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Solar Wind and Heliosphere

Luciano Rodriguez
Royal Observatory of Belgium

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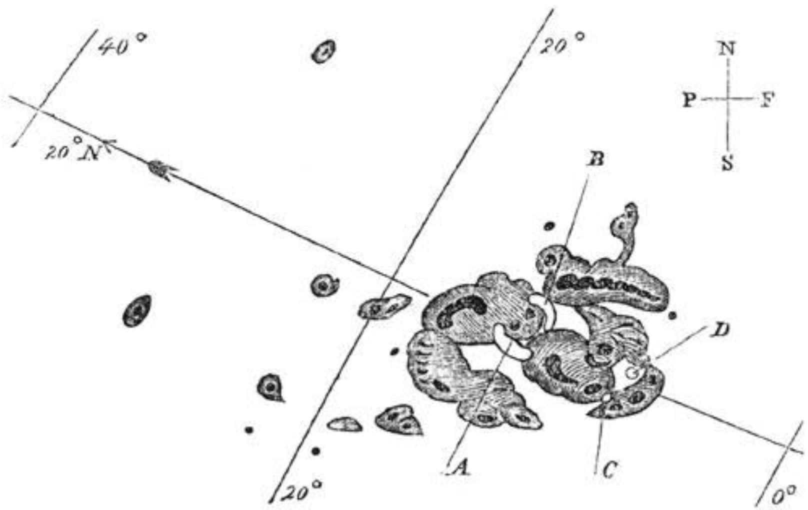
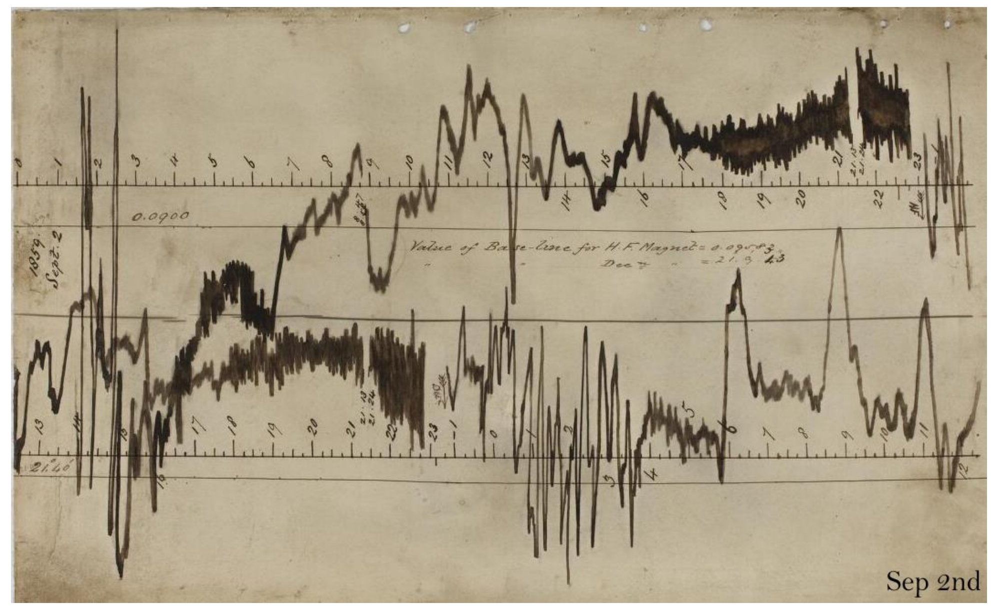
The solar wind, 1st hints of it

- Carrington - 1859



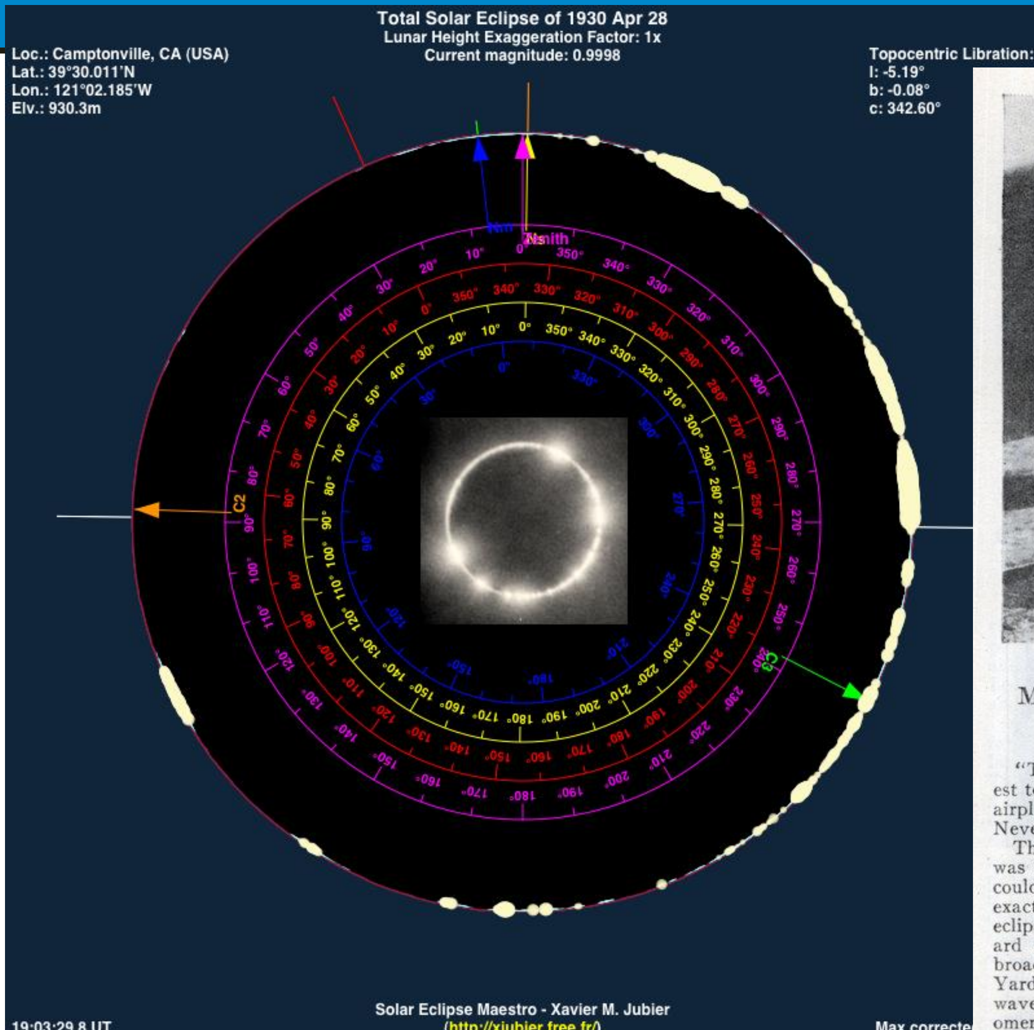
Carrington noticed two rapidly brightening patches of light near the middle of a sunspot group he was studying (A and B). In the following minutes the patches dimmed again while moving with respect to the active region, finally disappearing at positions C and D.

This unusual event was also independently observed by R. Hodgson, another British astronomer.



The 'Carrington Event' of 1859 Recorded at Greenwich Observatory, London

The solar wind, 1st hints of it



MAKE TALKING MOVIE OF LATEST ECLIPSE

"TALKING MOVIES" recorded the latest total eclipse of the sun from an Army airplane over Claremont Field, Calif. Never before had this been done.

The definite scientific object of the feat was to determine, more accurately than could be done with stop watches, the exact moment of each phase of the eclipse. The "talkie" part of the standard sound film recorded time signals broadcast from the Mare Island Navy Yard, picked up on the plane's long-wave receiver. Through them, astronomers can measure the exact time of each picture within one fifth of a second. Then they will use the data to correct their predictions of the next eclipse.

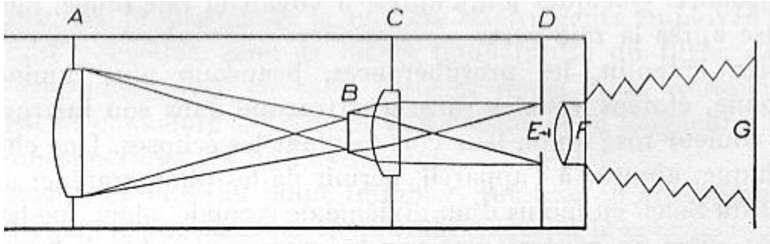
Often an eclipse of the sun may be observed for a half minute or more, but this one gave astronomers only one and three fifths seconds to take pictures of the total phase. Consequently members of ground parties rehearsed their parts in advance. When the moment of totality arrived, they fed plates into the cameras with the rapidity of a gun crew.

Here is what one camera got during the brief period of total eclipse at Camptonville, Calif.

the solar corona should be very hig
extends into space.

The solar wind, 1st hints of it

Lyot, with his coronagraph, calculated it to be 600 000 K (this was not accepted quickly).

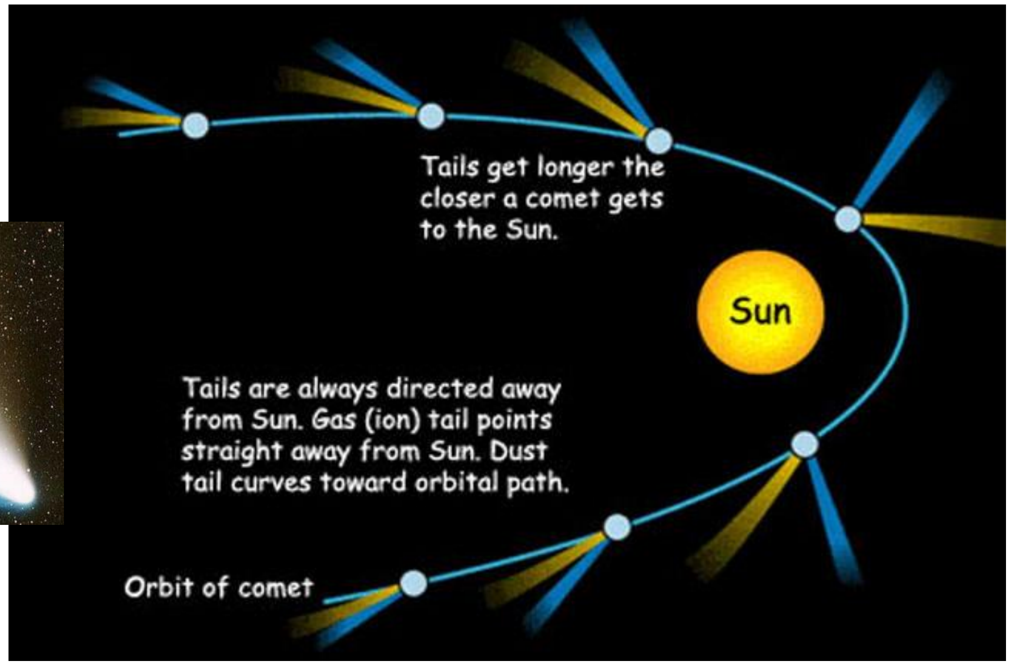


Spectroscopy explained that the until then element called "coronium" did not need to exist, the high coronal temperatures could be explained by the emission from highly ionized Fe.

In the 1950s Chapman calculated the properties of a gas at such a temperature: it would be such a superb conductor of heat that it must extend way out into space, beyond the orbit of the Earth

The solar wind, 1st hints of it

- 1940-50s Biermann noticed that comet tails always points away from the sun. He postulated that this happens because the sun emits a steady stream of particles that pushes the comet tail away.



- He suggested that gas is often flowing radially outward from the Sun in all directions from the sun with velocities ranging from 500 to 1500 km/s

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The solar wind, 1st hints of it

Solar Corpuscular Radiation and the Interplanetary Gas

GENTLEMEN,—

The object of this letter is to draw attention to the fact that there are strong reasons against the assumption, made in some recent papers, that a stationary interplanetary gas exists which contributes, for example, to the polarized component of the zodiacal light.

(1) The acceleration of the ion tails of comets (type I of Bredichin) has been recognized as being due to the interaction between the corpuscular radiation of the Sun and the tail plasma.[1, 2] The observations of comets indicate that there is practically always a sufficient intensity of solar corpuscular radiation to produce an acceleration of the tail ions of at least about twenty times solar gravity (the mean value[3] being ∼ 100, the maximum value several thousand times solar gravity). The mass density of the tail plasma should not be different by more than a few powers of ten from that of the interplanetary gas ($\sim 10^{-21}$ g/cm^3, at 1 A.U. near the plane of the ecliptic, from observations[4] of the polarization of the zodiacal light); near the head of the comet the mass density of the cometary plasma should be larger than 10^{-21} g/cm^3 in typical comets.* There is no reason why similar interactions should not be expected between the solar corpuscular radiation and a stationary interplanetary plasma; it follows that an assumed interplanetary cloud (which near 1 A.U. could only be ionized) would not remain stationary, since an additional acceleration of only a fraction of solar gravity would remove it before long.

(2) The particle density of the solar corpuscular radiation is not very

Biermann, 1957

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The solar wind, 1st hints of it

well known. Unsöld and Chapman[5] estimated 10^5 cm^{-3} at 1 A.U. in a very strong magnetic storm; values of the order of some 10^2 cm^{-3} for normal geomagnetically quiet conditions (when activity is observed only at polar stations) would be consistent with their estimate, and such values have

It follows from this, that in fact the co-rotating atmosphere in a certain sense belongs to the Sun, and may have a temperature of the order of that of the corona (10^6 degrees), whereas no considerable flow of heat by con-

(4) If the identity of the solar corpuscular radiation and the interplanetary gas is accepted, one should expect fluctuations in the polarized component of the zodiacal light. Up to now the observations do not seem to allow any conclusion as to whether this expectation is confirmed or not. Suitable new observations would therefore seem to be highly desirable.

I am, Gentlemen,
Yours faithfully,
L. Biermann.

Max-Planck-Institut für Physik,
Gottingen, Böttingerstr. 4
1957 March 27

References

(1) L. Biermann, *Zs. f. Ap.*, **29**, 274, 1951; and *Zs. f. Naturf.*, **7a**, 127, 1952.

Biermann, 1957

History of the solar wind discovery

- Parker realized that the heat flowing from the sun in Chapman's model and the comet tail blowing away from the sun in Biermann's theory had to be the result of the same *phenomenon.*

Parker performed the calculations to show that even though the sun's corona is strongly attracted to the sun by solar gravity, it is such a good conductor of heat that it is still very hot at large distances from the sun.

In any atmosphere, the average velocity of atoms, molecules and ions depends on their temperature. Since gravity weakens as distance from the sun increases, the outer coronal atmosphere escapes into interstellar space.

> Then again, if Biermann's conclusions are correct, we should like to know what configuration of the general solar dipole magnetic field we might expect in interplanetary space. Ionized gas, streaming outward with more or less spherical symmetry from the sun, would be expected to carry the general solar field with it, so that the lines of force are everywhere in the radial direction and extend far out into interplanetary space.

Parker, 1958

History of the solar wind discovery

temperatures. On the other hand, we do not know of any mechanism which might result in gas leaving the sun at 1000 km/sec and which does not originate as a consequence of a high coronal temperature. Therefore, we shall for the present adopt the supposition

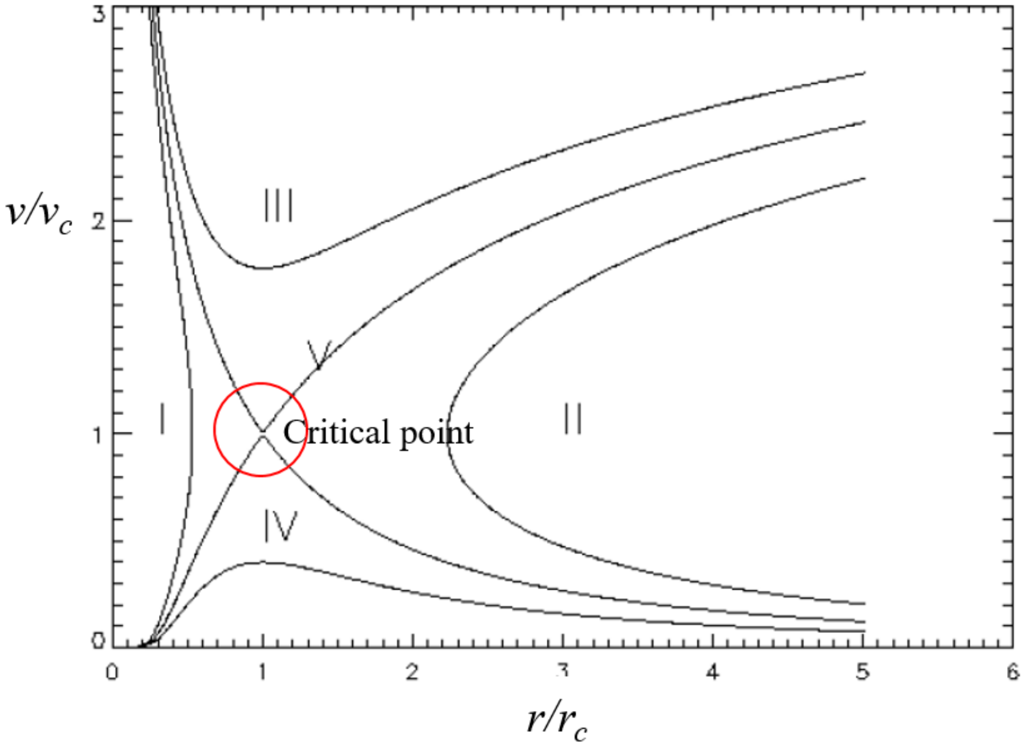
much as 1.5×10^{29} ergs/sec. Naturally, such a view will ultimately require a careful re-examination of coronal heating mechanisms, taken up in the following paper.

A coronal temperature of 2 or 3×10^6 °K over an extended region around the sun would seem to be, then, the simplest origin of the outflowing gas suggested by Biermann.

Therefore, we tentatively suggest that the gas flowing out from the sun is not field-free but carries with it magnetic lines of force originating in the sun. Hence, with the more or less steady outflow suggested by Biermann, we expect a radial solar magnetic field, falling off approximately as $1/r^2$ in interplanetary space.

Parker solutions for the solar wind

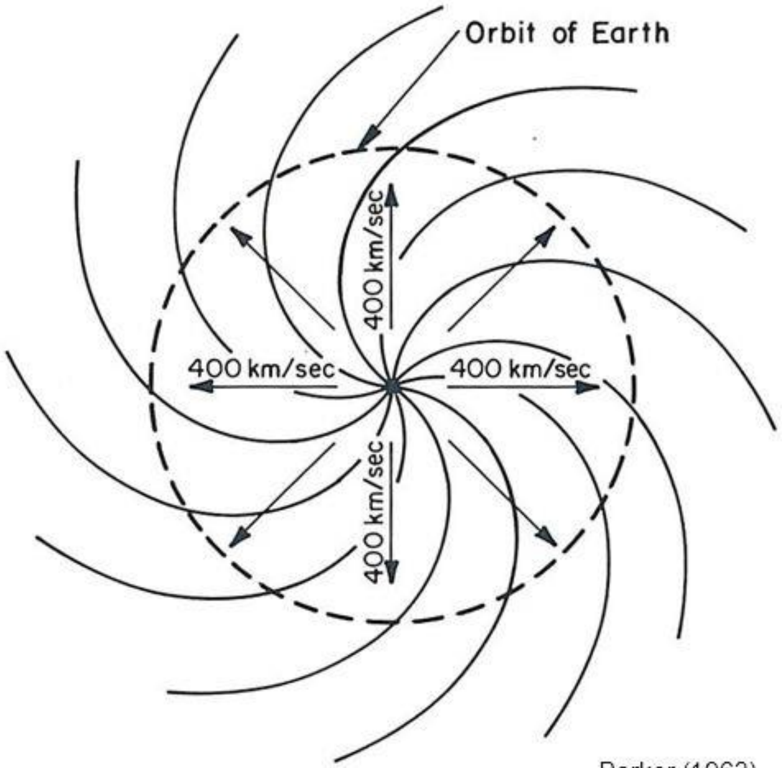
- Solution I and II are double valued. Solution II also doesn't connect to the solar surface.
- Solution III is too large (supersonic) close to the Sun - not observed.
- Solution IV is called the solar breeze solution.
- Solution V is the solar wind solution (confirmed in 1960 by Mariner II). It passes through the critical point at $r = r_c$ and $v = v_c$.



The Parker spiral

The Parker Spiral Field

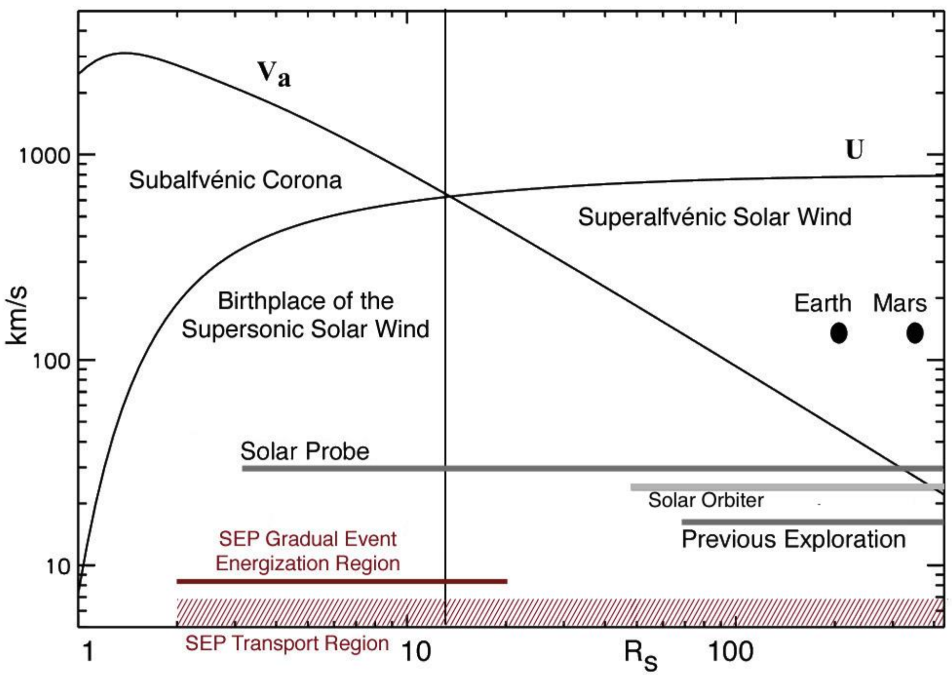
- The solar magnetic field is frozen in to the radial outflowing solar wind. Thus, due to the Sun's rotation, the magnetic field lines adopt an Archimedean spiral configuration.
- The angle to the radial direction of the magnetic field depends on distance, latitude and the local solar wind velocity.



Parker (1963)

History of the solar wind discovery

The paper on it he submitted to the *Astrophysical Journal* in 1958 was rejected by two reviewers. It was saved by then editor Subrahmanyan Chandrasekhar, who received the 1983 Nobel Prize in physics.

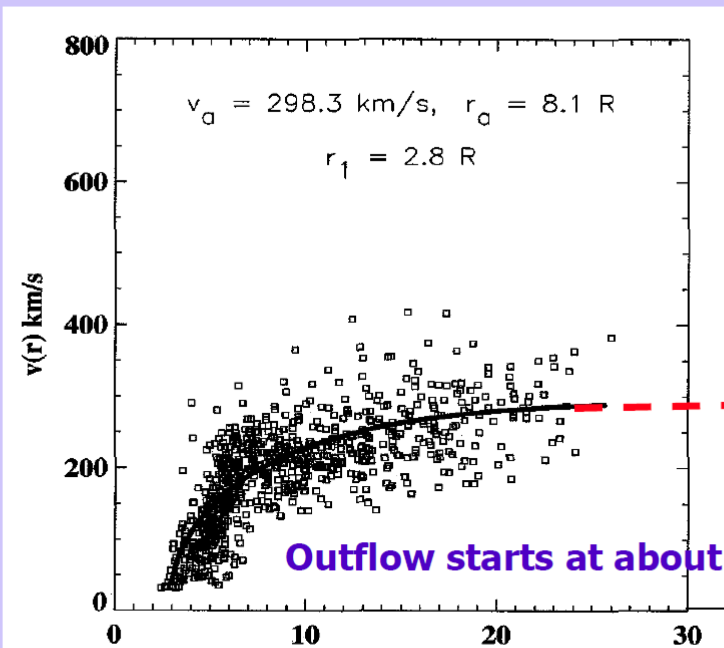


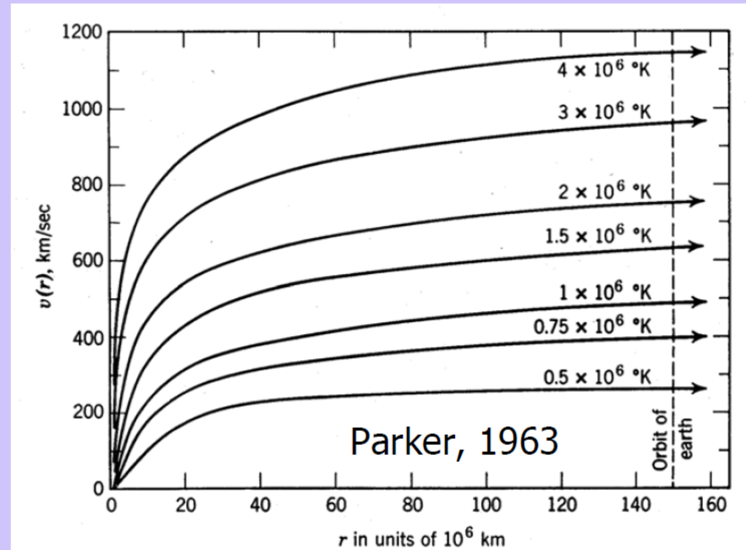
In the 1960s the theory was confirmed through direct satellite observations of the solar wind, which also made it possible to explain magnetic storms, auroras, and other solar-terrestrial phenomena.

It explained how things happening on the Sun were related to others happening at the Earth a few days later.

Speed profile of the slow solar wind

Speed profile as determined from plasma blobs in the wind





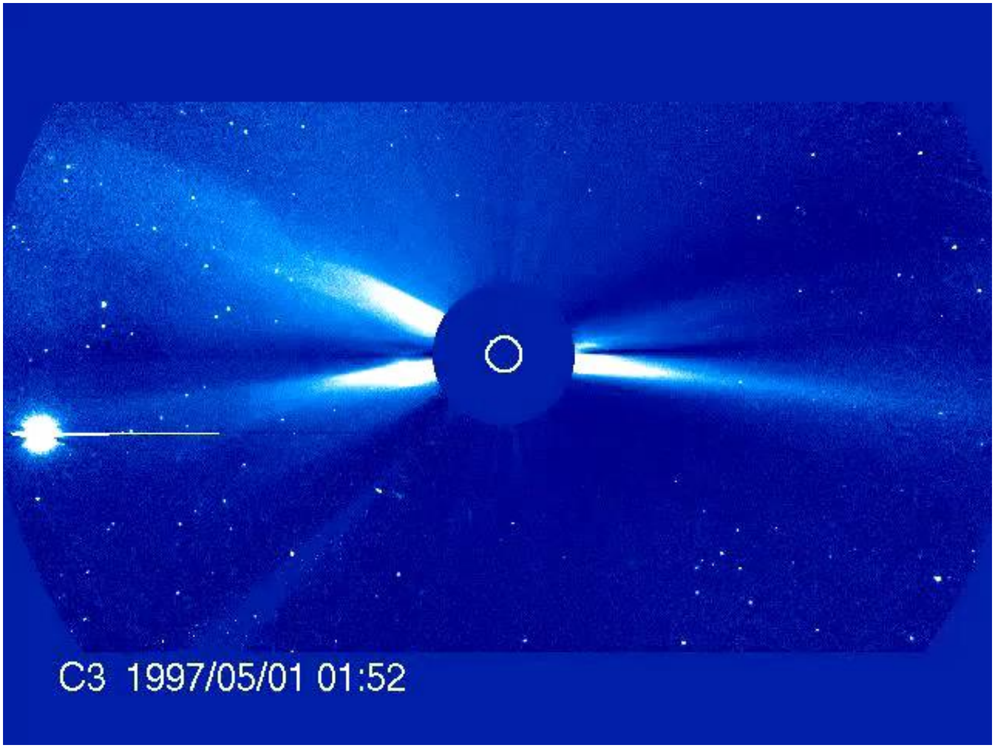
Outflow starts at about 3 R_S

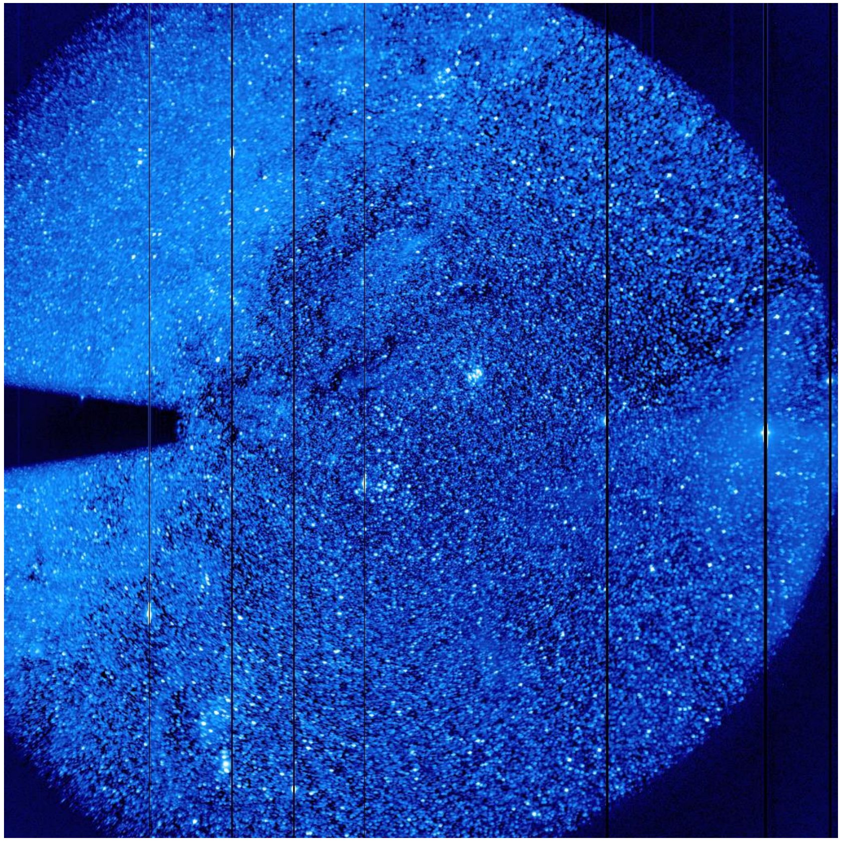
Radial distance / R_S **60**

Sheeley et al., Ap.J., **484**, 472, 1998

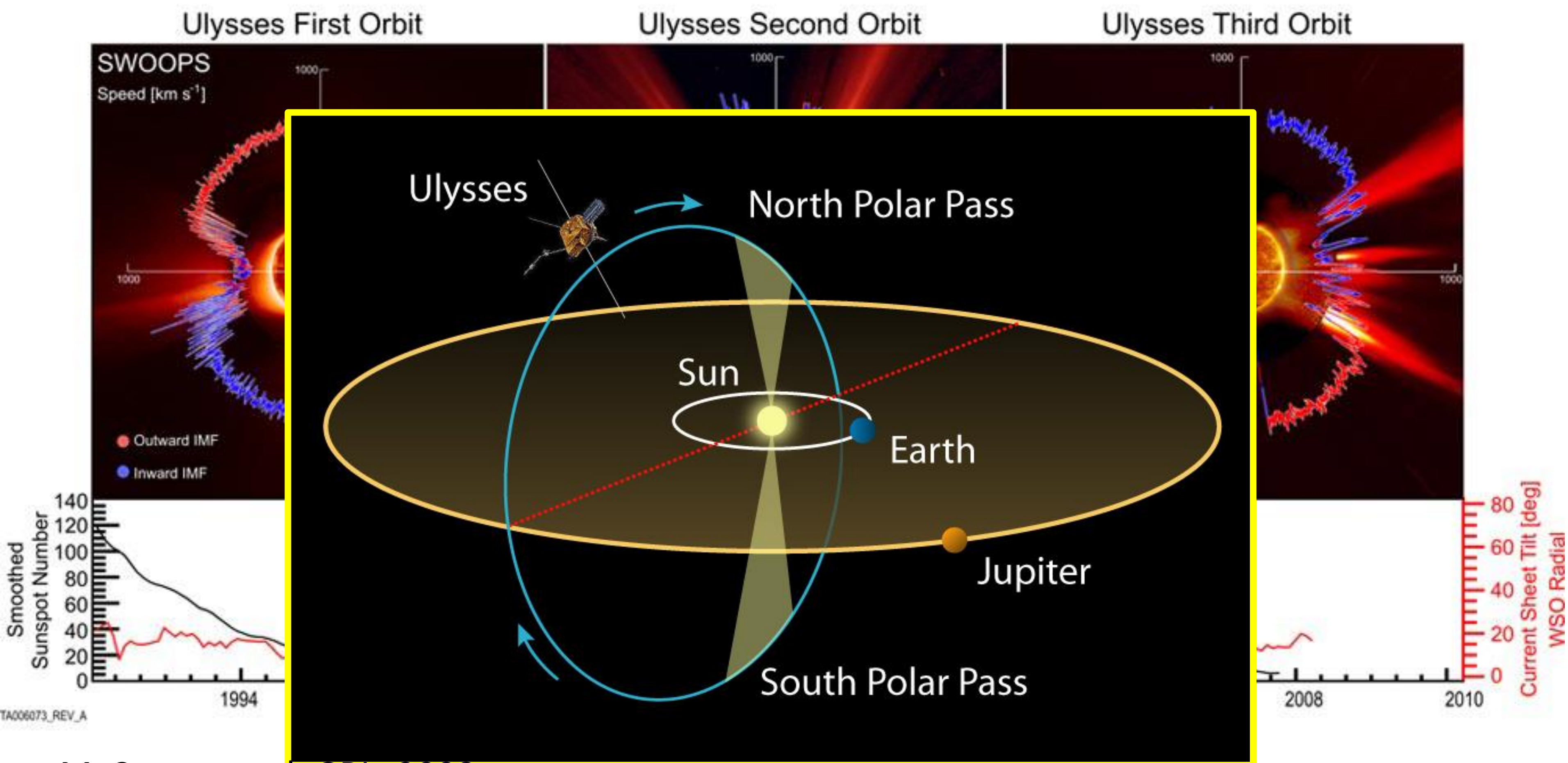
Consistent with Helios data

The solar wind made visible



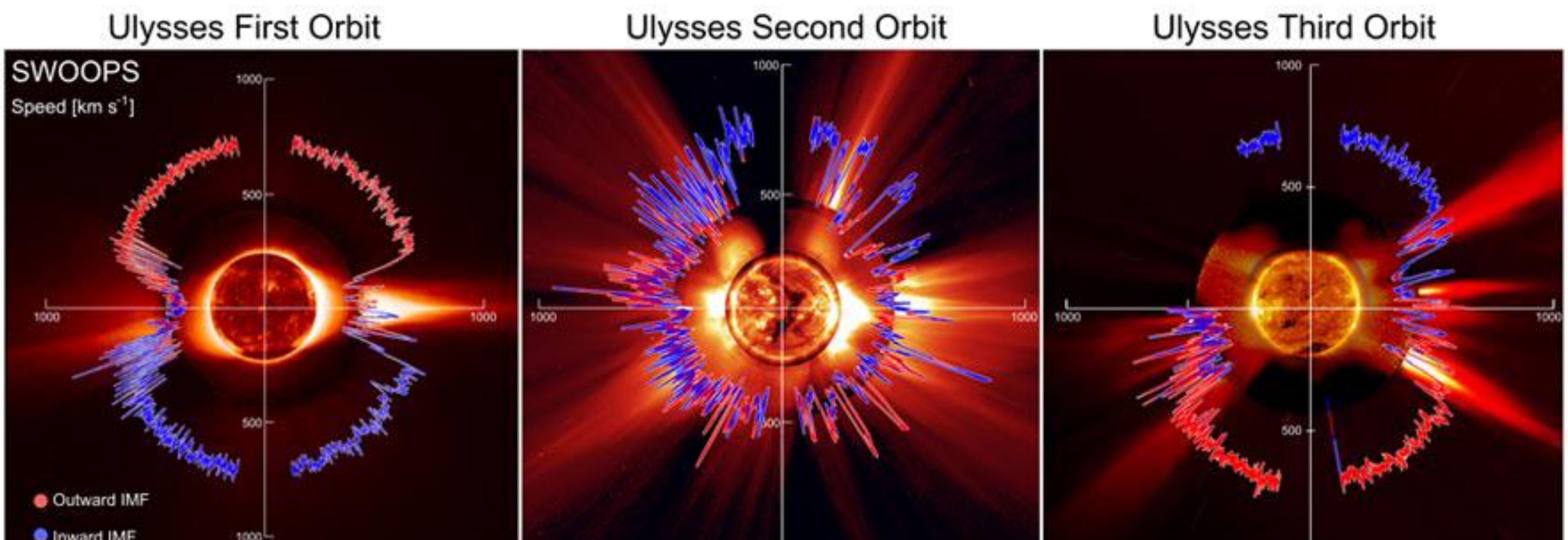


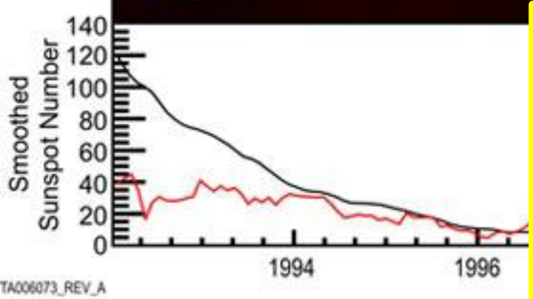
Two types of solar wind



McComas et al. GRL, 2008

Two types of solar wind



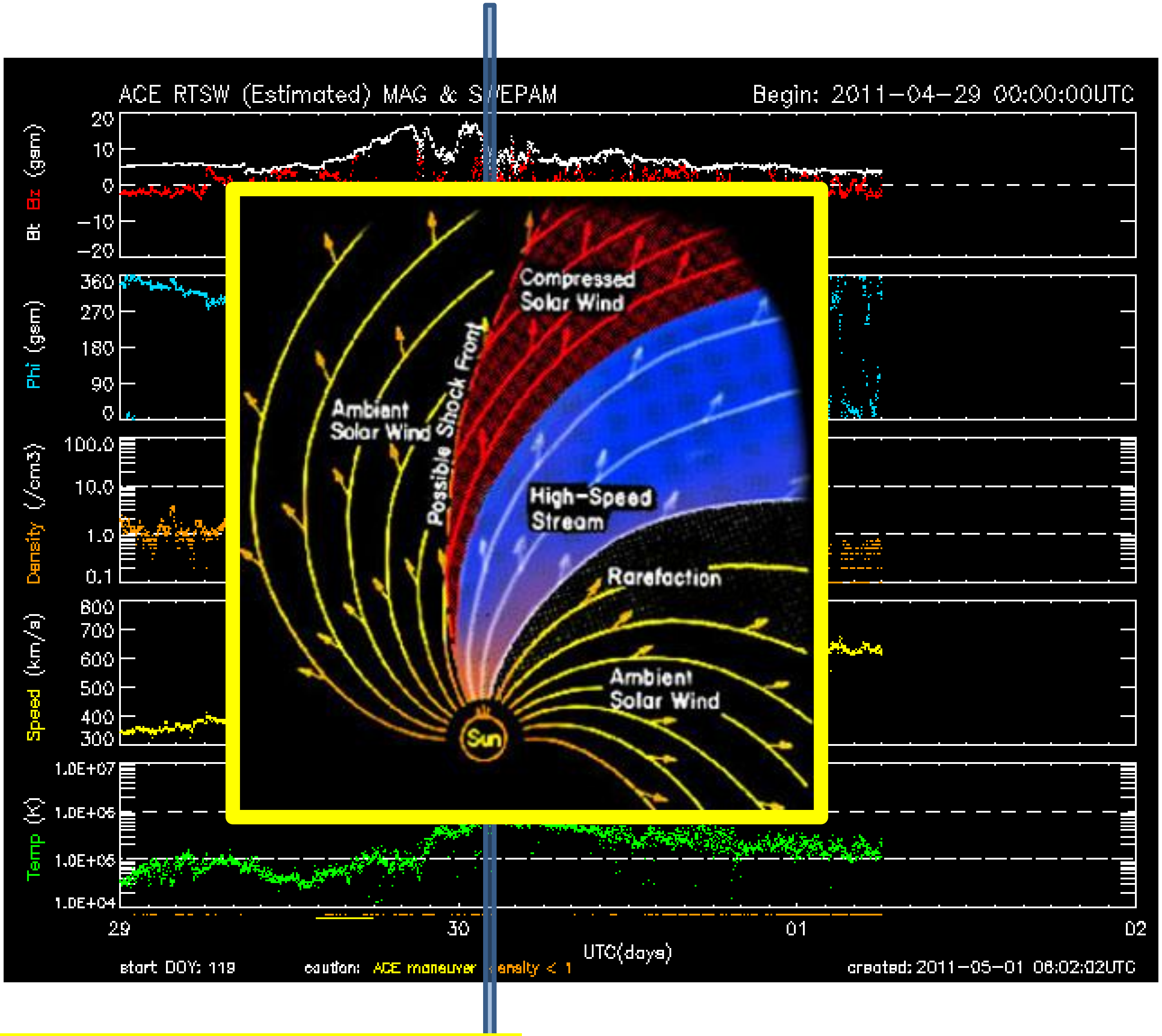


McComas et al., 2008

Parameter	Slow Wind (<400 km/s)	Fast Wind (>600 km/s)
vp [km/s]	327	702
np [cm-3]	8.3	2.7
Fp [108cm-2s-1]	2.7	1.9
nα/np [%]	3.8 (highly variable)	4.8 (stationary)
Tp [10^4 K]	3.4	23
Source	Helmet streamers, loops	Coronal holes
Signatures	Very variable	Stationary

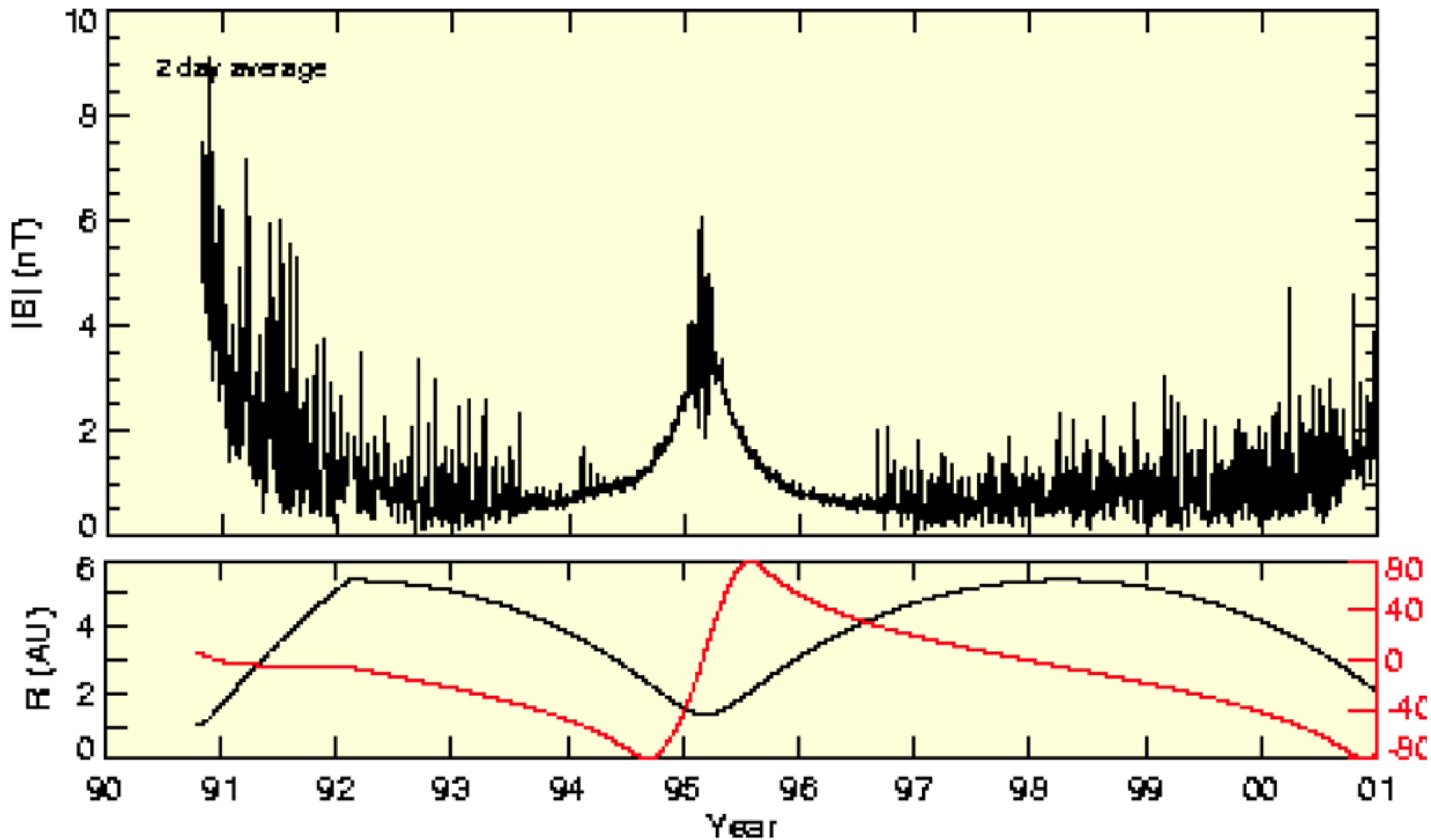
Rodriguez, 2005

Two types of solar wind



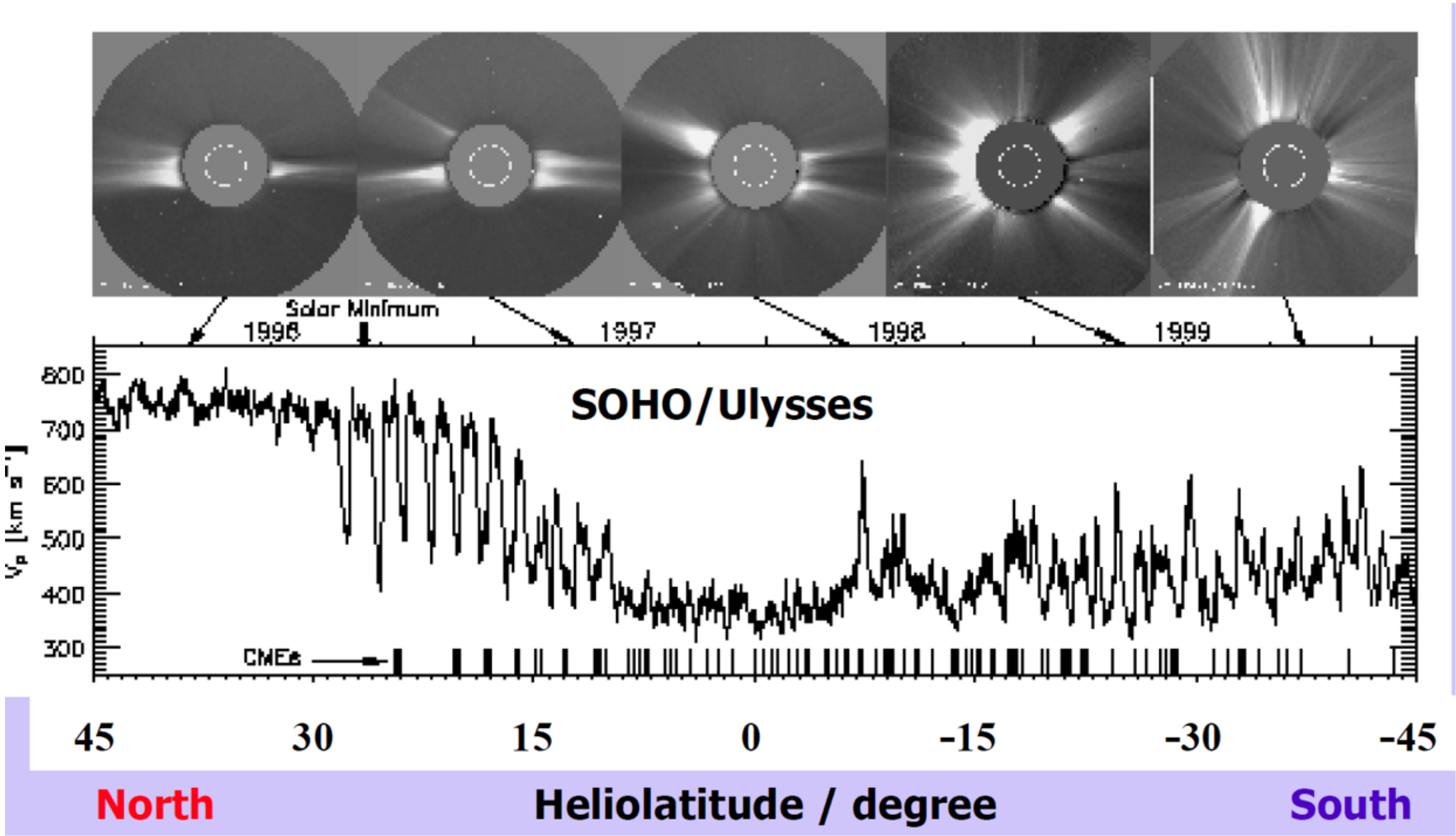
CIR: Corotating Interaction Region

Heliospheric magnetic field variation



McComas et al. 2008

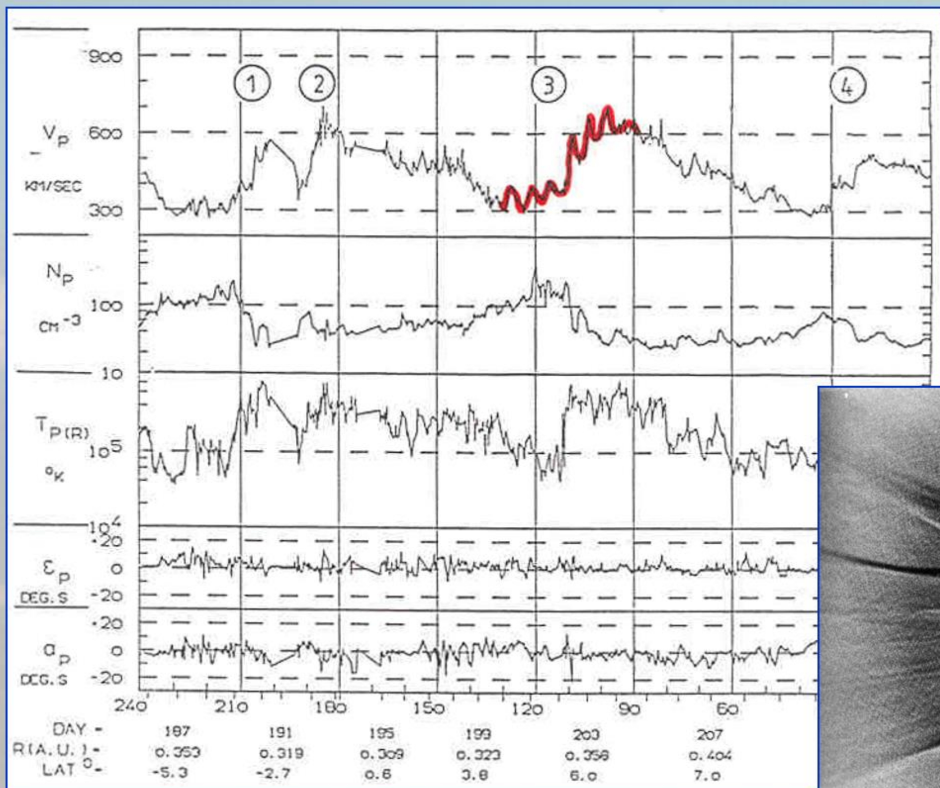
Changing corona and solar wind

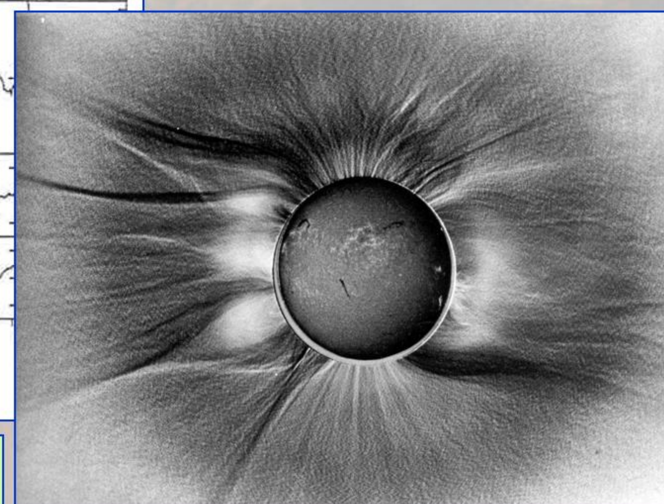


McComas et al. 2000

The filamentary structure of the solar wind

The filamentary structure of the solar wind





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.

R. Schwenn

The solar wind at the Earth

- The solar wind shapes the Earth's magnetosphere and supplies energy to its many processes.
- Its density at the Earth's orbit is around 5 ions per cubic centimeter--far, far less than that of the "best vacuum" obtainable in labs on Earth.
- The distribution of ions in the solar wind generally resembles the distribution of elements on the Sun-- mostly protons, with 4% helium and smaller fractions of oxygen and other elements.

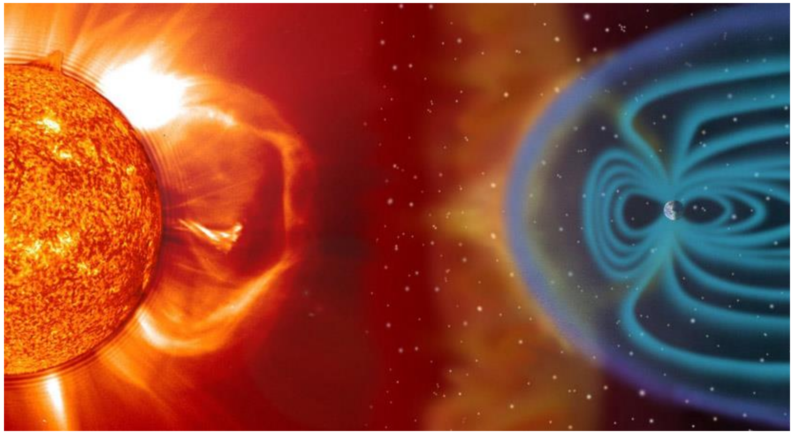


Table 1. Typical parameters of the slow solar wind at 1 AU.

Flow speed v_p	350 km s^{-1}
Proton density n_p	9 cm^{-3}
Flux density $n_p v_p$	3×10^8 cm^{-2} s^{-1}
Composition	96% protons, 4% He^+ ions, minor constituents, plus an adequate number of electrons to maintain nearly perfect charge neutrality
Proton temperature T_p	4×10^4 K
Electron temperature T_e	1.5×10^5 K
Magnetic field B	4 nT

Schwenn, 2000

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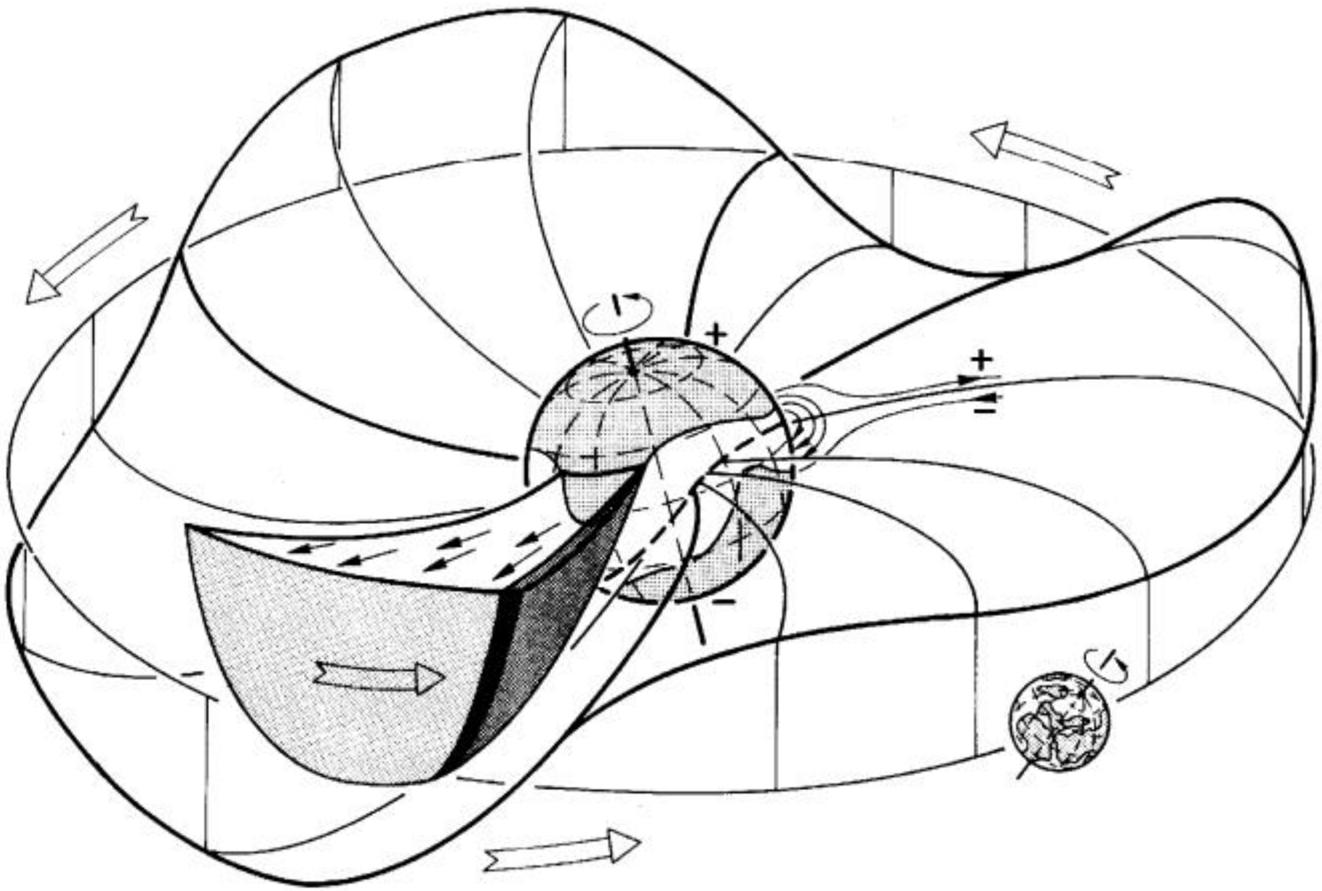
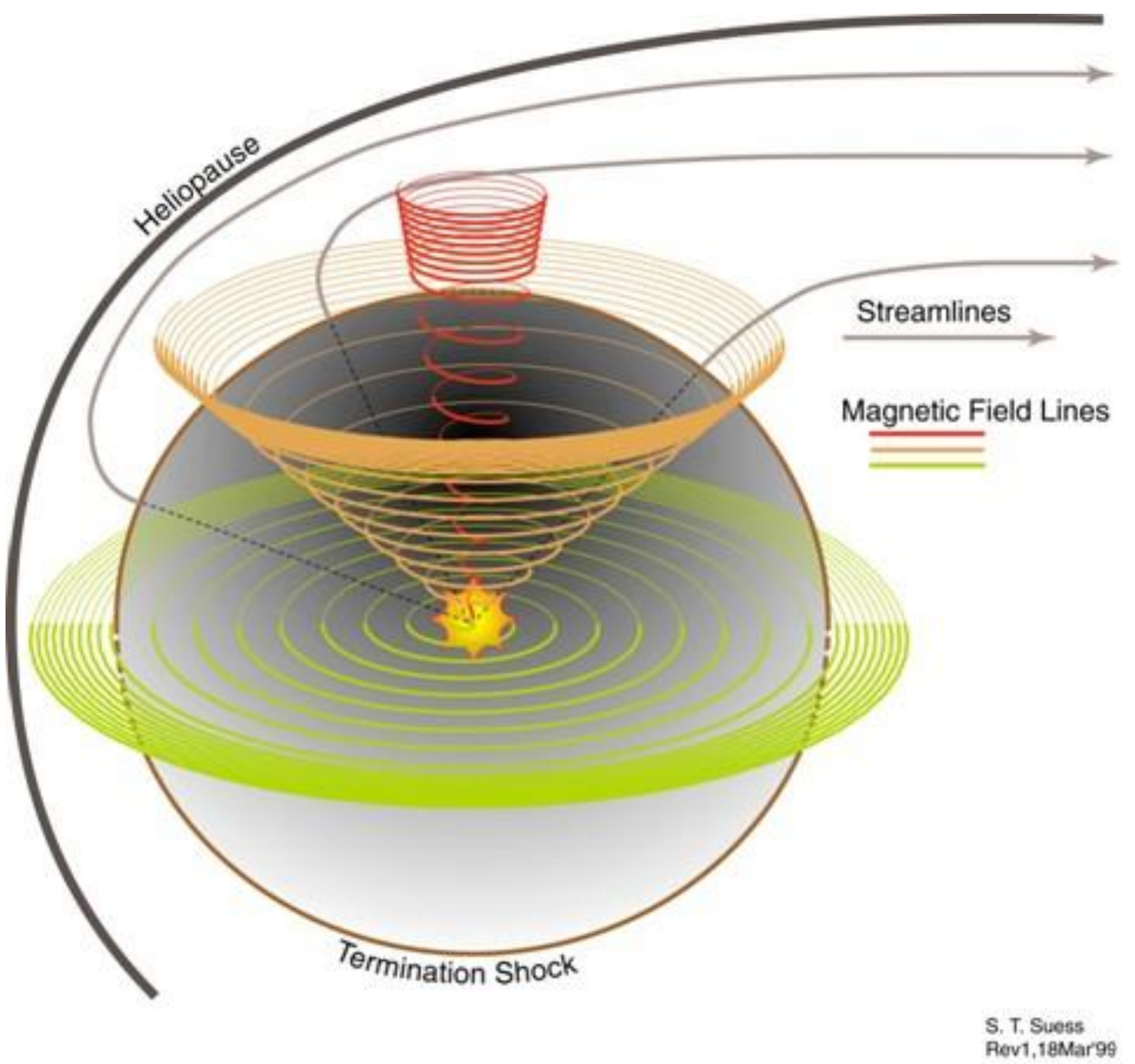
Going 3D



Alfven, 1977

From solar wind to heliosphere



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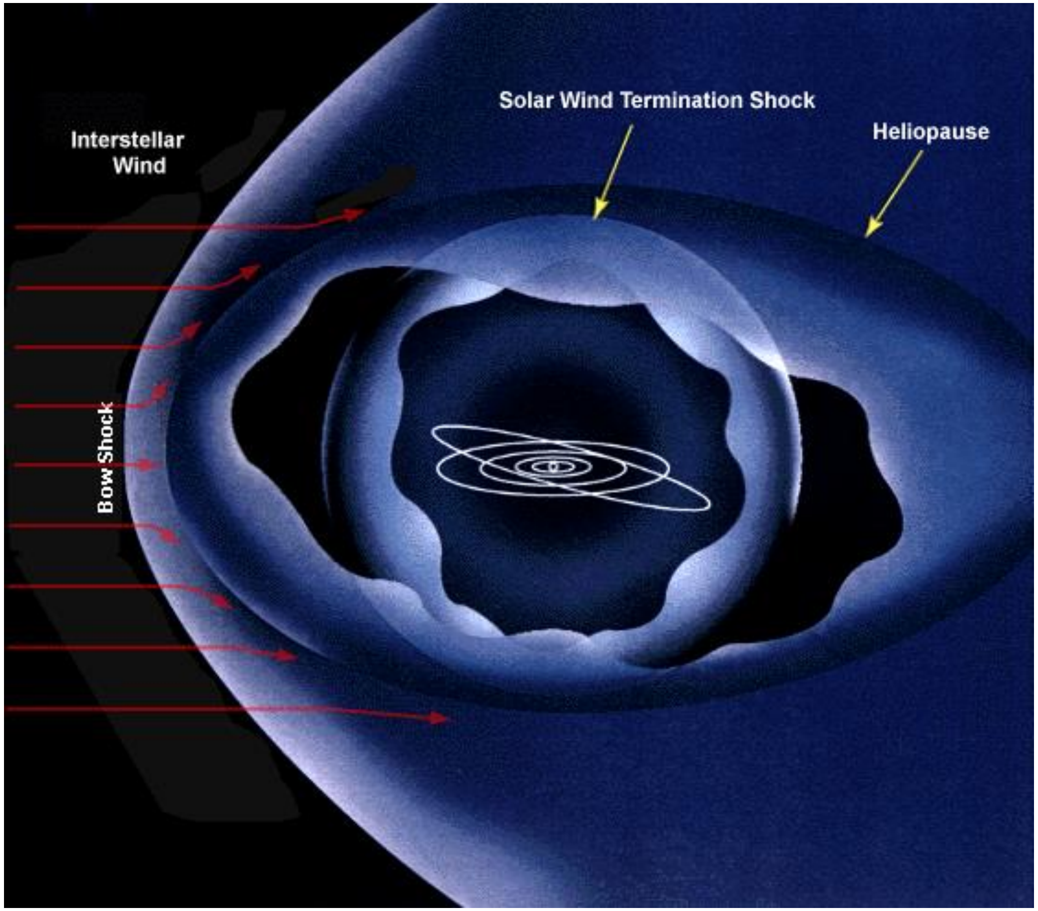
The heliosphere



The heliosphere is created by the solar wind and its interaction with the interstellar medium

Energetic particles in the heliosphere

- **Solar Cosmic Rays (SCR)** occur

  1. in connection with flares, with some 100 MeV, rarely up to GeV,
  2. at shock fronts
     - CME driven,
     - at planetary bow shocks,
     - at shocks at Corotating Interaction Regions (CIRs)

- **Galactic Cosmic Rays (GCR)** are

  1. energetic particles accelerated outside our solar system, i.e. in our galaxy or outside, with energies up to 10^{21} eV.
  2. The „Anomalous Component of Galactic Cosmic Rays“ (ACR).

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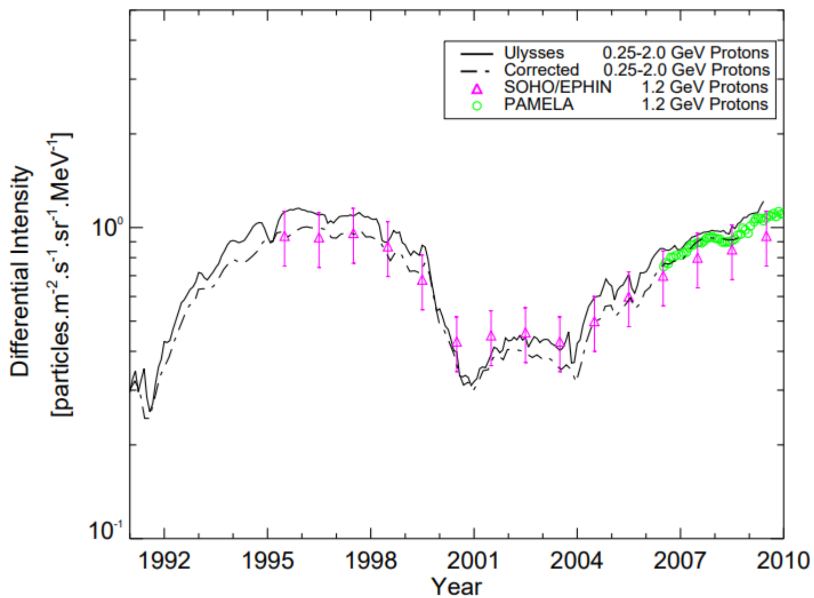
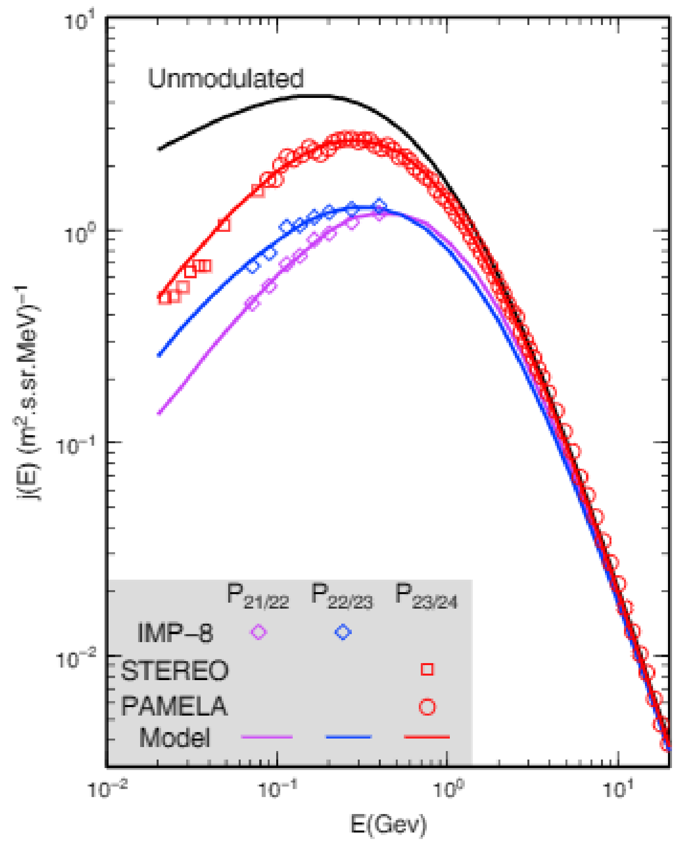
The modulation of GCR



Shen and Qin, 2017



Zhao et al., 2014

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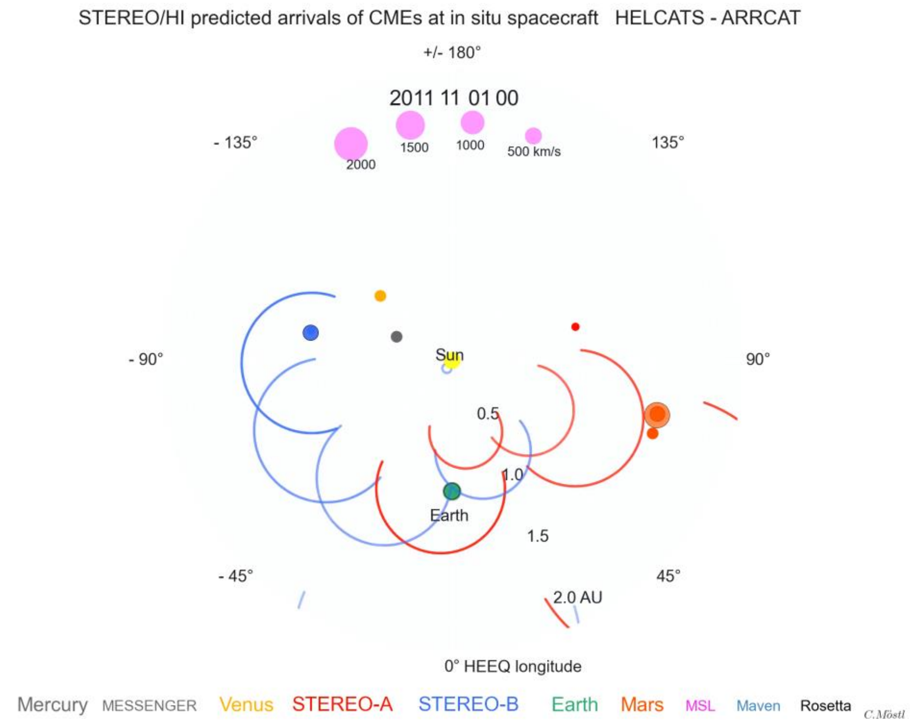
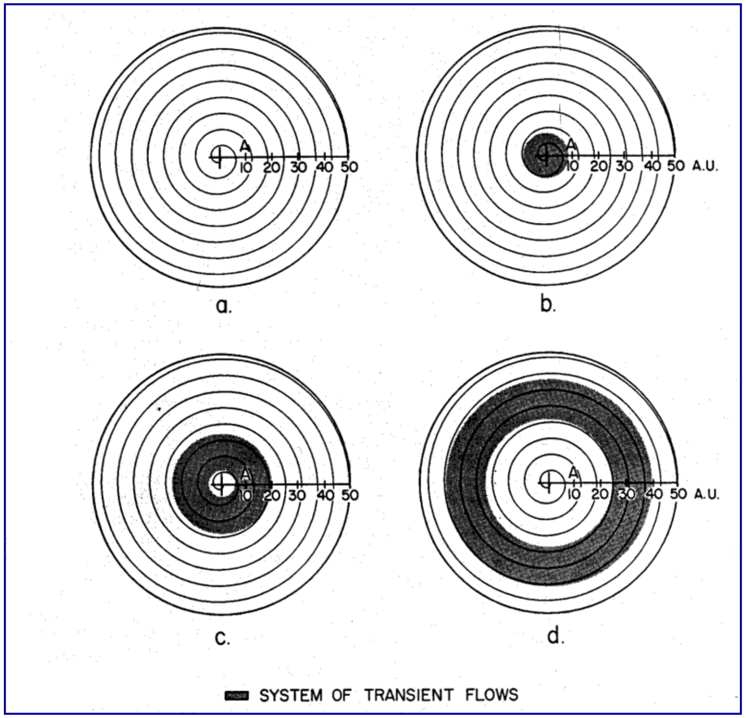
The modulation of GCR

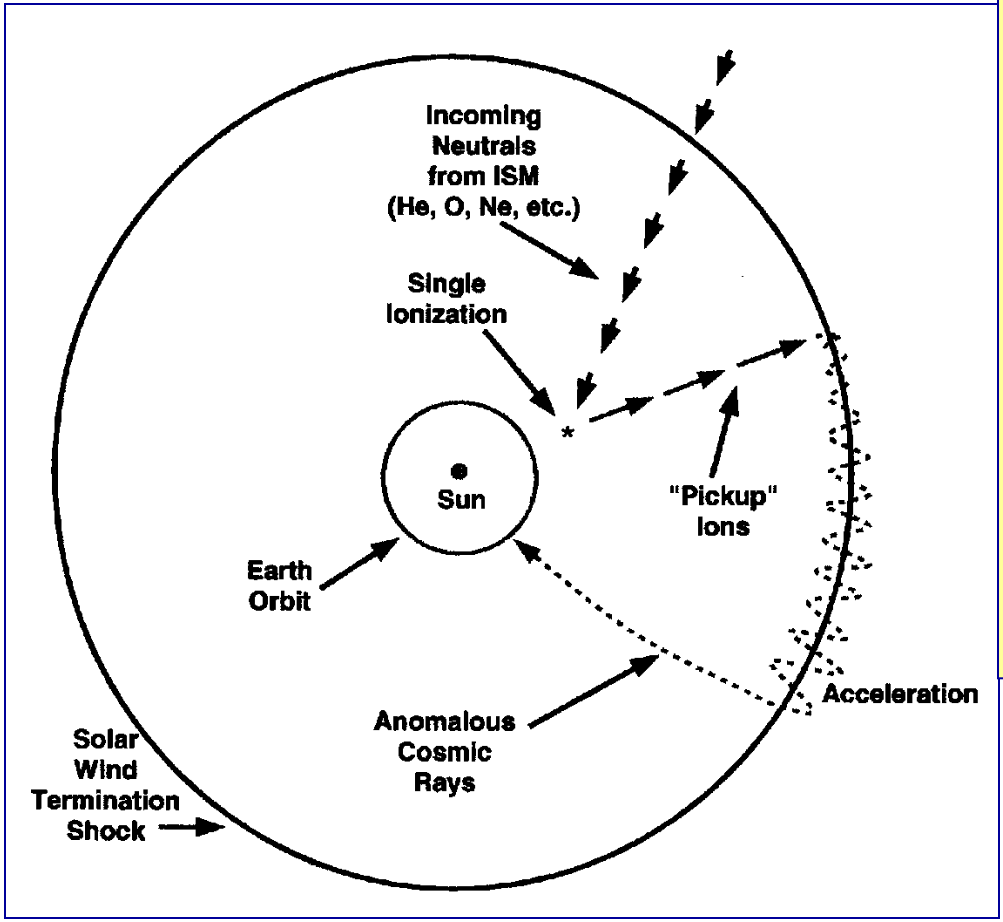
At very large distances from the Sun, the CIRs and transient flows from CMEs form „global merged interaction regions“ (GMIRs).





These large-scale shells of turbulent plasma in GMIRs surround the whole Sun and are rather efficient in shielding the heliosphere from GCRs.

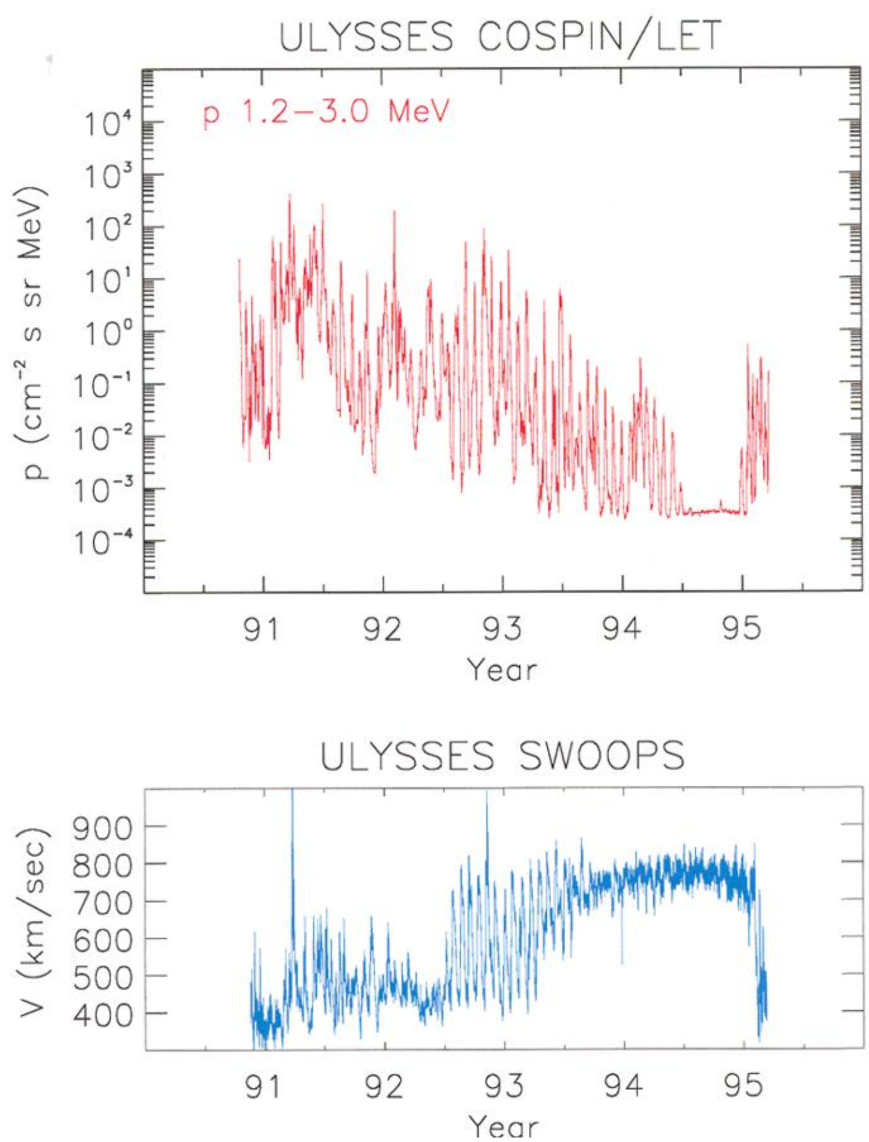
The Anomalous Cosmic Radiation (ACR)



The origin of the„anomalous“ component of the cosmic radiation (ACR):

1. Interstellar neutral particles penetrate the inner heliosphere.
2. They become singly ionized by solar UV radiation.
3. The ions are picked up by the solar wind and swept to the outer heliosphere.
4. At the termination shock they are accelerated to some 10 MeV/nucleon.
5. They may enter the inner heliosphere again and appear as ACRs.

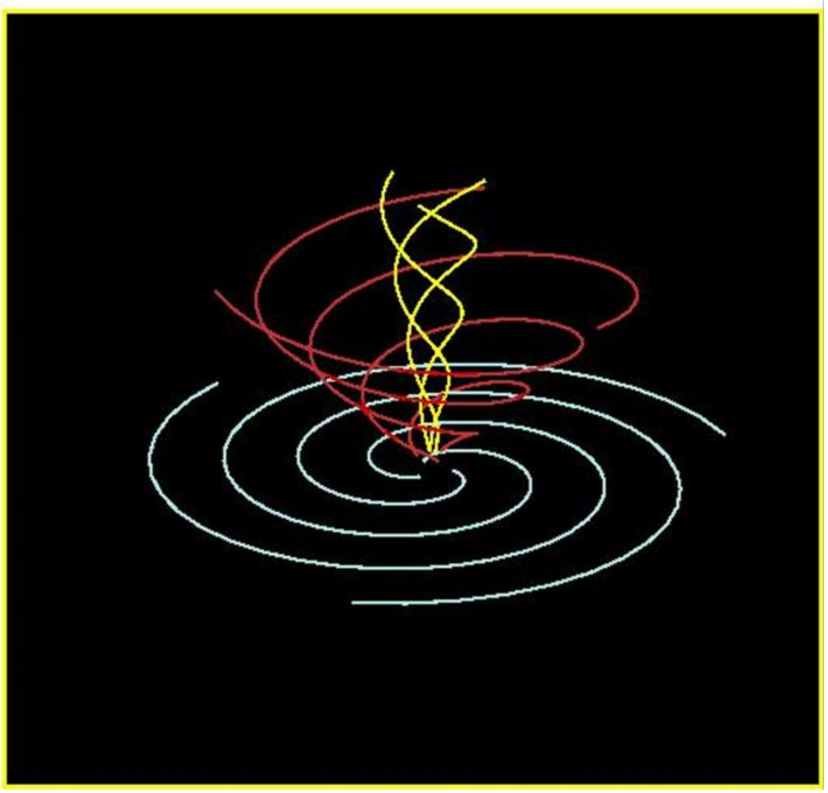
A surprise at high latitudes



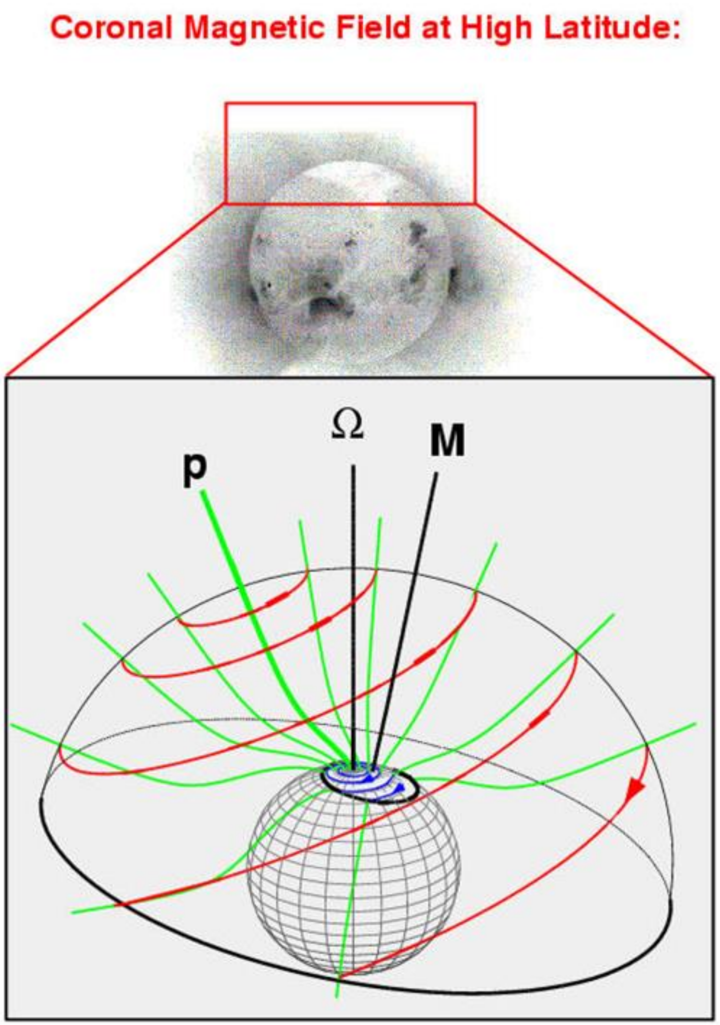
A new understanding of the heliospheric B

Heliospheric Magnetic Field
Parker, 1958

The classical model

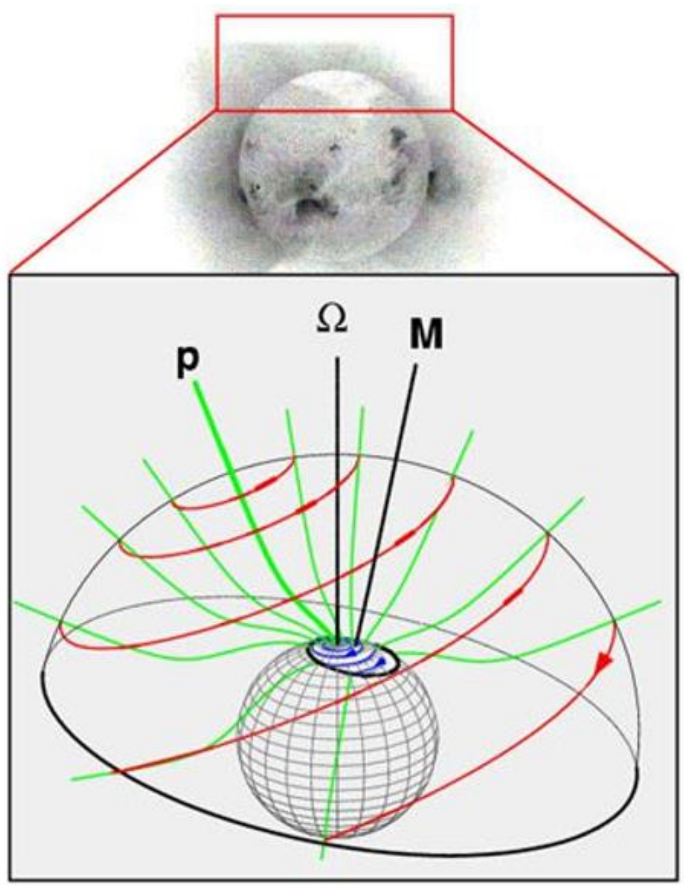


A new understanding of the heliospheric B

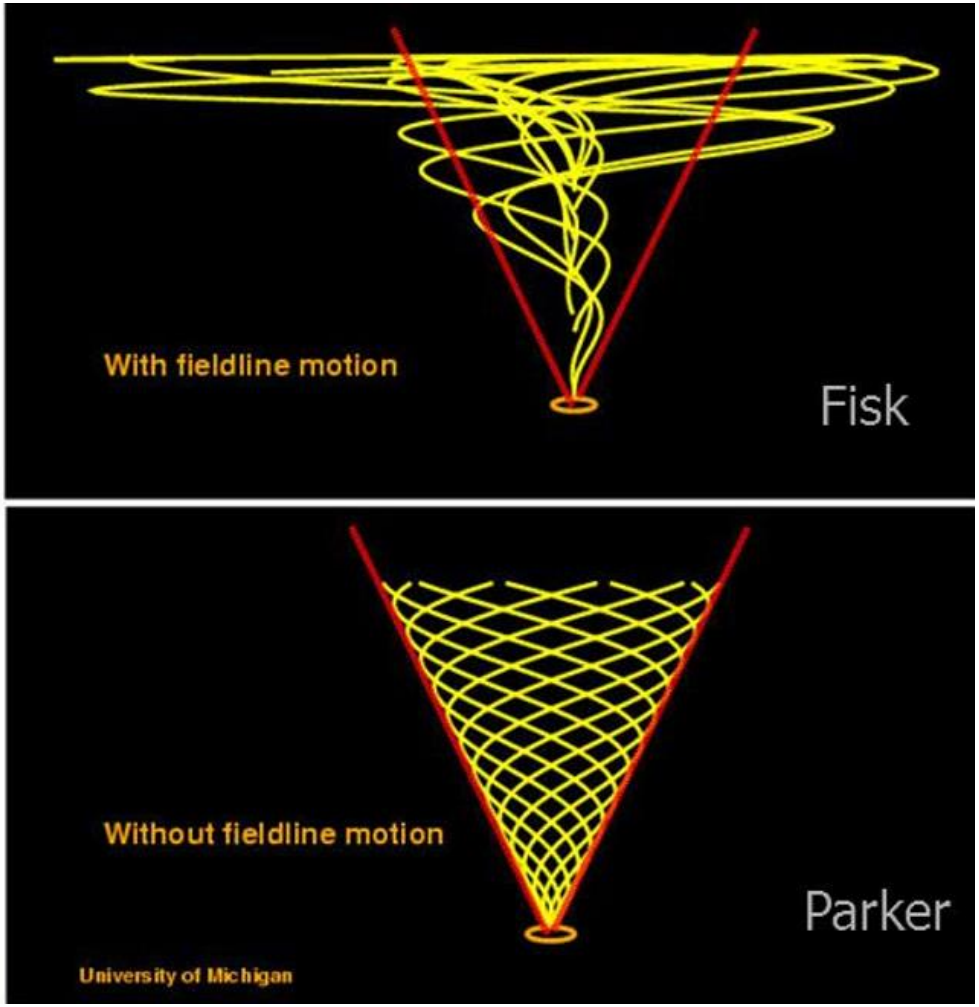


- Different axis orientation
- Differential rotation

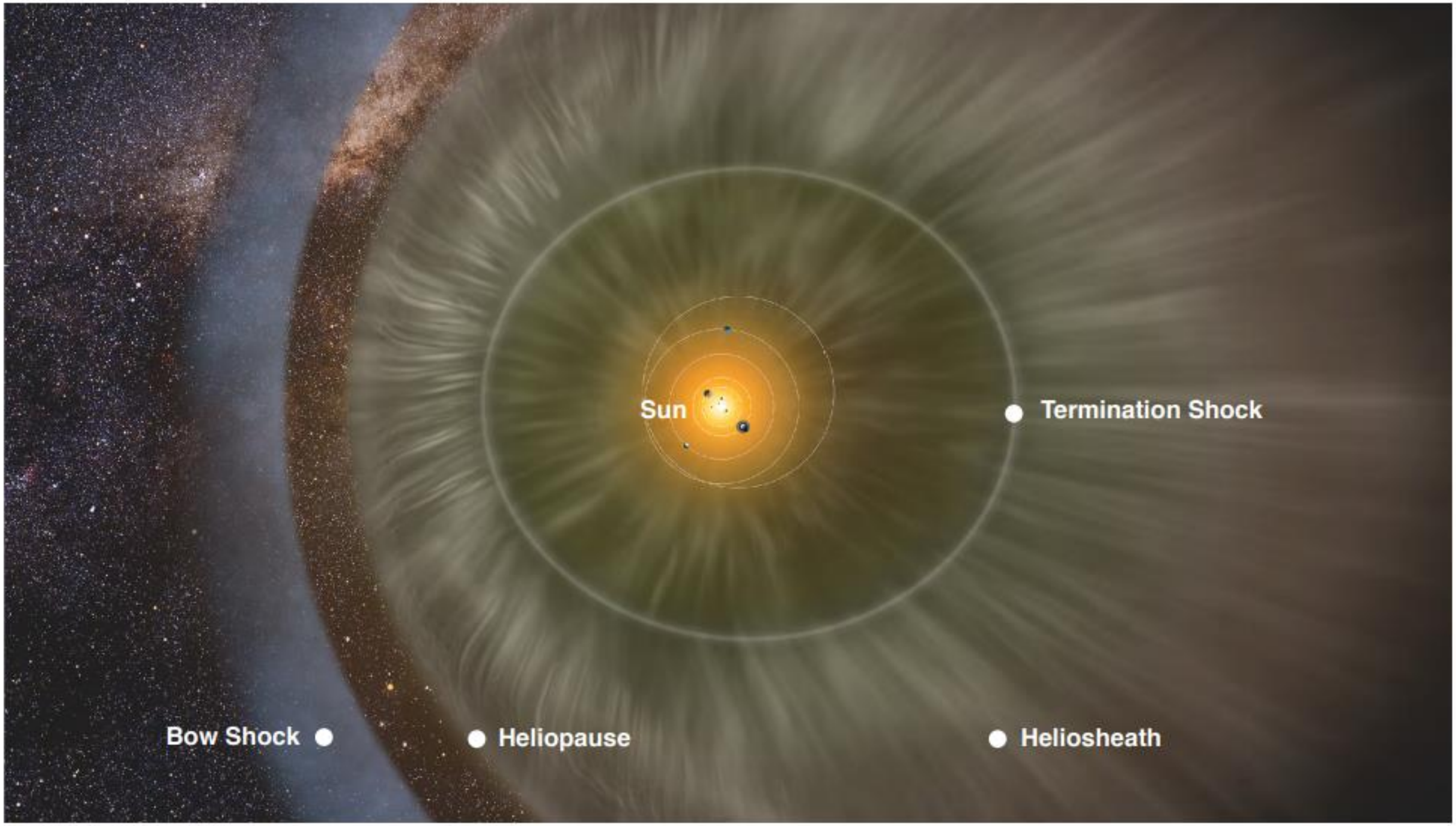
A new understanding of the heliospheric B



Fisk, 1996



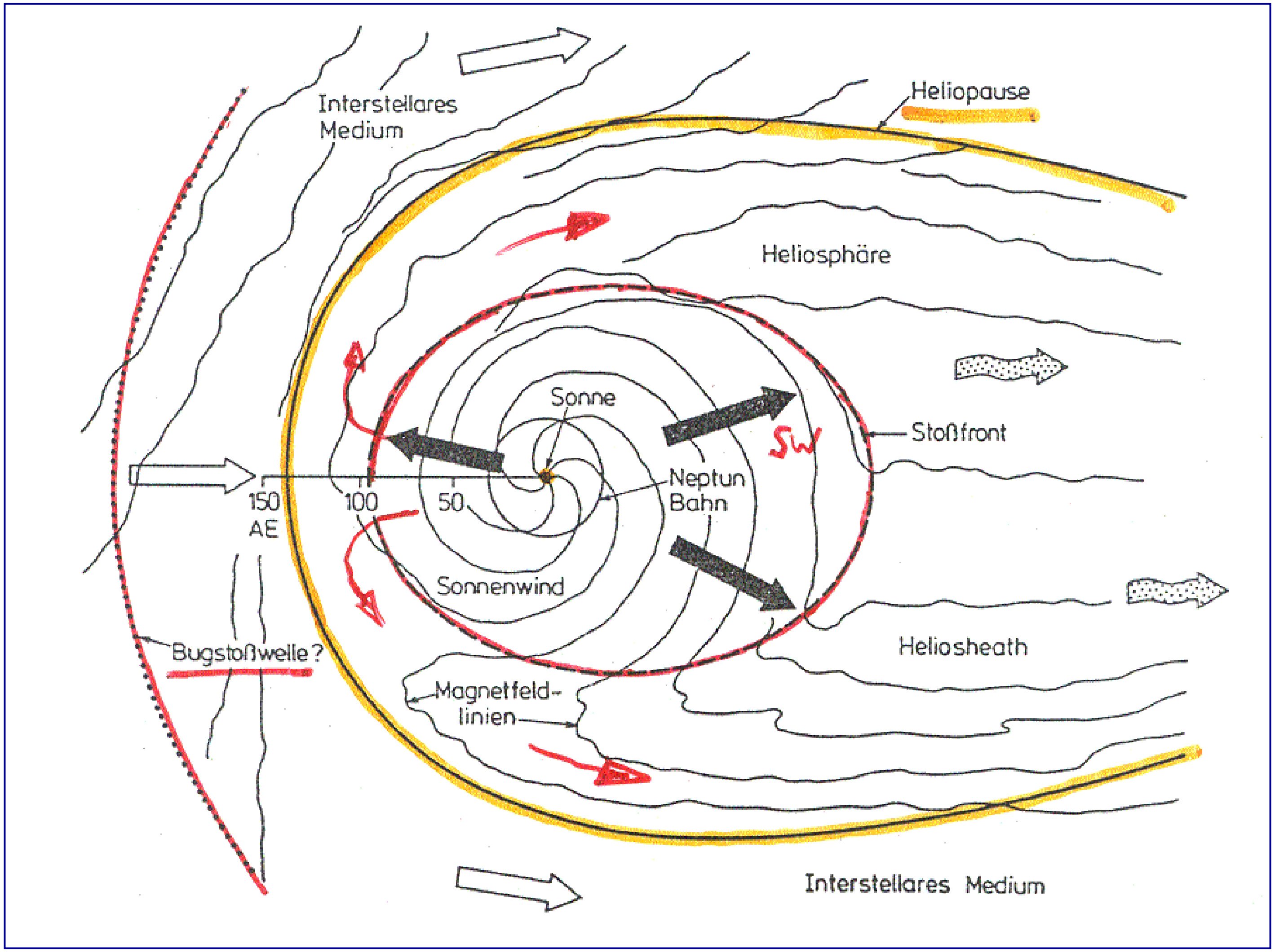
The heliosphere boundaries



The Heliosphere

Credit: NASA/IBEX/Adler Planetarium

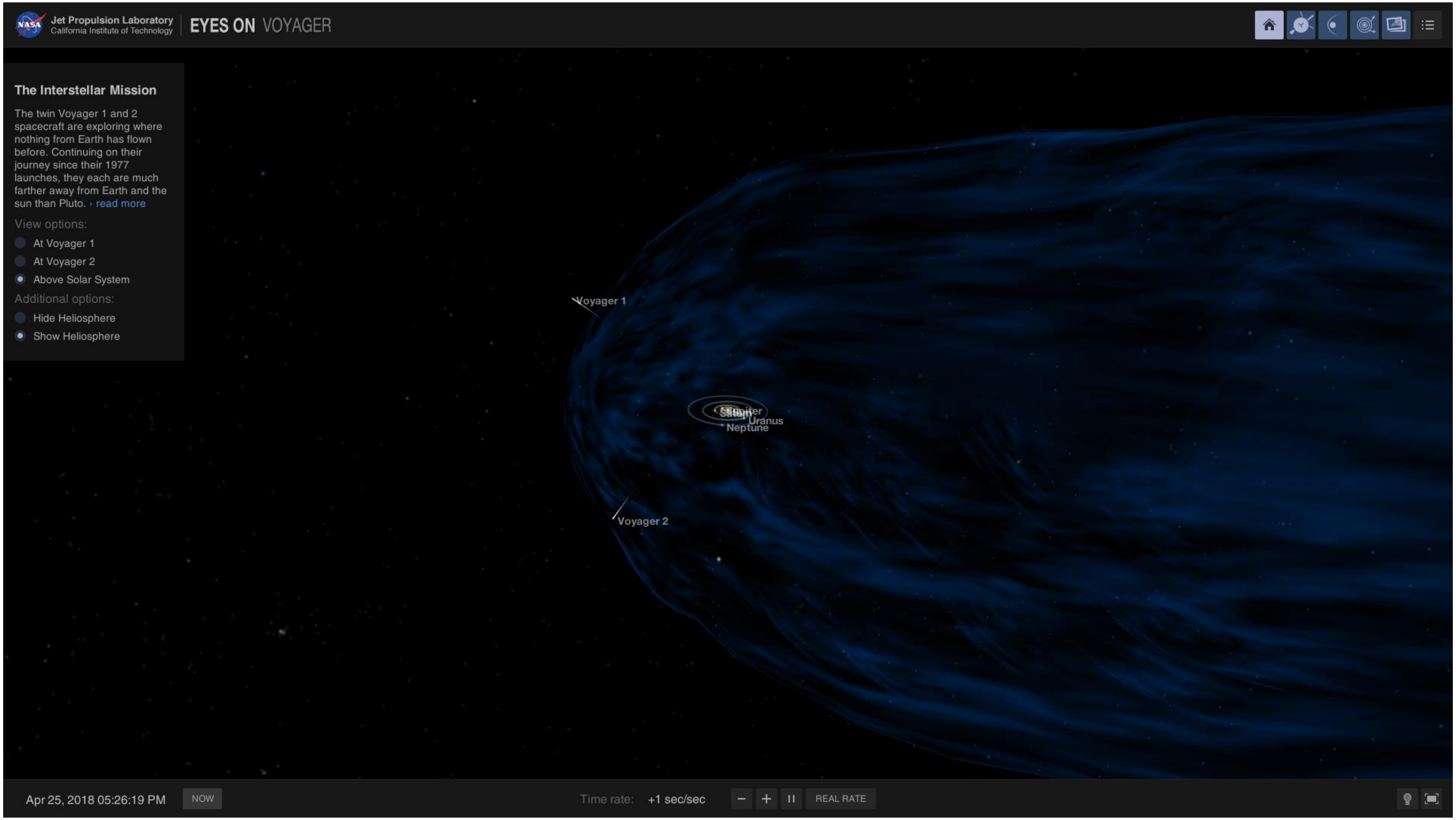
The heliosphere boundaries



The Voyagers

The Vs in real time

https://voyager.jpl.nasa.gov/mission/



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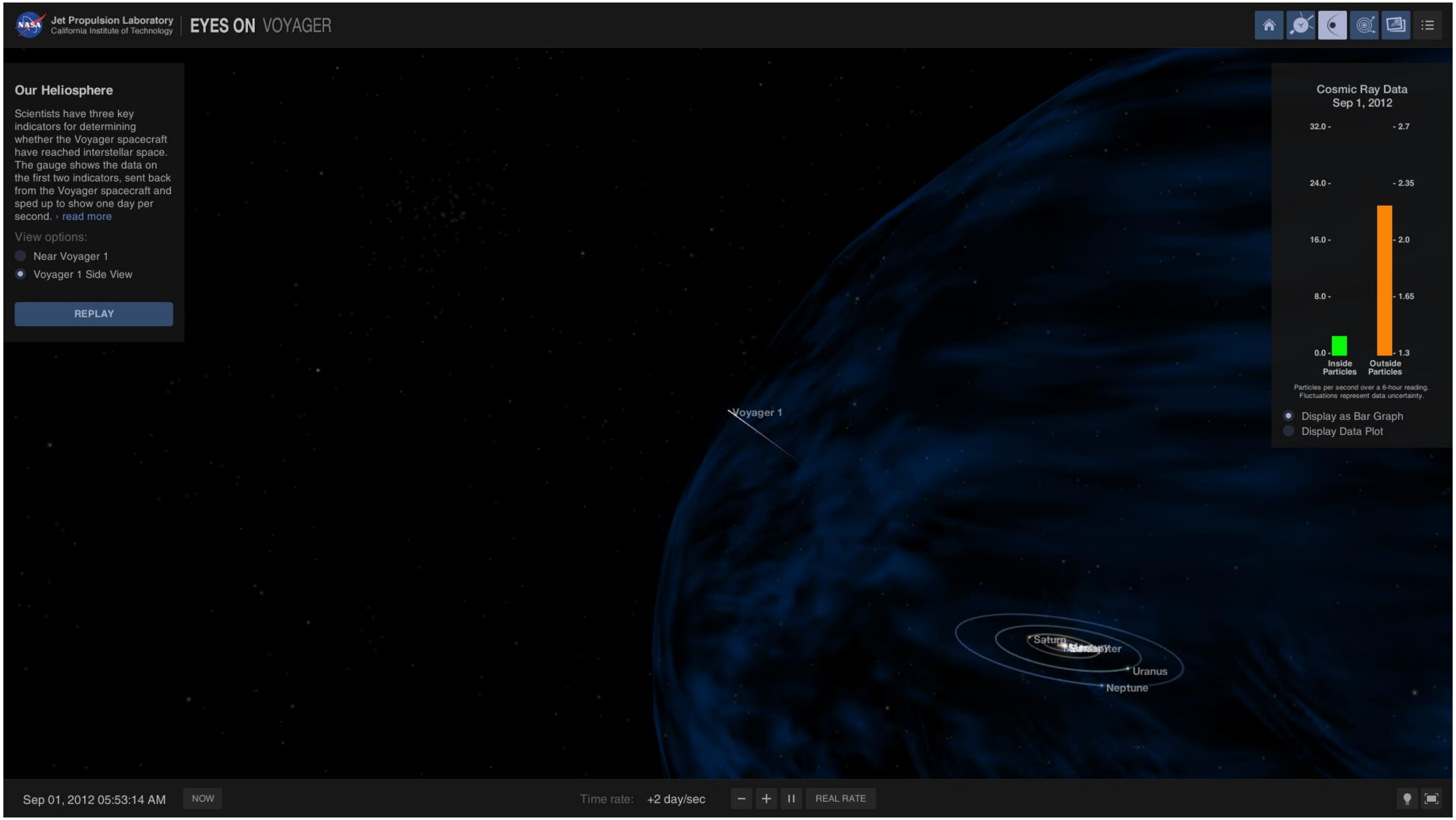
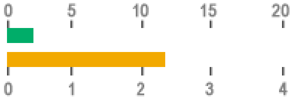
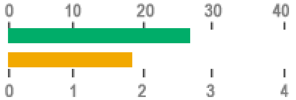
Voyager 1 reaching interstellar space



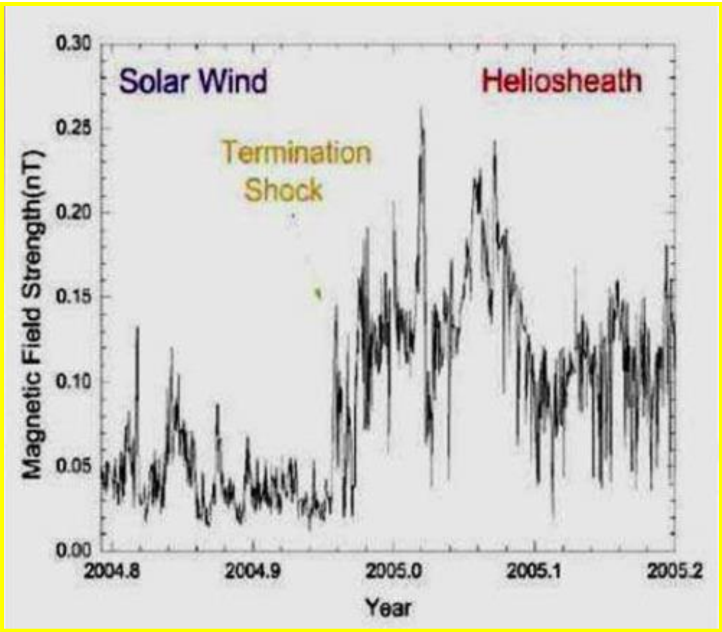
The Voyagers in real time

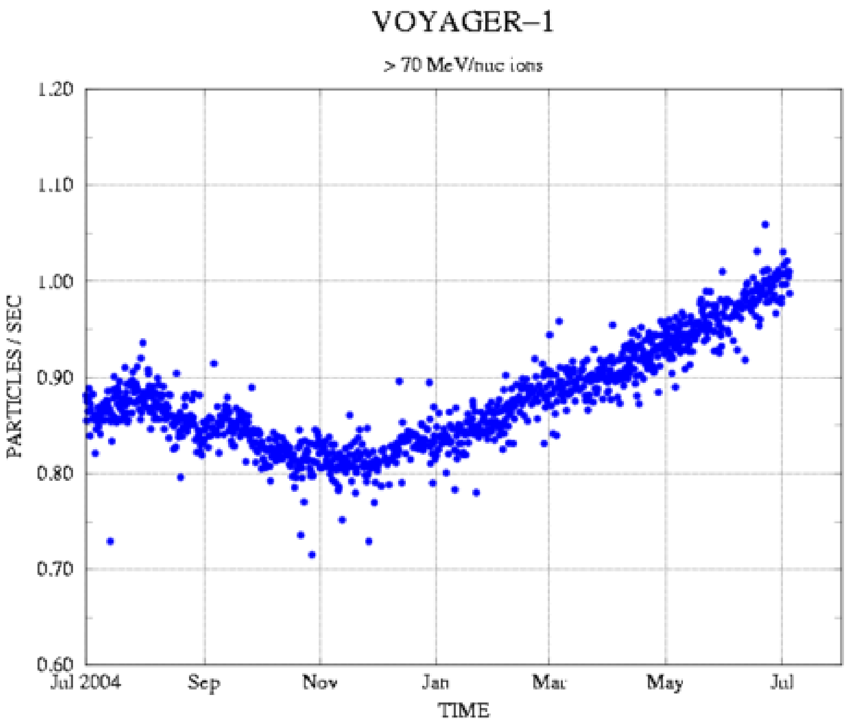
Mission Status

	Voyager 1	Voyager 2
Launch Date	Mon, 05 Sept 1977 12:56:00 UTC	Sat, 20 Aug 1977 14:29:00 UTC
Mission Elapsed Time	40 : 07 : 20 : 23 : 41 : 39 YRS MOS DAYS HRS MINS SECS	40 : 08 : 05 : 22 : 08 : 39 YRS MOS DAYS HRS MINS SECS
Distance from Earth	21,138,955,992 km	17,523,836,615 km
	141.30519301 AU	117.13961257 AU
Distance from Sun	21,231,719,127 km	17,554,248,769 km
	141.92527626 AU	117.34290526 AU
Velocity with respect to the Sun (estimated)	16.9995 kps	15.3741 kps
One-Way Light Time	19:35:11 (hh:mm:ss)	16:14:13 (hh:mm:ss)
Cosmic Ray Data		

IMP MET

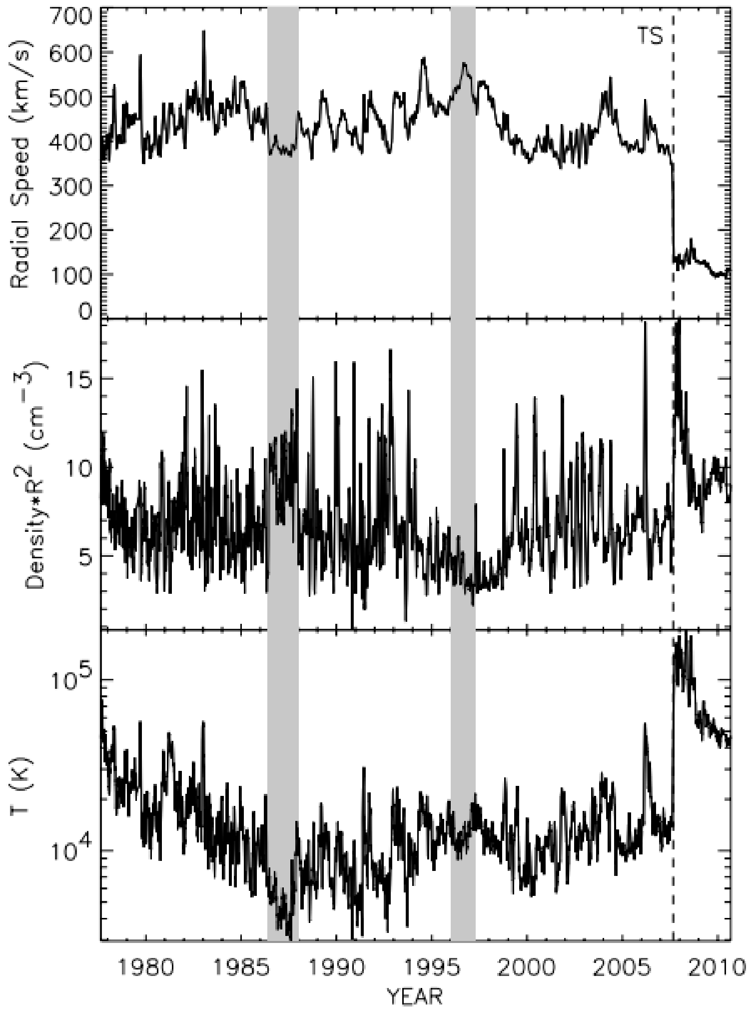
The termination shock crossing of V1





December 15, 2004 @ 94 AU

The termination shock crossing of V2



August 30, 2007 @ 84 AU

And into interstellar space…

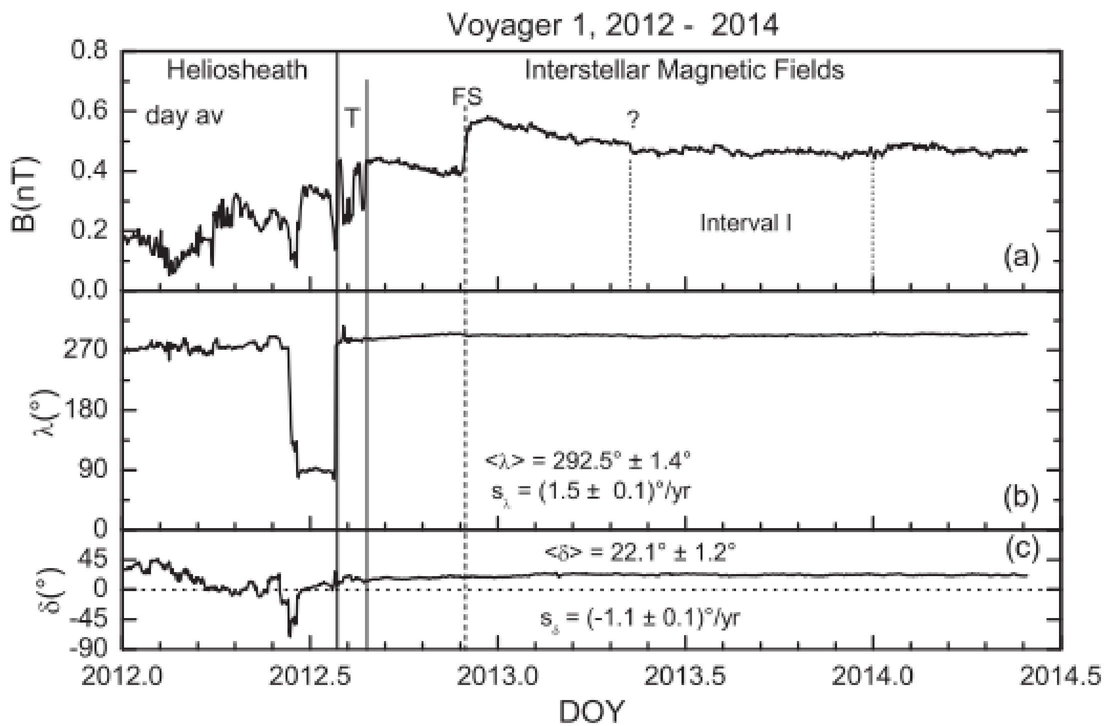


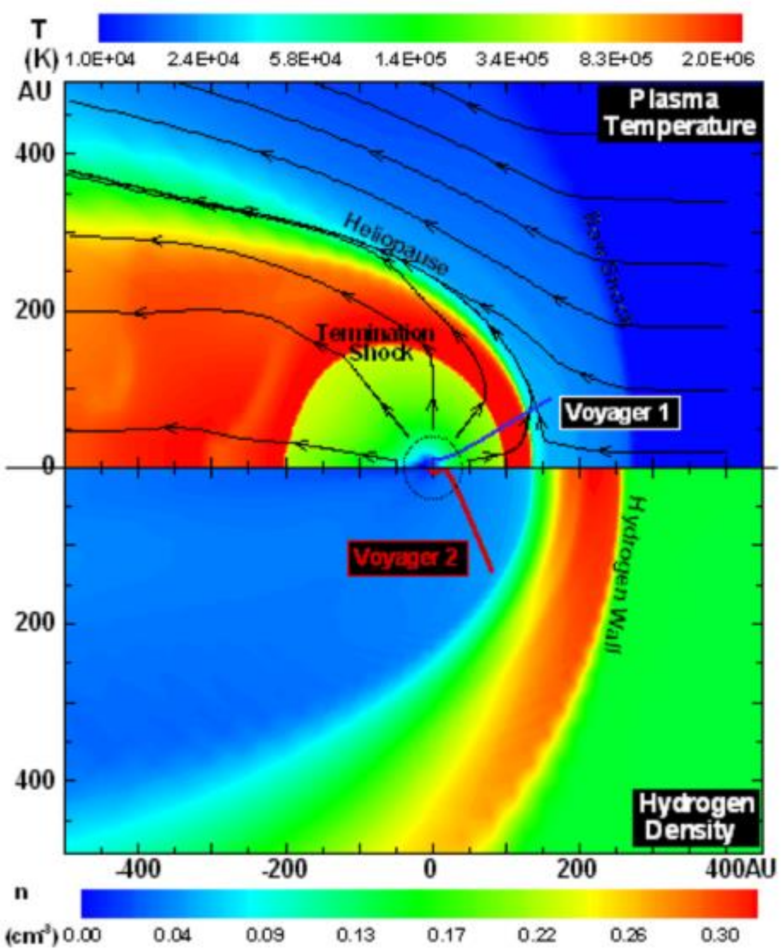
Figure 1. Daily averages of (a) magnetic field strength ***B***, (b) azimuthal angle λ, and (c) elevation angle δ vs. time between 2013.00 and 2014.41. Notable features are the constancy of the direction of the magnetic field throughout the year, and the small fluctuations of the average magnetic field strength.

Burlaga and Ness, 2014

Royal Observatory of Belgium

And into interstellar space…

- Energetic particles are also showing the boundary.
- Density derived from plasma waves is consistent with models.



Richardson and Burlaga, 2013

V2 should provide final confirmation !

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Summary

- The solar corona expands into space through the solar wind.
- Between 1859 and 1958, the observational and theoretical foundations of the solar wind were laid down.
- The solar wind fills the heliosphere with plasma and magnetic fields.
- It affects the Earth and life on it, and the other planets and solar system bodies.
- The solar wind has different characteristics depending on its source region at the Sun and the interactions it undergoes.
- The heliosphere is shaped by the interstellar medium.
- We know where the heliospheric boundaries are and we have a glimpse of what lies beyond.

Further reading

- https://news.nationalgeographic.com/news/2003/08/0827_030827_kyotoprizeparker.html
- http://www.astro.umontreal.ca/~paulchar/grps/histoire/newsite/sp/great_moments_e.html
- https://www-spof.gsfc.nasa.gov/Education/wsolwind.html
- https://www.tcd.ie/Physics/people/Peter.Gallagher/lectures/ss_sss/PY4A01_lecture18_solar_wind.ppt
- R. Schwenn, H. Peter et al. lectures at: http://www.mps.mpg.de/solar-system-school/downloads
- Solar Wind: Global Properties (Schwenn, 2000)