The Solar Corona and the Solar Wind

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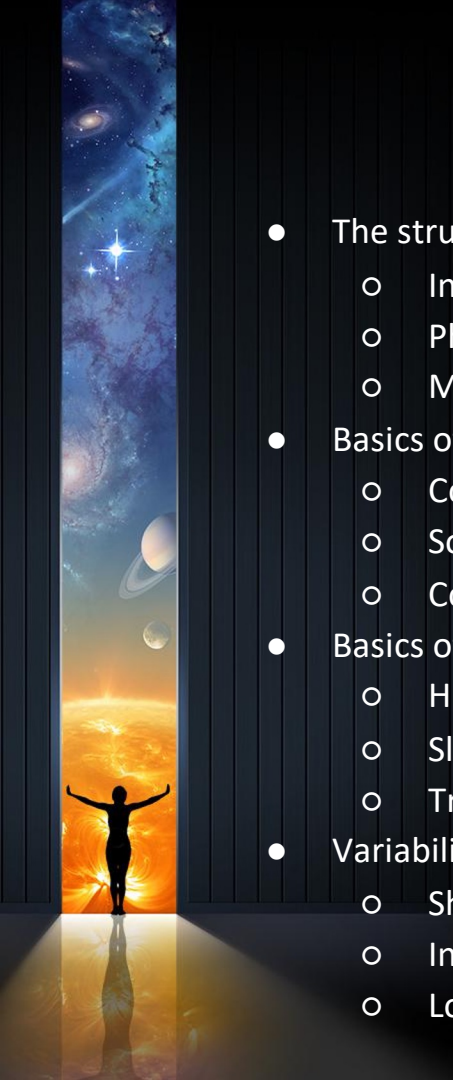
Pronouns: she/they

with a lot of help from C.N. Arge, C.E. DeForest, E. De Jong, J.A. Klimchuk, T. A. Kucera, J.S. Newmark, P. C. Liewer, V. Uritsky, P.R. Young, and especially Simone Di Matteo

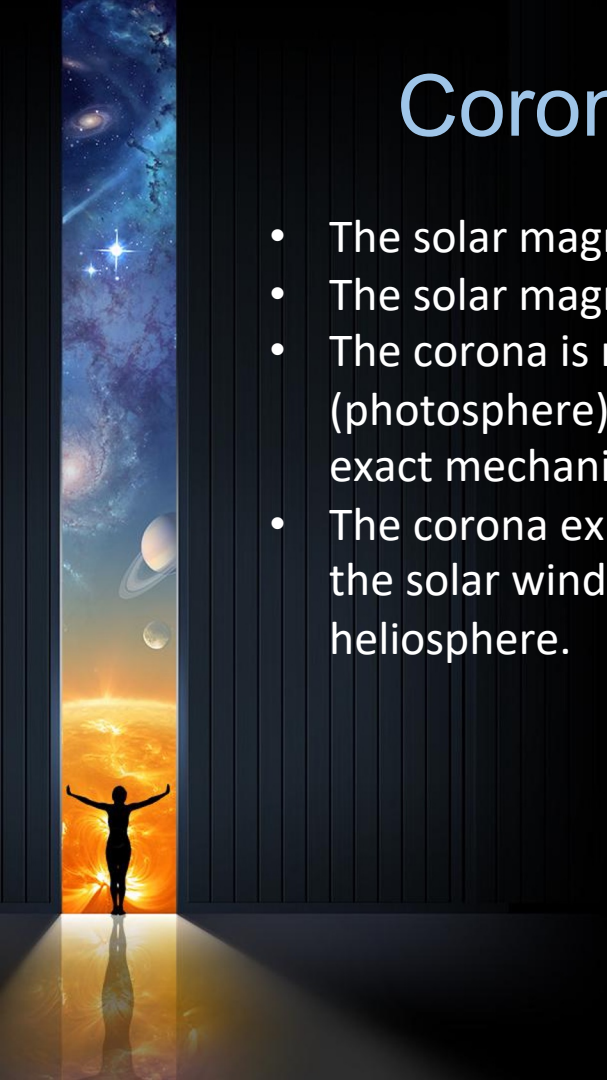
18 July 2023



(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



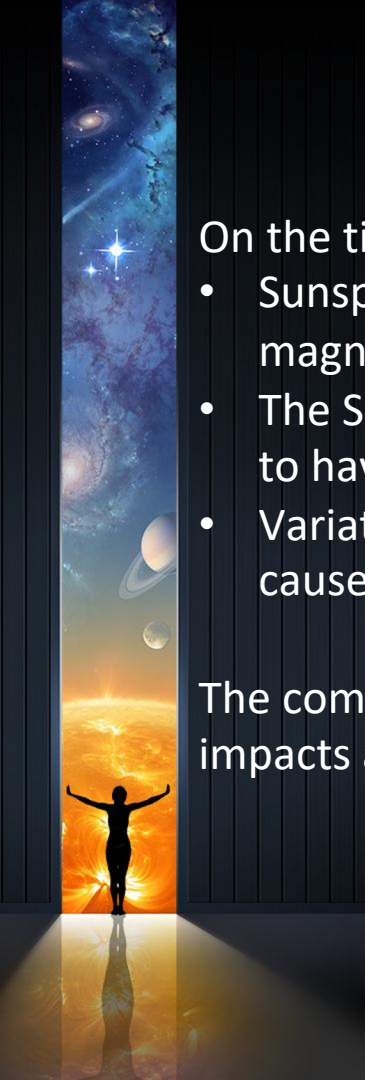
- The solar magnetic field is generated in the Sun's interior.
- The solar magnetic field extends to form the solar corona.
- The corona is much hotter than the visible surface of the Sun (photosphere). The source of the heat is magnetic in nature, but the exact mechanism is still under debate.
- The 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



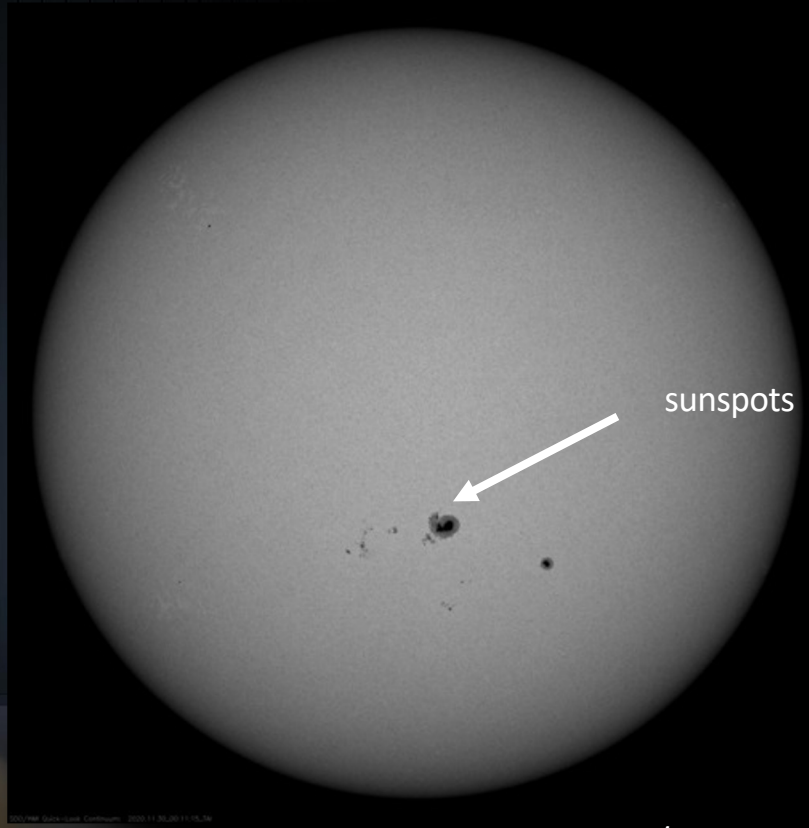
On the timescale of months, there are also important variations.

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



SDO/HMI, NASA

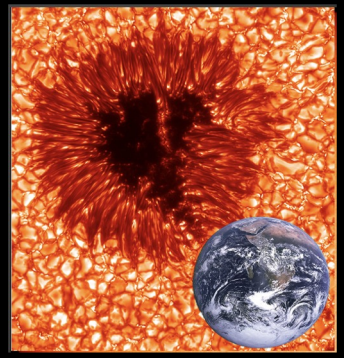


Image credit: The Royal Swedish Academy of Sciences, V.M.J. Henriques (sunspot), NASA Apollo 17 (Earth)

Granulation due to underlying plasma convection

Sunspot (Earth to scale)

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

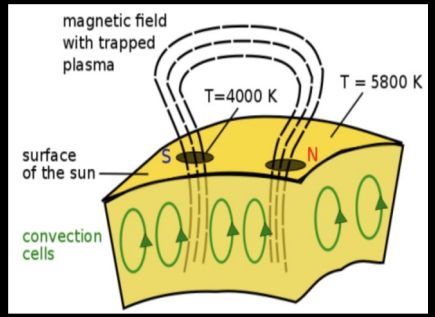
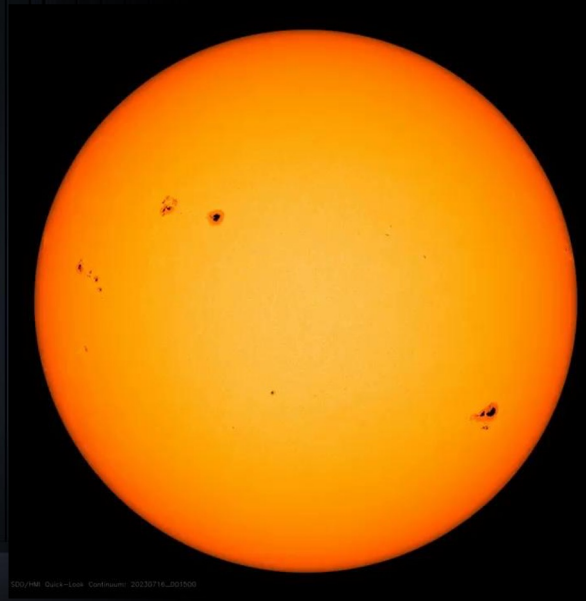
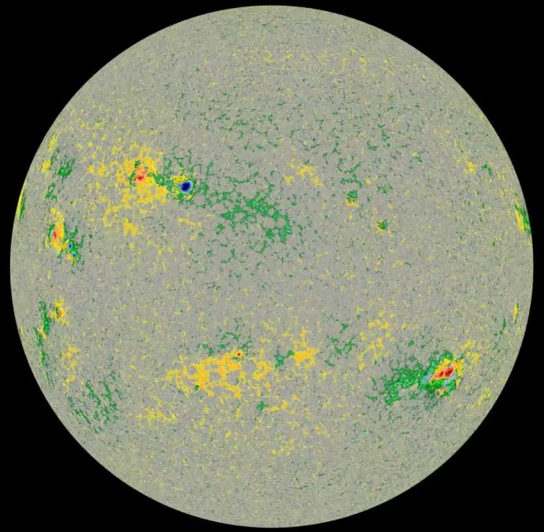


image adapted from: http://cse.ssl.berkeley.edu

There are many ways to observe the Sun

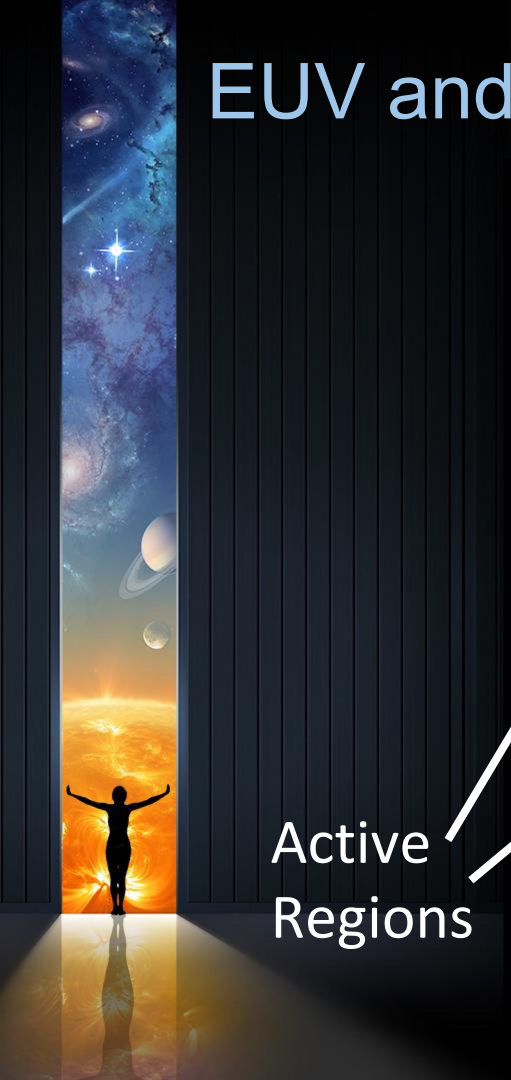
We are living in the outermost atmosphere of a magnetic variable star.
There are many ways to view the Sun and its atmosphere as it extends into the solar wind.

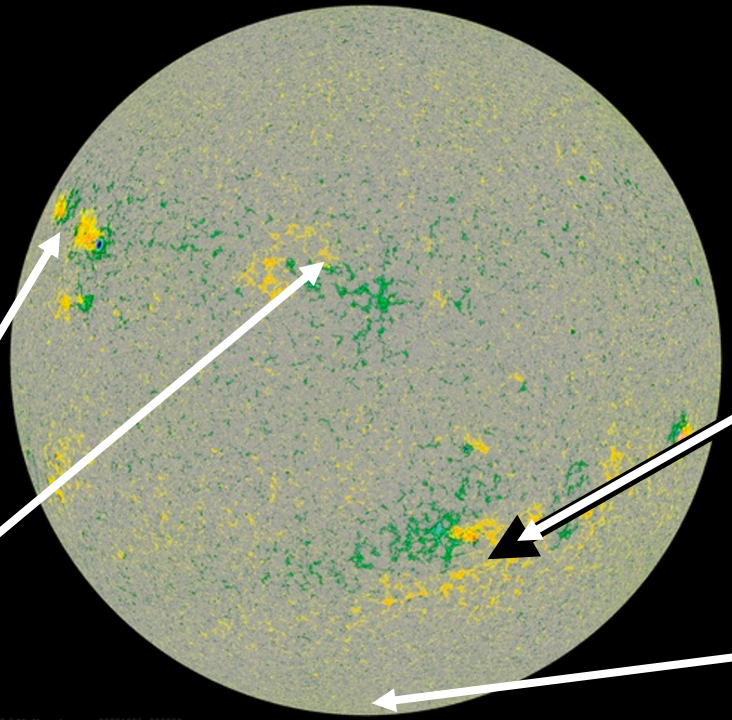




8 April 2024 *http://www.greatamericaneclipse.com*

EUV and X-rays reveal the super-hot corona





Active Regions

Filament Channel

Coronal holes

SDO/AIA, NASA

Why is the corona so hot?

There are

- **Alfv**
  wave
  wave
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  cyclo

- **Nano**
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- **Turb**
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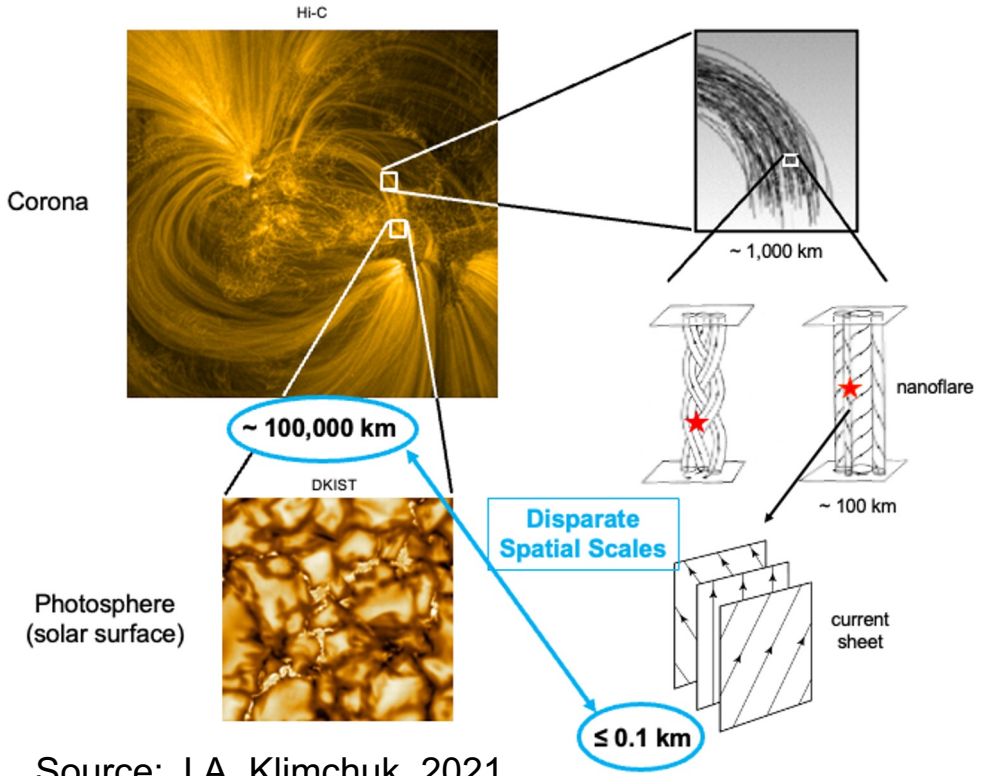

Source: J.A. Klimchuk, 2021

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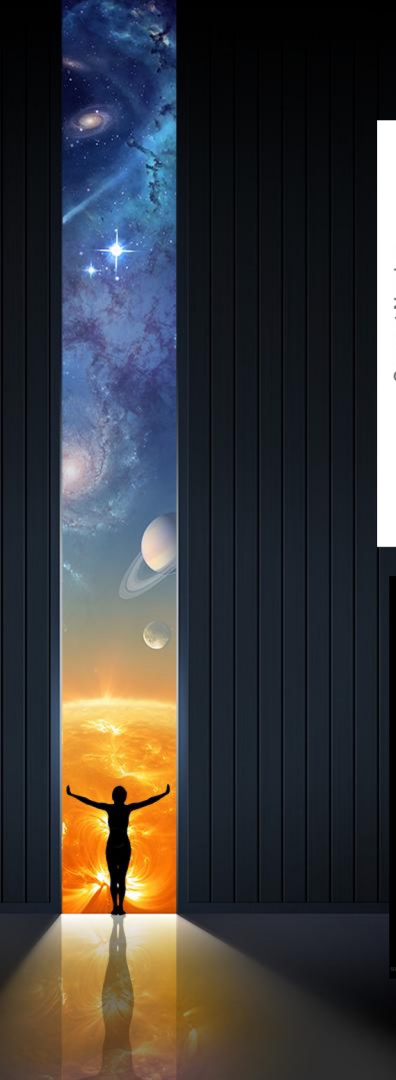
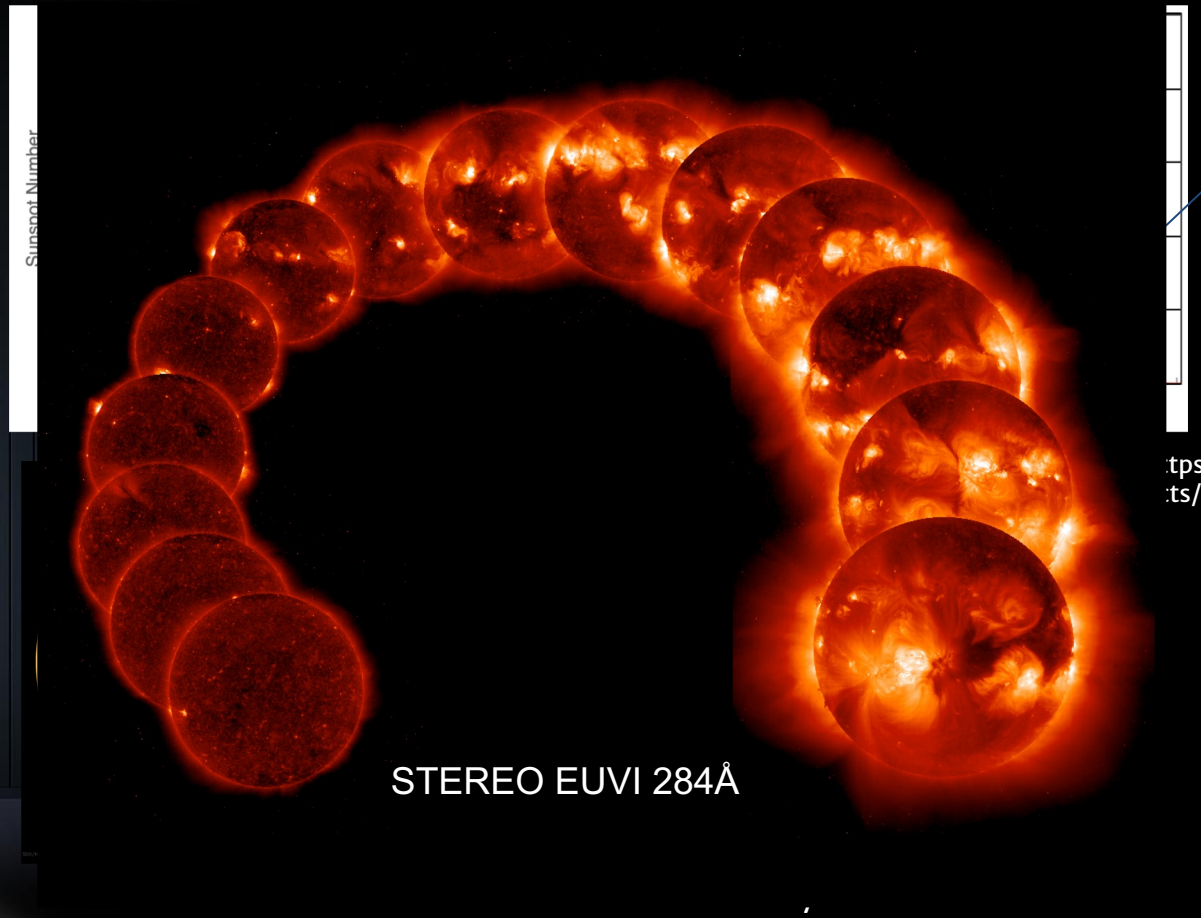
Solar Cycle variations



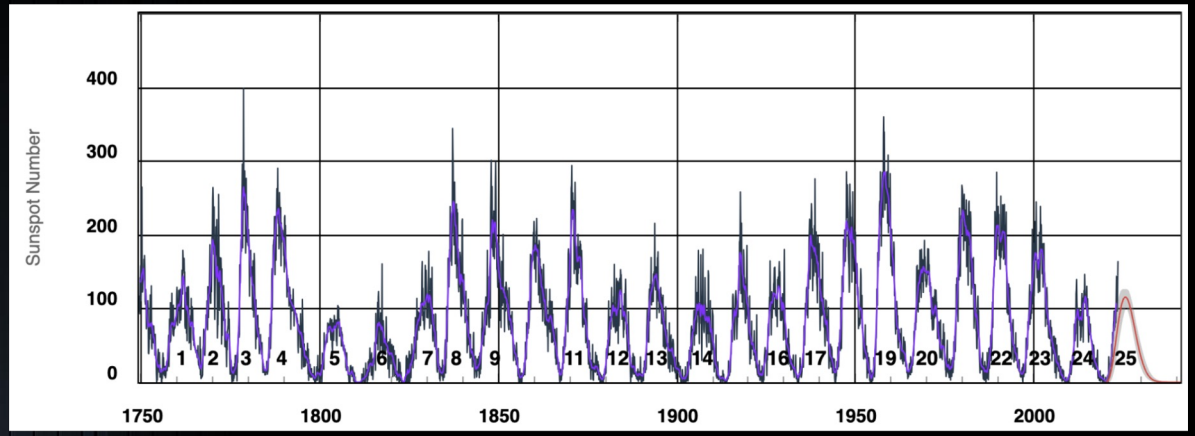


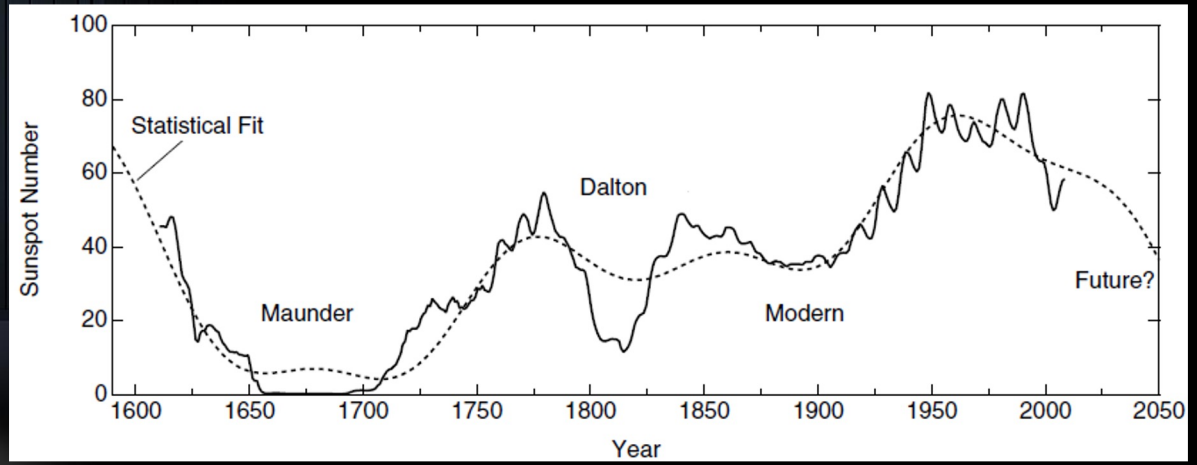
Solar cycle 25 is outpacing predictions!

tps://www.swpc.noaa.gov/prod
ts/solar-cycle-progression

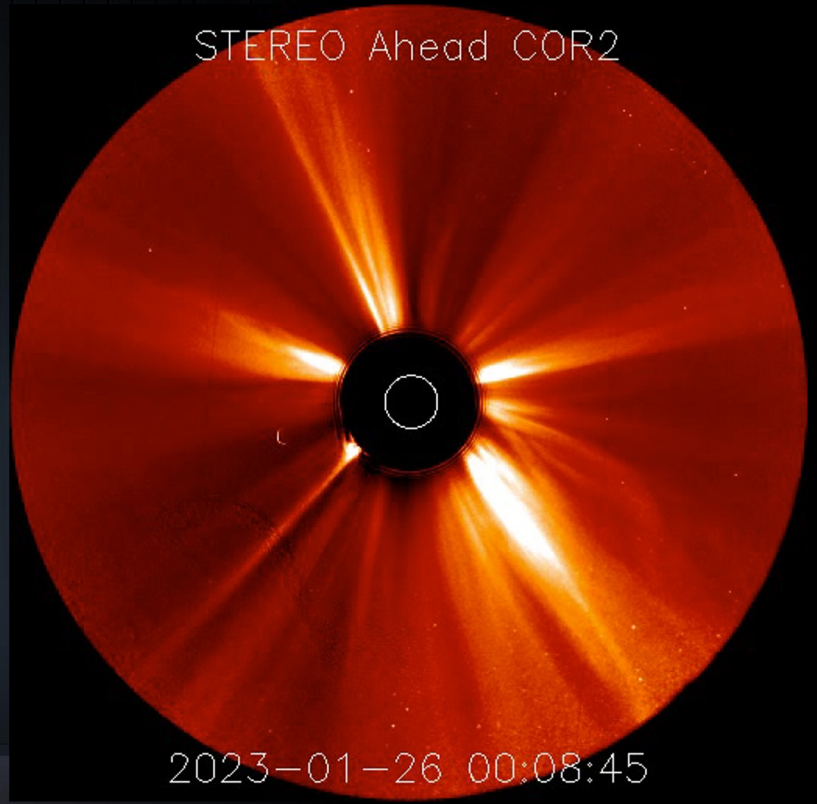
NASA SDO HMI

Longer timescale variations





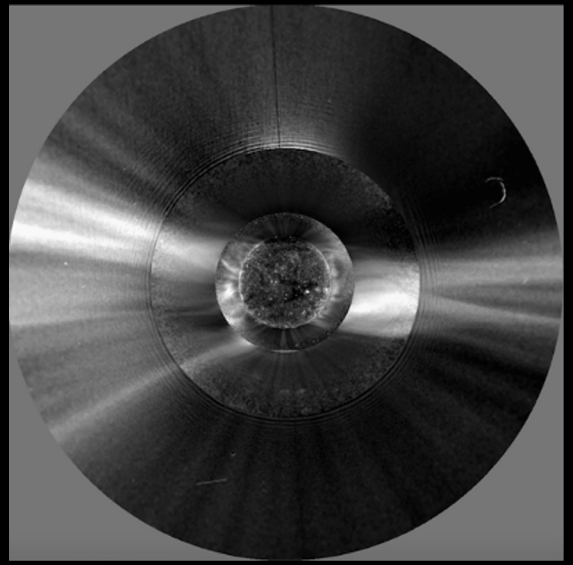
Coronagraphs provide extended observations



SOHO/ESA & NASA

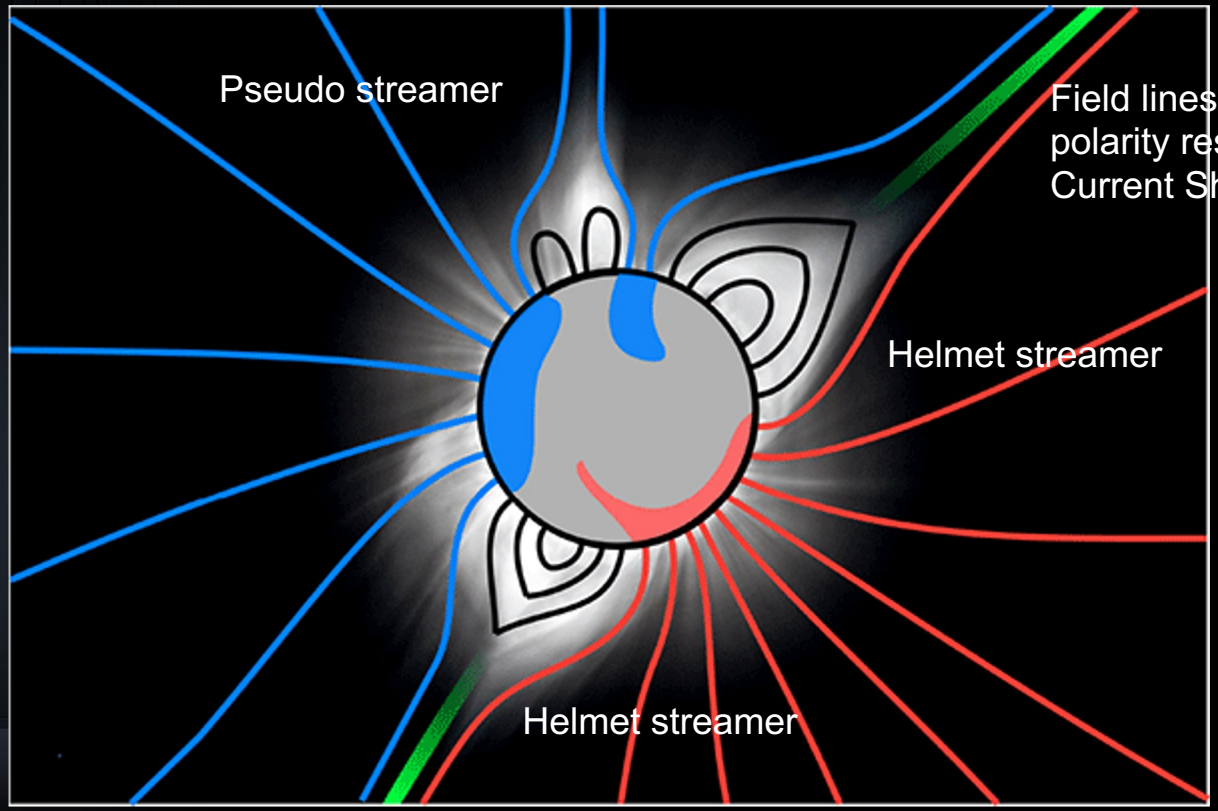
Credit: N. Alzate

STEREO EUVI-COR1-COR2



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

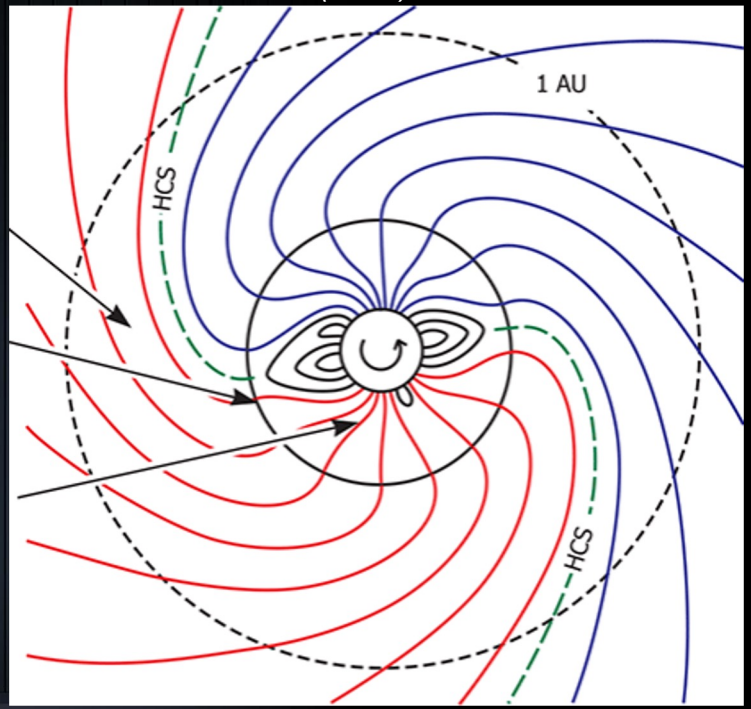
Revealing coronal magnetic structures



Credit: M. J. Owens (2020)

The corona expands outward to form the solar wind

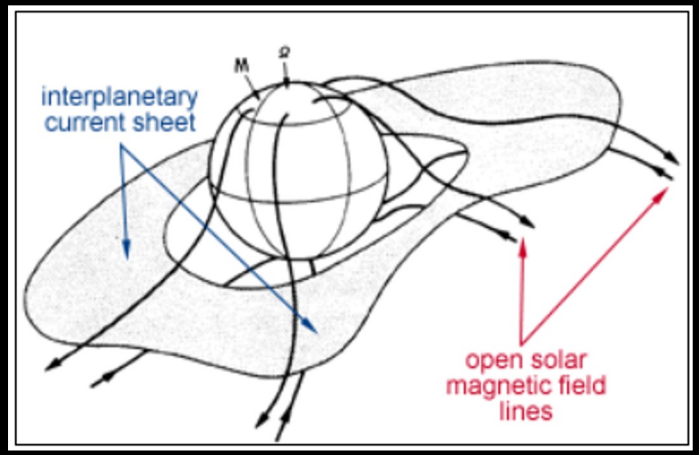
Credit: M. J. Owens (2020)



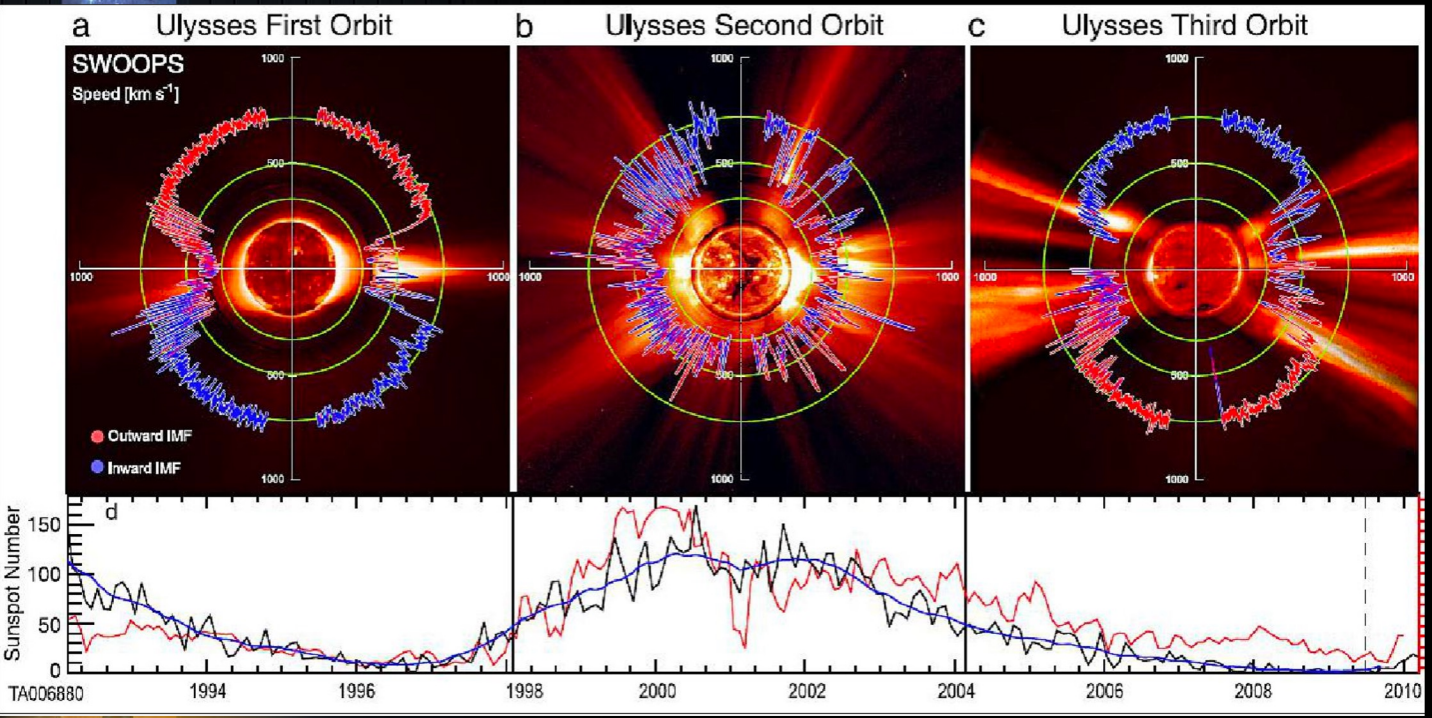
Red/blue indicate magnetic field directed outward/inward in the ecliptic plane

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



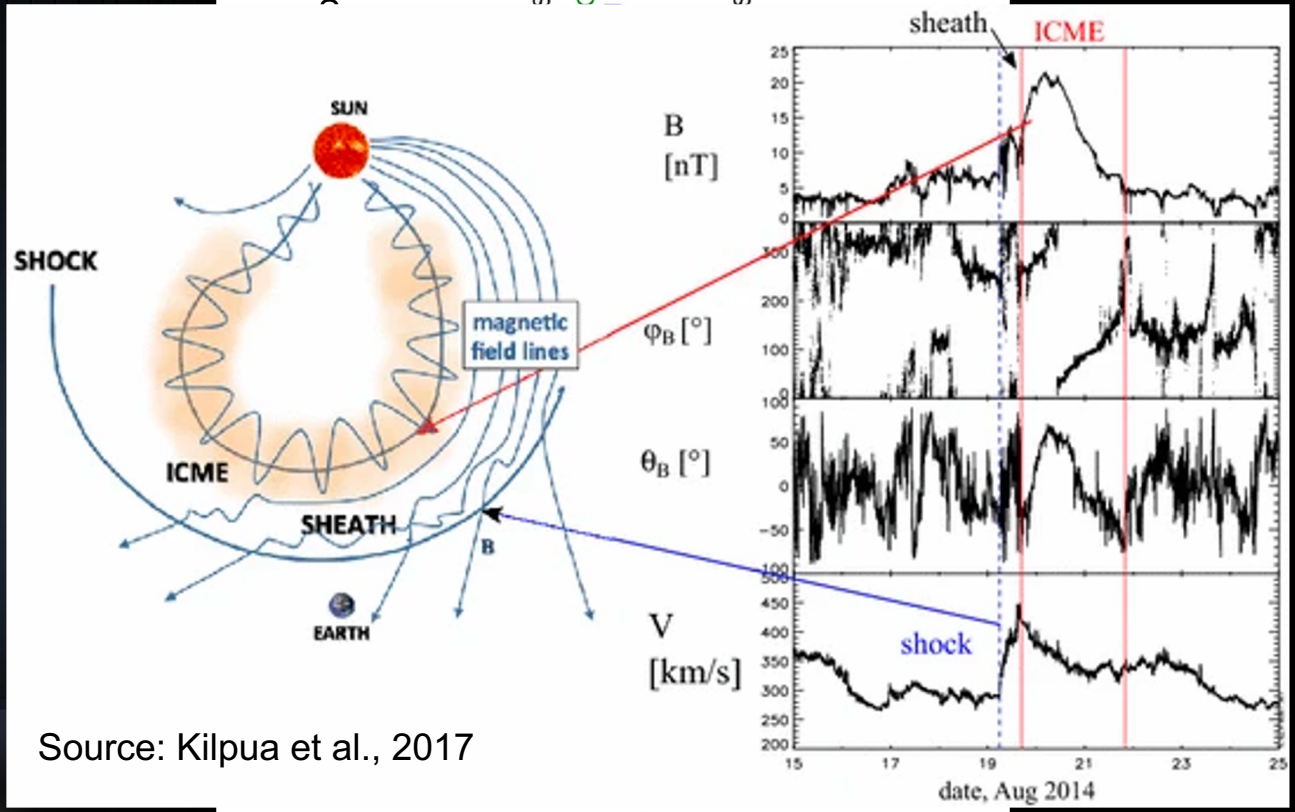
Typical solar wind parameters at 1 *AU*

	slow wind	fast wind
V (km s^{-1})	350	750
n_e (m^{-3})	1×10^7	3×10^6
T_e (K)	1.3×10^3	1×10^5
T_p(K)	3×10^4	2×10^5
B (nT)	3	6
v_A (km s^{-1})	20	70

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

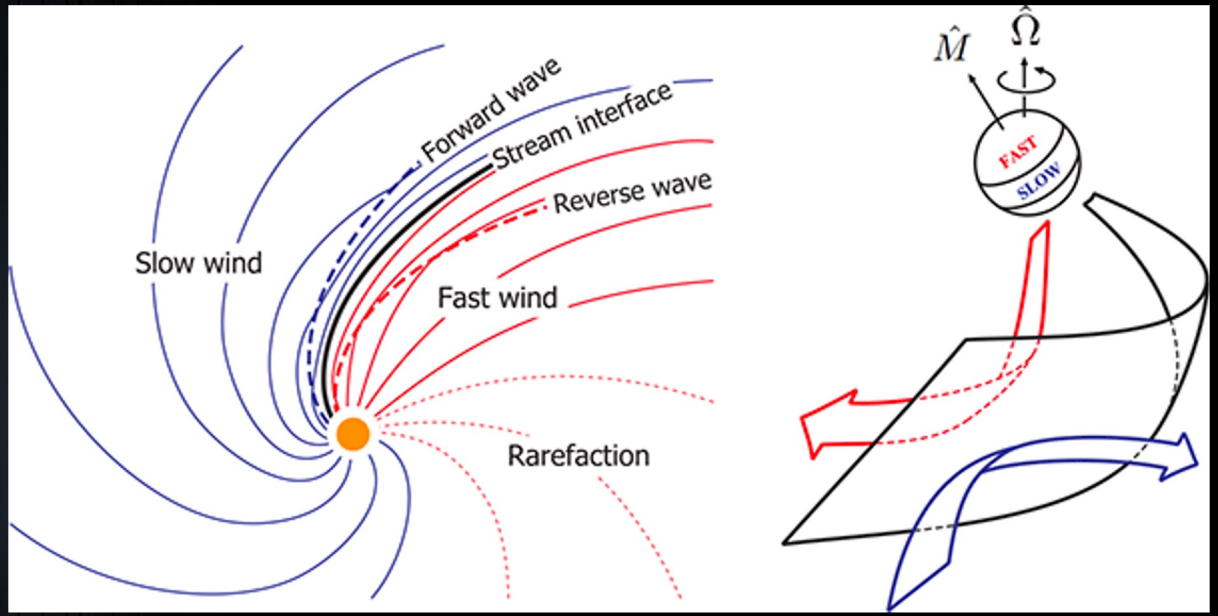
Source: McComas et al. 2008, Scherer et al. 2022

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



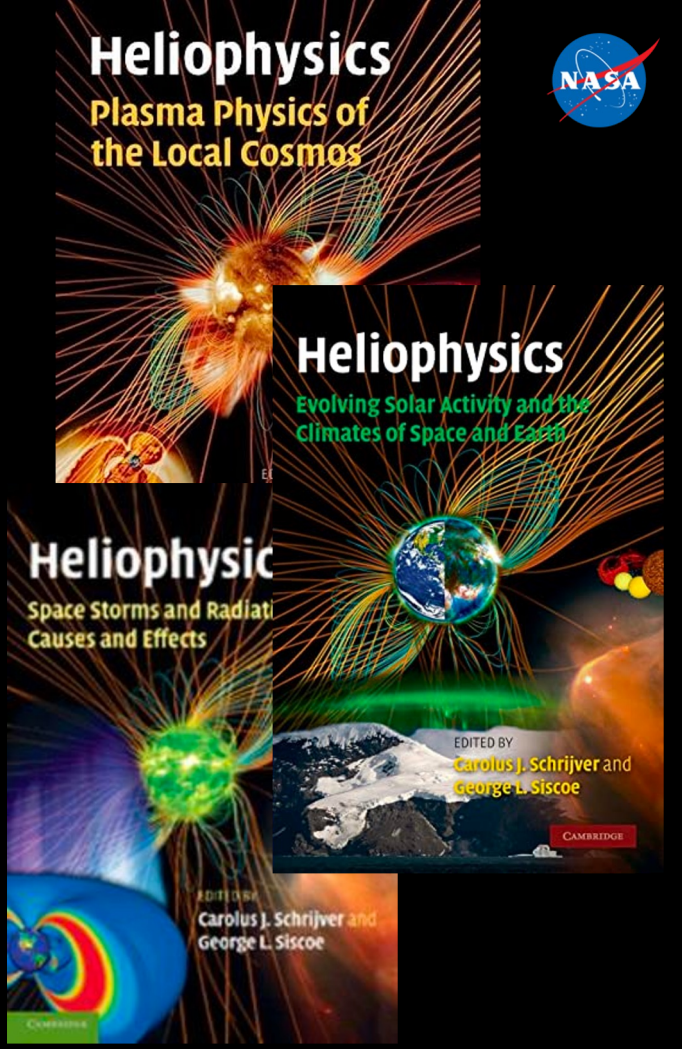
Source: Owens, 2020

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

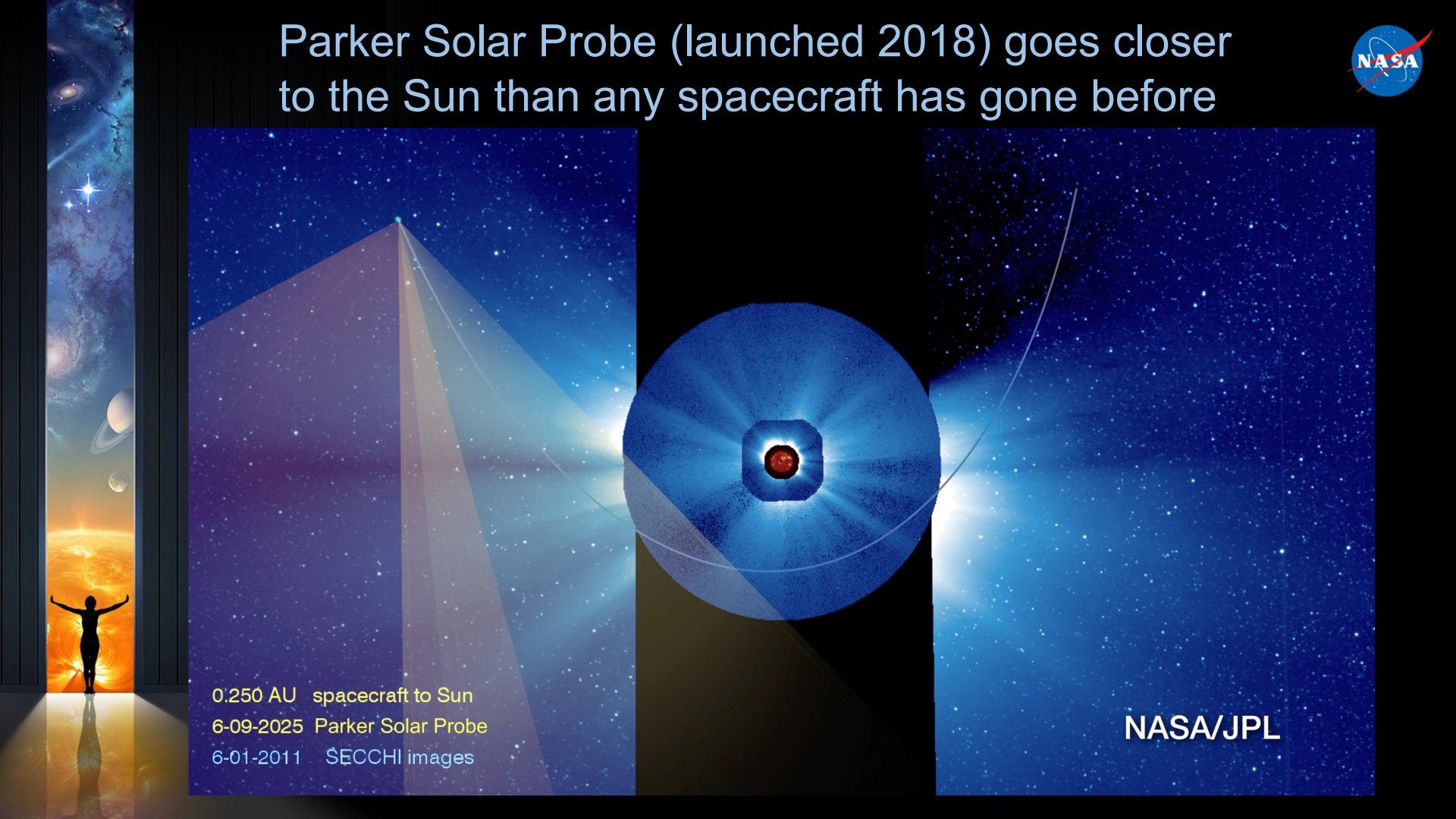
The textbooks were authored by many great heliophysics scientists.

Has anything new happened since then?

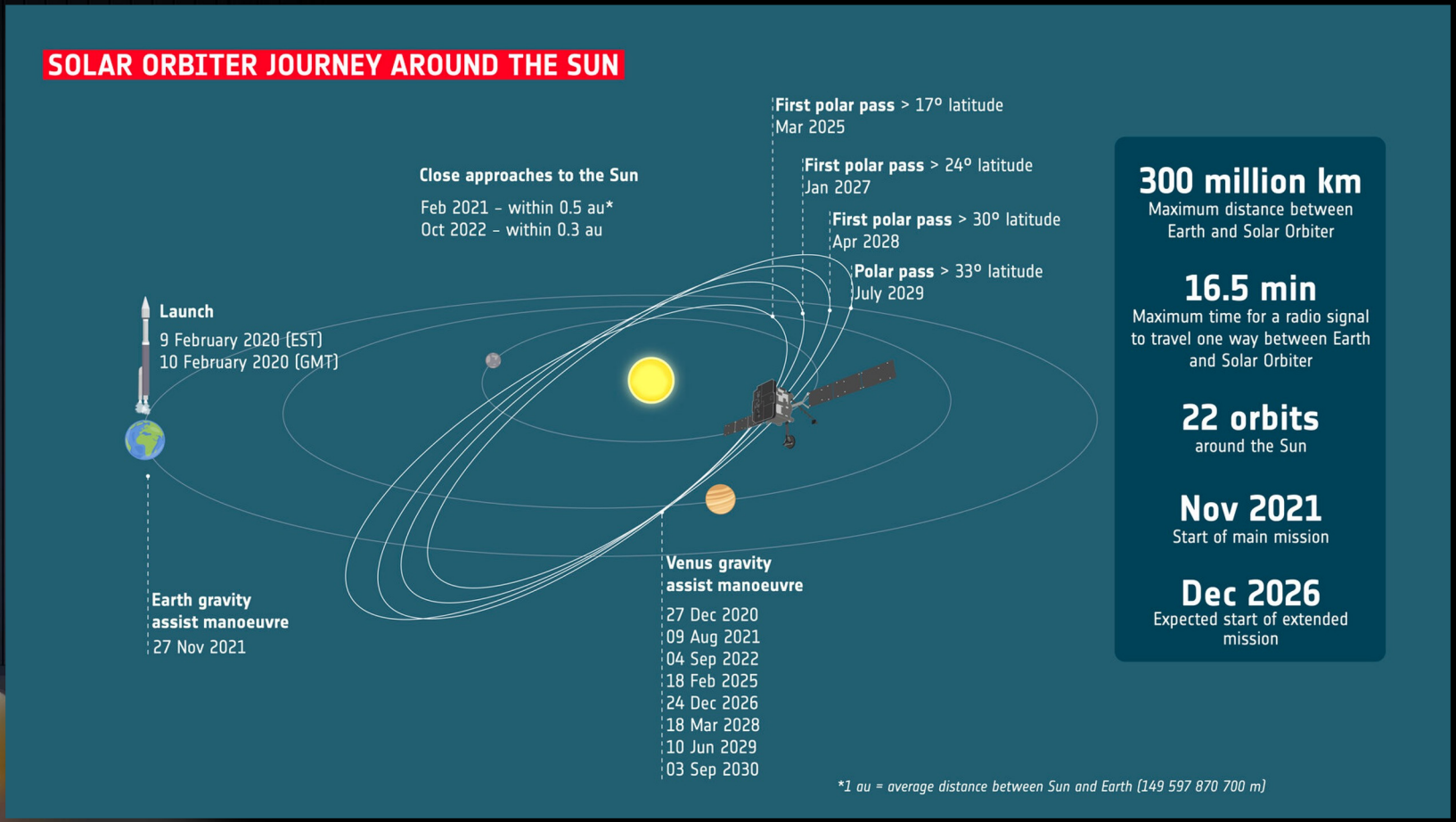
(Short answer: Yes)
((Longer answer: Yes, a lot))



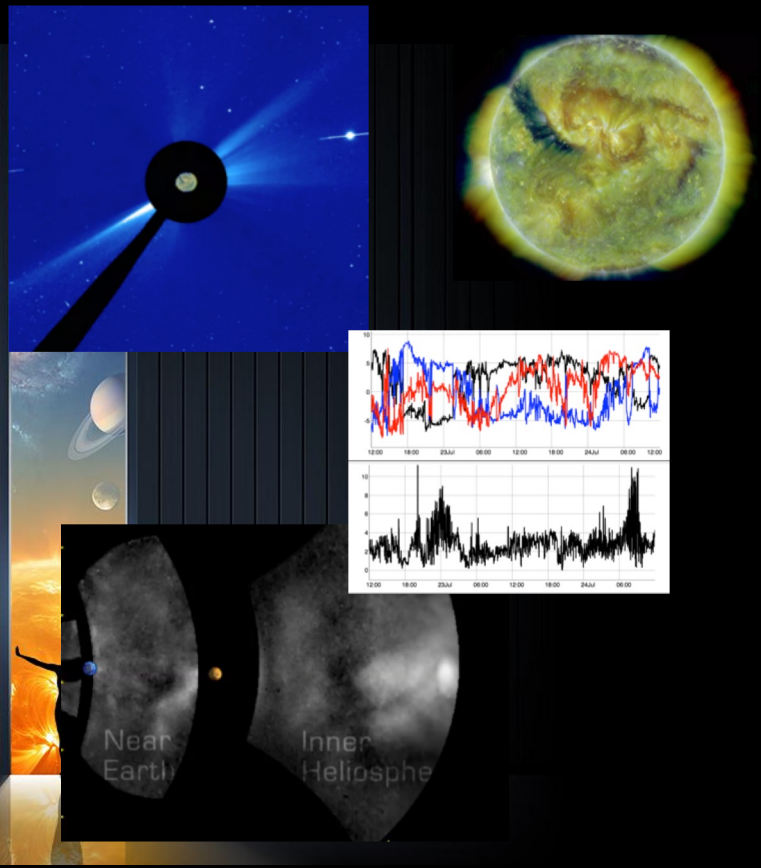
Parker Solar Probe (launched 2018) goes closer to the Sun than any spacecraft has gone before



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



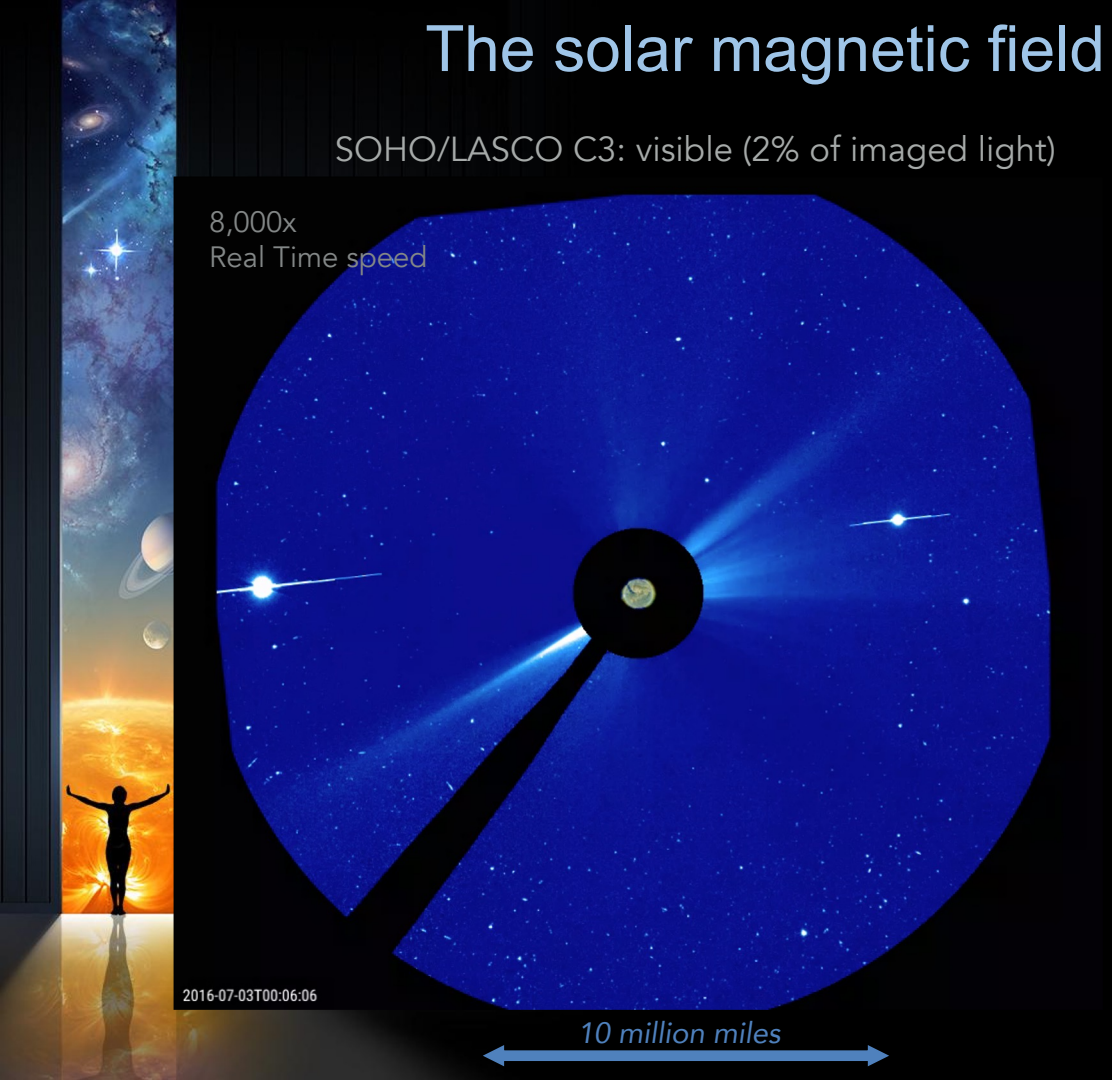
Understanding the source of the solar wind



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?

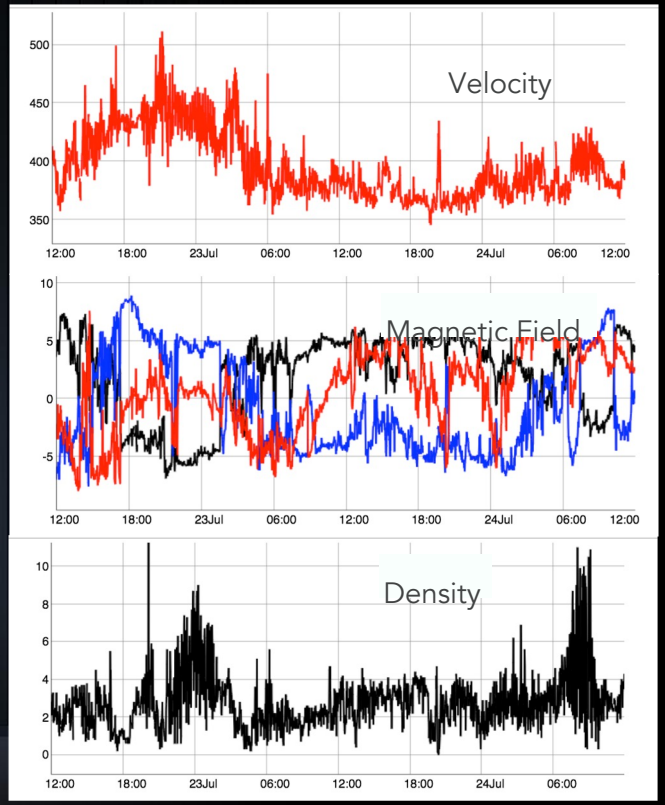
The solar magnetic field is complex



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



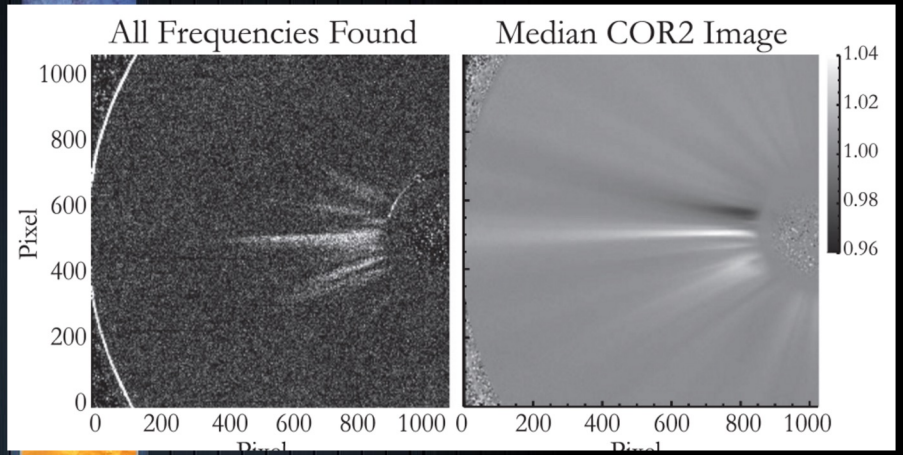
In situ observations have shown how the slow solar wind, in particular, exhibits tremendous multi-scale structure. This heralds an apparent return to complex, fine-scale features.

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

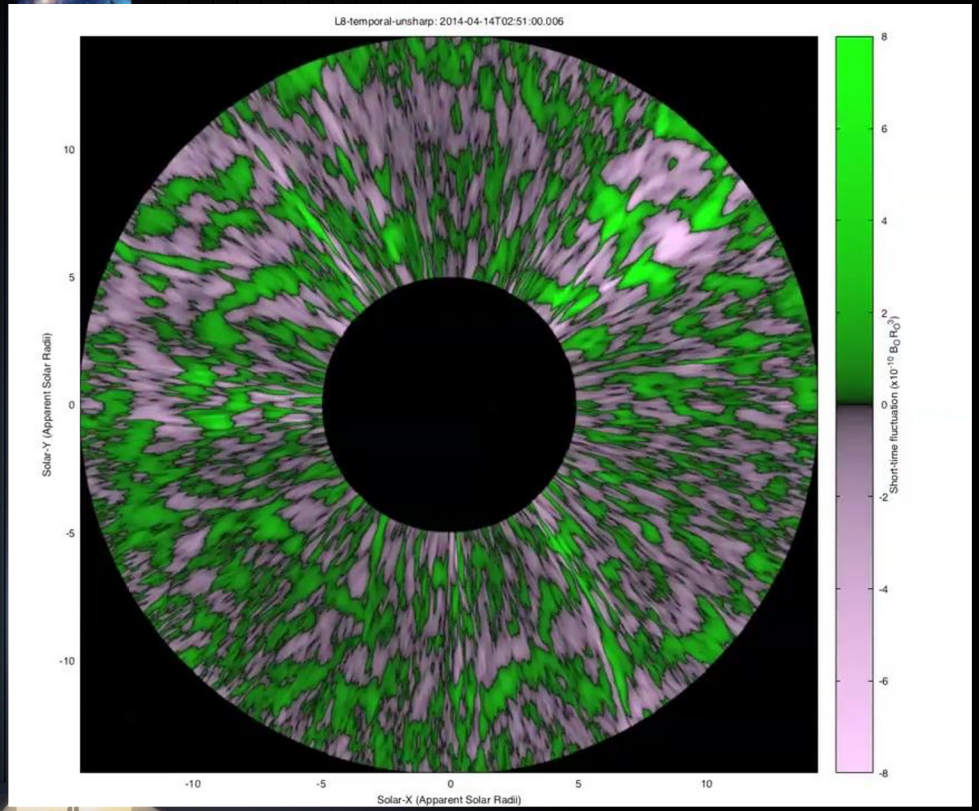


If you watch a movie you can see variations and flows.

- 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



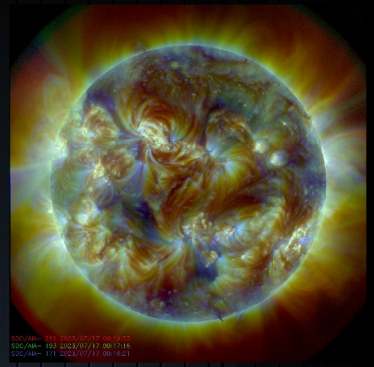
Now this looks like what we were expecting!

- 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)

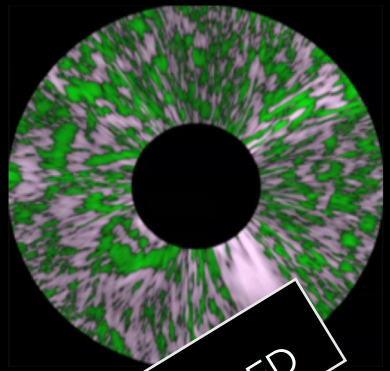
COR2 campaign data filtered with comoving Gaussian mask (DeForest et al., 2018)

Understanding the source of the solar wind



Inner corona

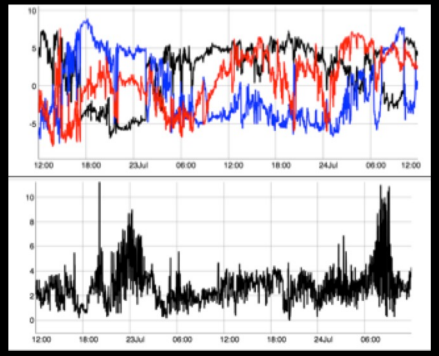
"Complex"



Out

REALLY COMPLICATED

(??)



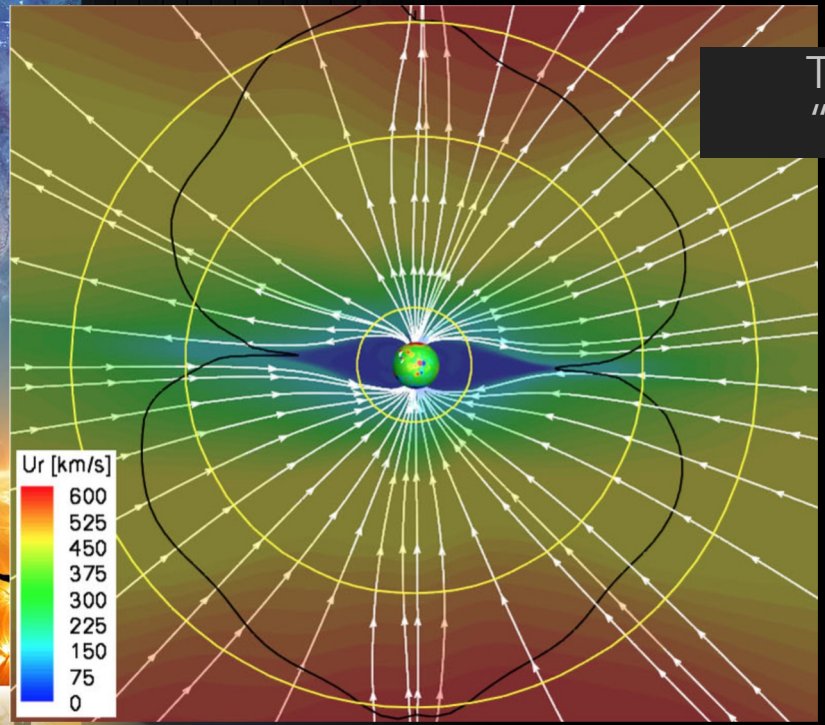
SW/Heliosphere

"Complex"

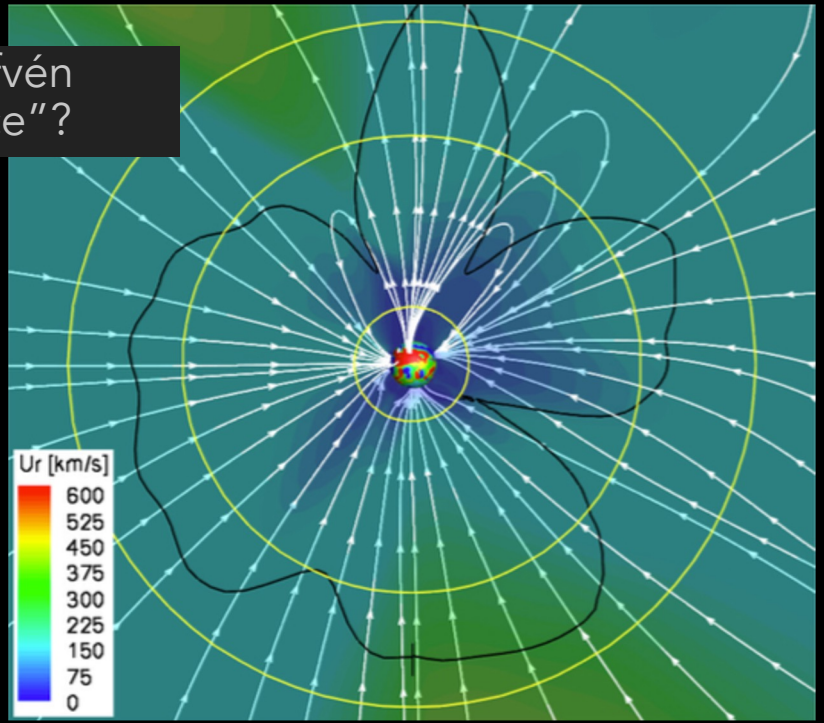
The outer corona only *appears* to be simple because of the way it is commonly observed (integrating density structures along the line of sight).

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

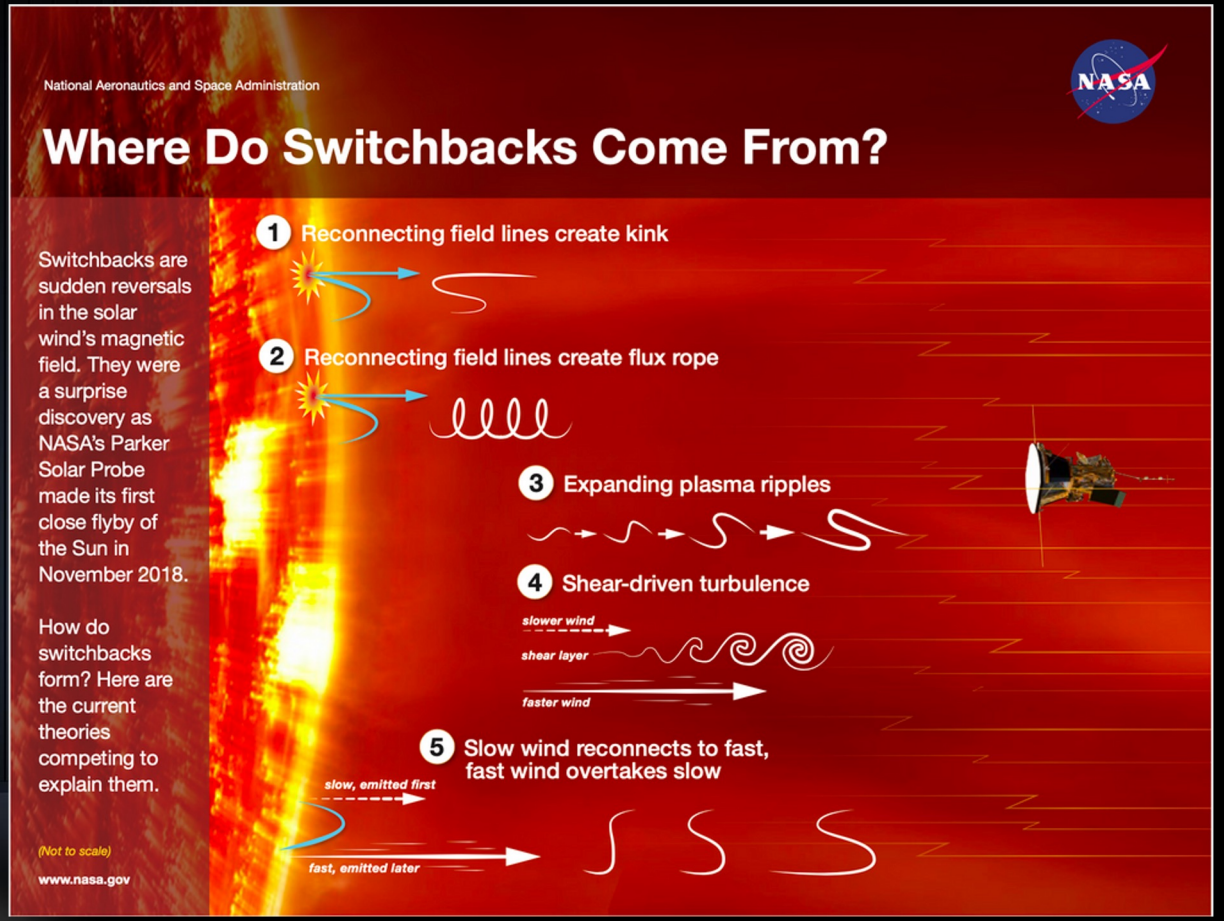


The Alfvén "surface"?



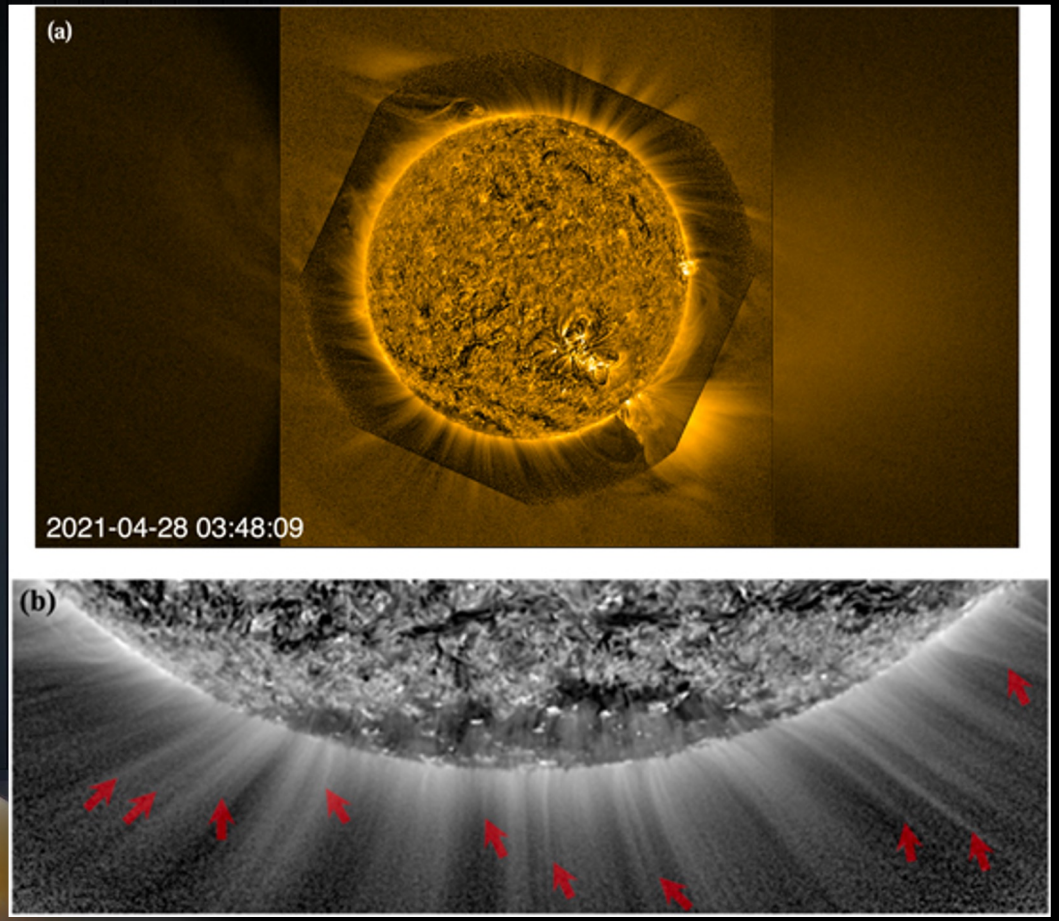
Alfvén surface model: Cohen 2015

Understanding the source of the solar wind



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

Understanding the source of the solar wind



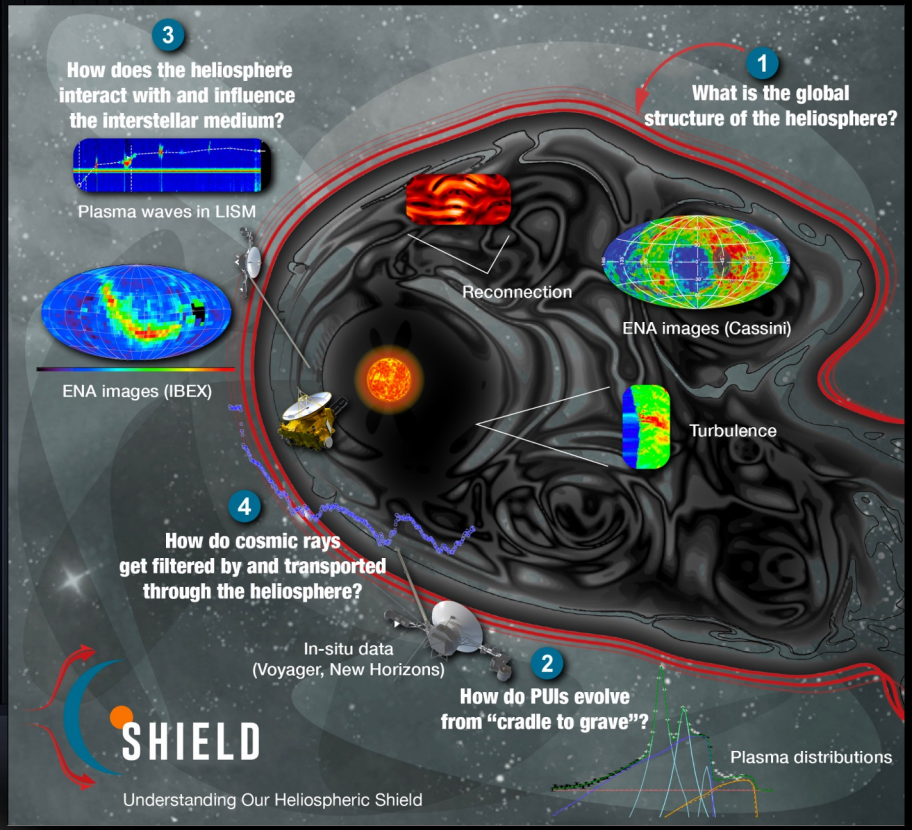
Raouafi et al., 2023:

“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!



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More important science to come!

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