The Solar Wind

Ian. G. Richardson
Department of Astronomy,
University of Maryland, College Park
and
Heliophysics Science Division,
NASA Goddard Space Flight Center

(*DeForest et al.*, 2016)

How does the Sun influence space weather?

Electromagnetic radiation:

- **X rays** (e.g., solar flares) Varies on minute to solar cycle timescales
- **Extreme Ultra Violet** (EUV)
- **Visible light** (~constant)
- **Infra-red** (~constant)
- **Radio wavelengths** (kHz to GHz). Minutes to solar cycle timescales => radio interference

Energetic particles (electrons, protons, heavy ions)

- **Solar energetic particles (SEPs**): Tens of keV to GeV energies => radiation hazards to astronauts, spacecraft, aviation, ionosphere
- **"Galactic" cosmic rays**: Intensity modulated by solar activity Tens of MeV/n to >10 GeV => Radiation hazard to long duration space flight.

The Solar Wind

- Expansion of the Sun's hot corona into interplanetary space.
- **Ionized plasma** consisting of electrons, protons and heavier ions that contains "structures" ranging in size from kinetic scale "turbulence" to large (~AU) scale.
- Properties are controlled by conditions on the Sun including transient eruptions and long-lived features, and by interactions between structures in the solar wind.

Direct physical connection between the Sun and Earth.

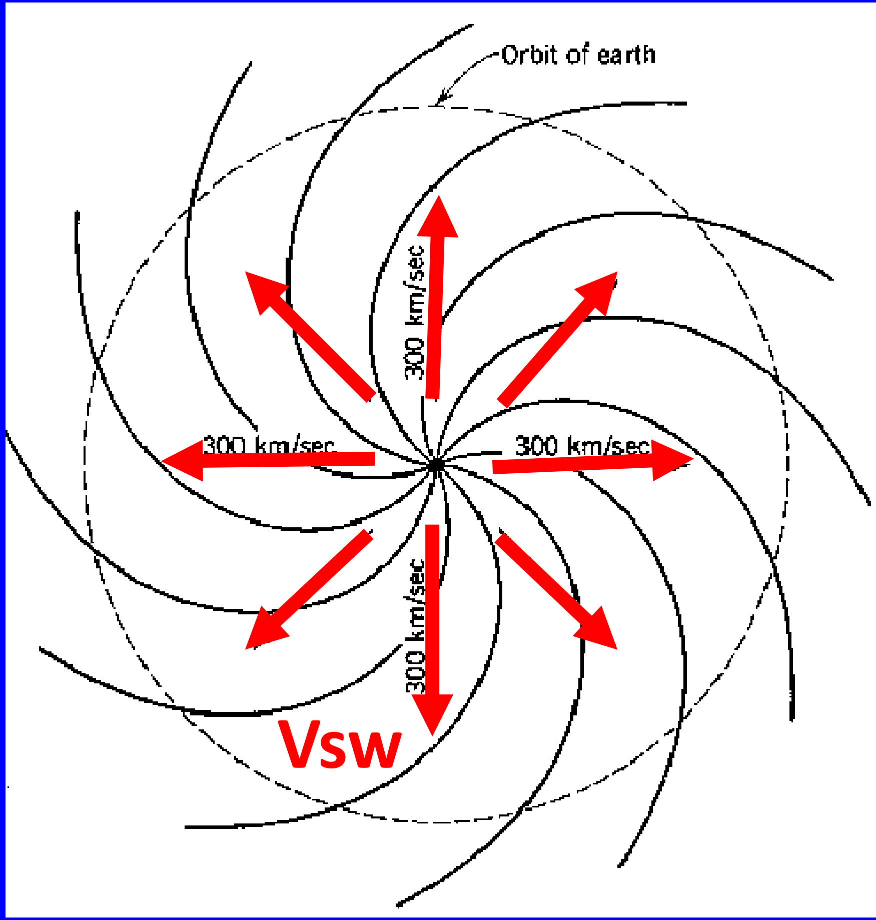
Solar "Wind" (*Parker*, 1958)

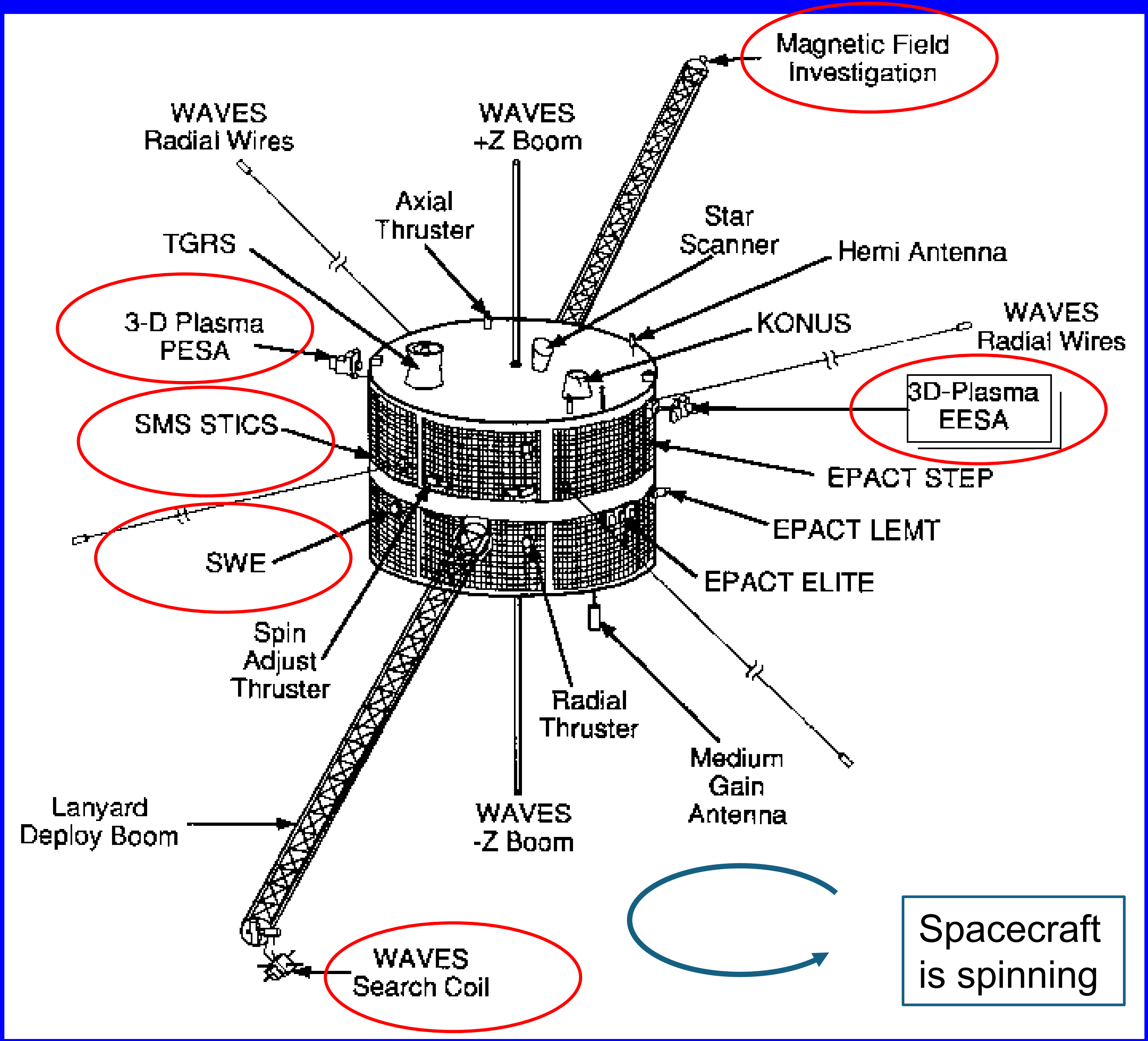
Theory: Expansion of the hot (~Mk) solar corona into interplanetary space produces a supersonic "solar wind" rather than a slower "solar breeze".

Solar wind flows out ~ radially.

Rotation of the Sun (period ~26 days) produces Archimedean spiral flow streamlines and interplanetary magnetic field configuration.

Inclined at ~45° to the radial direction at 1 AU for V_{sw}~400 km/s.



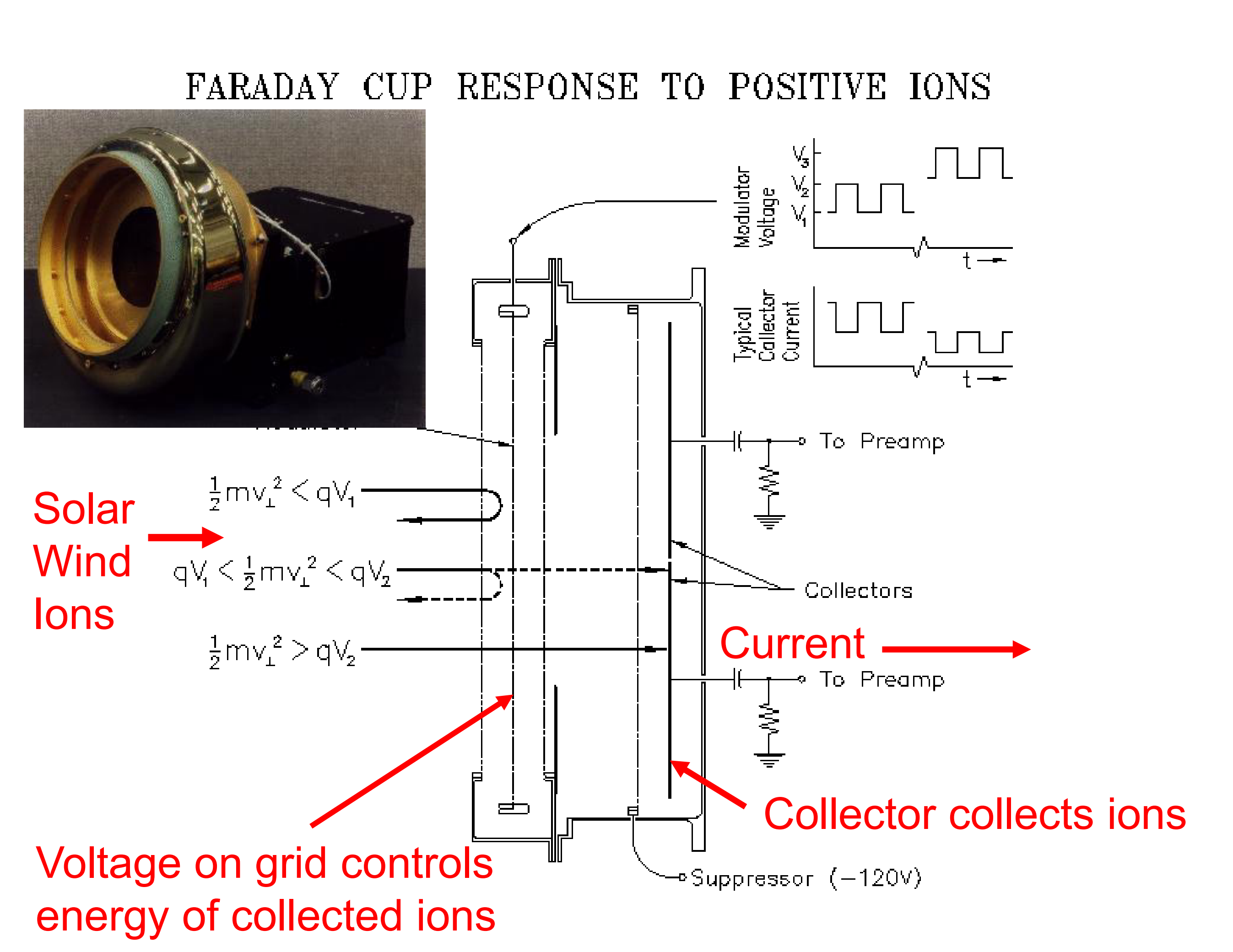


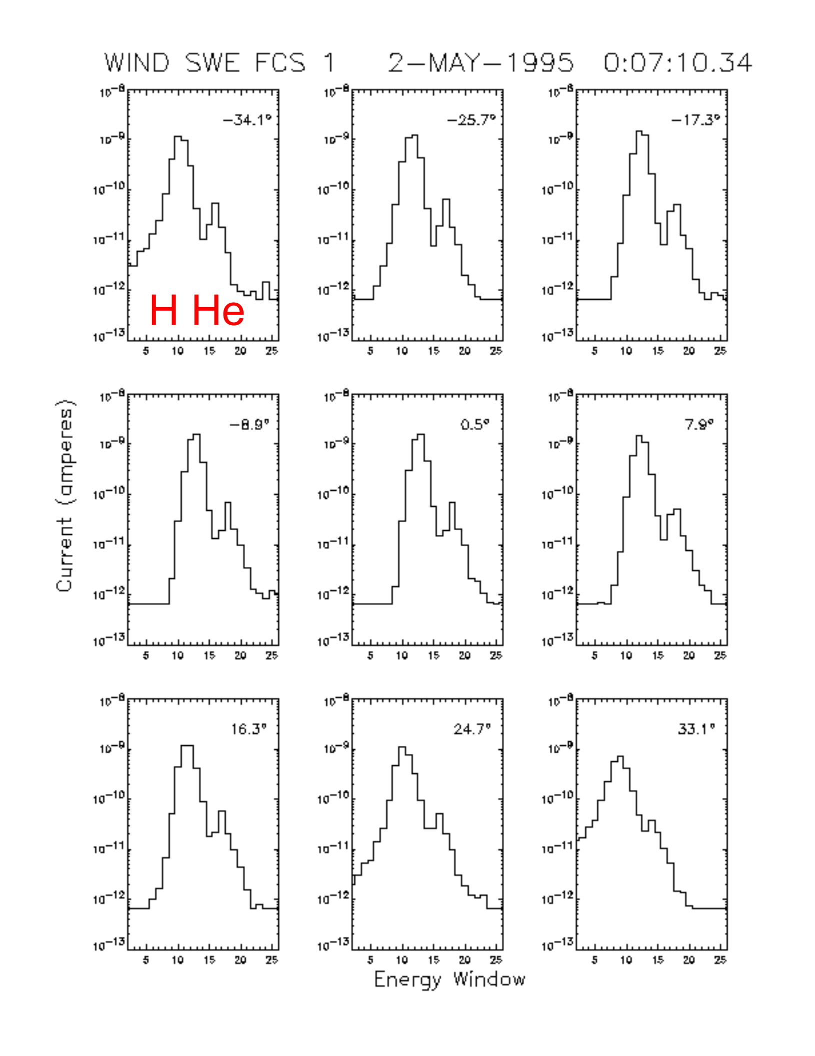
How do we Observe the Solar Wind?

Direct observations by spacecraft instruments measuring the properties of the solar wind plasma ions/electrons and magnetic field.

Instruments on the Wind Spacecraft

Solar Wind Plasma Measurement Using a Faraday Cup





MIT Space Plasma Group

HELIOPHYSICS SYSTEM OBSERVATORY

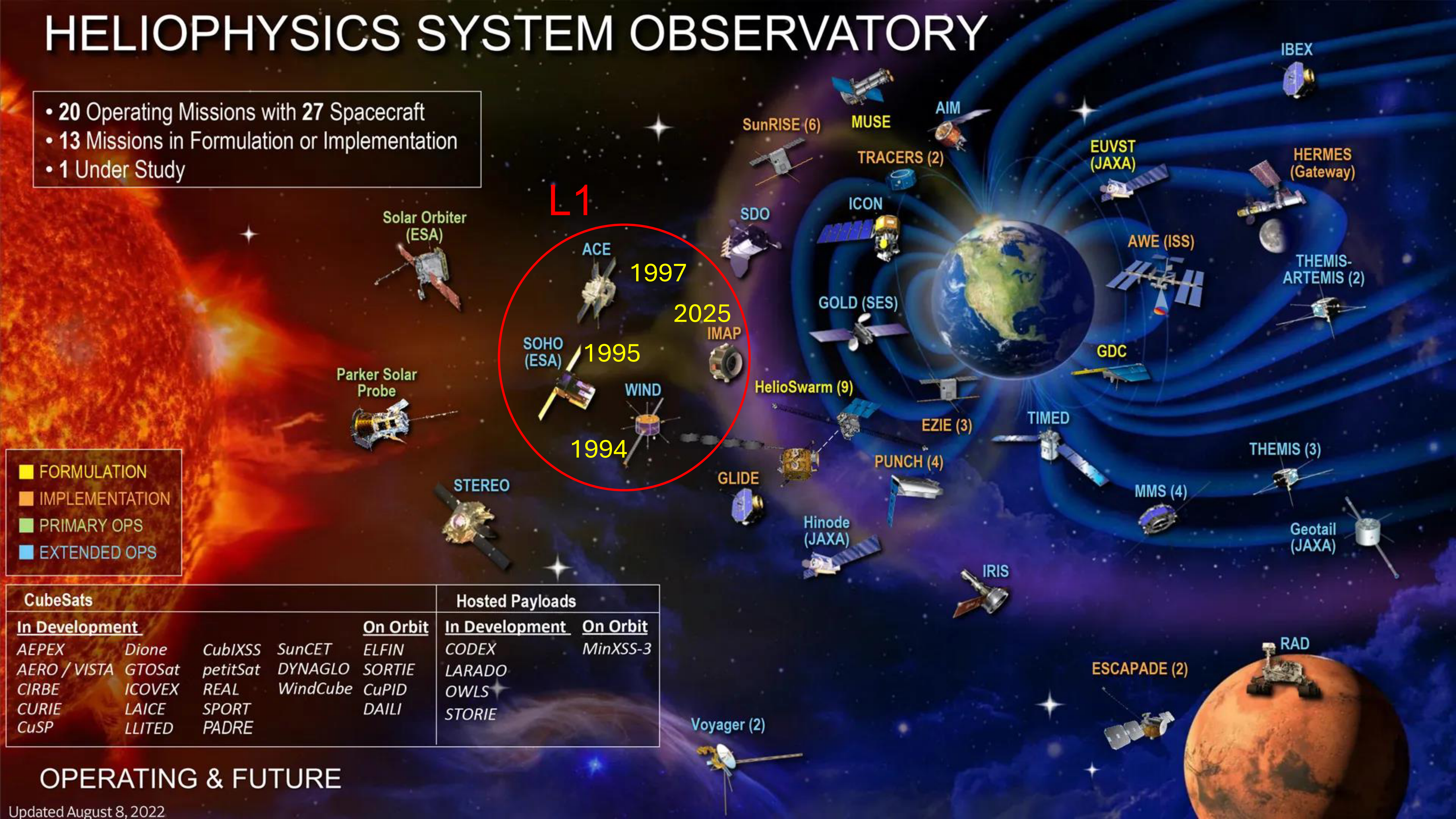
- **20** Operating Missions with **27** Spacecraft
- **13** Missions in Formulation or Implementation
- **1** Under Study

- FORMULATION
- IMPLEMENTATION
- PRIMARY OPS
- EXTENDED OPS

CubeSats					Hosted Payloads	
In Development				**On Orbit**	**In Development**	**On Orbit**
AEPEX	*Dione*	*CubIXSS*	*SunCET*	*ELFIN*	*CODEX*	*MinXSS-3*
AERO / VISTA	*GTOSat*	*petitSat*	*DYNAGLO*	*SORTIE*	*LARADO*	
CIRBE	*ICOVEX*	*REAL*	*WindCube*	*CuPID*	*OWLS*	
CURIE	*LAICE*	*SPORT*		*DAILI*	*STORIE*	
CuSP	*LLITED*	*PADRE*				

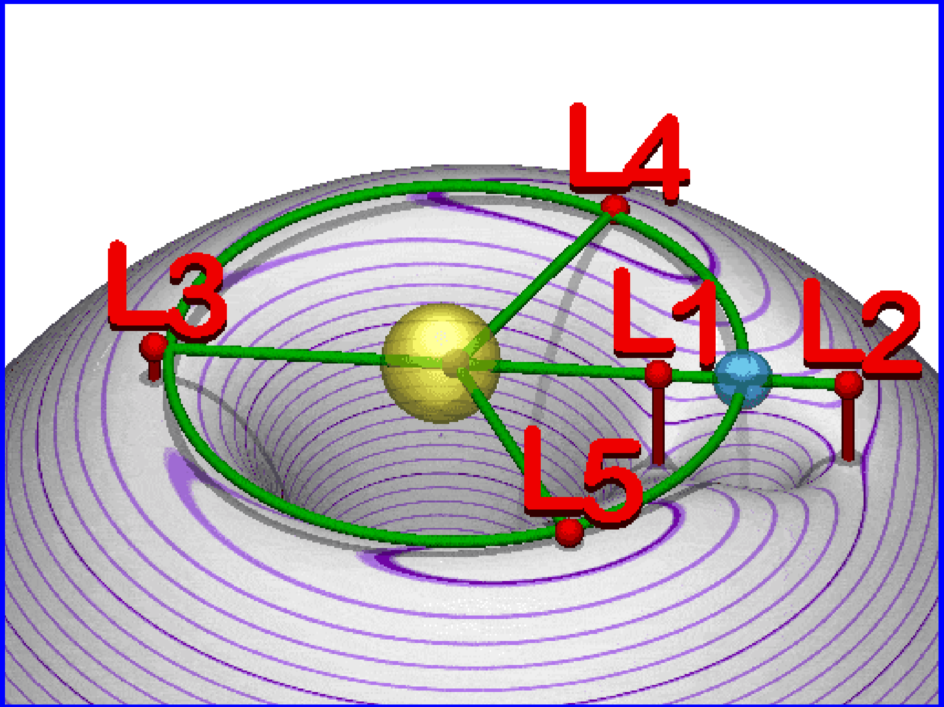
OPERATING & FUTURE

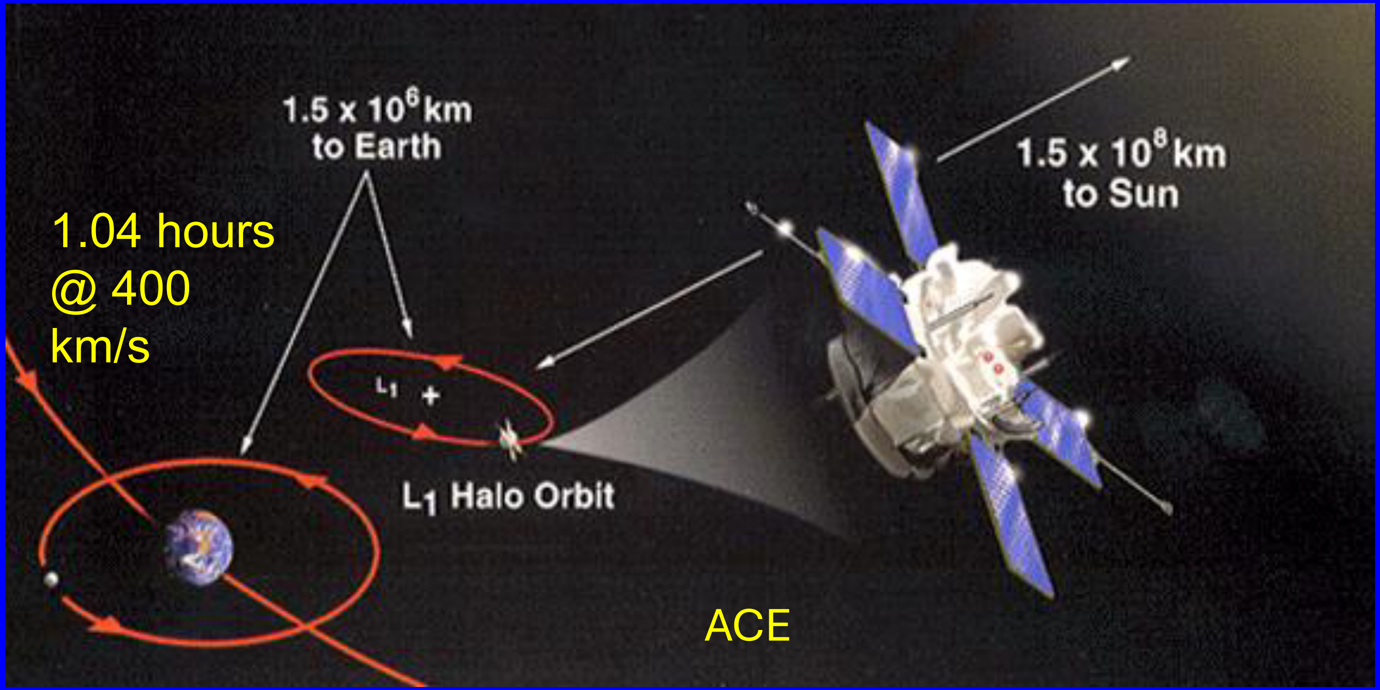
Updated August 8, 2022



HELIOPHYSICS SYSTEM OBSERVATORY
• 20 Operating Missions with 27 Spacecraft
• 13 Missions in Formulation or Implementation
• 1 Under Study
L1
ACE
1997
2025
IMAP
SOHO (ESA)
1995
WIND
1994
Solar Orbiter (ESA)
Parker Solar Probe
STEREO
SunRISE (6)
MUSE
AIM
TRACERS (2)
SDO
ICON
GOLD (SES)
HelioSwarm (9)
GLIDE
EZIE (3)
PUNCH (4)
Hinode (JAXA)
IRIS
TIMED
IBEX
EUVST (JAXA)
HERMES (Gateway)
AWE (ISS)
THEMIS-ARTEMIS (2)
GDC
THEMIS (3)
MMS (4)
Geotail (JAXA)
ESCAPADE (2)
RAD
Voyager (2)
FORMULATION
IMPLEMENTATION
PRIMARY OPS
EXTENDED OPS
CubeSats
In Development
AEPEX
AERO / VISTA
CIRBE
CURIE
CuSP
Dione
GTOSat
ICOVEX
LAICE
LLITED
CubIXSS
petitSat
REAL
SPORT
PADRE
SunCET
DYNAGLO
WindCube
On Orbit
ELFIN
SORTIE
CuPID
DAILI
Hosted Payloads
In Development
CODEX
LARADO
OWLS
STORIE
On Orbit
MinXSS-3
OPERATING & FUTURE
Updated August 8, 2022

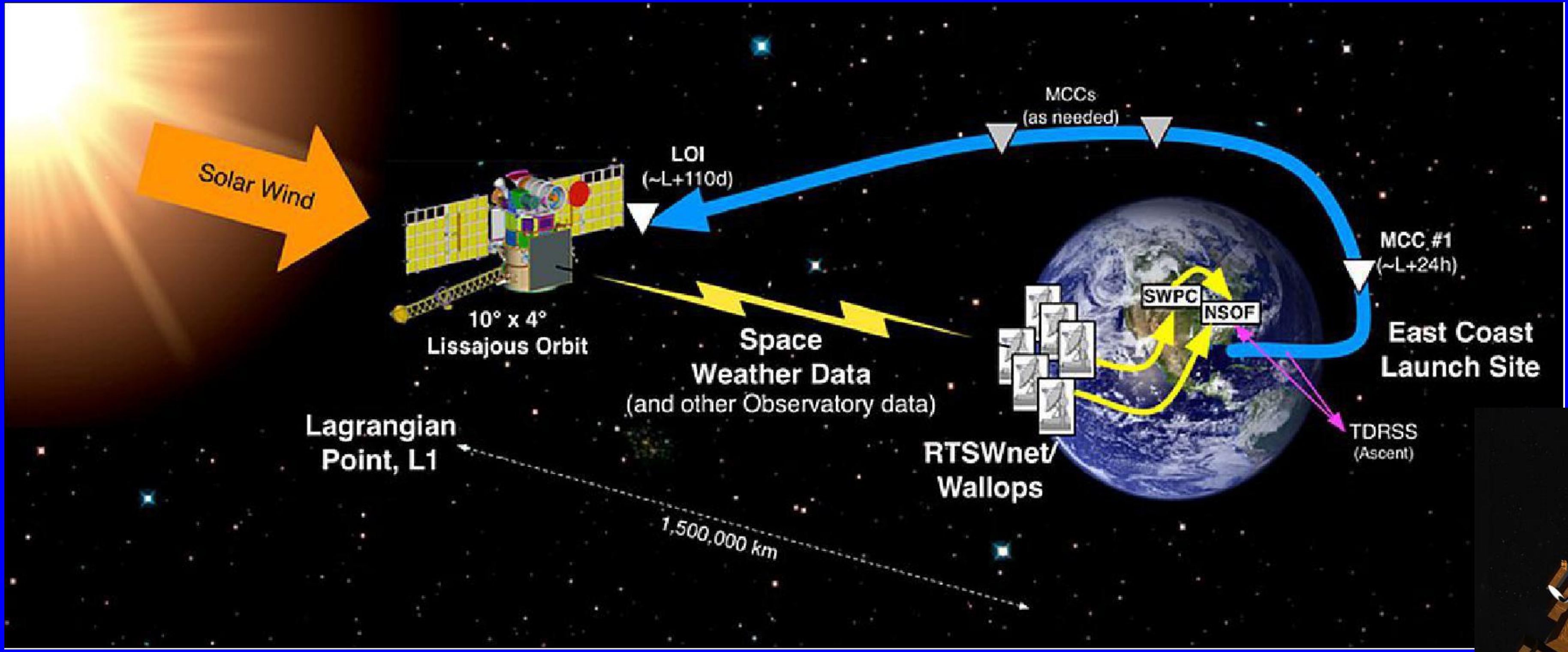
L1 is a stable location, but spacecraft are placed in (different) halo orbits about L1 to reduce radio interference from the Sun – **L1 spacecraft are off the Sun-Earth line**





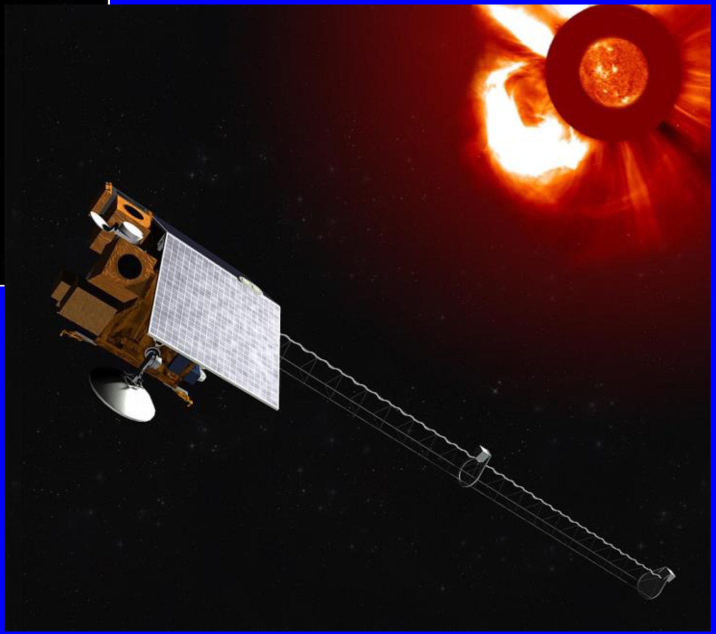
A new arrival at L1 with solar wind instruments!
Aditya-L1 (2023, India)

Deep Space Climate Observatory DSCOVR (2015, NASA-NOAA) USA – Focused on Earth Observations but with real-time solar wind measurements to support operations.



ACE and DSCOVR provide real-time solar wind data to support operations.

Future NOAA L1 Mission for operations:
SWFO-L1 (2025)



Examples of Missions Observing the Solar Wind

Parker Solar Probe 0.046-0.73 AU (2018-present)
Solar Orbiter 0.28-0.91 AU (2020-present)
Mercury Orbiters: MESSENGER (2004-20015, Mercury)
Bebicolombo (2018, en route to Mercury)
Helios 1 and 2 ~0.3-1 AU (1974-1984)
Mariner 2: Earth to Venus (1962-1963)

1 AU

- **Near Earth:**
  - **Earth Orbit**: e.g., IMP 7/8, Cluster, MMS.
  - **L1:** ISEE-3, ACE, Wind, SOHO, DSCoVR, Aditya-L1 (IMAP, SWFO-L1)

- **Other: STEREO A and B: Heliocentric orbit near 1 AU** (2006-present)

Spacecraft at Mars e.g., MAVEN (2013-present).
Ulysses 1.35-5.4 AU (out of the ecliptic) (1990-2009)
Planetary missions to Jupiter/Saturn (e.g. Cassini) **and beyond** (New Horizons)
Pioneer 10 1-80 AU (1972-2002) and **Pioneer 11 1-43 AU** (1973-1995)
Voyager 1 (1977, ~160 AU) and 2 (1977, ~140 AU)

Study of the solar wind is limited by the lack of observations!

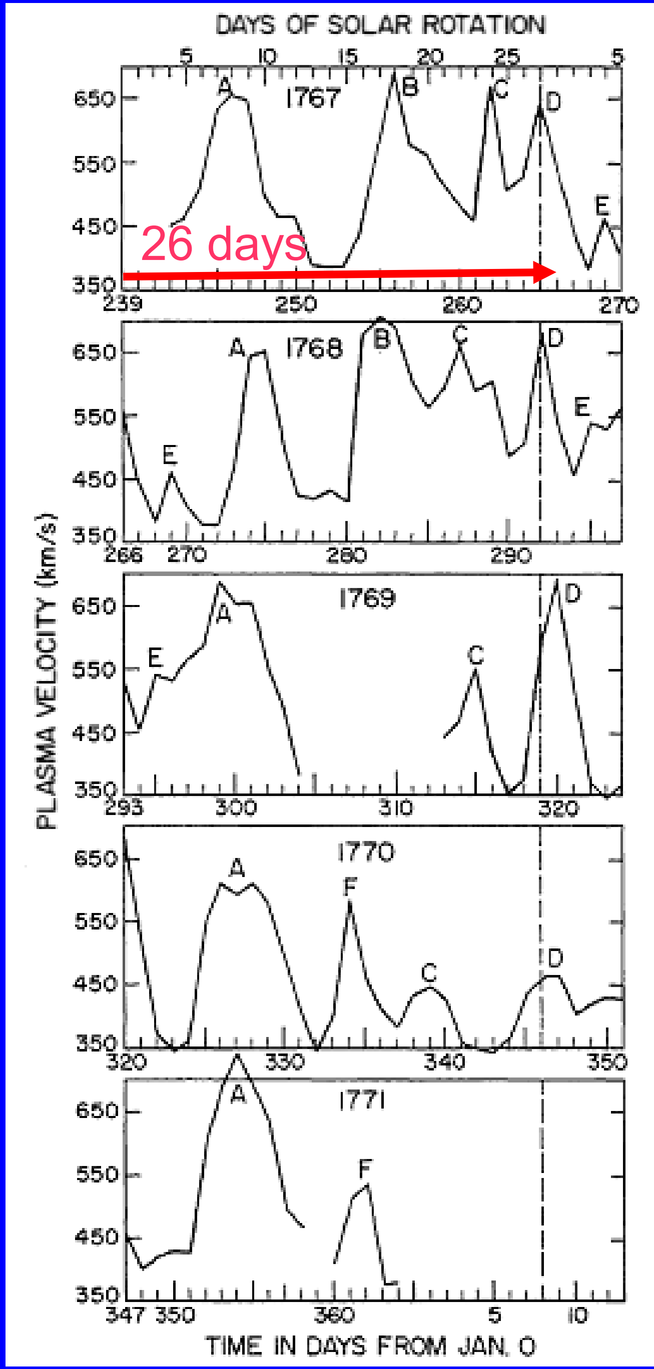
- **For space weather operations, need continuous monitoring of the solar wind, in particular upstream of Earth, with low latency (the time to acquire the data, transmit it to ground, produce data products and pass them to operations).**

Parameter	Mean Value	5-95% Range
Speed (km/s)	468	320 – 710
Density (protons/cc)	8.7	3.2 – 20 + ~5% He + heavier ions, equal number of electrons
|B| (nano-Tesla)	6.6	2.2 - 9.9
Proton Temperature (K)	120,000	10,000 - 300,000
Electron Temperature (K)	140,000	90,000 - 200,000
Alfven Speed (km/s)	50	30 – 100
Sound Speed (km/s)	63	41 – 91
Alfvenic Mach No.	10.7	4.4 – 20
Sonic Mach No.	7.7	5.6 – 10

Typical properties of the Solar Wind at 1 AU

The solar wind carries **1.7×10^{27} ergs/s of kinetic energy** on the average through a sphere at 1 au compared to **0.05×10^{27} ergs/s of thermal energy** and **0.025×10^{27} ergs/s of magnetic energy**. => kinetic energy is dominant. (http://www.windows.ucar.edu/)

Solar Wind Speed During Five Solar Rotations

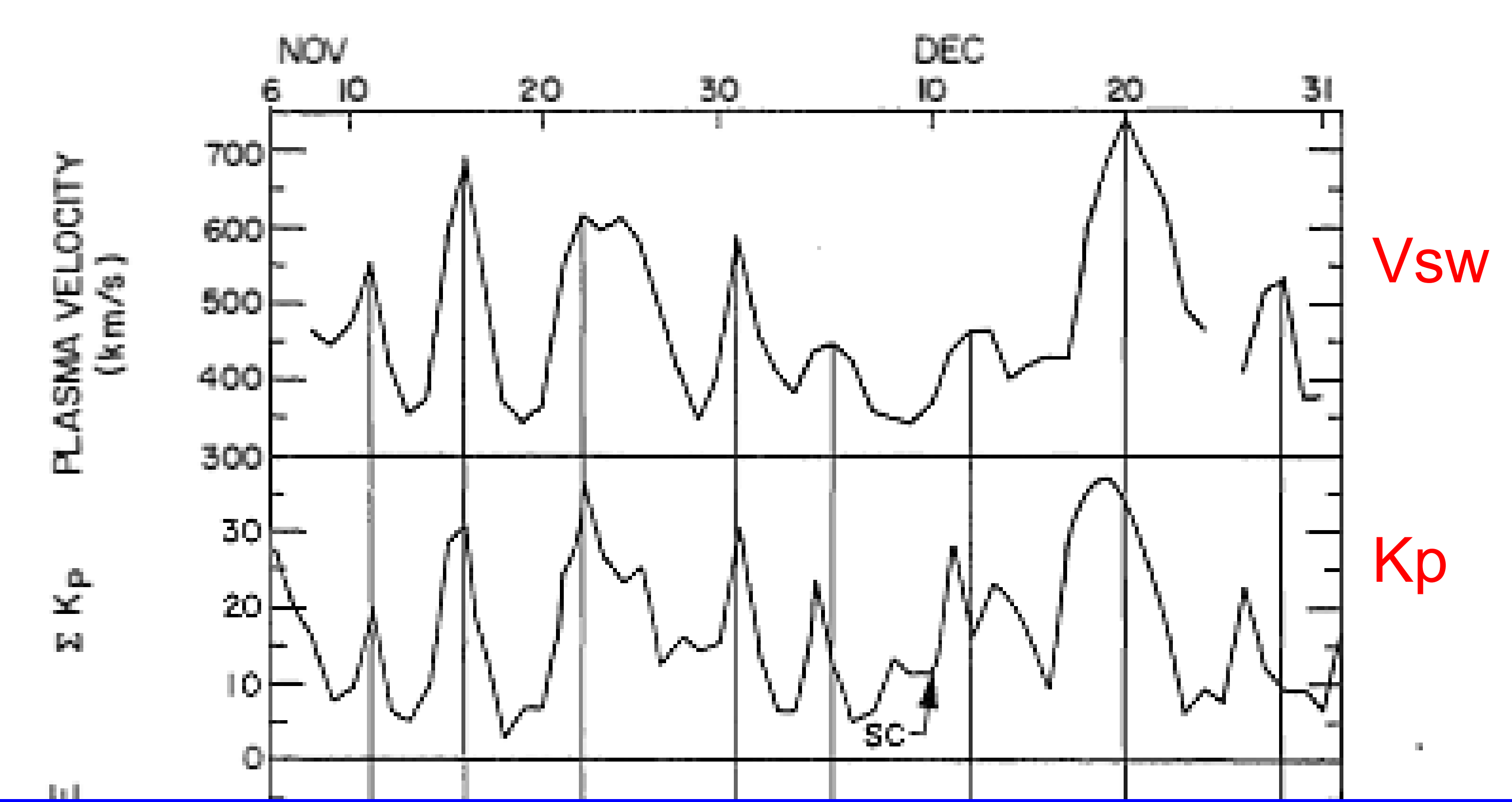


Snyder and Neugebauer (1962); Snyder et al. (1963) Discovery of Corotating High-Speed Solar Wind Streams

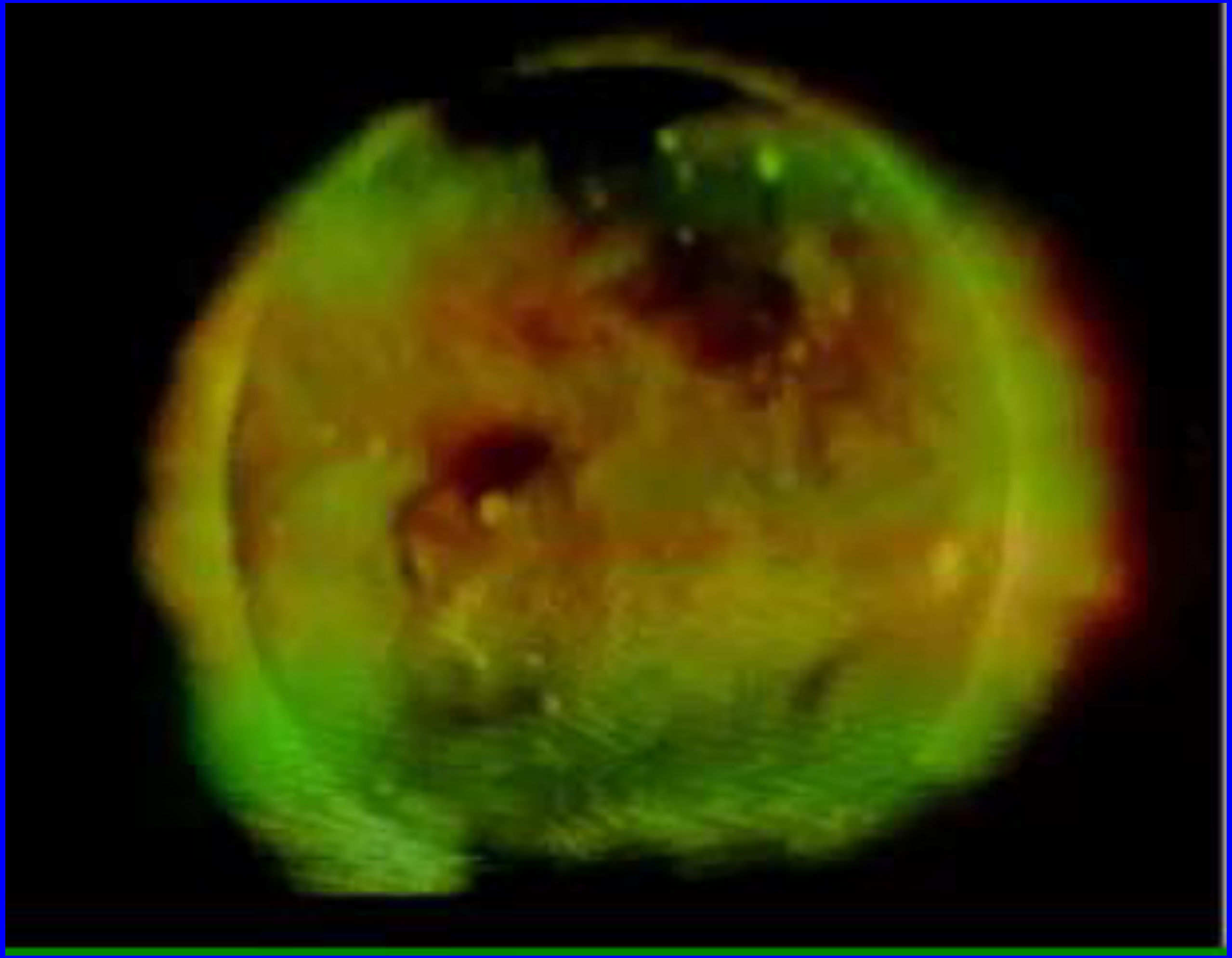
Solar wind (in this interval in 1962) was organized into **fast streams** (~600 km/s) separated by **slower solar wind**.

Some streams persisted for at least 4 solar rotations => corotating with the Sun

Solar wind speed is closely correlated with enhanced geomagnetic activity (Kp index) => recurrent geomagnetic enhancements (*Snyder et al.*, 1963)



Discovery of “Coronal Holes” by Skylab Soft X-Ray Telescope (1973-1974)



https://solarscience.msfc.nasa.gov/images/skylab.mpg

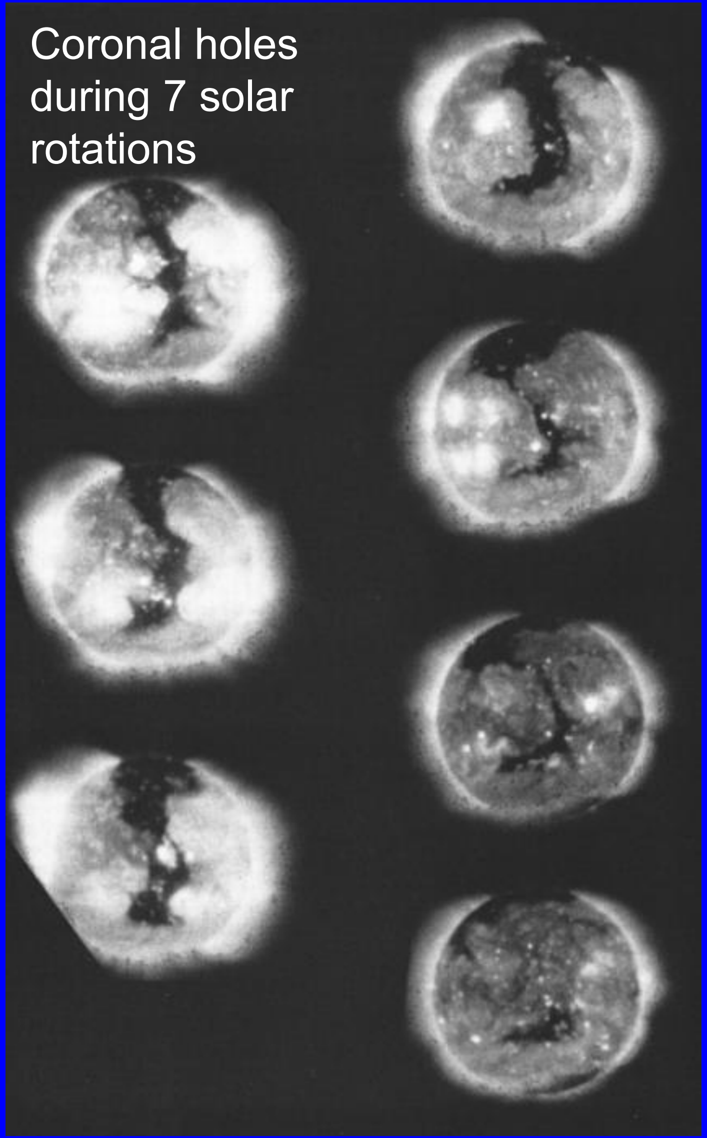
Dark regions are coronal holes.

Corotate with the Sun.

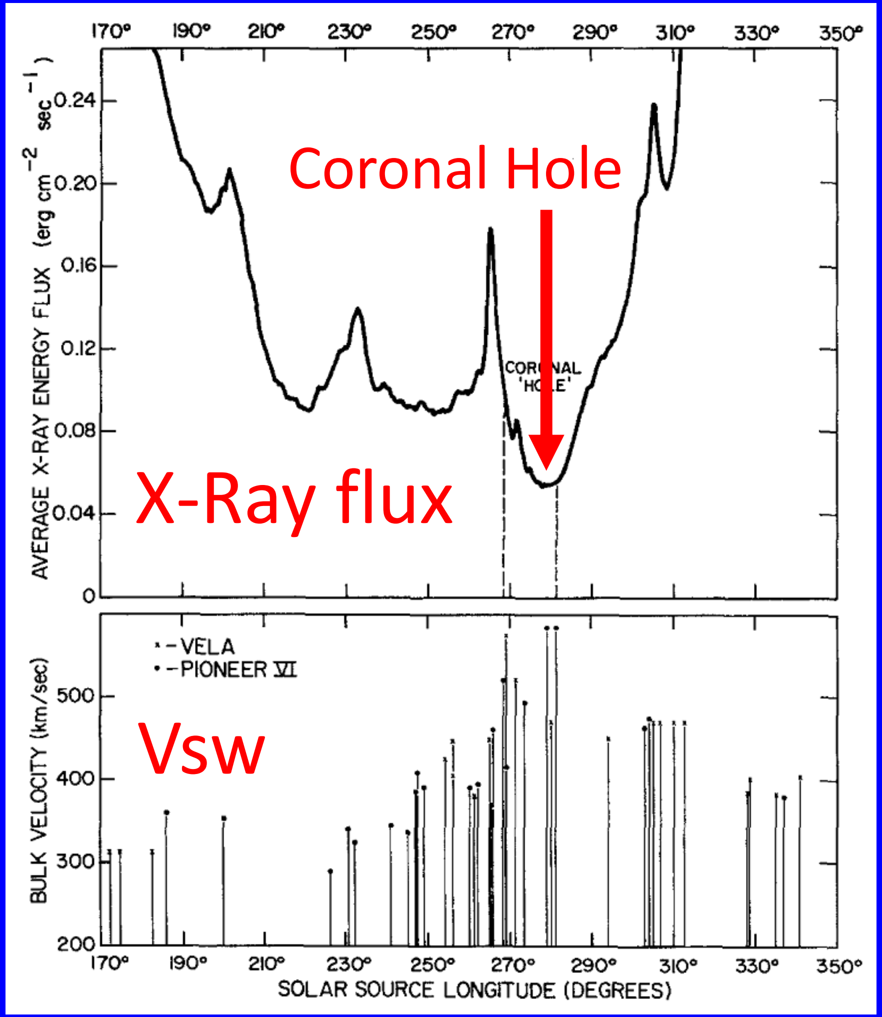
Can last for several solar rotations.

Prominent “Boot of Italy” equatorward extension of coronal hole at north pole.

Association of Skylab Coronal Holes With High-Speed Solar Wind Streams

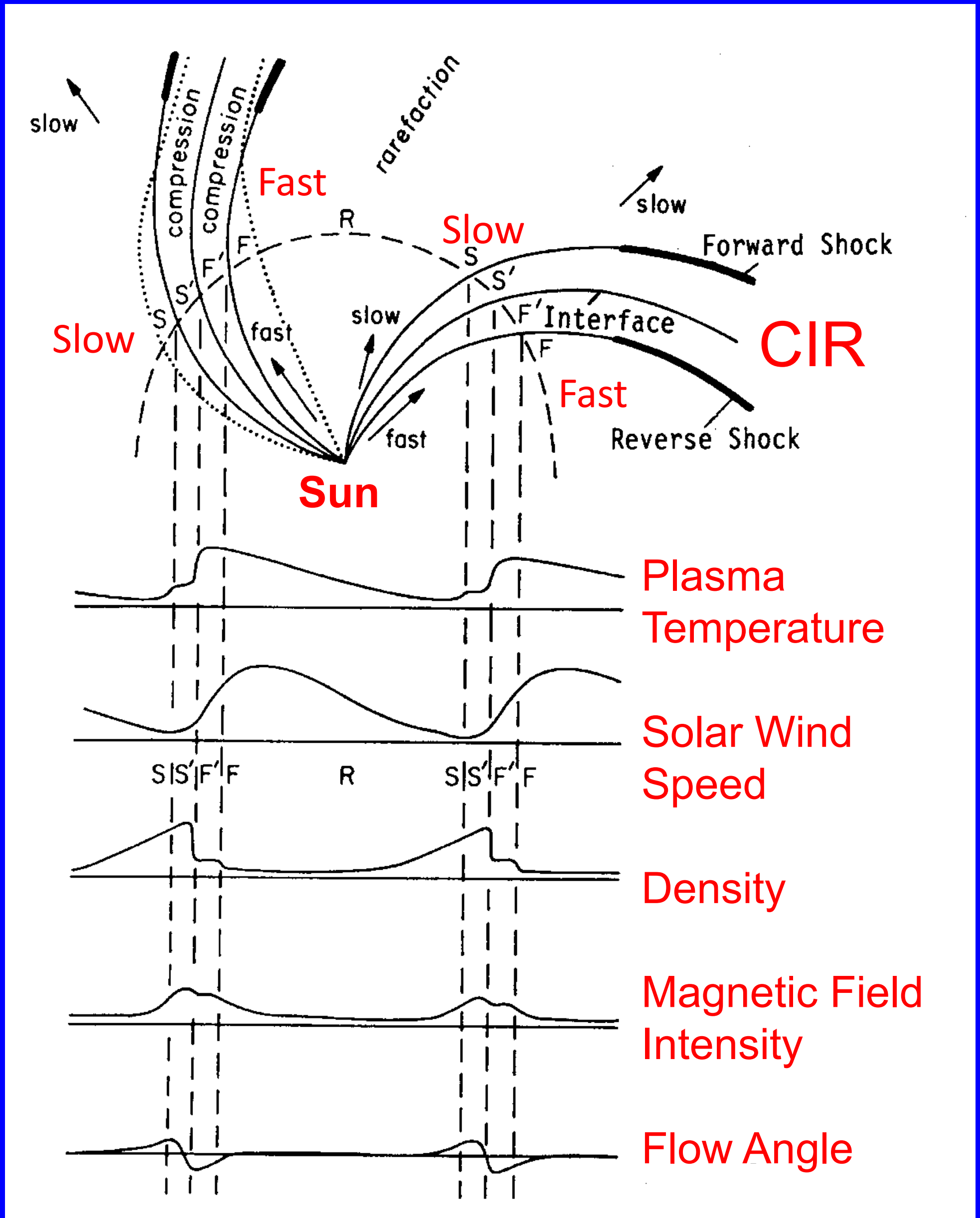


Zirker, 1977



Krieger et al., 1973

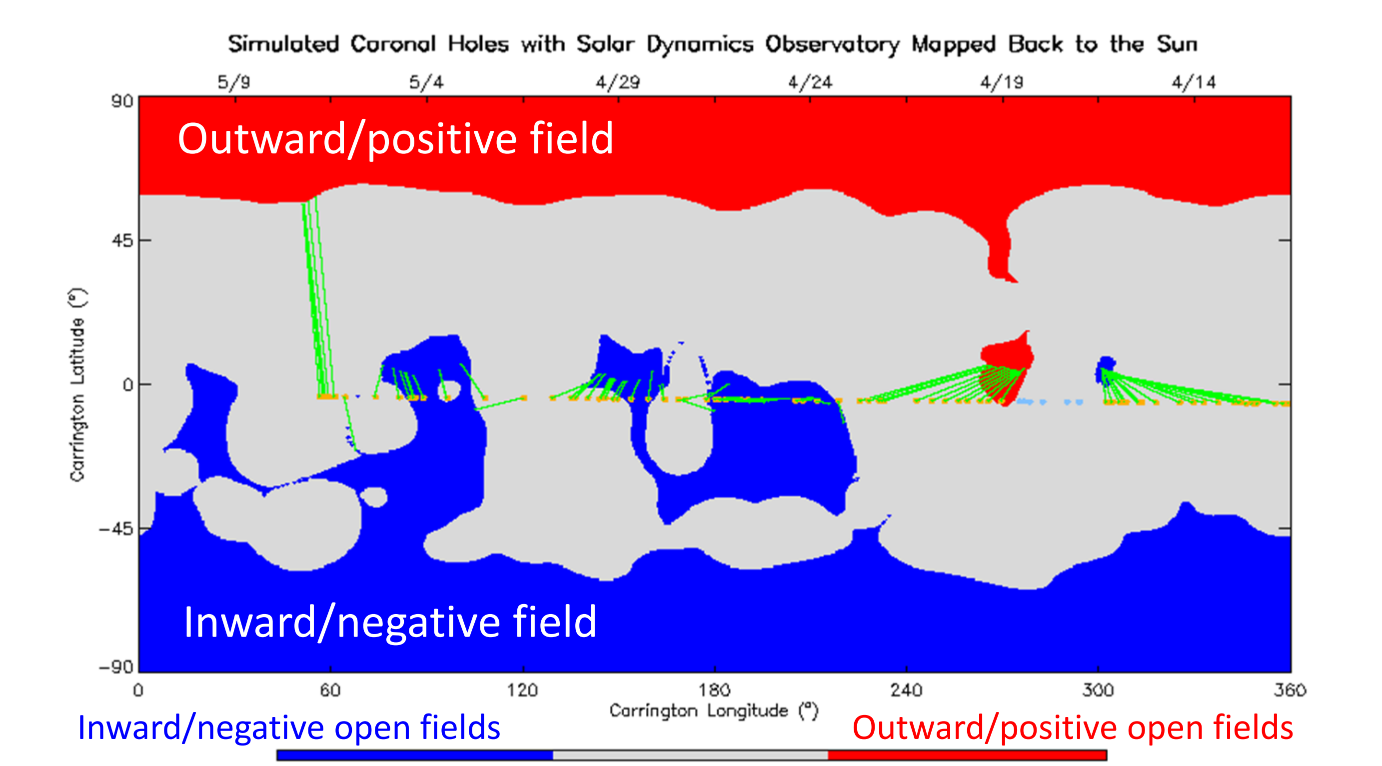
Formation of Corotating/Stream Interaction Regions (CIRs/SIRs)



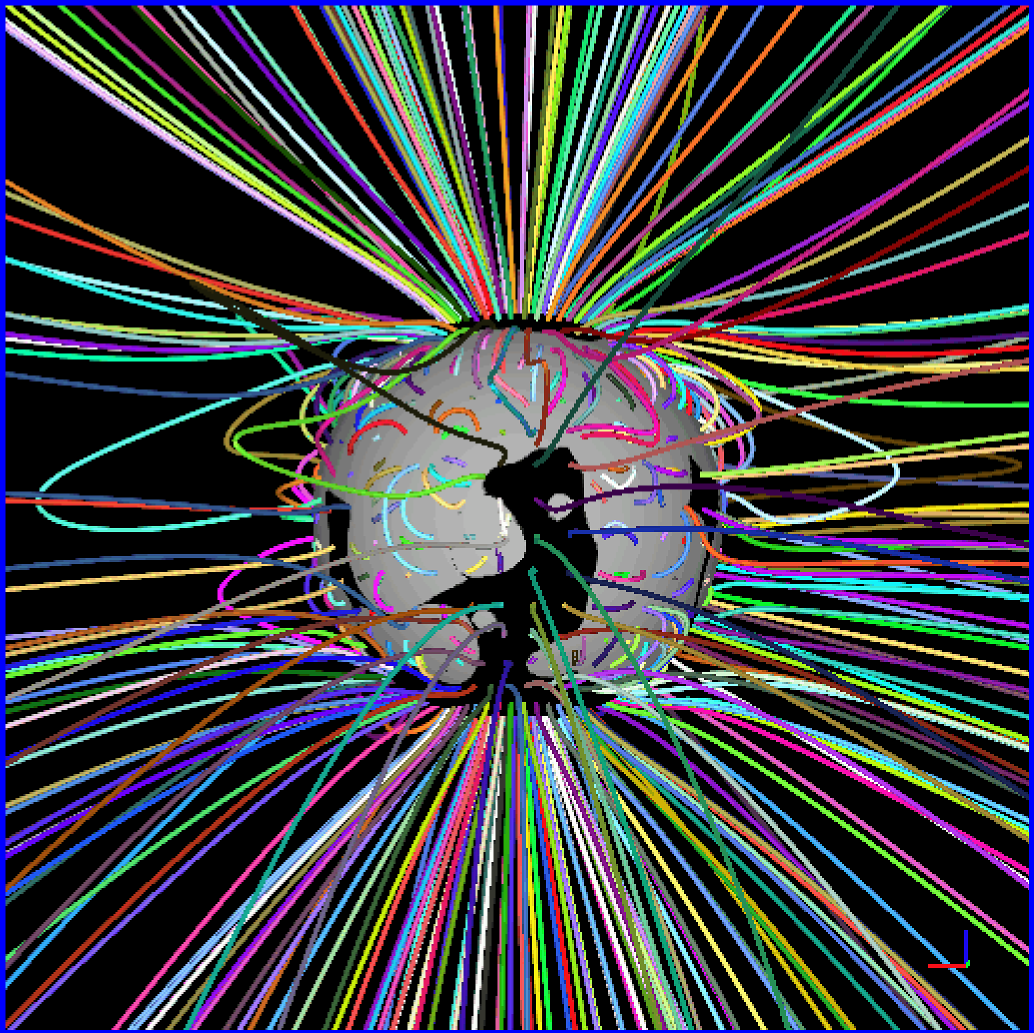
Richardson et al., 1996, after *Belcher and Davis,* 1971

- Interaction of fast solar wind with the slow wind ahead of it forms regions of compressed plasma – corotating interaction regions.
- Elevated density and magnetic field intensity.
- Characteristic profiles at 1 AU.
- May be bounded by shocks (typically beyond ~2 AU)
- Review paper: Solar wind stream interaction regions throughout the heliosphere, I.G. Richardson, Living Rev. Sol. Phys. (2018) 15:1 https://doi.org/10.1007/s41116-017-0011-z

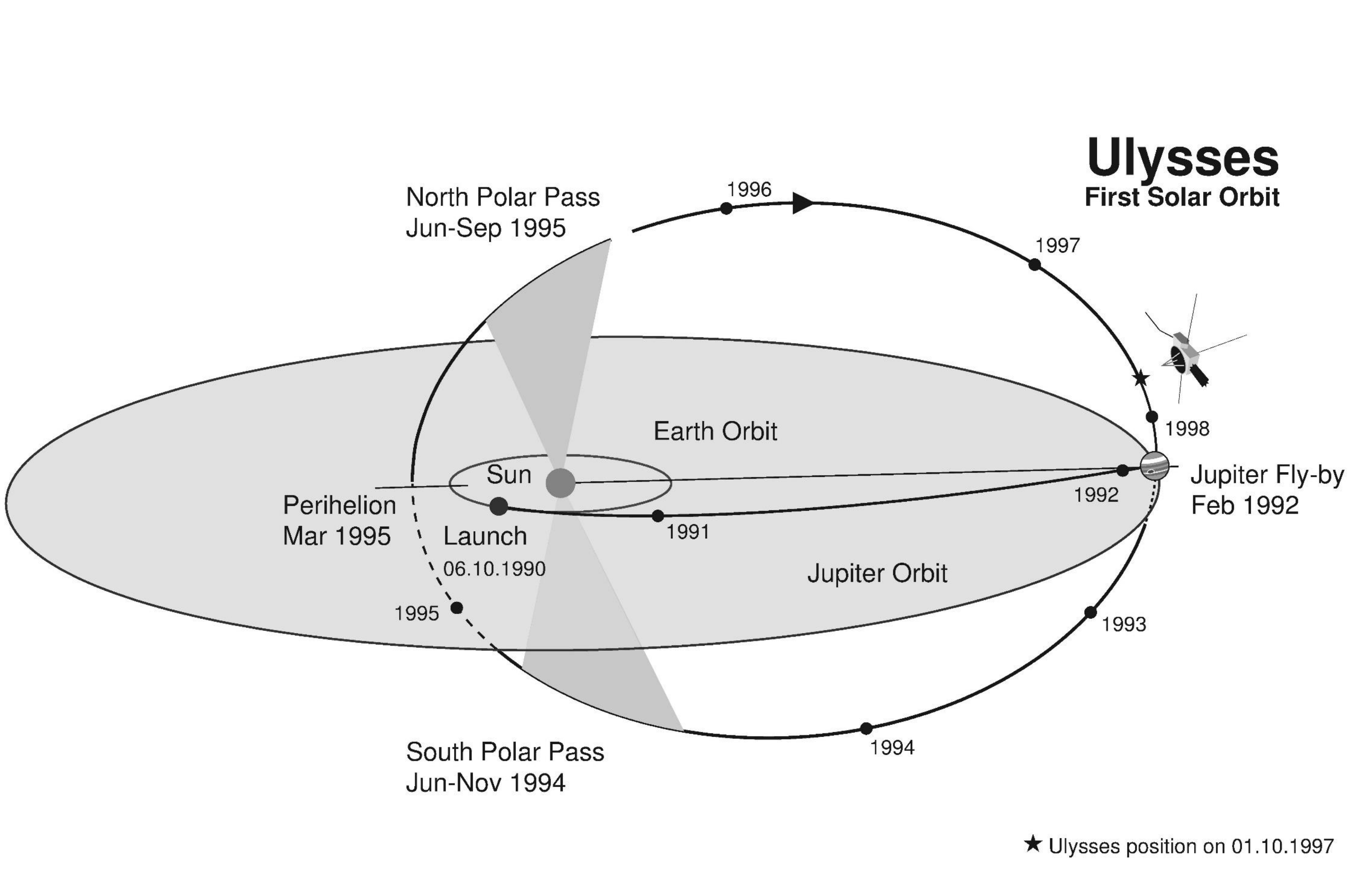
Coronal Holes and Coronal Magnetic Fields Derived From SDO HMI Magnetogram Data for Carrington Rotation 2216 (May 2019, Solar Minimum) (Predictive Sciences)



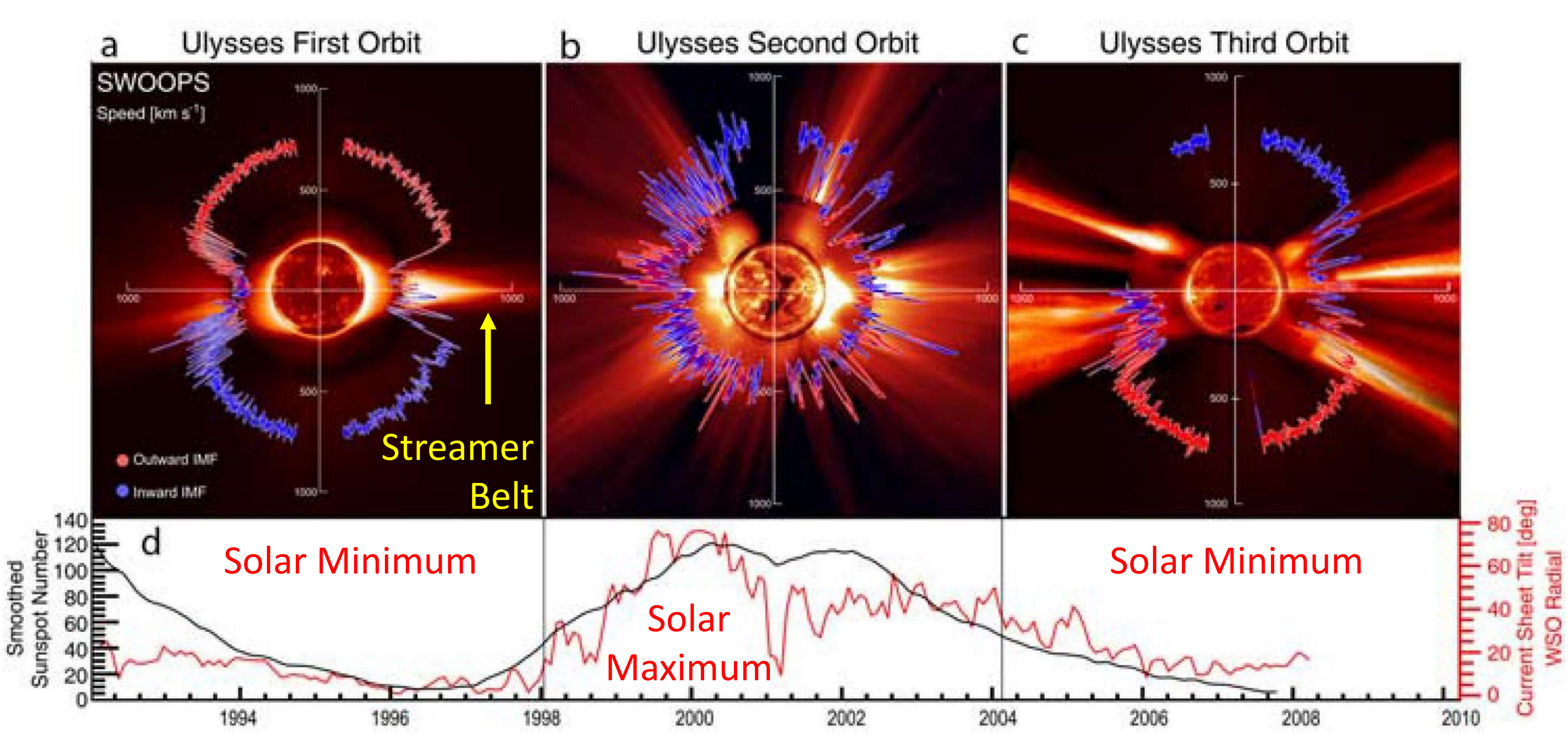
Open Field Lines From Coronal Hole



www.predsci.com

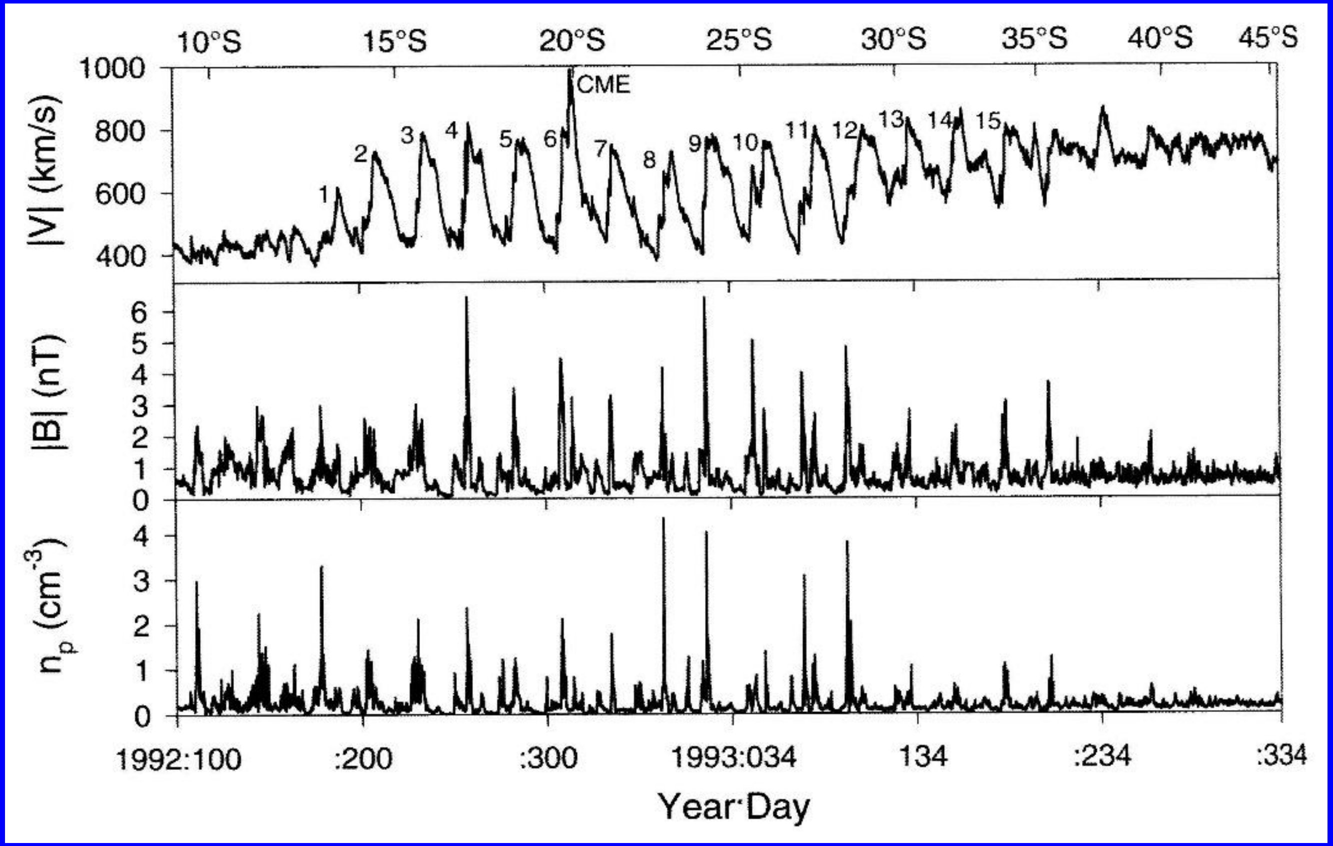

Ulysses
First Solar Orbit
North Polar Pass
Jun-Sep 1995
1996
1997
1998
Earth Orbit
Sun
Perihelion
Mar 1995
Launch
06.10.1990
1991
1992
Jupiter Fly-by
Feb 1992
Jupiter Orbit
1995
1993
1994
South Polar Pass
Jun-Nov 1994
★ Ulysses position on 01.10.1997

Latitudinal Variation in Vsw Observed by Ulysses During Three Orbits of the Sun



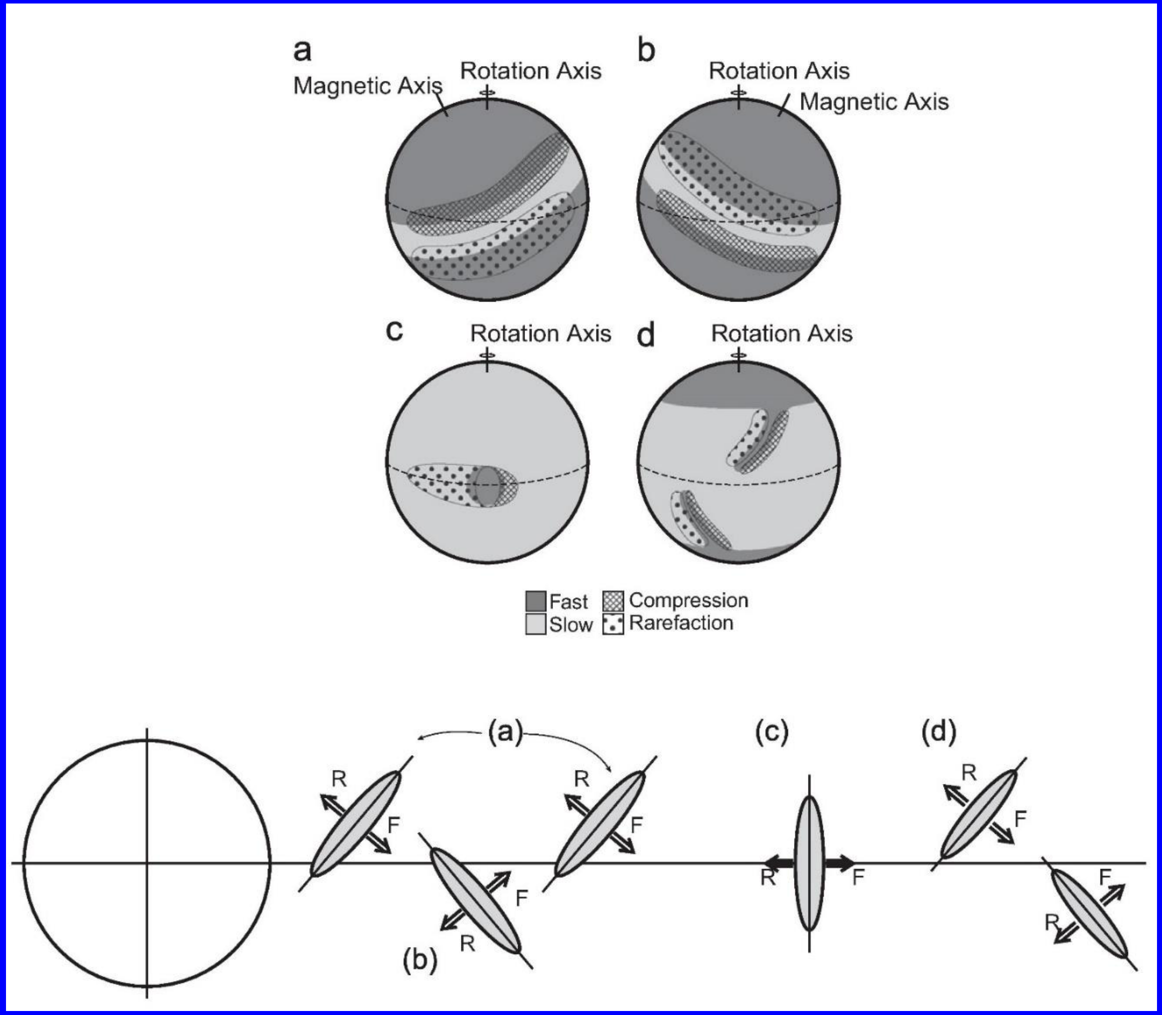
McComas et al. (2008)

Interaction Regions at Ulysses During Ascent to Higher Southern Latitudes



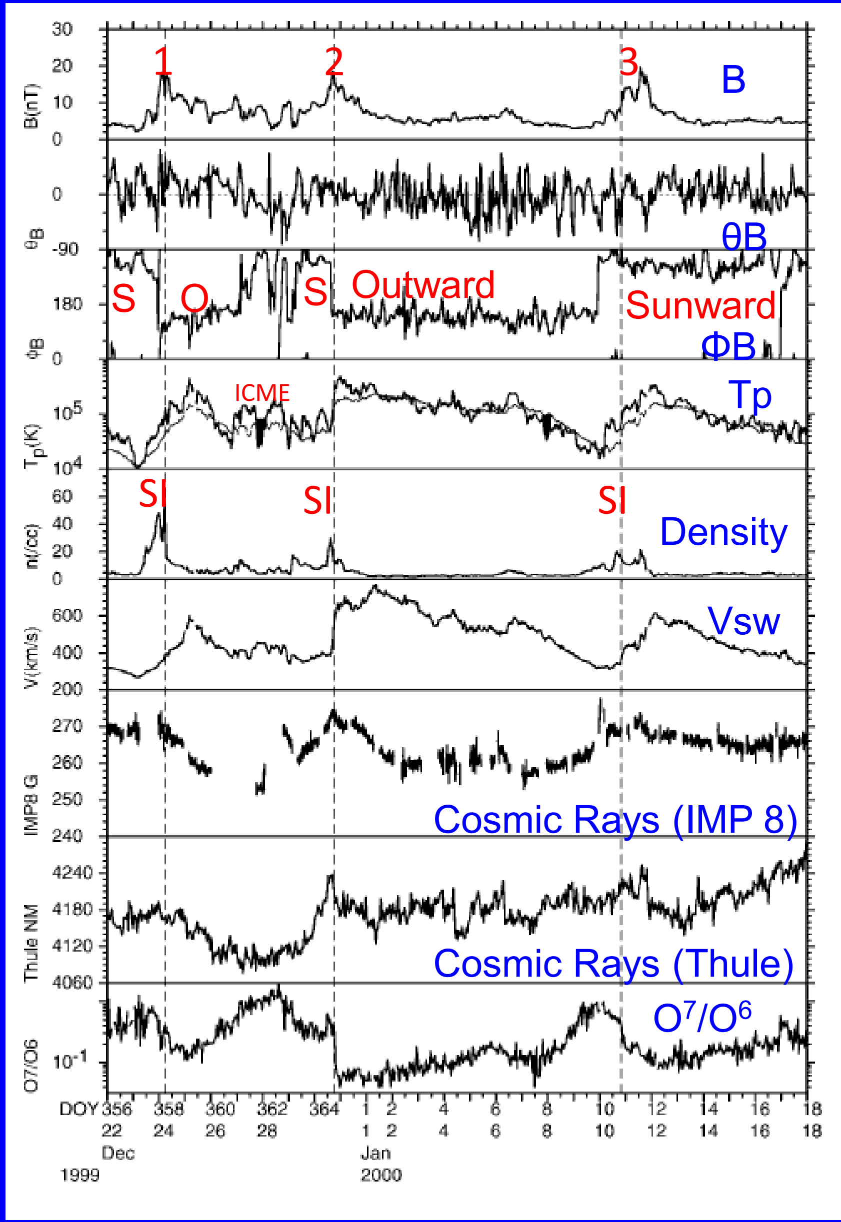
Bame et al. (1993)

Interaction Region Orientations for Different Coronal Hole Configurations



Riley et al. (2012)

Three CIRs/SIRs in One Solar Rotation in Dec. 1999-Jan. 2000



Richardson, 2004

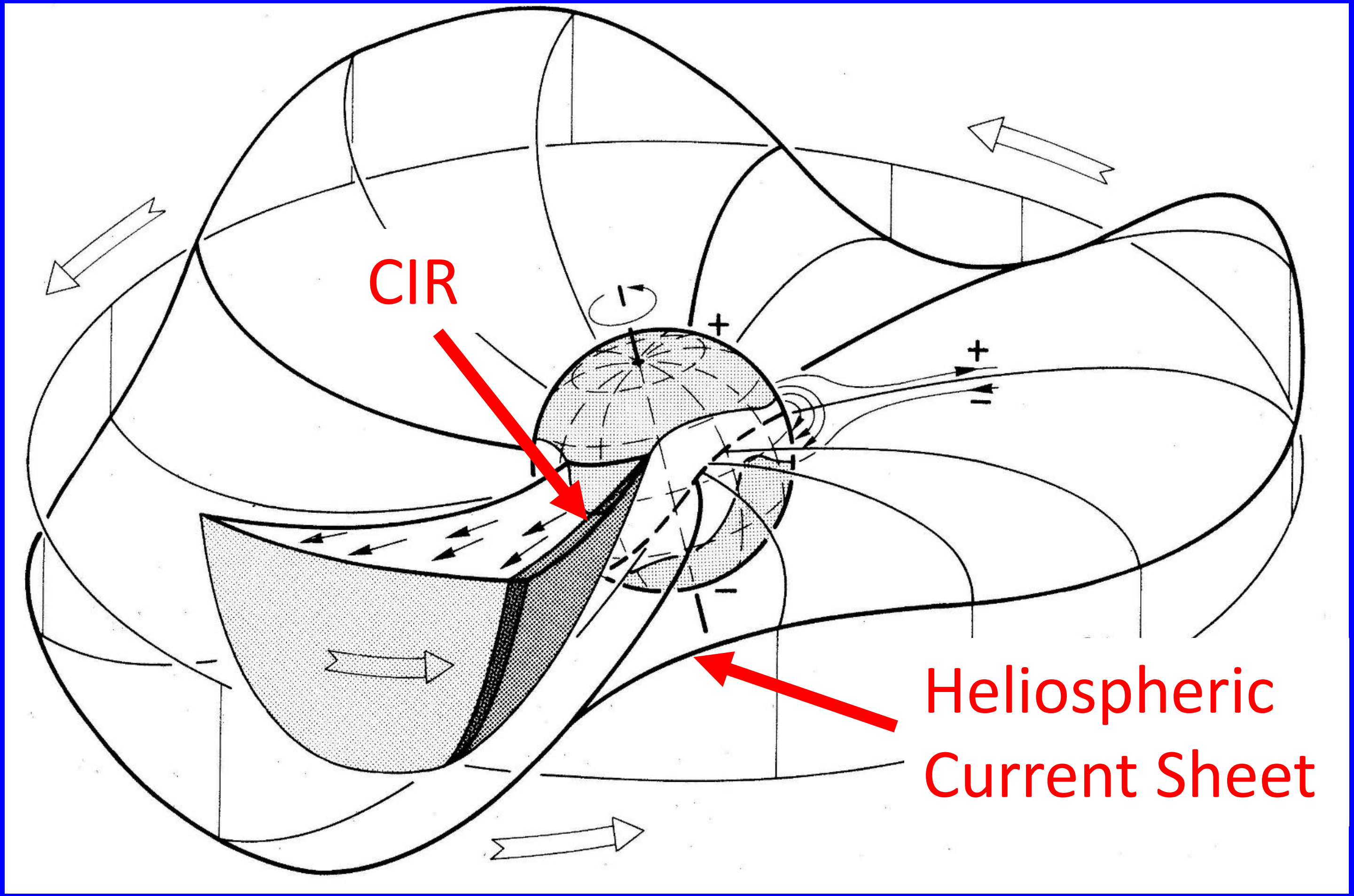
SI= stream interface

Note also modulations in the Galactic cosmic ray intensity

Differences in oxygen charge states (O^7/O^6 ratio) in slow and fast solar wind, and abrupt changes at the stream interfaces. **Suggest different sources for fast and slow solar wind.**

Magnetic "sector boundaries"/crossings of the heliospheric current sheet close to CIRs.

Heliospheric Current Sheet May be "Swept Up" by a CIR



"Heliospheric current sheet" separating outward and inward fields lies above the streamer belt in the slow solar wind [at solar minimum].

Schwenn (1990)

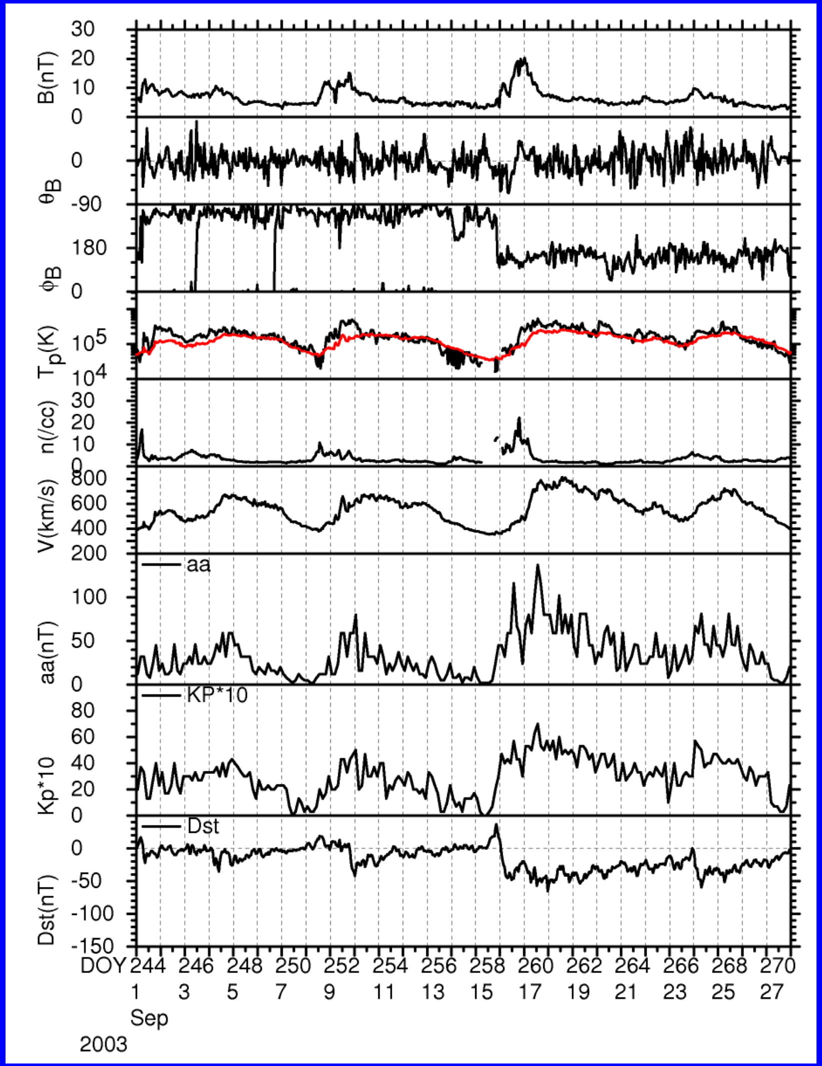
Comparison of Streams and Geomagnetic Activity in 2003 and 2009

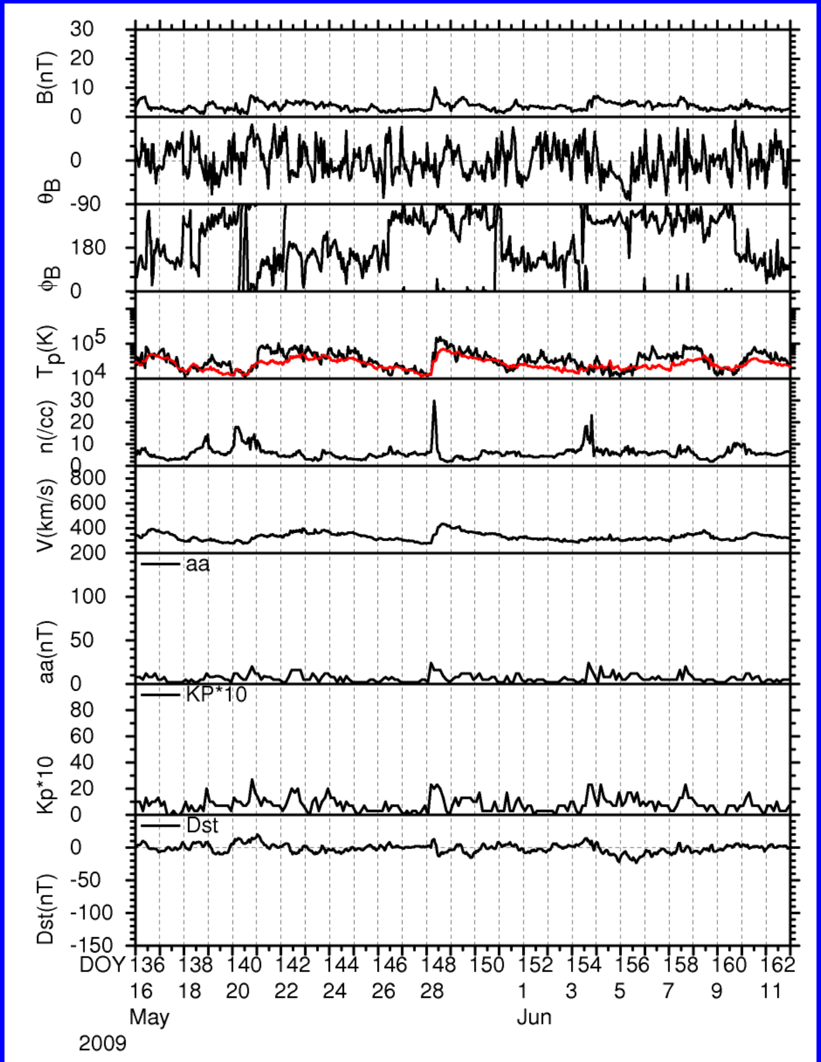
Vsw

aa

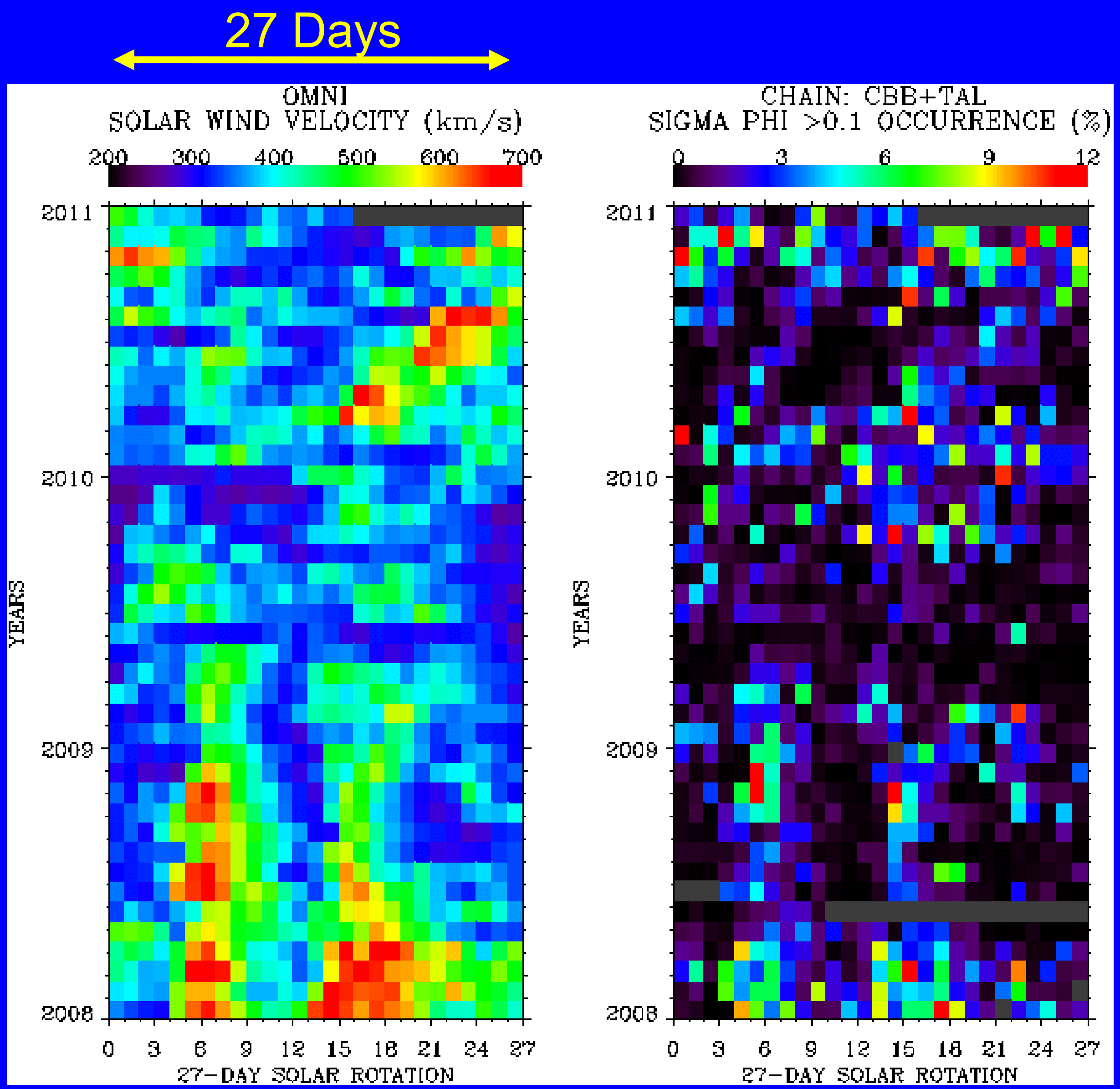
Kp

Dst



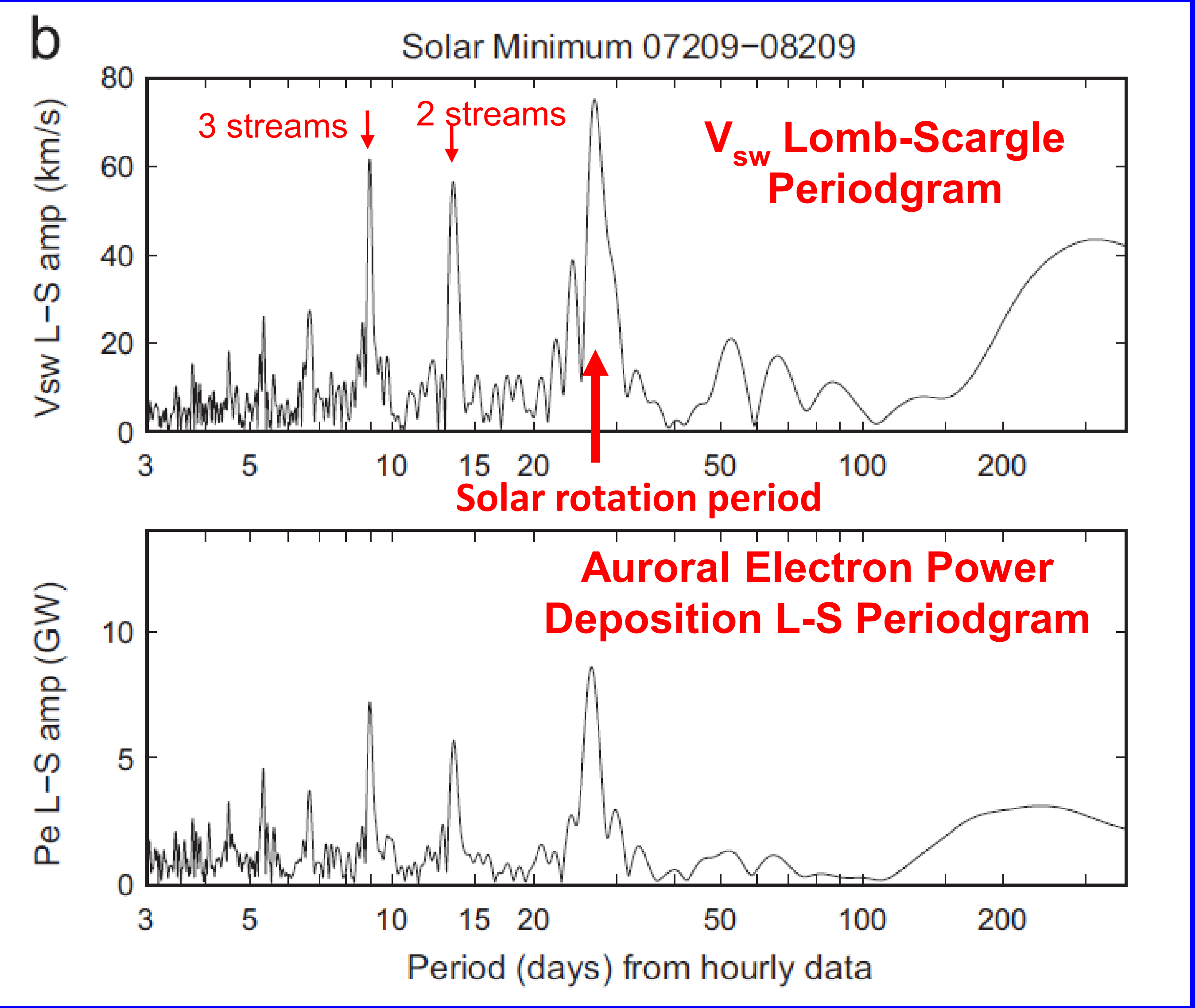


Solar Wind Speed and GPS Phase Scintillation Occurrence in 2008-2010



Prikryl, Jayachandran, Mushini, Richardson, 2012

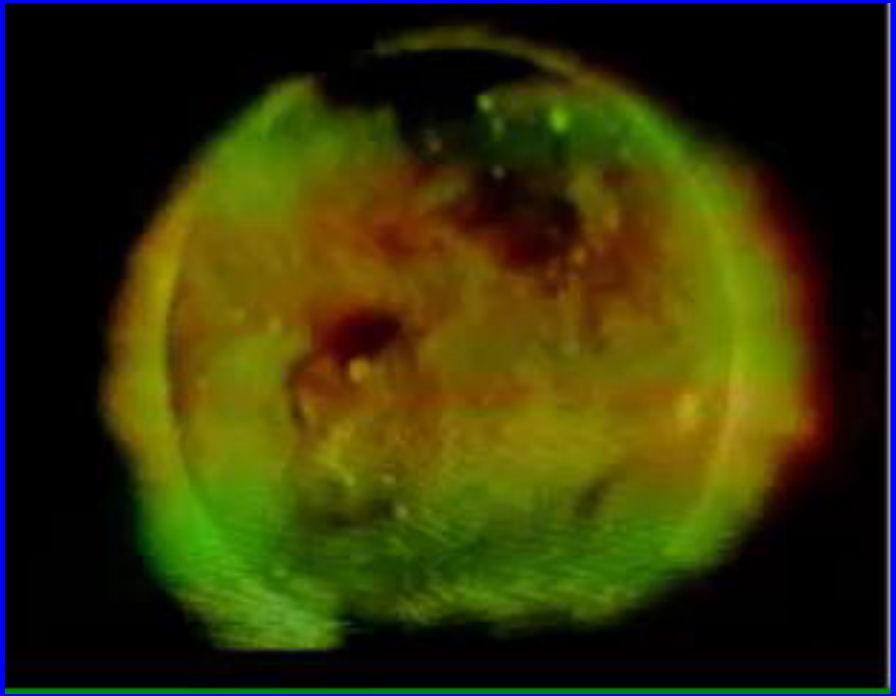
Similar Periodicities in Solar Wind Speed and Electron Power Deposition into the Auroral Zones (2007, doy 209 - 2008, doy 209)



Emery et al., 2009

Major Solar Drivers of Space Weather

Coronal Holes =>
Corotating High-speed Streams

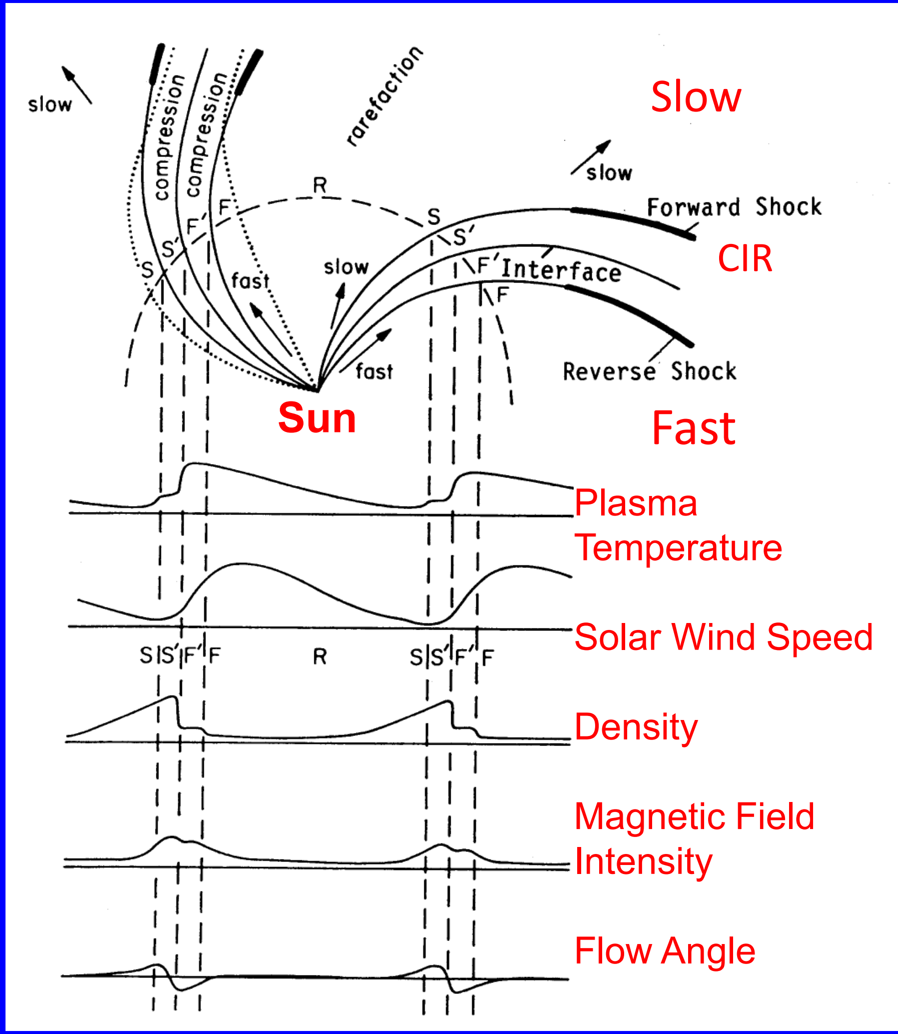


Skylab soft X-ray observations of a large coronal hole in 1973

Coronal Mass Ejections =>
Interplanetary Coronal Mass Ejections (ICMEs)

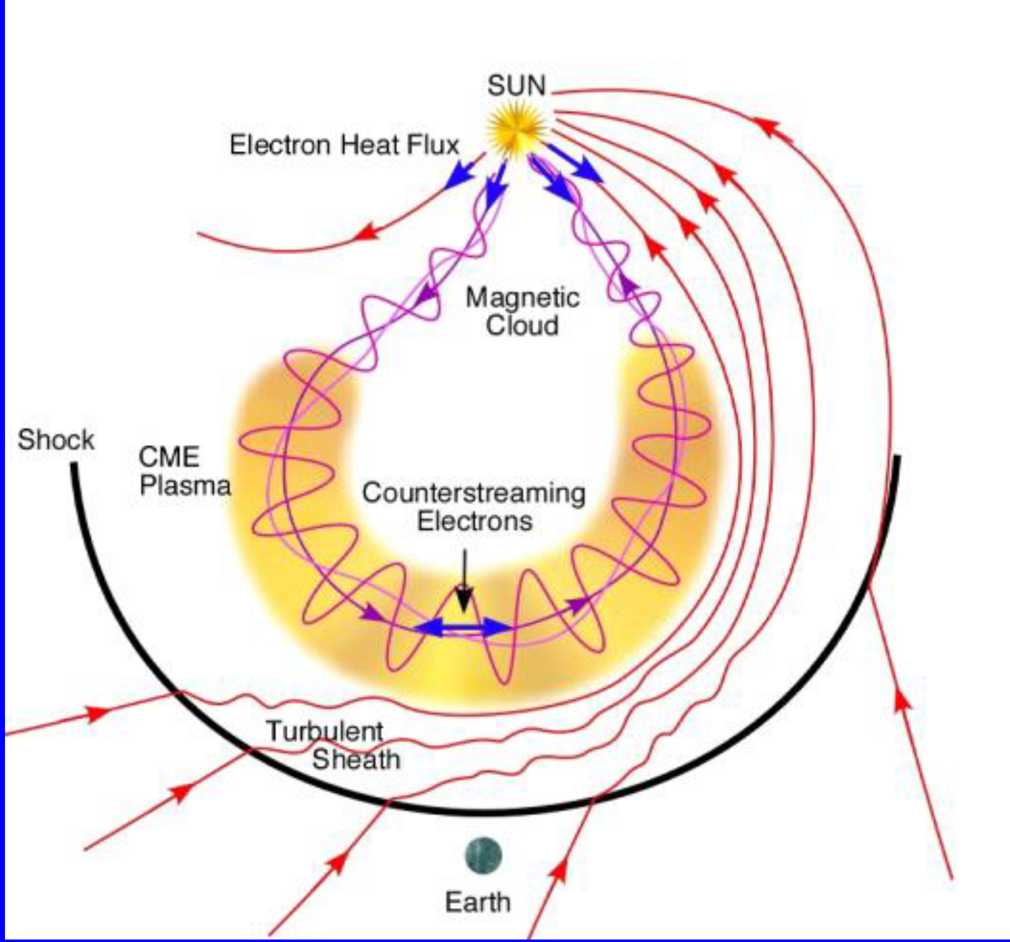
SOHO LASCO C3 coronagraph observations of CMEs in October-November, 2003

Corotating High-speed Streams



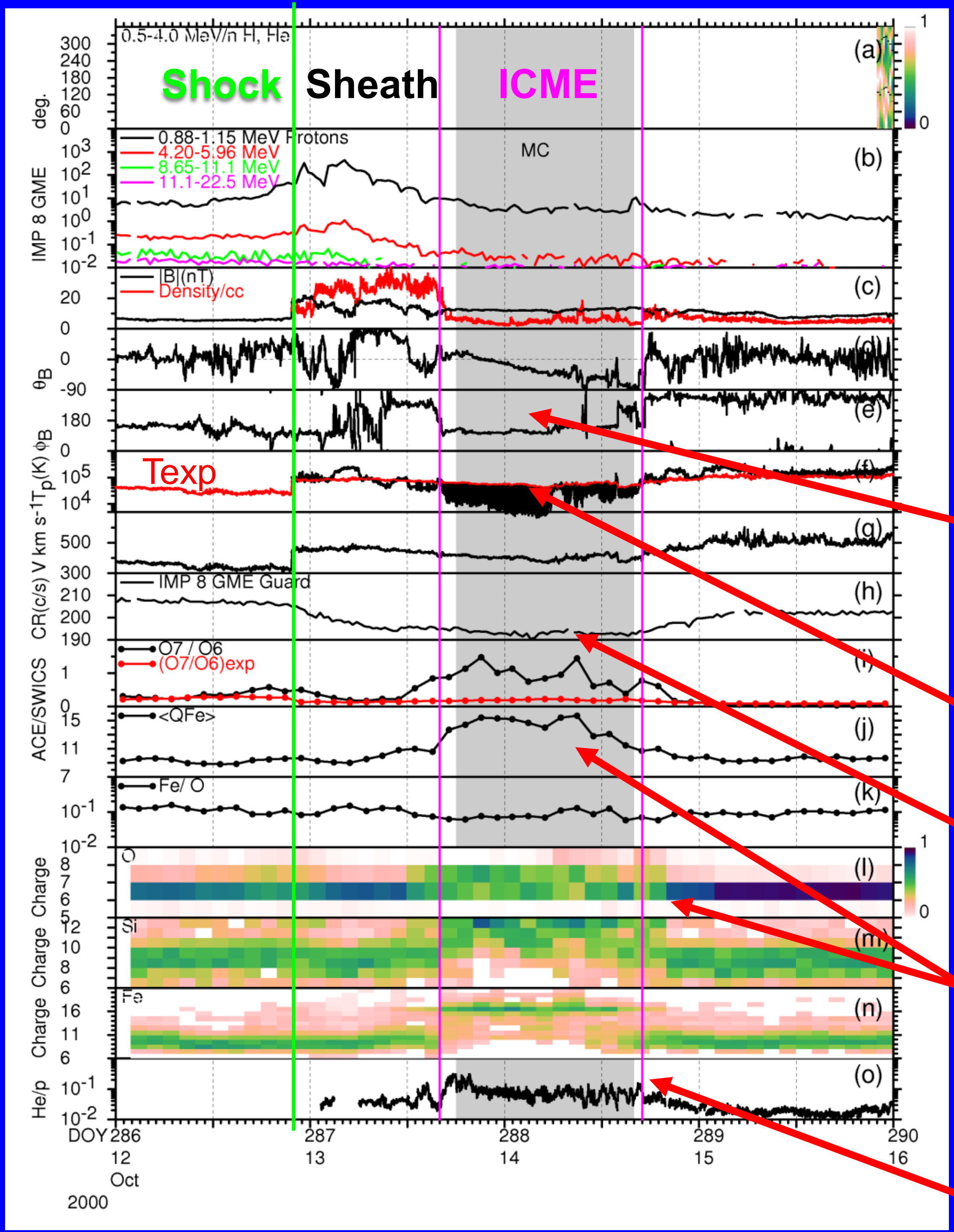
After *Belcher and Davis*, 1971

Interplanetary Coronal Mass Ejections (ICMEs)



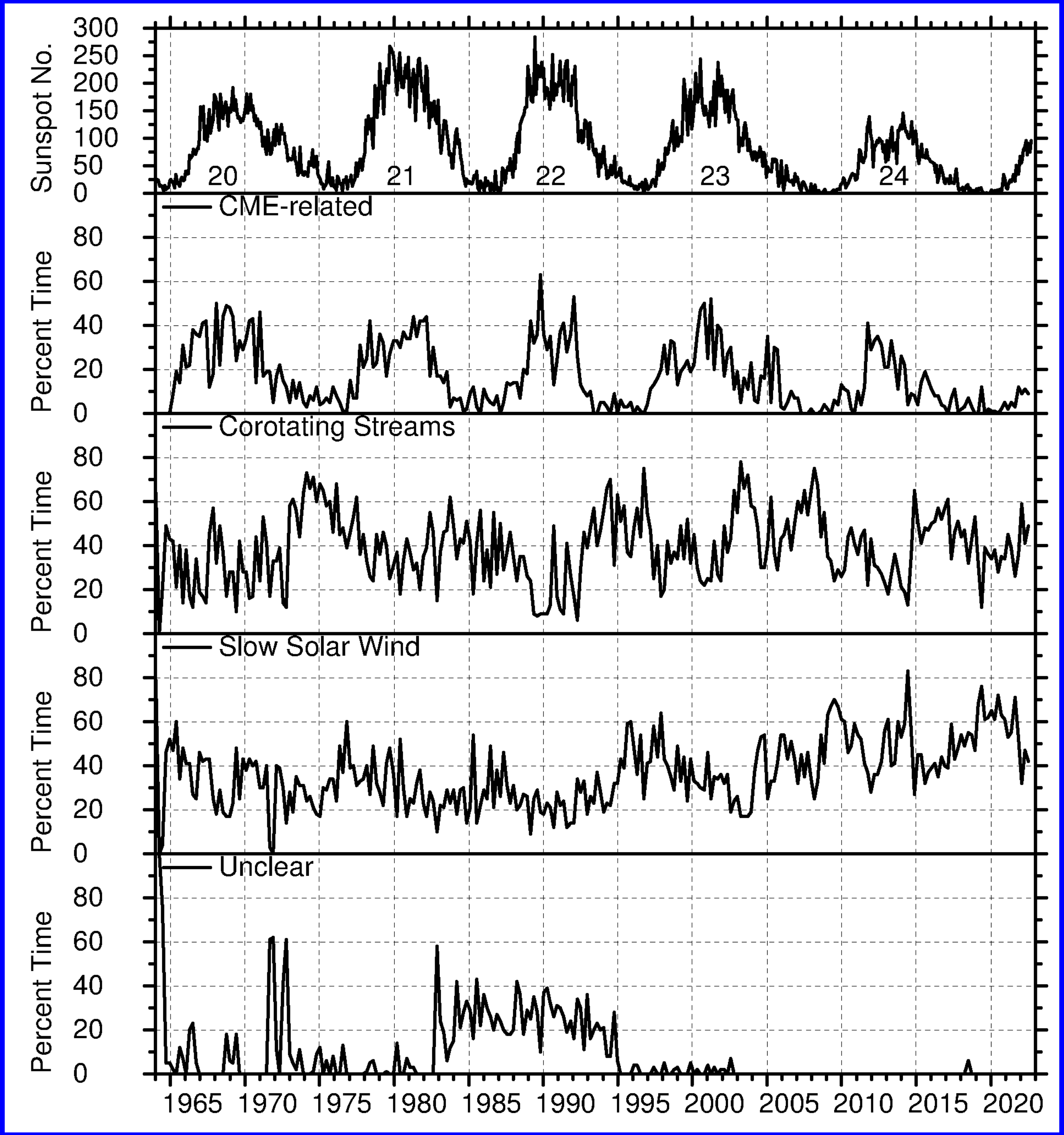
Zurbuchen and Richardson, 2006

Example of ICME Identification



Richardson and Cane, Sol. Phys., 2010

- Follows shock with a few hours delay (sheath);
- "Magnetic cloud" with field rotation (grey shading);
- Low T_p ($< 2\ T_{exp}$);
- Cosmic ray ("Forbush" decrease
- Enhanced solar wind ion charge states;
- Enhanced He/p;



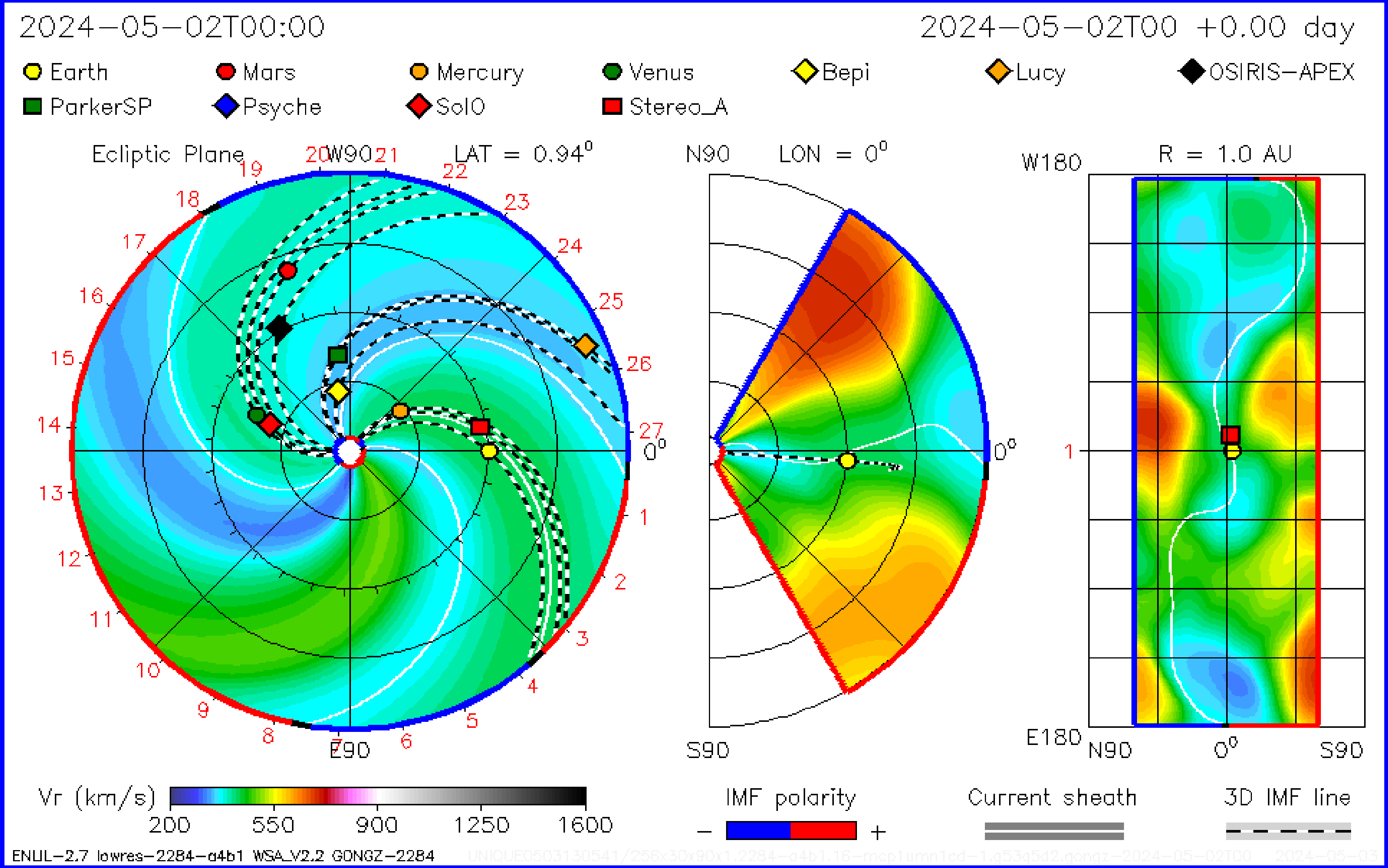
Percentage of time at Earth in "CME-related" flows, corotating streams, or slow solar wind over more than five solar cycles.

CME-related flows follow the solar activity (sunspot) cycle.

Corotating streams are more prominent during the declining phase and solar minimum.

Updated from Richardson and Cane, 2012

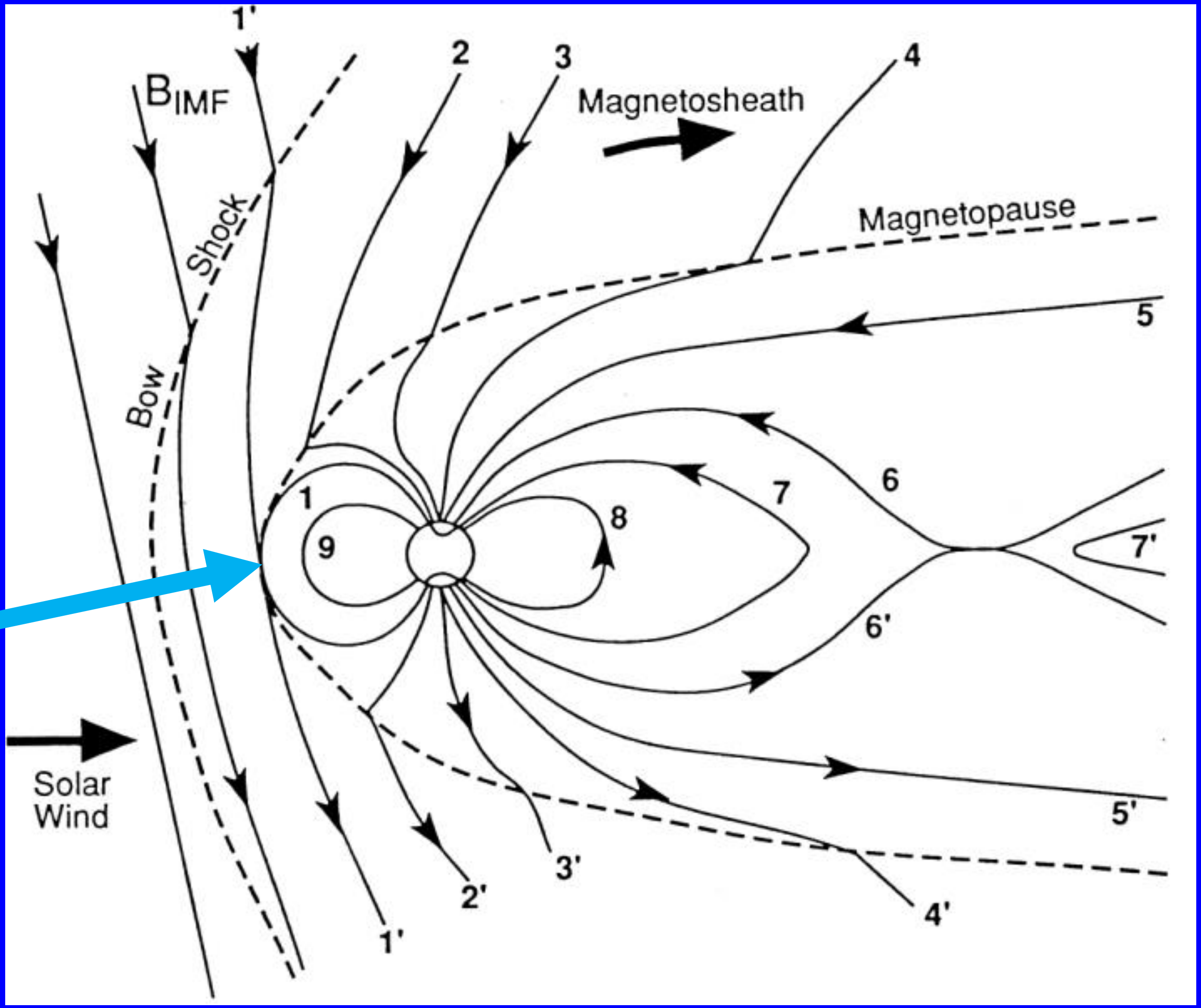
ENLIL+CONE MHD Model of the Solar Wind showing CIRs and prediction for Earth-directed CME
Observed at 2024-05-03, 02:48 UT; Longitude =-14.0, Latitude=29.0, Speed=841 km/s, Half Angle=43 deg.
From the DONKI database (https://kauai.ccmc.gsfc.nasa.gov/DONKI/)



Dayside Reconnection for Southward B_z ($E_y \approx V_{sw} B_s$) (*Dungey*, 1961) Favors Energy Input into the Magnetosphere, increased Geomagnetic Activity

Reconnected field lines are dragged over polar caps

Southward IMF; Opposite direction to Earth's magnetic field



Magnetic Reconnection

Hughes, 1995

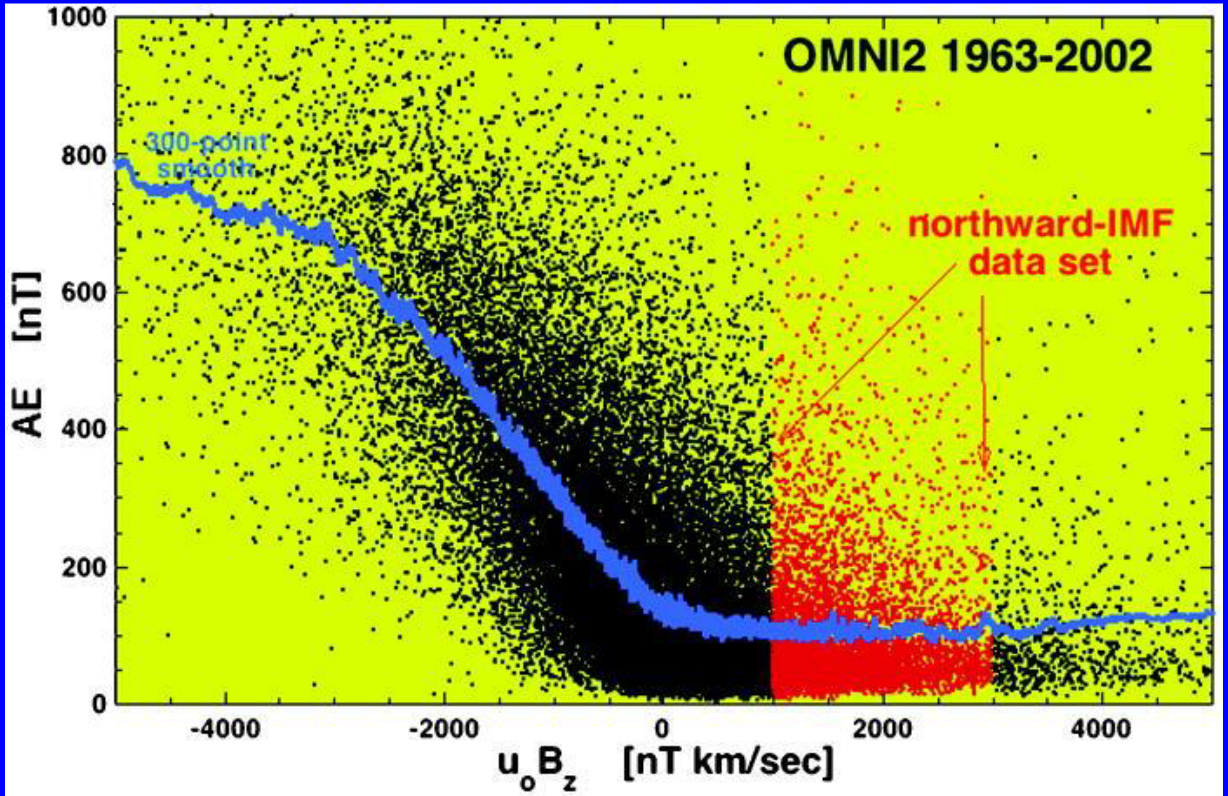
Reconnection rate is determined principally by:

- Strength (and duration) of the southward interplanetary magnetic field component

- Solar wind speed ($V_x B_s$=> dawn-dusk electric field, E_y)

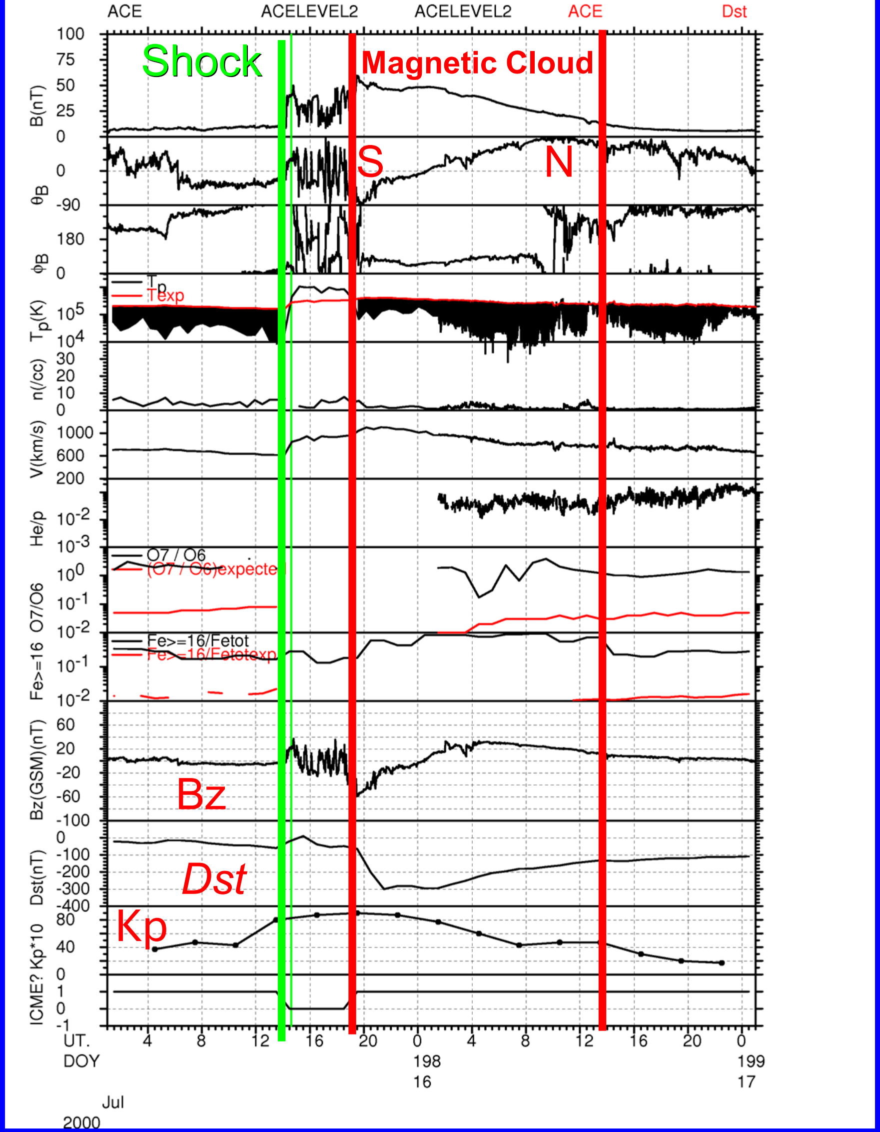
Dependence of Auroral Electrojet (AE) Index on VB_z Hourly Averages Over 40 Years

B South B North

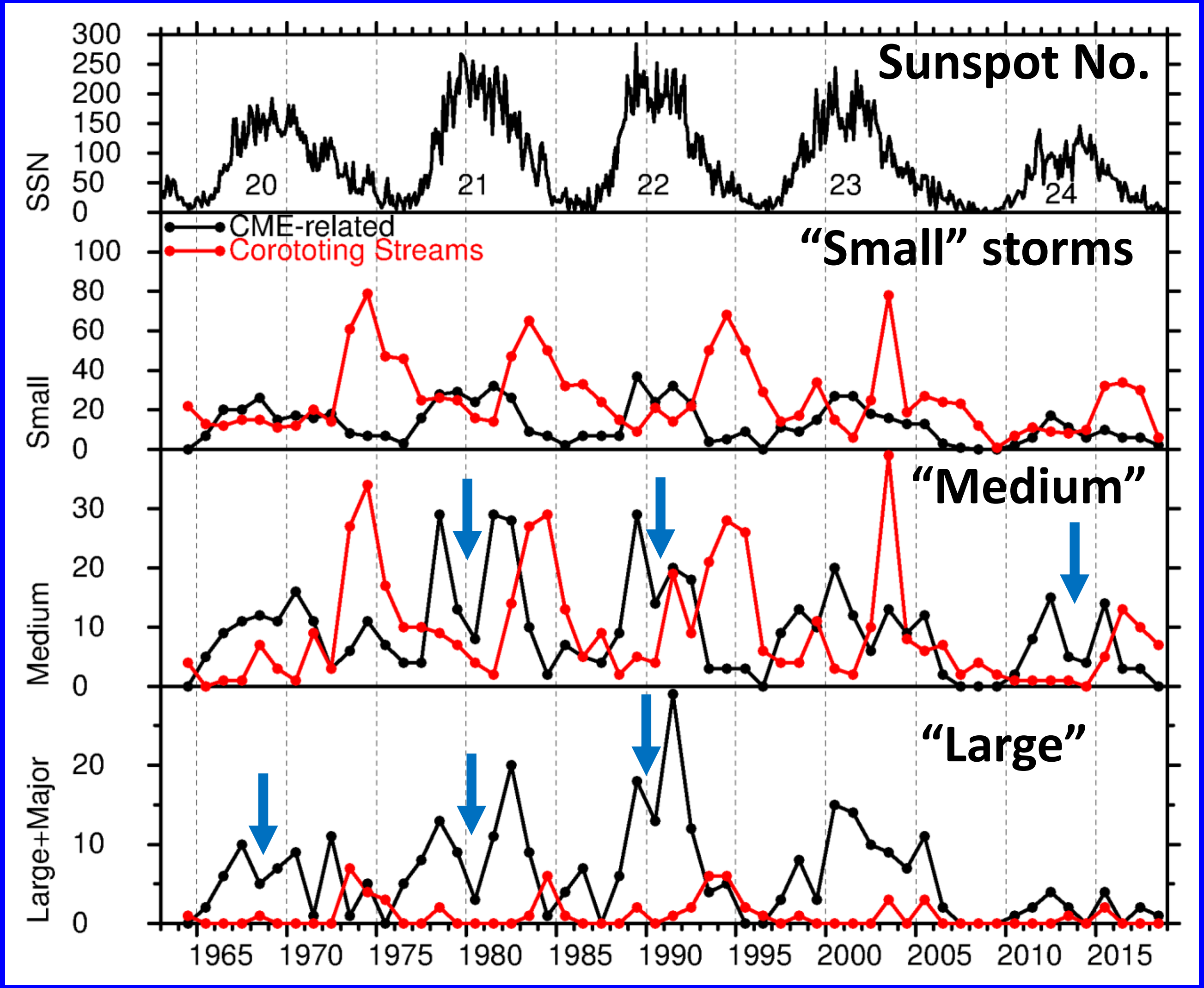


Borovsky, 2006

Solar Wind Parameters for July 15, 2000 Geomagnetic Storm



Geomagnetic "Storm" is produced by strong southward field in the leading part of the "magnetic cloud" (in this example).



Updated from Richardson and Cane, 2012, *Richardson et al.*, 2001; *Richardson*, 2006

Annual Number of Geomagnetic Storms (Kp Storm Days) in 1964-2018 Driven by CMEs and Corotating Streams

CME-driven storms follow the solar cycle and are dominant drivers of the largest storms.

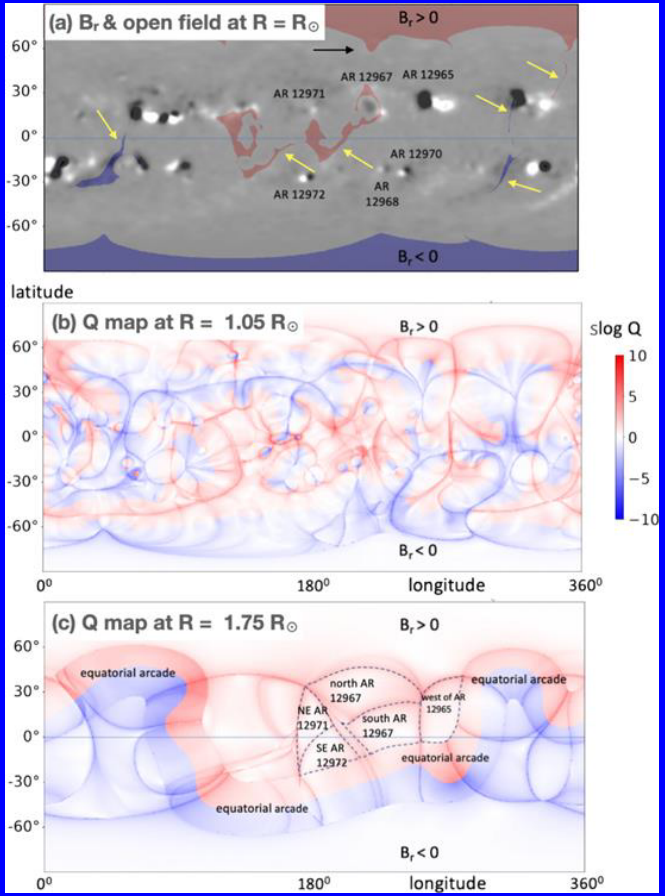
May be a temporary decrease in the CME storm rate near solar maximum/solar field reversal (e.g., 1980).

Stream-driven storms are most frequent during the declining phase of the solar cycle.

Slow Solar Wind: Likely has multiple sources; Topic of much active research!

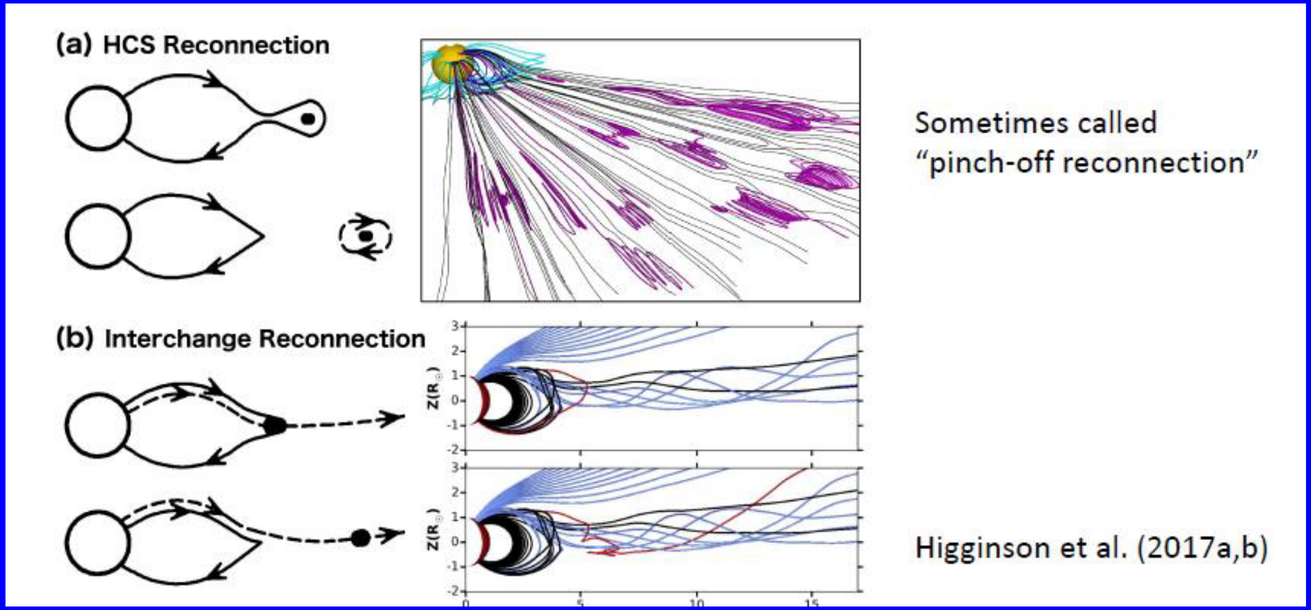
e.g., Upflows at the borders of active regions; Flows from the edges of coronal holes

The "S-Web"



Baker et al., 2023

Magnetic reconnection at the heliospheric current sheet

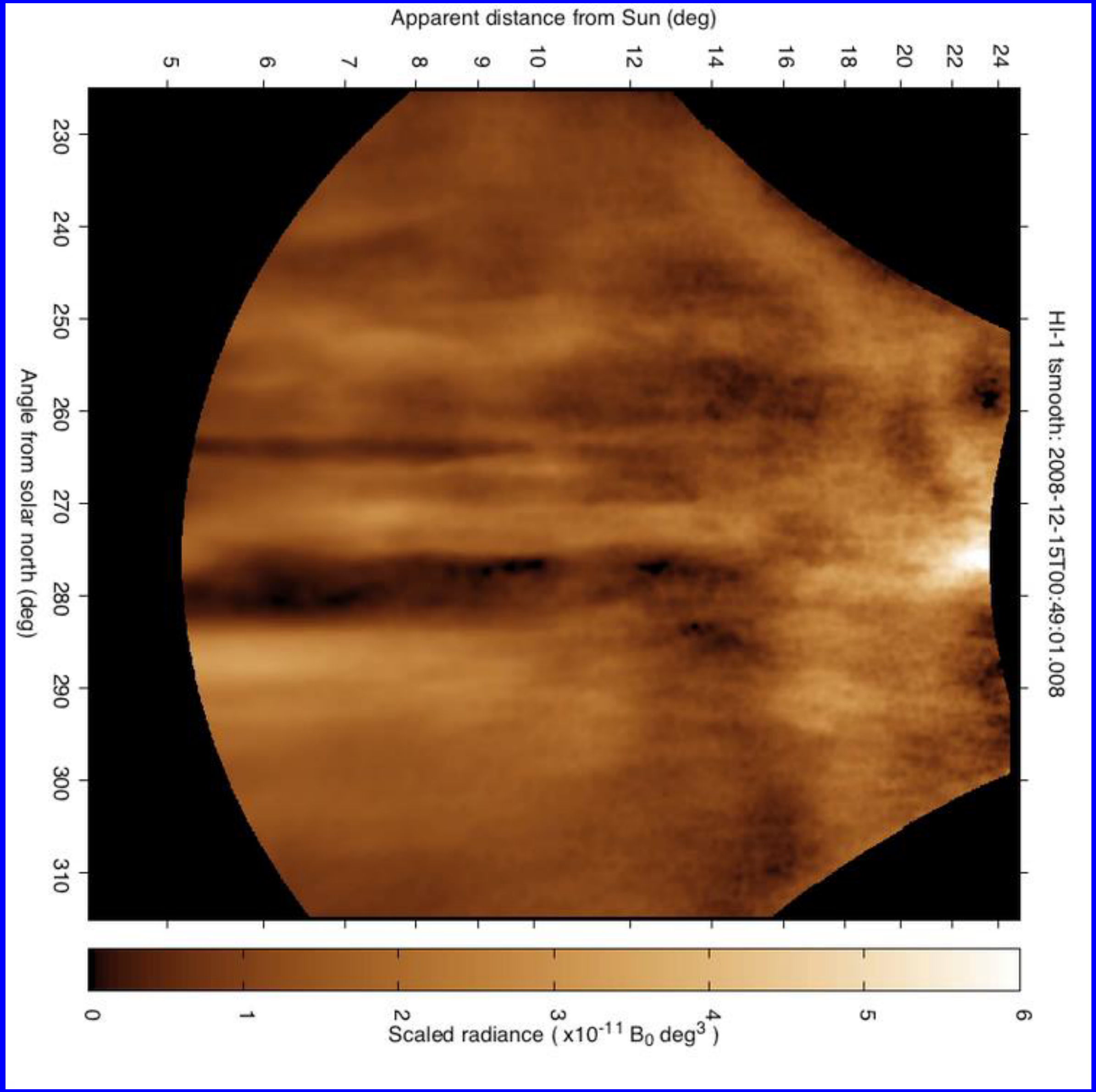


Slow solar wind is more variable (in time and space) than fast solar wind.

Generally not a major driver of space weather, but the embedded "mesoscale" solar wind structures can drive effects in the magnetosphere.

We can see structure in the solar wind using remote sensing (and a lot of image processing!)

SUN

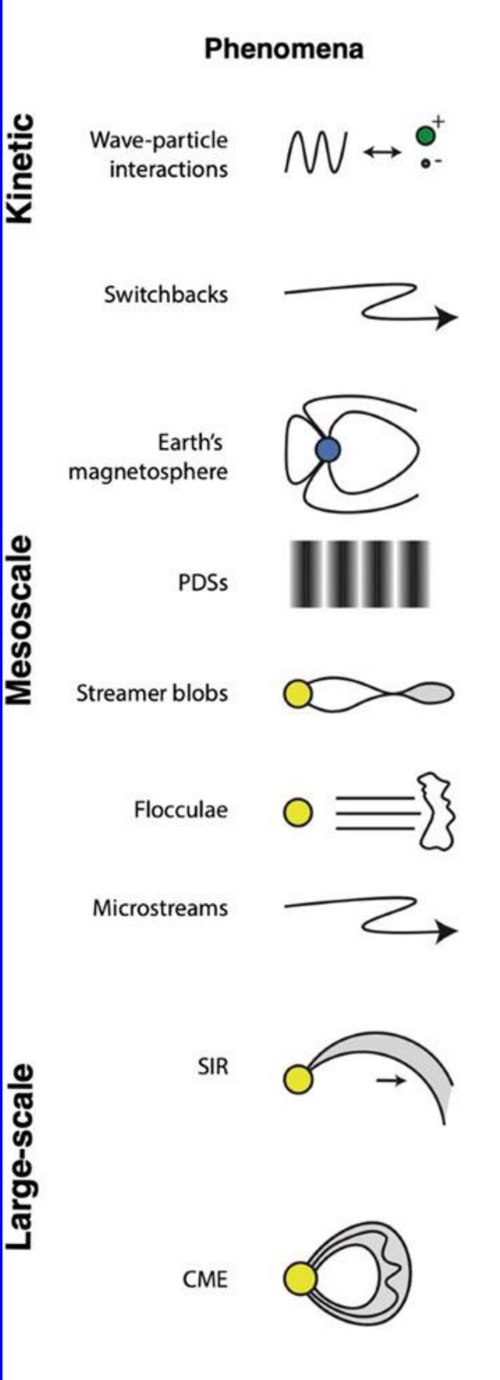


STEREO Hi-1 heliospheric imager (DeForest et al., 2016)

14 days of data in 2008 (solar minimum).

White light reflected by solar wind electron density variations.

Note the dense “streamer belt” near the equator and “coiled” transient (coronal mass ejection) near the end of the sequence.



Summary of Solar Wind Structures (Viall et al., 2021)

Summary:

The solar wind is a major driver of space weather, in particular the large scale solar wind structures (CIRs/SIRs and ICMEs).

Operational challenges include:
Real-time observations are from upstream spacecraft, mostly at L1 (<~1 hour warning, off the Sun-Earth line);

Limited observations of the wider solar wind away from Earth

Solar wind models are useful but can be improved.

Incomplete understanding of the solar sources of solar wind, in particular, slow solar wind and mesoscale structures, and their link with in-situ observations. (Parker Solar Probe, Solar Orbiter, PUNCH)