

# The Solar Corona and the Solar Wind



we're **OUT** there

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Pronouns: she/they

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Uritsky, P.R. Young, and especially Simone  
Di Matteo

18 July 2023



NASA



# (Very) General Topics: Solar Corona and Solar Wind

- The structure of the Sun: Where do the corona and solar wind come from?
  - Interior
  - Photosphere and Solar atmosphere
  - Magnetic features
- Basics of the solar corona
  - Coronal magnetic structure
  - Solar coronal features
  - Coronal heating
- Basics of the solar wind
  - High speed
  - Slow speed
  - Transitions and boundaries
- Variability:
  - Short-term variability (flares, CMEs, other transients)
  - Intermediate-term variability (feature evolution, solar rotation)
  - Long-term variability (solar cycle)





# Corona and Solar Wind in brief

- The solar magnetic field is generated in the Sun's interior.
- The solar magnetic field extends to form the solar corona.
- The corona is much hotter than the visible surface of the Sun (photosphere). The source of the heat is magnetic in nature, but the exact mechanism is still under debate.
- The corona expands to form the solar wind. The extended domain of the solar wind (past the planets and out to  $>100$  AU) is called the heliosphere.





# Corona and Solar Wind in brief

Nearly all variations in heliophysics are due to the magnetic field. There are general timescales of these variations:

- The solar cycle runs from “solar minimum” to “solar maximum”, over the course of 9-13 years. The standard way of measuring solar cycle is the “Sunspot Number,” but there are many manifestations of the cycle.
- The cycle itself also varies over millennia, including long periods of dormancy.
- On the timescale of minutes to hours: Flares and coronal mass ejections (CMEs) are examples of energetic phenomena caused by the release of magnetic energy.
- Flares and CMEs originate in the solar atmosphere, but there are impacts on the solar wind (ICMEs, magnetic clouds, shocks, energetic particles) and planets (geomagnetic storms, ionospheric processes, energy atmospheric deposition, atmospheric loss)
- There are also small-scale transients on short timescales, that play important roles in fundamental processes.







# Corona and Solar Wind in brief

On the timescale of months, there are also important variations.

- Sunspots, magnetic active regions, and coronal holes are examples of solar magnetic features that evolve over the timescale of days to months
- The Sun's rotational period is about 27 days. Solar rotation causes the solar wind to have a "ballerina skirt" shape.
- Variations in the source of solar wind - with "high speed" and "slow speed" - cause the heliosphere to have very interesting structure.

The combination of short-term to long-term variations have a range of observable impacts at planetary magnetic environments.



# It begins in the Solar Interior



## The Convection Zone

Energy continues to move toward the surface through convection currents of heated and cooled gas in the convection zone.

## The Radiative Zone

Energy moves slowly outward—taking more than 170,000 years to radiate through the layer of the Sun known as the radiative zone.

## Sun's Core

Energy is generated by thermonuclear reactions creating extreme temperatures deep within the Sun's core.





The innermost layer of the sun we can see directly is the *photosphere*, observed in regular visible light

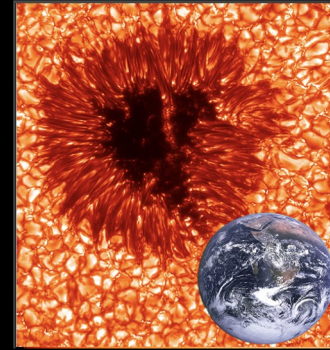
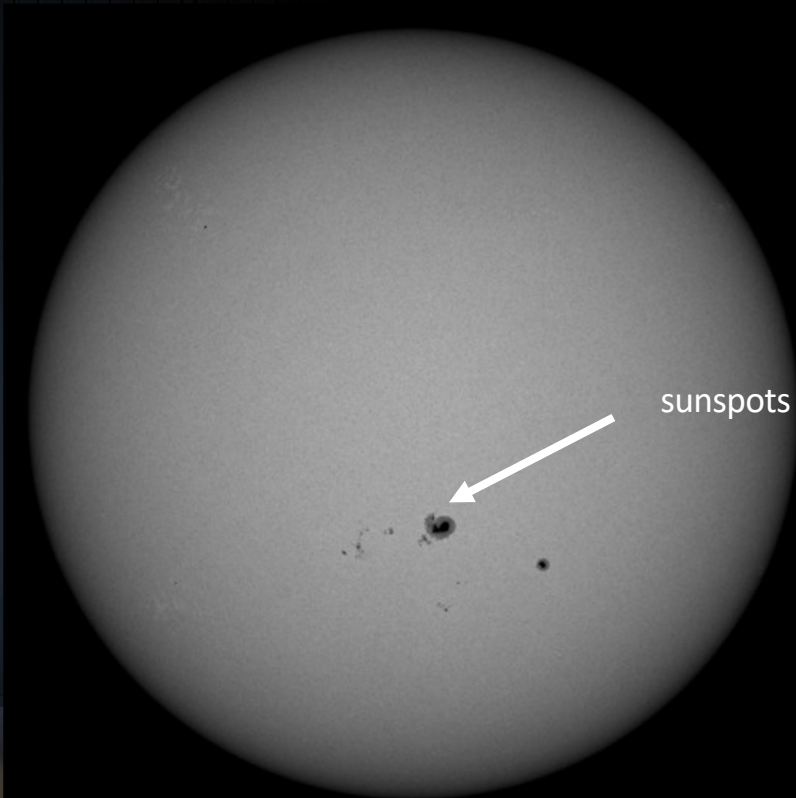
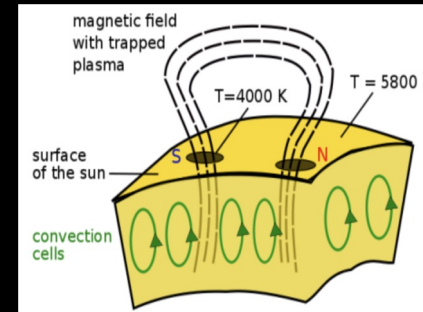


Image credit: The Royal Swedish Academy of Sciences, V.M.J. Henriques (sunspot), NASA Apollo 17 (Earth)

Granulation due to underlying plasma convection

Sunspot (Earth to scale)



Sunspots arise as a result of the emergence of strong magnetic field bundles

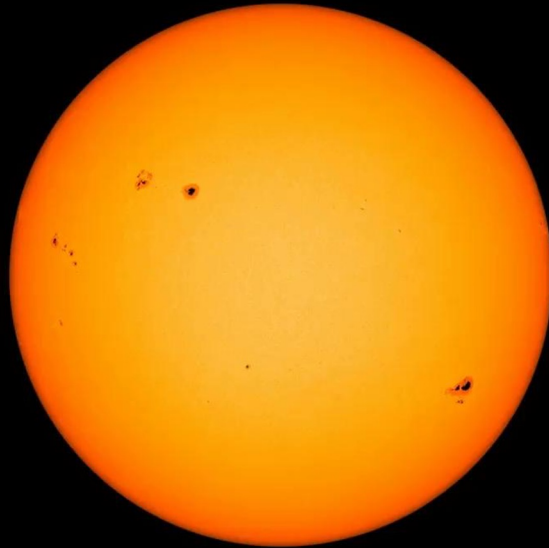
image adapted from: <http://cse.ssl.berkeley.edu>



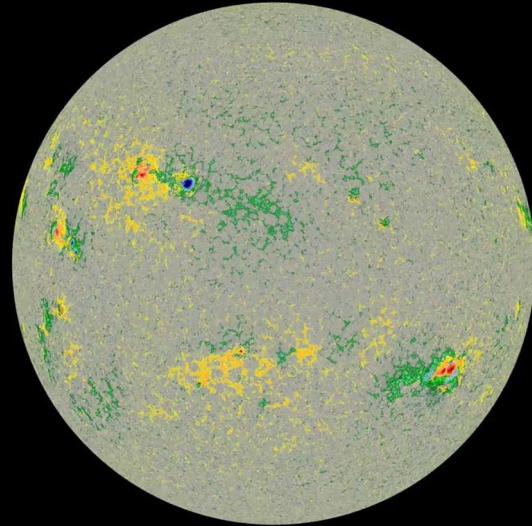


# There are many ways to observe the Sun

We are living in the outermost atmosphere of a magnetic variable star. There are many ways to view the Sun and its atmosphere as it extends into the solar wind.



SDO/HMI Quasi-Local Continuum 20230716\_201500



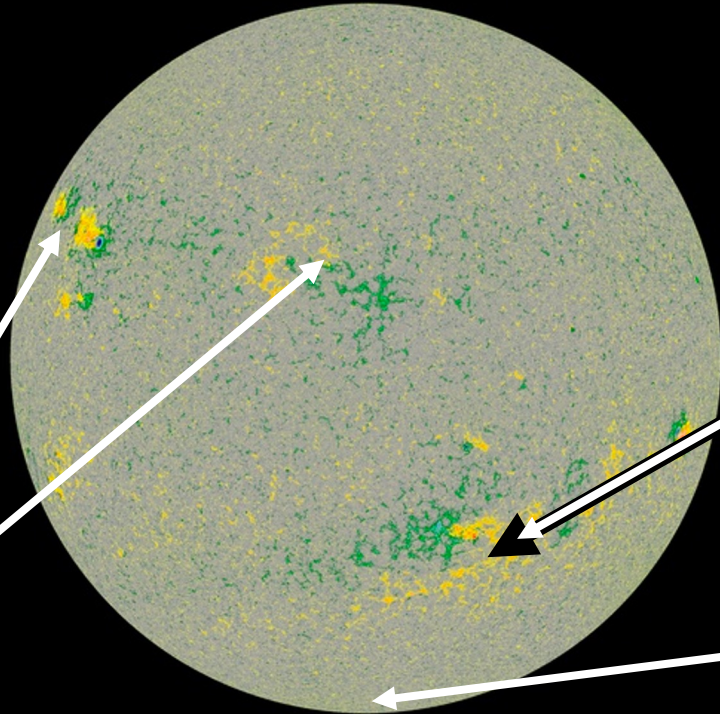
SDO/HMI Quasi-Local Magnetogram 20230716\_202000

8 April 2024

<http://www.greatamericaneclipse.com>



# EUV and X-rays reveal the super-hot corona



Active  
Regions

Filament  
Channel

Coronal  
holes

SDO/HMI Magnetogram: 20221026\_000000

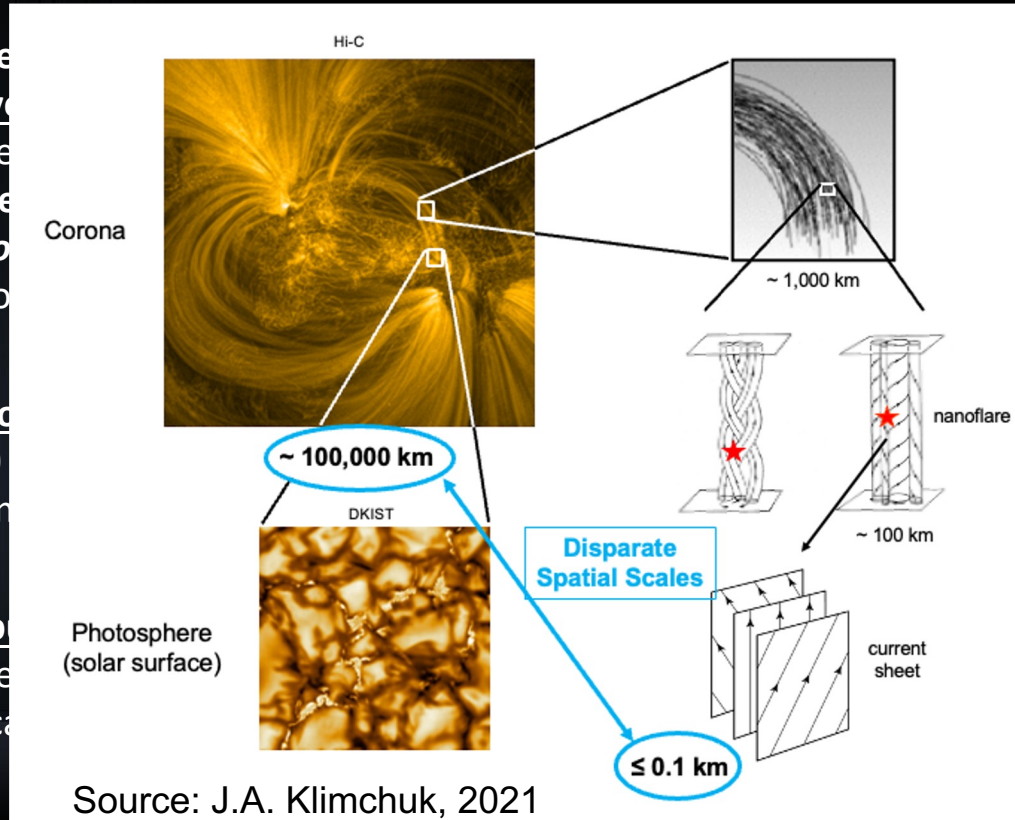
# Why is the corona so hot?

There are

- Alfvén wave
- wave wave
- cyclo cyclo
- cyclo cyclo

- Nano (~20 “star

- Turb wave at sca



ard, with a fraction of  
*phase-mixing of Alfvén*  
 e spatial volume and  
 electromagnetic ion  
 (energy).

all explosive events  
 es: energy  $\sim 10^{19}$  J. A

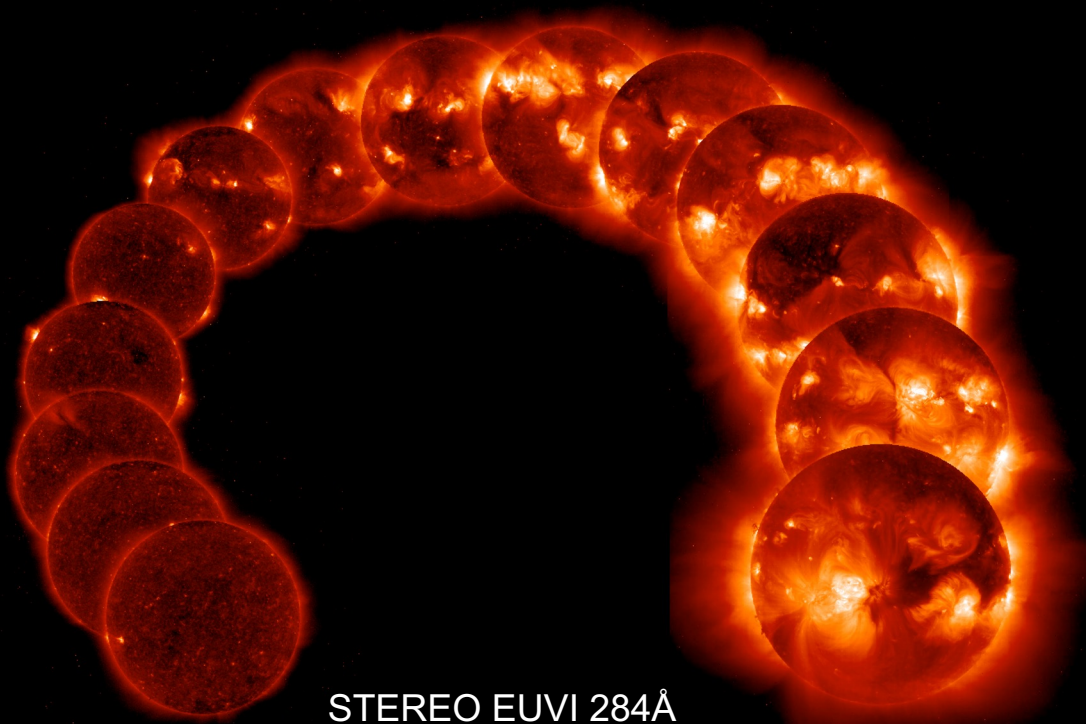
hase mixing. Short  
 es which are damped



# Solar Cycle variations



Sunsol Number

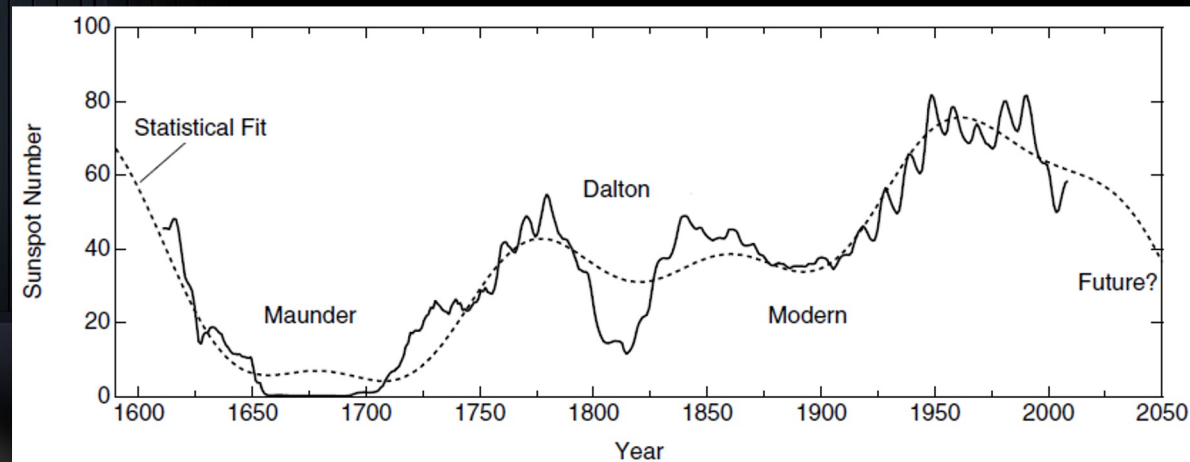
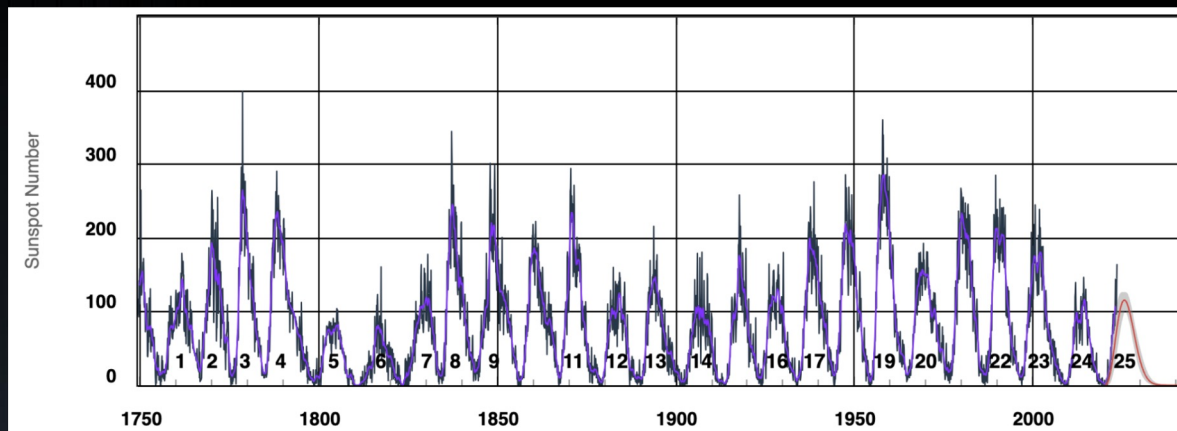


STEREO EUVI 284Å

Solar cycle 25 is  
outpacing  
predictions!

<https://www.swpc.noaa.gov/products/solar-cycle-progression>

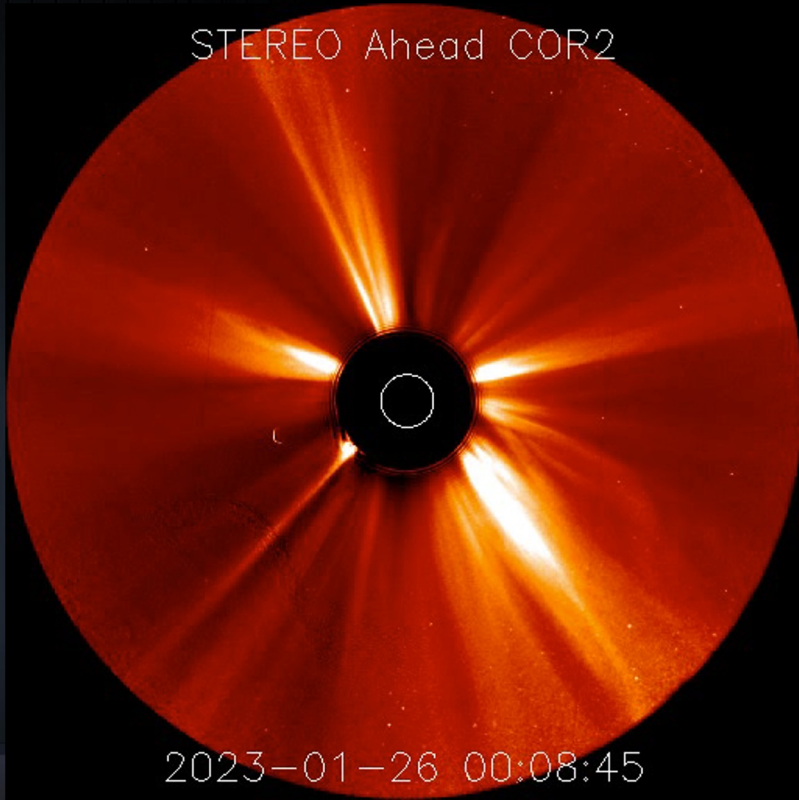
# Longer timescale variations



# Coronagraphs provide extended observations



STEREO Ahead COR2

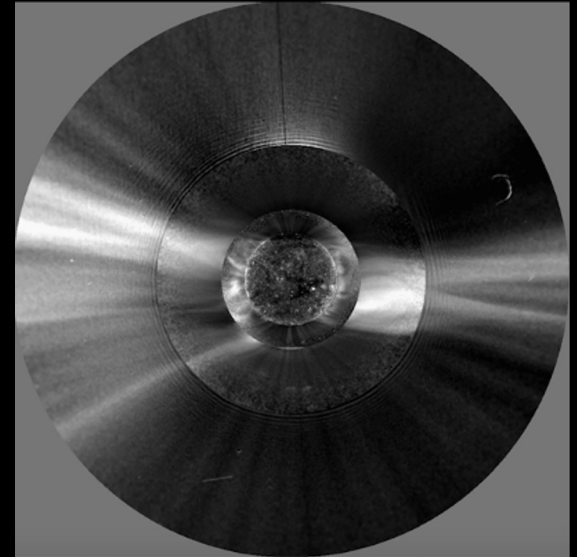


2023-01-26 00:08:45

SOHO/ESA & NASA

*Credit: N. Alzate*

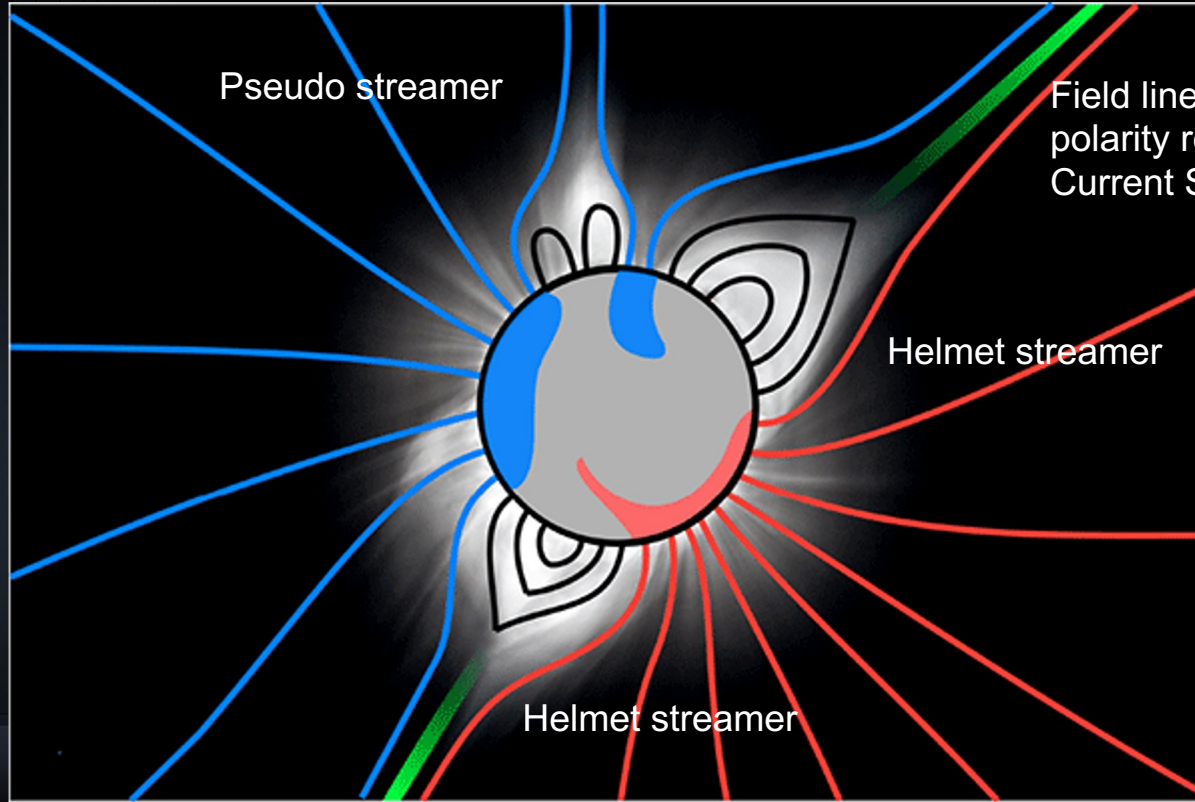
STEREO EUVI-COR1-COR2



Uninterrupted view with multi-instrument observations (when available!)



# Revealing coronal magnetic structures



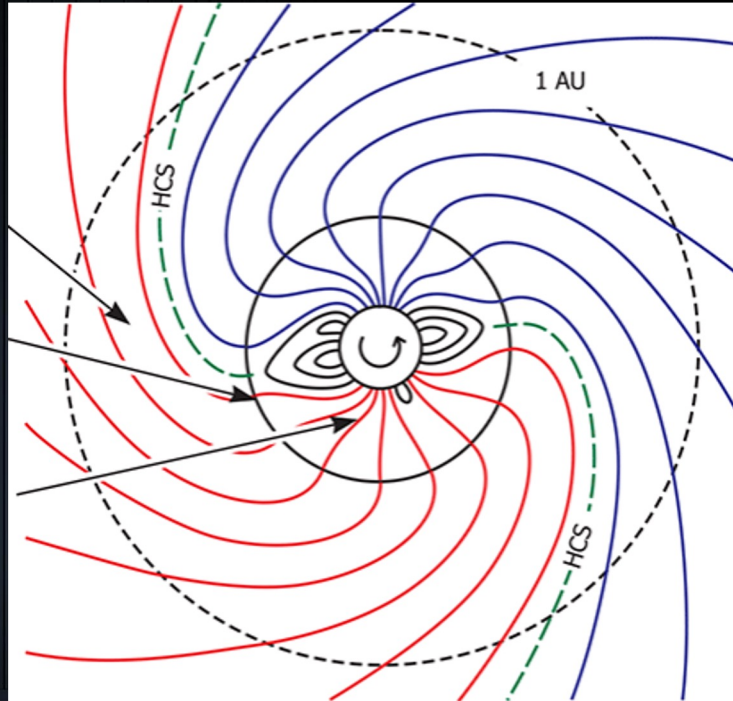
*Credit: M. J. Owens (2020)*





# The corona expands outward to form the solar wind

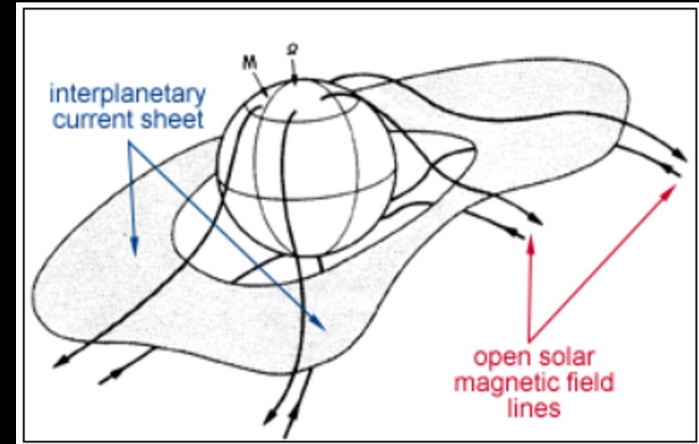
Credit: M. J. Owens (2020)



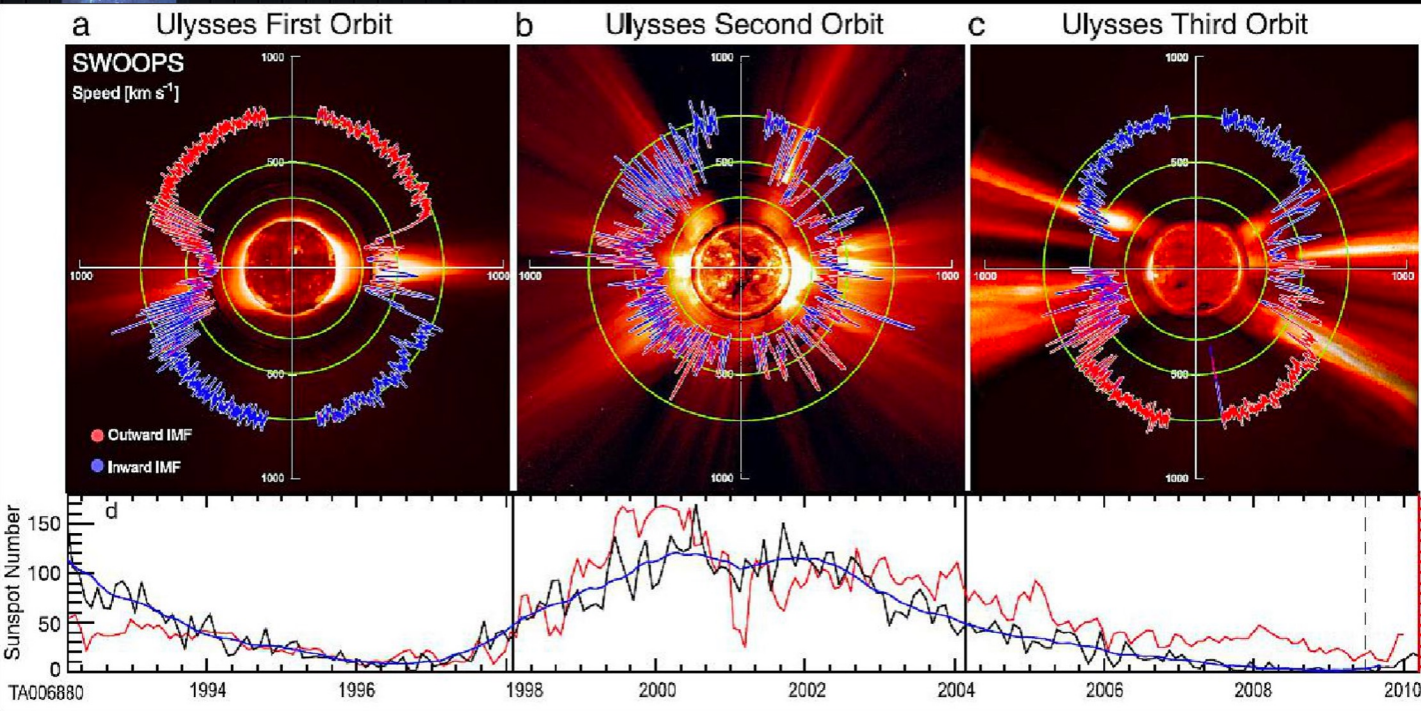
Red/blue indicate magnetic field directed outward/inward in the ecliptic plane

Magnetic field lines are dragged by the plasma into the Parker spiral

Polarity sector if observations above or below the Heliospheric Current Sheet which unfold as a “ballerina skirt” in 3D



# Solar wind speed depends on coronal features and solar cycle



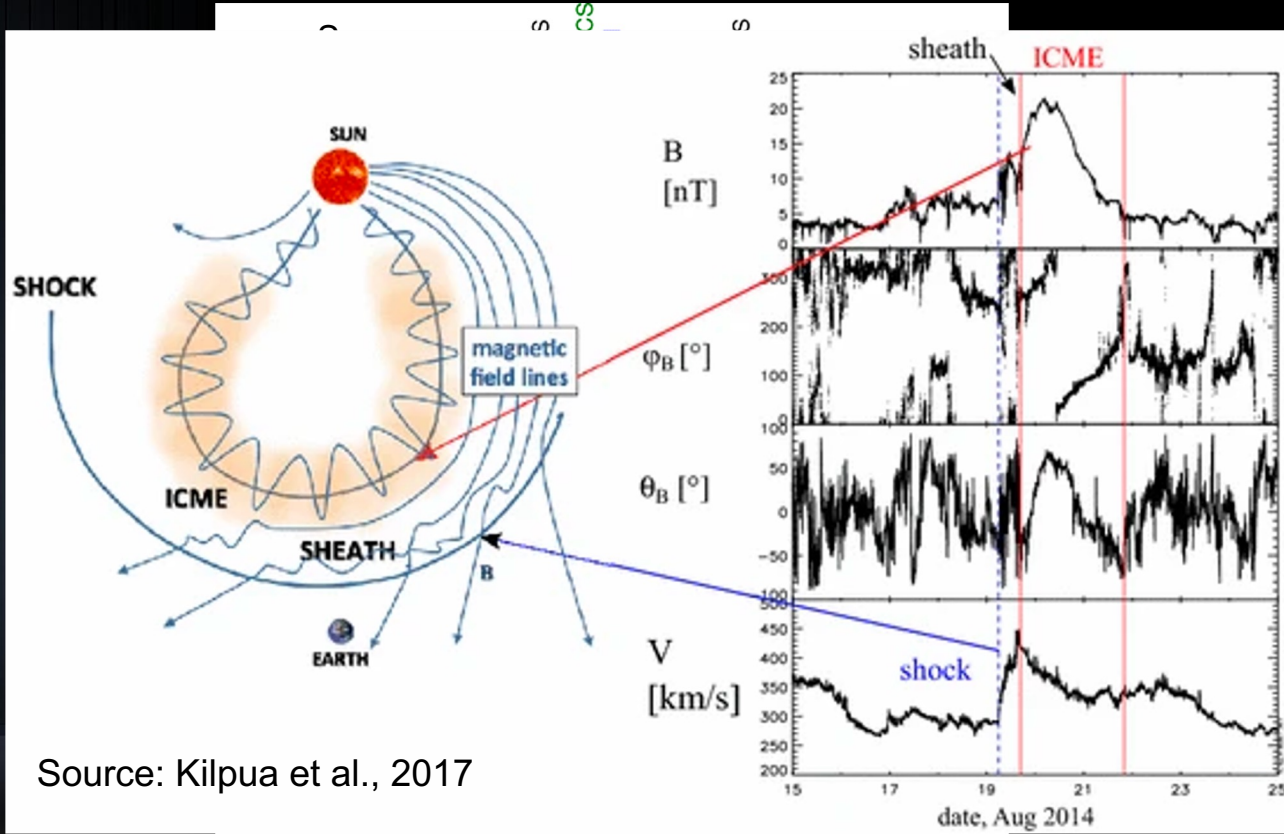
Typical solar wind parameters at 1 AU

	slow wind	fast wind
$V$ (km s <sup>-1</sup> )	350	750
$n_e$ (m <sup>-3</sup> )	$1 \times 10^7$	$3 \times 10^6$
$T_e$ (K)	$1.3 \times 10^3$	$1 \times 10^5$
$T_p$ (K)	$3 \times 10^4$	$2 \times 10^5$
$B$ (nT)	3	6
$v_A$ (km s <sup>-1</sup> )	20	70

$v_A = B / \sqrt{\mu_0 \rho_m}$  is the Alfvén velocity

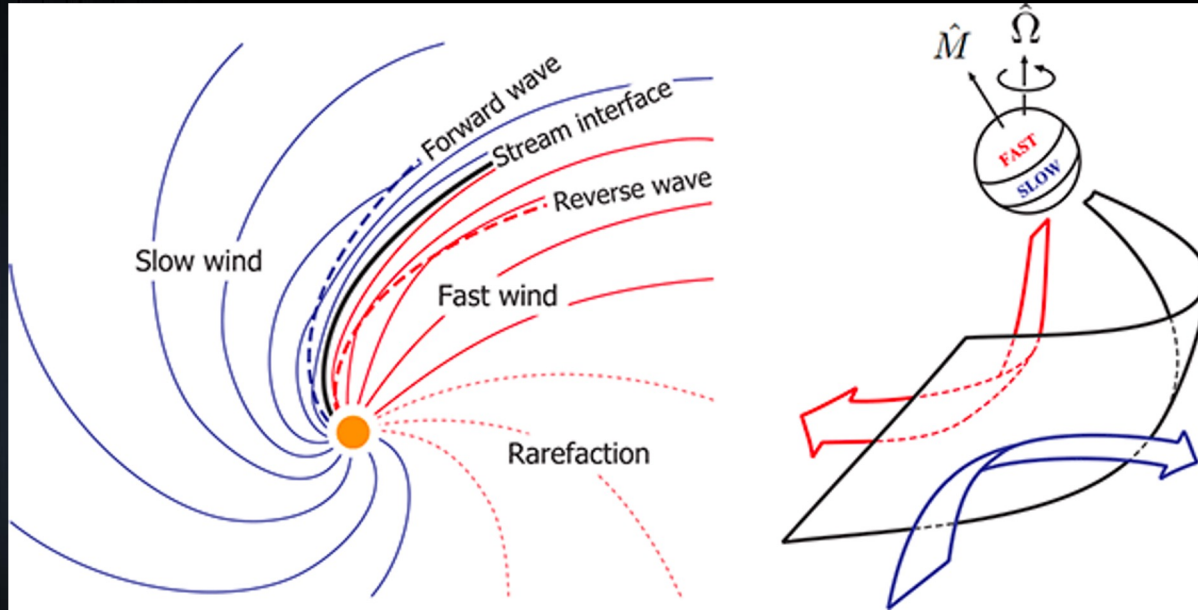


# In situ measurements challenge us to understand large-scale and small-scale structure



Source: Kilpua et al., 2017

# Large-scale coronal variations result in large-scale heliospheric variations



Source: Owens, 2020

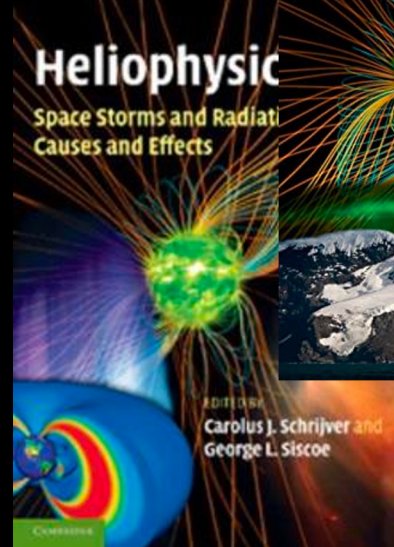
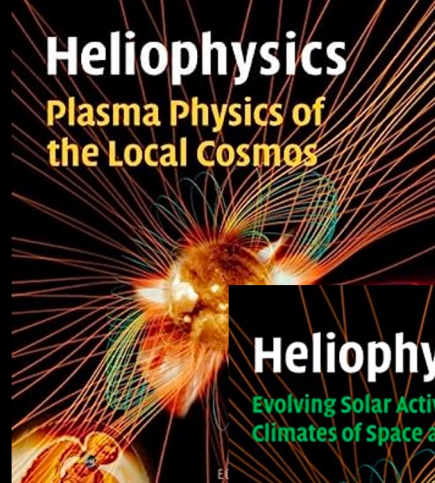
Most of what I've shown so far is explained in the Heliophysics textbooks with unprecedented detail and clarity.

The textbooks were authored by many great heliophysics scientists.

Has anything new happened since then?

(Short answer: Yes)

((Longer answer: Yes, a lot))

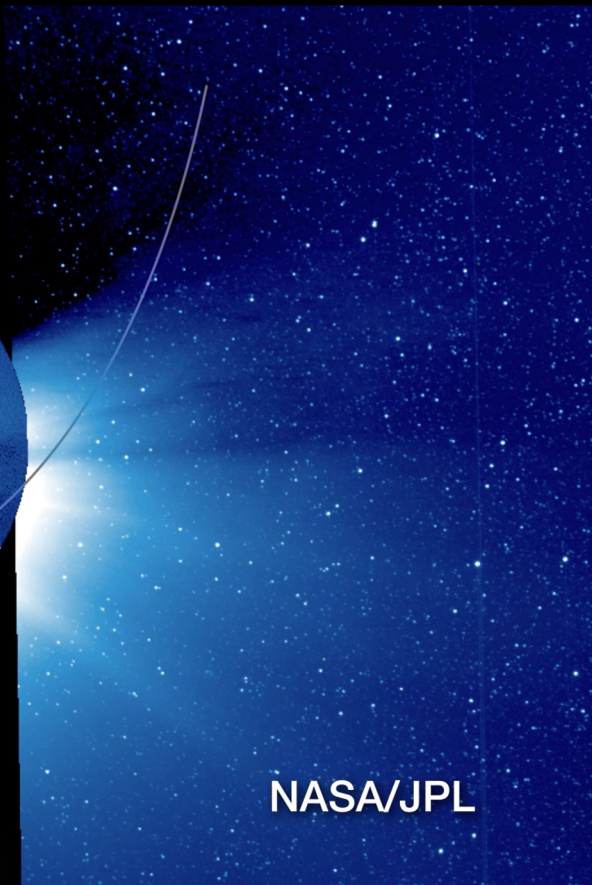
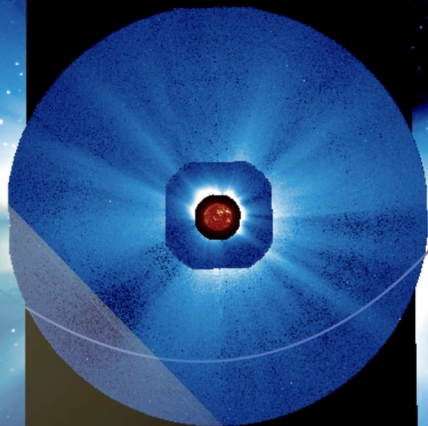




# Parker Solar Probe (launched 2018) goes closer to the Sun than any spacecraft has gone before



0.250 AU spacecraft to Sun  
6-09-2025 Parker Solar Probe  
6-01-2011 SECCHI images

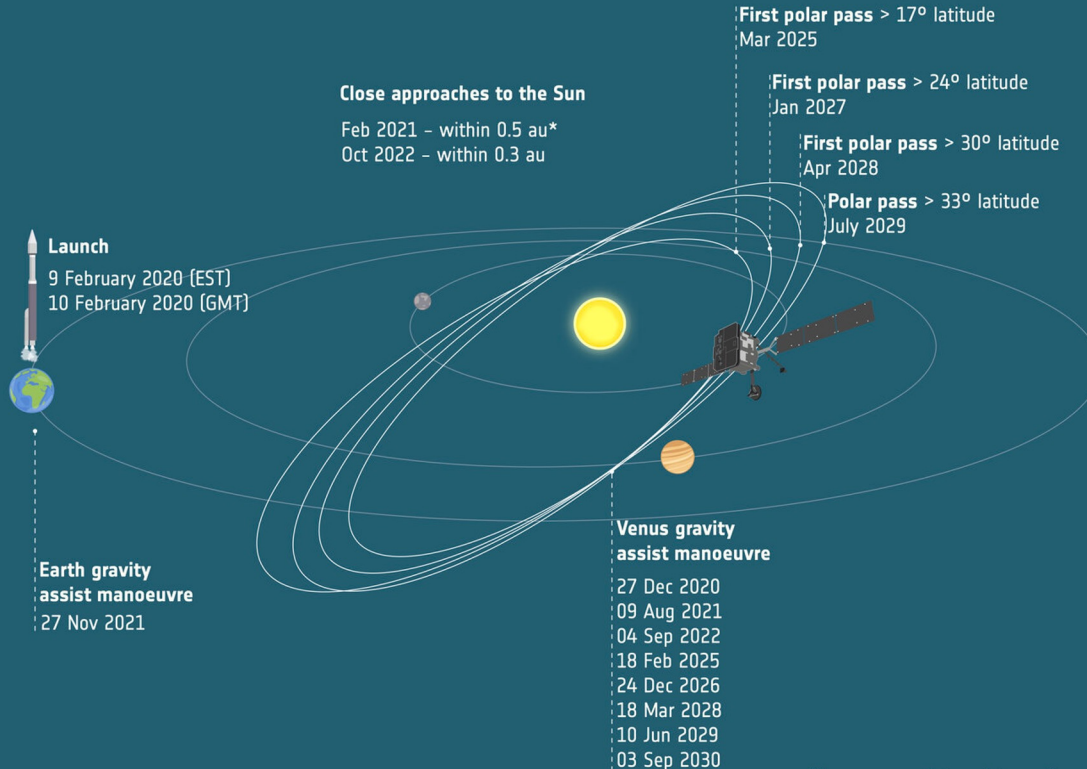


NASA/JPL

# Solar Orbiter (launched 2020) gives us a view outside the ecliptic



## SOLAR ORBITER JOURNEY AROUND THE SUN



**300 million km**

Maximum distance between Earth and Solar Orbiter

**16.5 min**

Maximum time for a radio signal to travel one way between Earth and Solar Orbiter

**22 orbits**

around the Sun

**Nov 2021**

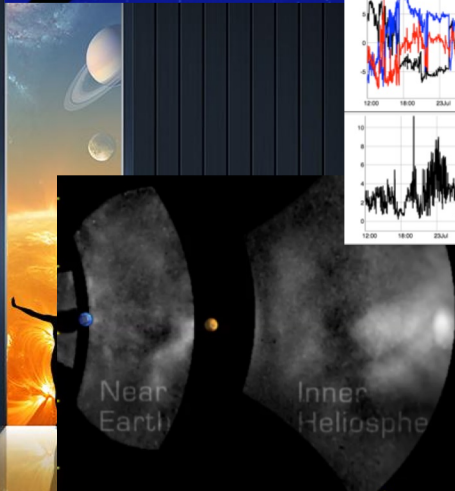
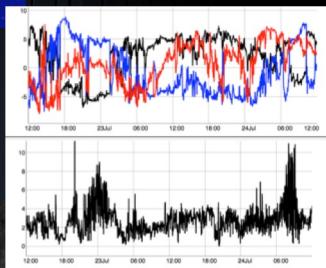
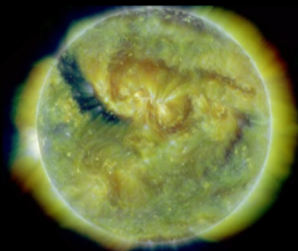
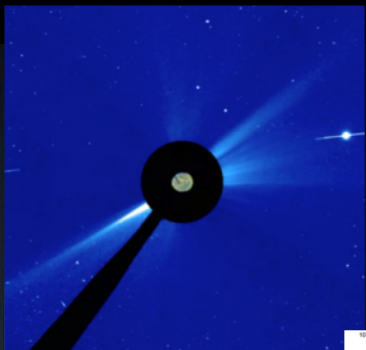
Start of main mission

**Dec 2026**

Expected start of extended mission

\*1 au = average distance between Sun and Earth (149 597 870 700 m)

# Understanding the source of the solar wind



Decades of observations, both *in situ* and remote sensing, have allowed us to examine how the corona evolves into the heliosphere.

- 1) How do structures in the inner corona supply the solar wind that forms the heliosphere?
- 2) What processes govern this transition? Can we define and identify the outer limit of the corona/ inner boundary of the heliosphere?

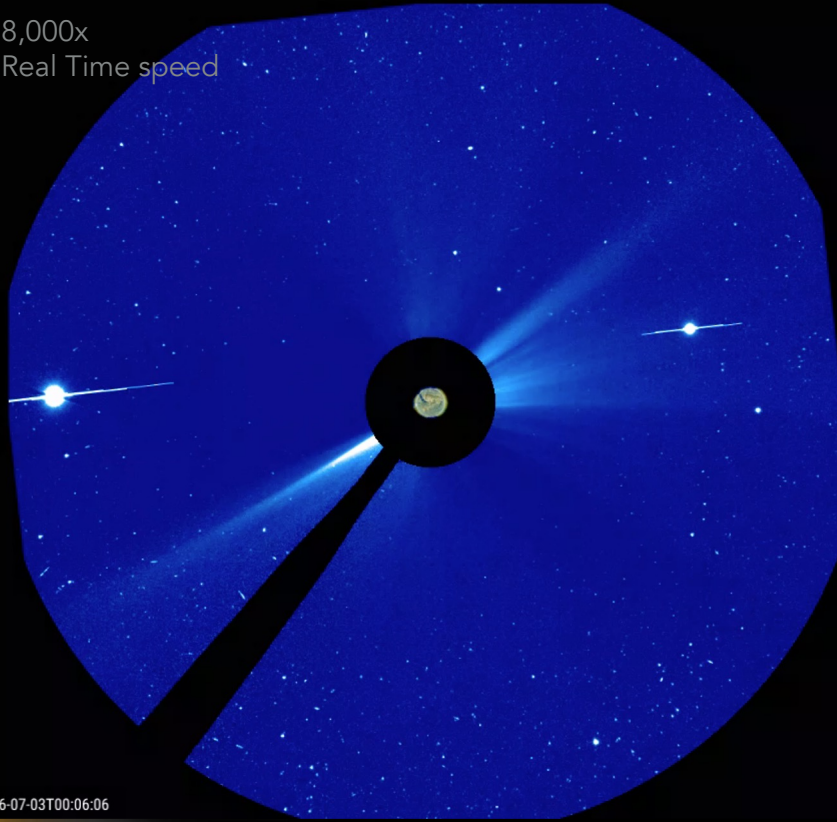


# The solar magnetic field is complex



SOHO/LASCO C3: visible (2% of imaged light)

8,000x  
Real Time speed



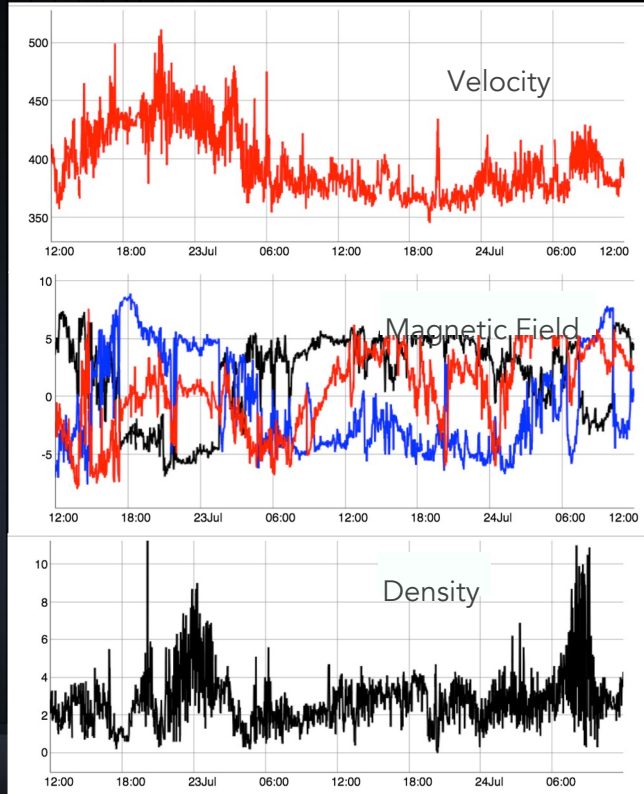
10 million miles

But if you move out a bit, it seems like the outer corona is much calmer. In the absence of major transients, the impression is that the fields become mostly smooth and radial after a few solar radii.

So... let's zoom out even more, to 1 AU and beyond (~100 million miles). What would we expect this to look like?



# Then it gets complicated again



*In situ* observations have shown how the slow solar wind, in particular, exhibits tremendous multi-scale structure. This heralds an apparent return to complex, fine-scale features.

So what's the story? Why does the solar wind structure go from complex, to simple, and back to complex again?

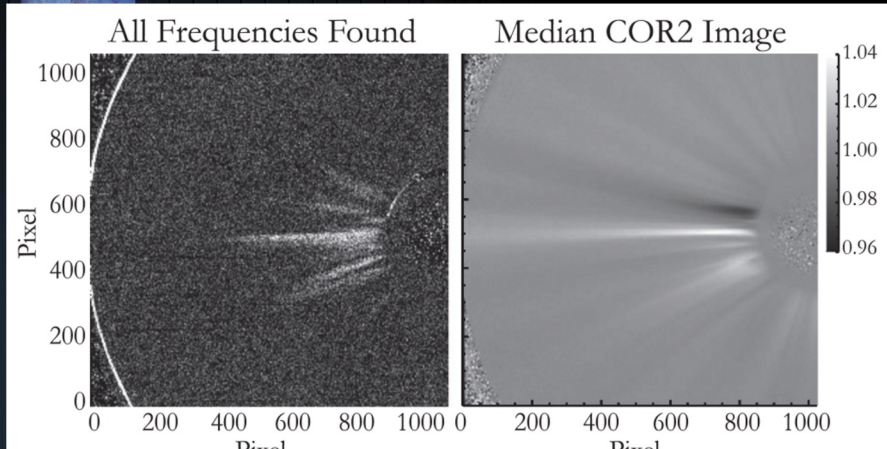
If so, what processes govern these transitions?

Are we even asking the right questions?

# The corona is ever varying



If you watch a movie you can see variations and flows.

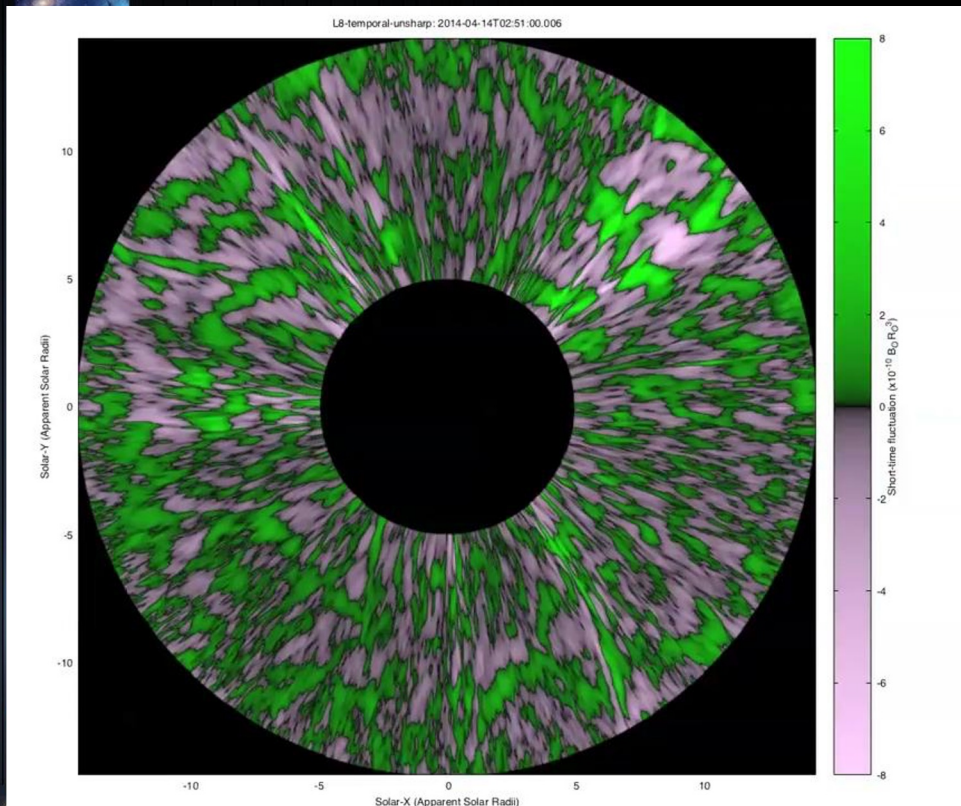


- Sheeley (1997): blobs are good tracers of solar wind
- Viall & Vourlidas (2015): more than tracers, this *may be* the solar wind itself

Everywhere signal – flows. So let's enhance the signal.



# It depends on how you look at it



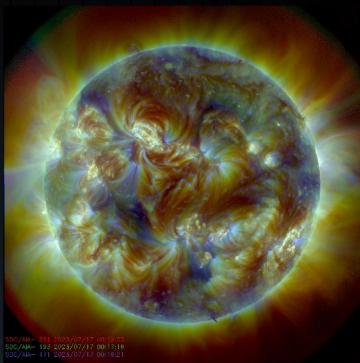
Now this looks like what we were expecting!

- Ubiquitous structure
- Small deviations in flow velocity are discernible
- Myriad speeds are present and intermingled.
- Entire FOV can be used to derive flow values

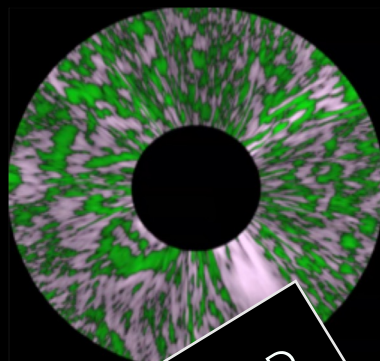
(Comparable to Higginson & Lynch, 2018)



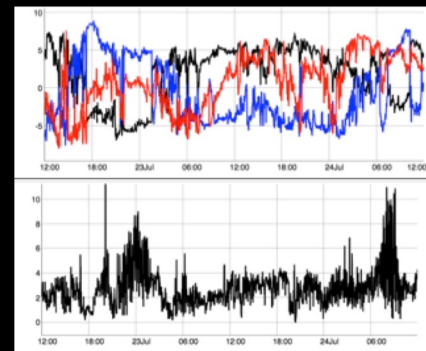
# Understanding the source of the solar wind



Inner corona  
"Complex"



Out  
REALLY  
COMPLICATED  
(??)



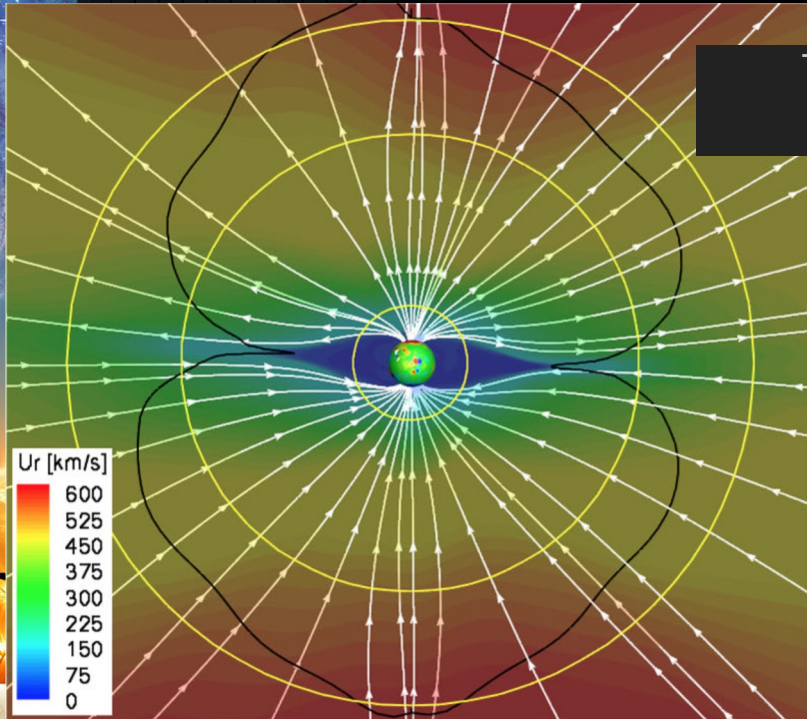
SW/Heliosphere  
"Complex"

The outer corona only *appears* to be simple because of the way it is commonly observed (integrating density structures along the line of sight).

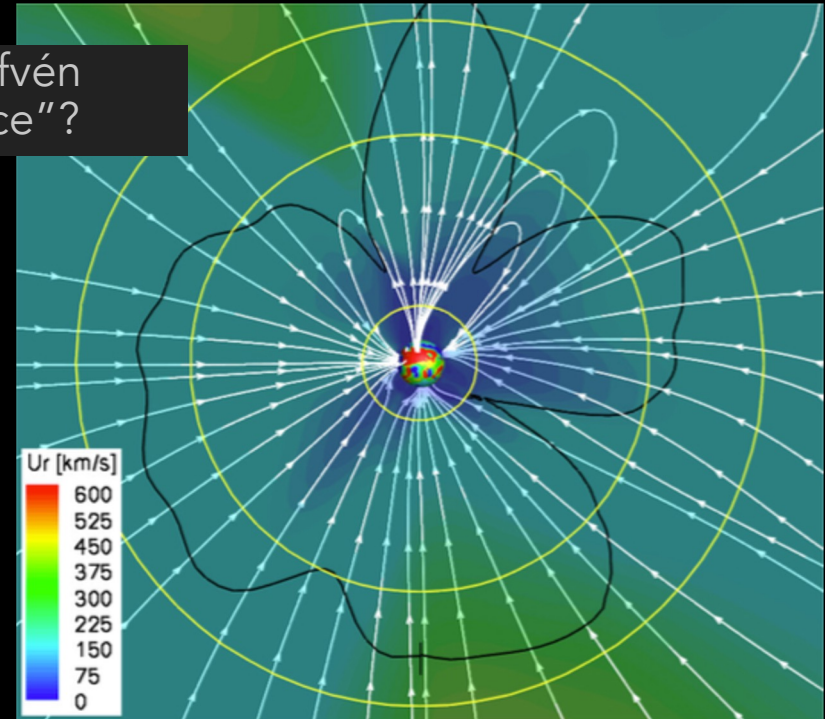
This implies that the *source* of the solar wind is inconstant, ever varying. The development of turbulence further along is even more interesting.



# The transition from corona to solar wind



The Alfvén  
"surface"?



Alfvén surface model: Cohen  
2015



# Understanding the source of the solar wind



National Aeronautics and Space Administration



## Where Do Switchbacks Come From?

Switchbacks are sudden reversals in the solar wind's magnetic field. They were a surprise discovery as NASA's Parker Solar Probe made its first close flyby of the Sun in November 2018.

How do switchbacks form? Here are the current theories competing to explain them.

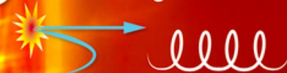
(Not to scale)

[www.nasa.gov](http://www.nasa.gov)

**1** Reconnecting field lines create kink



**2** Reconnecting field lines create flux rope



**3** Expanding plasma ripples



**4** Shear-driven turbulence



**5** Slow wind reconnects to fast, fast wind overtakes slow



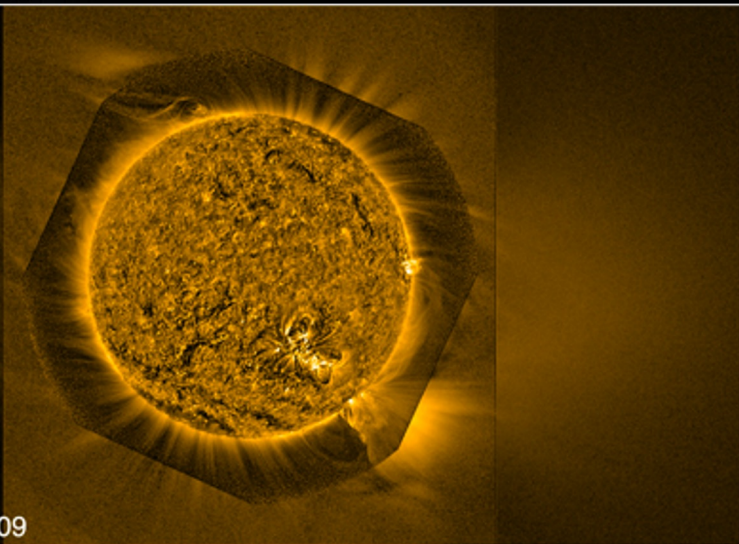
Credits: NASA's Goddard Space Flight Center/Miles Hatfield/Lina Tran/Mary-Pat Hrybyk Keith

# Understanding the source of the solar wind

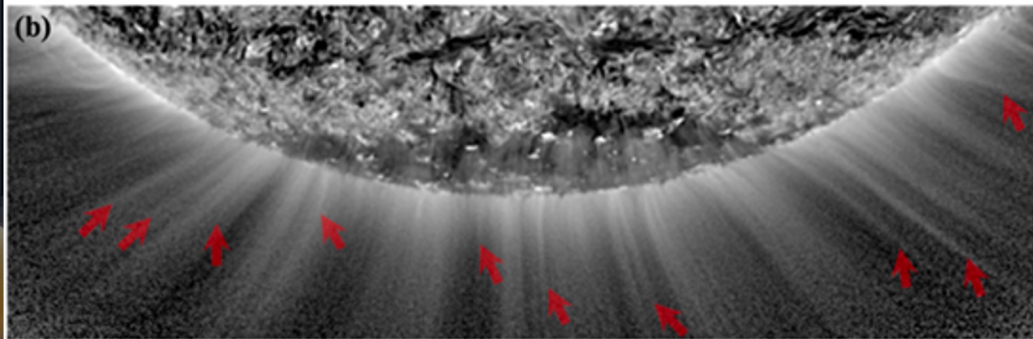


(a)

2021-04-28 03:48:09



(b)



Raouafi et al., 2023:

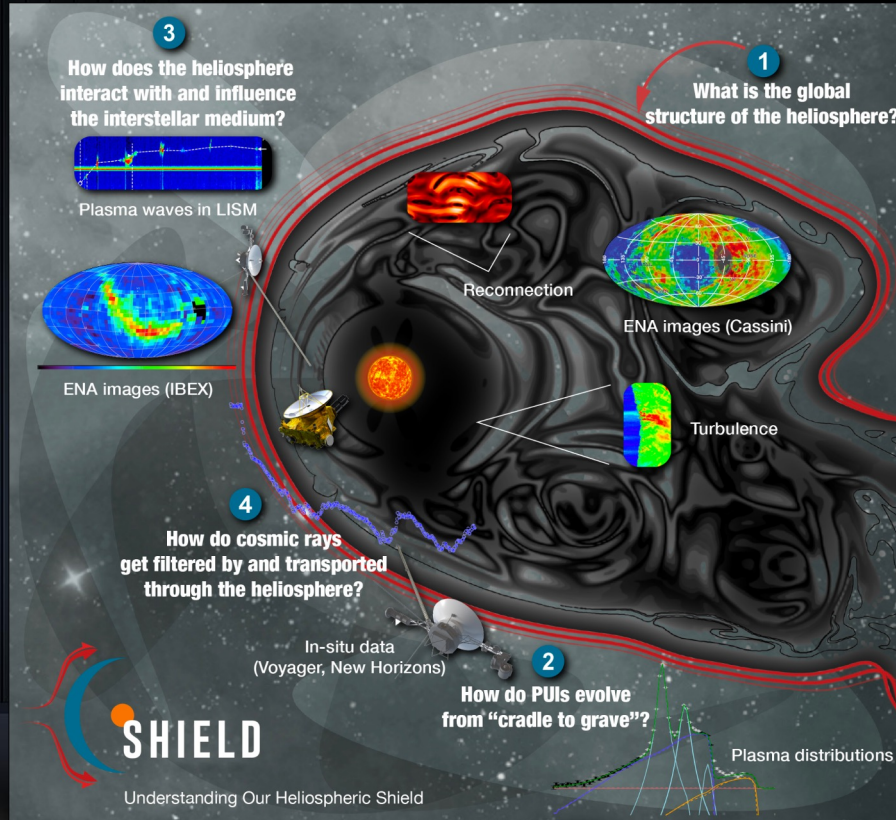
“We argue that the physical mechanism that heats and drives the solar wind at its source is ubiquitous magnetic reconnection in the form of small-scale jetting activity (a.k.a. jetlets).”

This jetting activity, like the solar wind and the heating of the coronal plasma, is ubiquitous regardless of the solar cycle phase.

Each event arises from small-scale reconnection of opposite-polarity magnetic fields producing a short-lived jet of hot plasma and Alfvén waves into the corona.”



# More important science to come!



Attend SHIELD Webinars!

<https://shielddrivecenter.com/>



# More important science to come!



Join us on  
helionauts.org!!

The screenshot displays the Helionauts forum board interface. At the top, there is a navigation bar with a hamburger menu, a search icon, and a "New Topic" button. Below this, there are filters for "all categories", "all tags", and sorting options: "Latest", "New (2)", "Unread (18)", "Top", "Categories", and "Board" (which is highlighted). The main content area is divided into three columns, each representing a different category: "Missions & Instruments", "Coding", and "Science". Each column lists several discussion topics with their titles, dates, and user avatars. At the bottom of the interface, there are navigation options for "Replies", "Views", and "Activity".

Category	Topic Title	Date
Missions & Instruments	About the Missions & Instruments category	May '21
	PUNCH Flow Tracking	Jun 15
	Coordinate Transformation ACE RTN to GSE	May 26
	Earth Orbit data for SDO with Lon/Lat/Altitude?	May 3
	STEREO/WAVES and WIND/WAVES data access for 2022?	Apr 20
	PySPEDAS and Tplot datetime conversion for Wind spacecraft	Jan 24
	SDO AIA Spikes removal	Nov '22
	Relation Between Flux and Phase	Nov '22
Coding	About the Coding category	Jun '20
	Sunpy 5.0 released	29d
	Discussion on Best Practices for Reviewing Software Papers	Jun 15
	Installing ApexPy on OS X	Jun 13
	Moon Ephemeris in GSE, Cartesian (x,y,z)	Jun 5
	CDAWeb search solar parameters	May 18
	STEREO HI images	May 16
	Sunpy 5.0 release candidate	May 16
GPU-Based Field Line Tracing	Apr 15	
Science	About the Science category	Sep '21
	Optical flow in the space-time frequency domain with Dirac Delta distributions	Jun 15
	Global Semi-Empirical Magnetospheric Density/Temperature Model	May 17
	Is there a solar flare GOES X-ray fluence dataset?	Feb 9
	Solar Wind Source Surface	Feb 2
	Feedback on Acceleration from Ionization during Flares	Dec '22
	Ionization rate of hydrogen in solar chromosphere	Nov '22
	Coronal inversion codes?	Jul '22