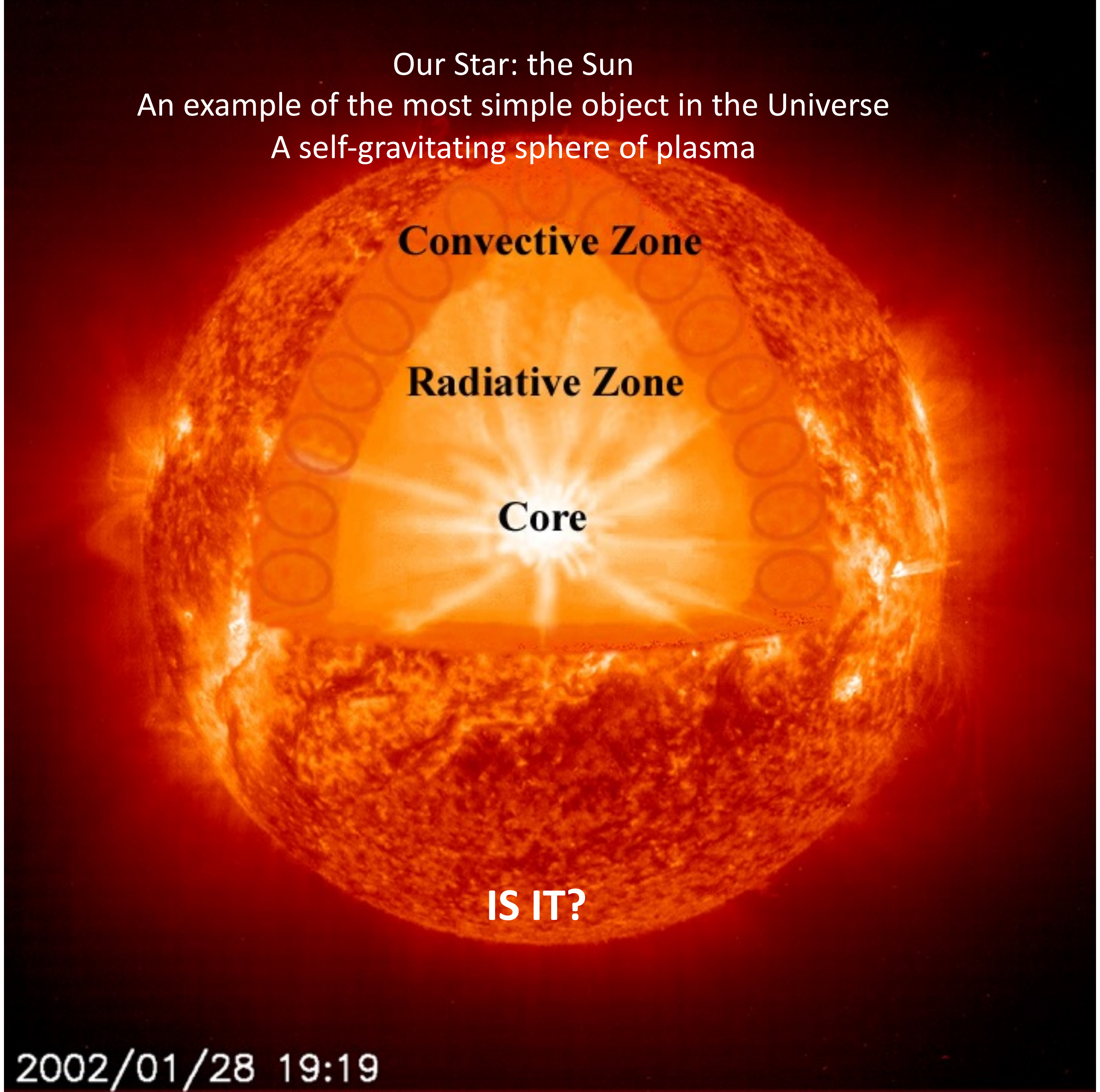
TOR VERGATA
UNIVERSITÀ DEGLI STUDI DI ROMA

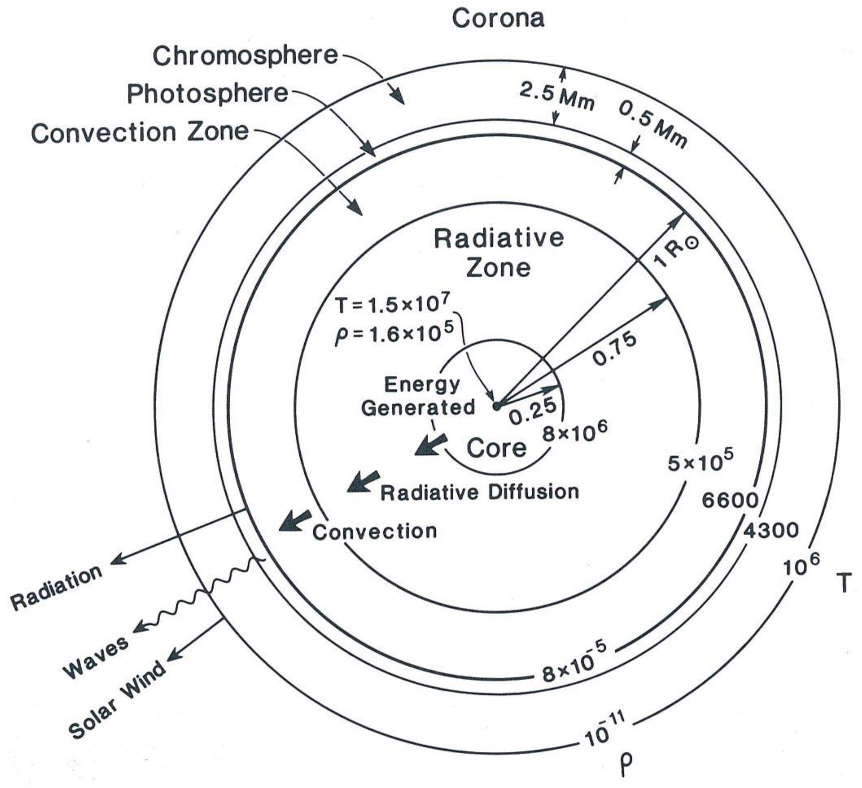
Solar and heliospheric observations in the era of Solar Orbiter

Luca Giovannelli

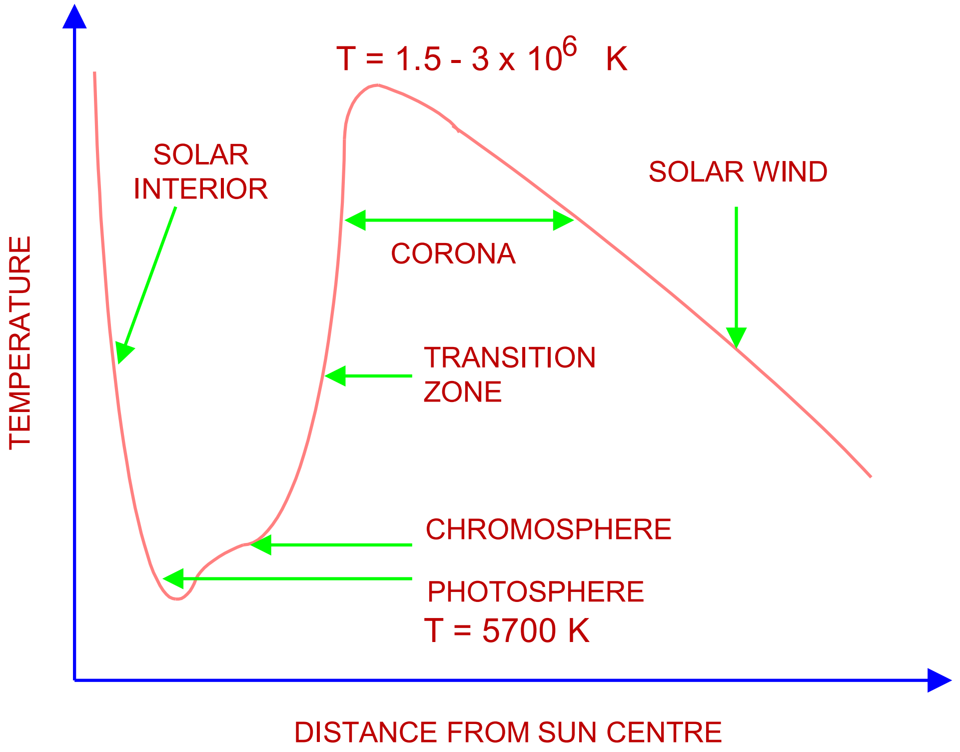
Our Star: the Sun
An example of the most simple object in the Universe
A self-gravitating sphere of plasma

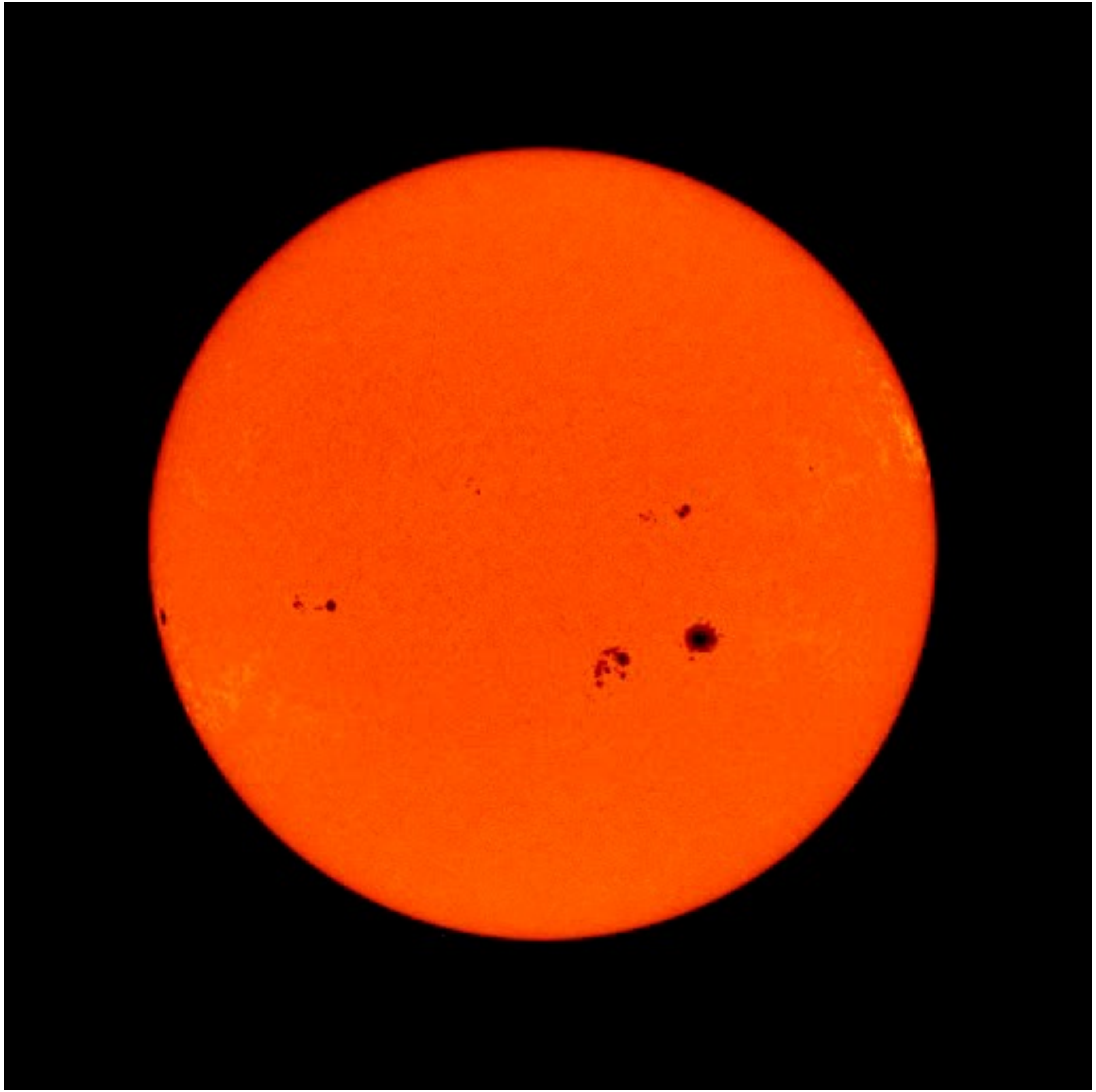


Overview of solar interior and atmosphere



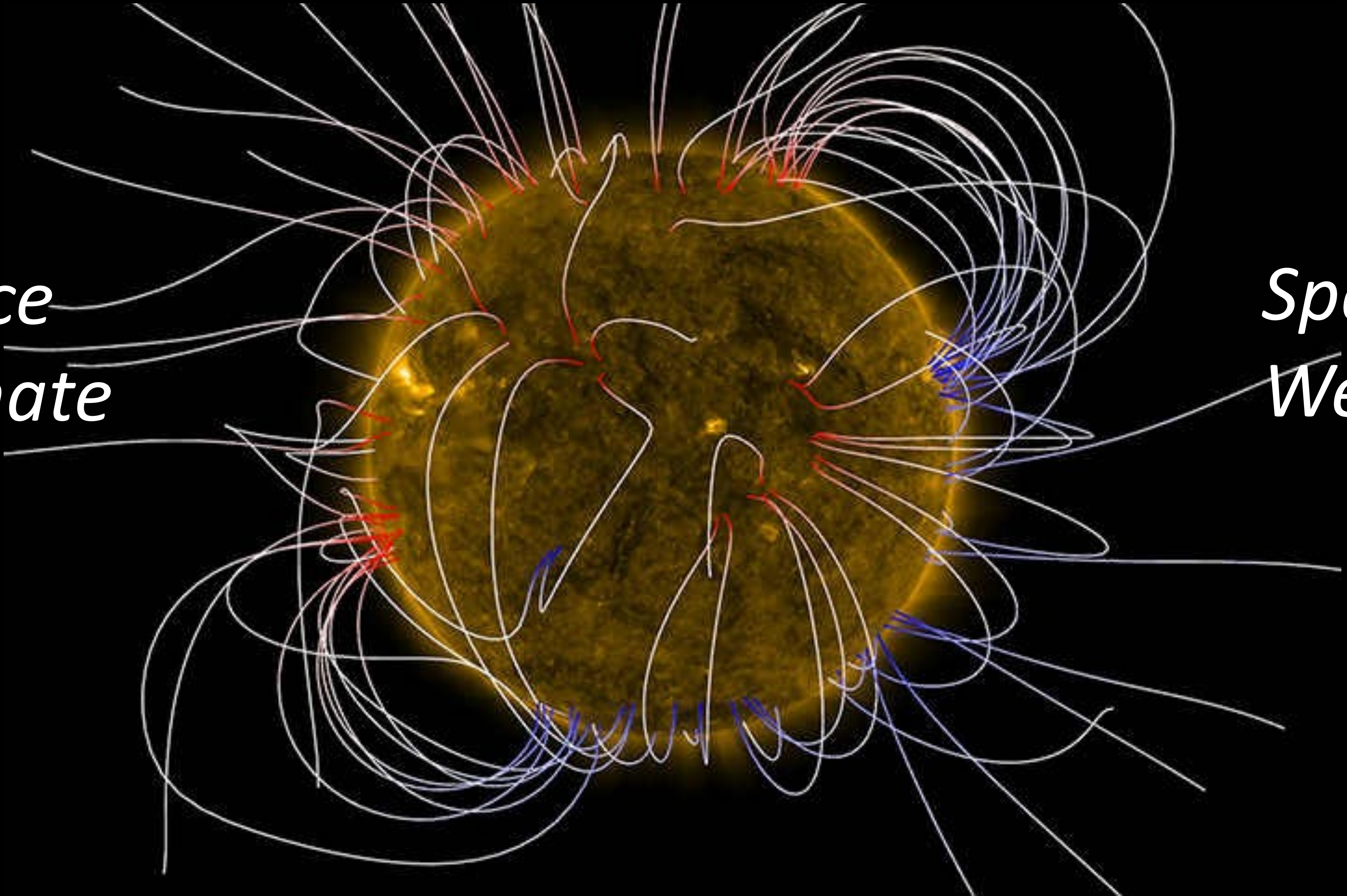
Priest (1995)





A magnetic star!

Space Climate



Space Weather

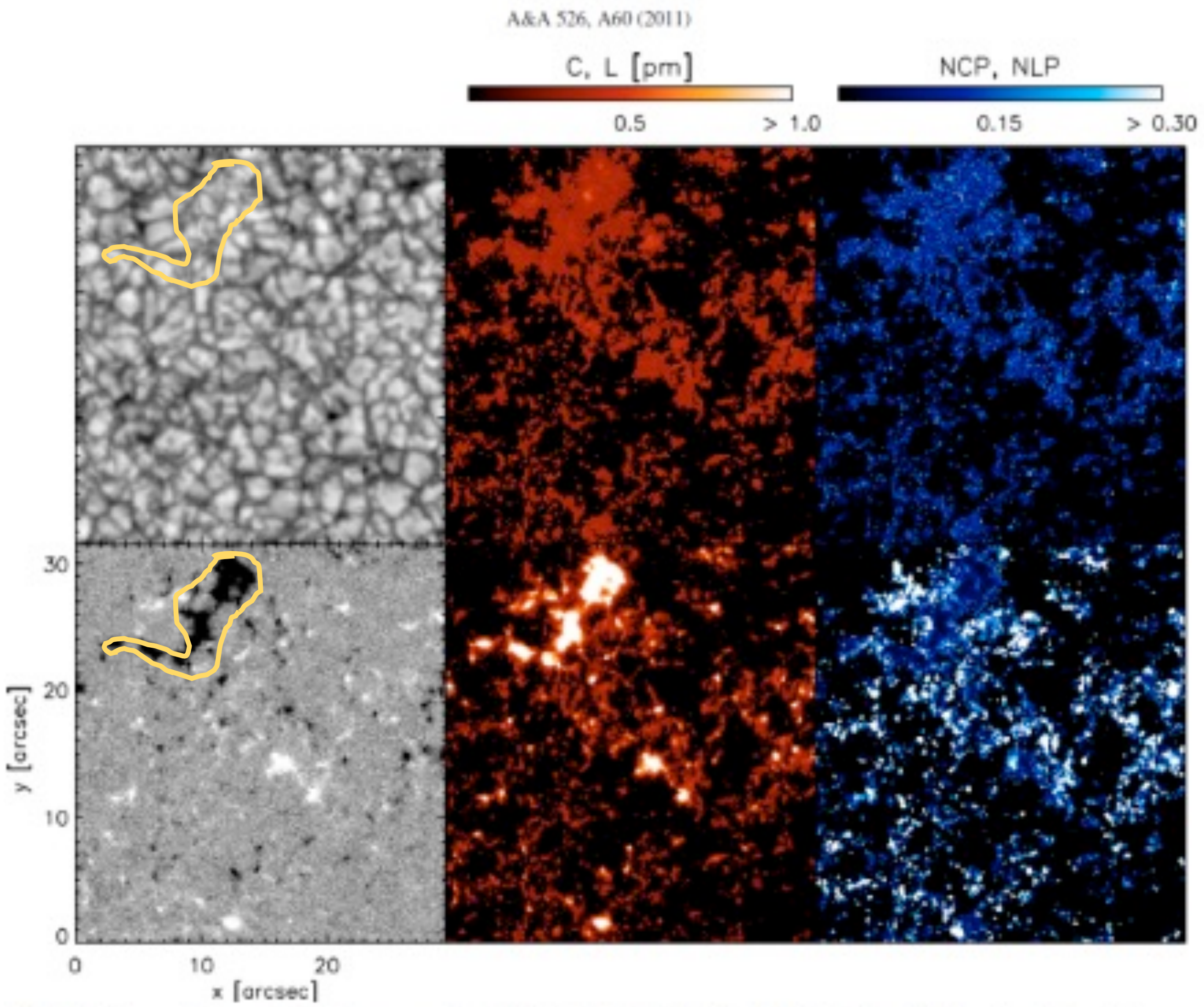


Fig. 2. Main observational properties of the representative 29.52" × 31.70" subfield selected for in-depth analysis. Continuum intensity (*upper-left panel*), total linear polarization (*L*, *upper-central panel*), net-linear polarization (*NLP*, *upper-right panel*), COG magnetogram saturated at ±200 G (*lower-left panel*), total circular polarization (*C*, *lower-central panel*), and net-circular polarization (*NCP*, *lower-right panel*). The total polarization maps are both saturated at 1 pm, while the net-circular and net-linear polarization maps are saturated at 0.3. Black pixels in *L*, *C*, *NLP*, and *NCP* maps represent regions with signals below the threshold for inversion. The bars on top represent the color palettes adopted for the two pairs of images below them.

Viticchié +, *Interpretation of HINODE SOT/SP asymmetric Stokes profiles observed in the quiet Sun network and internetwork*, A&A 526, A60 (2011)

"Our Sun, a fairly typical star in a fairly typical galaxy, is not a boring spherical static ball of gas but a complex evolving tangled medium of plasma and magnetic fields that produces structure in the form of convection cells, sunspots, and solar flares."

In PATTERN FORMATION AND DYNAMICS IN NONEQUILIBRIUM SYSTEMS, Michael Cross & Henry Greenside, Cambridge Univ. Press

One of the key questions we are addressing is **how does a simple physical system like the Sun produce such a complex dynamics?**

The inherent nonequilibrium state of the solar structure is the answer.

Convection is a paradigm of a nonequilibrium system.

Driving a system away from equilibrium produces space-time symmetry breaking and consequent emergence of **structures** and **pattern**.

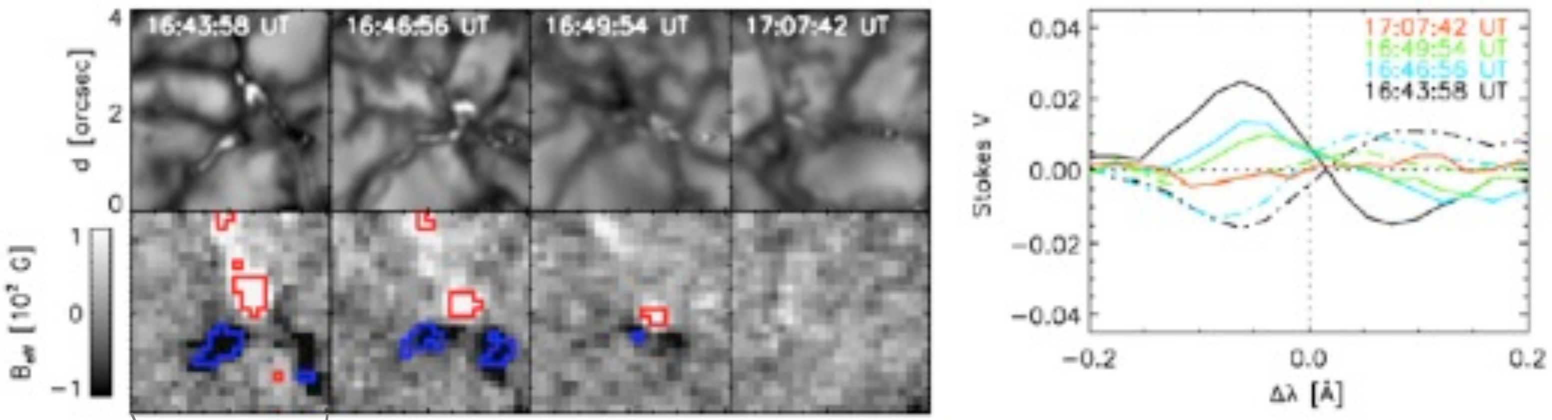


Figure 5. Selection of four instants from the BP cancellation process. First row: *G*-band filtergram. Second row: COG magnetic flux density (images are saturated at 100 G). Contour plot: kG fields regions as obtained from the inversion analysis of Stokes *V* profiles; positive (red contours) and negative (blue contours) polarity regions are represented. Right plot: Fe I 630.25 nm Stokes *V* profiles calculated as average over a 0.″5 × 0.″5 box around the position of the minimum (solid line) and maximum (dot-dashed line) magnetic flux densities for each time instant. Stokes *V* profiles are normalized to the continuum intensities. For 17:07:42 UT a single 0.″5 × 0.″5 box fixed at the interaction point is used to calculate the average profiles.

Viticchié +, *Imaging Spectro-polarimetry with IBIS: Evolution of Bright Points In the Quiet Sun*, ApJ, 700:L145–L148, 2009

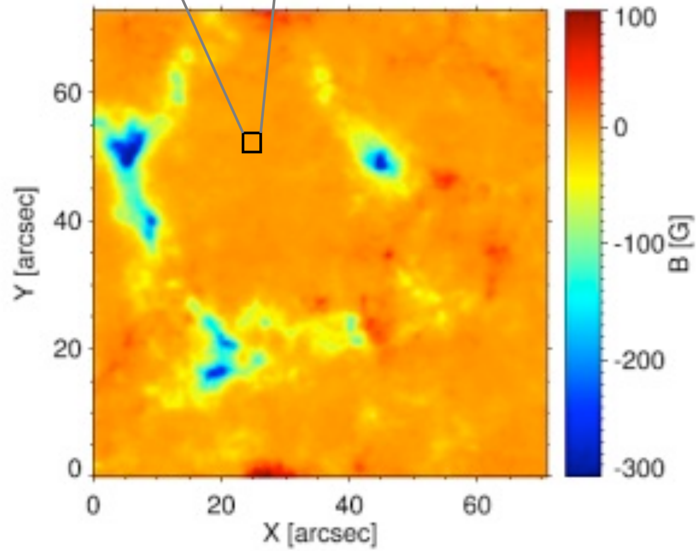
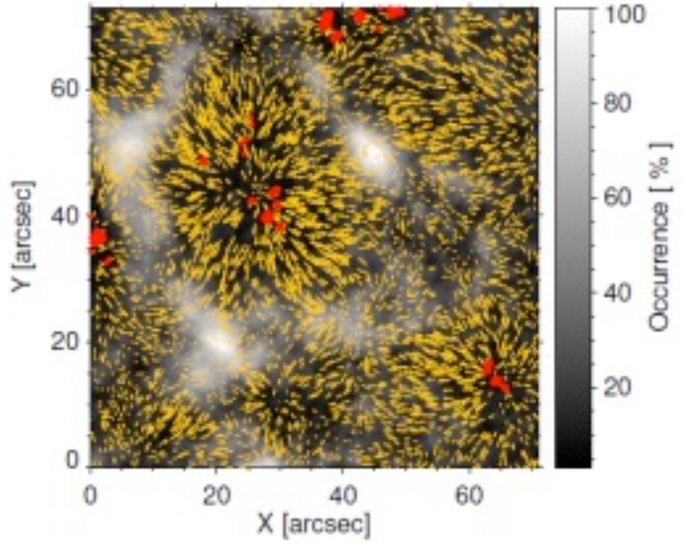


Fig. 1. Mean magnetogram of the FoV averaged over ~24 h, the whole time range of the series.



Giannattasio +, *Occurrence and persistence of magnetic elements in the quiet Sun*, A&A 611, A56, 2018

The black square shown in the lower left figure is purely indicative of the scale of the two images.

From the quiet sun to the active regions

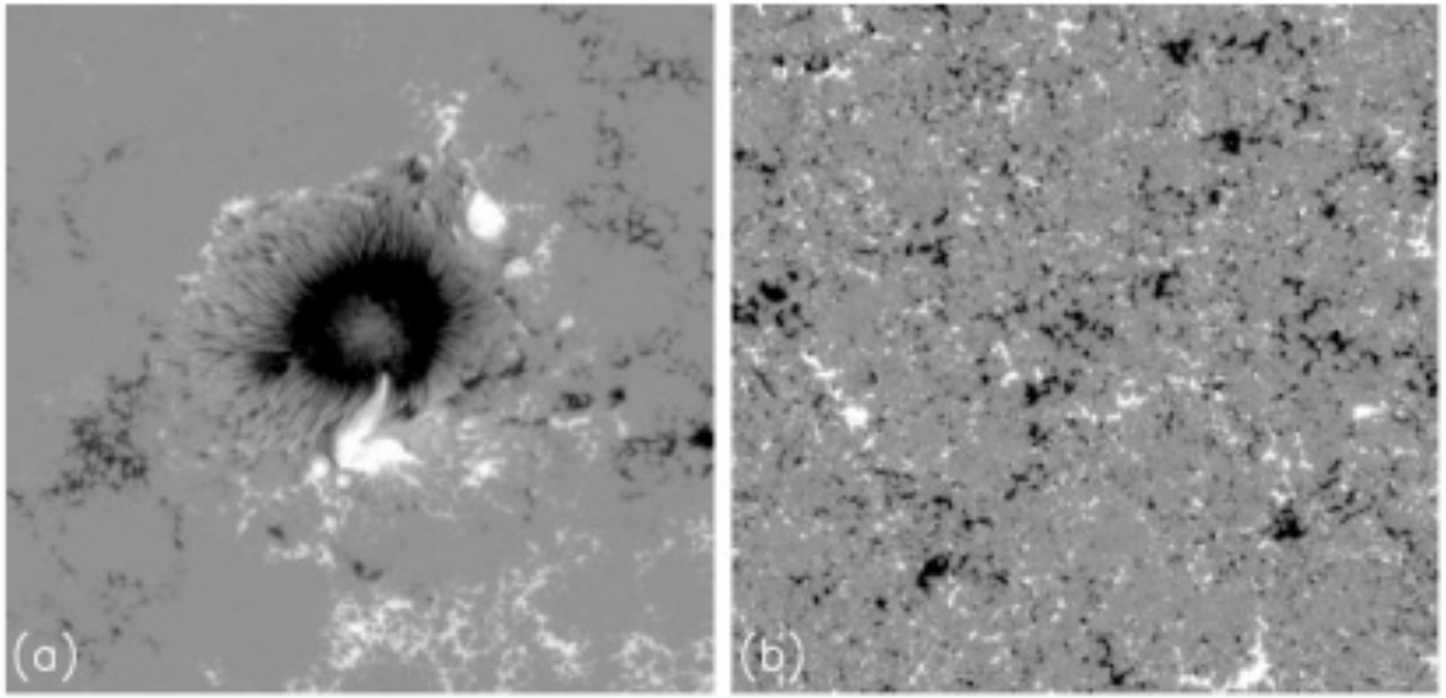


Figure 1: Stokes V in blue wing of 630.2 nm line from Hinode. Around a sunspot (a) and in the quiet Sun (b), showing the wide range in size of magnetic structures on the Sun. The dimensions of both figures are 110 Mm and the pixel size is 108 km. Image reproduced by permission from Parnell *et al.* (2009), copyright by AAS.

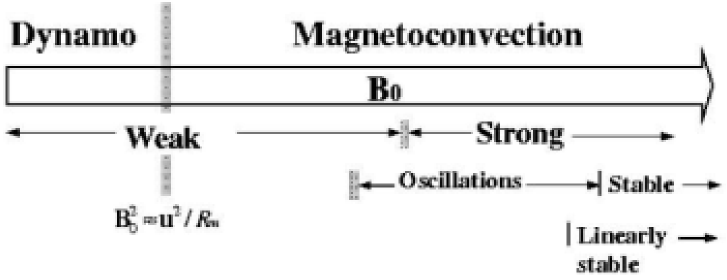


Fig. 4.—Schematic representation of the different regimes obtained as the value of the net magnetic flux through the box is increased. Thick solid lines denote hard transitions, while fuzzy lines indicate more gradual transitions.

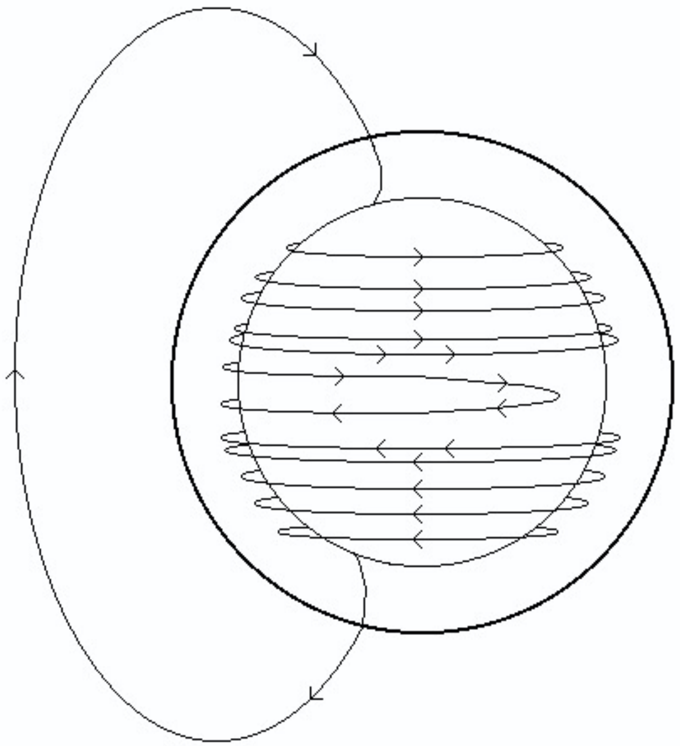
The solar surface is covered with magnetic features with spatial scales from smaller than can currently be resolved to active regions covering up to 100 Mm. These evolve on a correspondingly wide range of time scales, from seconds for the smallest observed features, to months for some active regions.

R. Stein, *Solar Surface Magneto-Convection*, Living Rev. Solar Phys., 9, 2012

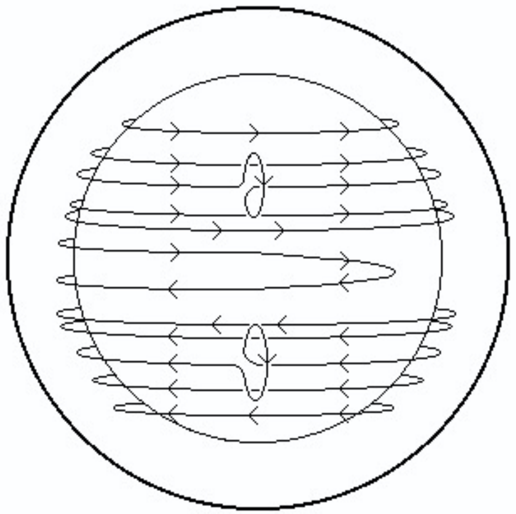
On the extreme left are cases in which the imposed field is zero and on the extreme right, cases in which the imposed field is strong enough to suppress convection altogether.

Cattaneo, Emonet, Weiss, On the interaction between convection and magnetic fields, ApJ, 588:1183–1198, 2003

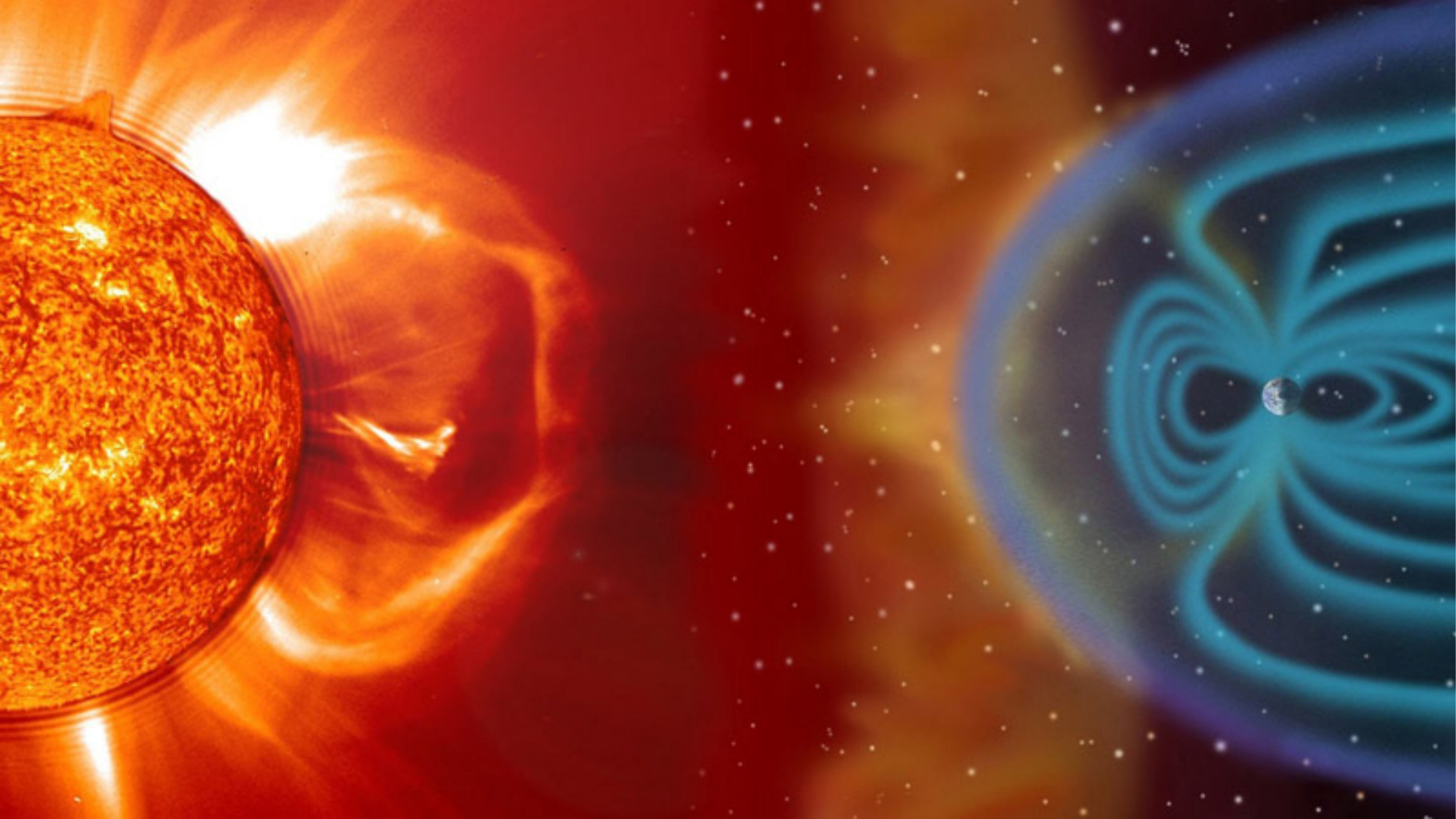
The solar dynamo – primarily at the base of the convection zone



The ω-effect



The α-effect



The solar wind

- The solar wind, consisting of ionised coronal plasma, flows supersonically and radially outward from the Sun due to the large pressure difference between the hot solar corona and the interstellar medium.

Parker model of the solar wind

Parker(1958) was the first to propose a model of the solar wind assuming a steady flow of plasma independent of time, as opposed to a static corona.

Property at 1 AU

Speed (v)	~400 km/s
Number density (n)	$\sim 10\ cm^{-3}$
Flux (nv)	$\sim 3\times10^{8}\ cm^{-2}\ s^{-1}$
Magnetic field (Br)	~3 nT
Proton temperature (Tp)	$\sim 4\times10^{4}$ K
Electron temperature(Te)	$\sim 1.3\times10^{5}$ K (>Tp)
Composition (He/H)	~1 – 30%
+ trace heavier elements	

Parker's Solar Wind Model

In 1958, motivated by diverse indirect observations, E. N. Parker developed the first fluid model of a continuously expanding solar corona driven by the large pressure difference between the solar corona and the interstellar plasma. His model produced low flow speeds close to the Sun, supersonic flow speeds far from the Sun and vanishingly low pressures at large heliocentric distances. In view of the fluid character of the model, he called this continuous supersonic expansion the "solar wind".

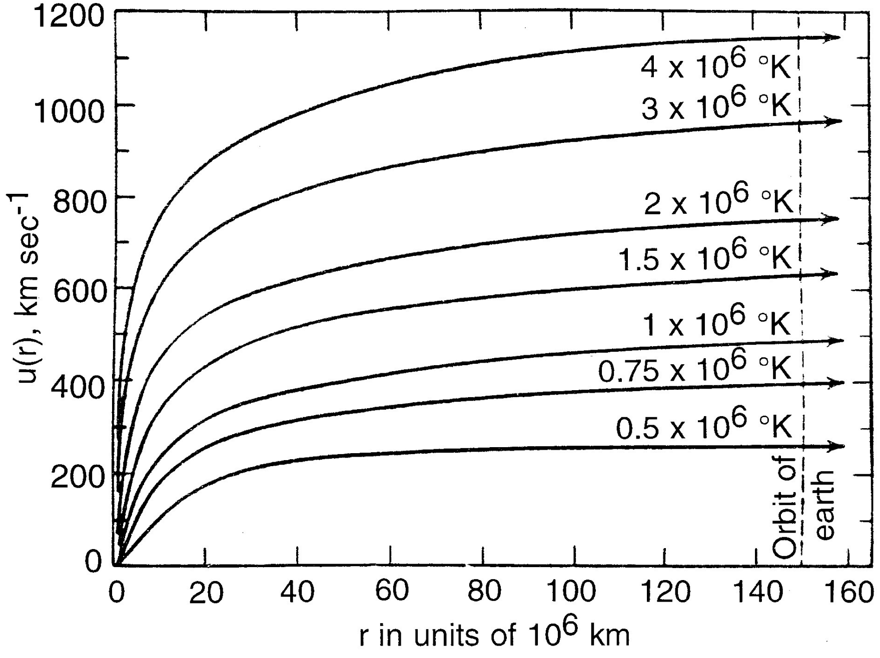
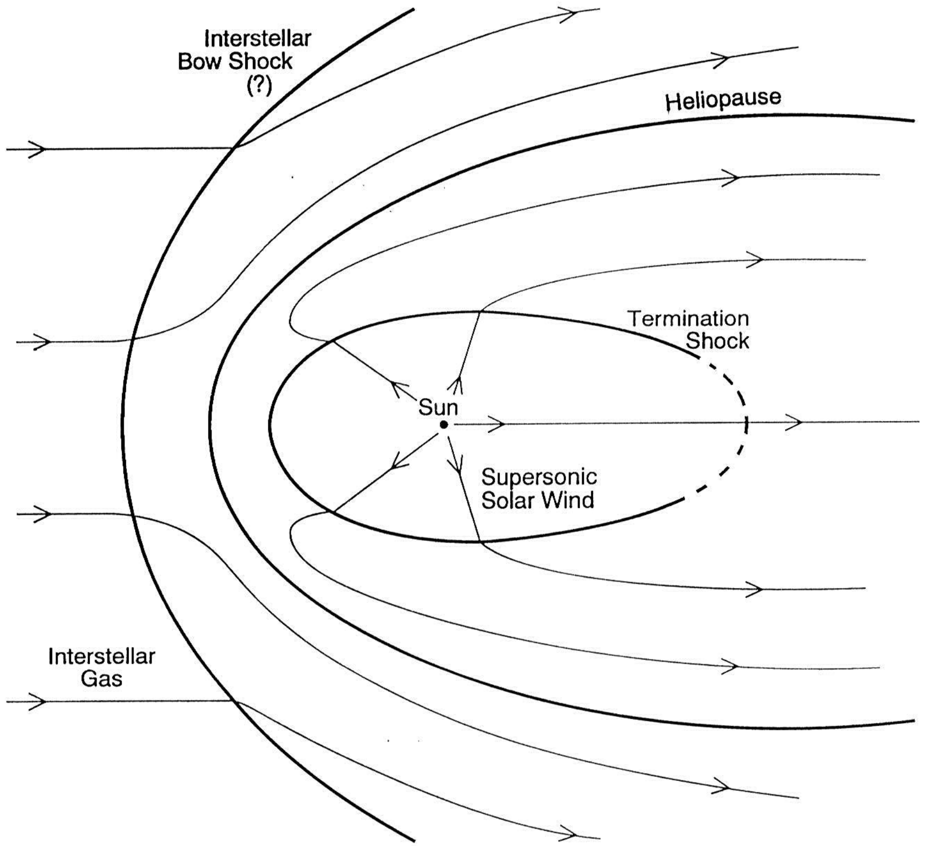
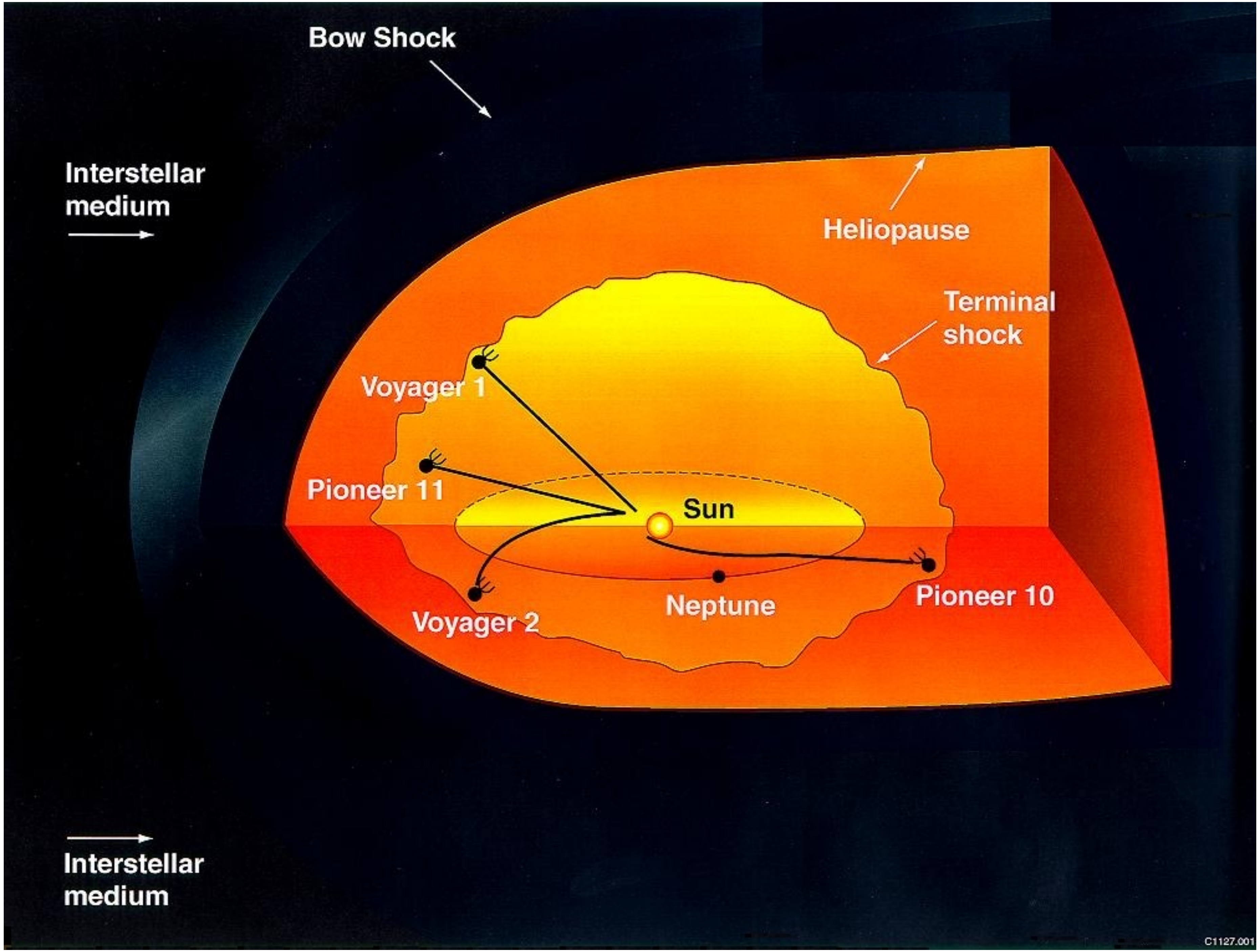


FIGURE 1 E. N. Parker's original solutions for solar wind flow speed as a function of heliocentric distance for different coronal temperatures. Subsequent work has demonstrated that the simple relationship between coronal temperature and solar wind speed illustrated here is incorrect. [From E. N. Parker (1963). "Interplanetary Dynamical Processes." Interscience, New York. Copyright © 1963. Reprinted with permission of John Wiley & Sons, Inc.]

The Heliosphere

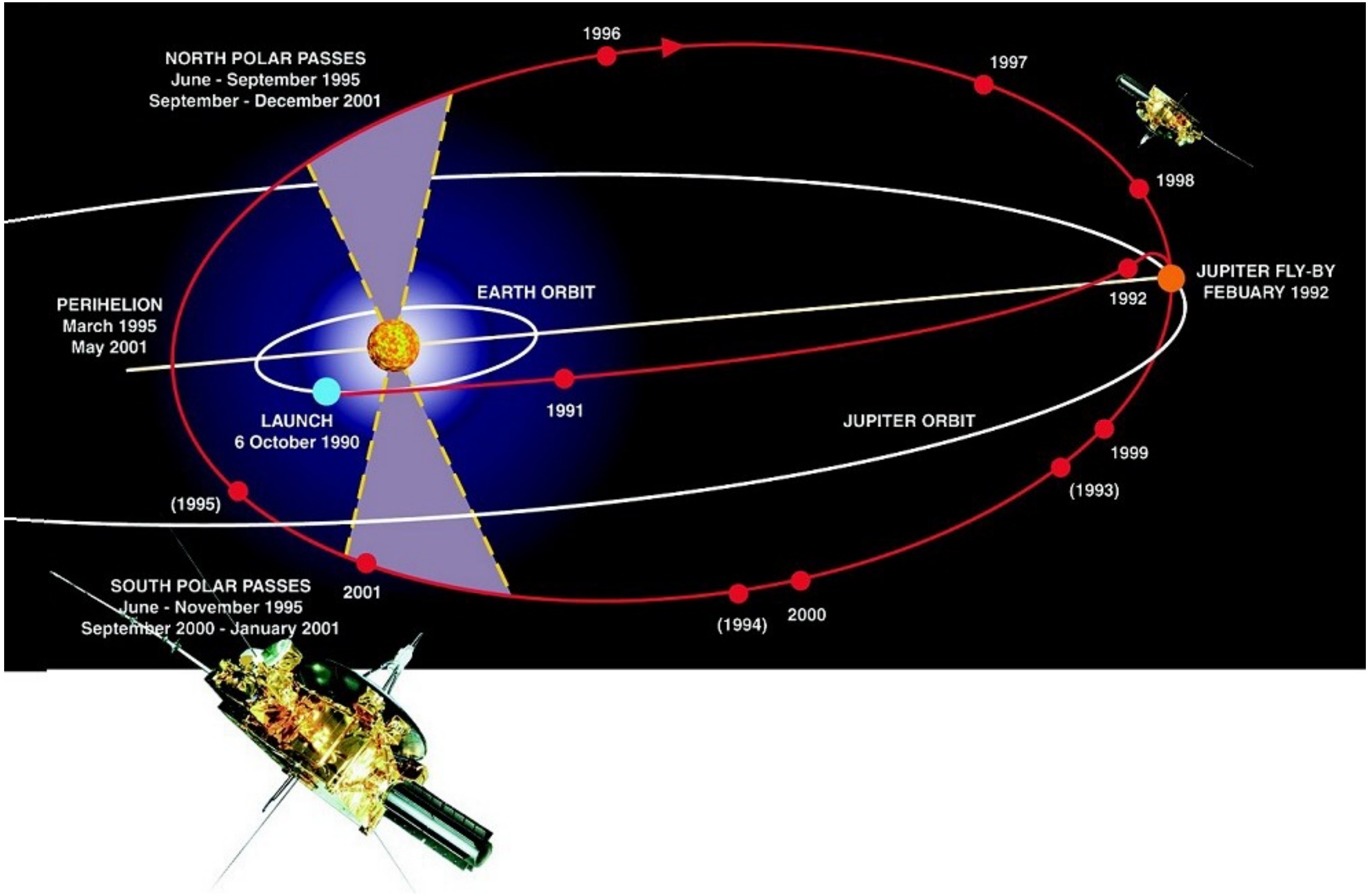
- The heliosphere is the volume of space, enclosed within the interstellar medium, formed by, and which contains, the outflowing solar wind and the Sun's magnetic field.
- The size of the heliosphere (greater than 100 AU) is determined by a balance between the dynamic pressure of the solar wind and the pressure of the interstellar medium.




Bow Shock
Interstellar medium
Heliopause
Terminal shock
Voyager 1
Pioneer 11
Sun
Voyager 2
Neptune
Pioneer 10
Interstellar medium
C1127.001

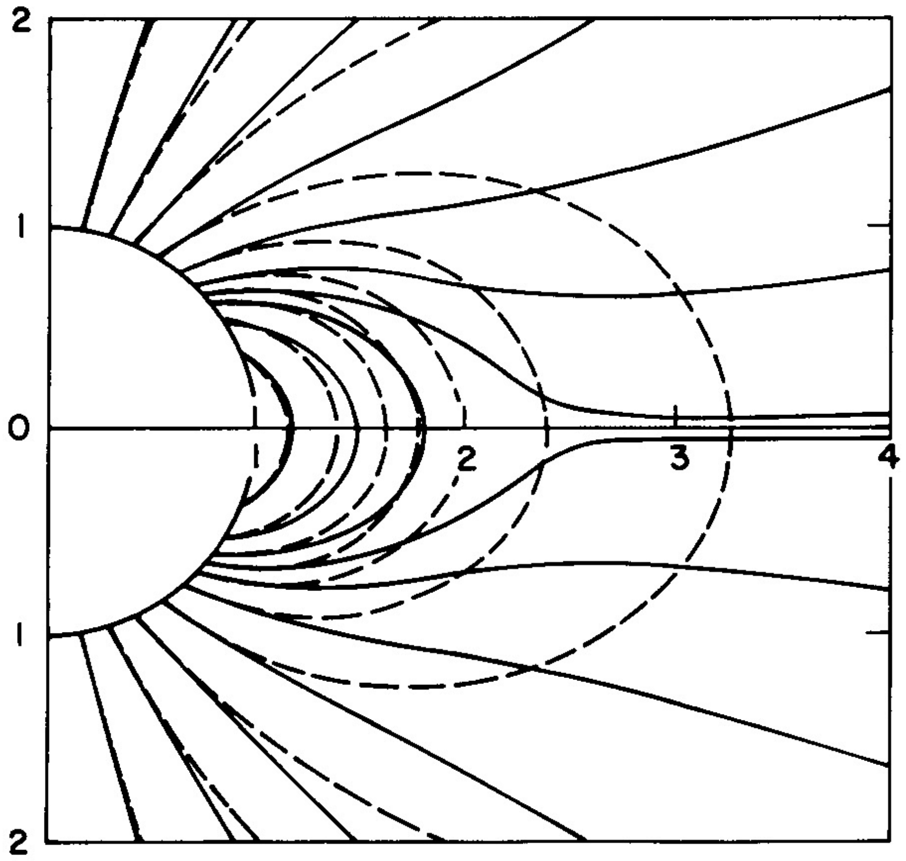
Heliospheric Spacecraft

- The first observations of the solar wind were made in the vicinity of the Earth in the early 1960s.
- Pioneer 10 and 11, launched in 1972 and 1973 were the first spacecraft to explore beyond 1 AU. Contact with these spacecraft have now been lost although Pioneer 10 was tracked to nearly 80 AU.
- Voyager 1 and 2 were launched in 1977. Both have scientific instruments still operating. Voyager 1 crossed the termination shock in 2004 at 94.5 AU, has now reached 126 AU and continues out towards the heliopause. Voyager 2, following behind at 103 AU, crossed the termination shock at 84 AU in 2007.
- Helios 1 and 2, launched in 1974 and 1976, explored the inner heliosphere in the ecliptic plane between 0.3 and 1 AU from the Sun.
- Ulysses, launched in 1990 into a ~6 year period orbit of the Sun inclined at 80.2° to the solar equator, with perihelion at 1.3 AU and aphelion at 5.4 AU. It was thus the first spacecraft to explore the 3D structure of the heliosphere over a large latitude range. Operations ceased in 2009 after nearly 3 orbits.
- STEREO, launched in 2006, consists of two spacecraft at 1 AU separating in solar longitude ahead of and behind the Earth. They carry instrumentation aimed at obtaining stereoscopic views of the Sun and to make multi-point in-situ measurements of the solar wind.

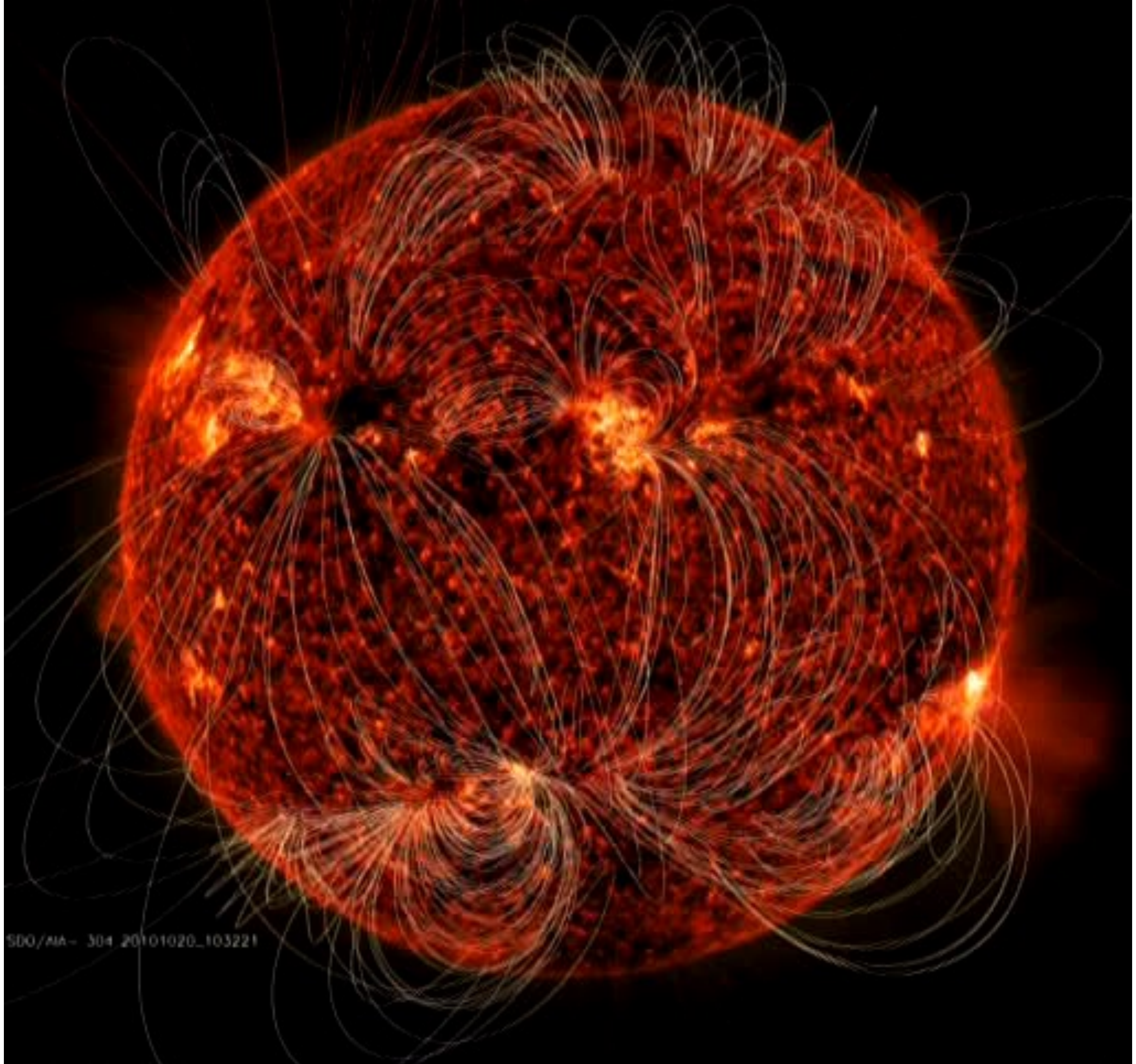

1996
NORTH POLAR PASSES
June - September 1995
September - December 2001
1997
1998
JUPITER FLY-BY
FEBUARY 1992
1992
PERIHELION
March 1995
May 2001
EARTH ORBIT
LAUNCH
6 October 1990
1991
JUPITER ORBIT
1999
(1993)
(1995)
2001
SOUTH POLAR PASSES
June - November 1995
September 2000 - January 2001
(1994)
2000

The heliospheric magnetic field

- The heliospheric magnetic field is a result of the Sun's magnetic field being carried outward, frozen in to the solar wind.
- Within the corona, the magnetic field forces dominate the plasma forces.
- As the field strength decreases with distance, beyond the Alfvén radius at a few solar radii, the plasma flow becomes dominant, and the field lines are constrained to move with the solar wind.

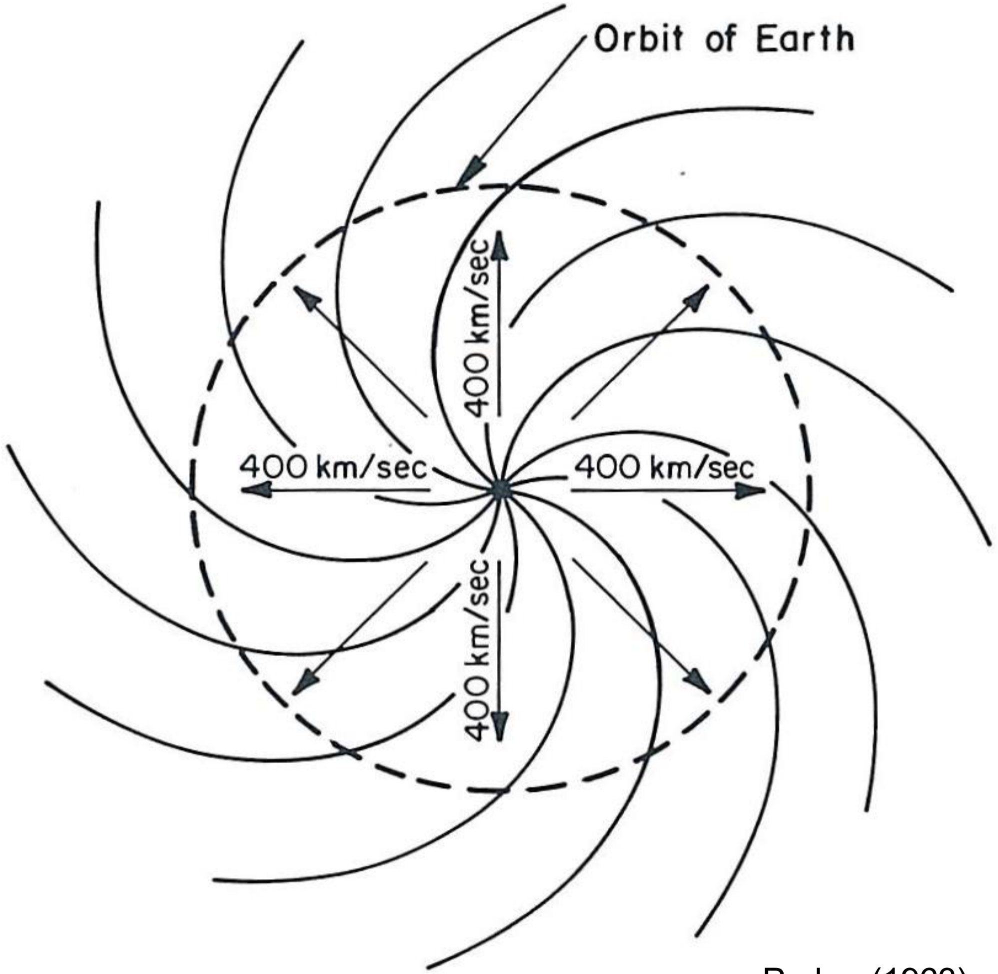


Model of Pneumann and Kopp (1971)


SDO/AIA- 304 20101020_103221

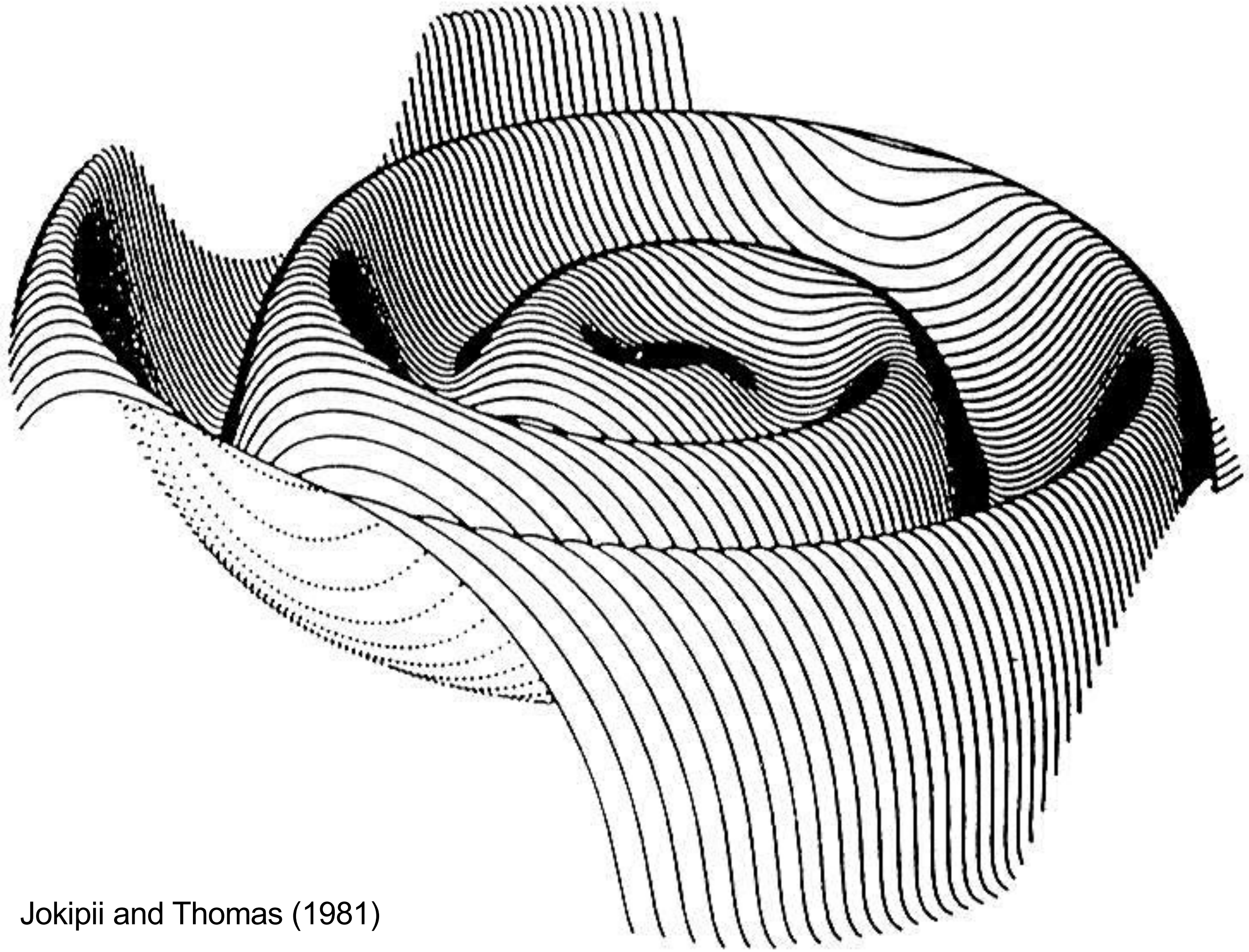
The Parker Spiral Field

- 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.



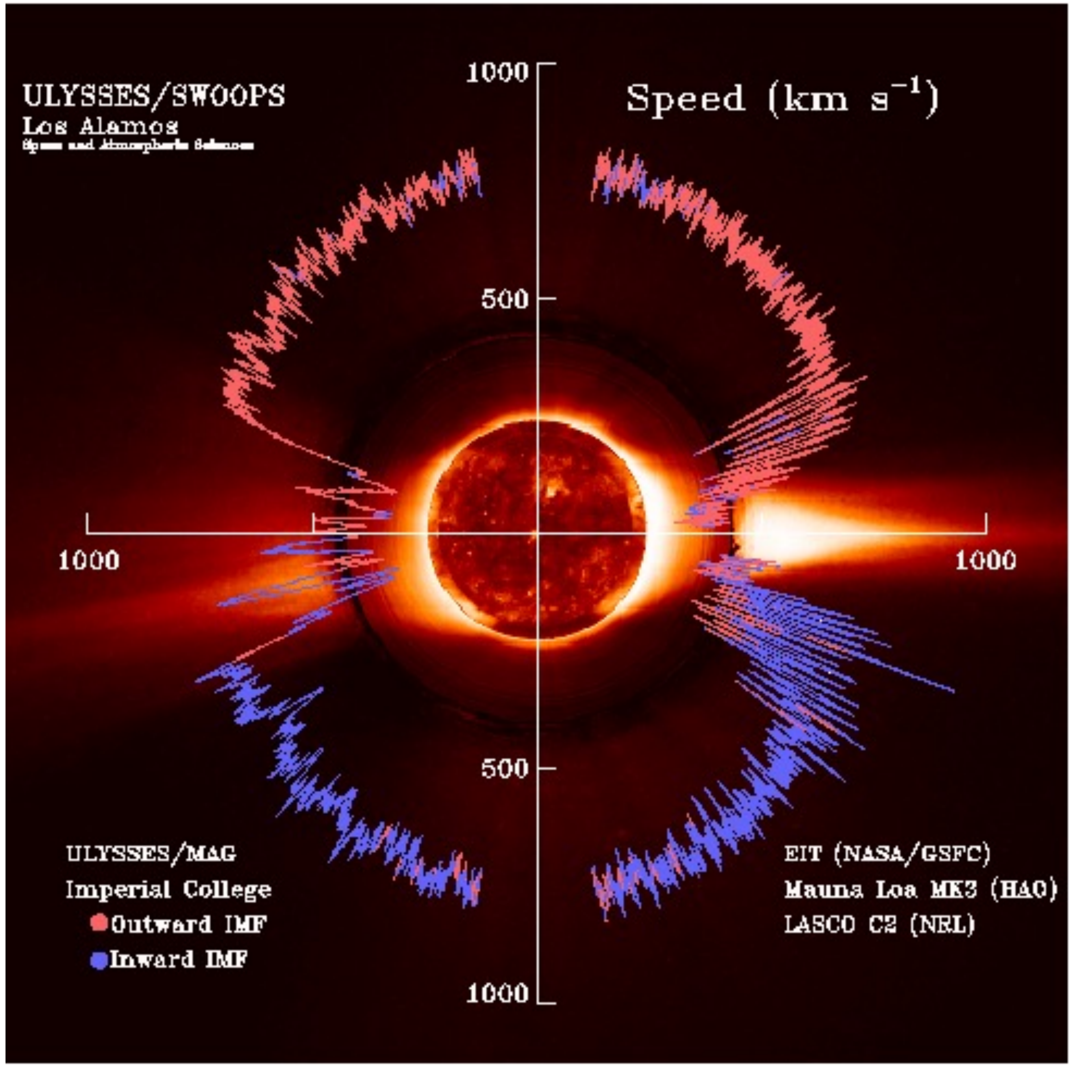
Parker (1963)

The current sheet mapped out into the heliosphere…



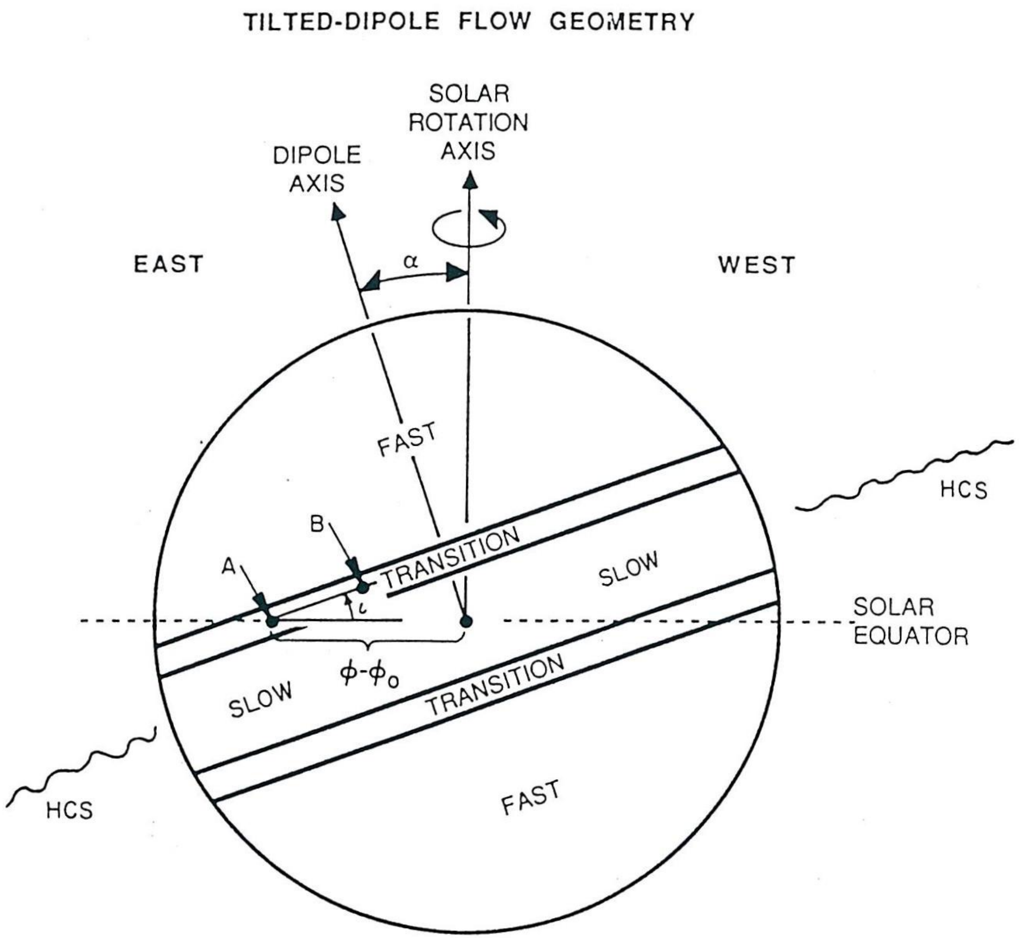
Jokipii and Thomas (1981)

- Ulysses found continuous fast solar wind (~750 km/s) at high latitudes at solar minimum in agreement with the idea that fast solar wind originated in coronal holes. This fast wind was associated with large stable polar coronal holes.
- Slow solar wind is associated with the streamers seen in coronagraph images, but its exact source is unclear.



McComas et al (1998)

- Close to solar minimum the flow pattern close to the Sun can be approximated as a band of slow wind at low latitudes, centred on the Sun's dipole equator, with fast wind at all higher latitudes.
- This pattern of fast and slow solar wind is occasionally disturbed by transient flows associated with coronal mass ejections.



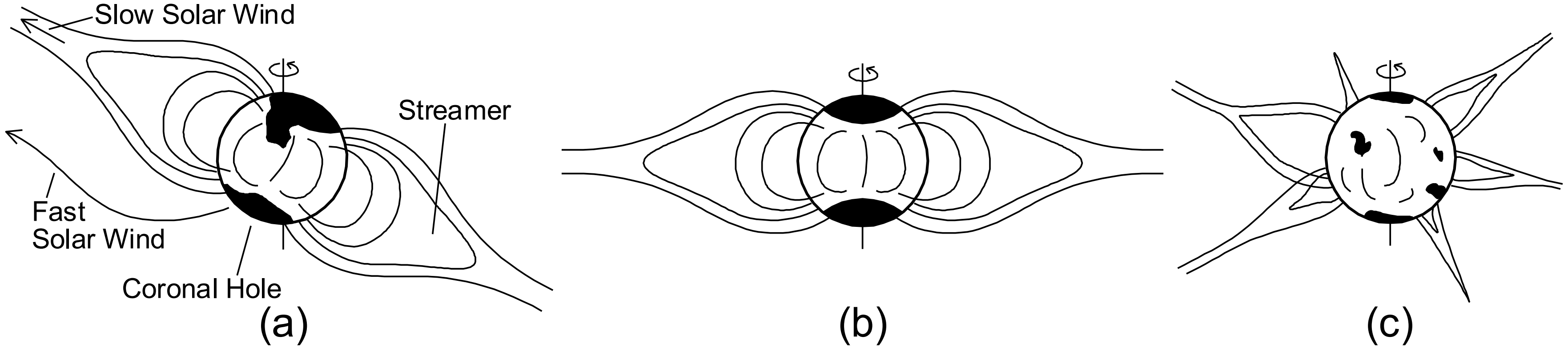
Pizzo (1991)

Characteristics of slow and fast solar wind

Property at 1 AU	Slow wind	Fast wind
Speed (v)	~400 km/s	~750 km/s
Number density (n)	~10 cm^{-3}	~3 cm^{-3}
Flux (nv)	~3×10^{8} cm^{-2} s^{-1}	~2×10^{8} cm^{-2} s^{-1}
Magnetic field (Br)	~3 nT	~3 nT
Proton temperature (Tp)	~4×10^{4} K	~2×10^{5} K
Electron temperature(Te)	~1.3×10^{5} K (>Tp)	~1×10^{5} K (<Tp)
Composition (He/H)	~1 – 30%	~5%

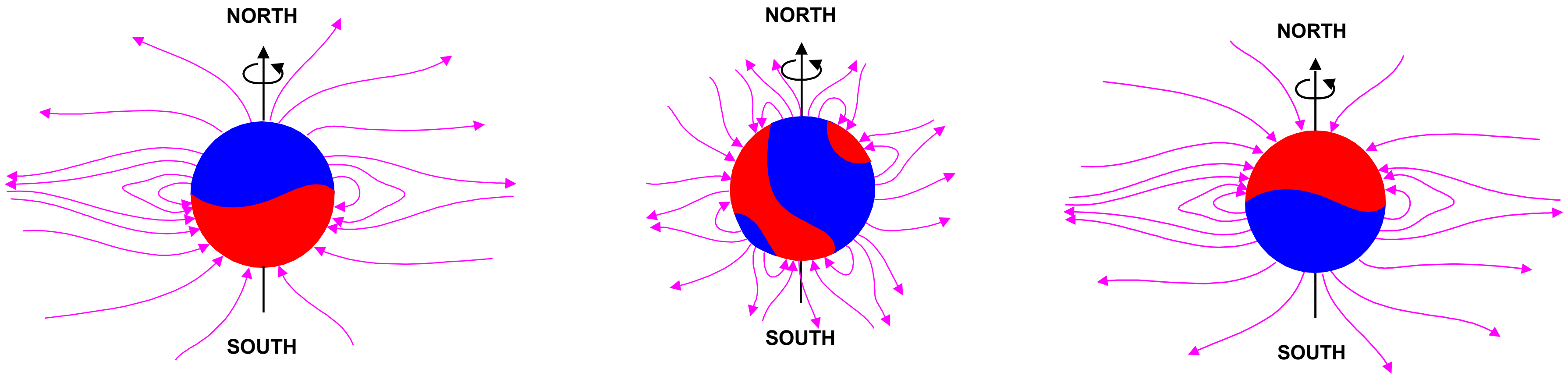
Solar cycle evolution

- The tilt of the underlying solar dipole field and hence of the heliospheric current sheet and the band of slow wind is a function of the solar cycle, with least tilt near solar minimum.
- Alternatively, the evolution of the coronal field can be viewed as the strength of the dipole component decreasing as solar activity increases so that the higher order components of the solar field have a greater effect.



Suess et al (1998)

- This evolution culminates in the reversal of the Sun's magnetic field during the solar maximum period.

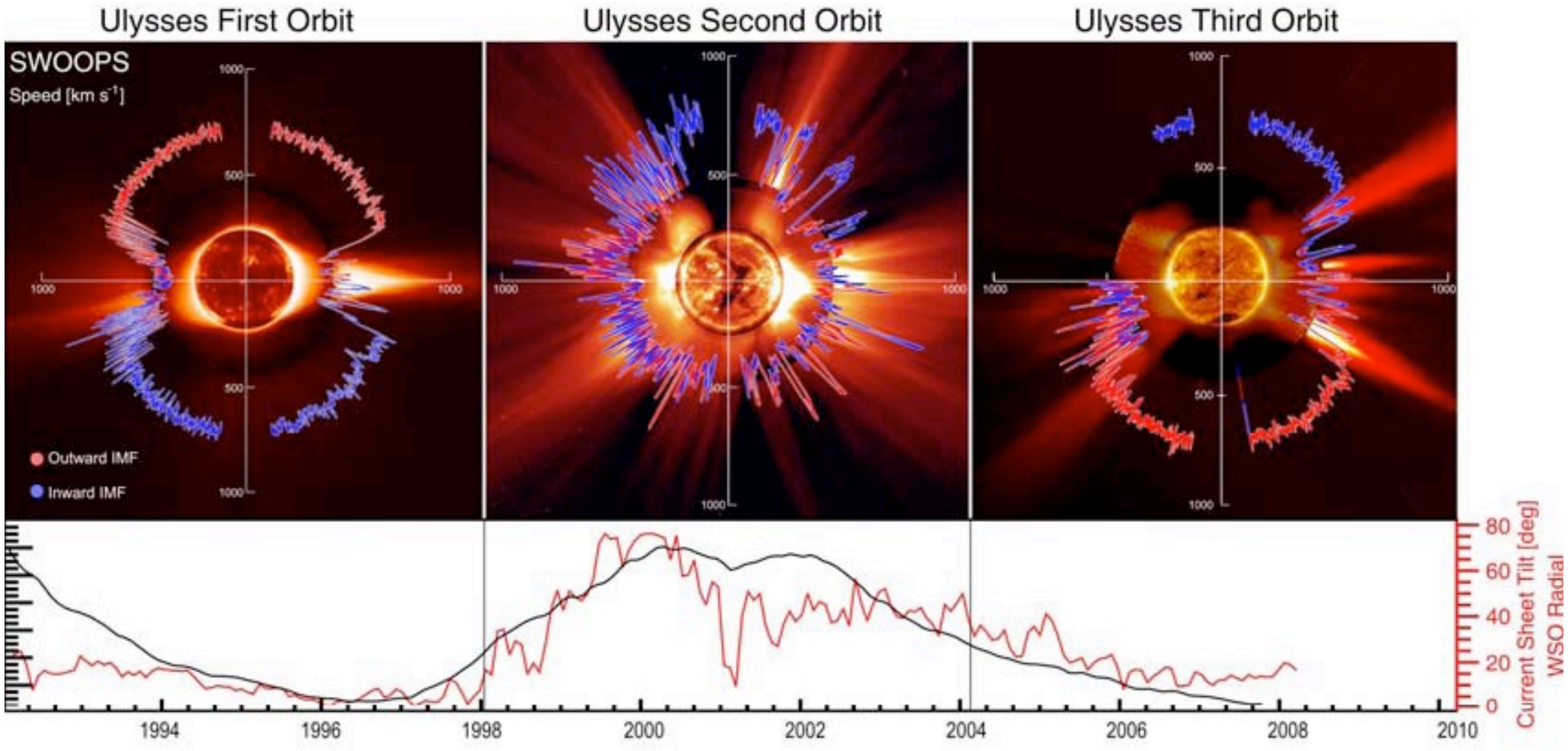


CORONAL MAGNETIC FIELD LINES AT SOLAR MINIMUM ACTIVITY

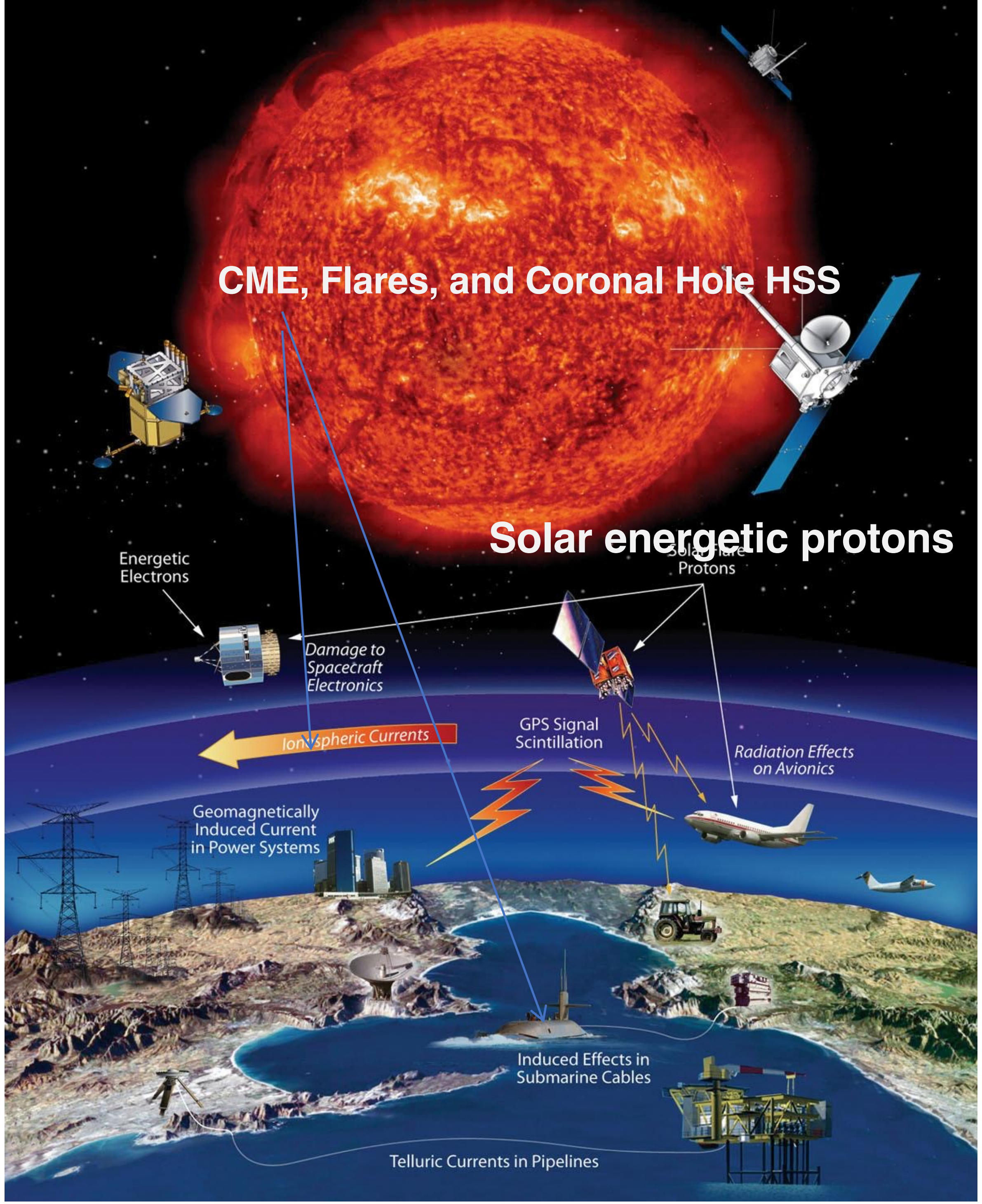
CORONAL MAGNETIC FIELD LINES AT SOLAR MAXIMUM ACTIVITY

CORONAL MAGNETIC FIELD LINES AT NEXT SOLAR MINIMUM

- At solar maximum the large polar coronal holes disappear and are replaced by smaller, generally short lived coronal holes at all latitudes. Ulysses observed fast and slow wind at all latitudes in the southern hemisphere.



McComas et al, (2008)



The Sun
maker of space weather

CME, Flares, and Coronal Hole HSS

Three very important solar wind disturbances/structures for space weather

✓**Radiation storm**
- **proton radiation (SEP) <flare/CME>**
- **electron radiation <CIR HSS/CME>**

✓**Radio blackout storm <flare>**

✓**Geomagnetic storm**
- **CME storm (can be severe)**
- **CIR storm (moderate)**

Two Main Drivers for the Magnetosphere

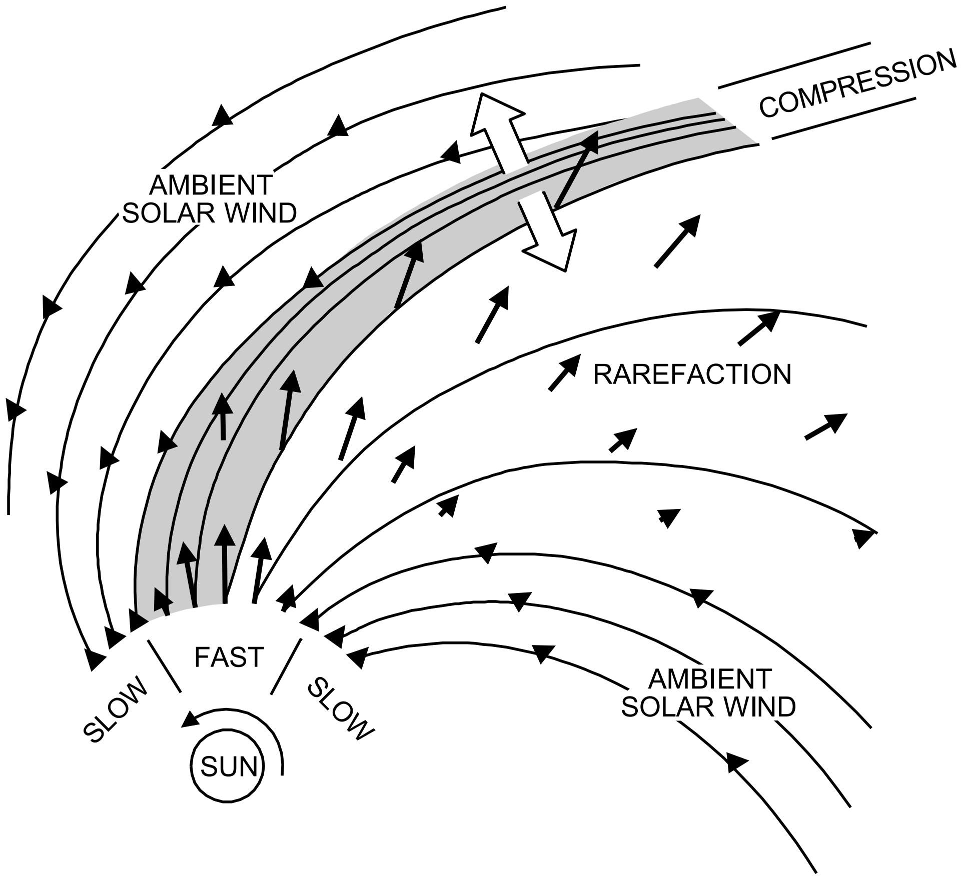
- CME (Coronal Mass Ejection)
- CIR (Corotating Interaction Region) High Speed solar wind Stream (HSS)

Geomagnetic storm

- **CME storm (can be severe) Kp can reach 9**
- **CIR storm (moderate) Kp at most 6**

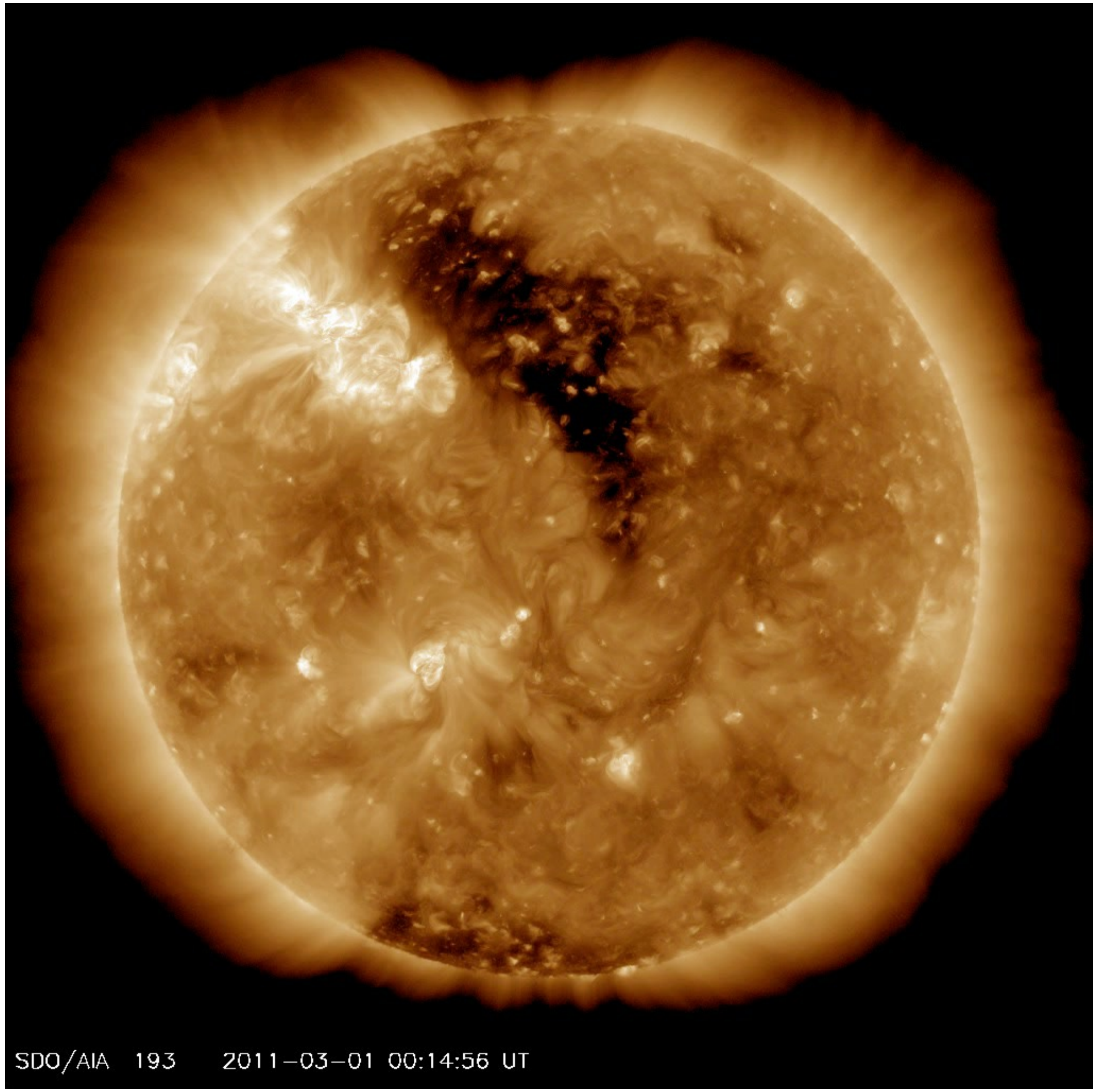
Corotating Interaction Regions

- Interaction regions form wherever fast solar wind 'catches up' with slower wind ahead of it.
- A compression region forms where the magnetic field lines and plasma 'pile up'. The resulting pressure waves can steepen into shocks.
- When a fast solar wind stream originates from a stable coronal hole persisting over many solar rotations, the resulting interaction region pattern corotates with the Sun.
- Ulysses provided new results on the three dimensional geometry of Corotating Interaction regions.



Pizzo (1985)

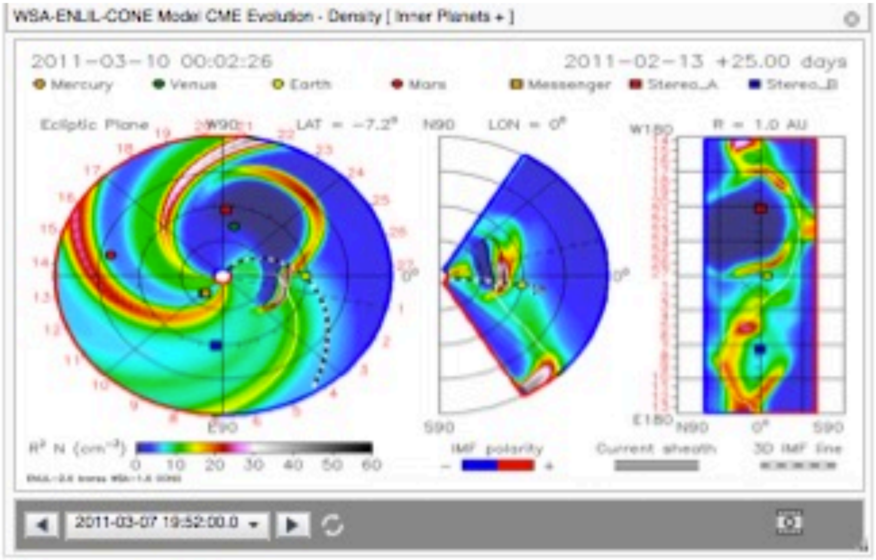
Coronal Hole HSS

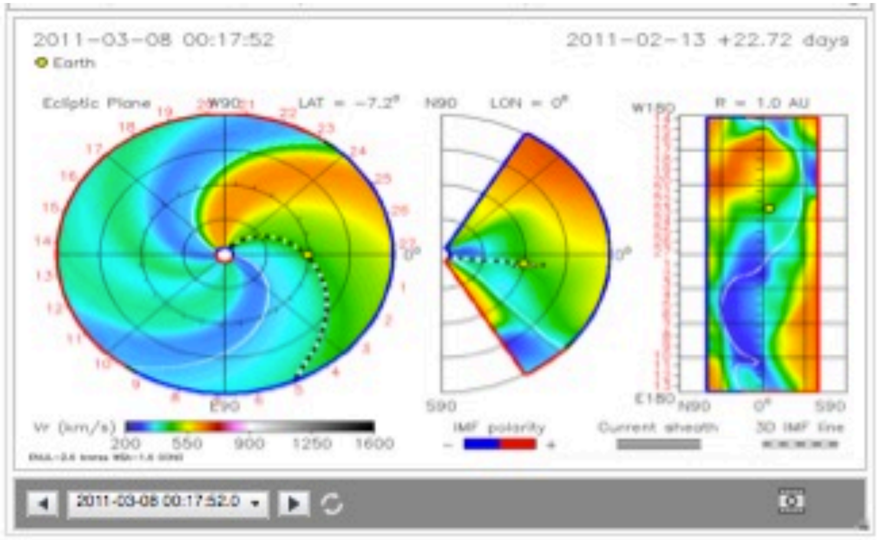


Mar 1, 2011

June 4, 2012

Forecasting capability enabled by ENLIL



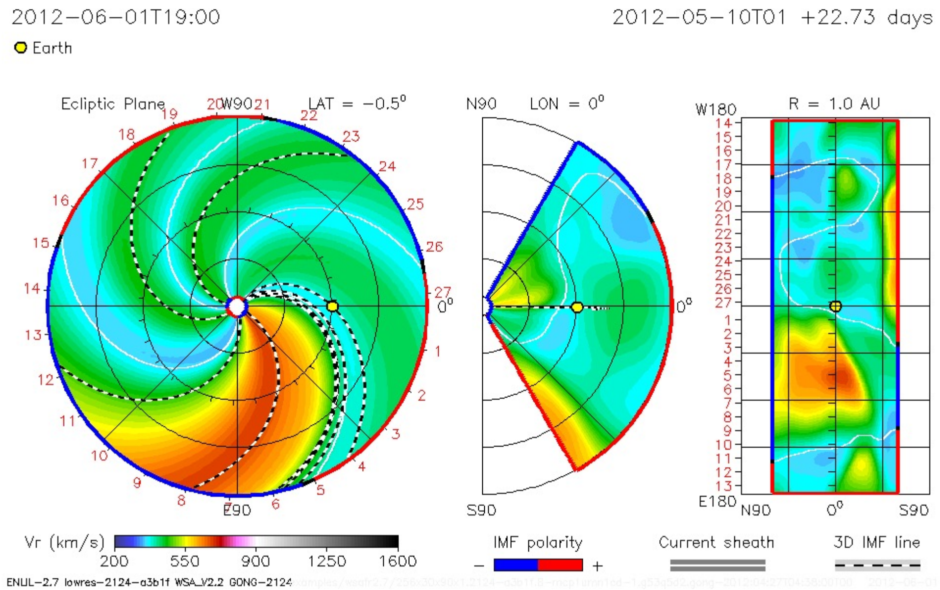


WSA+ENLIL+cone

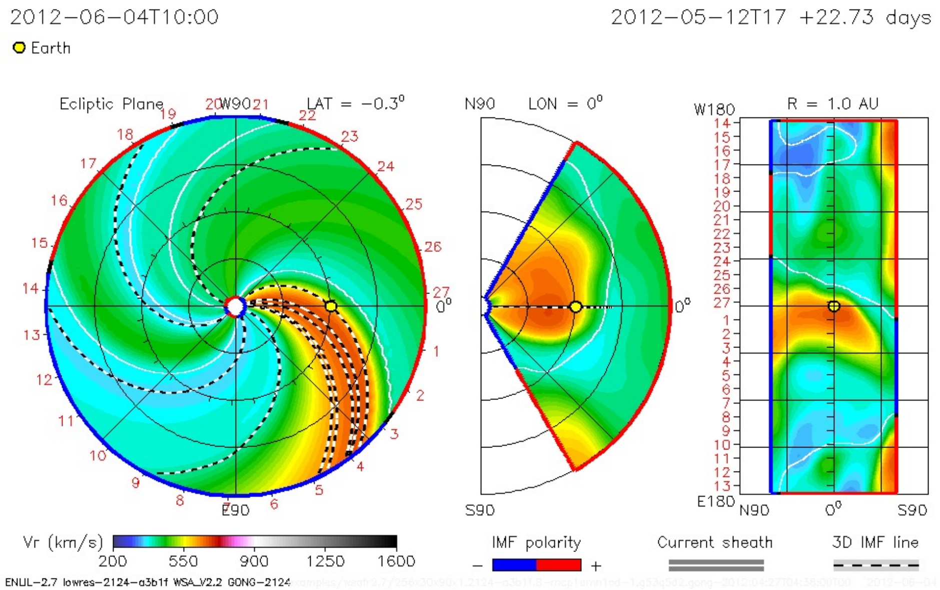
Predicting impacts of CMEs

WSA+ENLIL

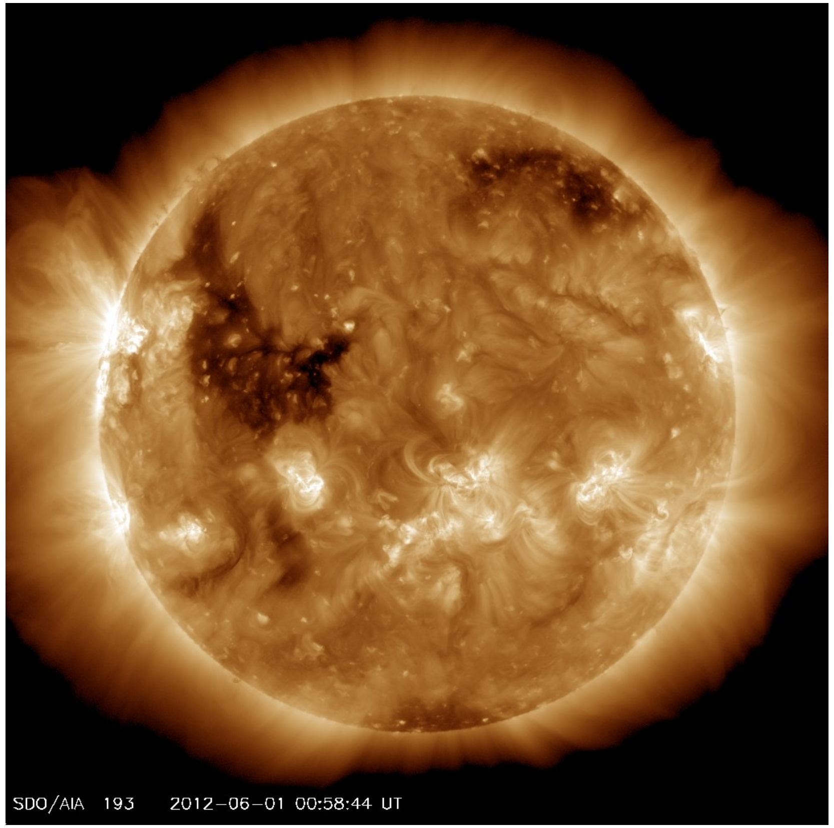
Modeling and predicting the ambient solar wind



2012-06-01T19:00
2012-05-10T01 +22.73 days
Earth
Ecliptic Plane
W90
LAT = -0.5°
N90
LON = 0°
W180
R = 1.0 AU
E90
S90
E180
N90
0°
S90
Vr (km/s)
200 550 900 1250 1600
IMF polarity
– +
Current sheath
3D IMF line
ENLIL-2.7 lowres-2124-a3b1f WSA_V2.2 GONG-2124



2012-06-04T10:00
2012-05-12T17 +22.73 days
Earth
Ecliptic Plane
W90
LAT = -0.3°
N90
LON = 0°
W180
R = 1.0 AU
E90
S90
E180
N90
0°
S90
Vr (km/s)
200 550 900 1250 1600
IMF polarity
– +
Current sheath
3D IMF line
ENLIL-2.7 lowres-2124-a3b1f WSA_V2.2 GONG-2124



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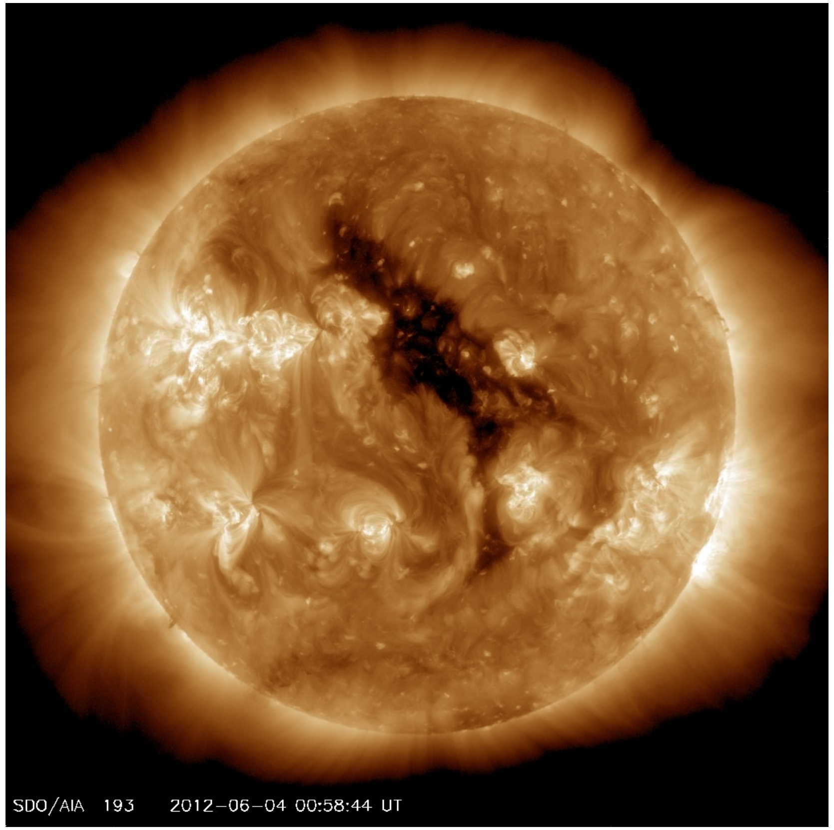
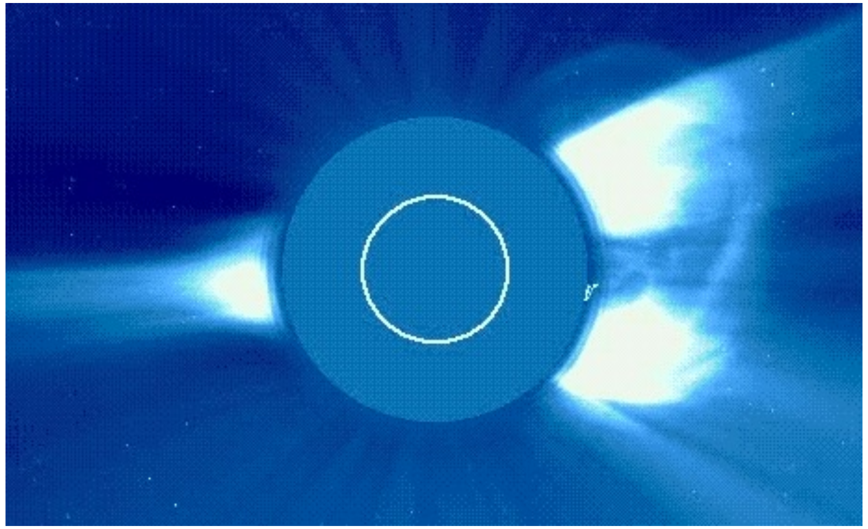
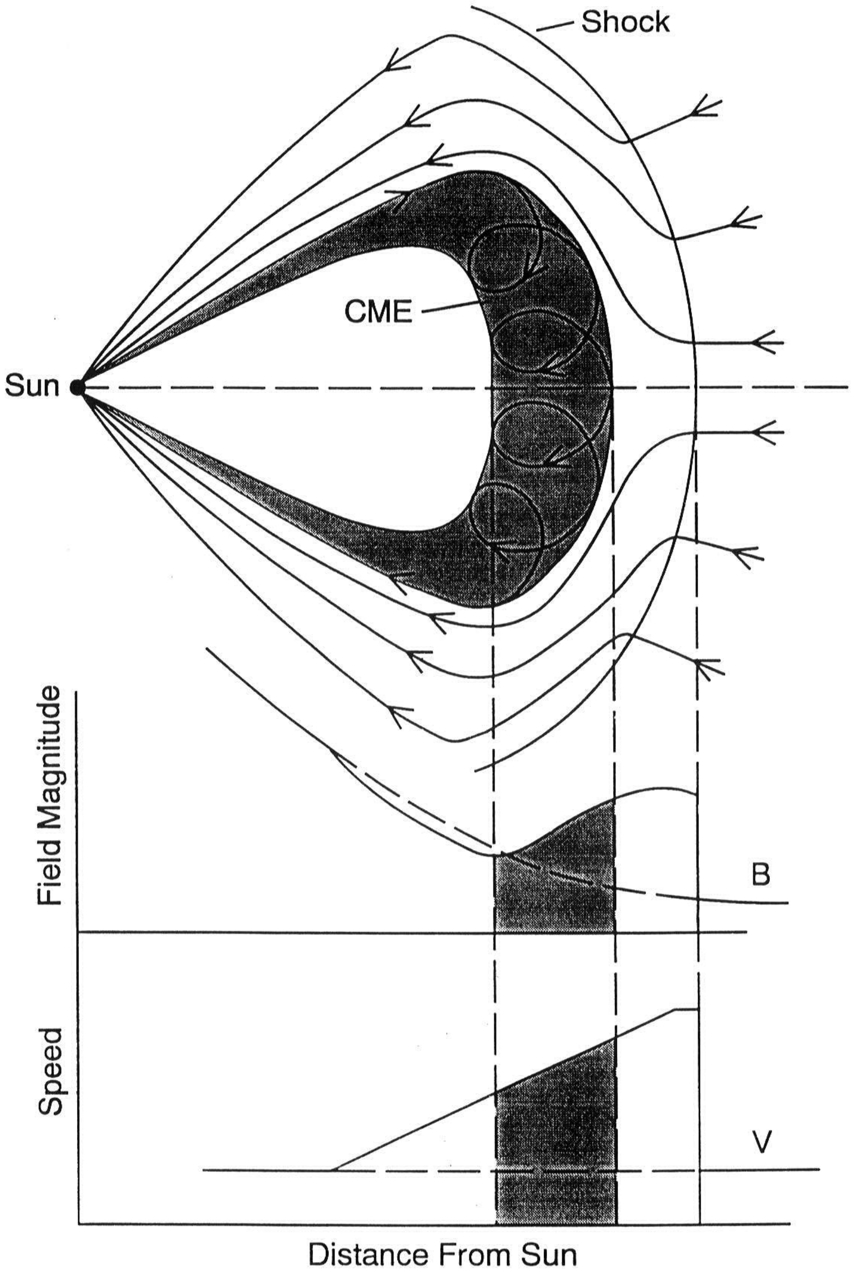


SDO/AIA 193 2012-06-04 00:58:44 UT

Coronal Mass Ejections

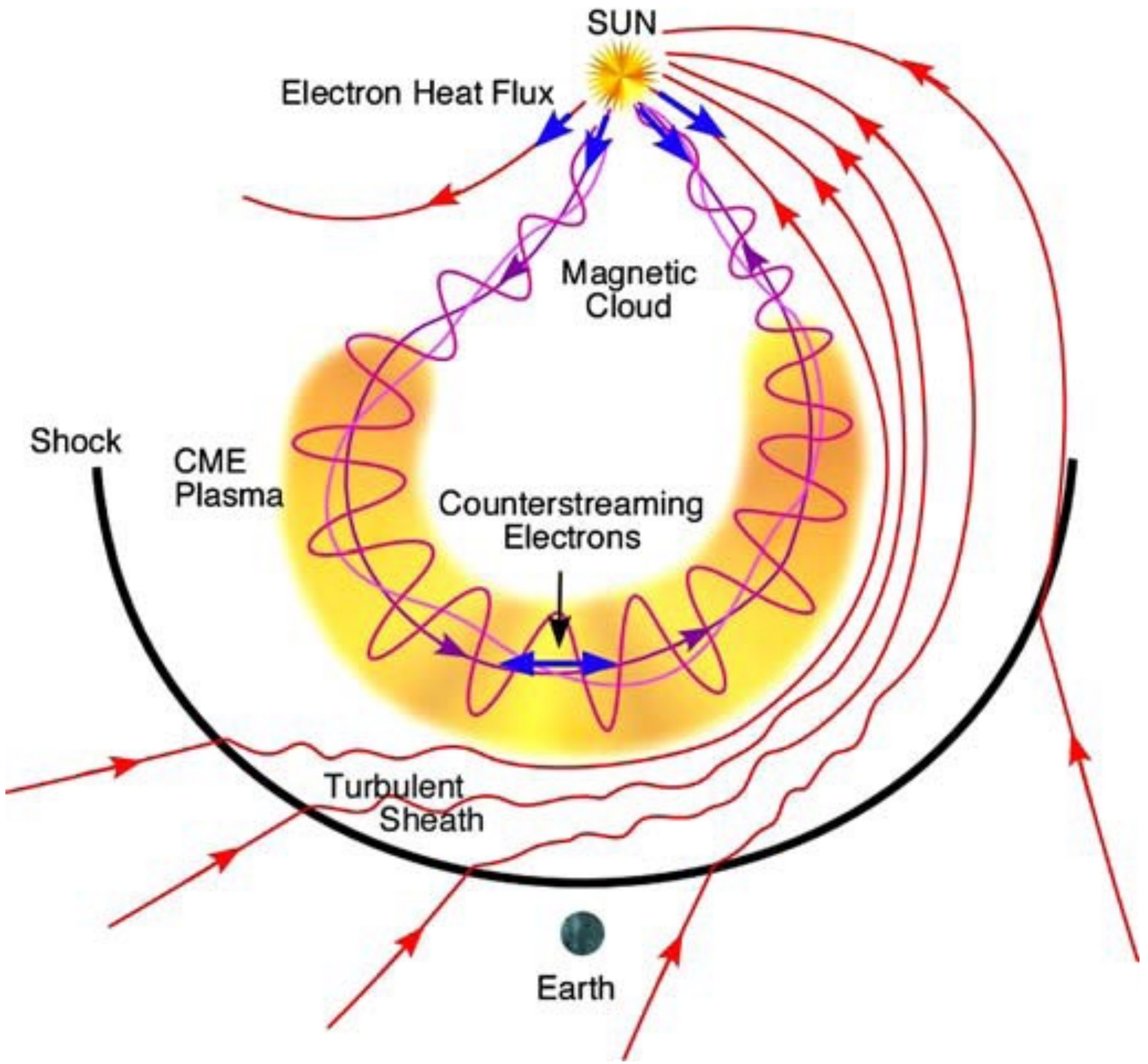
- Fast coronal mass ejections can interact with solar wind ahead of them in a similar way to high speed streams to produce compression regions and shocks.



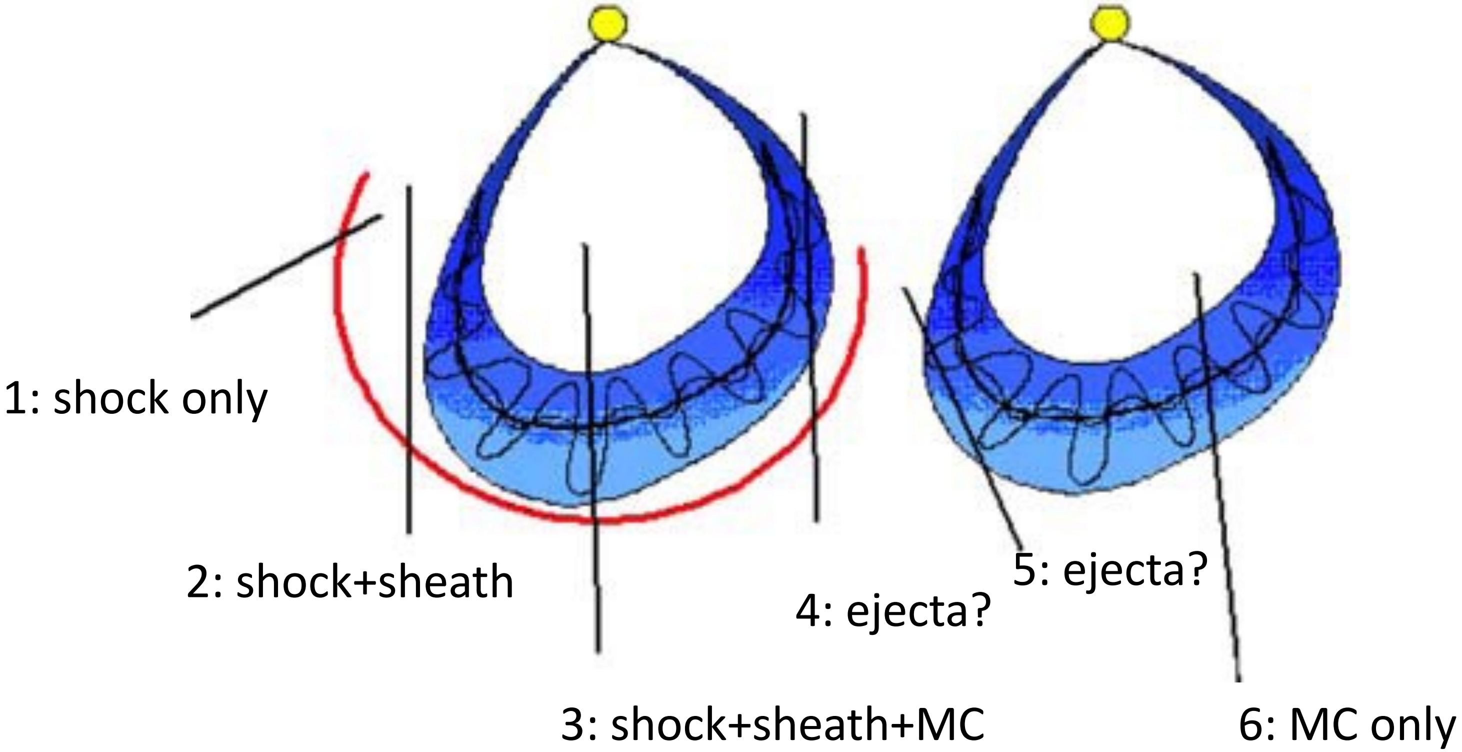


Gosling (1998)

Schematic of the three-dimensional structure of an ICME and upstream shock



In-Situ signature can be quite complex

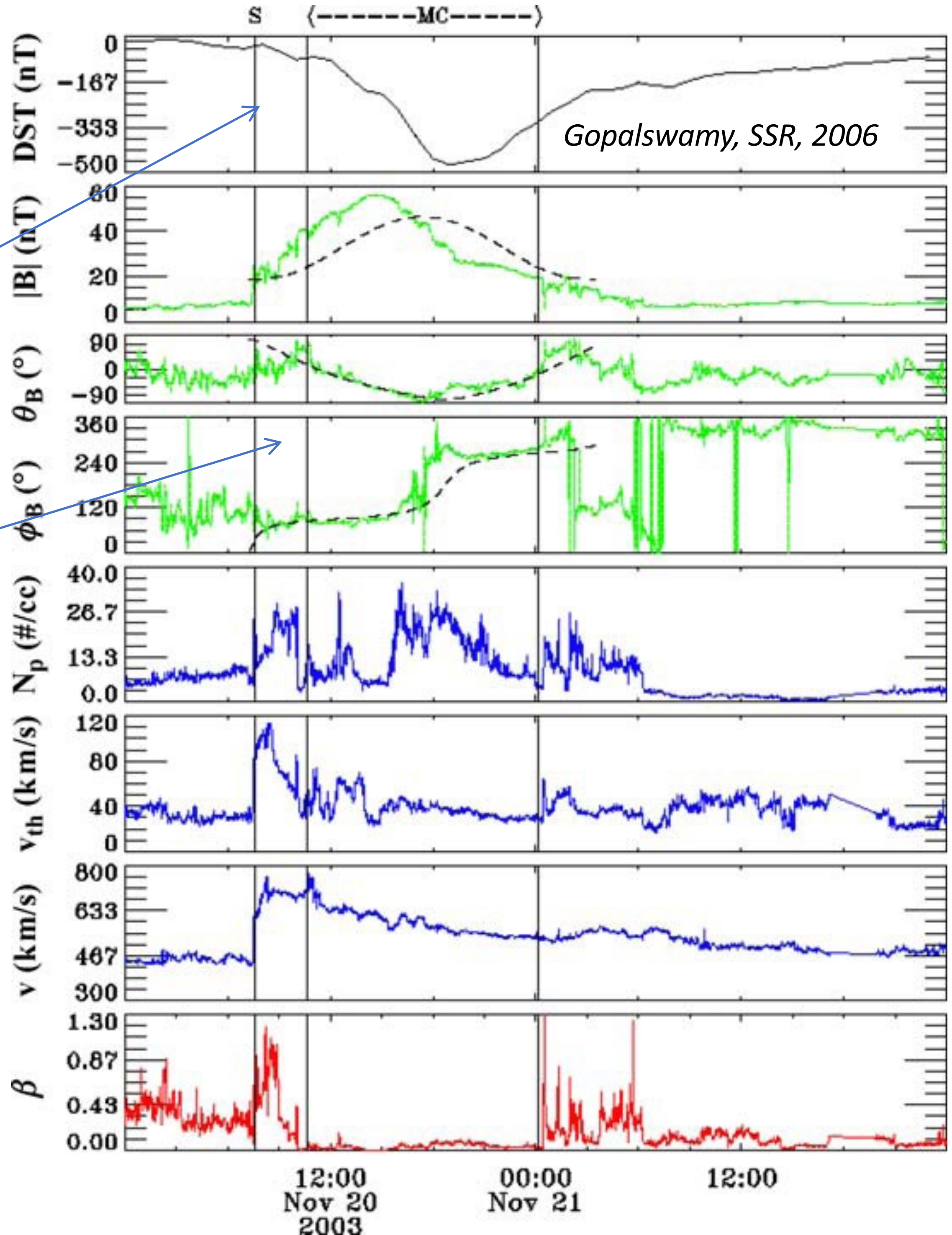


Textbook example of ICME in-situ signature

shock

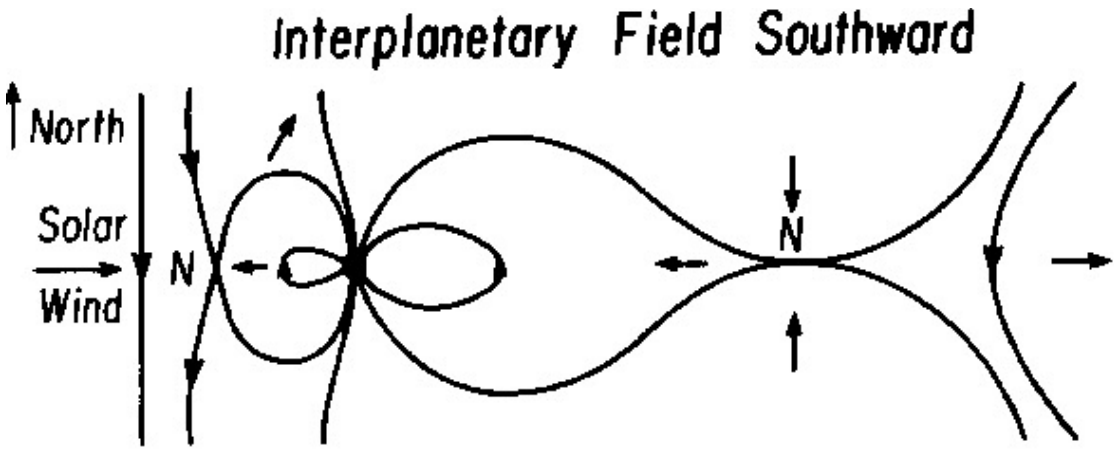
sheath

Magnetic cloud

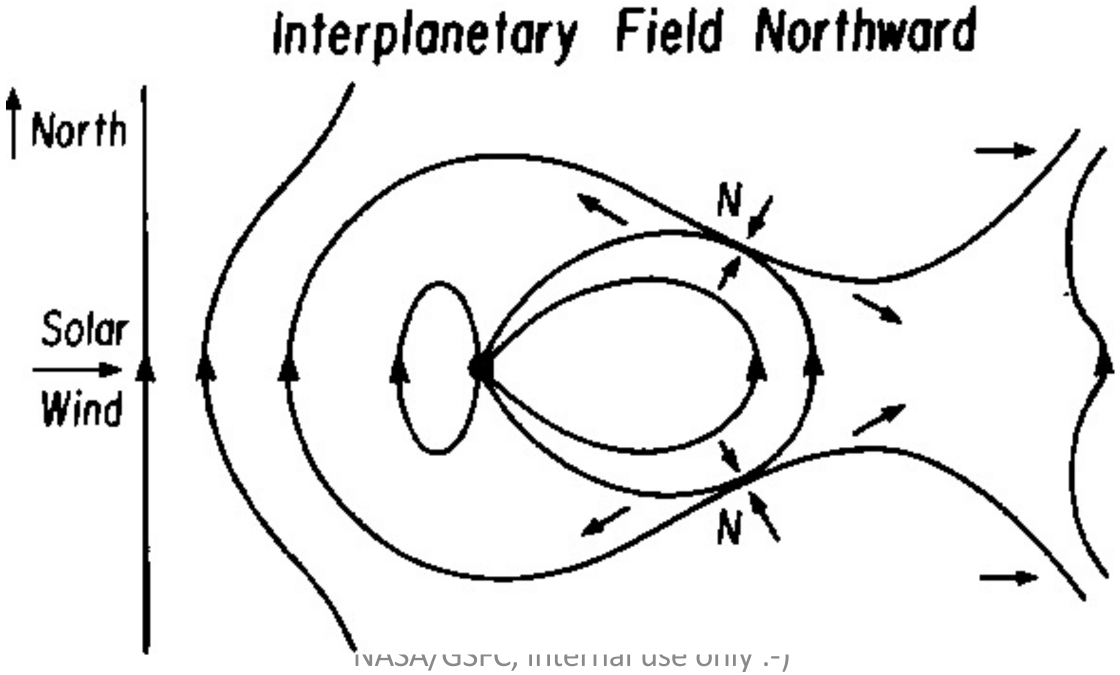


Two major types of solar wind-magnetosphere interactions

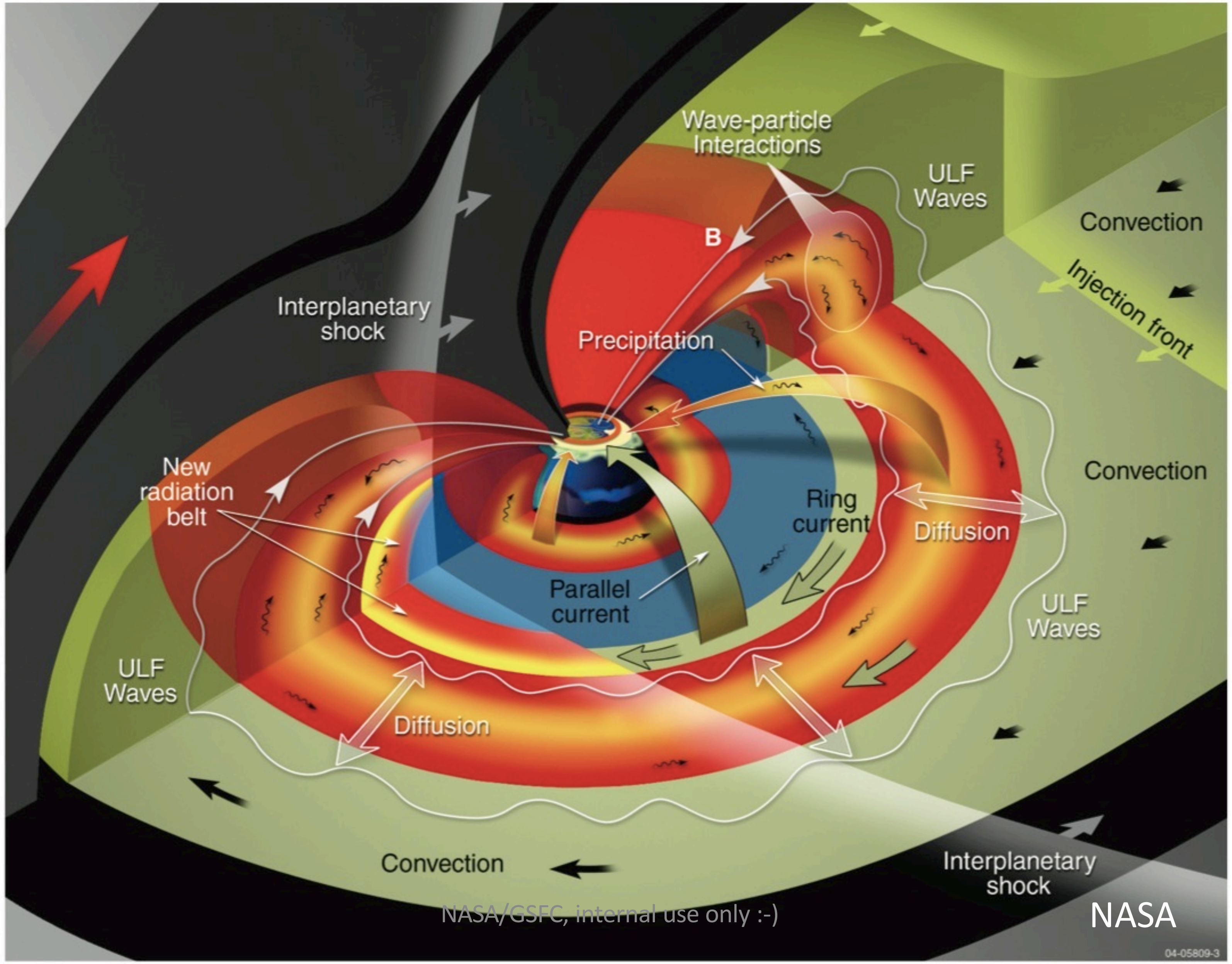
Southward IMF



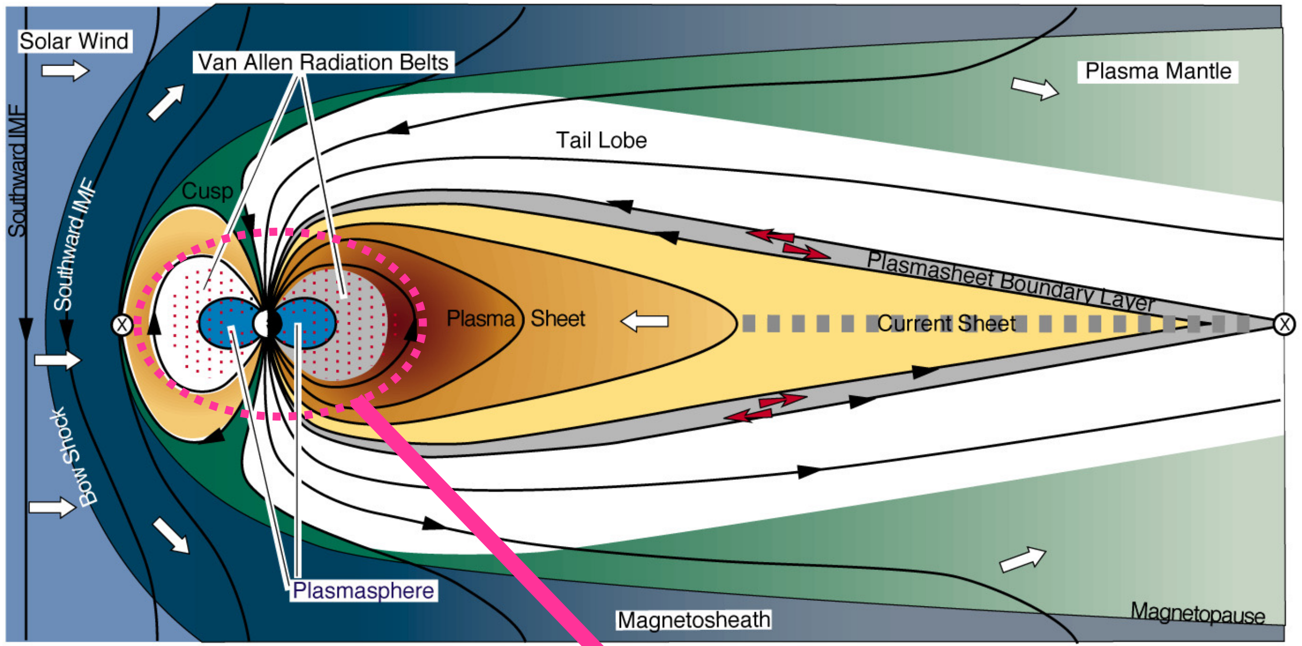
Northward IMF



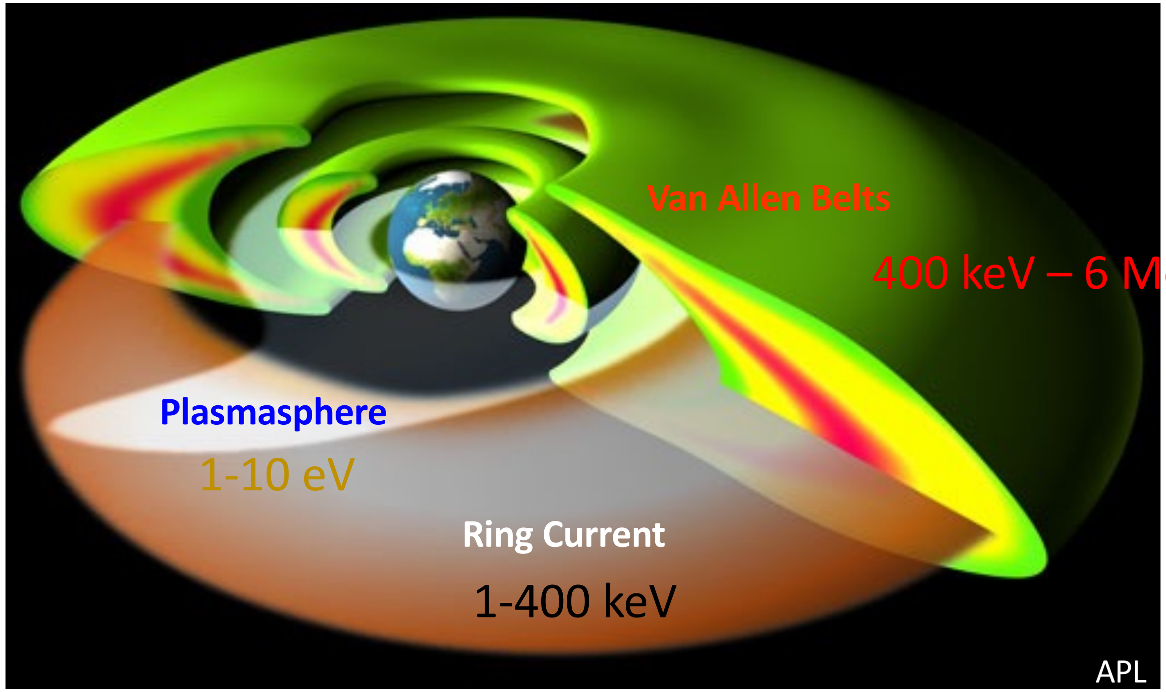
The Earth’s Magnetosphere



The Earth's Magnetosphere



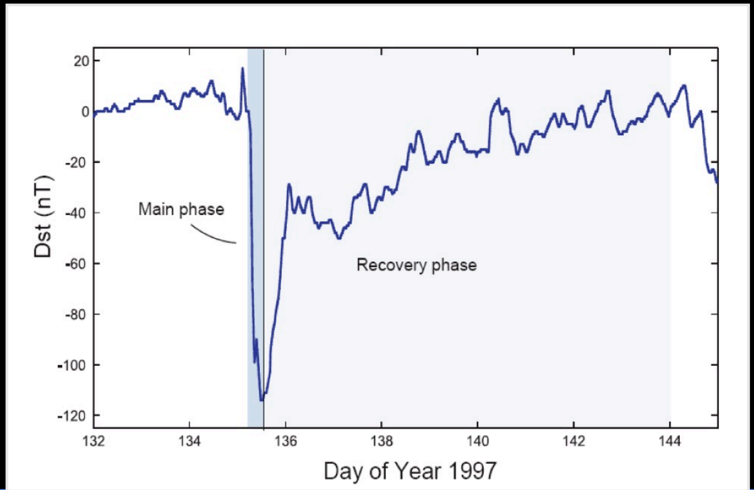
Inner Magnetosphere:
Up to ~ 10Re



Magnetic Storms

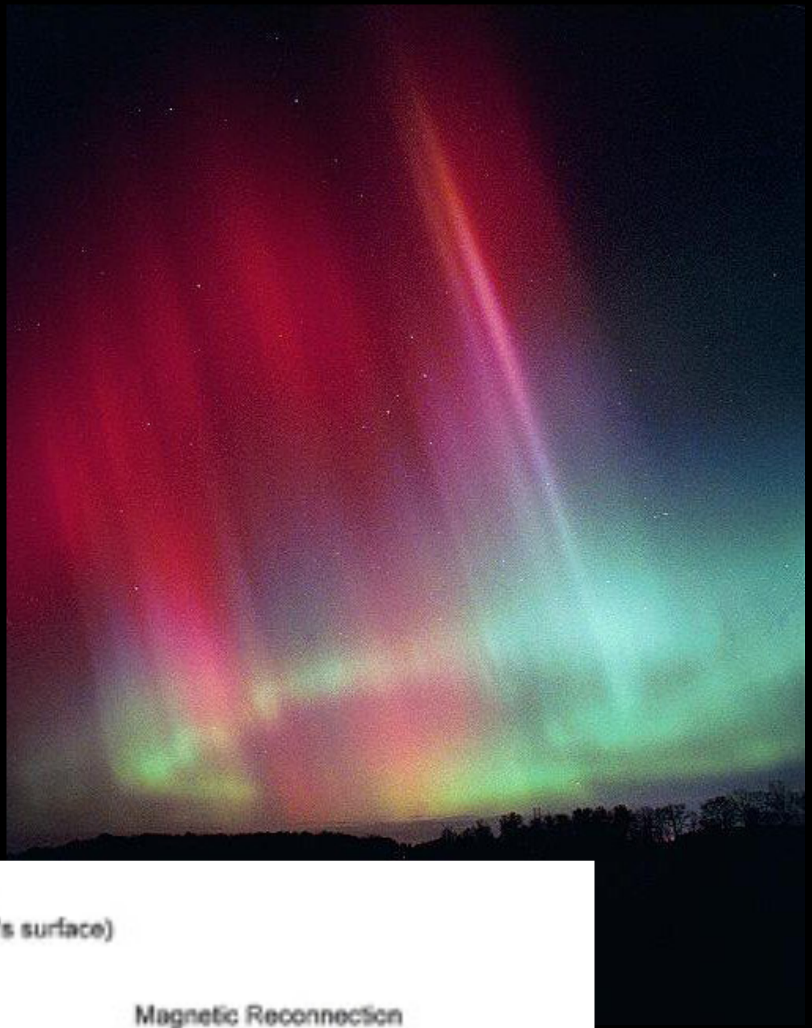
- Most intense solar wind-magnetosphere coupling
- Associated with solar coronal mass ejections (CME), coronal holes HSS
- IMF Bz southward, strong electric field in the tail
- Formation of ring current and other global effects

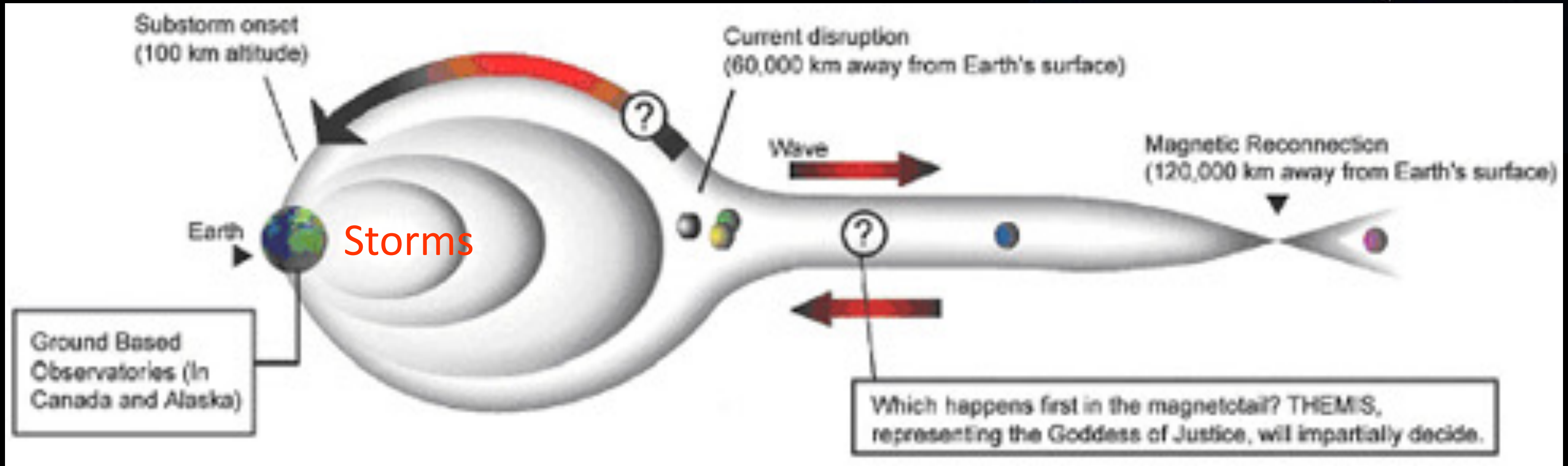
- Dst measures ring current development
  - Storm sudden commencement (SSC), main phase, and recovery phase
  - Duration: days



Substorms

- Instabilities that abruptly and explosively release solar wind energy stored within the Earth's magnetotail.
- manifested most visually by a characteristic global development of auroras
- Last ~ hours





NASA

esa

European Space Agency

Solar Orbiter

Mission Status + Science Planning

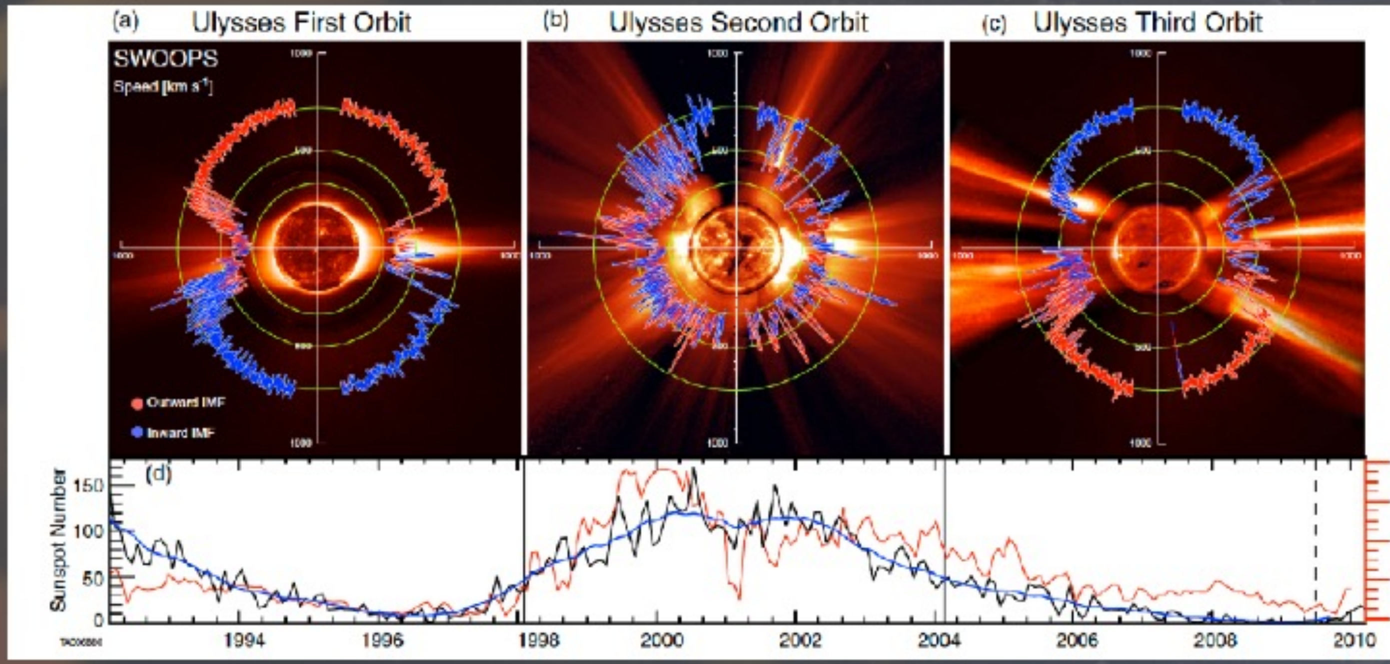
Getting Ready for the Nominal Mission Phase

Daniel Müller
Solar Orbiter Project Scientist
ESTEC

Anik De Groof
Solar Orbiter Instrument Operations Scientist
ESAC

Solar Orbiter
Overarching science question

How does the Sun create and control the heliosphere – and why does solar activity change with time?

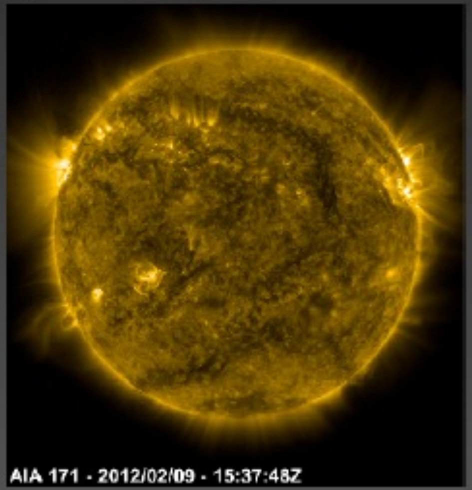


McComas et al., ApJ 2013

Mission overview:
Müller et al., A&A Special Issue, 2020

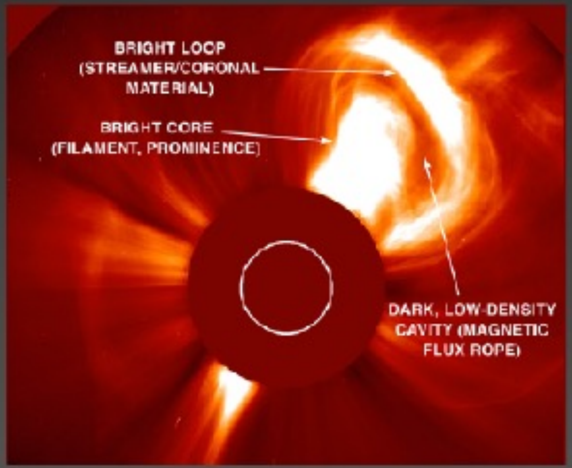
Top-level science objectives

#1: How and where do the solar wind plasma and magnetic field originate?

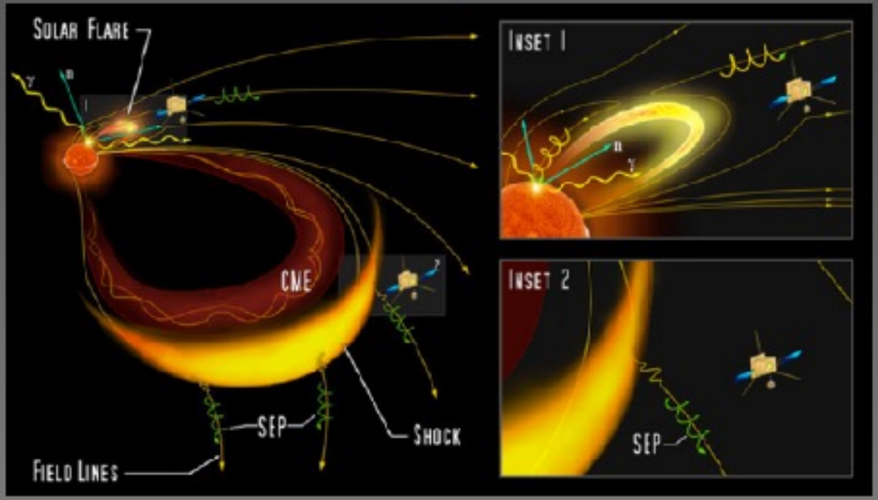


Disentangling space/time structures requires viewing a given region for more than an active region growth time (~ 10 days)
→ Need to go closer to the Sun

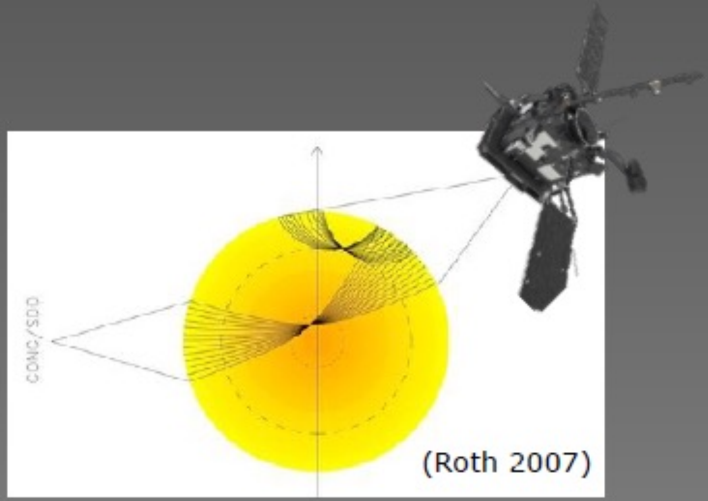
#2: How do solar transients drive heliospheric variability?

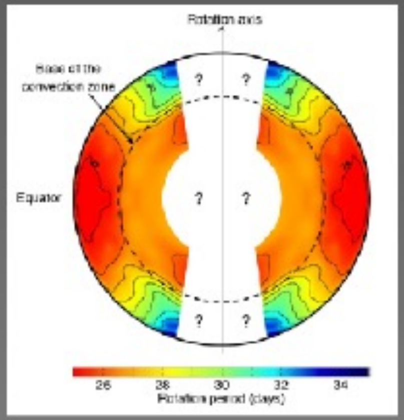


#3: How do solar eruptions produce energetic particle radiation that fills the heliosphere?



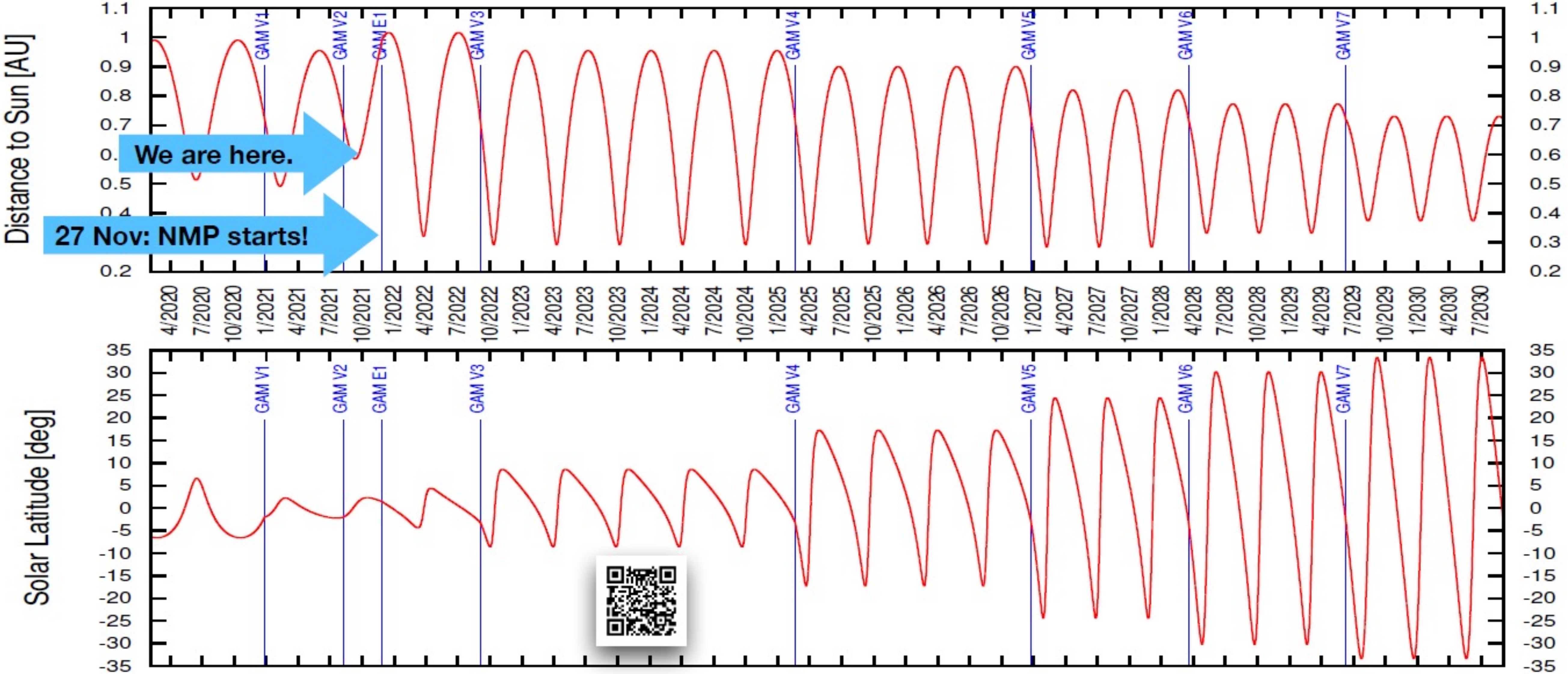
#4: How does the solar dynamo work and drive connections between the Sun and the heliosphere?



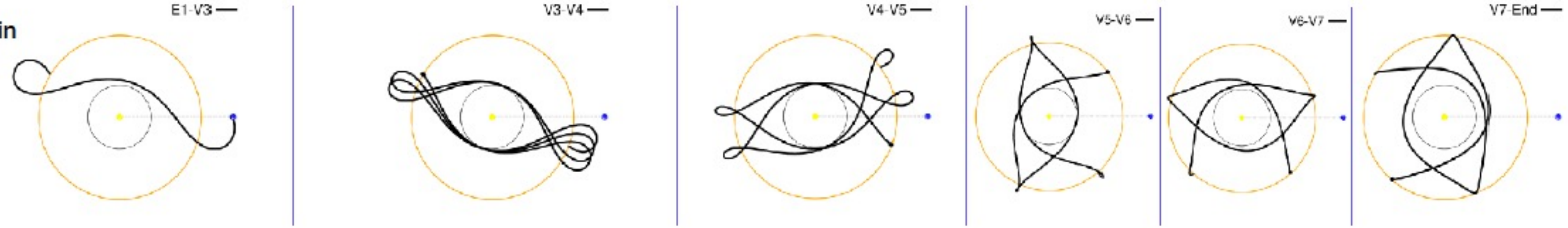


Mission Summary

- Joint ESA/NASA mission
- Launch: 10 Feb 2020 (UTC)
- Currently in Cruise Phase:
  In situ instruments operating nominally, remote-sensing instruments being readied for start of nominal mission phase (NMP)
- Nov 2021: Start of 4-year NMP, with first close perihelion @0.32 au in March 2022
- Followed by extended mission phase, with max. solar latitude ~33°

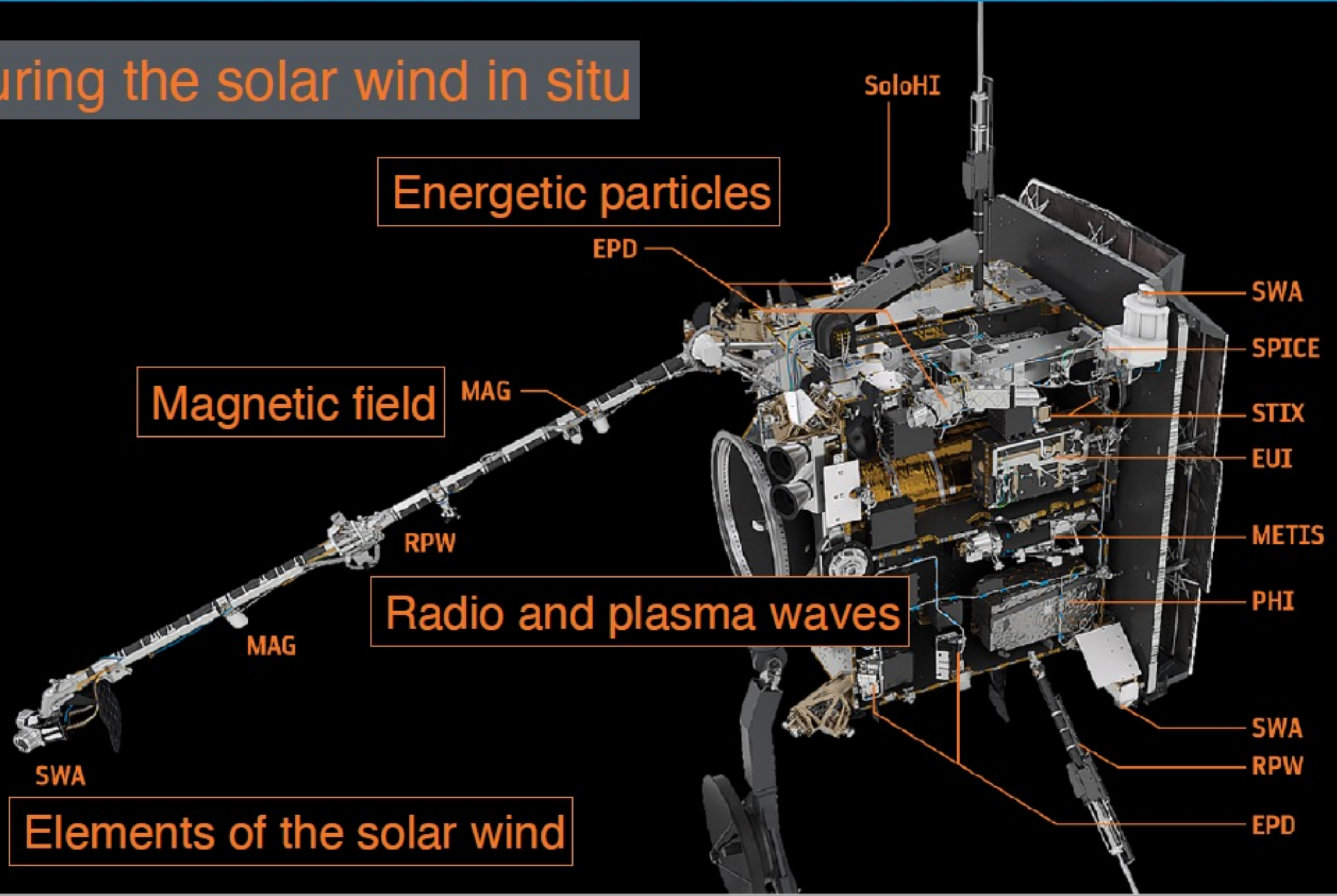


Solar Orbiter's trajectory in Geocentric Solar Ecliptic coordinates (Earth = blue dot)

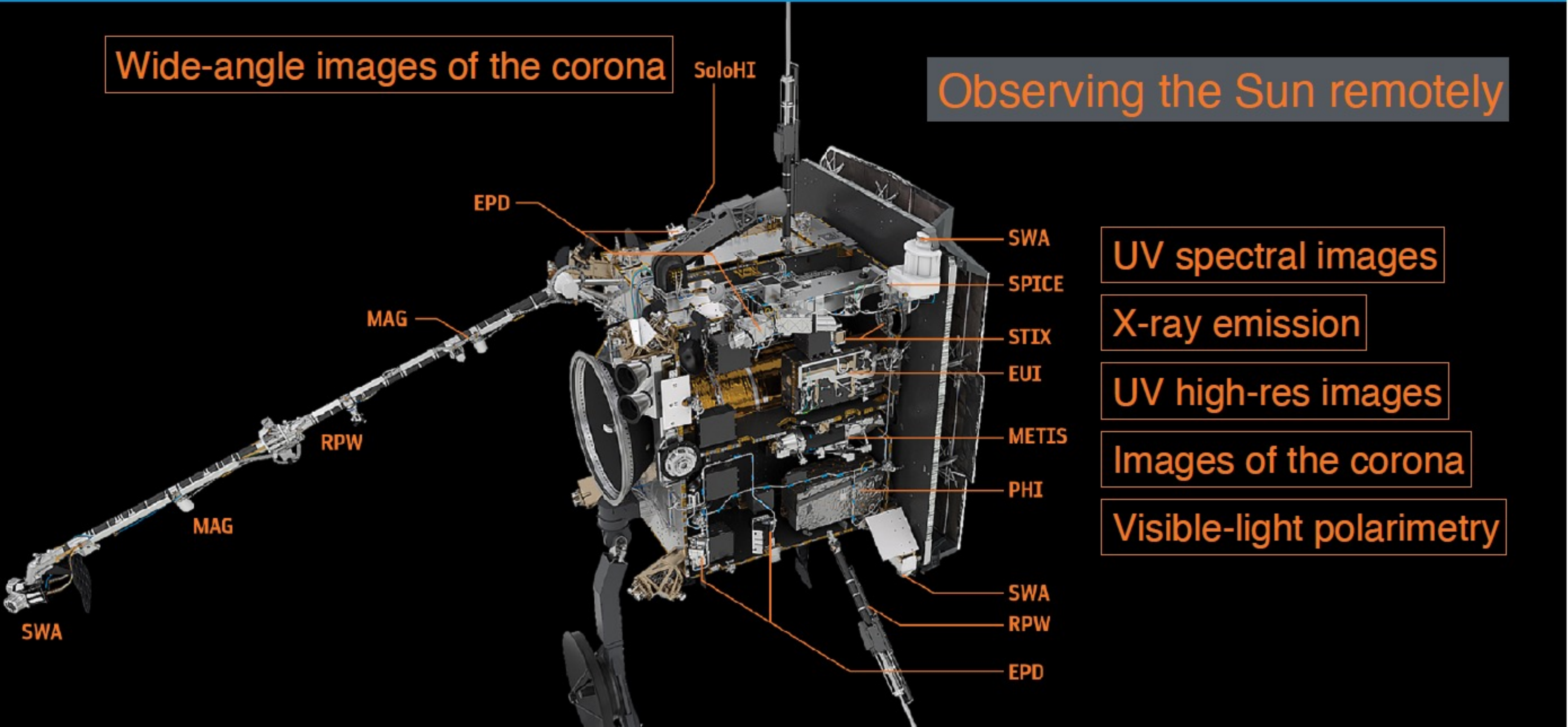


Solar Orbiter Payload

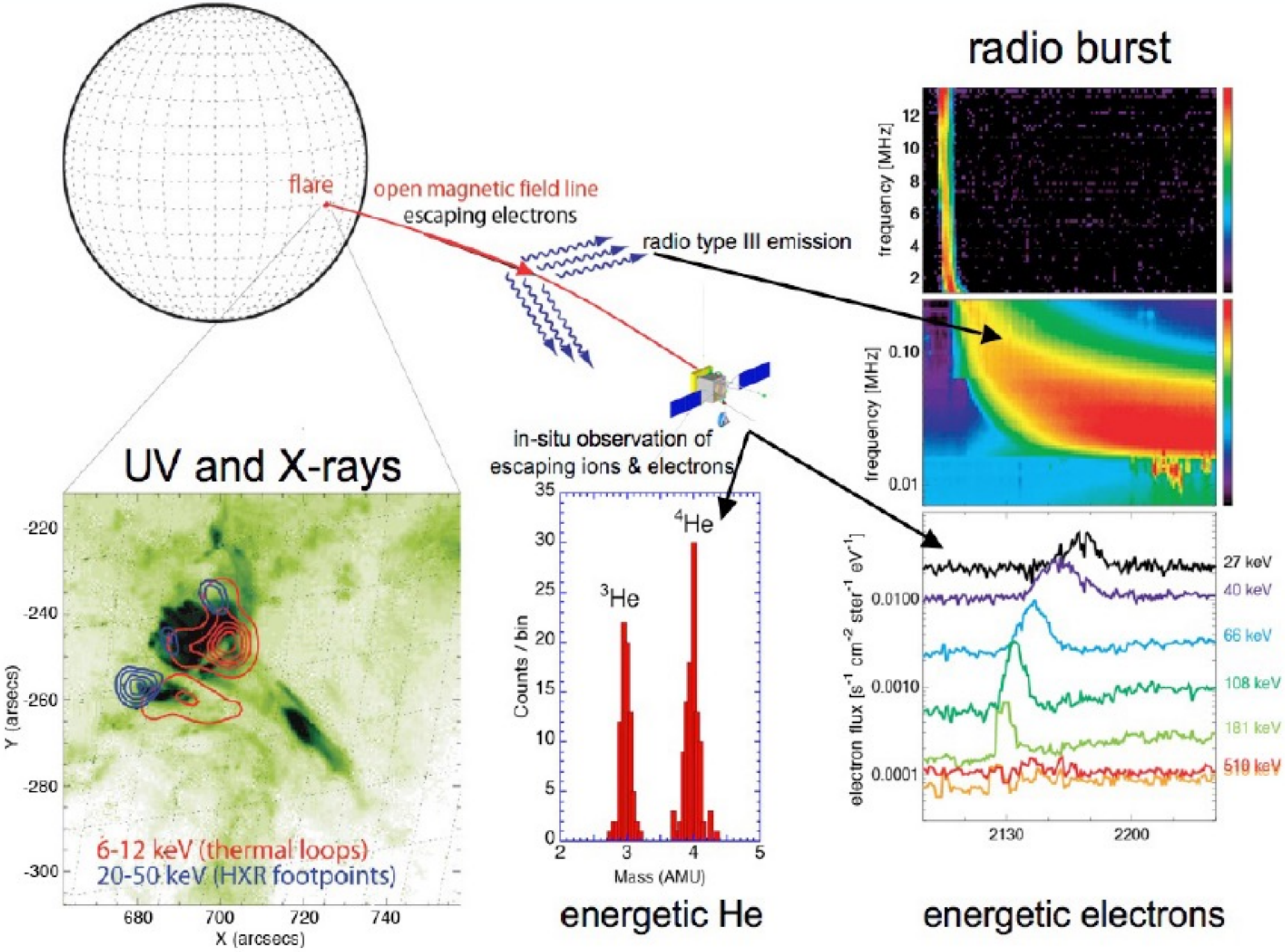
Measuring the solar wind in situ



Solar Orbiter Payload



Solar Orbiter = Linking in-situ and remote-sensing observations

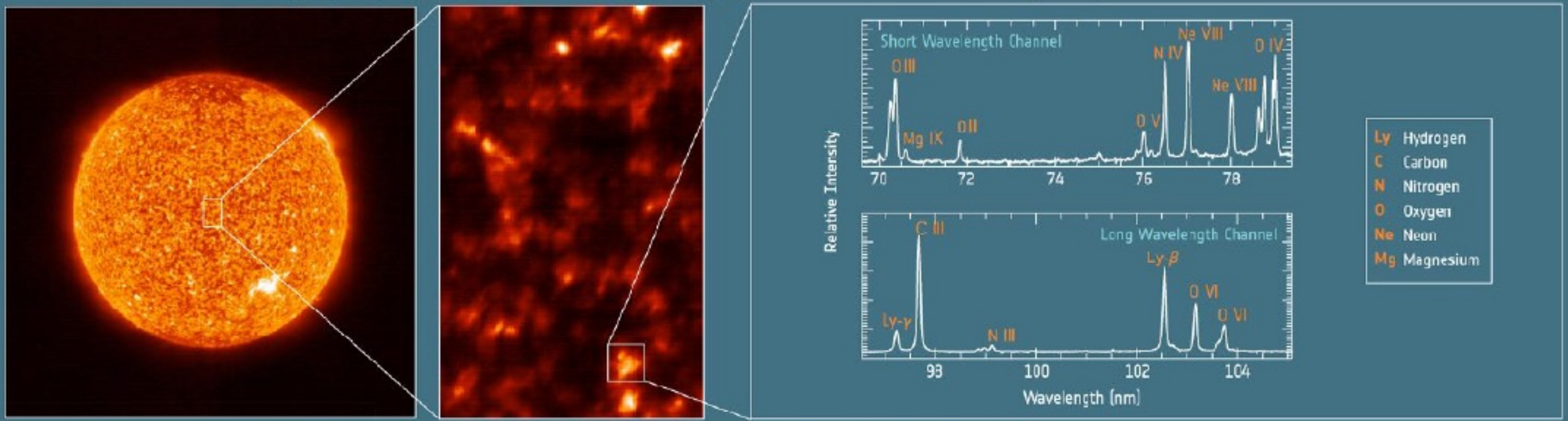


COMBINING REMOTE OBSERVATIONS AND IN SITU MEASUREMENTS

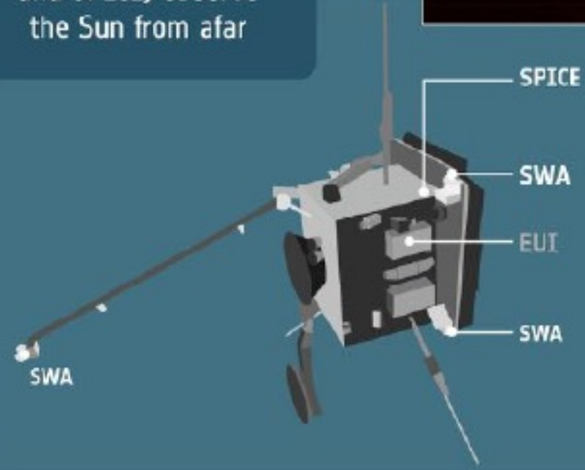
Both sets of data are used to piece together a more complete picture of what is happening on the Sun and in the solar wind, the flow of electrically charged particles that is continuously released by our star.

Extreme Ultraviolet Imager **(EUI)**

Spectral Imaging of the Coronal Environment **(SPICE)**

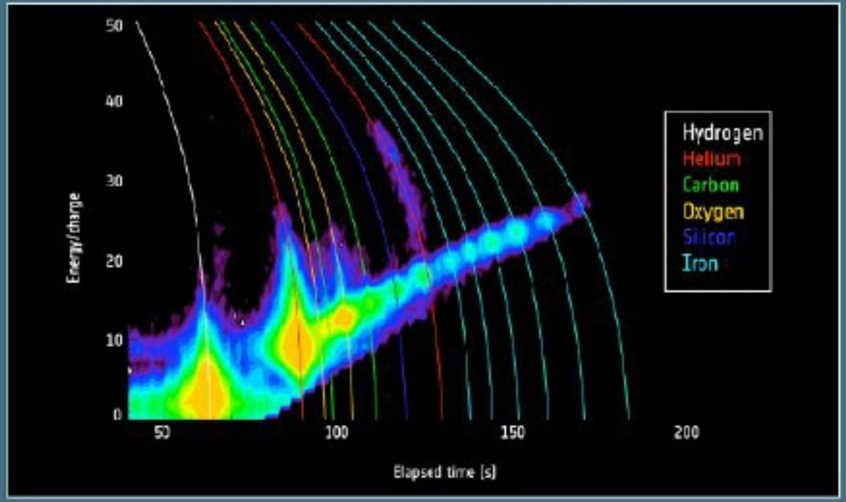


The **remote-sensing instruments** (such as EUI and SPICE) observe the Sun from afar



The ***in situ* instruments** (such as SWA) measure the electric and magnetic fields, and the particles near the spacecraft

Solar Wind Analyser **(SWA)**

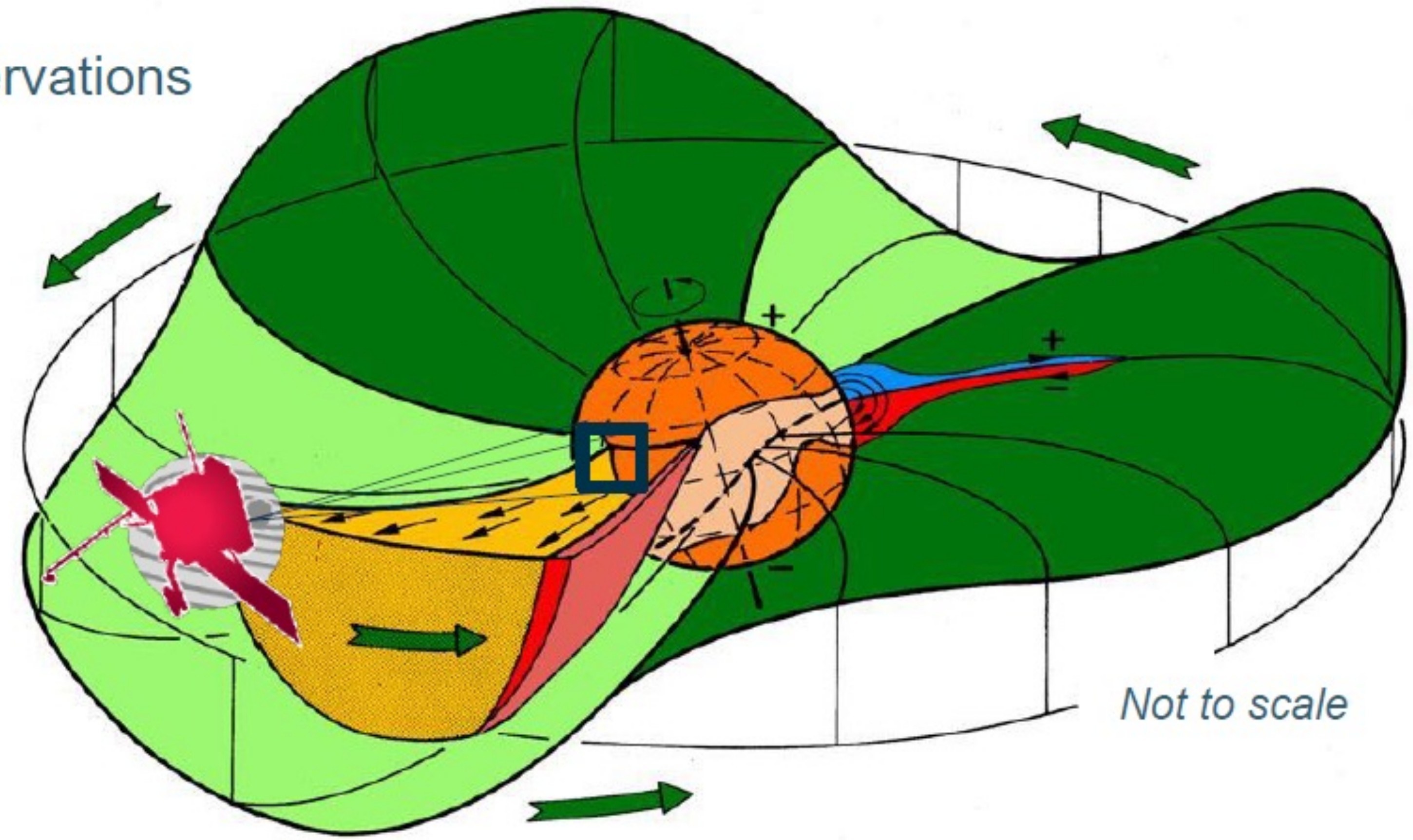


#TheSunUpClose

Solar Orbiter's complement to other solar observatories

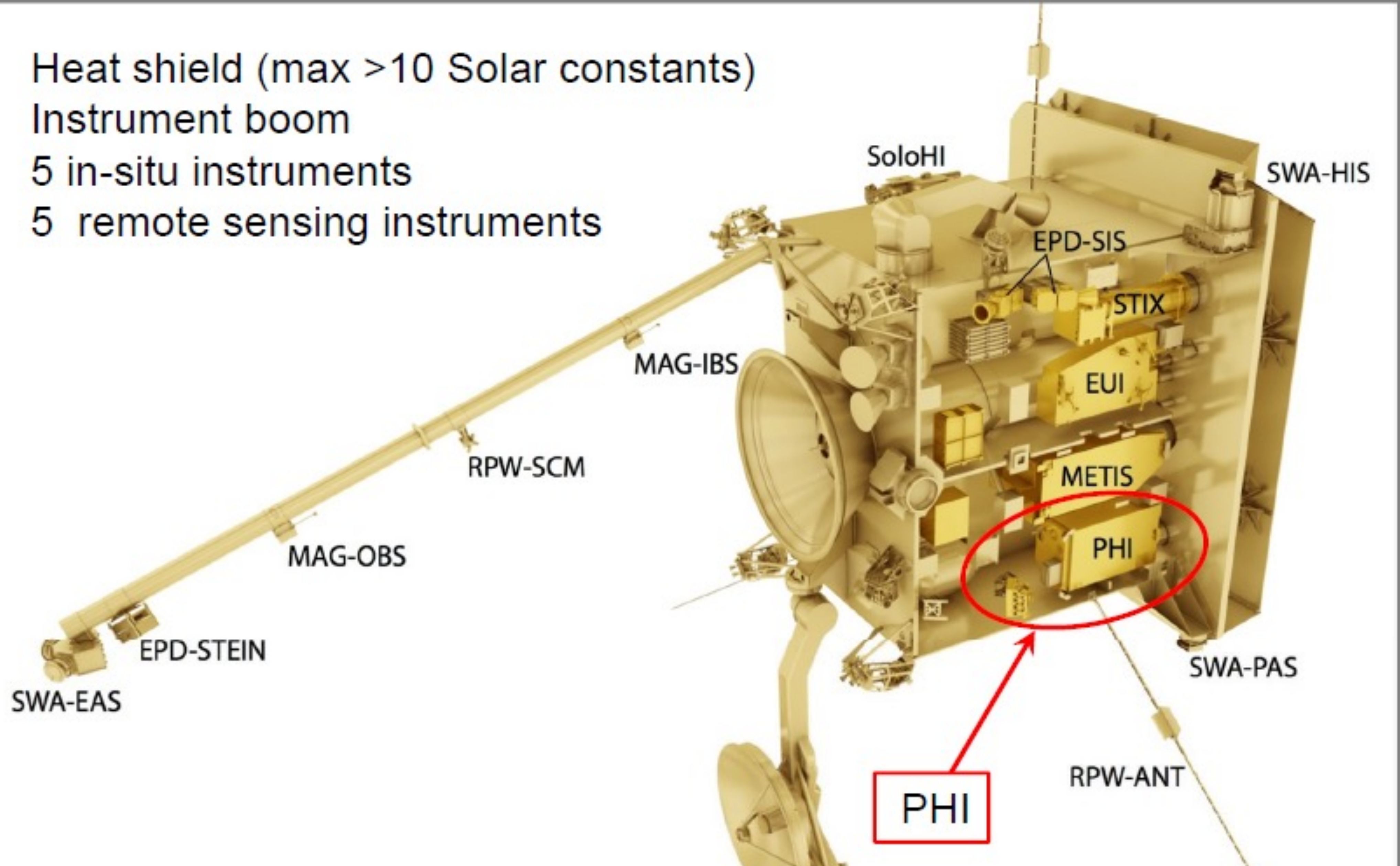
Solar Orbiter is quite different from previous solar missions

- Unique **orbit** around the Sun: changing viewpoint w.r.t. Earth, changing solar distance & latitude
- Changing **science opportunities**
- **Limited resources** require us to
  - Concentrate remote-sensing (RS) observations in RS windows
  - Plan long time ahead
  - Store data onboard
- Linking Sun and Heliosphere requires in-situ and RS payload to be **coordinated**
- Coordinated payload observations: **Solar Orbiter Observation Plans (SOOPs)**



The Solar Orbiter Payload

Heat shield (max >10 Solar constants)
Instrument boom
5 in-situ instruments
5 remote sensing instruments



SO/PHI science

- SO/PHI will probe the solar interior and provide the magnetic field at the solar surface that drives transient and energetic phenomena in the solar atmosphere and the heliosphere
- Polarimetry and local helioseismology provided by SO/PHI will be central to reach 3 of the 4 top-level science goals of Solar Orbiter
- SO/PHI will be the main instrument needed to answer the Solar Orbiter top-level science question: How does the solar dynamo work and drive connections between the Sun and the heliosphere?

SO/PHI Science

solar orbiter

Q1: How and where does the solar wind plasma and magnetic field originate in the corona?

Q2: How do solar transients drive heliospheric variability?

Q3: How do solar eruptions produce energetic particle radiation that fills the heliosphere?

Q4: How does the solar dynamo work and drive connections between the Sun and the heliosphere?

Q5: PHI stand-alone science goals:

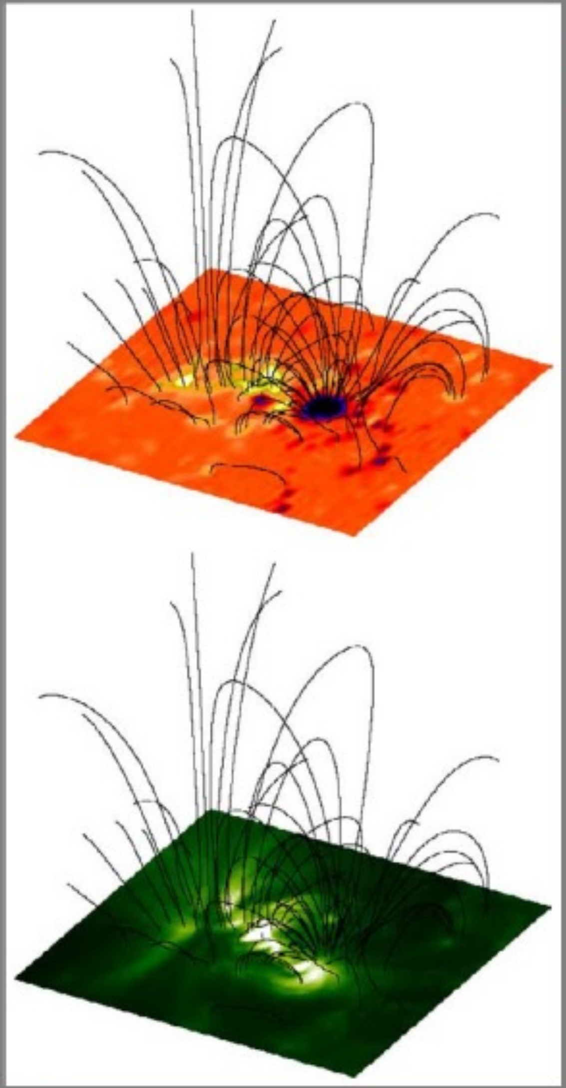
- What is the nature of magnetoconvection?
- How do active regions and sunspots evolve?
- What is the global structure of the solar magnetic field?
- How strongly does the solar luminosity vary and what is the source of these variations?

Atmospheric Coupling

SO is designed to probe the Sun from its interior up to the heliosphere.

SO with both remote sensing and in-situ measurements aims to address the largely unsolved problems of the origin of the solar wind as well as transport phenomena in the heliosphere

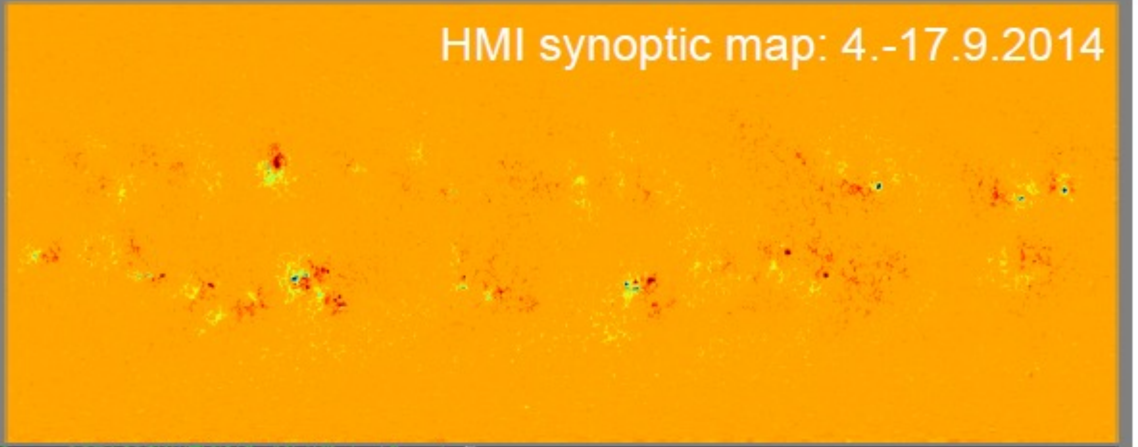
SO/PHI will provide the photospheric magnetic field structure, i.e. an essential boundary condition needed to achieve these goals



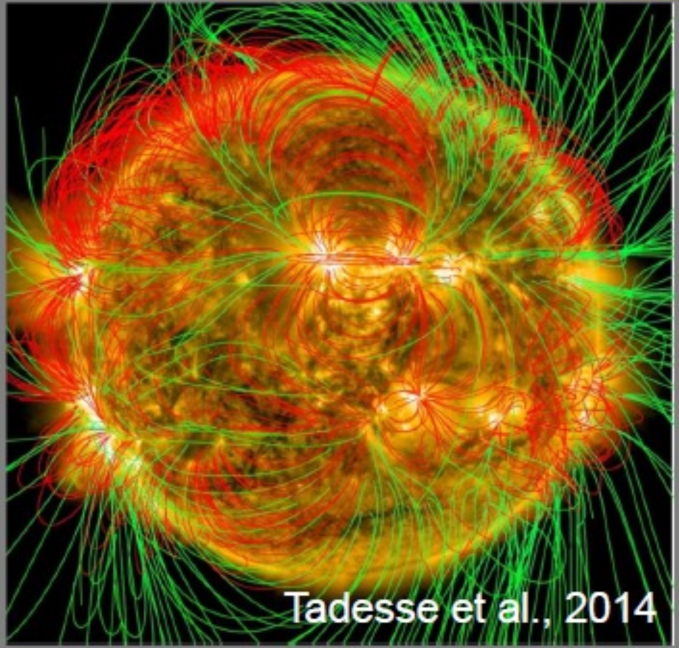
Marsch et al., 2004

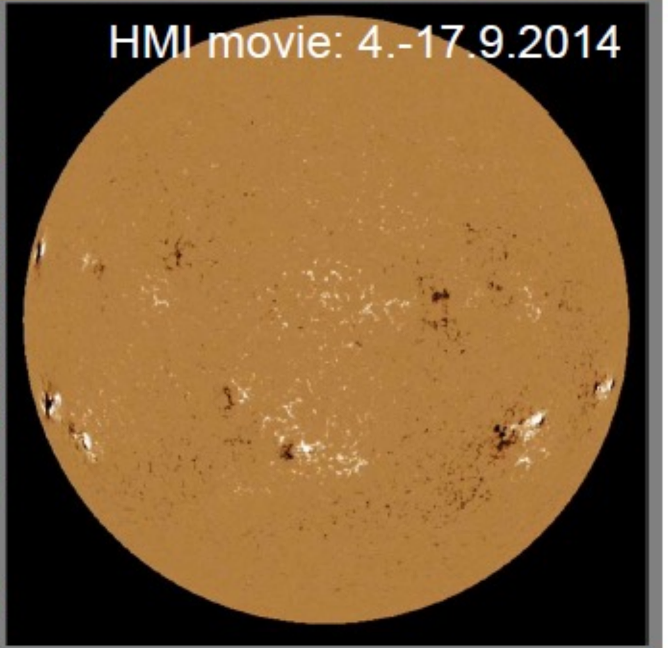
Near Co-rotation and Global Sun

SO's close perihelion transits enables to follow surface structures for more than half of a rotation period, i.e. up to 23 days



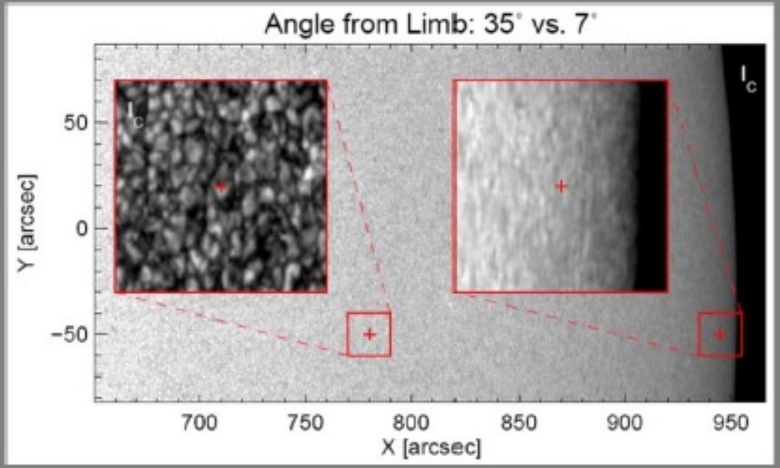
Vantage points far from Earth allow for near instantaneous 4π magnetic maps

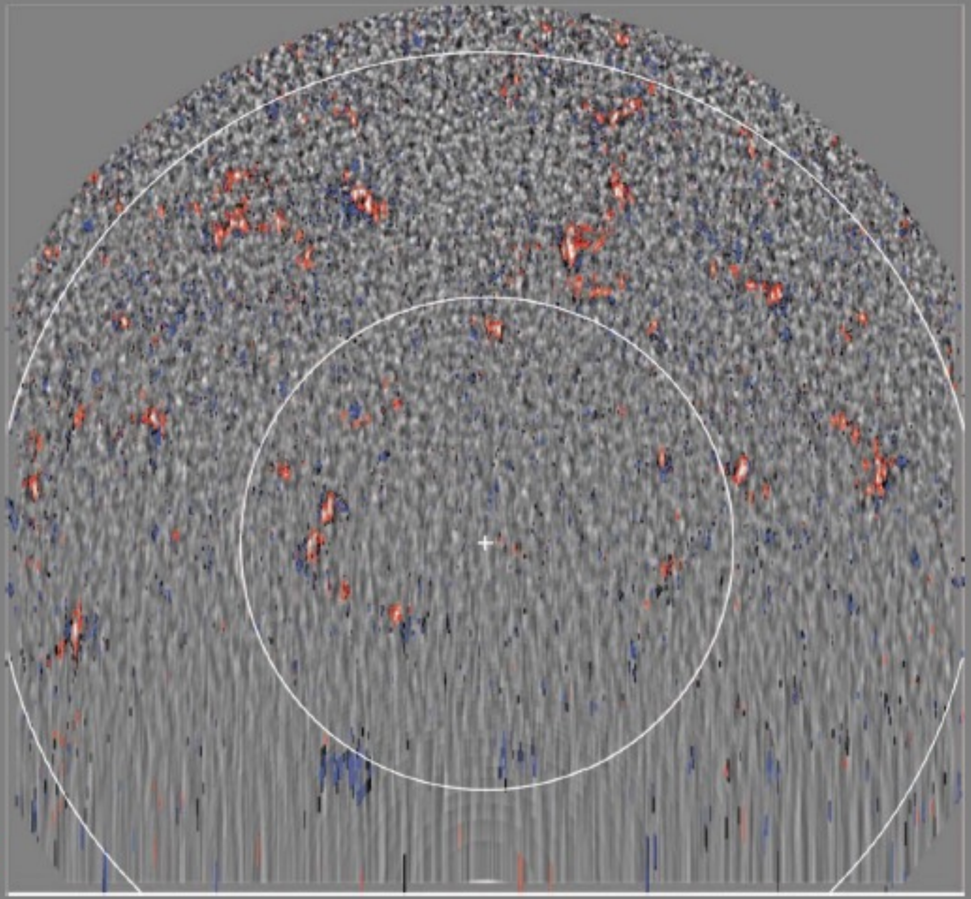




Polar Science

Polarimetric and dynamic studies of the solar polar regions from the ecliptic plane suffer from geometric foreshortening. SO/PHI will be the first polarimeter looking at the poles from a heliographic latitude > 7°



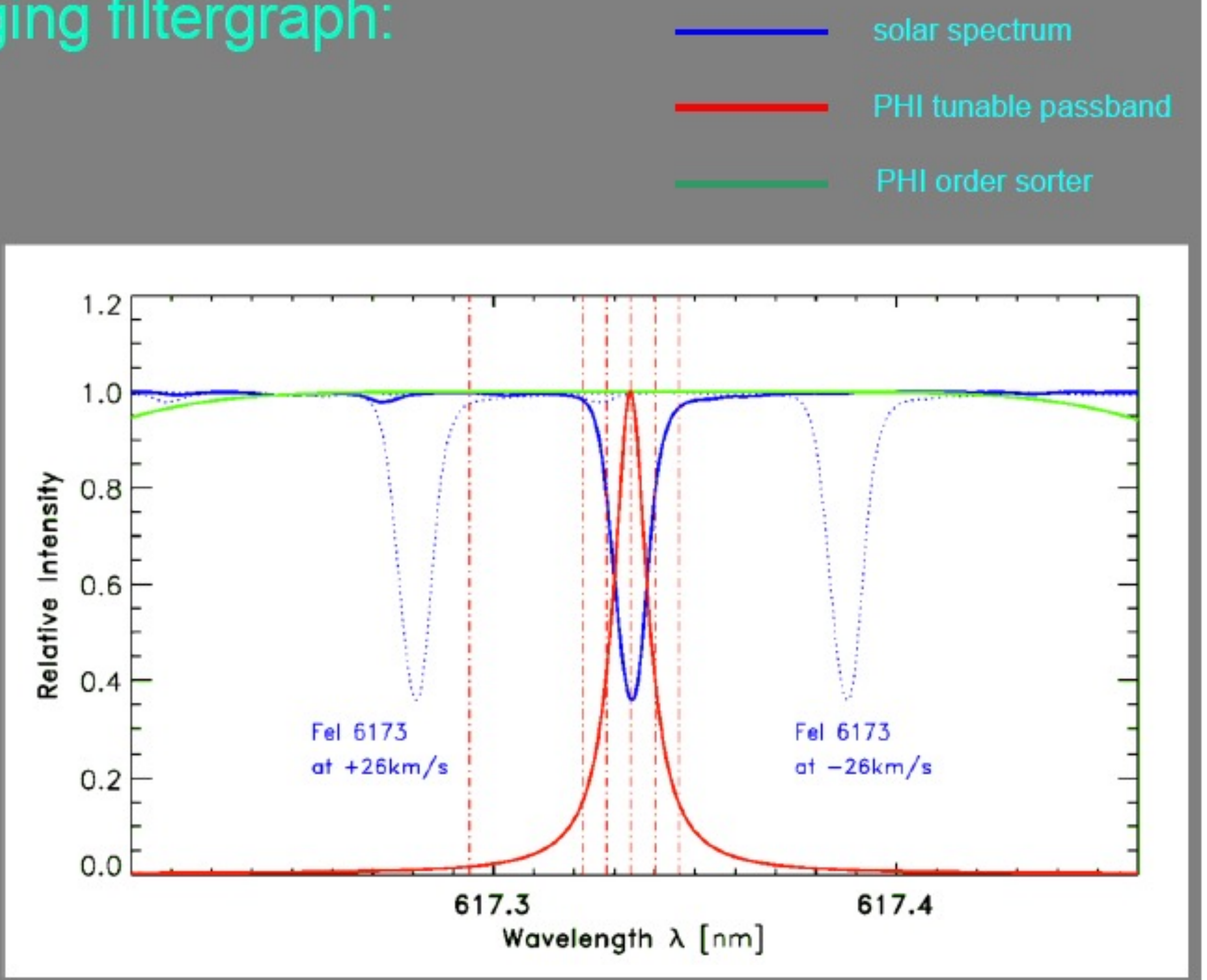


Tsuneta et al., 2008

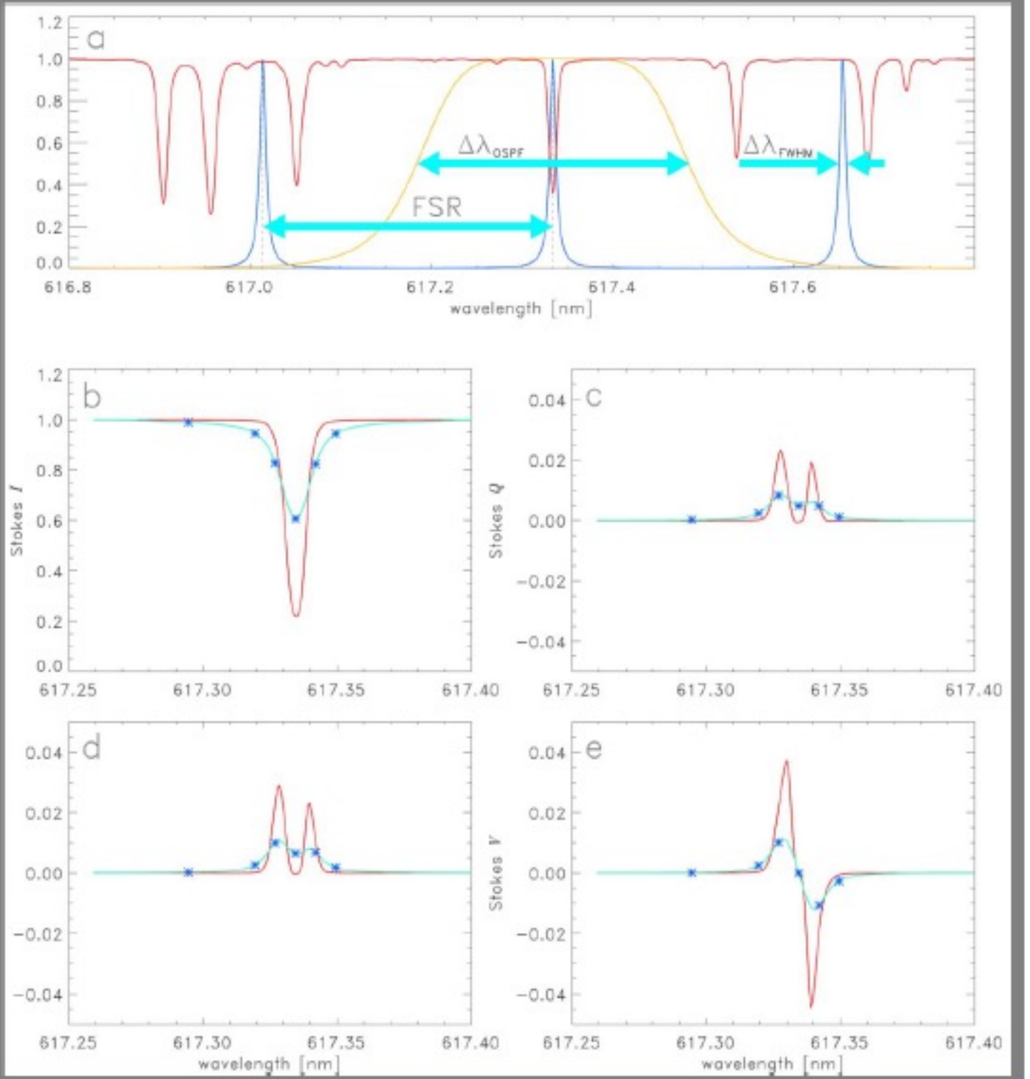
SO/PHI Measurement Principle

PHI is a tunable imaging filtergraph:

- Scans over a magnetic sensitive photospheric absorption line (FeI 617.3nm)
- Narrow-band filtergrams at 6 spectral positions
- Full polarimetric information
- On-board data processing & inversion



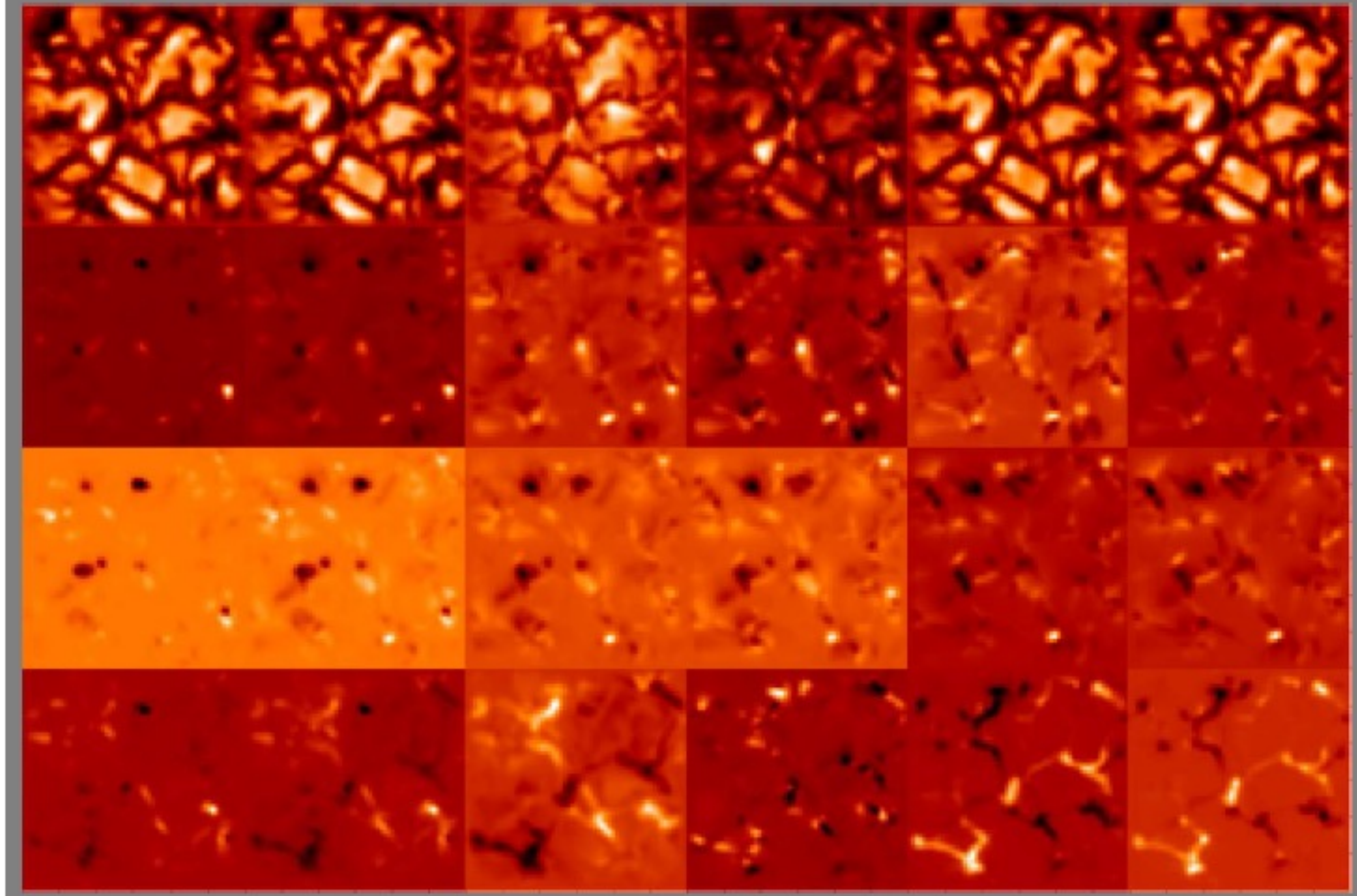
SO/PHI Measurement Principle (II)



SO/PHI Primary Observables

Full Stokes maps at 6 wavelength positions:

-400 -160 -80 0 80 160 [mÅ]



I

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V

after onboard data calibration and polarimetric demodulation !

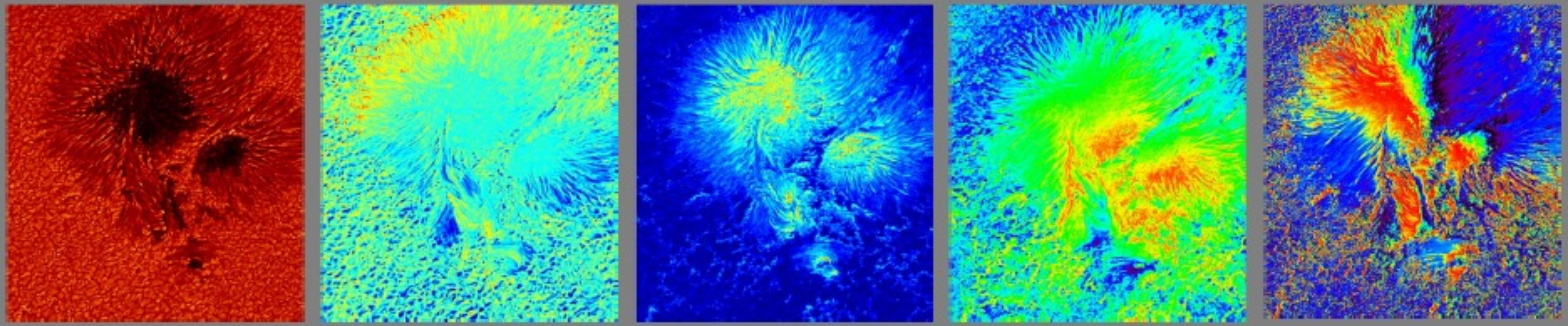
SO/PHI Data Products

PHI data products:

	Dynamic range	Noise
continuum intensity, I_c	-	$\leq 10^{-3}$
LOS velocity, v_{LOS}	±5km/s	≤ 40m/s
LOS magnetic field strength, B_{LOS}	±3.5kG	15 G
magnetic field inclination, γ	180°	1°
magnetic field azimuth, φ	±180°	2°

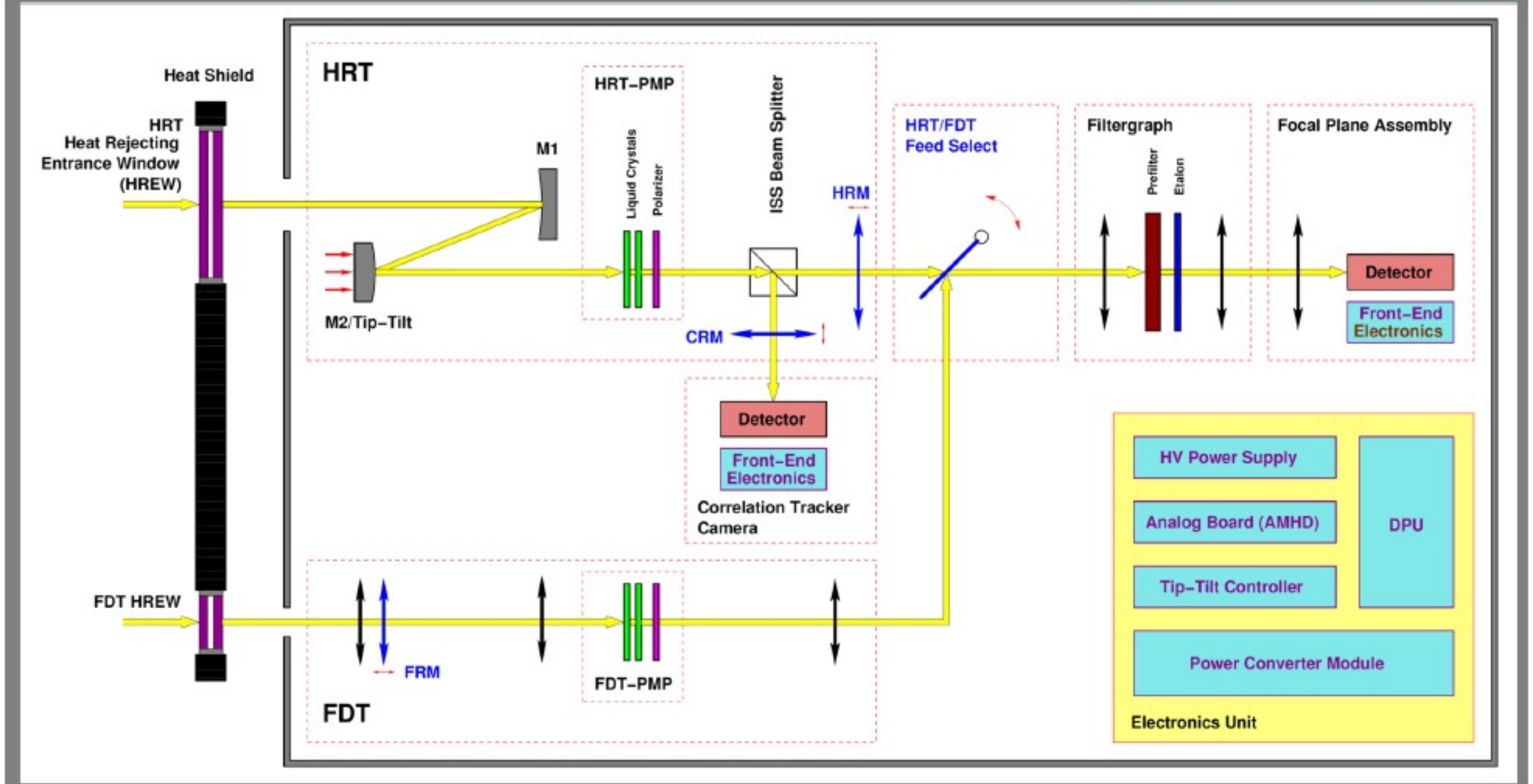
PHI requirements:

- high-resolution data
- full-disk data
- 2k x 2k FOV
- 1 data set per minute



SO/PHI Functional Diagram (simplified)

solar orbiter



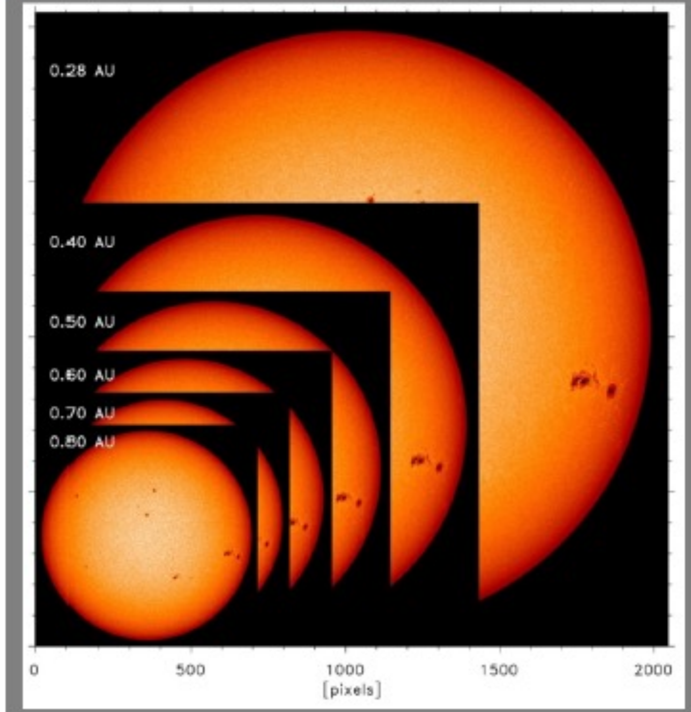
2 Entrance windows
2 Telescopes

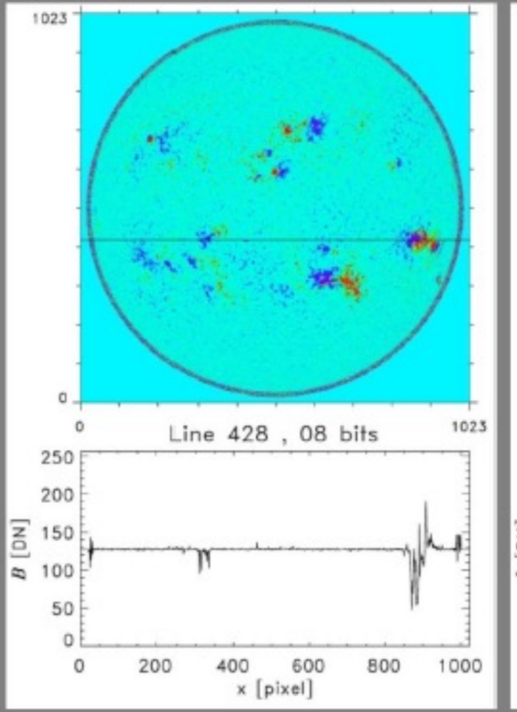
4 Mechanisms
1 Active mirror

2x2 Tunable LCVRs
1 Tunable etalon

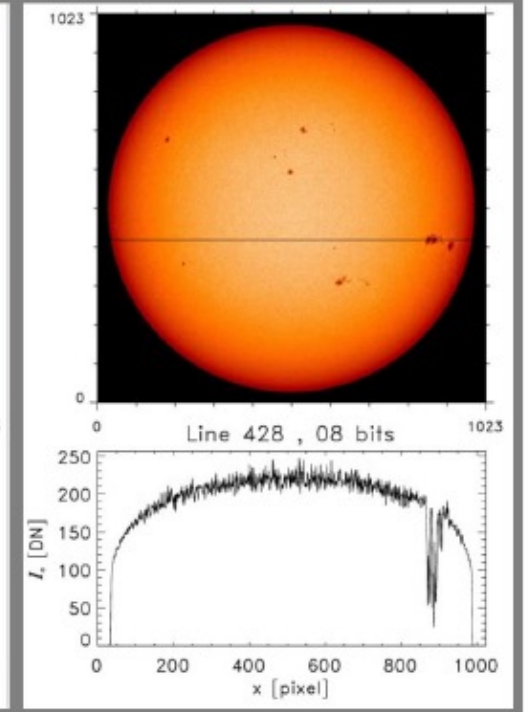
2 APS cameras

SO/PHI Synoptic Mode - proposed



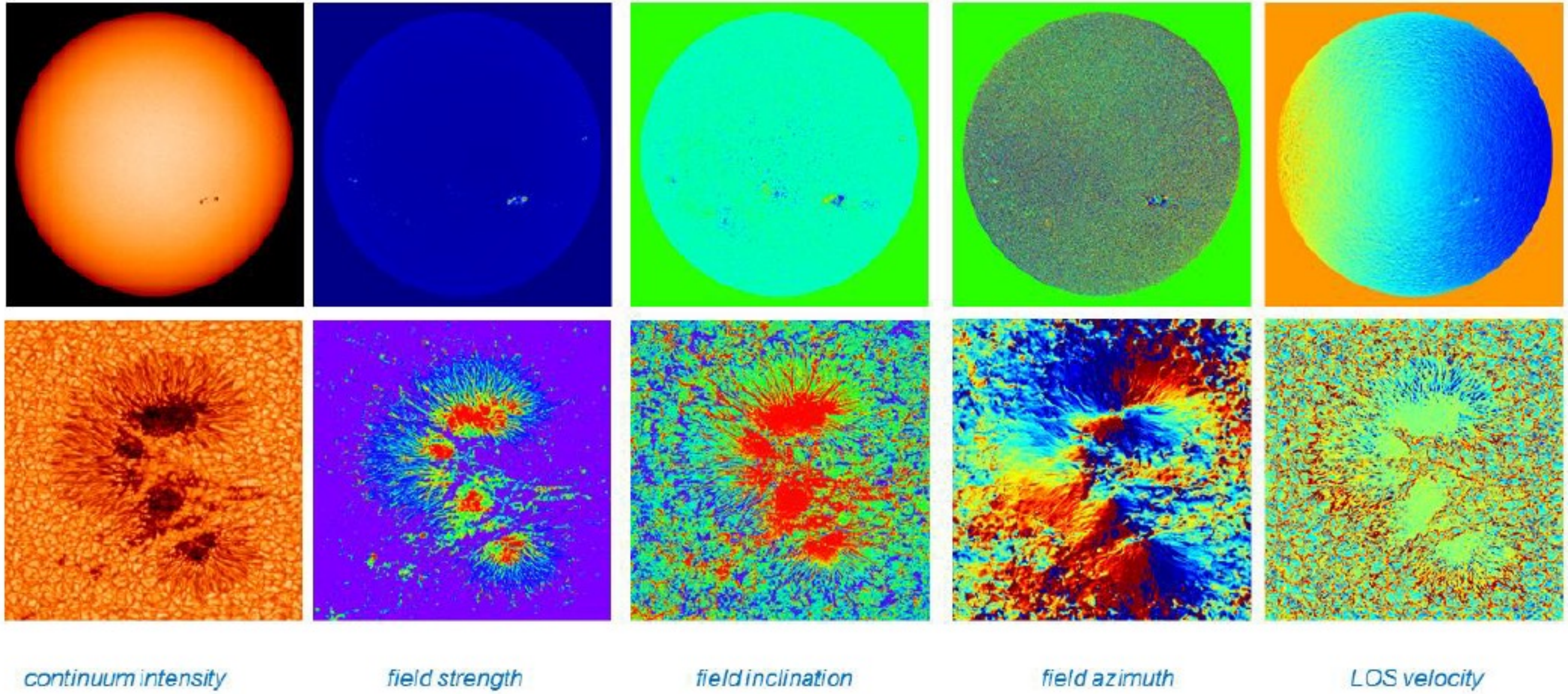


Magnetogram



Continuum intensity

- Full-disk data sets:
  - Continuum intensity
  - Magnetic field vector
  - Dopplergram (tbc)
- 1-4 data sets per day or longitude interval
- 1k x 1k maximum size (rebinning for d < 0.5 AU)

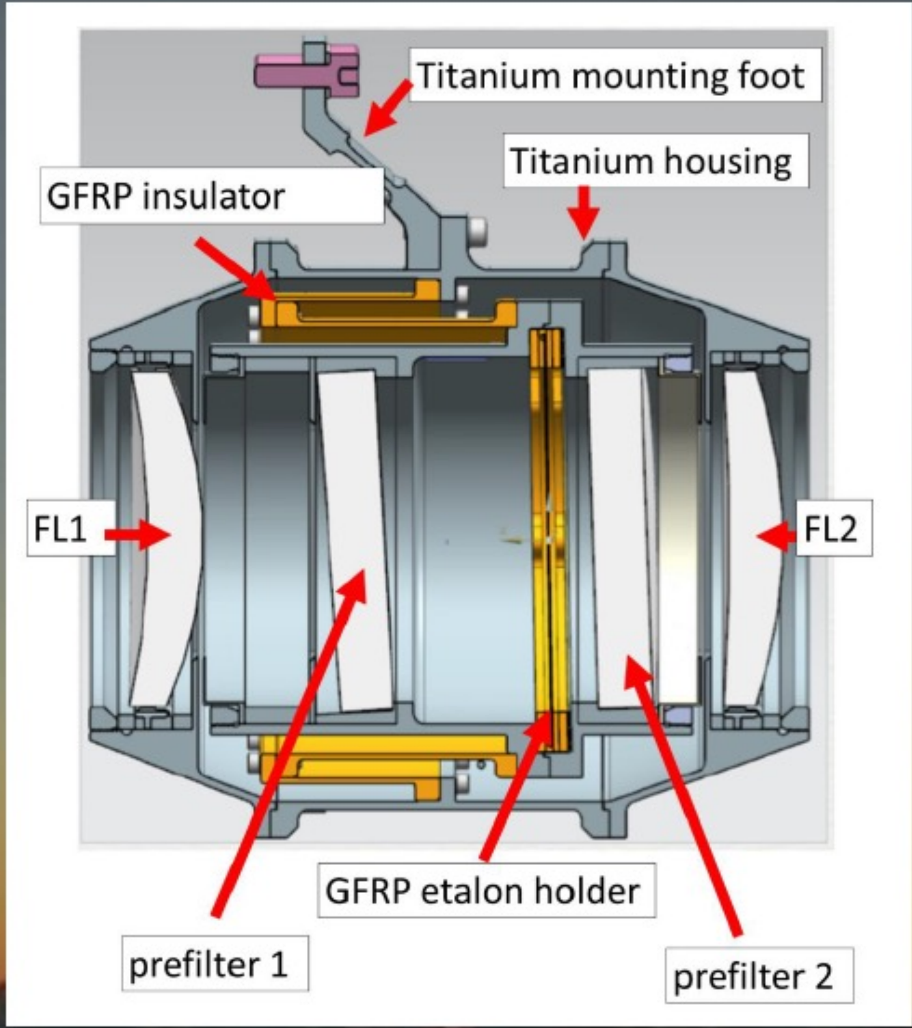

continuum intensity
field strength
field inclination
field azimuth
LOS velocity

The spectroscopic analysis system

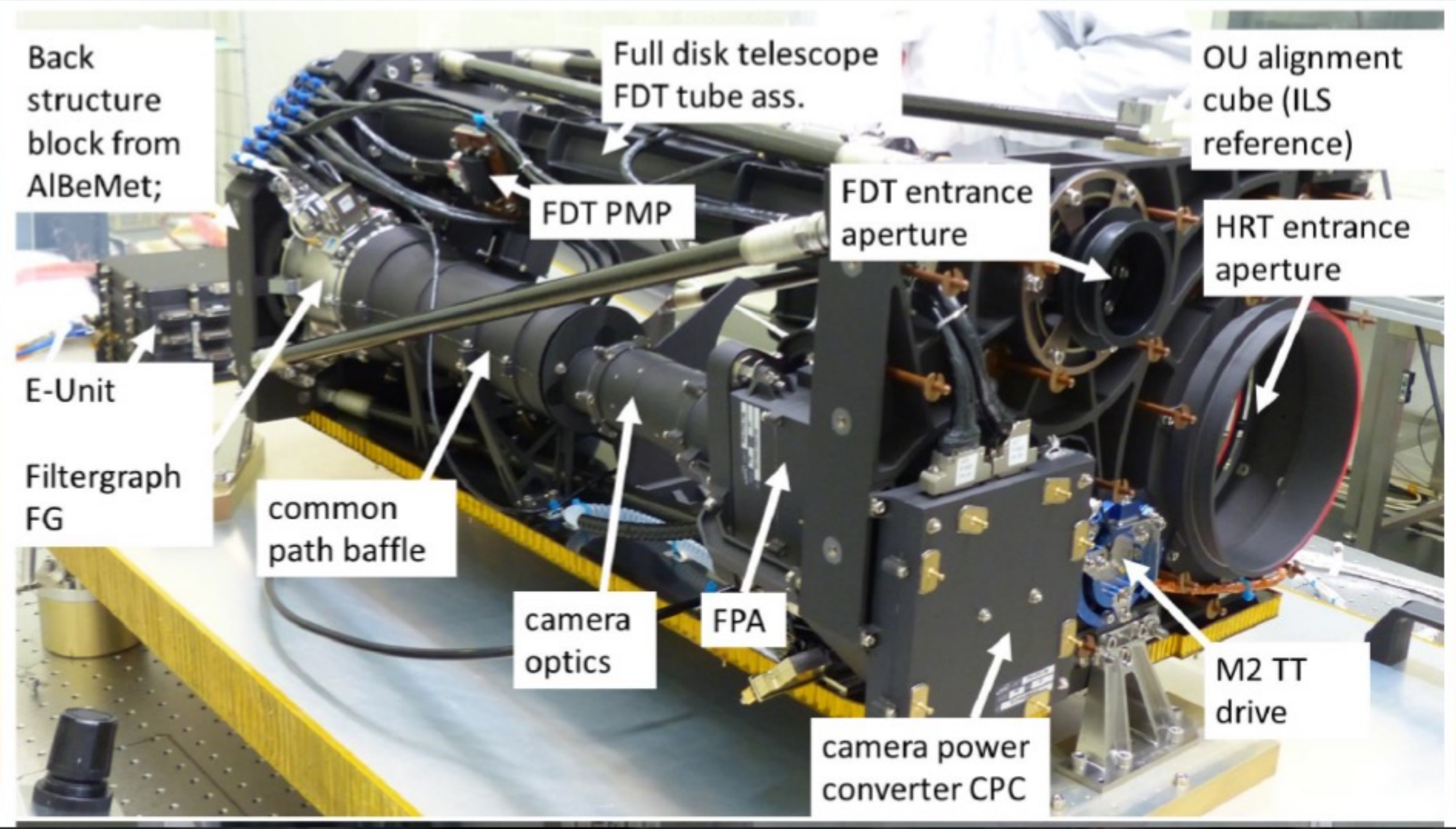
- based on 1 tunable $LiNbO_3$ Fabry Perot etalon and a non-tunable narrow band filter (bandpass ~100mÅ, 2.8Å, resp.)
- telecentric configuration
- fixed relation between „etalon focus“ and science FPA
- utmost care about thermal stability

for more details: follow talk by Thierry Appourchaux

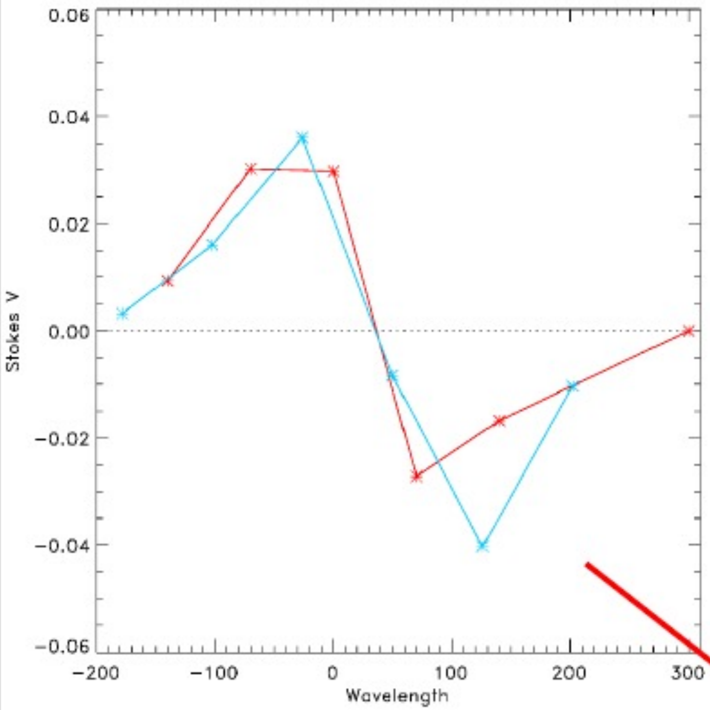
Filtergraph thermal concept

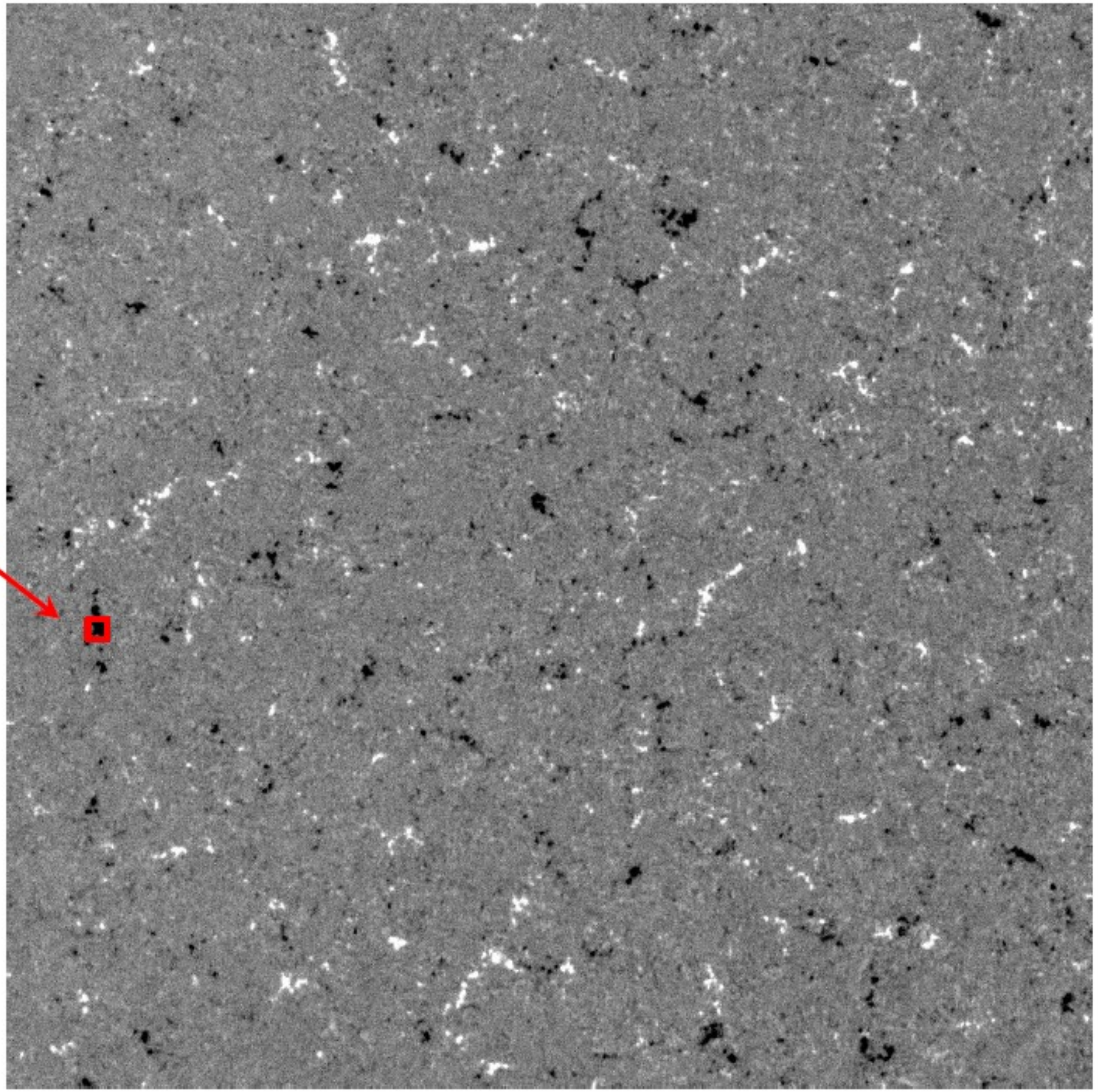


development and qualification by IAS, France


Back structure block from AlBeMet;
Full disk telescope FDT tube ass.
OU alignment cube (ILS reference)
FDT PMP
FDT entrance aperture
HRT entrance aperture
E-Unit
Filtergraph FG
common path baffle
camera optics
FPA
camera power converter CPC
M2 TT drive

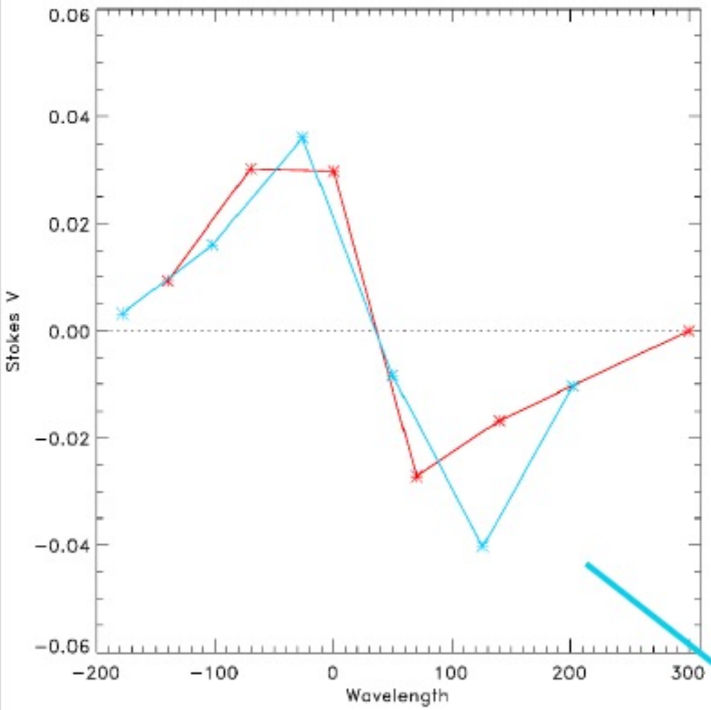
HRT Polarimetry: comparison with HMI

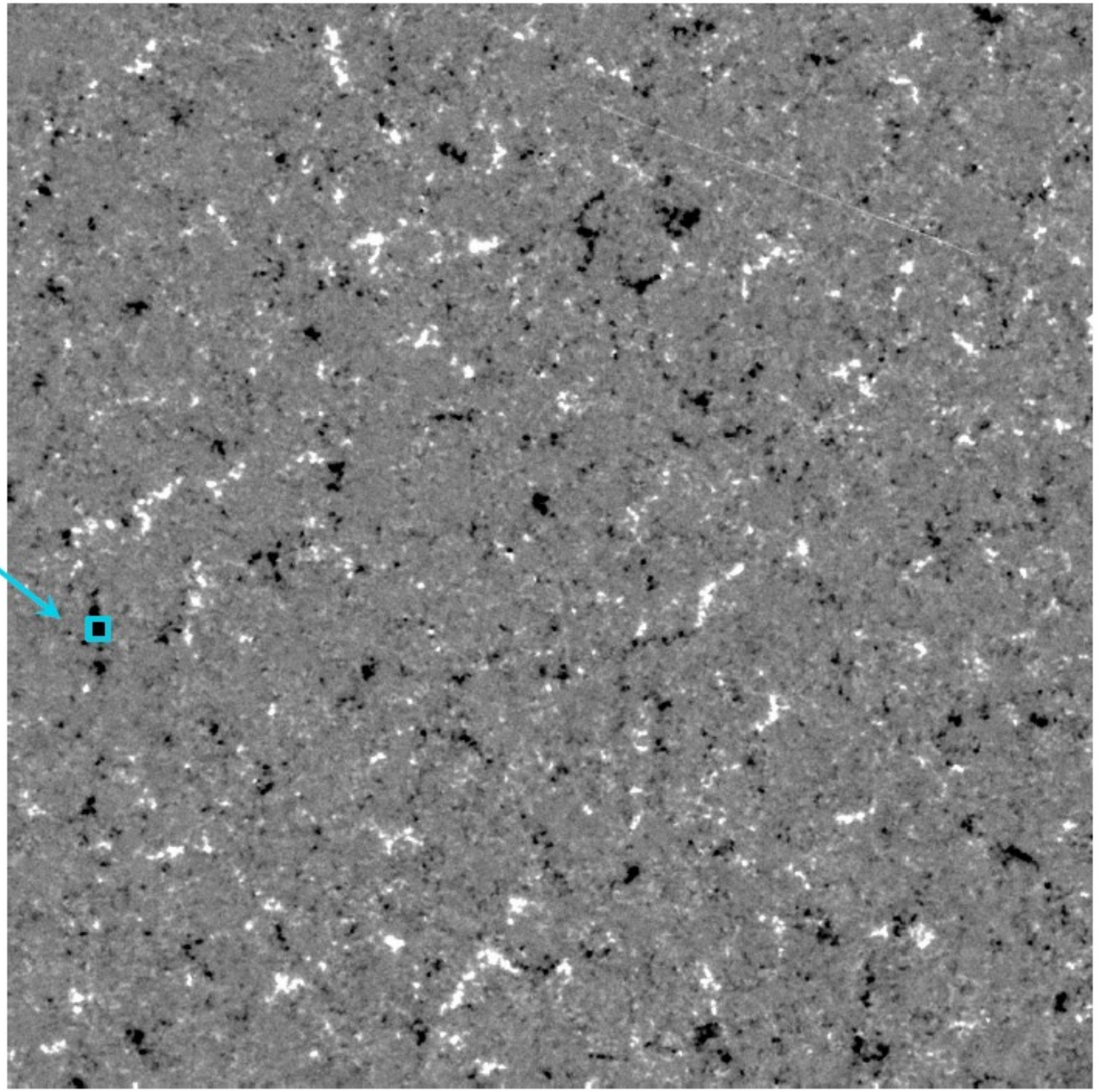




SO/PHI/HRT
2020-04-20
Stokes V
10-min average
(scaled to ±0.5%)

HRT Polarimetry: comparison with HMI





SDO/HMI
2020-04-20
Stokes V
12.5-min average
(scaled to ±0.5%)