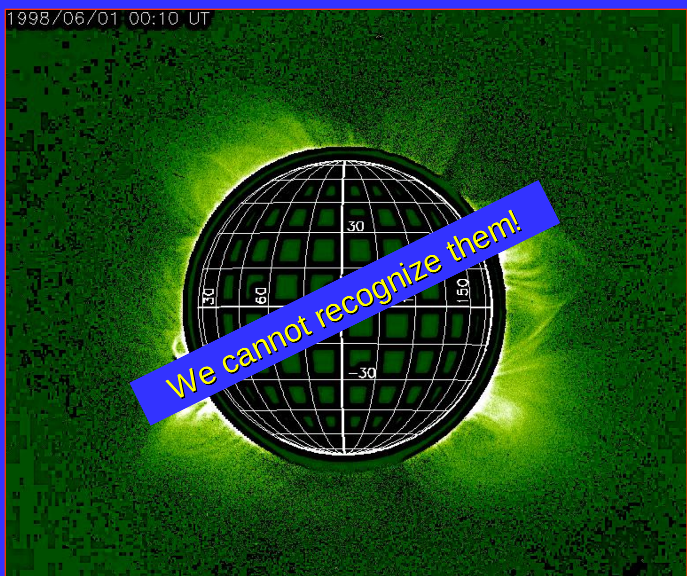
Helios at 60 Rs

60

Speed profiles of the slow solar wind, as determined from “leaves in the wind”

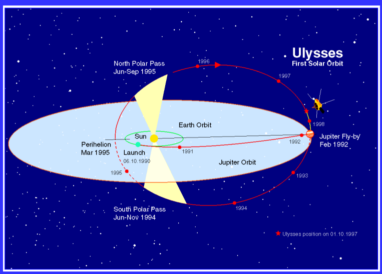
Note: coherent outward flow of slow solar wind starts only at about 3 R_{s}. The profile is consistent with in-situ speed profiles obtained by Helios between 60 and 210 R_{s}.

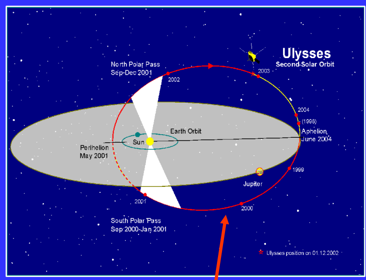
The sources of slow solar wind?



Mierla, 2005

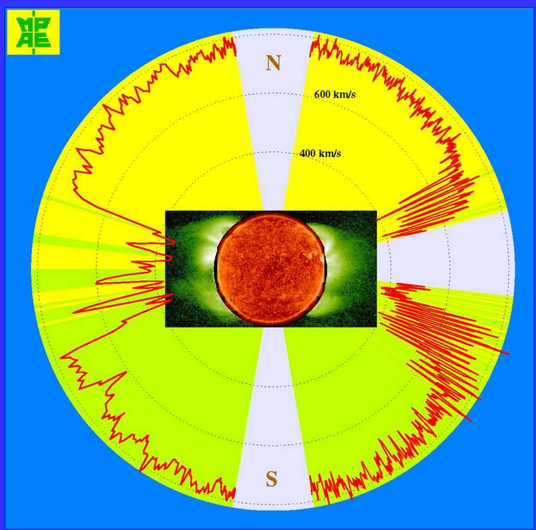
Ulysses observations





Present location January, 2006
The third and last revolution around the Sun

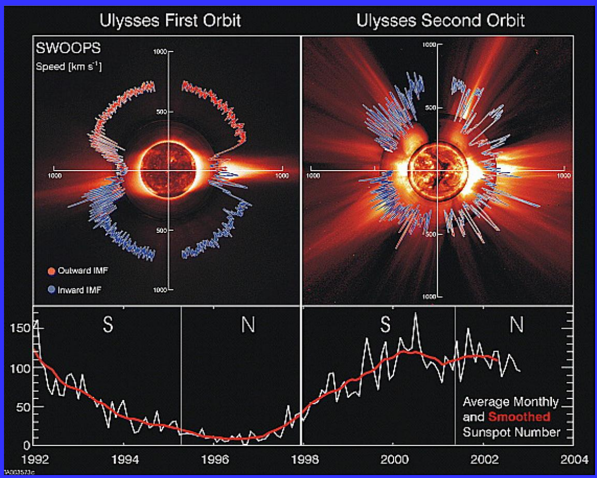
The 3D solar wind at activity minimum



Ulysses observations of solar wind speed and magnetic sector structure, observed during a full orbit around solar activity minimum.

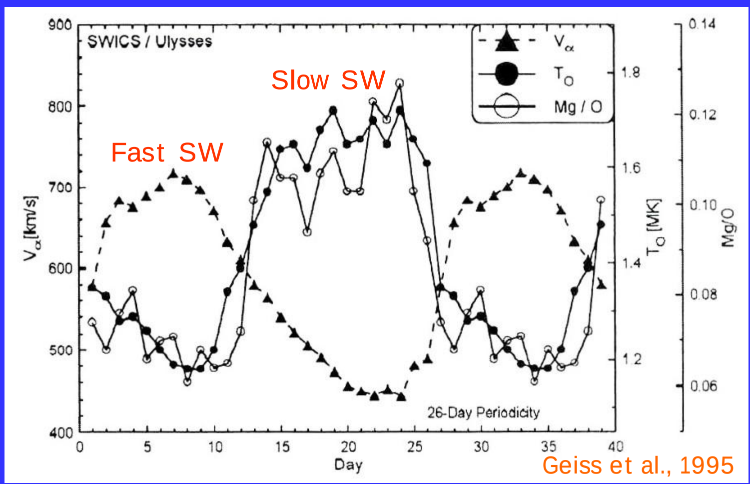
Ulysses was almost permanently encountering fast solar wind, except from a narrow, near-equatorial belt of slow solar wind, thus confirming earlier measurements (e.g., from IPS, Helios).

Minimum and maximun epochs are very different!



Solar wind element and charge state composition

and the large-scale stream structure

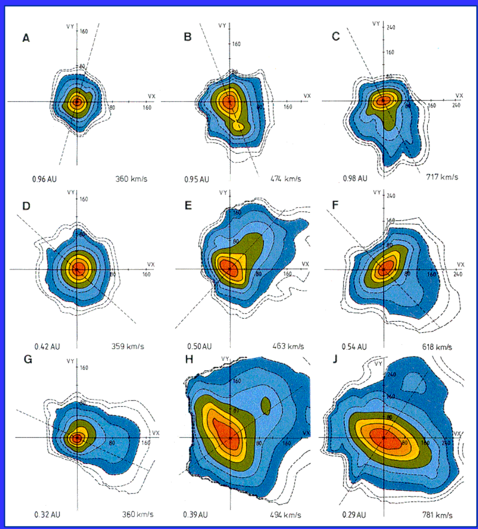


Signatures of stream structure in heavy ion composition and charge state, measured from **Ulysses**.

Proton velocity distributions

1 AU

0.3 AU



Slow SW

Fast SW

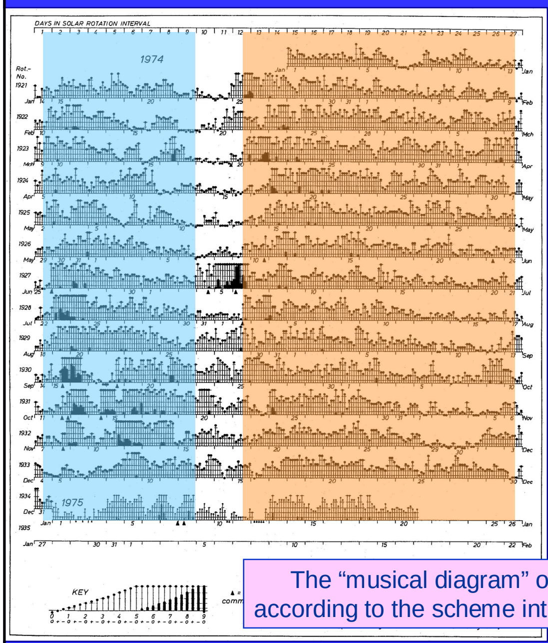
Proton 3D velocity distributions for various wind speeds and distances from the sun as measured by Helios

Note:

- Thermal speeds are much less than bulk speeds, i.e., supersonic flow at Mach ~10,
- the slow wind is pretty isotropic,
- in the fast wind, $T_{perp} > T_{par}$,
- in the fast wind, there is often a second component, at higher speed.

Marsch et al., 1982

High speed streams: M-regions!



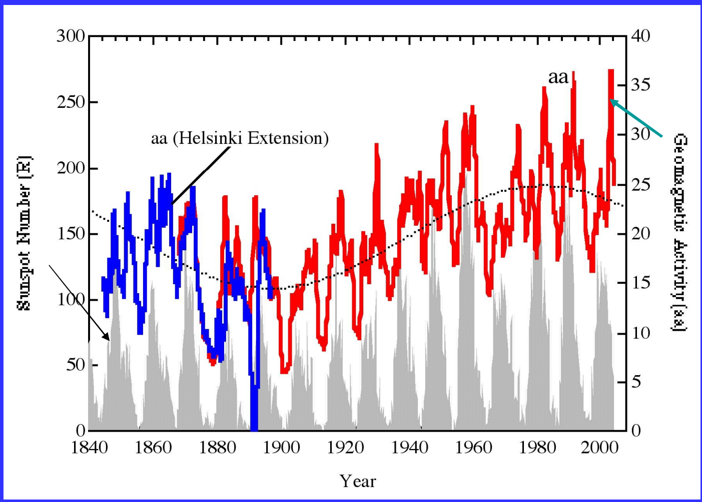
The “musical diagram” of geomagnetic activity, according to the scheme introduced by Bartels (1930)

High speed streams from coronal holes (i.e. the “inactive” sun) cause moderate geomagnetic activity:

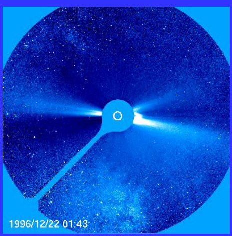
They are most prominent in the years right before activity minima.

Then, the polar coronal holes may have large extensions reaching to equatorial latitudes such that the high speed streams appear in the ecliptic plane as well.

Solar cycle and the Earth



Solar Wind Sources and their variations over the activity cycle



Key questions still waiting for answers:

- Two types of corona and solar wind: basic differences?
- Where and how is the slow solar wind emerging?
- How is the fast wind accelerated to its extreme speeds?
- Why that sharp boundaries between coronal and solar wind states?
- How to recognize CMEs and flares before they occur?
- 11 year activity and 22 year Hale cycles: significance for Sun-Earth system?