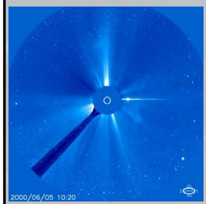
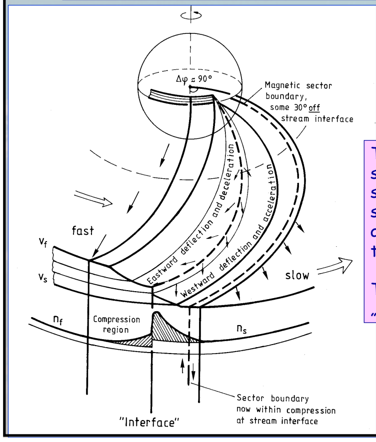
Physics of the heliosphere: an introduction



Lectures at the
International Max-Planck-Research School
Oktober 2002
by Rainer Schwenn, MPAe Lindau

3. Solar wind and corona in 3D
- Stream boundaries and interactions
- The 3D heliosphere at activity minimum
- Puzzles at high latitudes
- A new understanding of heliospheric rotation
- The two states of the solar wind

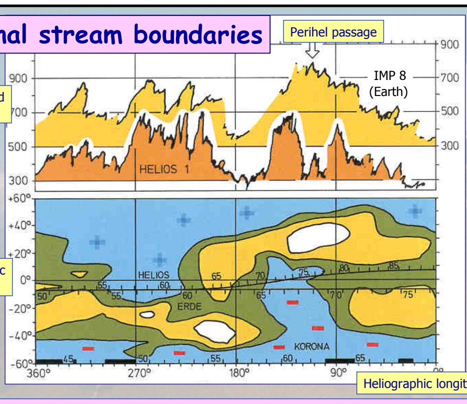
Scheme of the radial evolution of a CIR



The originally sharp front separating streams of different speed widens because of stream-stream interactions. By about 1 AU all solar wind has been "processed" this way.

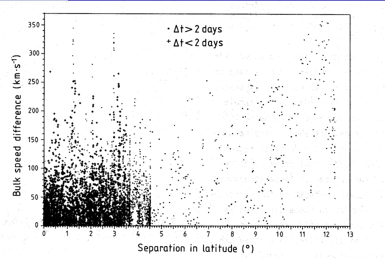
That marks the border between „inner" and „outer" heliosphere.

Latitudinal stream boundaries



Solar wind stream structure, seen nearly simultaneously from 1 AU and from 0.3 AU (**IMP** and **Helios 1**) in early 1975, associated with coronal hole structure. Note that Helios passed the northern boundary of the fast stream, while IMP at low latitude did not.

Latitudinal stream boundaries



The difference ΔV in proton bulk speed measured by the two HELIOS probes as a function of their separation in heliographic latitude Δλ. Each point represents an average over 1° in solar longitude. The crosses denote cases with corotation times of less than two days.

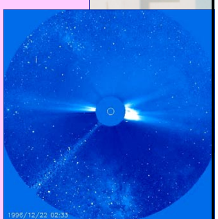
The whole difference between slow and fast flow may occur over 1° in latitude.
This was our 1976 argument for the solar wind being a two-state-phenomenon!

Summarizing our observations of "leading", "trailing" and "latitudinal" boundaries, we conclude that fast streams near 0.3 AU exhibit sharp boundaries in all directions. This finding, taken together with the observation of mesa-like profiles of large fast streams near 0.3 AU, implies that possibly because of new critical points developing in highly diverging flows (Kopp and Holzer, 1976), solar wind emerges from the corona in two different states, a "fast" and a "slow" one. This idea will be followed up in section 5.3 of this paper.

Two different types of solar wind!

1. Fast wind in high speed streams

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

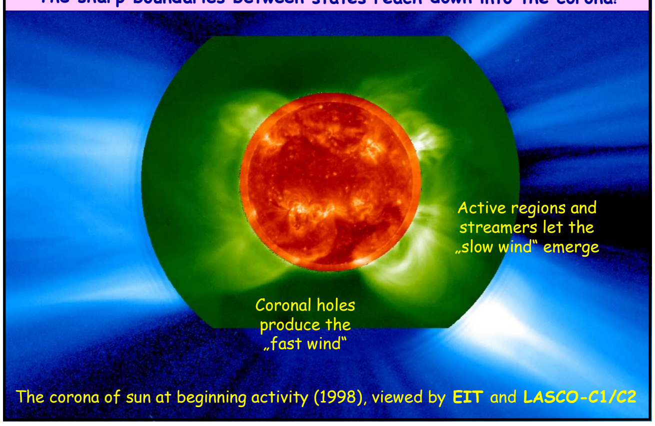


2. Low speed wind of "interstream" type

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

The two states of corona and solar wind

The sharp boundaries between states reach down into the corona!

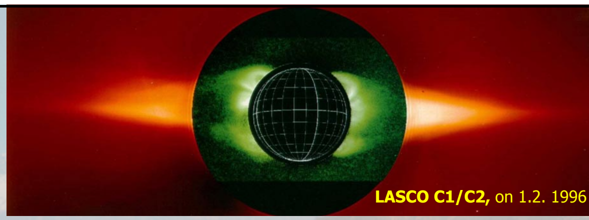


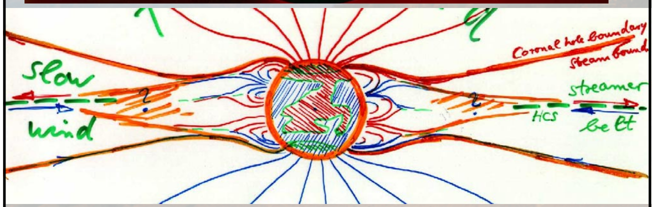
The corona of sun at beginning activity (1998), viewed by **EIT** and **LASCO-C1/C2**

The corona at activity minimum in early 1996 and its topology:

- 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.

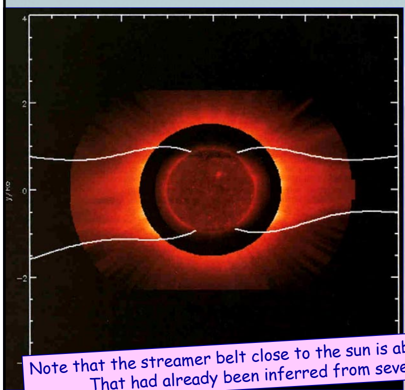
The streamer sheet (only 30 deg wide in interplanetary space!) and the HCS imbedded in it are products of the mid-latitude streamers close to the Sun, NOT of the activity belt near the equator!



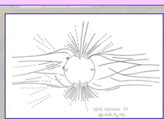


The corona at activity minimum in early 1996 and its topology.

The equatorial streamer belt

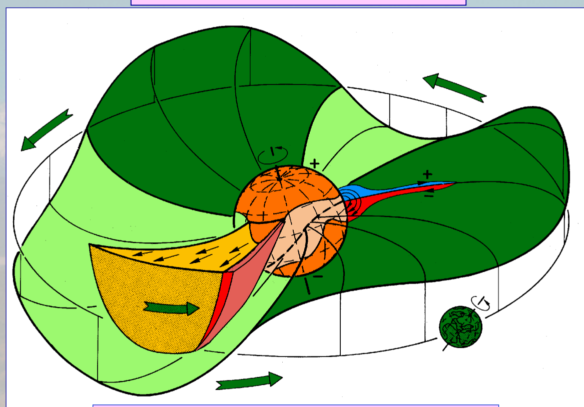


The boundaries of coronal holes and the streamer belt, as seen by **EIT** and **UVCS** on ***SOHO***



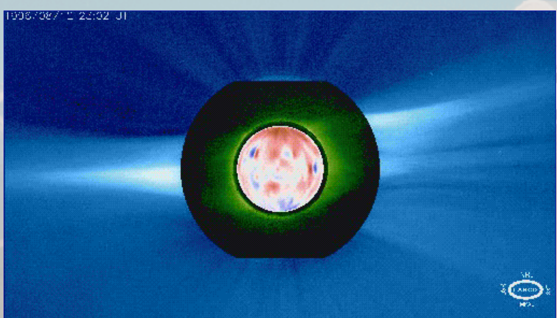
Note that the streamer belt close to the sun is about one solar diameter wide. That had already been inferred from several minimum eclipses.

See the ballerina dance!



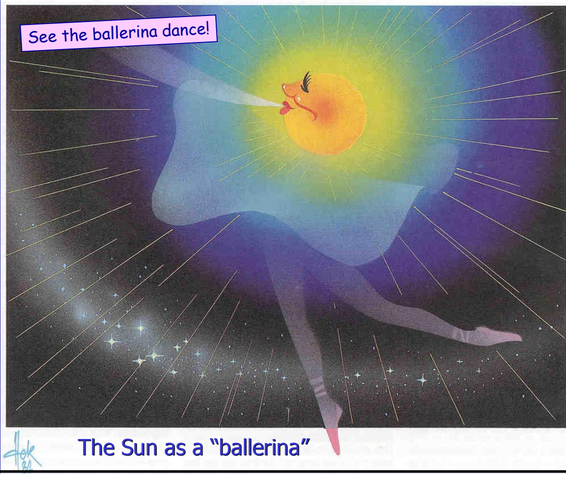
The Sun as a "ballerina", according to *Alfvén, 1977*.

See the ballerina dance!



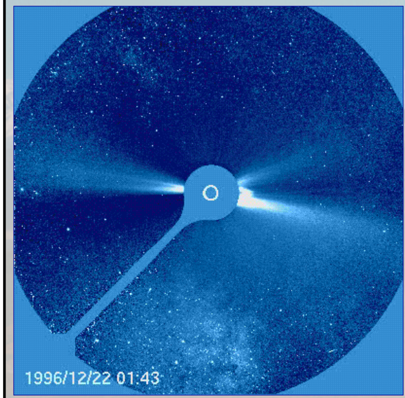
The Sun and its corona at solar activity minimum during the Whole Sun Month (WSM) in 1996, seen by the **LASCO C1/C2** coronagraphs on ***SOHO*** and the **WSO** magnetograph

See the ballerina dance!



The Sun as a "ballerina"

The solar wind made visible

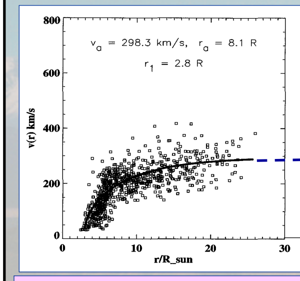


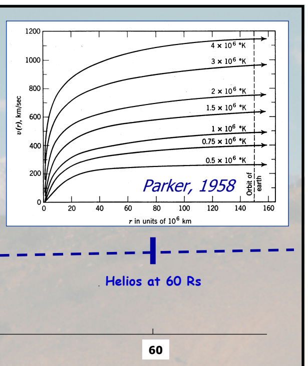
Never seen before:
the „smoke clouds" near the equatorial plane are due to inhomogeneities in the solar wind, which thus becomes visible!

Note further:
- The moving star field,
- Our milky way which the Sun traverses right at Christmas,
- A little comet plunging into the Sun and evaporating

The „slow" solar wind,

at low latitudes

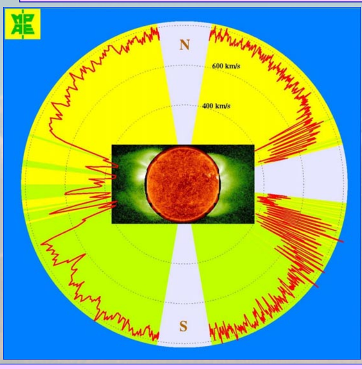




Speed profiles of the slow solar wind, as determined from „leaves in the wind"

Note: coherent outward flow 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.

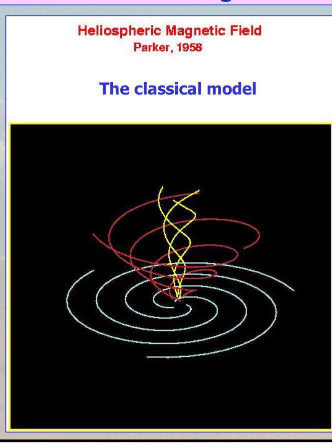
The 3D solar wind at activity minimum



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).

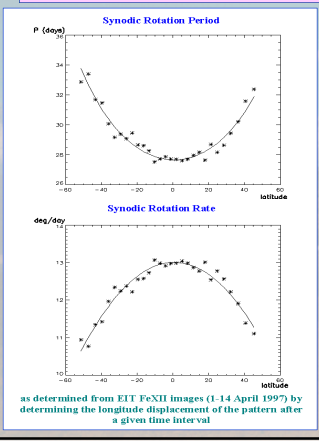
Ulysses observations of solar wind speed and magnetic sector structure, observed during a full execliptic orbit around solar activity minimum.

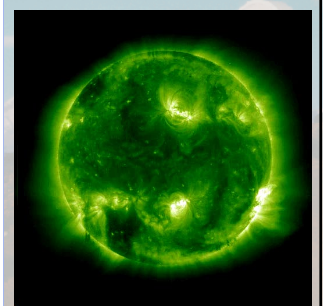
New understanding of heliospheric rotation



That's what we were educated with...

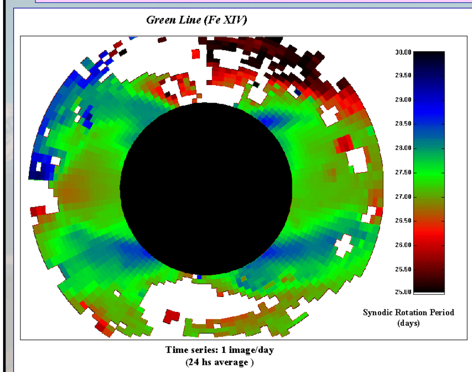
New understanding of heliospheric rotation





The short term motion of coronal patterns occurs accurately according to **differential rotation**

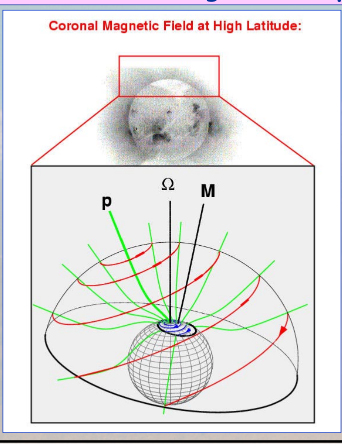
New understanding of heliospheric rotation



However, long-lived coronal patterns exhibit a uniform rotation of the whole corona at the equatorial rotation period (27.2 days).

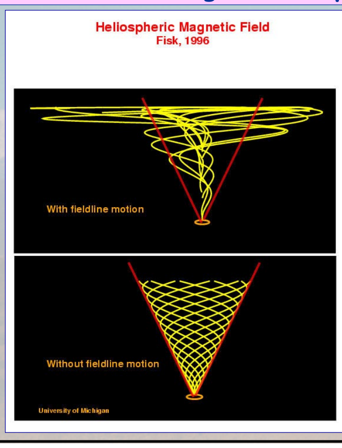
Rotation periods of corotating coronal features, determined from **LASCO-C1** data

New understanding of heliospheric rotation



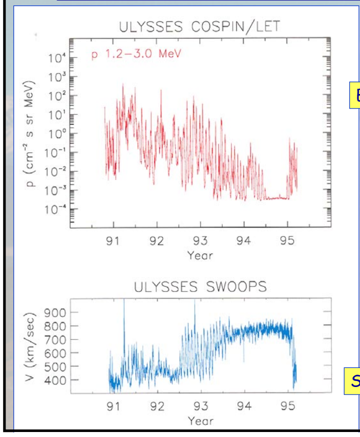
The new “Fisk” model. It involves differential rotation, the inclined solar axis and reconnection.

New understanding of heliospheric rotation



In this scheme, field lines emerging at high latitudes can reach down to low latitudes, where energetic particles might be injected.

A major surprise above the Sun's poles

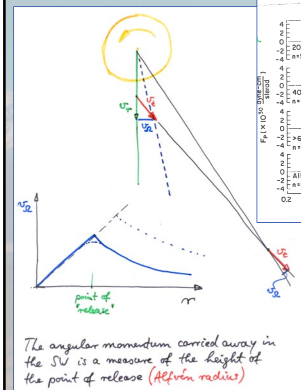


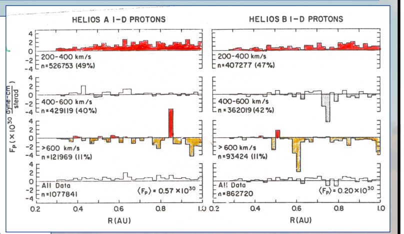
Energetic particles

A really puzzling observation in this context: On his passage to high latitudes, Ulysses finally left the streamer sheet, and no CIRs were seen in the solar wind any more. But energetic particles accelerated at CIRs remained! The Fisk model tries to explain how they reach those high latitudes.

Solar wind, CIRs

The solar wind carries away angular momentum





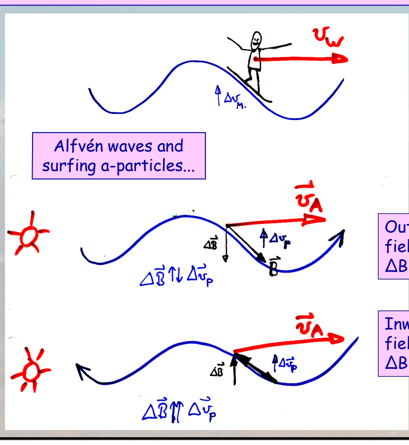
Results: • $F_p = 2 \times 10^{22}$ Nm sterad^{-1} (similar rotation for $\pm 4.6 \times 10^9$ yr possible...) Pizzo et al, '82

r_A (fast SW) $\approx 10\ r_\odot$; r_A (slow SW) $\approx 30\ r_\odot$

The Sun will not slow down much in the next few million years to come...

Another confirmation: fast solar wind is released much closer to the Sun!

The „fast“ wind: full of Alfvén waves

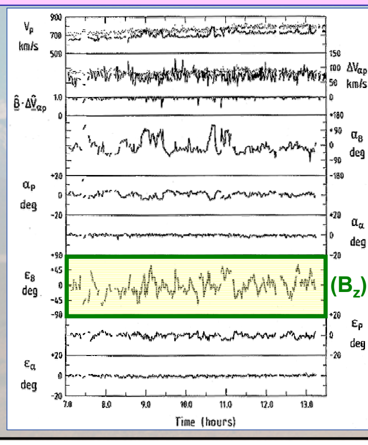


Alfvén waves and surfing a-particles...

Outward pointing magnetic field: ΔB and ΔV anticorrelated

Inward pointing magnetic field: ΔB and ΔV correlated

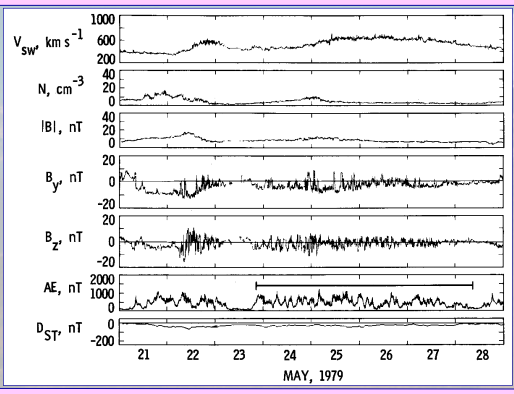
The „fast“ wind: full of Alfvén waves



Alfvén waves cause substantial deflections in both: flow direction and magnetic field. Note the anticorrelation!

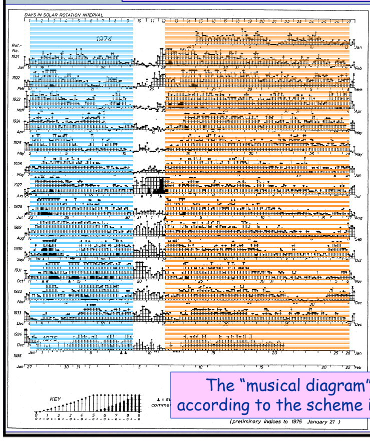
That is the origin of strong north-south field excursions in high speed wind streams

The „fast“ wind: full of Alfvén waves



Alfvén waves in high speed streams cause magnetic excursions including southward B_z-components which cause moderate geomagnetic effects!

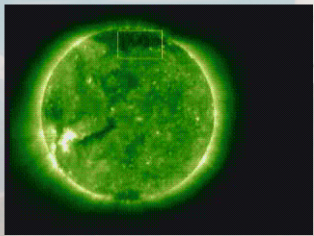
High speed streams: M-regions!



High speed streams from coronal holes (i.e. the inactive" sun) cause (moderate) geomagnetic activity:
They are the "M-regions"!
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.

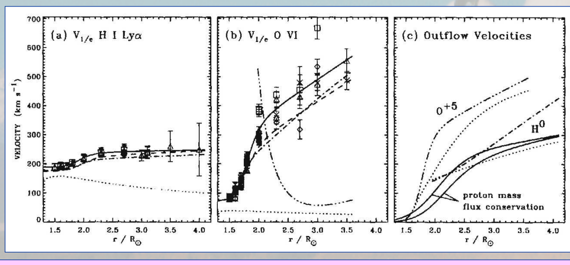
The "musical diagram" of geomagnetic activity, according to the scheme introduced by Bartels (1930)

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 „fast“ solar wind,
from high latitude coronal holes

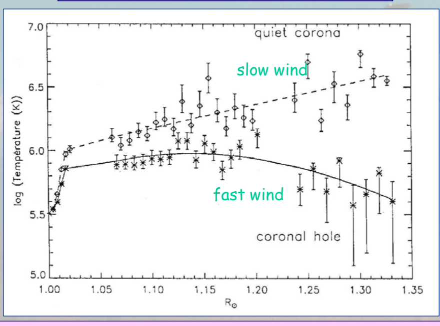


UVCS on SOHO measured the proton and O^{5+} ion thermal speeds in a coronal hole. For reference, the electron thermal speeds are shown as well.

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!

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

Strongly different — Proton density (cm^{-3})

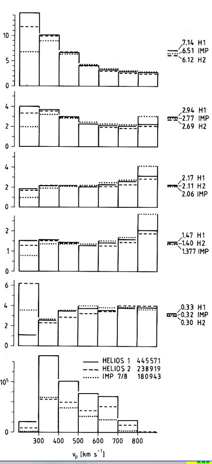
Significantly different! — Proton flux density ($cm^{-2}s^{-1}$)

Almost invariant! — Momentum flux density (10^5 N $cm^{-2}s^{-1}$)

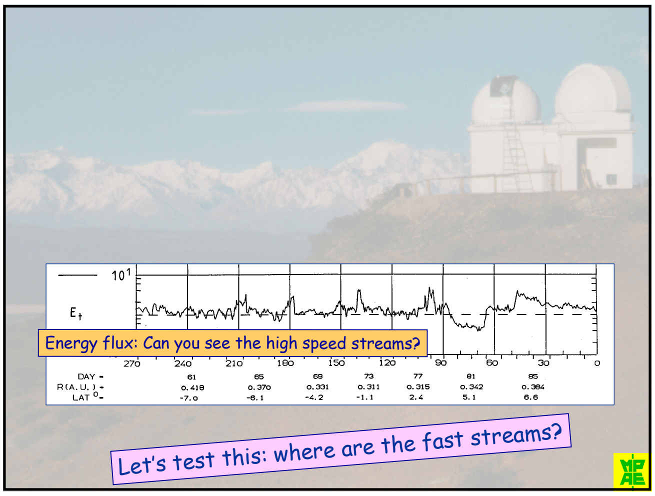
Also almost invariant! — Energy flux density (10 W cm^{-2})

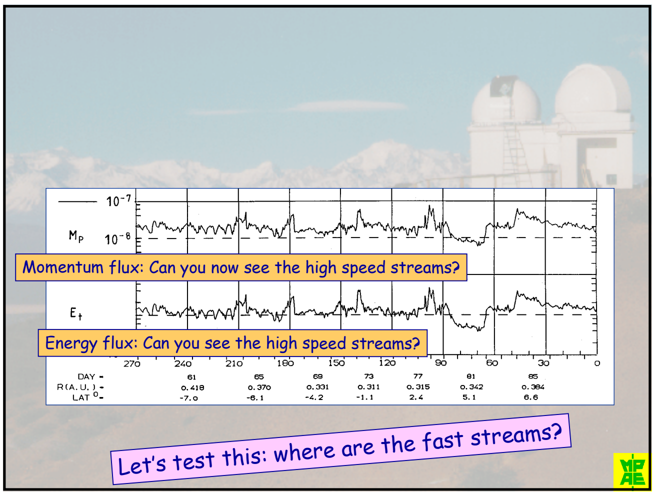
Significantly different! — Helium abundance (%)

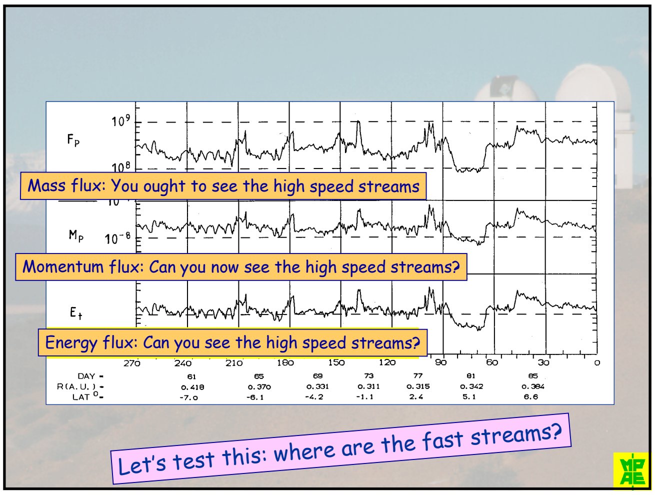
Number of measurements

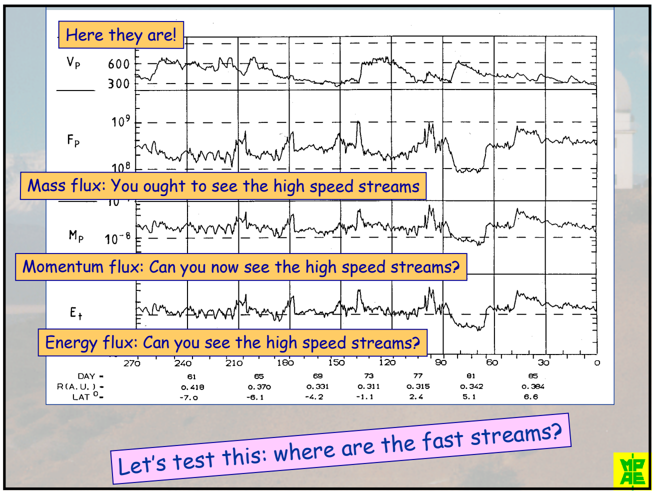


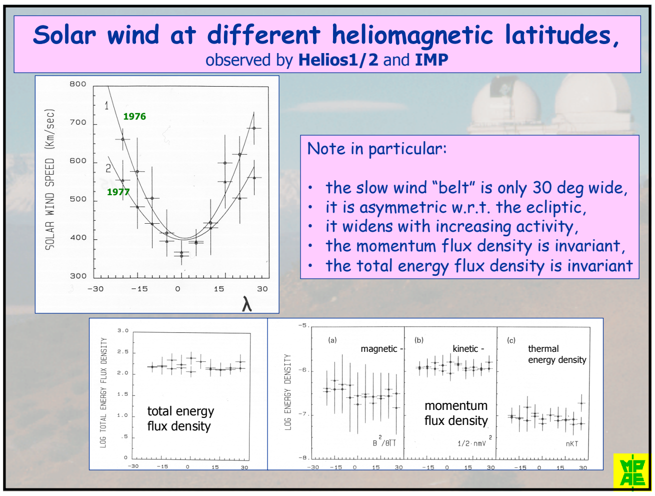
Differences and similarities between fast and slow solar wind

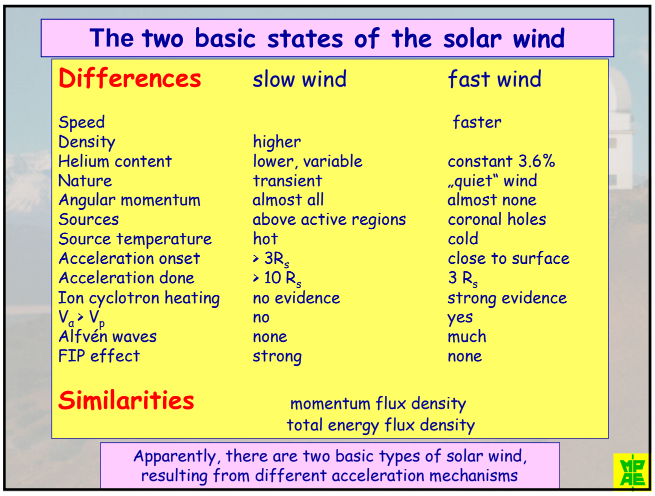

Energy flux: Can you see the high speed streams?
Let's test this: where are the fast streams?


Momentum flux: Can you now see the high speed streams?
Energy flux: Can you see the high speed streams?
Let's test this: where are the fast streams?


Mass flux: You ought to see the high speed streams
Momentum flux: Can you now see the high speed streams?
Energy flux: Can you see the high speed streams?
Let's test this: where are the fast streams?

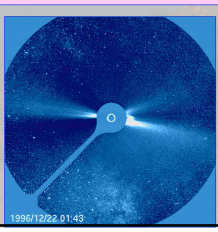

Here they are!
Mass flux: You ought to see the high speed streams
Momentum flux: Can you now see the high speed streams?
Energy flux: Can you see the high speed streams?
Let's test this: where are the fast streams?

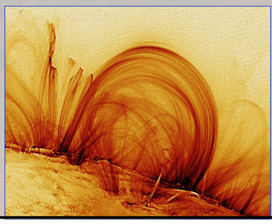

Solar wind at different heliomagnetic latitudes,
observed by Helios1/2 and IMP
SOLAR WIND SPEED (km/sec)
1976
1977
λ
Note in particular:
the slow wind "belt" is only 30 deg wide,
it is asymmetric w.r.t. the ecliptic,
it widens with increasing activity,
the momentum flux density is invariant,
the total energy flux density is invariant
total energy
flux density
magnetic
kinetic
thermal
energy density
momentum
flux density


The two basic states of the solar wind
Differences slow wind fast wind
Speed faster
Density higher
Helium content lower, variable constant 3.6%
Nature transient „quiet" wind
Angular momentum almost all almost none
Sources above active regions coronal holes
Source temperature hot cold
Acceleration onset > 3Rs close to surface
Acceleration done > 10 Rs 3 Rs
Ion cyclotron heating no evidence strong evidence
Va > Vp no yes
Alfvén waves none much
FIP effect strong none
Similarities momentum flux density
total energy flux density
Apparently, there are two basic types of solar wind,
resulting from different acceleration mechanisms

Basic questions about the solar wind still waiting to be answered

- How is the corona being heated?
- How is the slow wind released?
- What heats and accelerates the fast wind?
- Why these sharp boundaries?
- Spatial scales of the crucial physical processes?
- Differential rotation, rigid rotation, "Fisk effect"?
- Solar wind dropouts and other strange escapades?
- Abundance variations and FIP effect?
- ?





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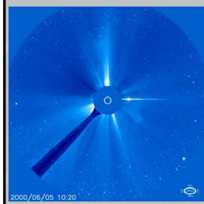

Lectures at the „Escuela Mexicana de Astrofísica 2002"
July 31 to Augst 7, 2002
by Rainer Schwenn, MPAe Lindau

3. Solar wind and corona in 3D

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- A new understanding of heliospheric rotation
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