Slow Solar Wind

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Outline of the talk

- Flows in the Solar Corona
- Solar Wind: Types and Origin
- Slow Solar Wind – near Sun Observations
- Slow Solar Wind – LASCO-C1 observations
- Slow solar wind – models
- Summary

Introduction

Flows in the solar corona:

- slow solar wind (*v ~ 400 km/s*); source: streamers (?)

- fast solar wind *(v ~ 700 km/s*); source: coronal holes

- coronal mass ejections (*from v < 100 km/s to v> 2000 km/s*); source: active regions, erupting filaments/prominence etc.

Solar Wind: First observations

S. Chapman and V. Ferraro proposed in 1931 that *bursts of particles emitted from the Sun would cause brief compression of the Earth's magnetic field called the SSC (Sudden Storm Commencement)*, often preceding large geomagnetic disturbances called magnetic storms. According to their model (now known to be erroneous), ***solar wind would only occur temporarily in connection with flares or other specific solar phenomena.***

In 1951 L. Biermann studied cometary tails and showed that the pressure of solar radiation alone can not explain his observations. ***Biermann suggested that solar wind exists always and essentially affects the formation of cometary tails.*** His estimate of about 500 km/s for the velocity of the continuously blowing solar wind, based on his observations of cometary tails, proved later to be amazingly accurate.

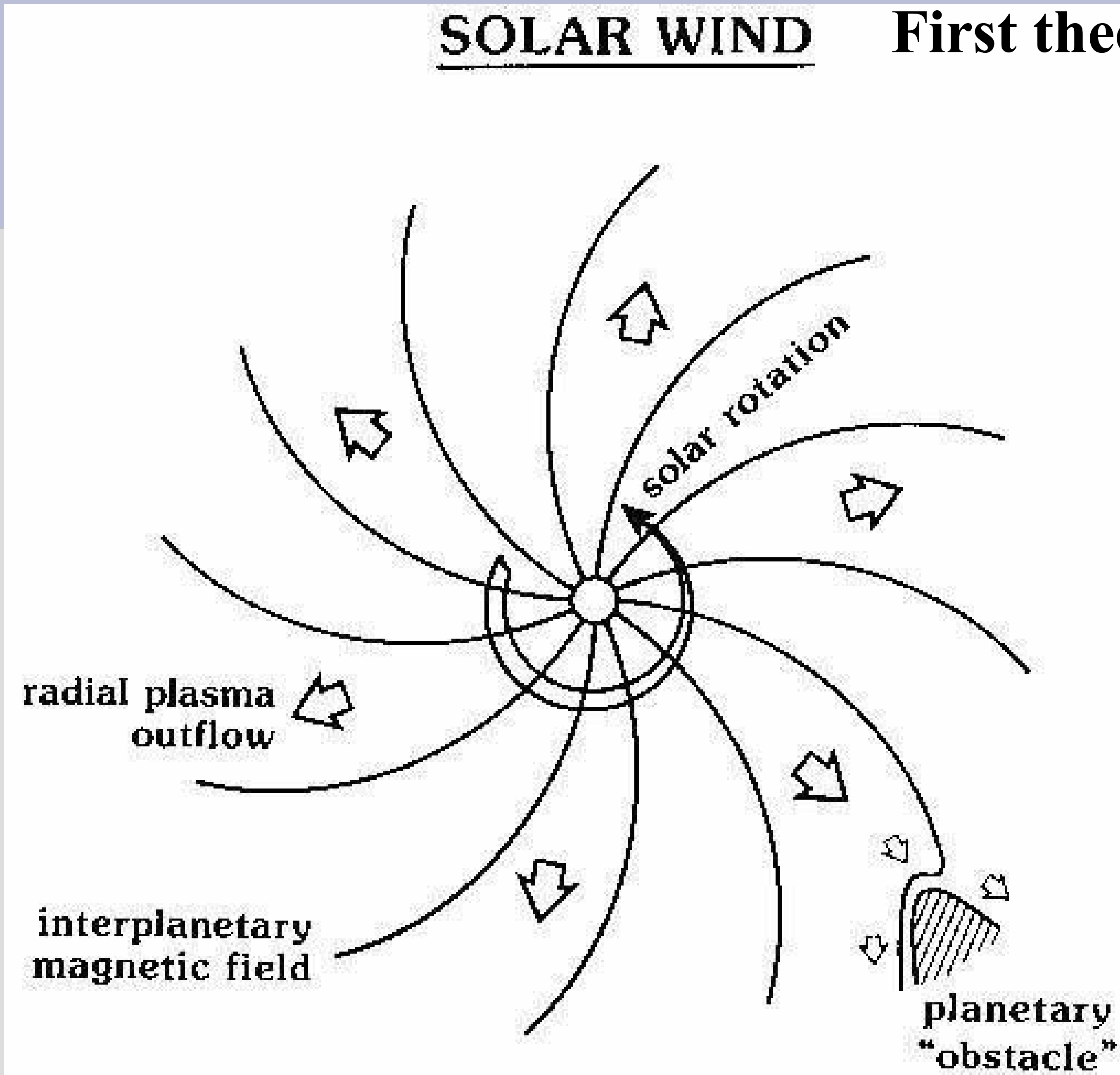
Solar Wind: First observations

This photo was taken by Roger Lynds at Kitt Peak, Arizona, on the morning of 1965 October 29.

The existence of solar wind was finally proven by the Soviet Lunnik-2 and 3 probes in 1960 after reaching out from the Earth's magnetosphere.

Moreover, the Mariner-2 probe confirmed the continuous flow of solar wind during its 4-month trip to the planet Venus in 1962.

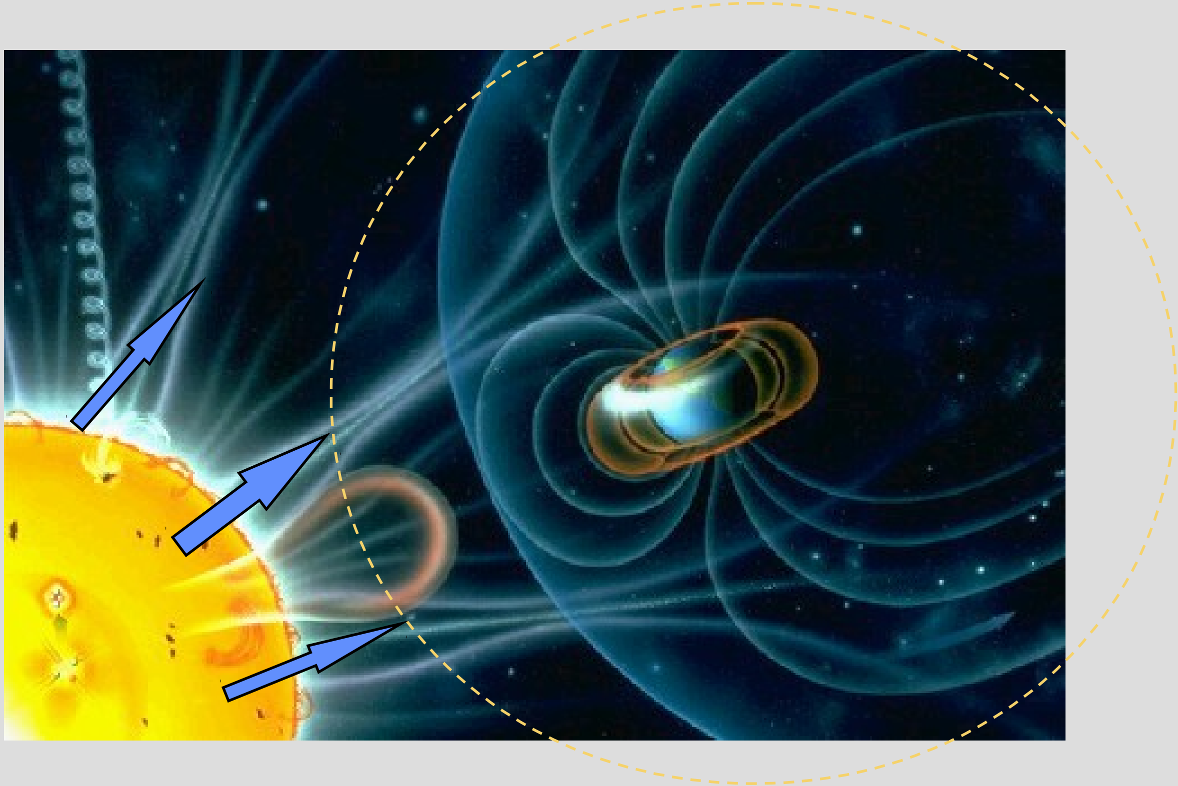
First theoretical approach



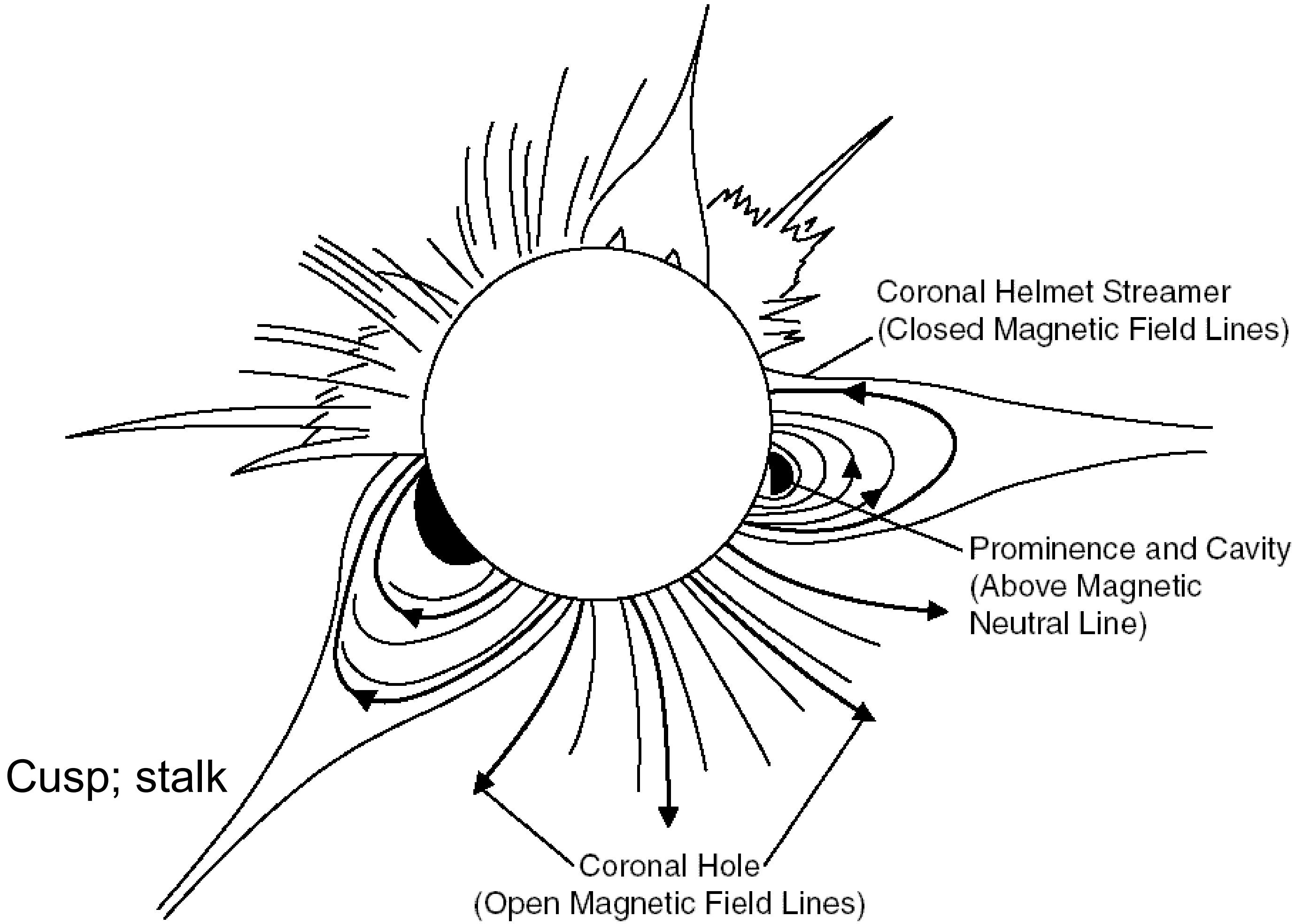
Parker 1958

The Solar Wind

A continuous flux of particles (ionized hydrogen (electrons and protons) with an 4% component of helium and trace amounts of heavy ions) which flows from the solar corona (T ~ 1MK) into interplanetary space.



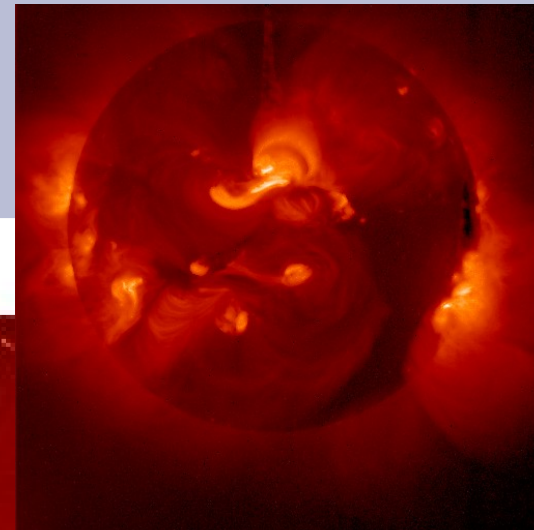
Flows in the solar corona: Sources

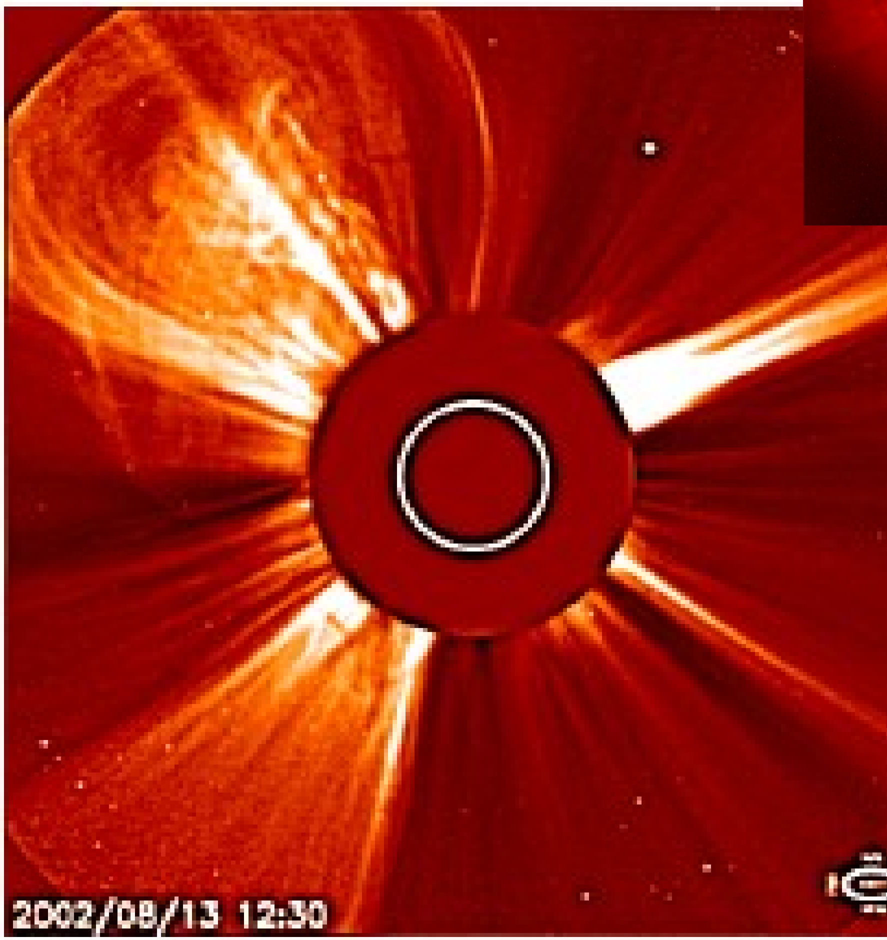


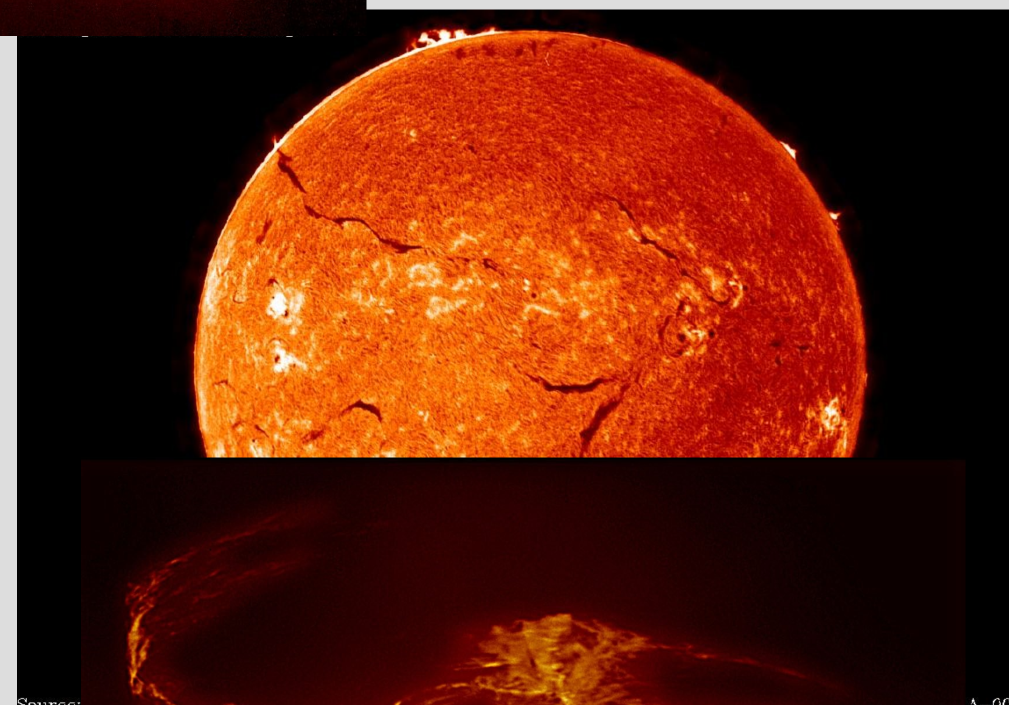
More realistic sketch of the structure of the corona and its presumed magnetic field. Adapted from Hundhausen [1995].

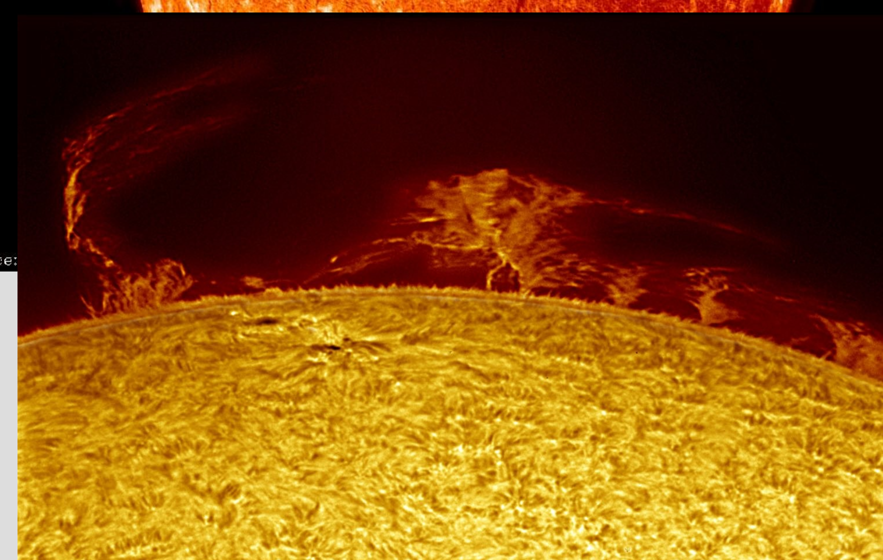
prominences

CMEs: Source Regions

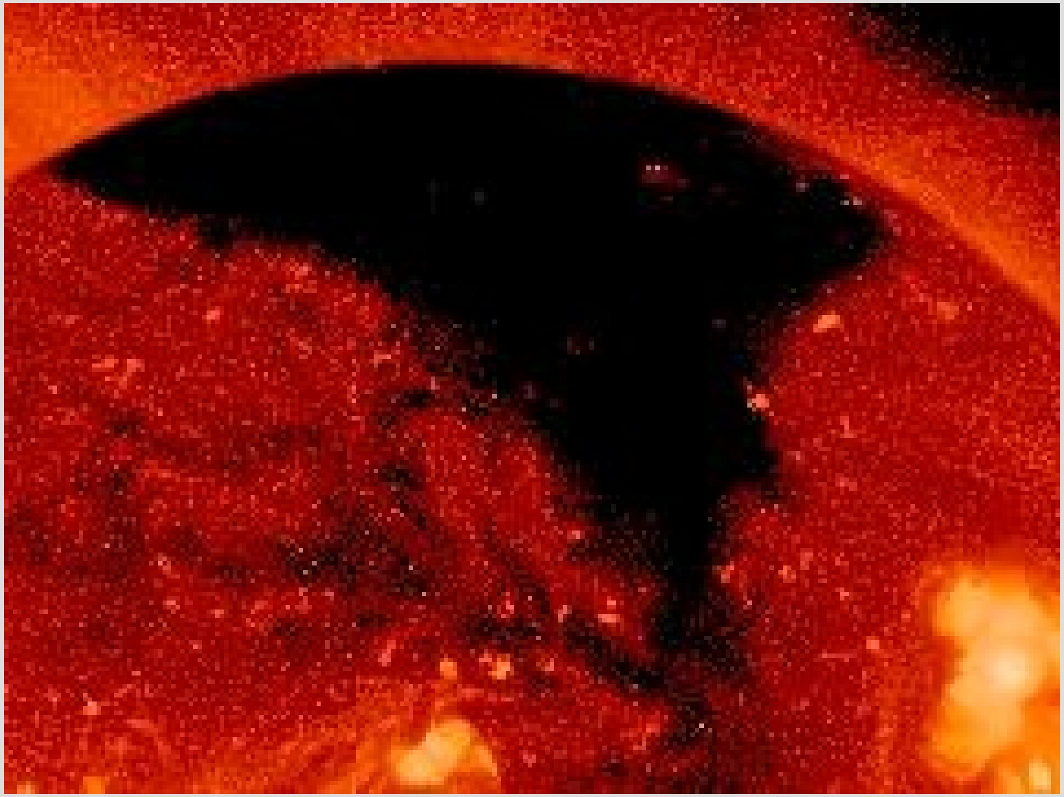








Fast Solar Wind: Source Region

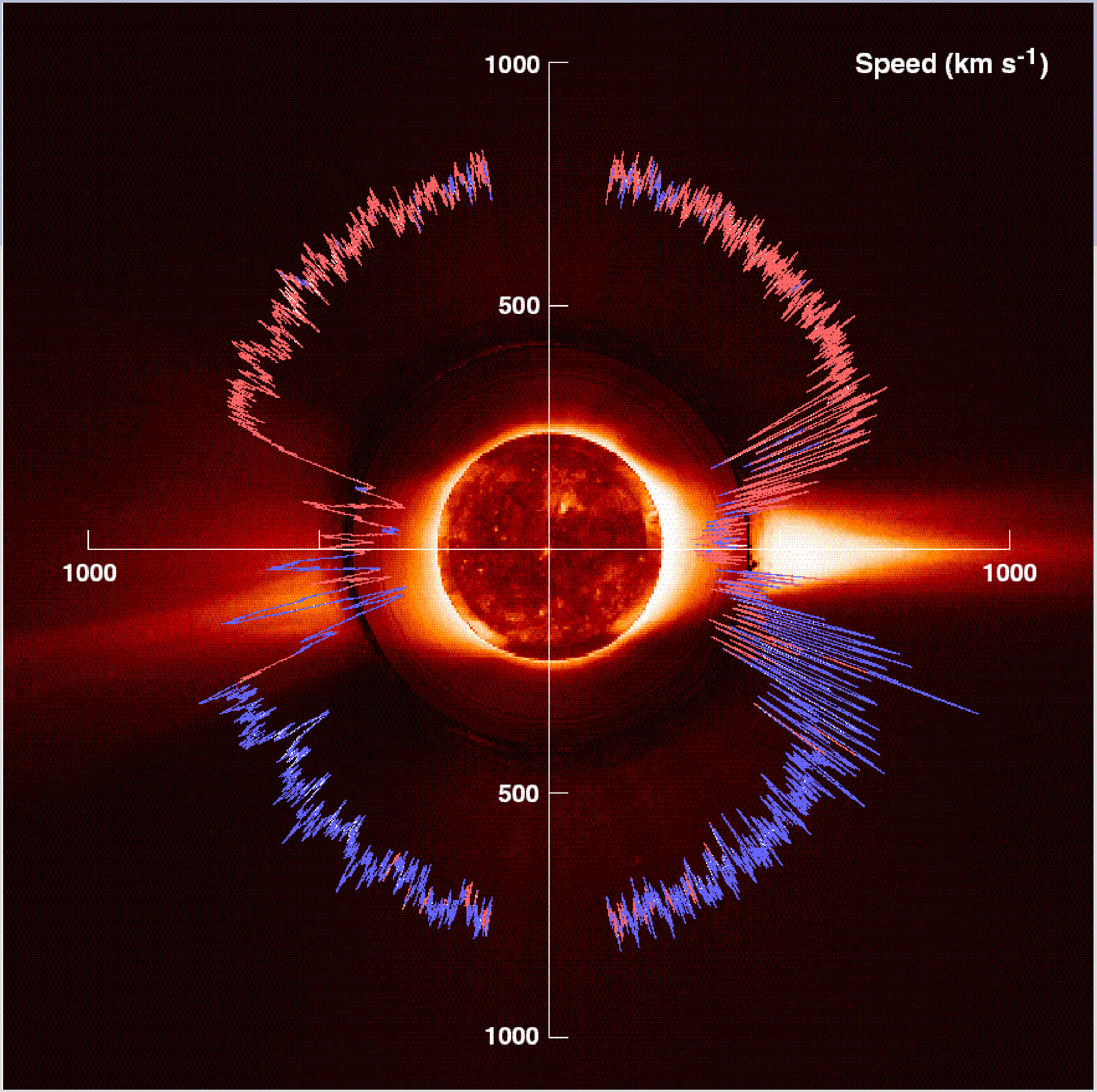


SXT/Yohkoh
(December, 2001)

The Solar Wind: properties

	Slow Wind	Fast Wind
Flow Speed V_p	250-400 km s^{-1}	400-800 km s^{-1}
Proton density	10.7 cm^{-3}	3.0 cm^{-3}
Proton flux density $n_p \cdot V_p$	$3.7 \cdot 10^8$ cm^{-2} s^{-1}	$2.0 \cdot 10^8$ cm^{-2} s^{-1}
Proton temperature T_p	$3.4 \cdot 10^4$ K	$2.3 \cdot 10^5$ K
Electron temperature T_e	$1.3 \cdot 10^5$ K	$1.0 \cdot 10^5$ K
Momentum flux density	$2.12 \cdot 10^8$ dyne cm^{-2}	$2.26 \cdot 10^8$ dyne cm^{-2}
Total energy flux density	1.55 erg $cm^{-2}s^{-1}$	1.43 erg $cm^{-2}s^{-1}$
Helium content	2.5%, variable	3.6%, stationary
Sources	Streamer belt	Coronal holes

Average solar wind parameters at 1AU, for the time around solar activity minimum (Schwenn 1999).

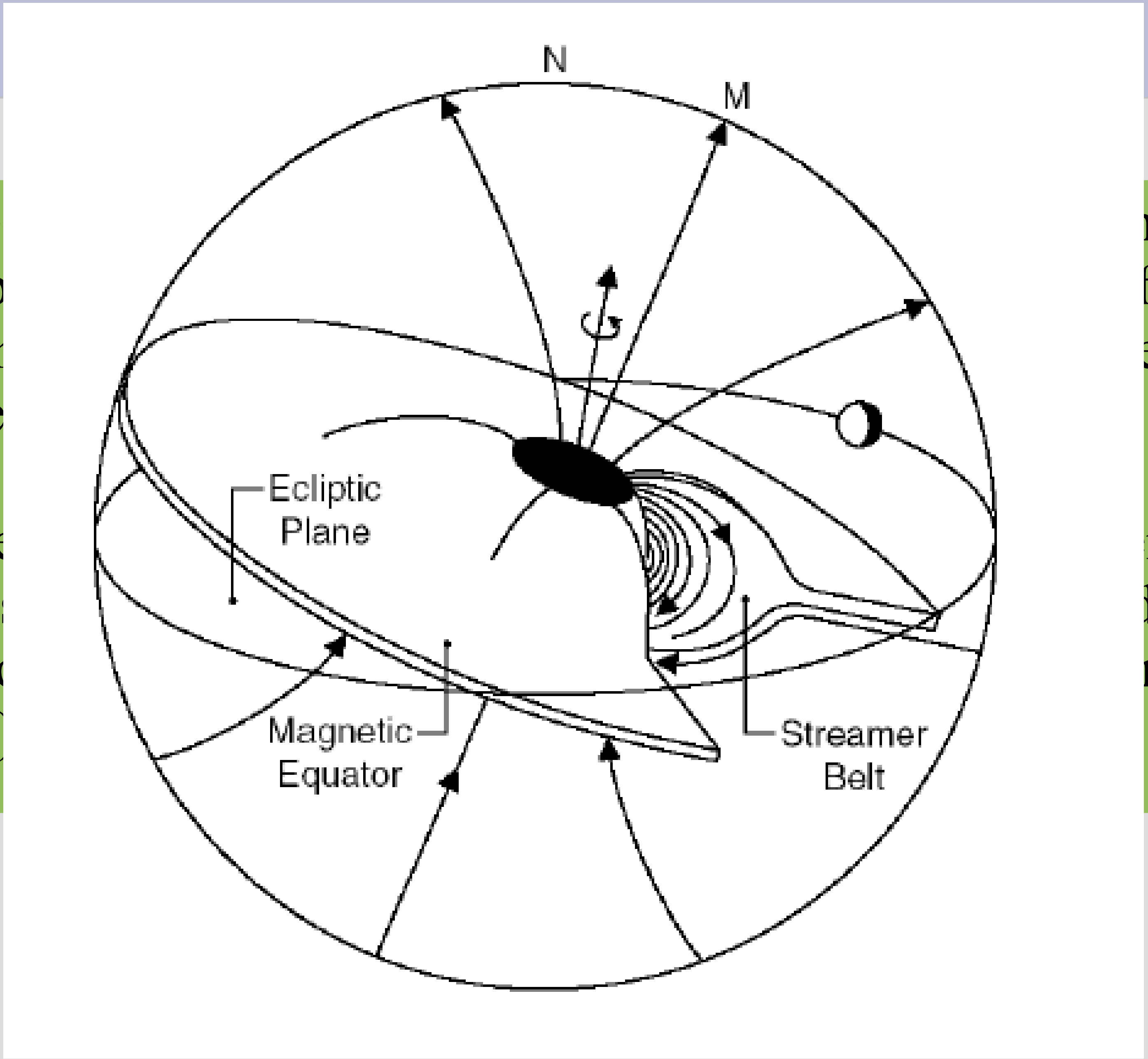


Speed (km s^{-1})
1000
500
1000
1000
500
1000

Slow Solar Wind (SSW): Near Sun Signatures

- Streamers are the prominent bright features in coronagraph images of electron-scattered white light emissions from the corona (e.g. Koutchmy and Livshits 1992).
- They overlie neutral lines where the large-scale magnetic photospheric field reverses the sign.
- The inner regions within about 2.5 R from the Sun center are believed to have closed magnetic fields, while the surrounding outer regions and the nearly radial extensions are believed to be regions with open magnetic fields.

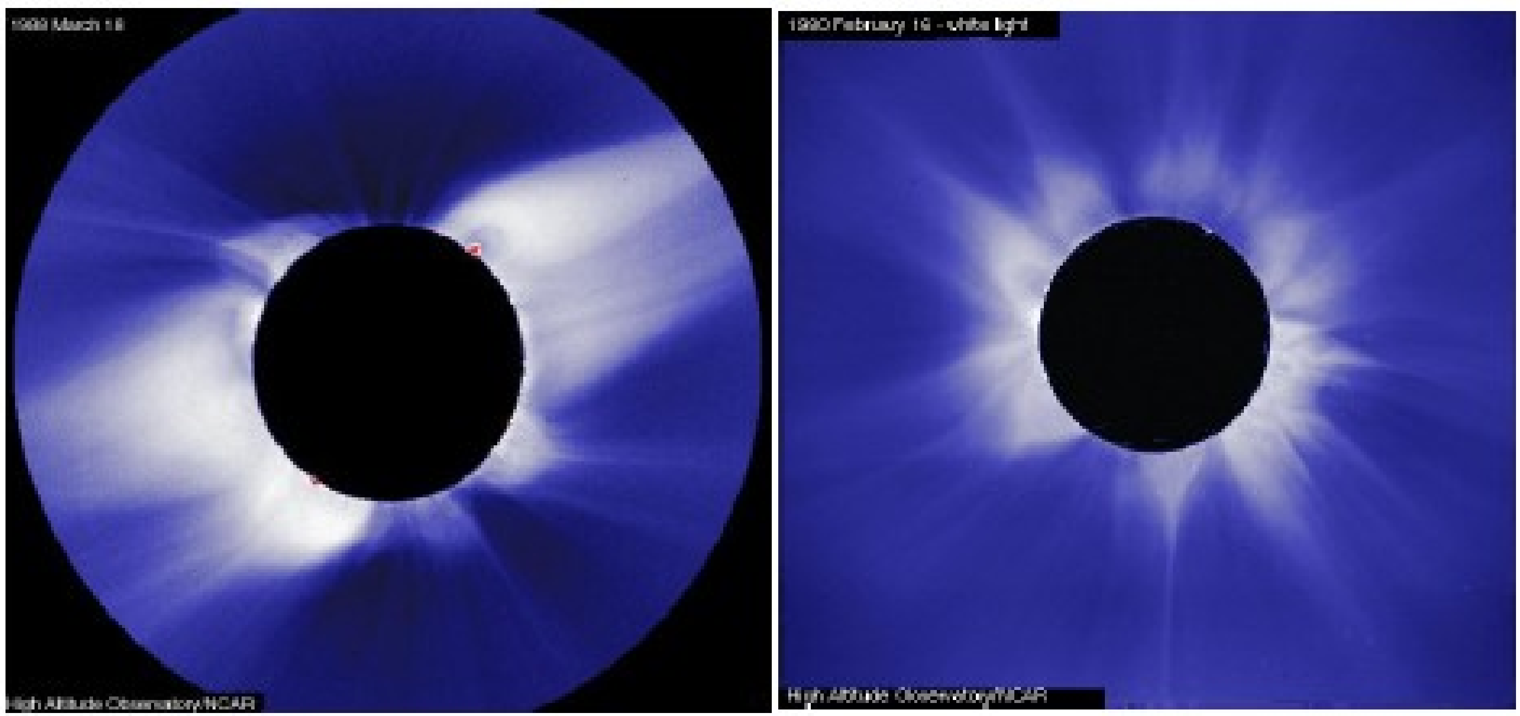
Slow Solar Wind (SSW): In-situ Signatures



- The ... streamers, comp... favor of the origi... elements are deple...
- Exte... nt the field rever... edge-on in the c... ments (Woo 1997)...

Observations of the SSW - streamers

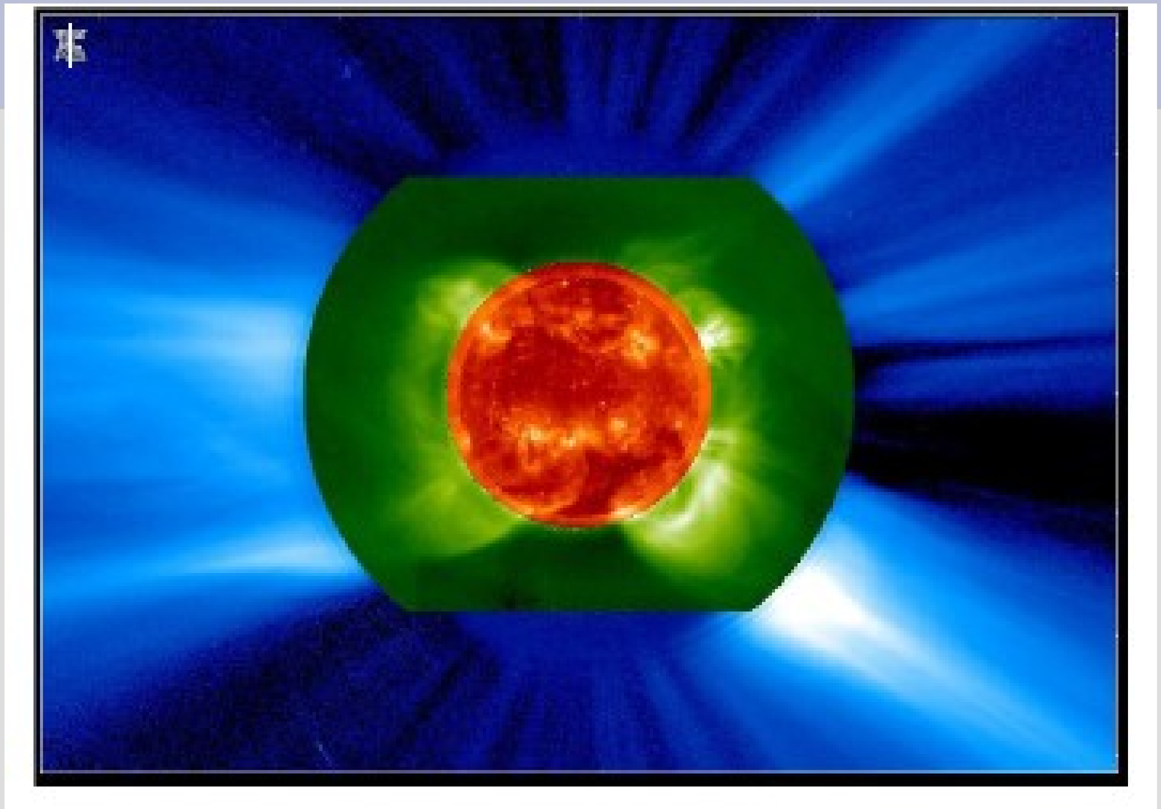
- white-light (*eclipses*):



The solar corona during the 1988 solar eclipse (left) and the 1980 solar eclipse (right).

Observations of the SSW - streamers

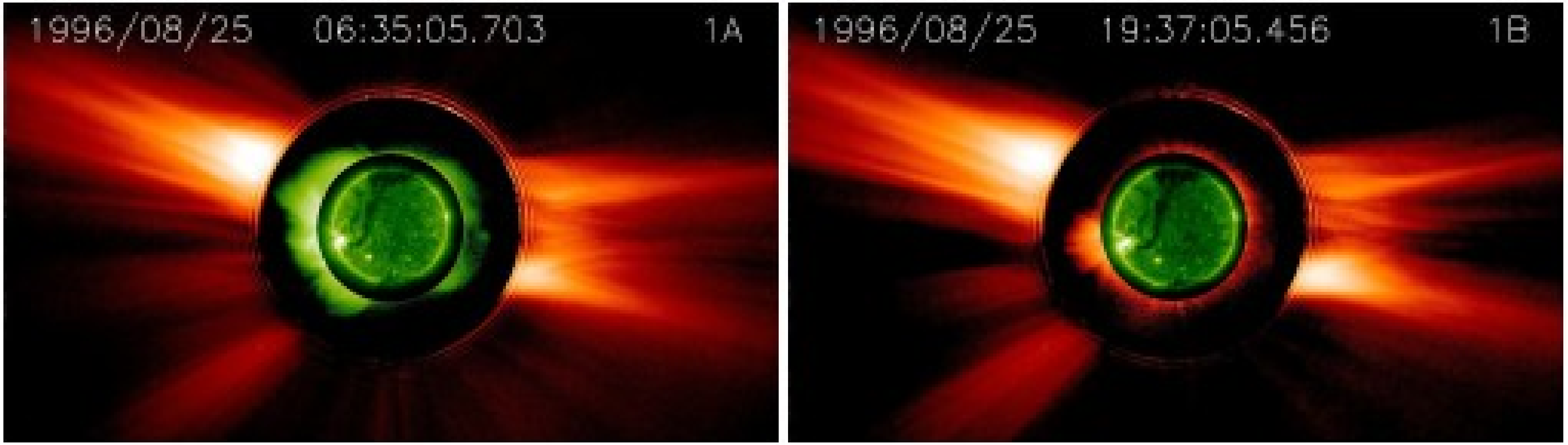
- white-light (*coronagraphs*):



The solar corona as seen by three instruments of SOHO (EIT (at center), C1 and C2. The EIT image shows the corona in UV light with the bright regions representing the active regions on the Sun. The LASCO-C1 image is taken in the line of Fe XIV (green) and shows the ions around the magnetic field lines (loop structures). The LASCO-C2 image (blue) shows the extended white light corona in the form of rays and helmet streamers.

Observations of the SSW

- more streamers



Observations of the SSW

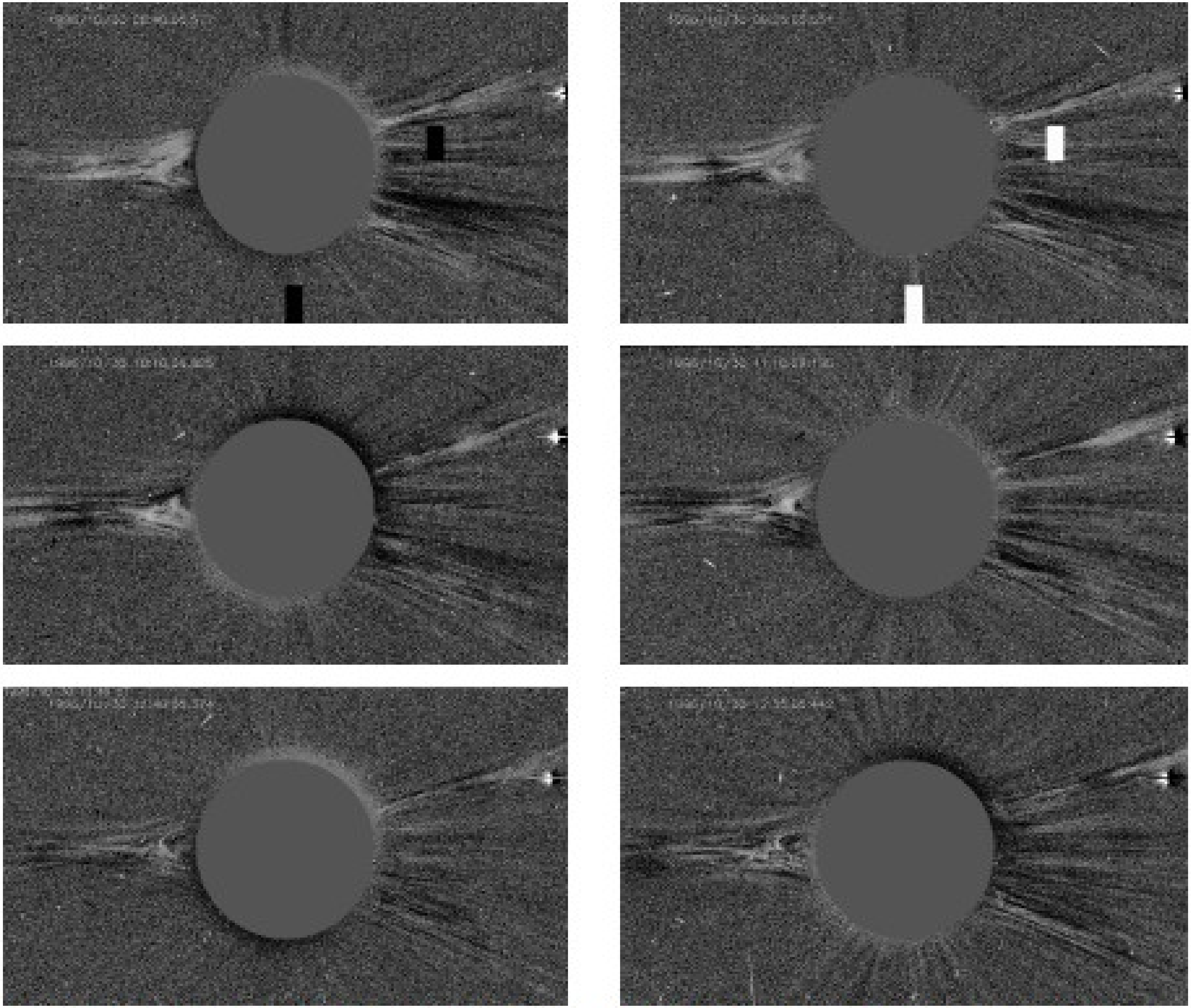
Blobs - *Sheeley et al. 1997*

Data from LASCO-C2 and C3 coronagraphs.

- bright ”blobs” moving out almost radially from the stalk of the streamers.

- blobs are characterized by low speeds and are continually emitted from the elongated tips of helmet streamers at 3 - 4 R from the Sun center.

- they start with speeds between 0 and 100 km/s and accelerates to speeds of 250 - 400 km/s in the outer part of the C3 field of view.



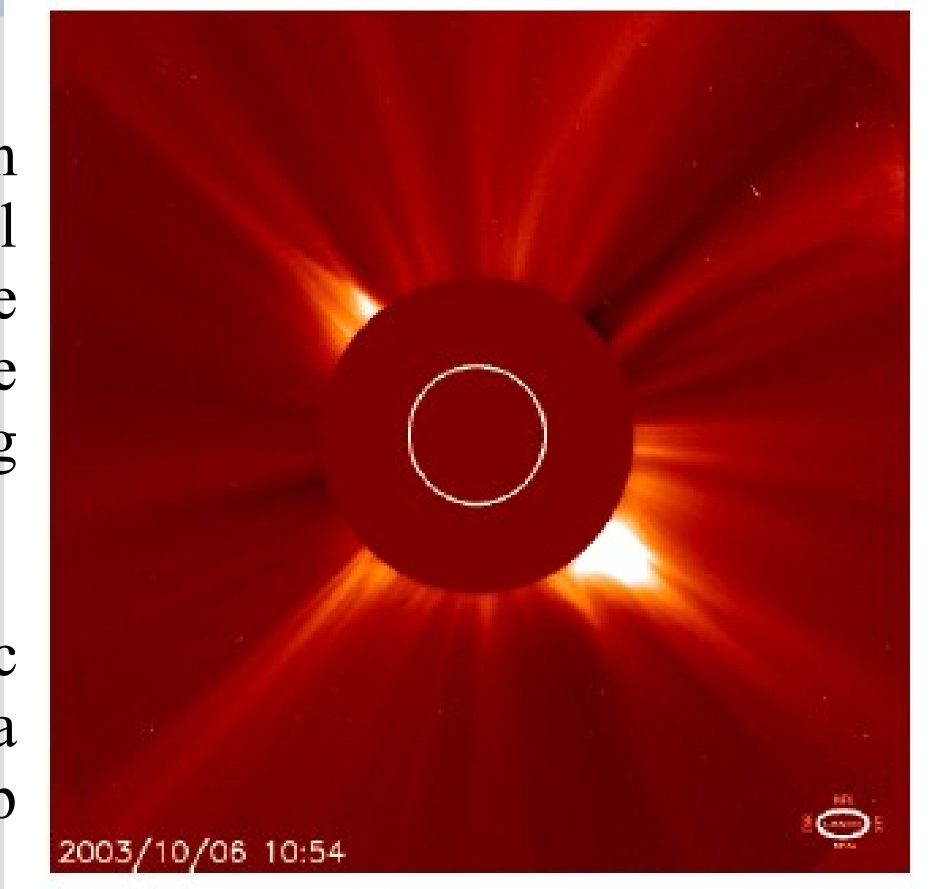
Running differencing of LASCO/C2 images, on 30th of October 1996, showing an elongated blob moving out on NW part of the Sun(08:40,09:25,10:10,11:10,11:40,12:35 UT)

Observations of the SSW

Rays - *Eselevich et al. 2001:*

- the rays are newly reconnected, open magnetic field lines carrying material that was originally trapped inside the closed helmet streamers. The blobs are small density inhomogeneities along these rays.

- the solar wind inside the ray (magnetic tube) represents a collisional plasma flow along the magnetic field at least up to $h < 5$ Rs.



Observations of the SSW

Raymond et al. 1997, Noci et al. 1997: UVCS observations – flows along the flanks of the streamers (the regions of open magnetic field lines near the streamer-coronal hole boundary) (d > 1.5 Rs).

Woo, 1997: radio occultation measurements (Voyager): flows from the stalk of the coronal streamer (d > 2.5 Rs).

Habbal et al., 1997: radio occultation measurements and ultraviolet observations (UVCS): the streamer stalks are the locus of the slowest solar wind.

Observations of the SSW

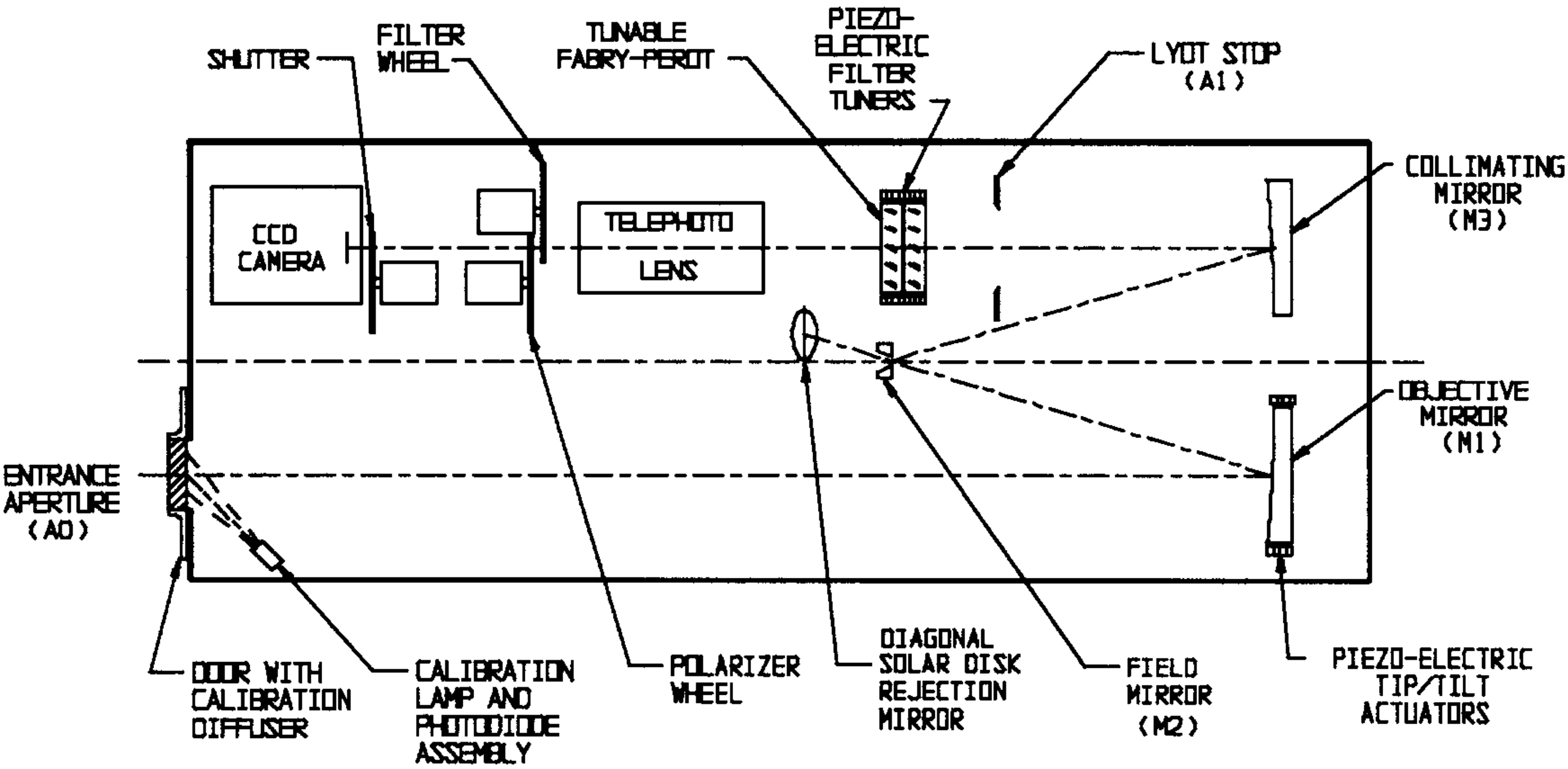
Abbo et al. 2003: UVCS data: likely sources of the slow wind:

1) the regions along the axis of streamer above 2.3 - 2.7 R and/or

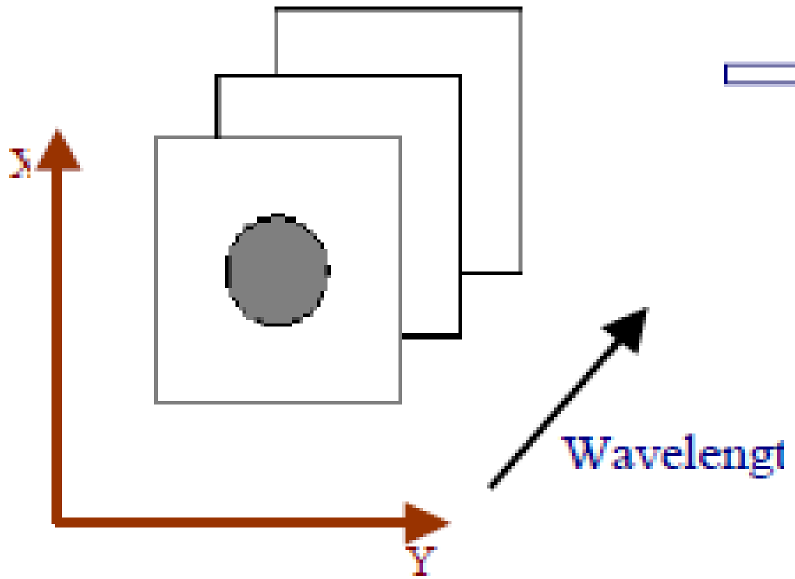
2) regions along and adjacent to the streamer boundary defined as 1/e O VI intensity contour level beyond 1.7 R.

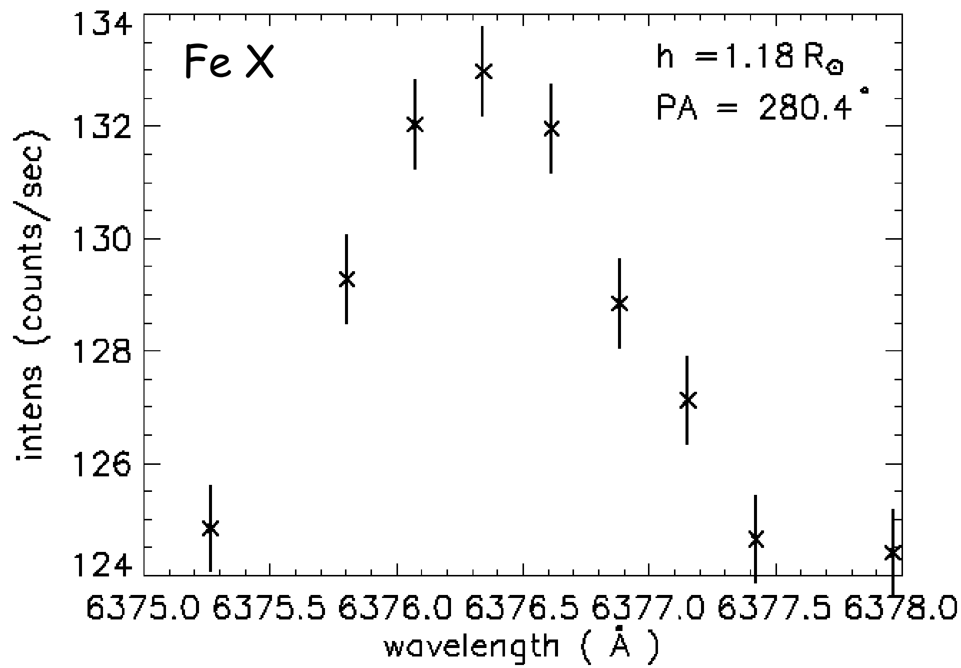
Strachan et al., 2002: UVCS + LASCO: streamer stalks (beyond the cusp) are sources of material for the bulk of the SSW at solar minimum.

SSW: LASCO-C1 The Instrument



SSW: LASCO-C1 data





Mierla et al. 2005

Line profile from a region on the Sun on 2nd of August 1996.

Determination of LOS Velocities

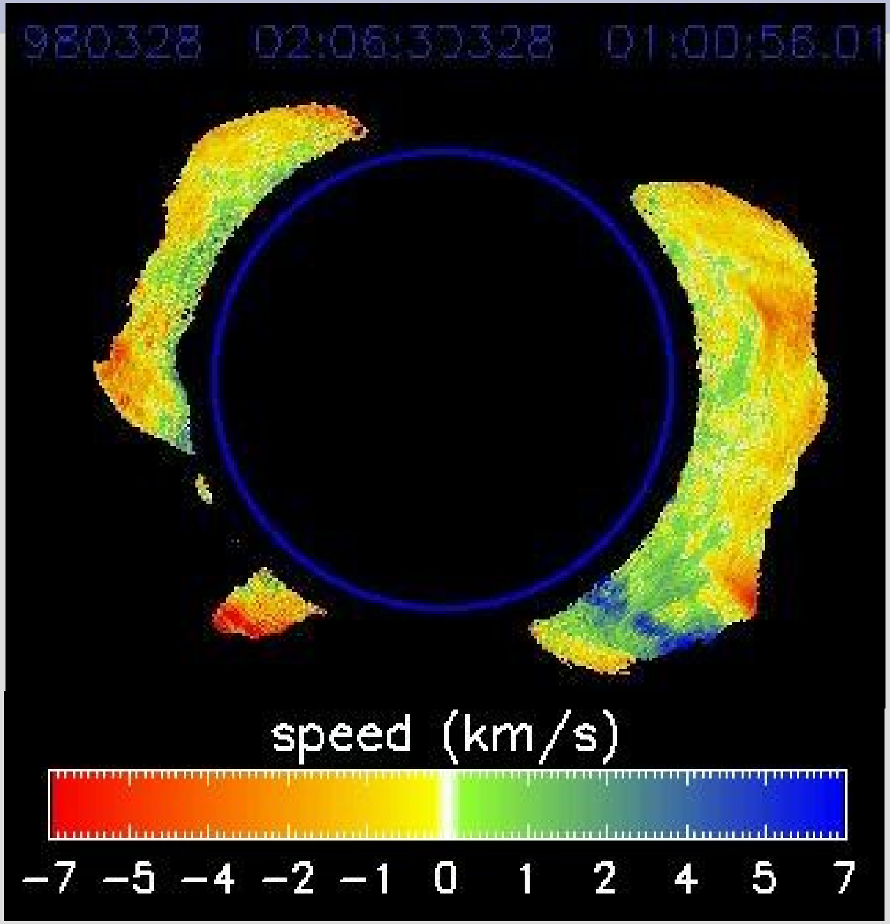
from the position of the emission line peak with respect to the reference line peak (average over the whole corona)

=> LOS velocities

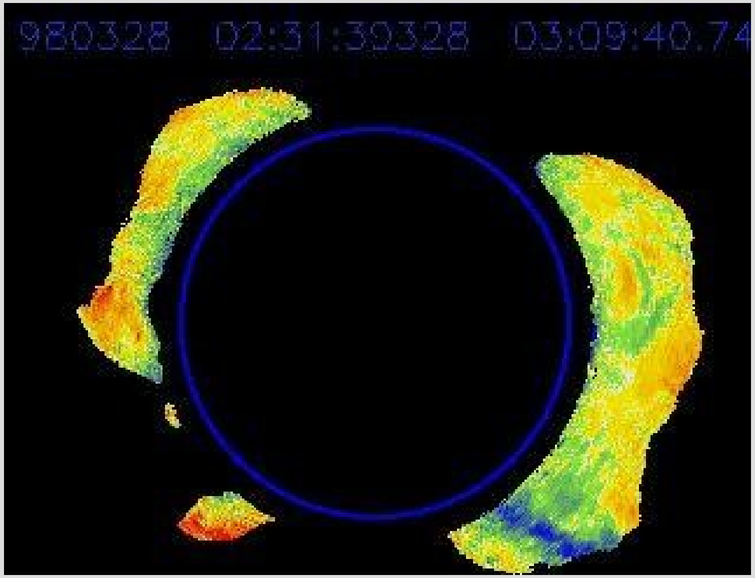
(0.1 Å ~ 5.6 km/s)

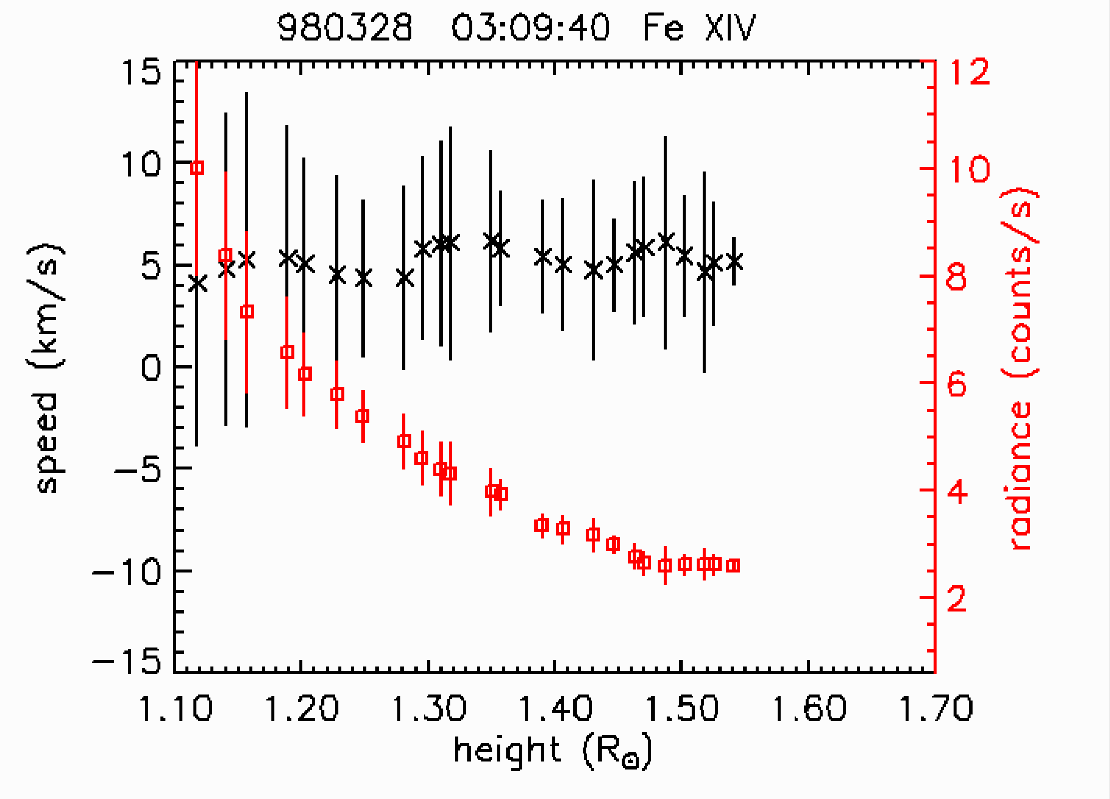
(0.1 Å ~ 4.7 km/s)

rotation of the solar corona compensated



Streamer - 1998



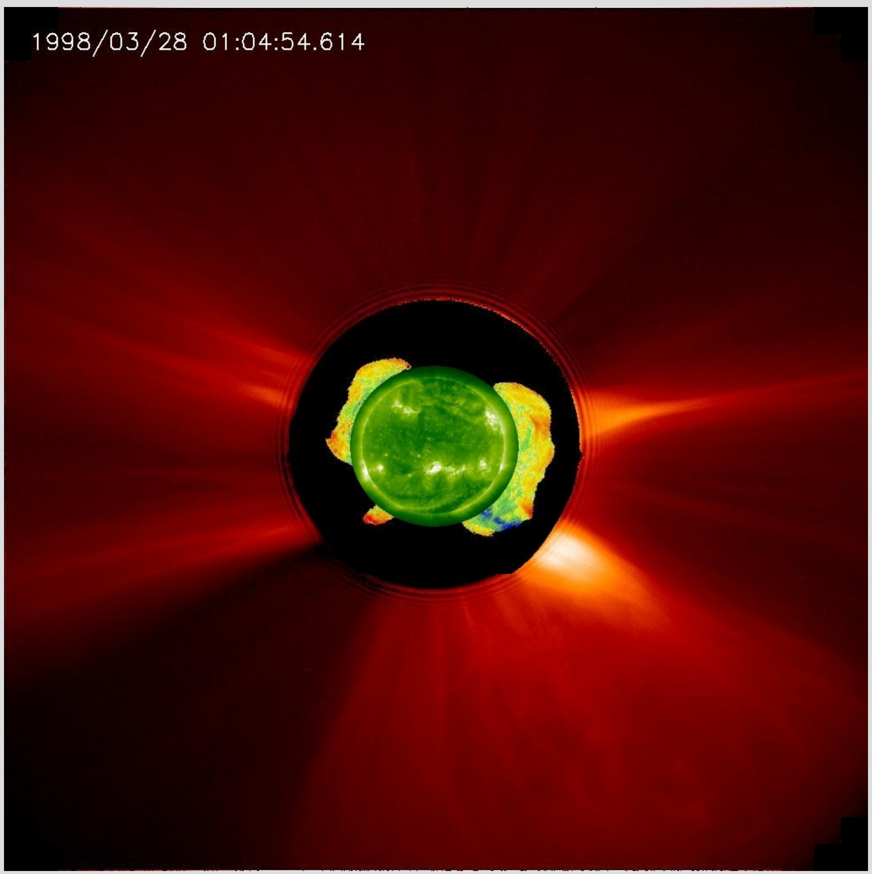


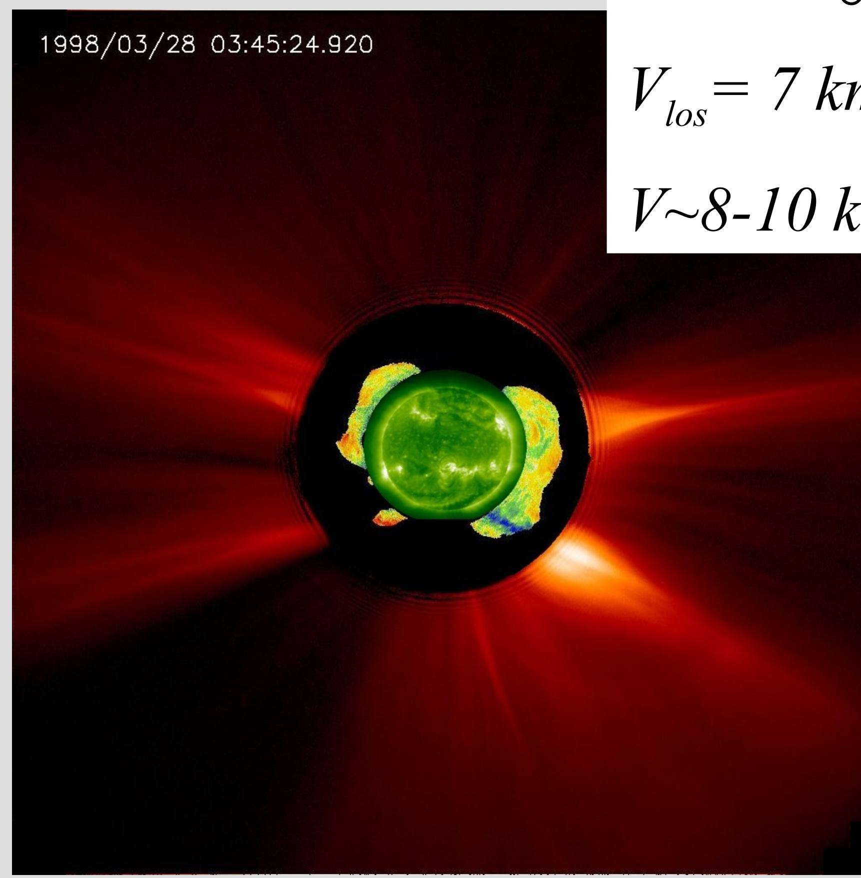
Streamer - 1998

$d = 1.3\ R_\odot$

$V_{los} = 7\ km/s$

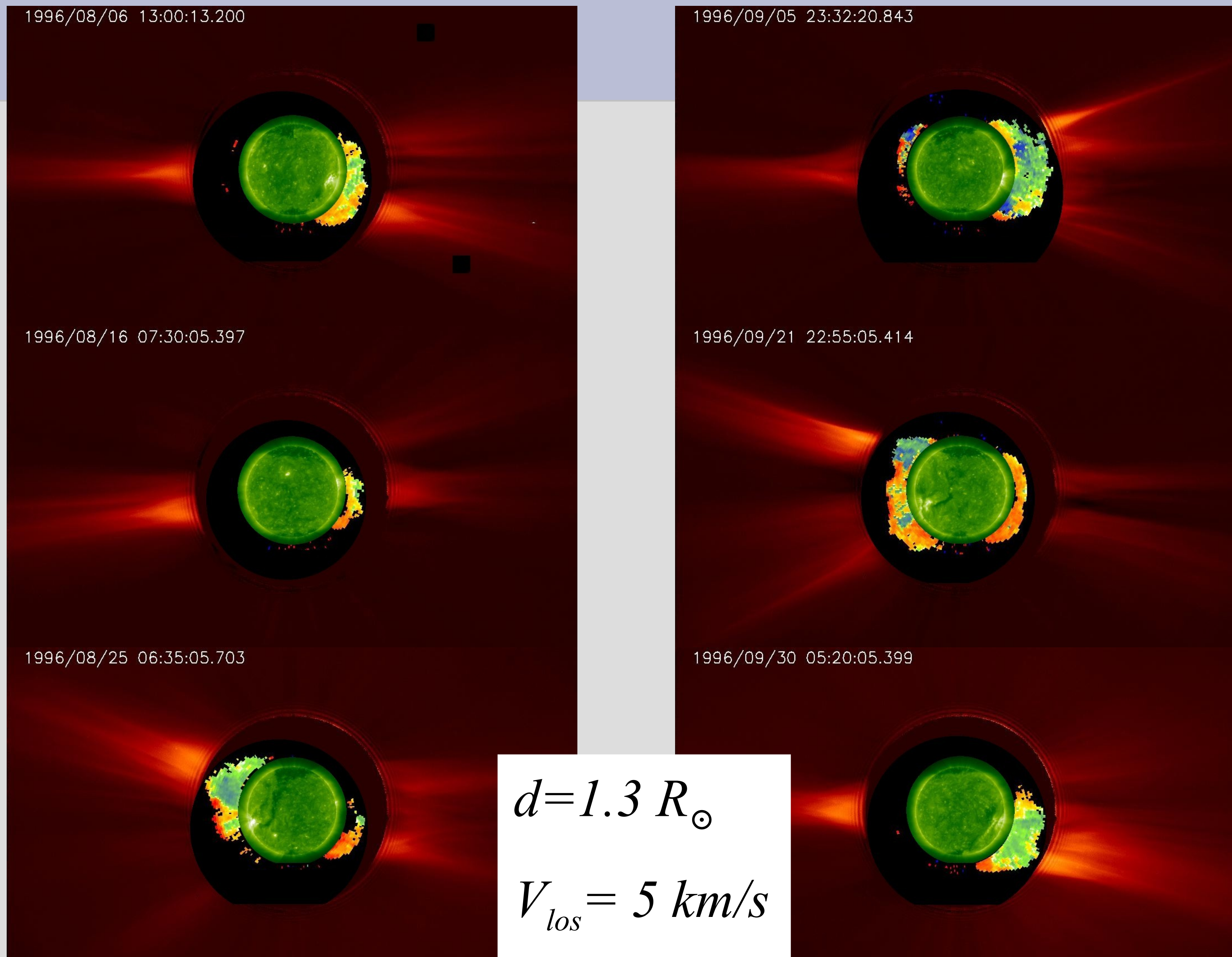
$V \sim 8\text{-}10\ km/s$





Combined EIT, C1 speed map and C2 images.

Streamers - 1996



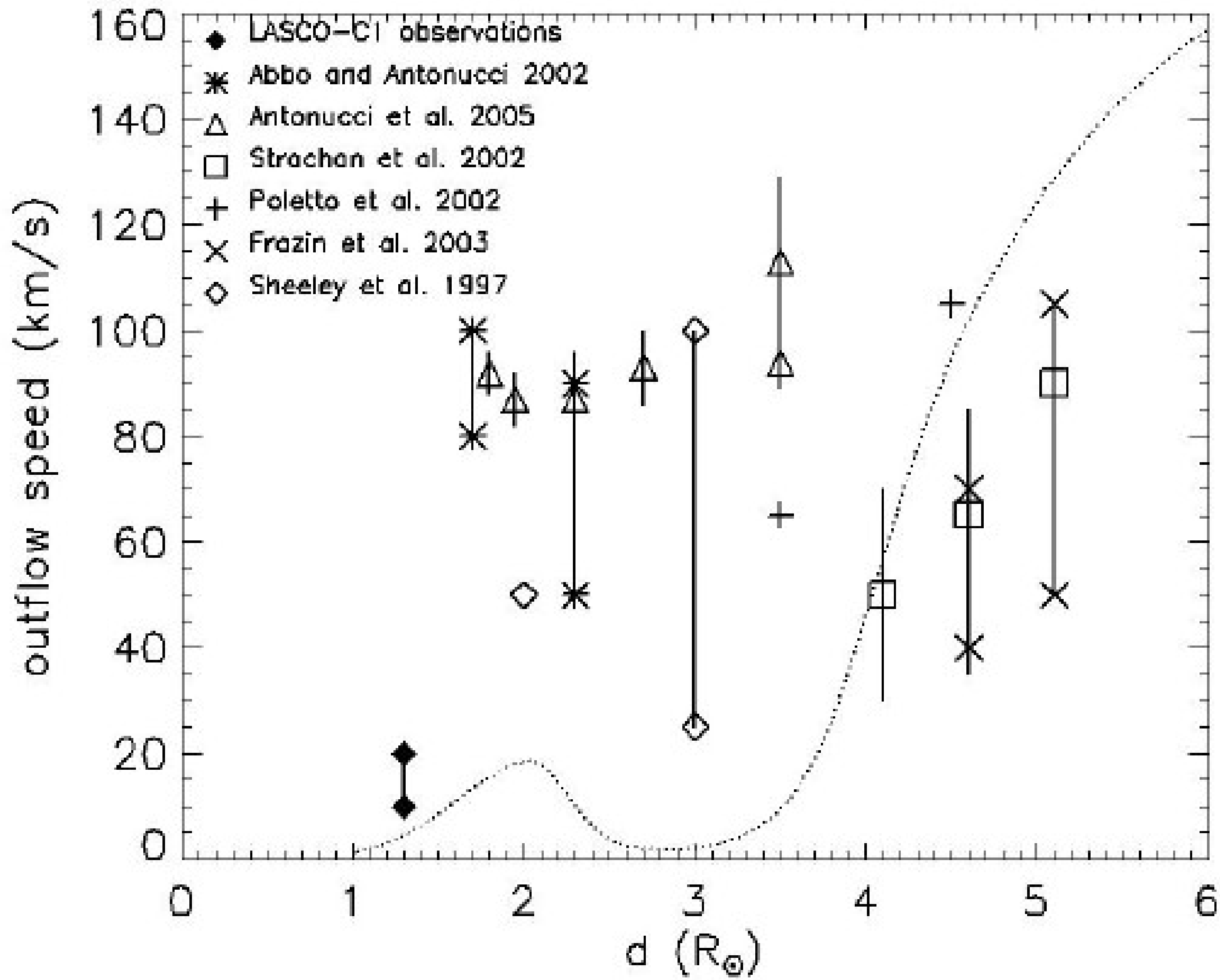
$d = 1.3\ R_\odot$

$V_{los} = 5\ km/s$

$V = 15\ km/s$

Mierla et al. 2007

Flows in the solar corona

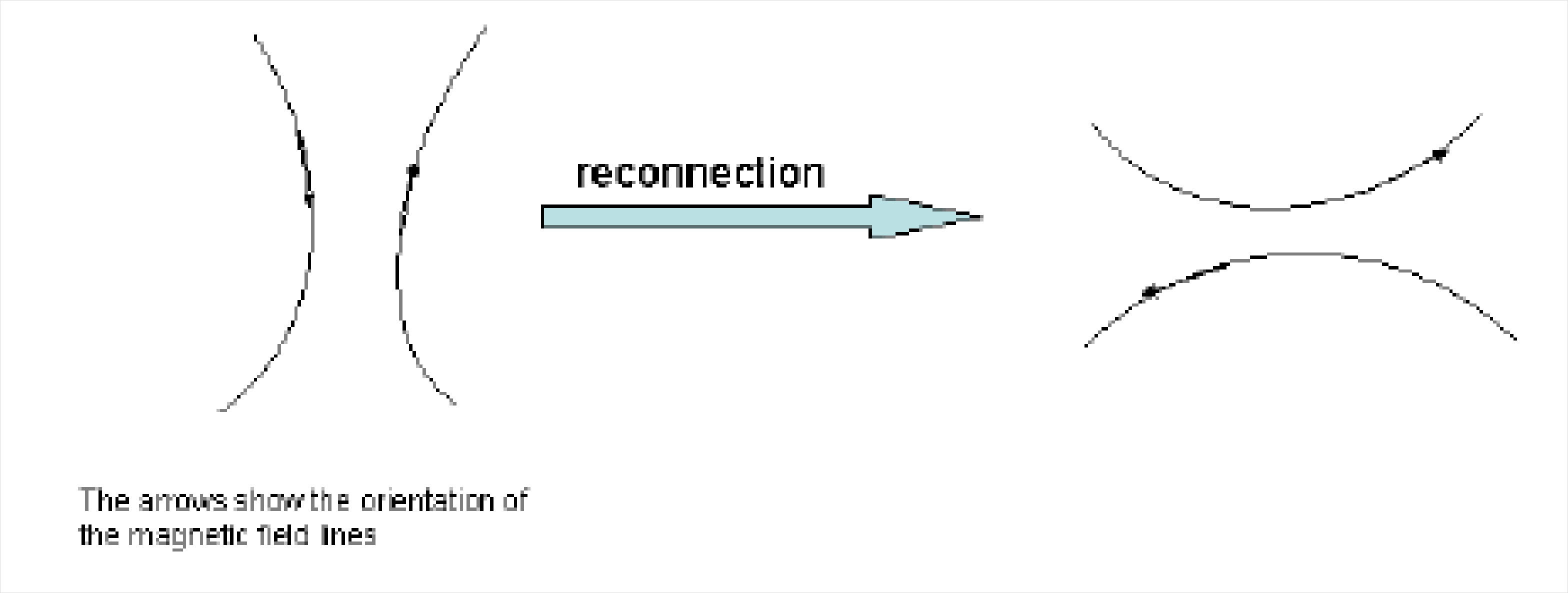


Mierla et al. 2008

The outflow velocities as observed with LASCO-C1, LASCO-C2 and UVCS at different heights in the corona. The dotted line indicate the theoretical speeds calculated by Chen and Li, 2004.

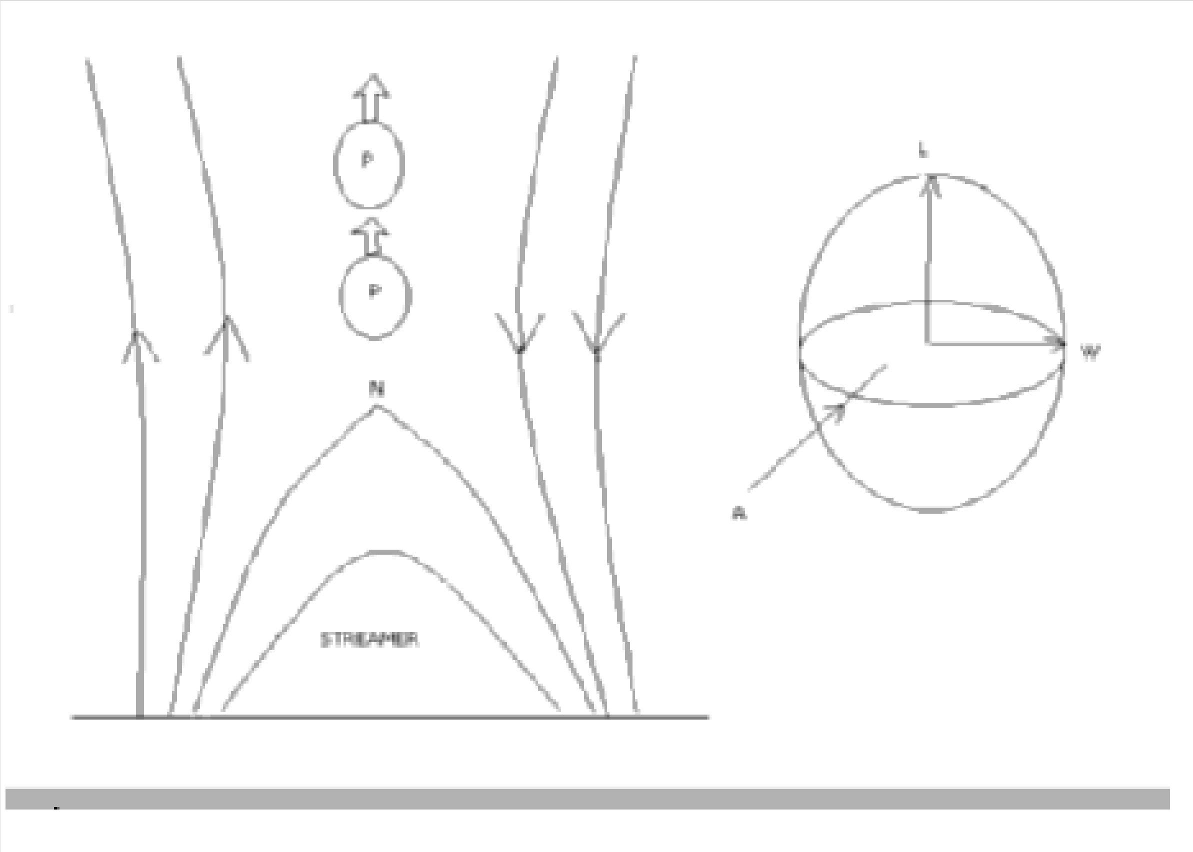
Slow solar wind-models

Wu & Wang, 2000
- a global coronal magnetic field model based on resistive MHD theory, which implies that the field topology will be changed due to the magnetic reconnection process (shown in the figure, for illustration)



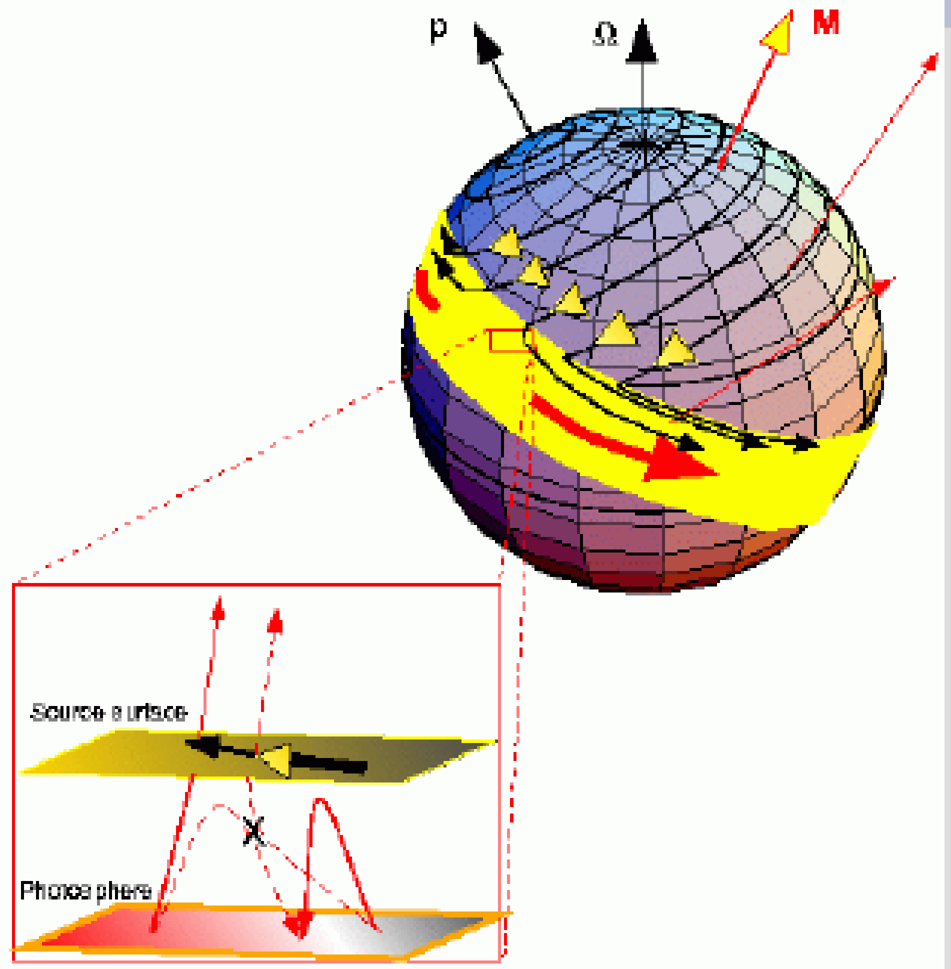
Slow solar wind-models

Schmidt 2000 - Model of accelerated plasmoids
-outward acceleration of the moving features close to the Sun is due to the magnetic forces associated with the solar wind magnetic field, and the decrease of their velocity toward solar wind speeds at larger heliocentric distances is due to aerodynamic drag forces.



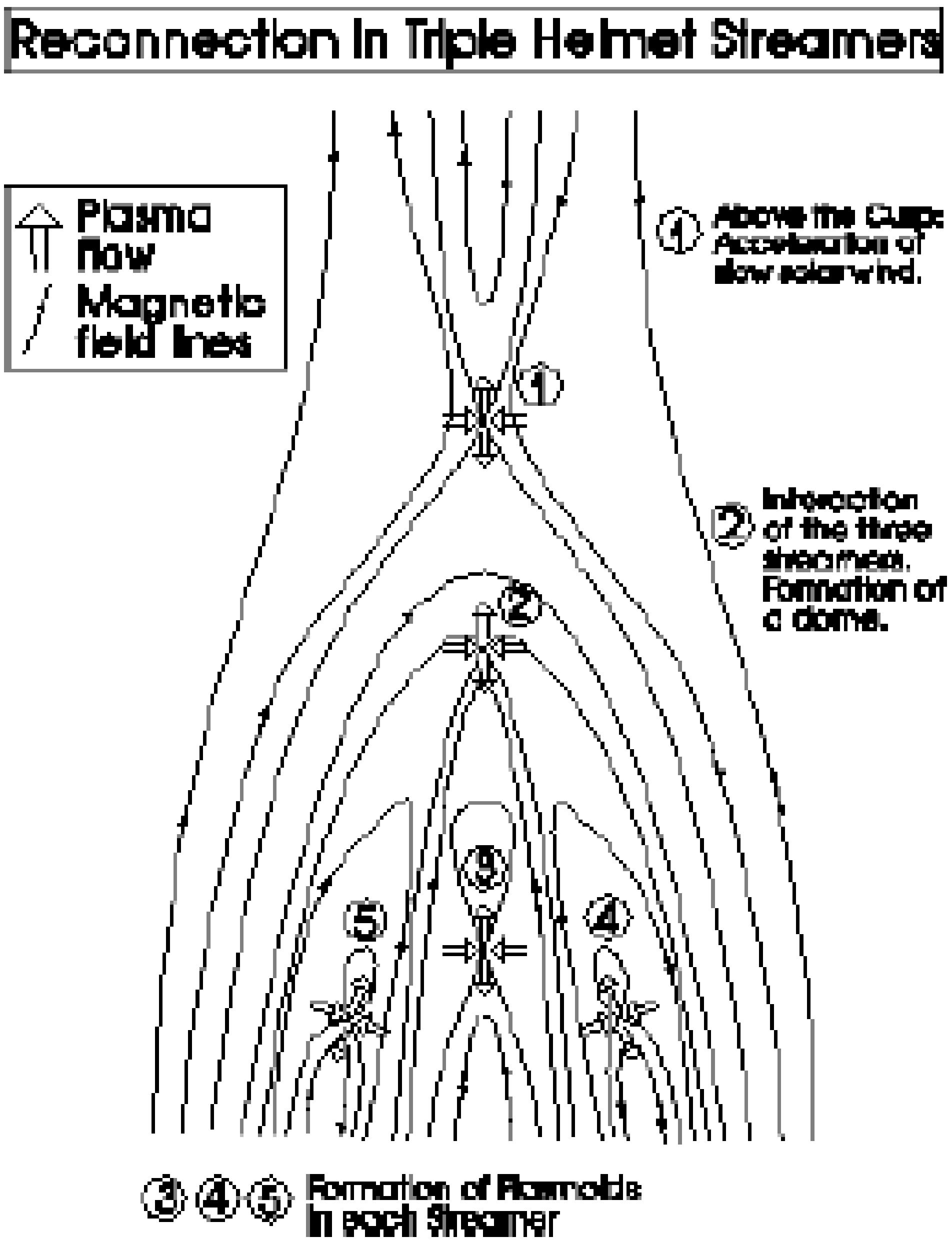
Slow solar wind-models

The model of ***Fisk (1996)*** is based on two effects: the differential rotation of the photosphere and the super-radial expansion of the magnetic field underneath the source surface. The interplay of these two effects leads to latitudinal excursions of the magnetic field lines. As a consequence, the polar magnetic field lines can ”diffuse” through the equatorial region and **reconnect** with closed magnetic field lines, releasing the plasma. Supposing that there are many different loops next to each other, this process leads to what is known as slow solar wind.



Slow solar wind-models

Wiegelmann et al. (1998, 2000) elaborate a model which explain the source of the SSW at minimum of solar activity.
Their results indicate that
a) the helmet streamer cusp transforms to a X-point and very small plasmoids are ejected into space.
b) small eruptions at the helmet streamer cusp may accelerate small amounts of plasma without significant changes of the equilibrium configuration and might that contribute to the non-stationary slow solar wind.



Summary

There are several theories and observations which try to explain SSW origin and mechanism.

It may originate:
a) at the level of streamer cusp (e.g. Sheeley et al. 1997, Strachan et al 2000),
b) in the regions surrounding the streamer, close to the streamer boundary (e.g. Fisk 1996, Ofman 2000) or
c) from both streamer cusp and streamer legs (e.g. Abbo et al. 2003).

The possible mechanisms are:
a) process of loop destabilization (e.g. Uchida et al. 1992).
b) plasmoid expulsion (e.g. Sheeley et al. 1997).
c) magnetic reconnection process (e.g. Fisk et al. 1998).

Mierla and Schwenn, 2012