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Solar wind driving of the radiation belts

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International School of Space Science
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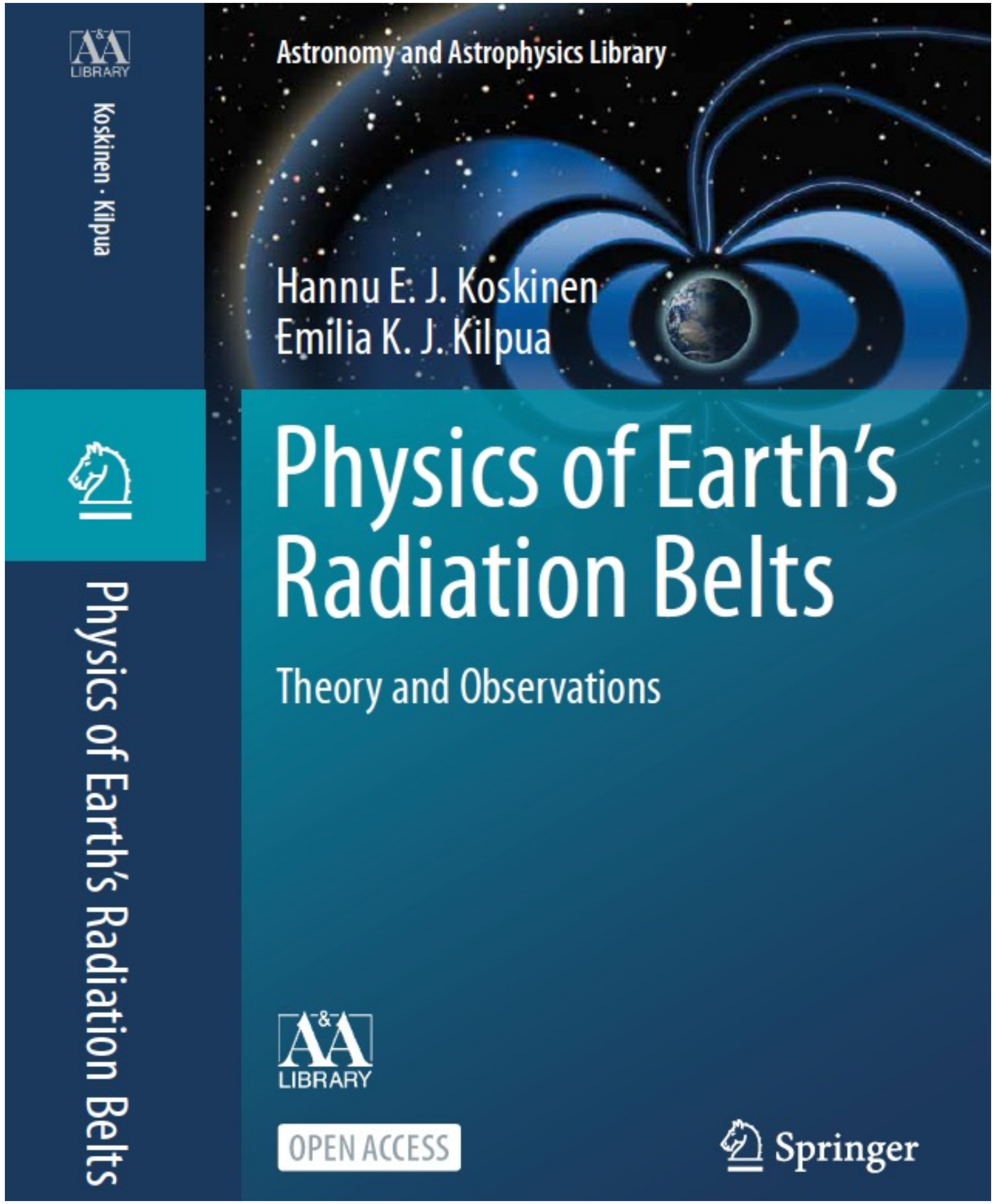

https://link.springer.com/book/10.1007/978-3-030-82167-8

Fully open access text book of the physics, theory and observations of radiation belts

Two review papers on solar wind drivers

Kilpua, E.K.J., H.E.J. Koskinen, H.E.J., T.I. Pulkkinen, Coronal mass ejections and their sheath regions in interplanetary space, Living Reviews in Solar Physics, 2017

Kilpua, E.K.J., A. Balogh, R. von Steiger, and Y. Liu, Geoeffective Properties of Solar Transients and Stream Interaction Regions, Space Sci. Review, 2017 (ISSI workshop in Bern, June 2016)

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Part 1: Solar wind drivers

Part 2: Radiation belt response

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Part 1: Structure

- General words about radiation belts and near-Earth space
- High-speed streams and stream interaction regions
- Coronal mass ejections
- Geomagnetic storms caused by them

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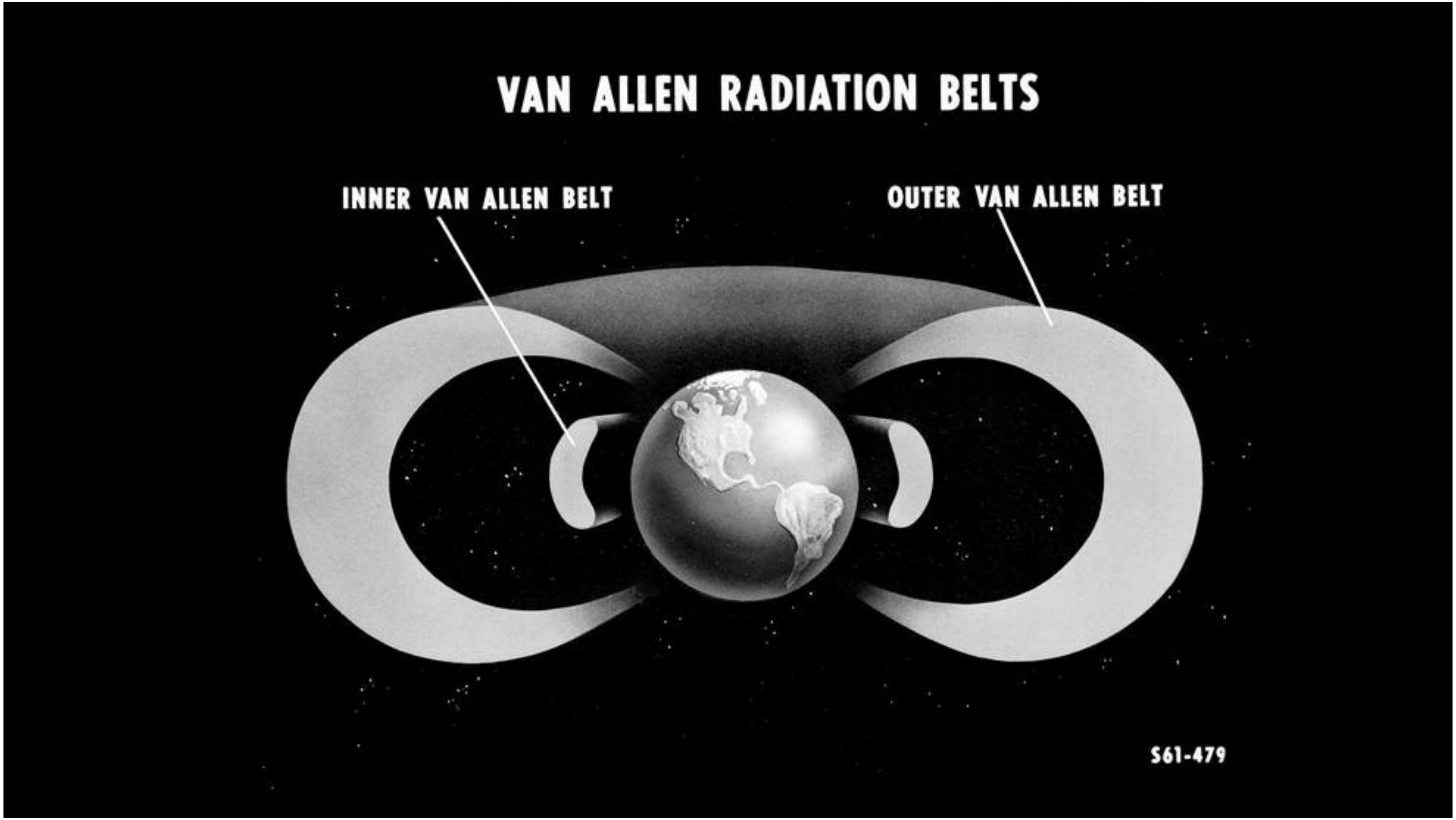

Credits: NASA's Goddard Space Flight Center/NASA’s Langley Research Center

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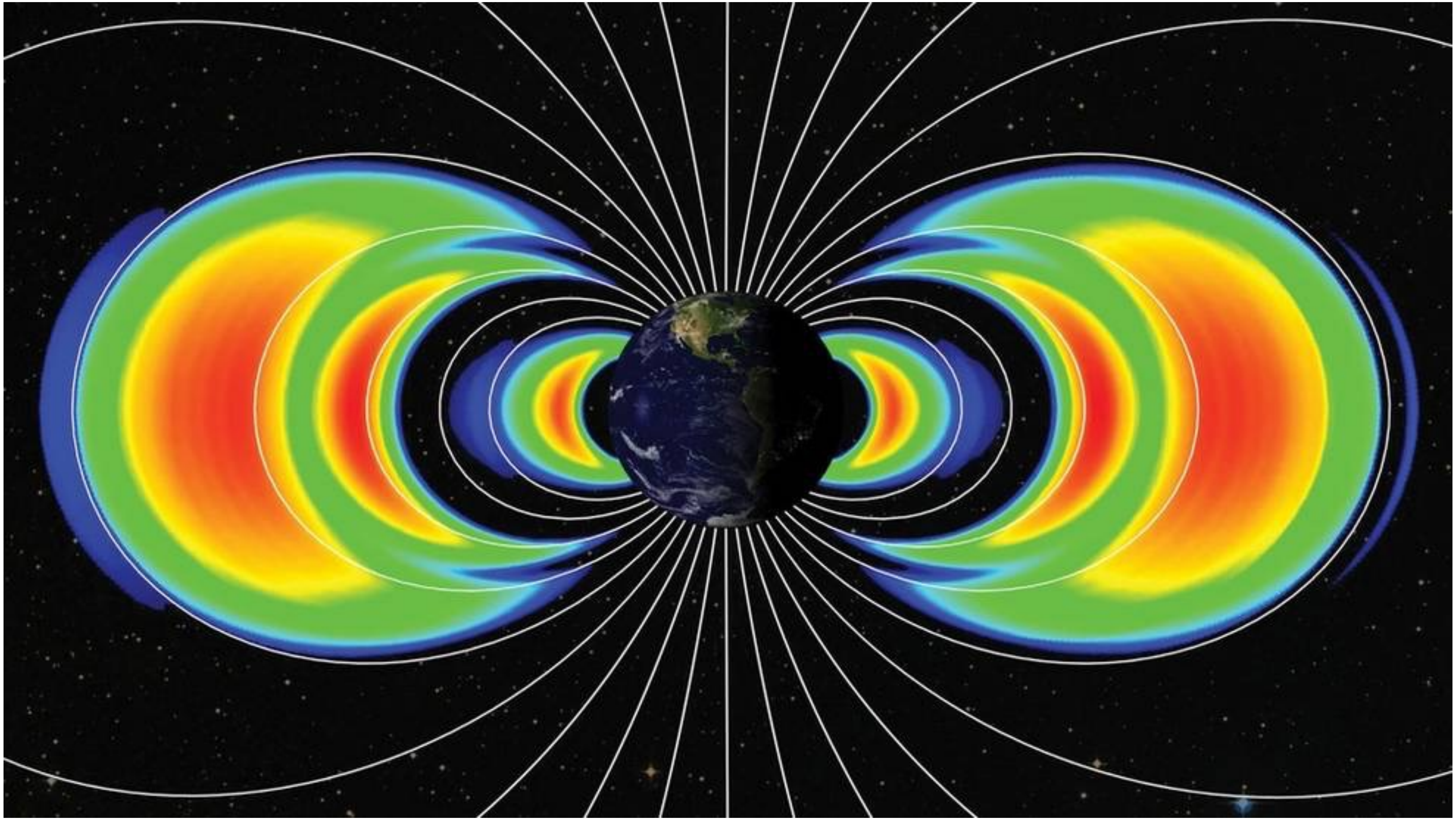

Credits: NASA's Goddard Space Flight Center/Johns Hopkins University, Applied Physics Laboratory

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Radiation belts are ultimately driven by the changing Sun and the variable solar wind with embedded eruptions

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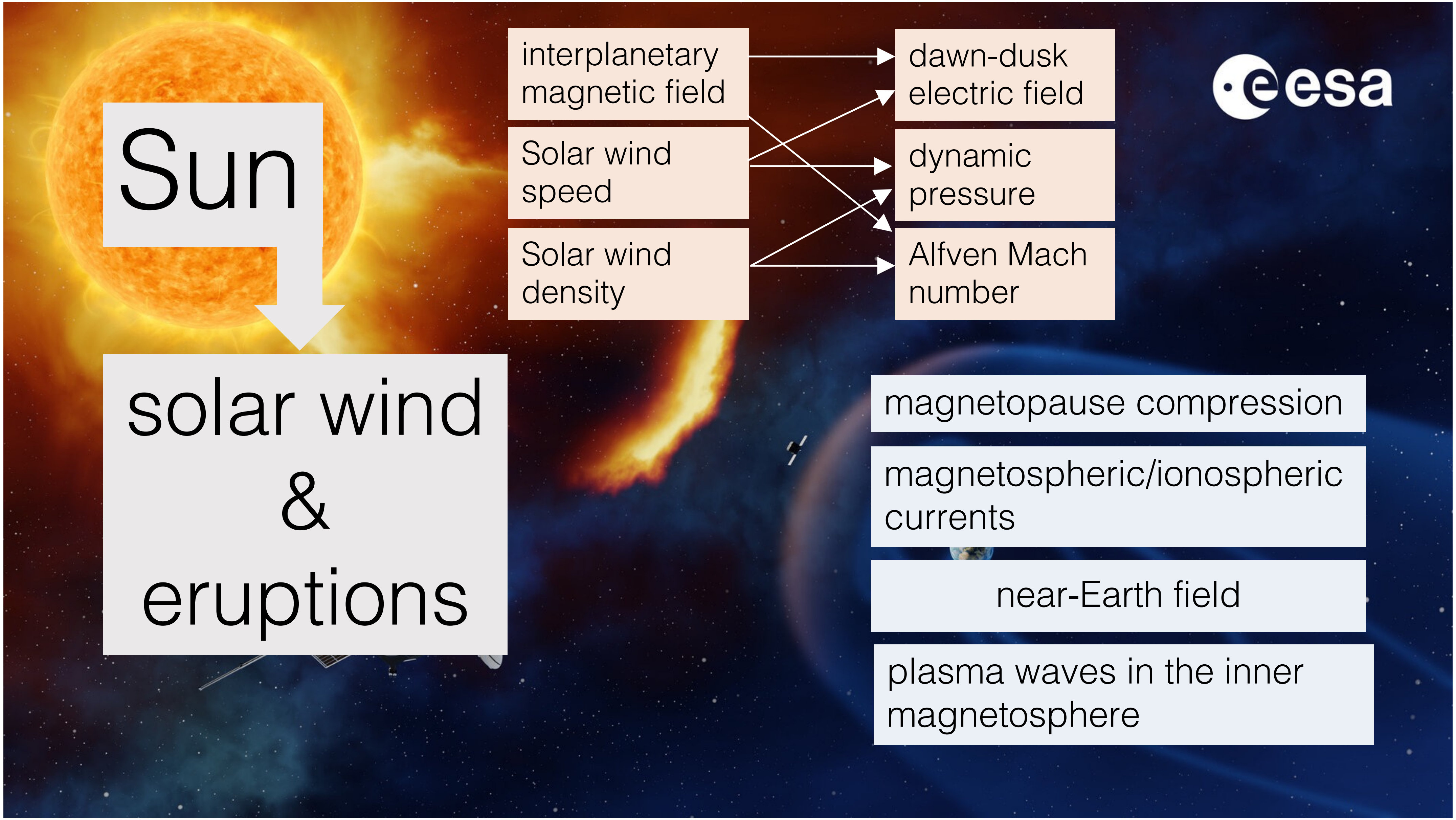

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Solar wind is not completely random. It consist of the streams and embedded eruptions from the Sun. Their properties vary with solar cycle.

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What are key large-scale heliospheric structures that force significantly the Earth’s magnetoshere?

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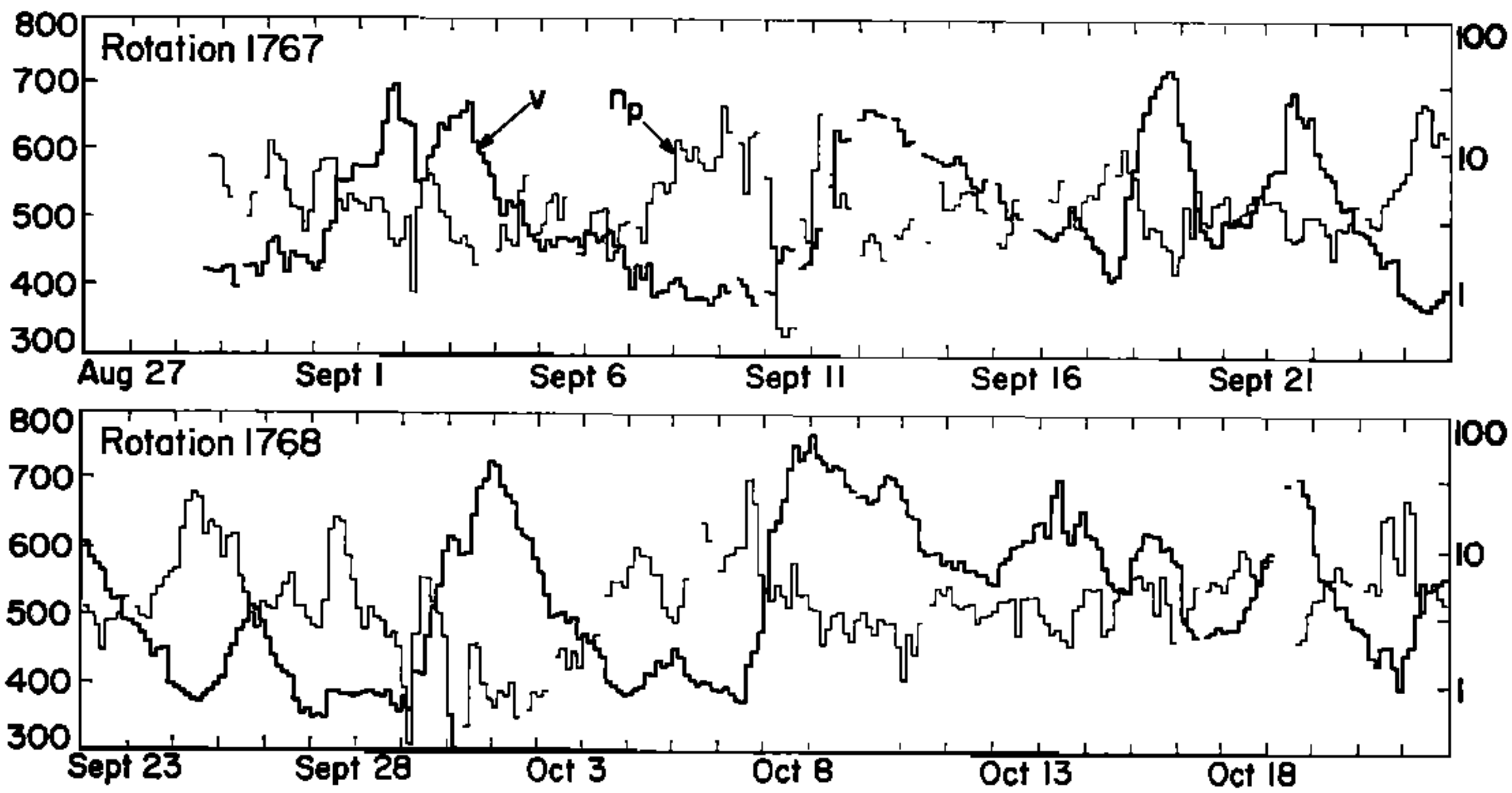

speed

density

Neugebauer & Snyder, 1962

Mariner 2 (launched in 1962) confirmed the existence of a continuous solar wind as suggested by Eugene Parker a few years earlier. This first extensive data of the solar wind already showed fast streams repeating in approximately 27-days usually preceded by high density.

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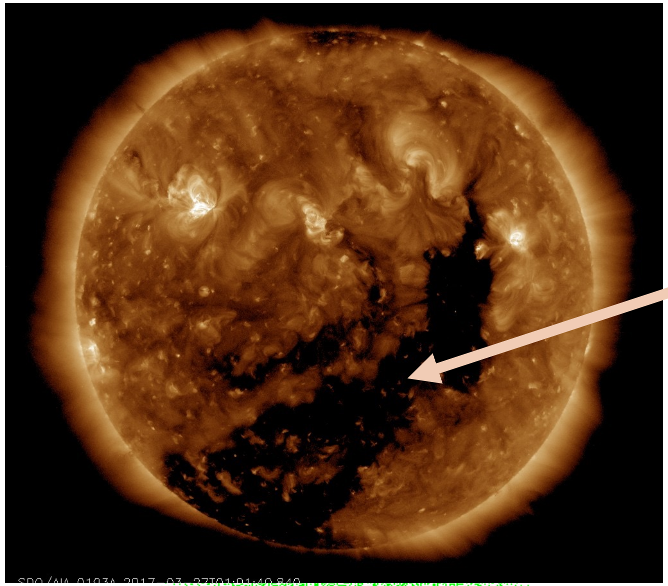

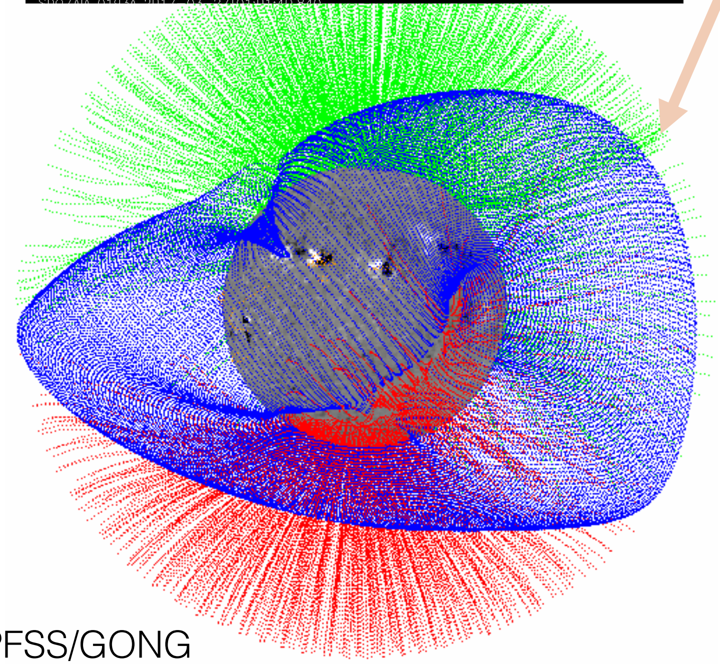

PFSS/GONG

<u>Fast wind($\gtrsim$ 550 km/s):</u> Origin from large coronal holes where the magnetic field lines are open to the heliosphere. It has generally low density, high temperature and large amplitude, low-frequency Alfvén waves embedded (observed first by Mariner 2) that originate from the photosphere.

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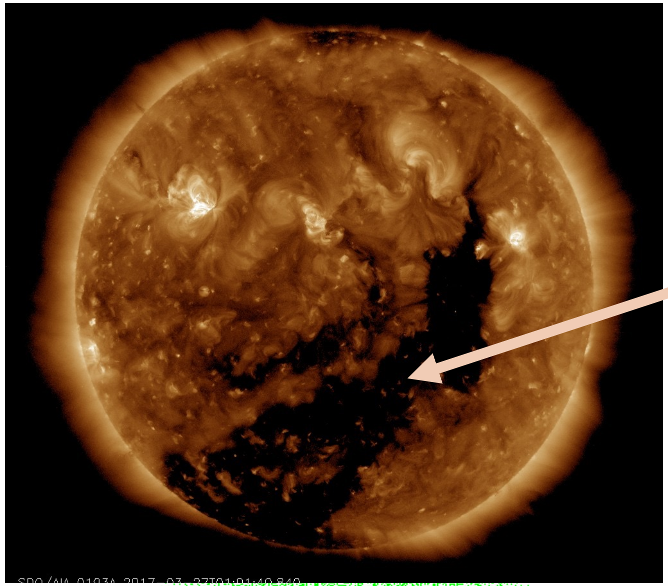

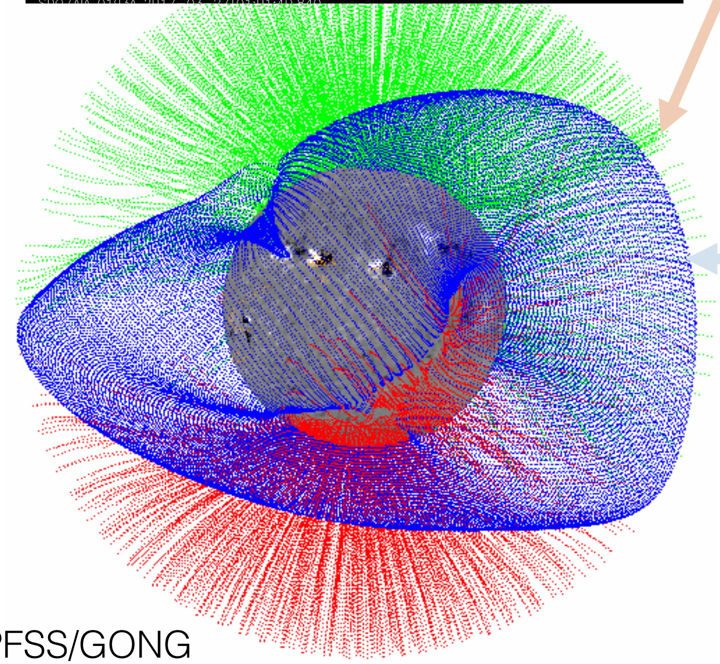

PFSS/GONG

<u>Fast wind(≳ 550 km/s):</u> Origin from large coronal holes where the magnetic field lines are open to the heliosphere. It has generally low density, high temperature and large amplitude, low-frequency Alfvén waves embedded (observed first by Mariner 2) that originate from the photosphere.

<u>Slow wind (≲ 550 km/s):</u> The origin is less clear. It is connected to the closed field lines of the streamer belt (released by magnetic reconnection), boundaries of coronal holes and/or active region outflows. The slow wind has higher density and lower temperature and is more variable than the fast wind.

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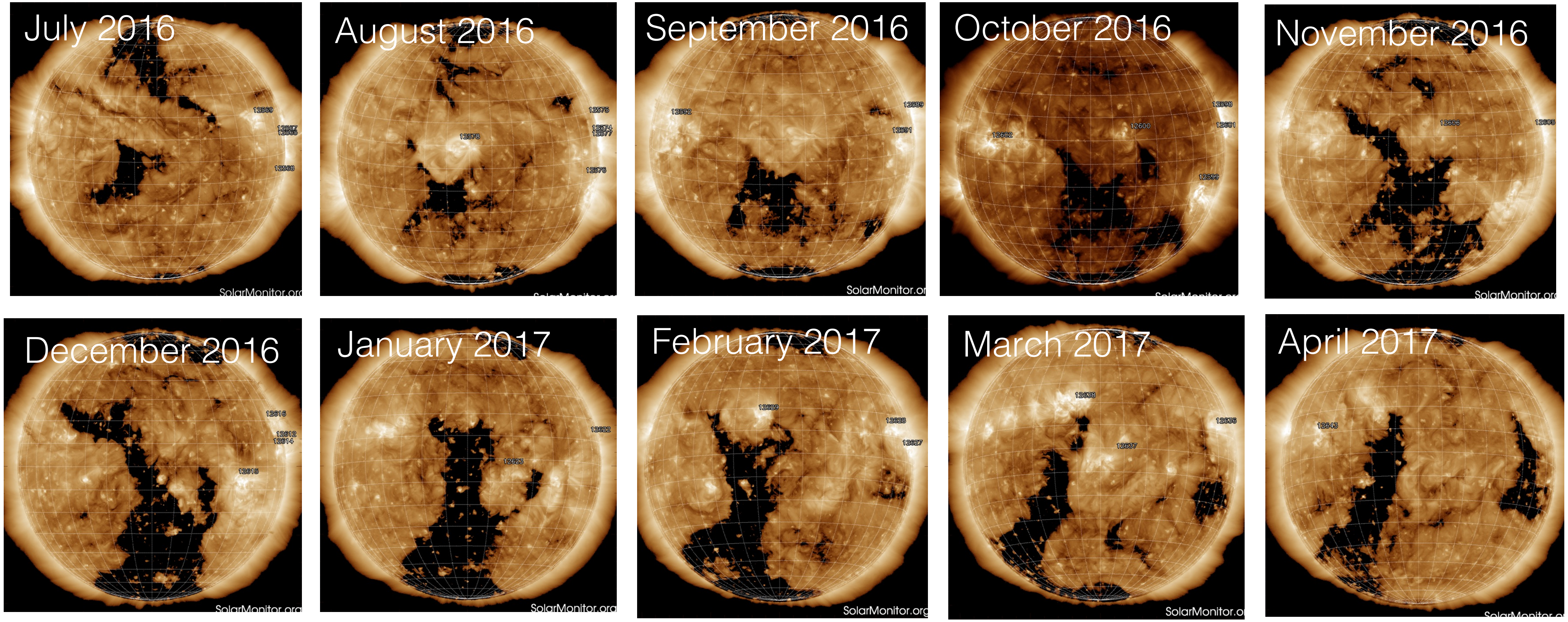

Coronal holes are long-lived structures that evolve relatively slowly (over several months) → fast streams sweep past us in ~27 intervals (several large coronal holes may exist)

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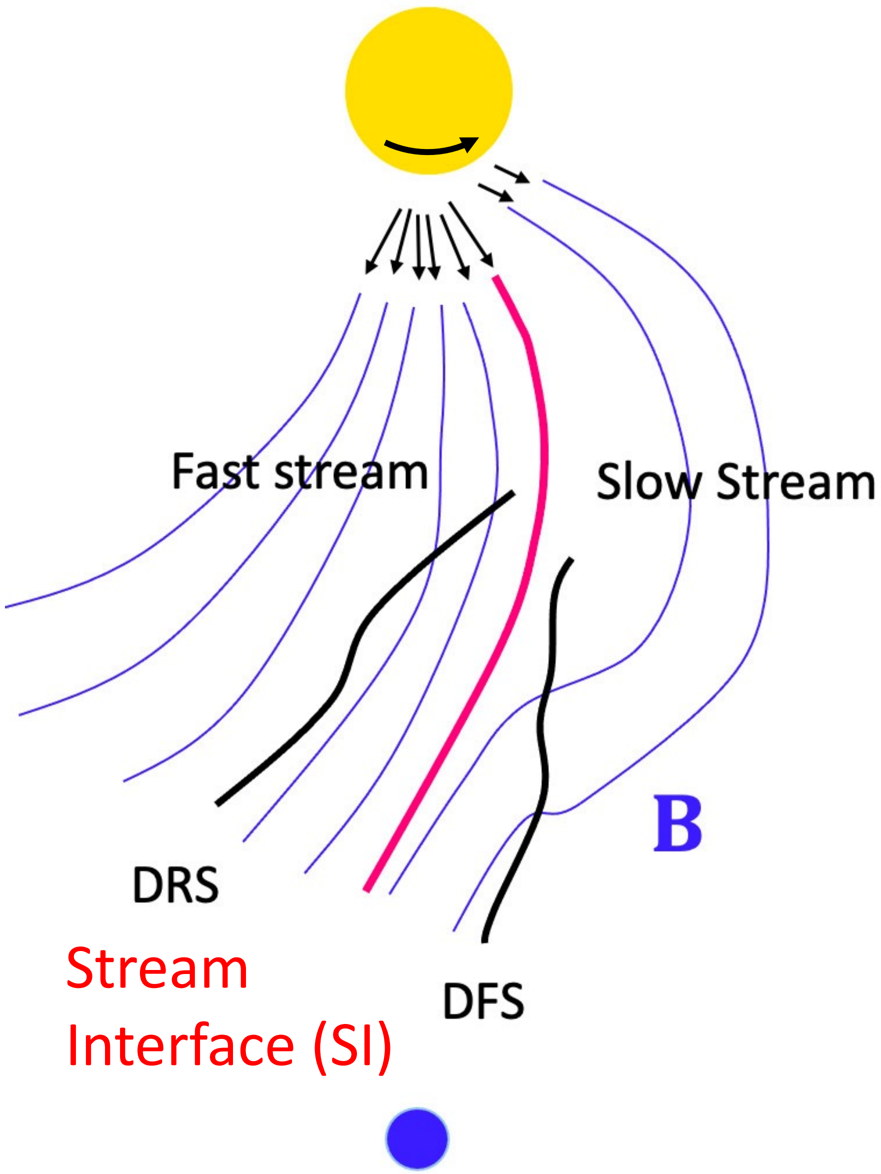

When a fast solar wind stream crashes the slow wind ahead a compressive region forms

Key structures

- Fast shock/developing shock*
- Slow-fast stream interaction region (SIR): ~1 day
- Stream Interface (SI) within a SIR separating the slow and fast wind
- Fast reverse shock/developing shock*
- Faster stream: ~several days (not all SIRs are followed by a fast stream, but there is a speed gradient)

*typically not fully developed at Earth's orbit

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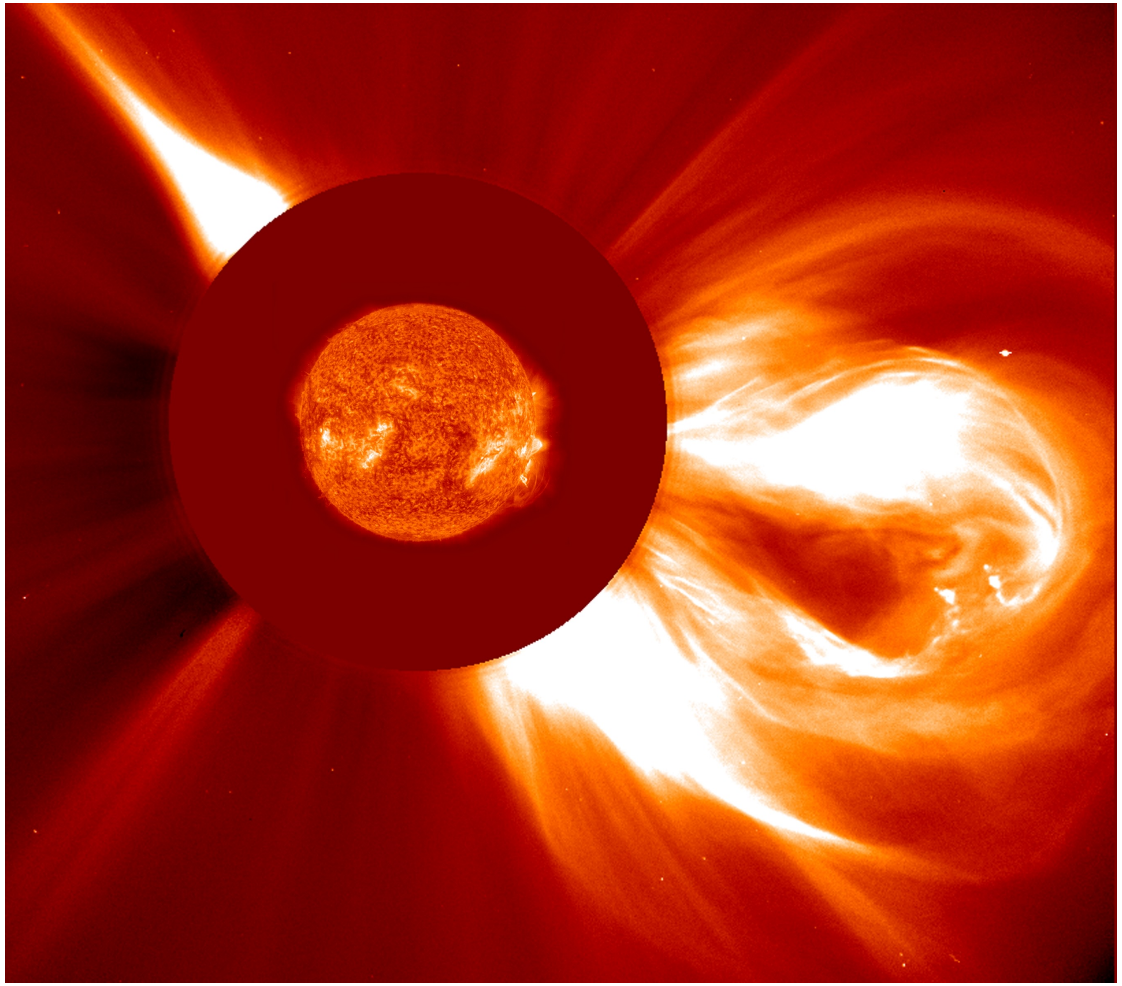

Coronal Mass Ejections (CMEs) were found in1970s when the first coronagraphs flew in space.

CMEs are huge eruptions of plasma ($1–2\times10^{12}$ kg) and magnetic field from the Sun at speeds ranging up to 2000 km/s.

Most CMEs originate from active regions at the Sun

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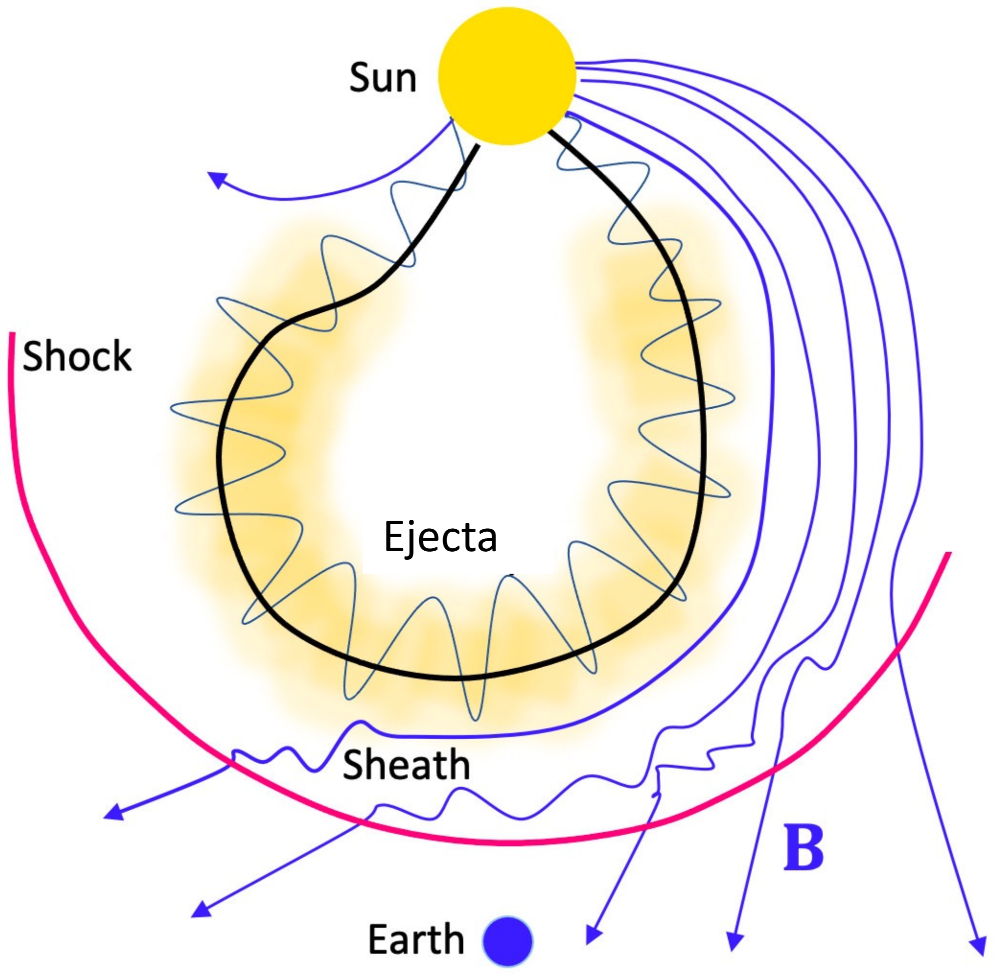

CMEs propagate into interplanetary space and are called interplanetary CMEs (ICMEs). They reach the Earth orbit (1 AU) in 1-5 days

ICMEs consist of three main parts

- Shock
- Sheath: ~9 hours/0.1 AU
- Ejecta ~1 day/0.3 AU

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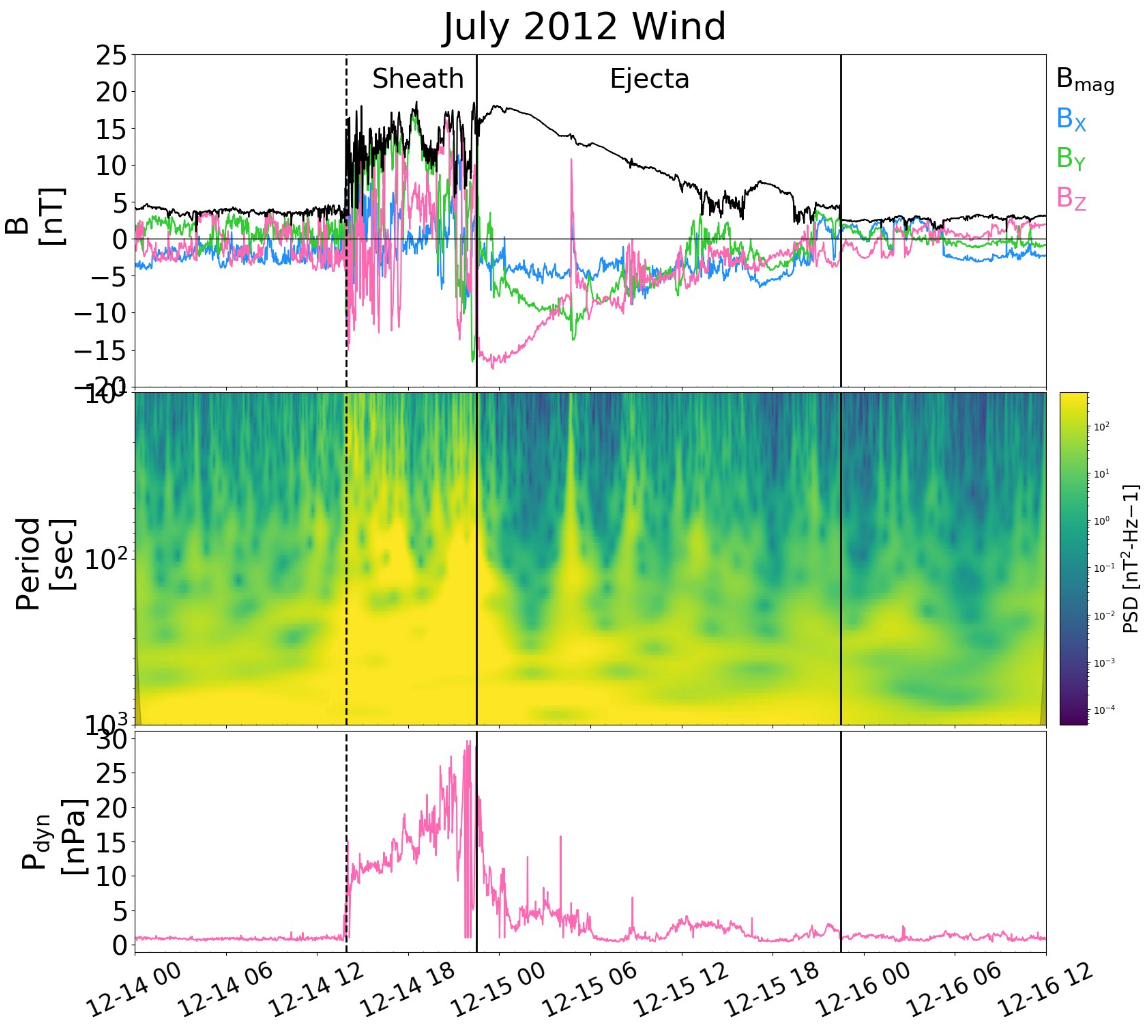

sheath

- highly variable field
- high dynamic pressure

ejecta

- smoothly changing field
- low dynamic pressure

magnetic cloud

- high magnetic field ($\gtrsim$ 10 nT)
- smooth field rotation
- low plasma beta (< 0.1)

Sheath and ejecta/magnetic cloud have distinctly different properties!

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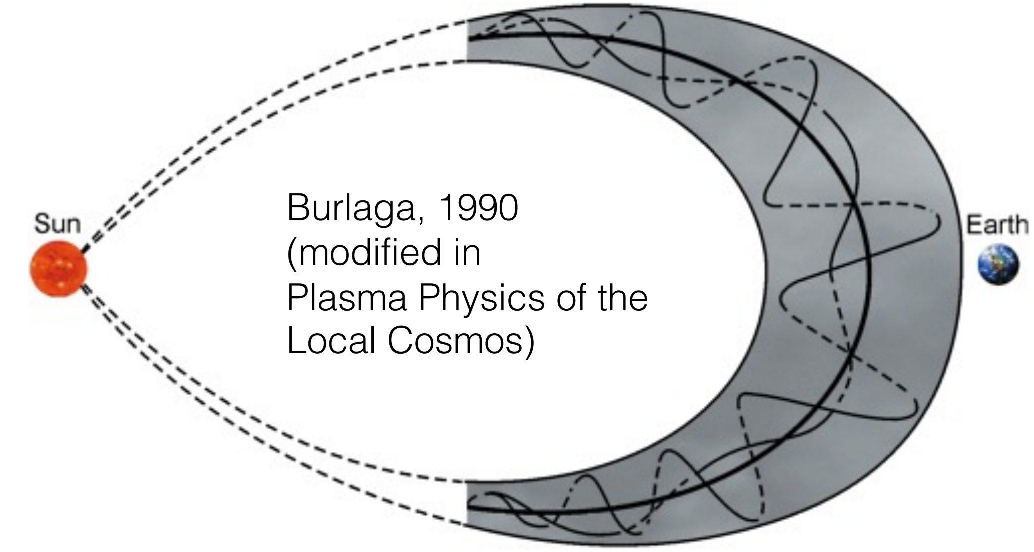
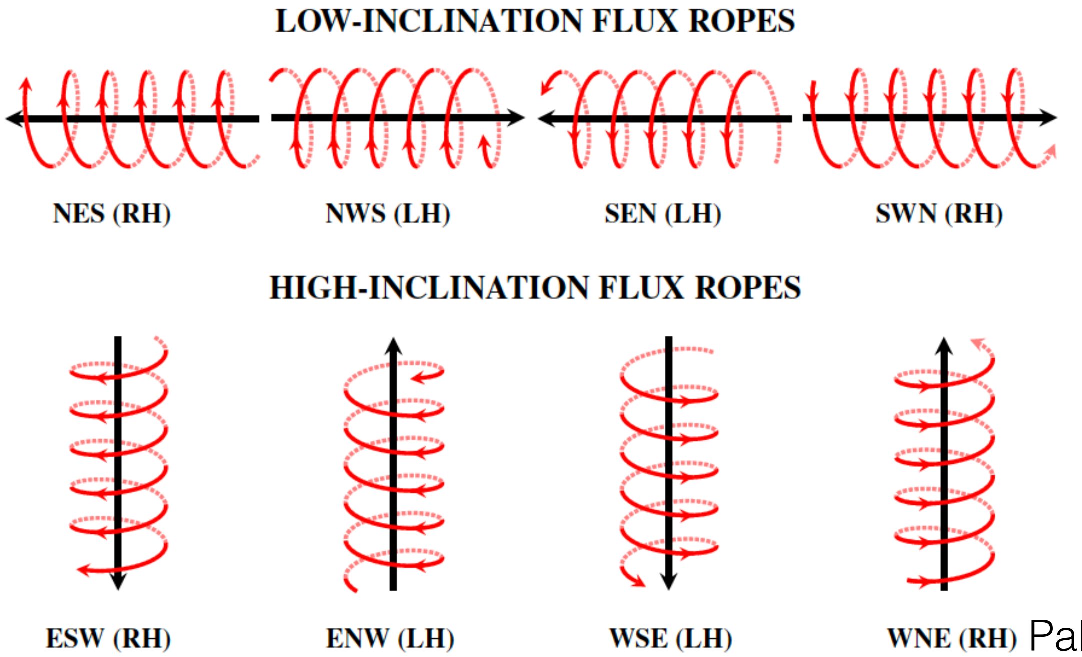


Burlaga, 1990 (modified in Plasma Physics of the Local Cosmos)



Palmerio et al., 2018

Underlying configuration of a magnetic cloud is a magnetic flux rope.

The way the field rotates within a flux rope varies depending on the

- magnetic helicity sign
- direction of the axial field
- tilt of the axis

Dominant flux rope types vary with solar activity cycle and 22-year magnetic cycle

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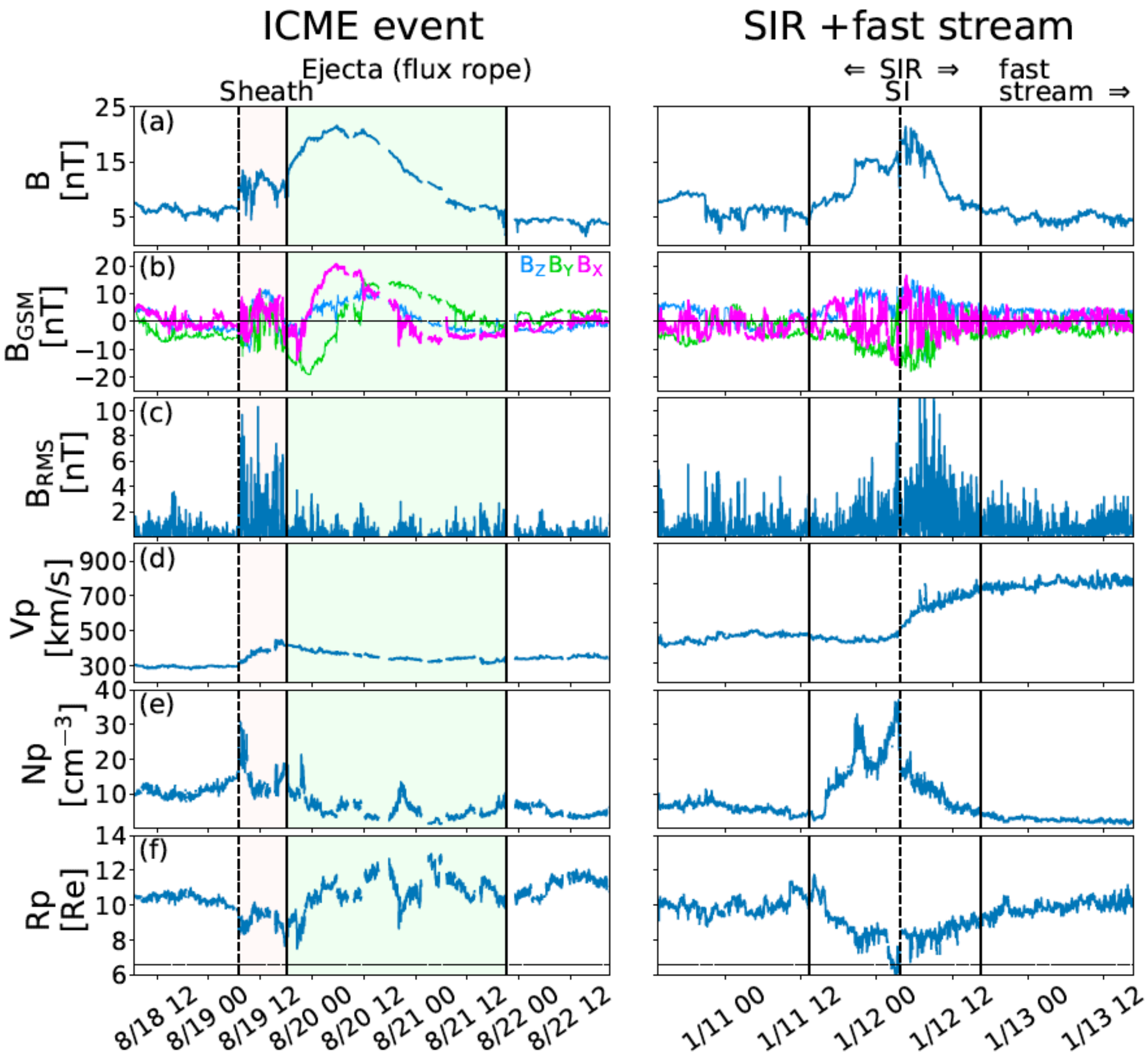

Ejecta (flux rope) and fast streams have smoother variations

Sheaths and SIRs are compressive structures and their properties can vary on short time-scales

→ variable solar wind forcing conditions

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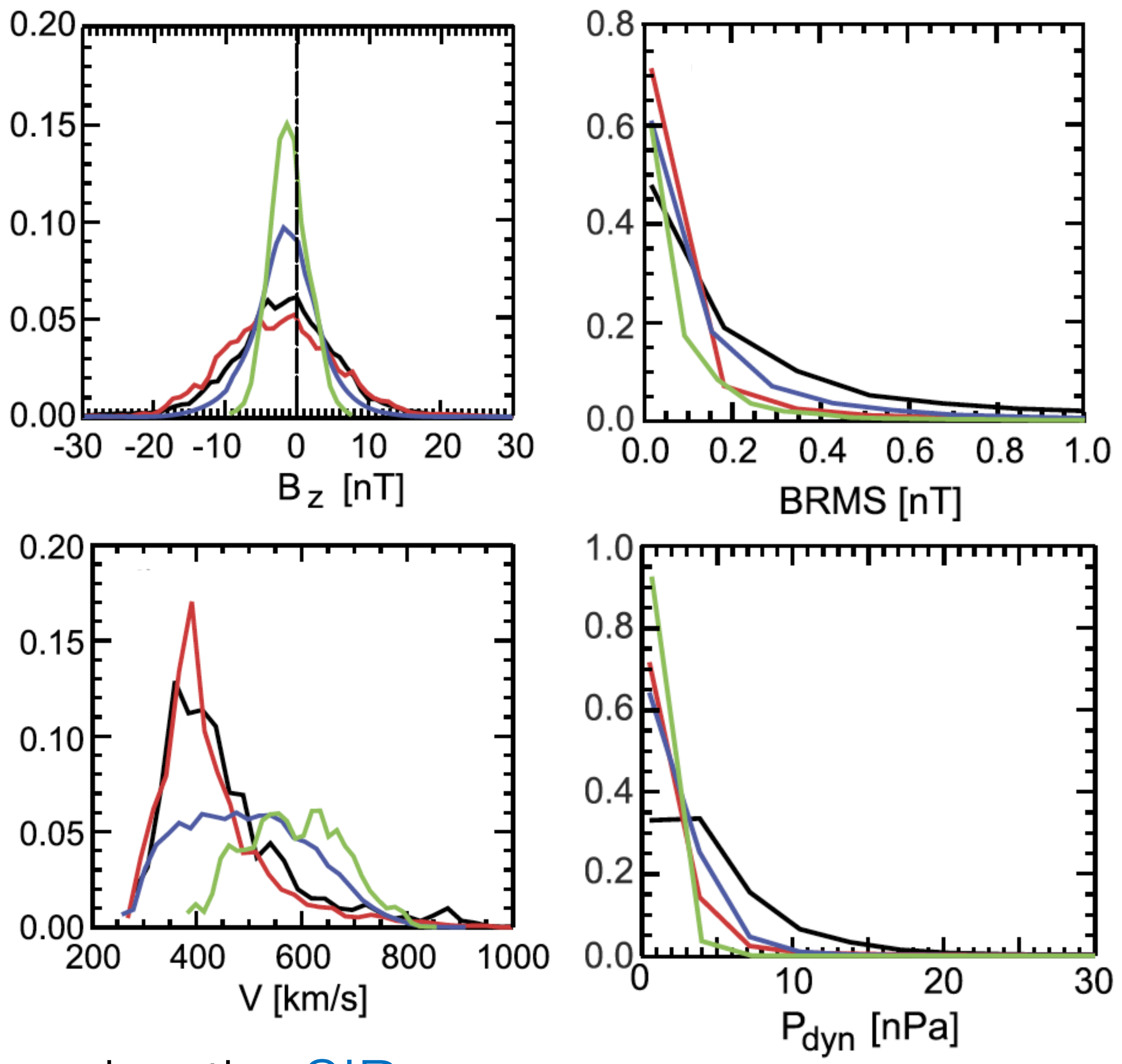

sheath SIR
ejecta Fast stream

Kilpua et al., SSR, 2017

ICMEs and sheaths cause the strongest magnetic fields in the solar wind

Sheaths and SIRs have clearly the highest dynamic pressure and field variability

→ large spread of solar wind parameters influencing the Earth

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slow wind | fast wind | shock | sheath | ejecta

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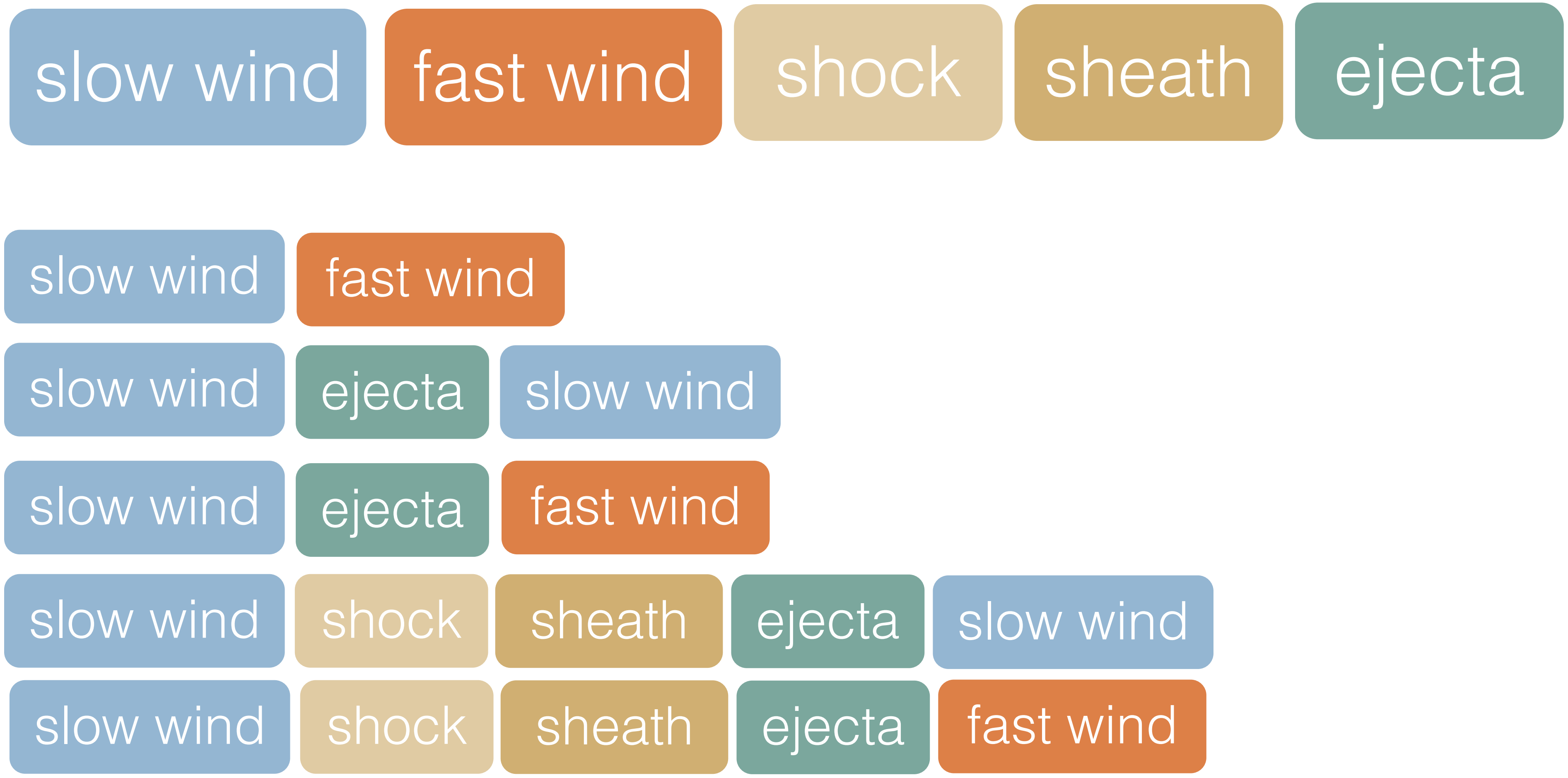

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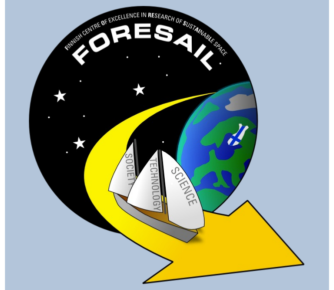

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slow wind | shock | sheath | ejecta | shock | sheath | ejecta | ETC.

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slow wind | fast wind | shock | sheath | ejecta

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→ ICMEs can also interact with each other!

→ Solar wind forcing vary considerably depending on what Sun provides us

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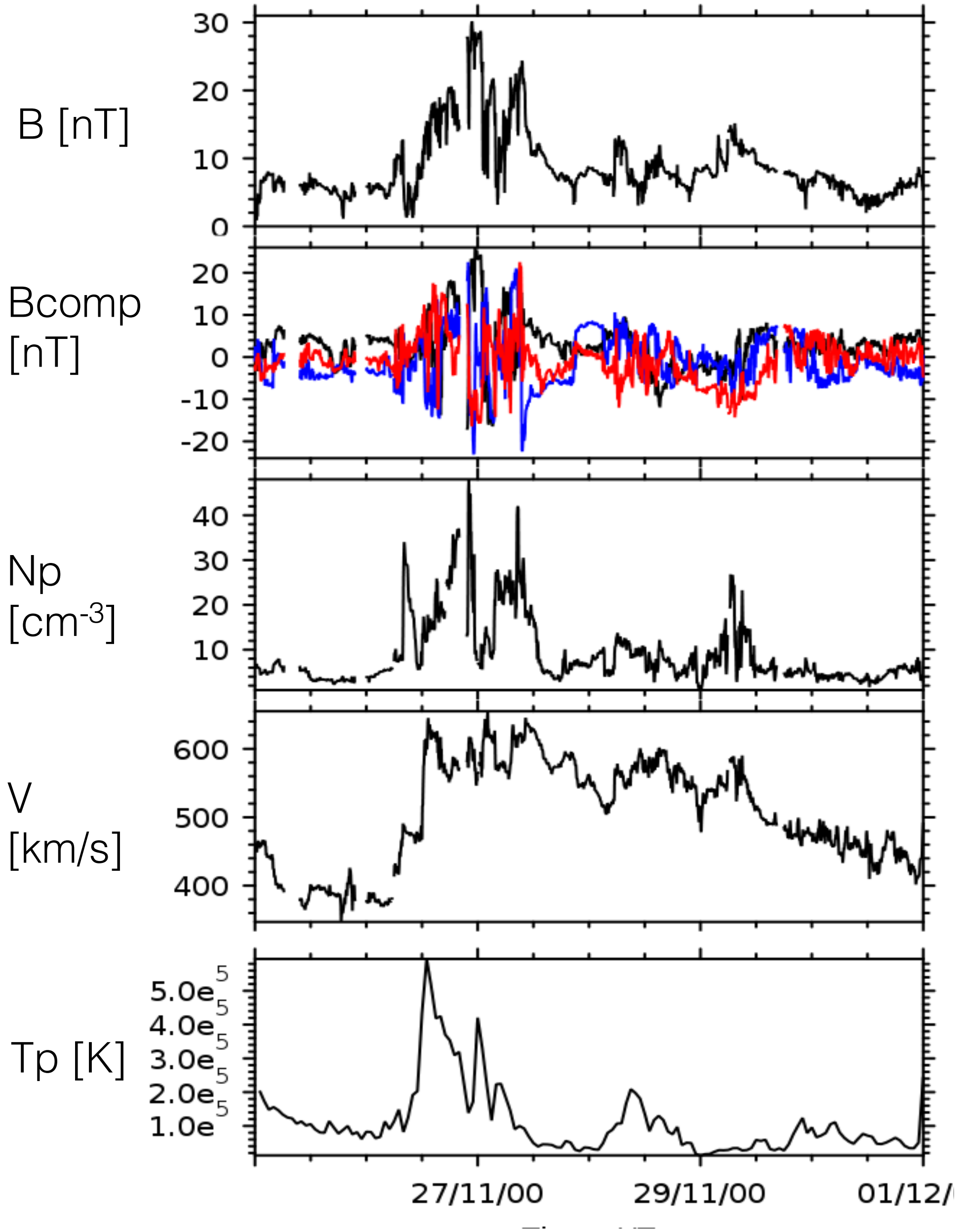

Interactions between ICMEs can result into a complex ejecta where individual characteristics may be lost. The results depend on the relative speed, direction and magnetic field configuration of the ICMEs.

→ Unpredictable, variable and sustained solar wind forcing

← In late November 2000 several successive ICMEs merged on their way from Sun to Earth. Multiple shocks detected, but individual ICMEs cannot be distinguished. (Burlaga et al. 2002)

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How does the occurrence of ICMEs and SIRs vary with solar activity cycle?

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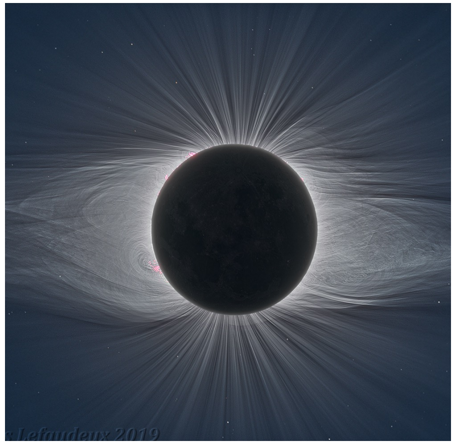
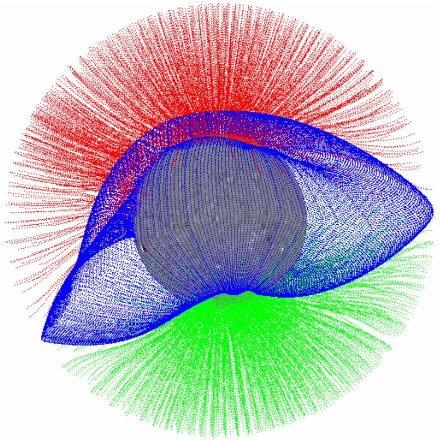
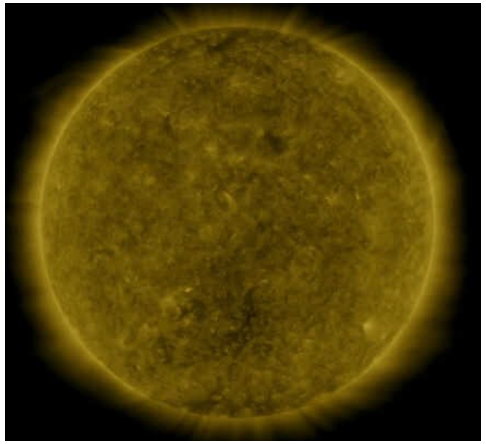
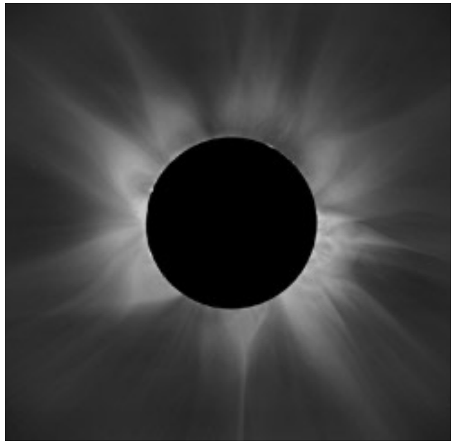
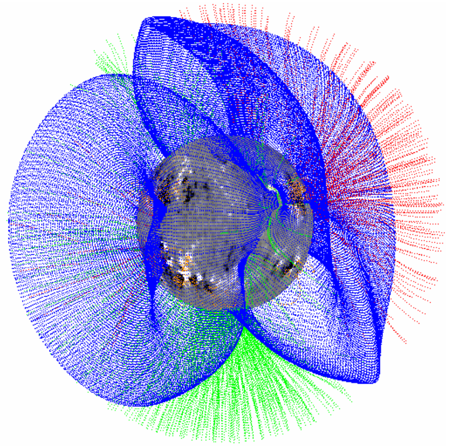
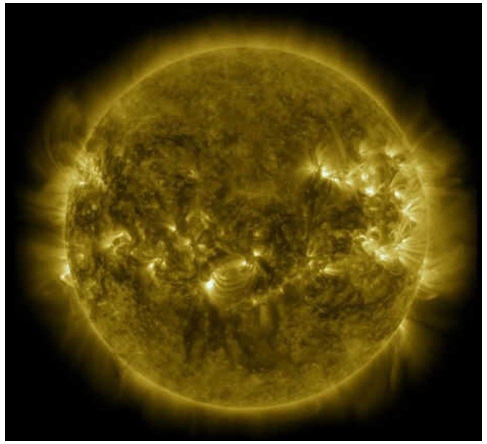




solar minimum

solar maximum

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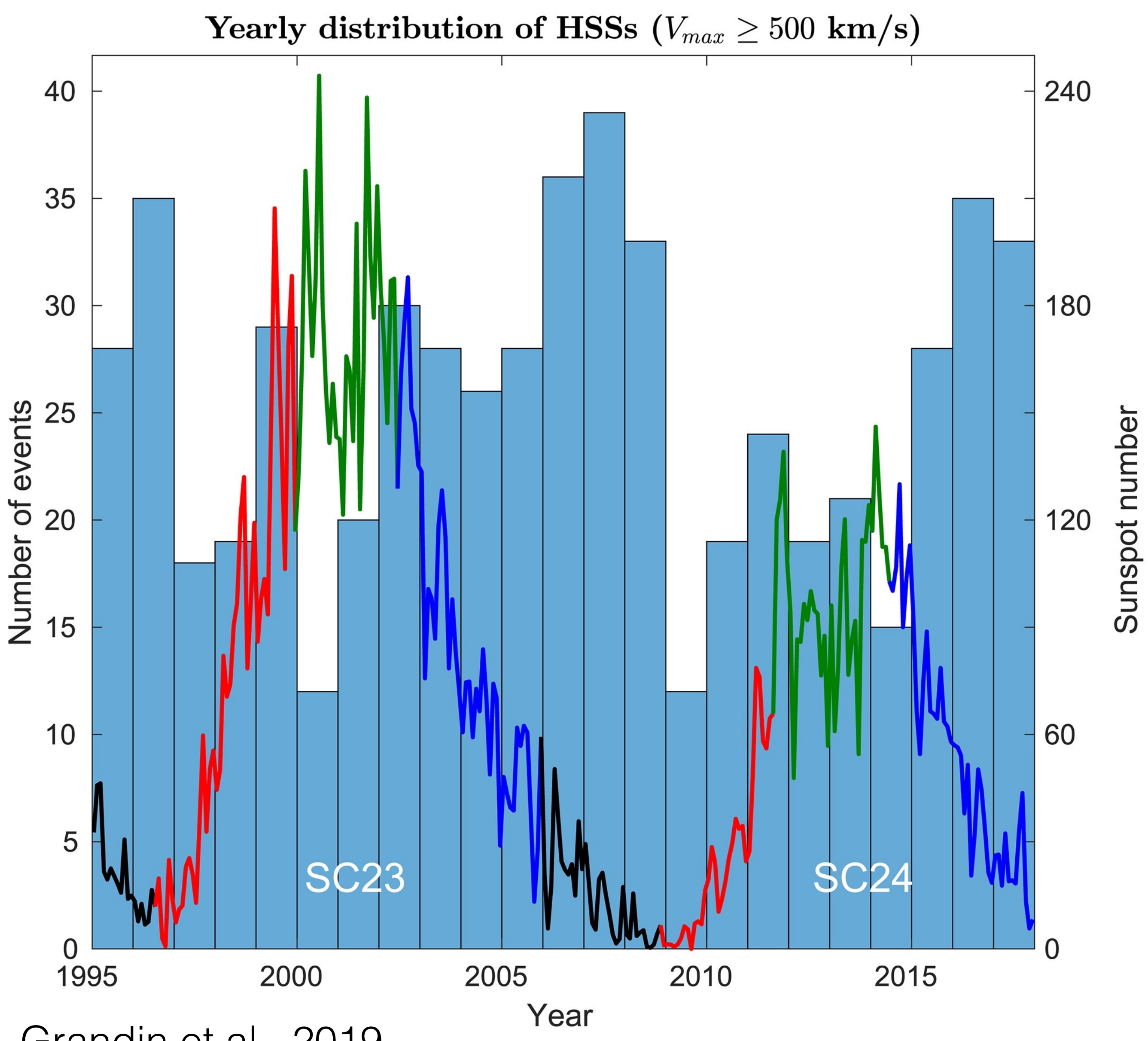

Grandin et al., 2019

Fast streams (and thus SIRs) are the most frequent during the late declining phase of solar activity cycle

This is due to the presence of large polar coronal holes that extend to the equator and beyond

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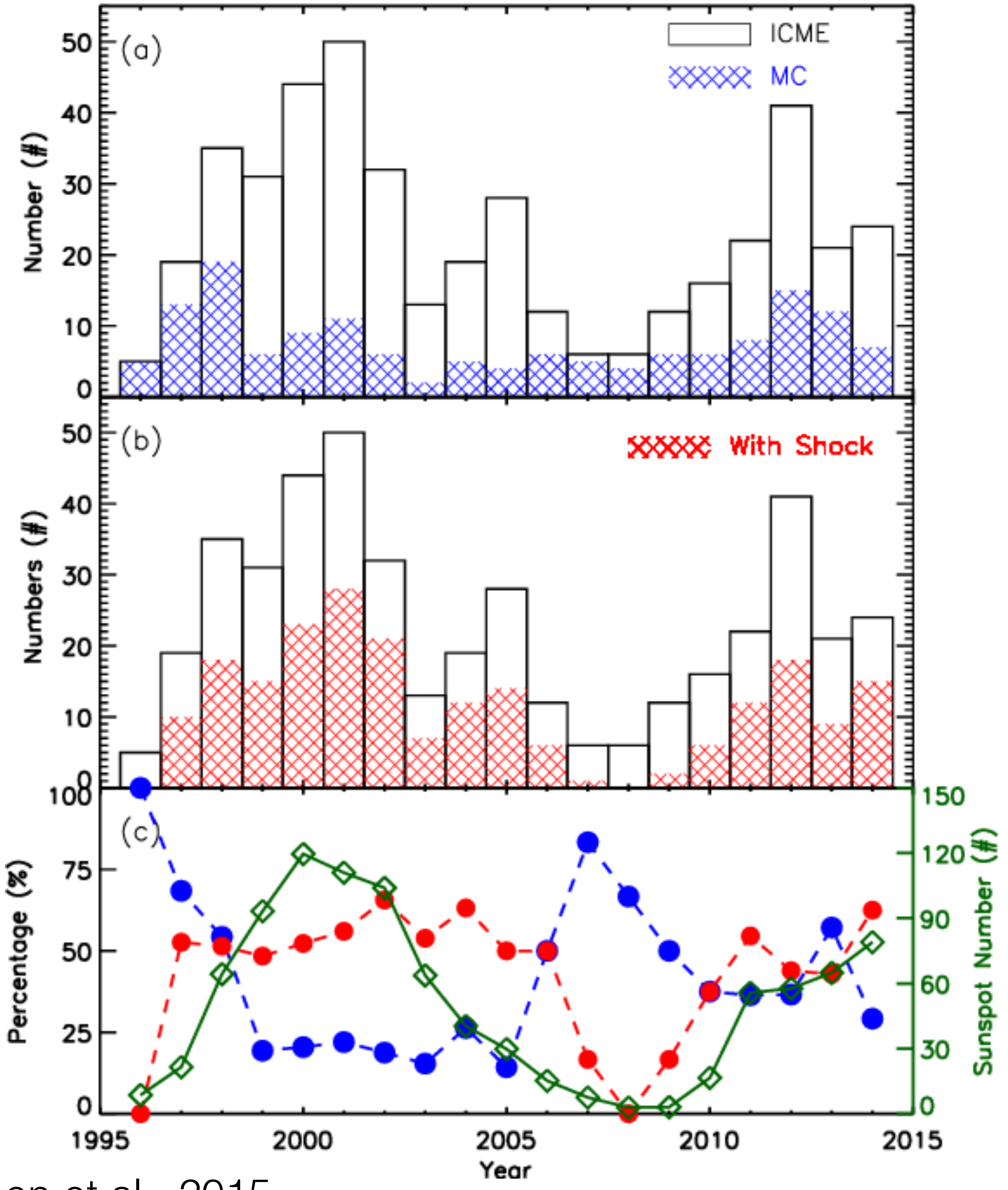

Shen et al., 2015

ICMEs and shock-driving ICMEs are clearly more frequent at the times of high solar activity

Fraction of magnetic clouds anti-correlates with solar activity → ICMEs have a more complex structure at solar maximum (on average about one-third of ICMEs are magnetic clouds)

a) annual rate of all ICMEs and magnetic clouds
b) ICMEs and ICMEs driving the shock
c) ratio of magnetic clouds to all ICMEs and ratio of ICMEs driving a shock to all ICMEs with the sunspot number

● ratio magnetic clouds to all ICMEs
● ratio shock driving ICMEs to all ICMEs

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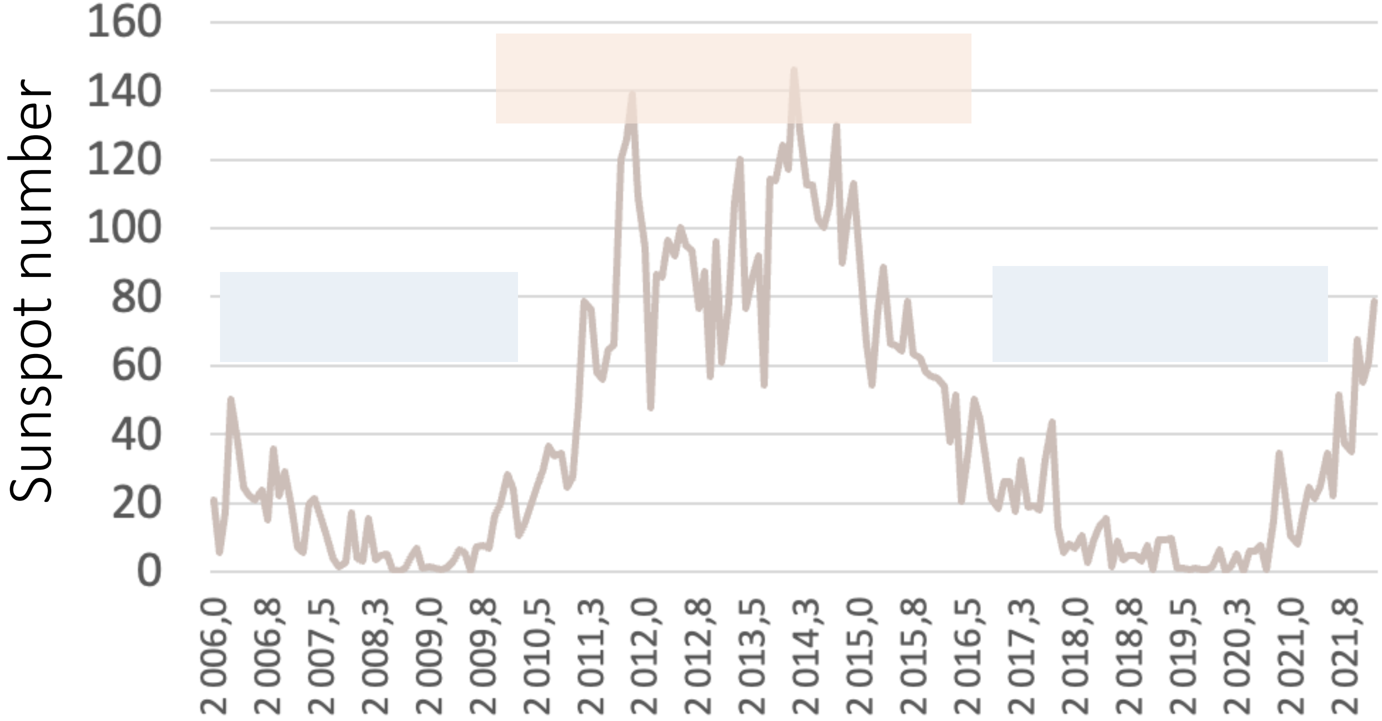

Solar maximum: Sun's global field multipolar

→ Coronal holes found at all latitudes
→ Up to several fast and strong CMEs per day
→ Solar wind at ecliptic is characterised by a complex stream structure with frequent ICMEs

Late declining phase/minimum: Sun's global field close to dipolar

→ Large and extended coronal holes
→ A few slow and weak CMEs (one per week)
→ Fast and slow streams dominate

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What kind of geomagnetic activity ICMEs and SIRs drive? (first a bit introduction to geomagnetic activity)

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Magnetic storm: World-wide depression of magnetic horizontal component at low latitudes (~ north) that lasts from several hours to days. Caused by the near-equatorial ring current. Carried mainly by protons of 20-200 keV at L = 2 – 7 transported and energized as they come from the tail due to enhanced magnetospheric convection.

Substorm: Global disturbances in the Earth's magnetosphere that lasts 2-3 hours. Energy stored in the tail lobes (field increases) → tail current increases → plasma sheet thins → dipole field stretches → dipolarization → particle injections around geostationary orbit + particle acceleration + pulsations in the geomagnetic field + auroral currents greatly intensify (tail current disrupts and closes to the ionosphere)

A storm ≠ many substorms. Storms require stronger forcing (fast solar wind and strong southward IMF). Substorms occur also isolated during relatively weak forcing.

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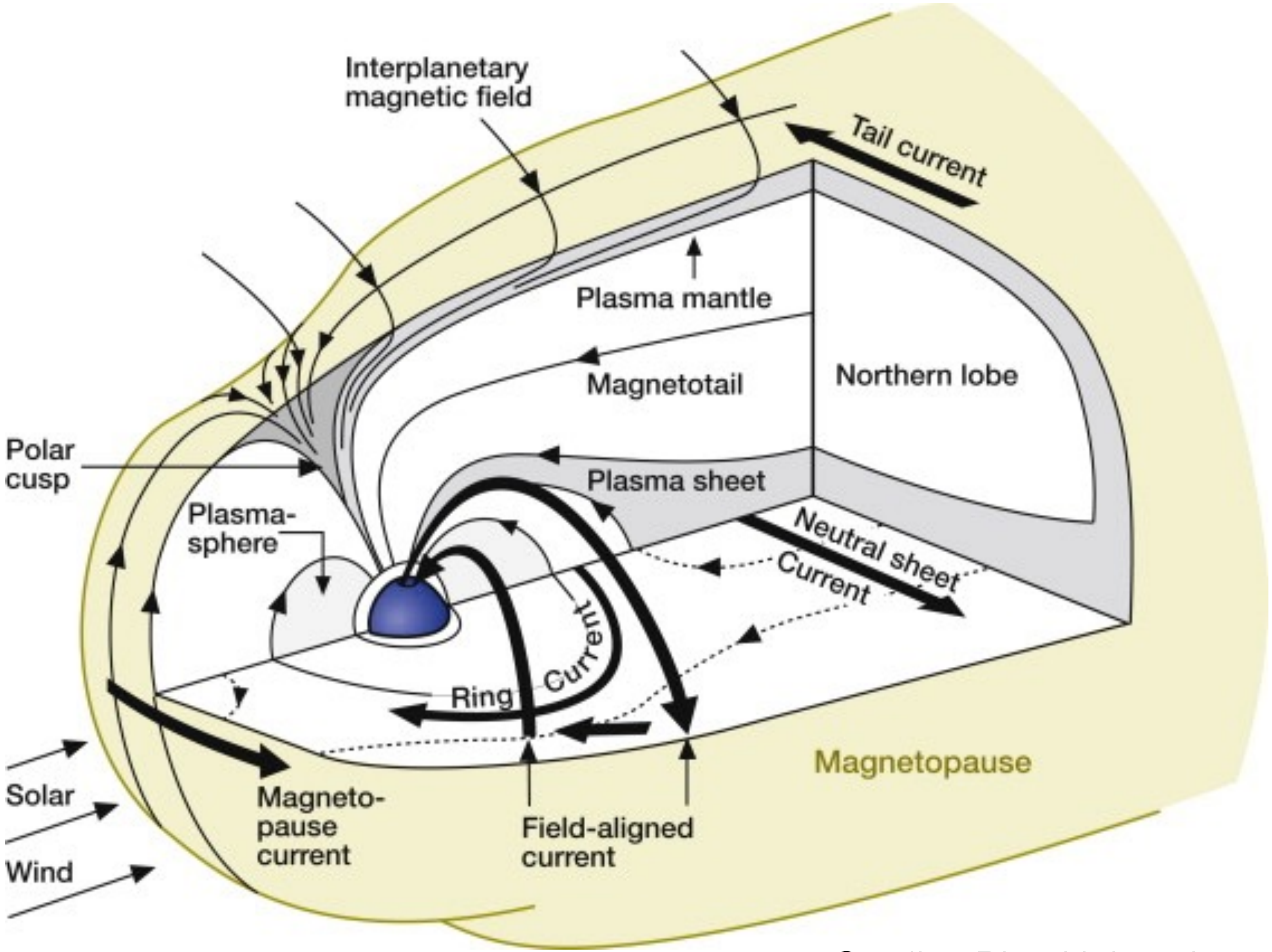

Credits: Rice University

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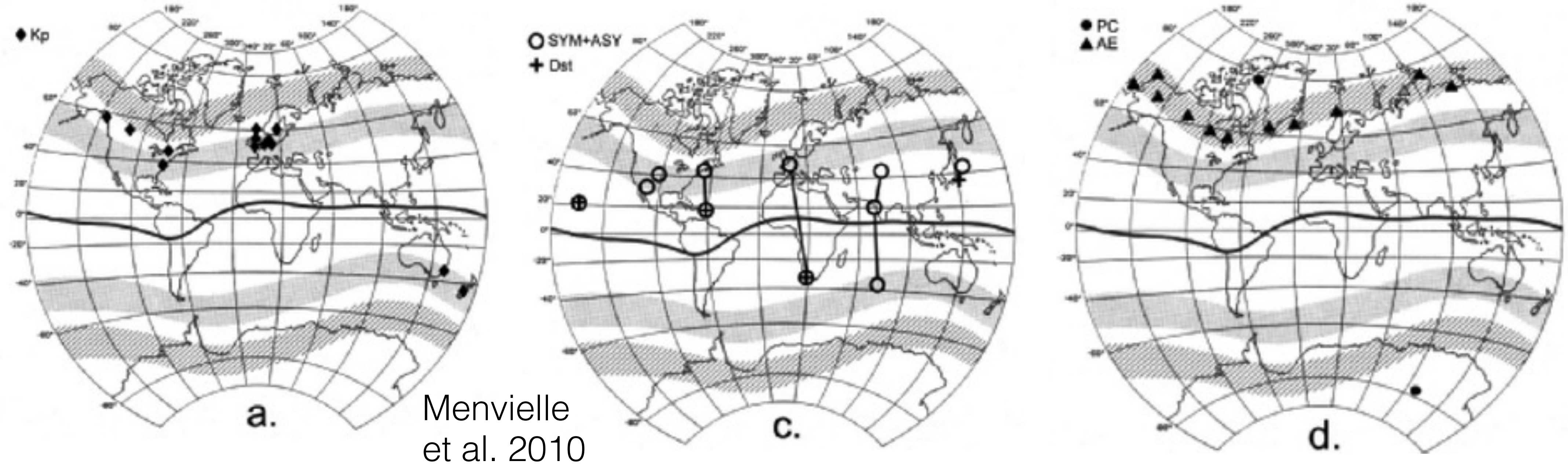

Menvielle et al. 2010

Kp index measures global activity. It is 3-hour index. Contribution from various current systems

SYM-H (1-minute) and Dst (1-hour) indices aim to measure the variations in the ring current.

AE index (1-minute) measures the strength of the auroral electrojets at high-latitudes

The level geomagnetic activity is measured using various geomagnetic indices. They are derived from the different sets of magnetometer stations distributed in longitude and/or latitude around the Earth and their variation reflect changes in different magnetospheric/ionospheric current systems

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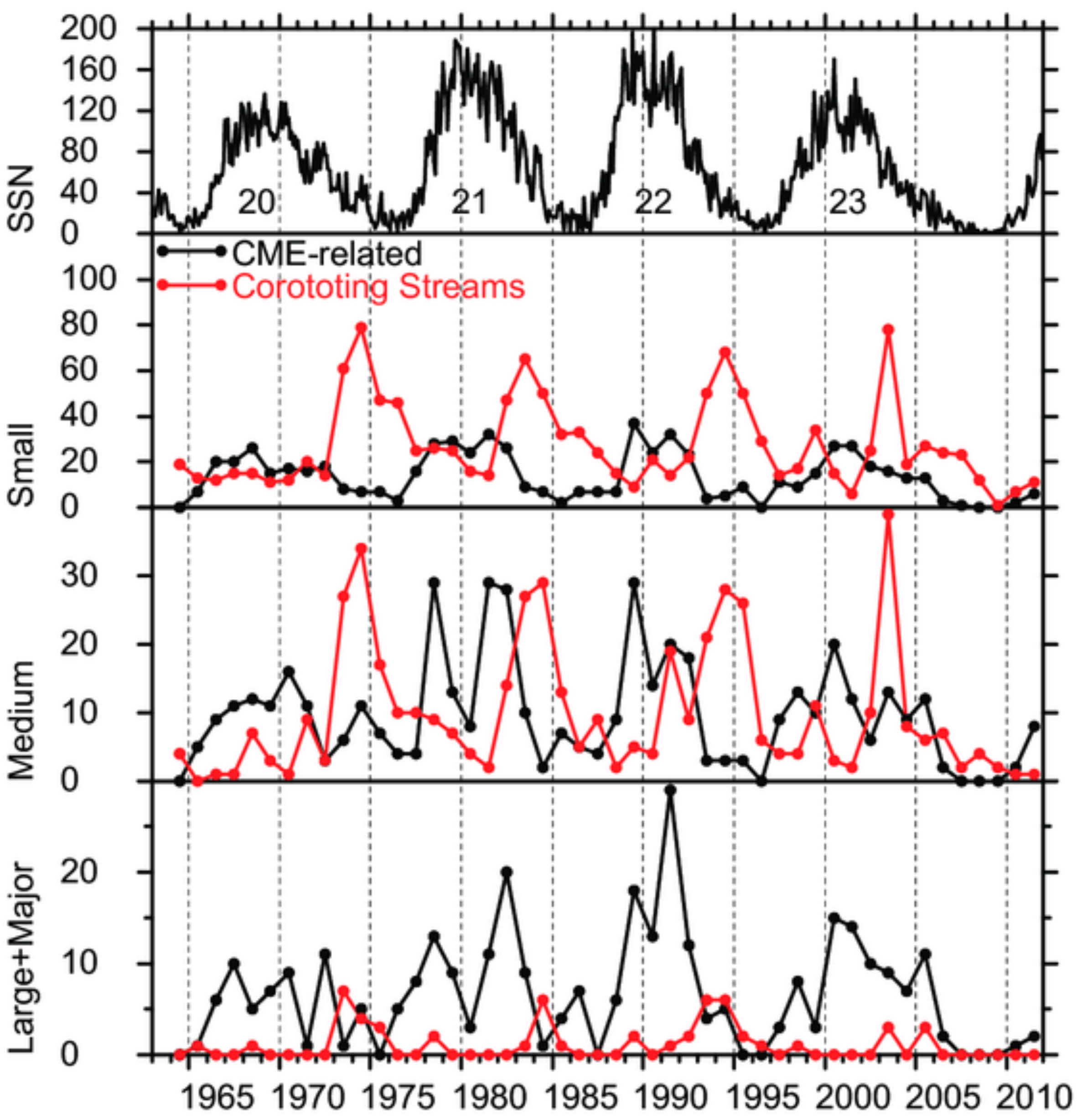

ICMEs and SIRs cause different types of storms

The rate of storms caused by ICMEs peaks near solar maximum. ICMEs drive practically all large and major storms because they can have the largest and most sustained southward IMF.

The rate of storms caused by SIRs peaks at the declining phase and solar minimum. SIRs drive mostly small/medium storms. The have typically less strong fields and the magnetic field direction fluctuates rapidly (→ continuous auroral activity).

Richardson and Cane, 2010

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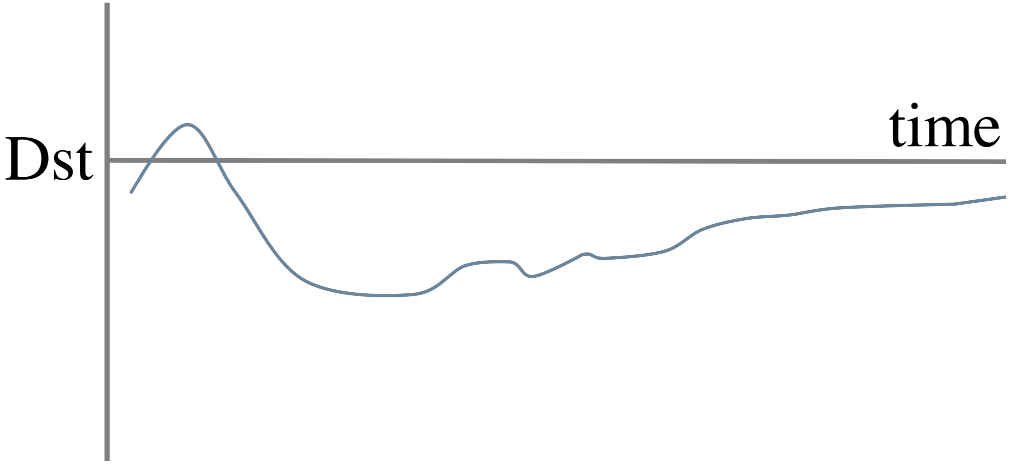
Storm Sudden Commencement	Main Phase	Recovery Phase



Positive Dst: Earth's field increases when high solar wind dynamic pressure pushes the magnetopause inward increasing the Chapman-Ferraro current.

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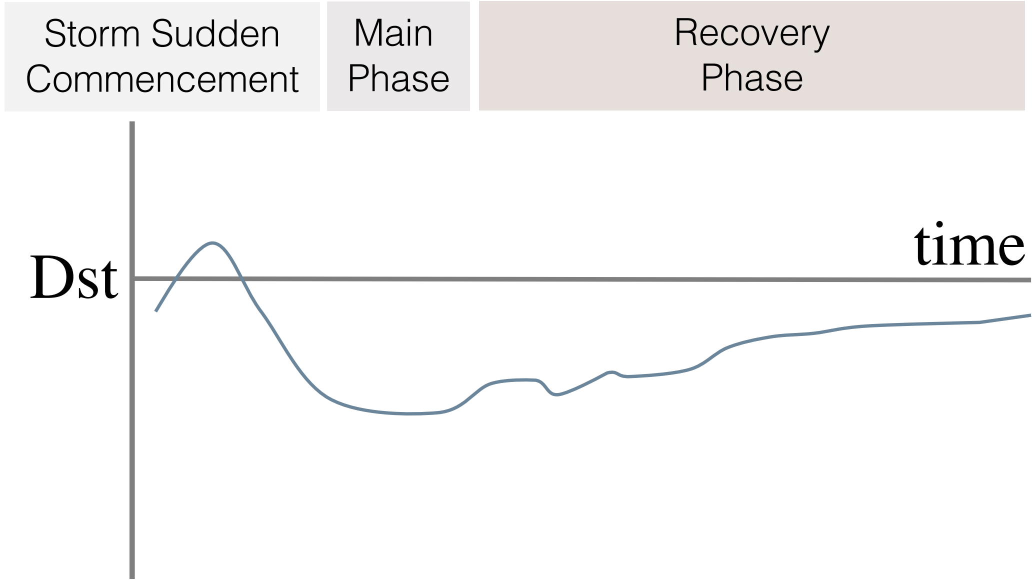

Positive Dst: Earth’s field increases when high solar wind dynamic pressure pushes the magnetopause inward increasing the Chapman-Ferraro current.

Negative Dst: Earth’s field weakens due to the enhancing ring current.

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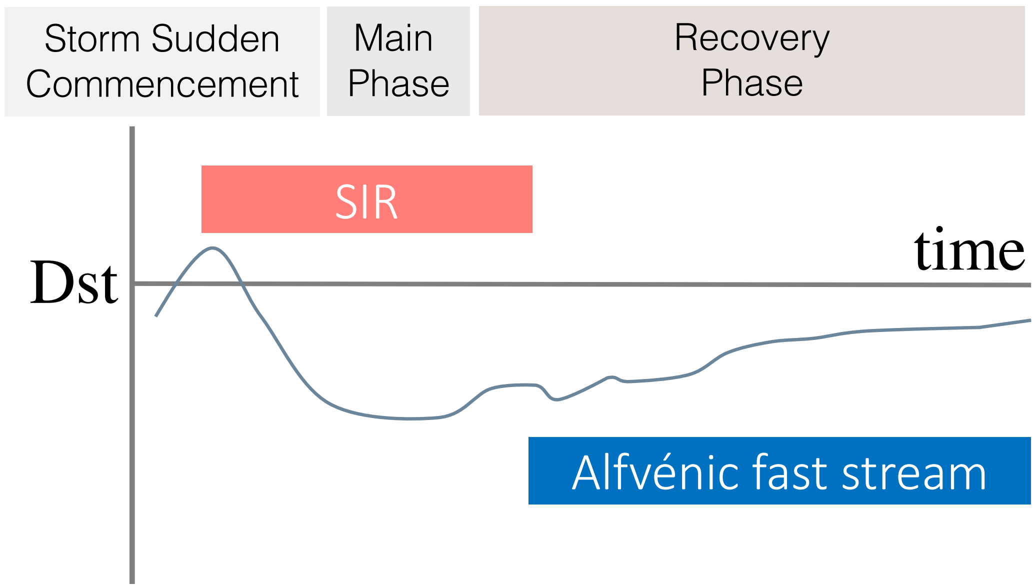

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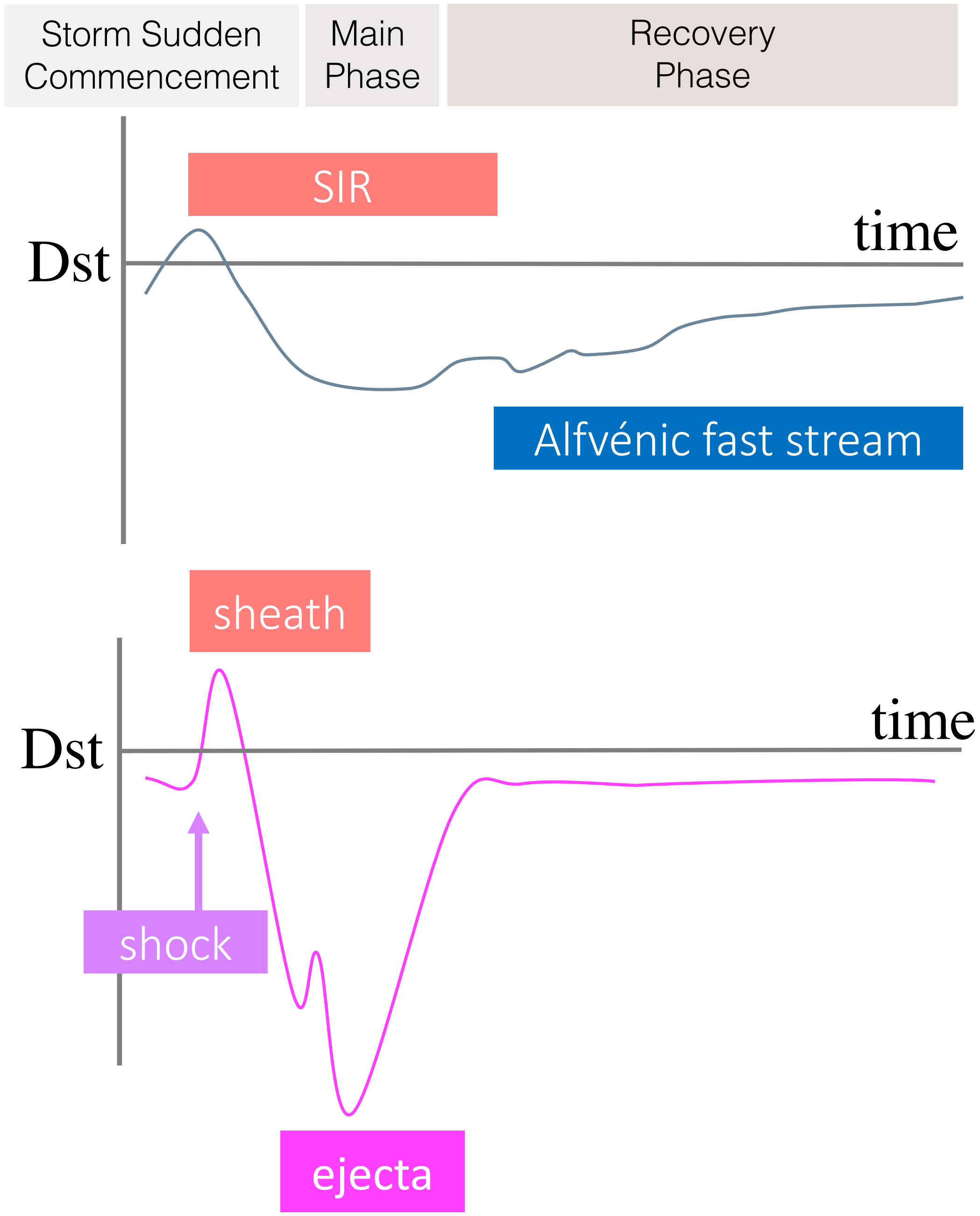

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ICMEs: Often two-step storms with the sheath causing the first dip and ejecta the second. Timing depends also on the magnetic structure of the flux rope. Fast initial recovery, but can be prolonged by a fast stream.

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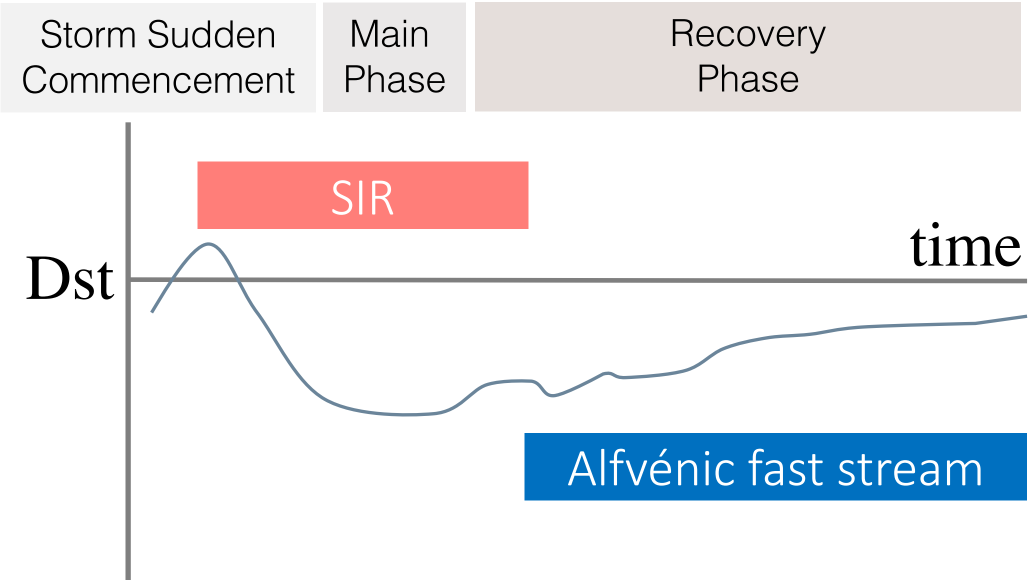

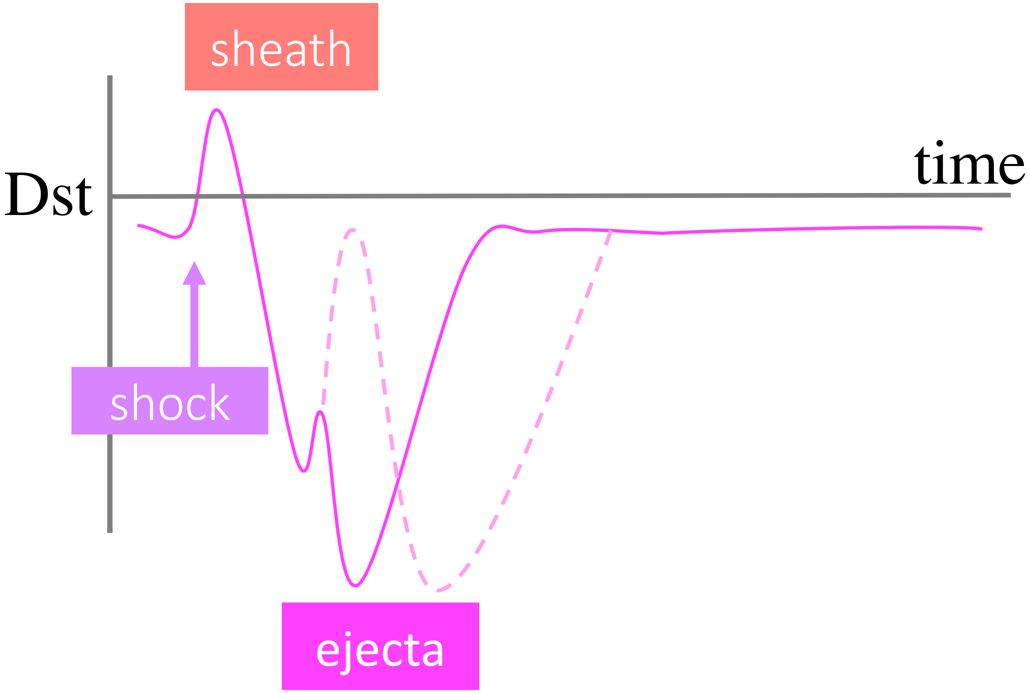

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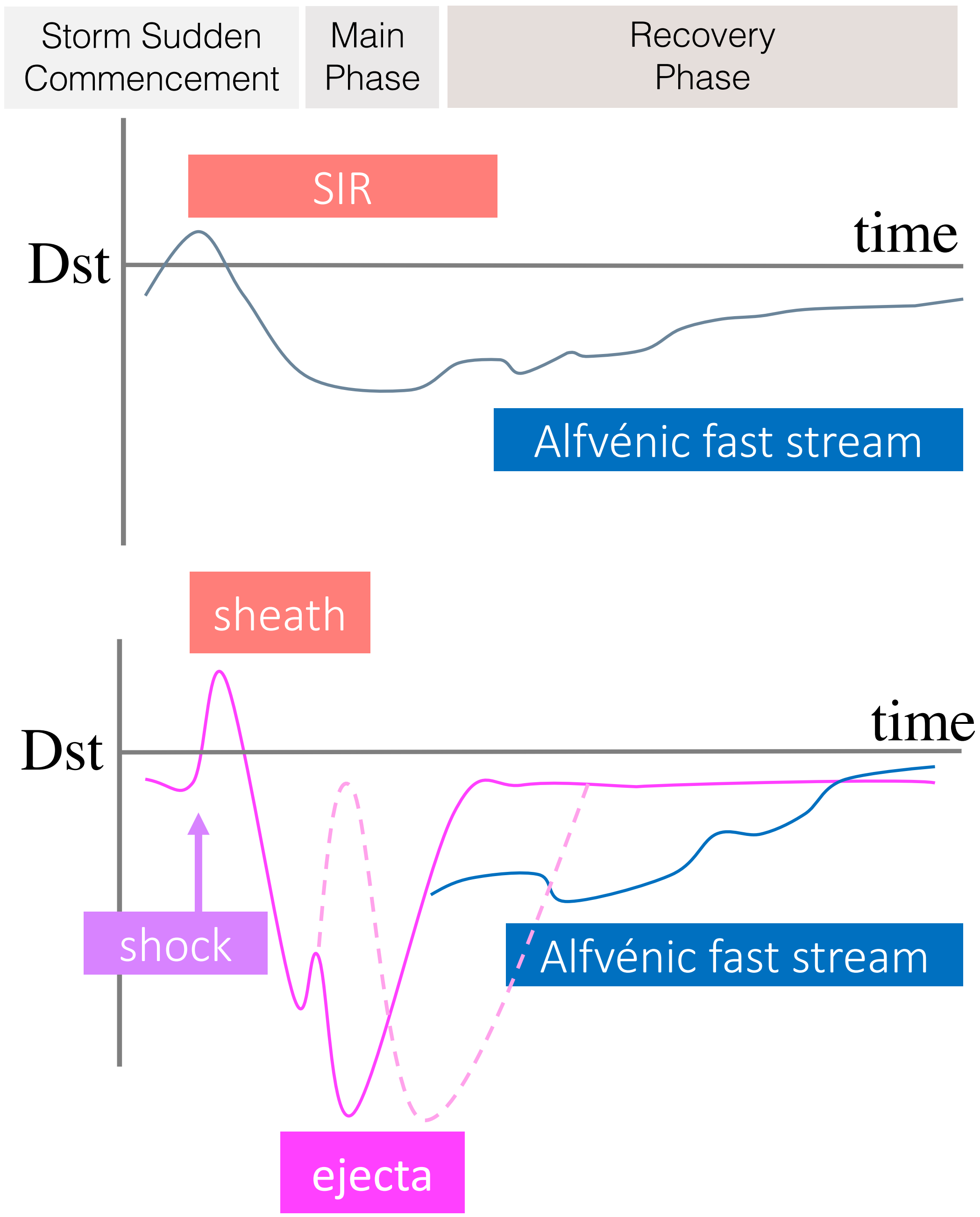

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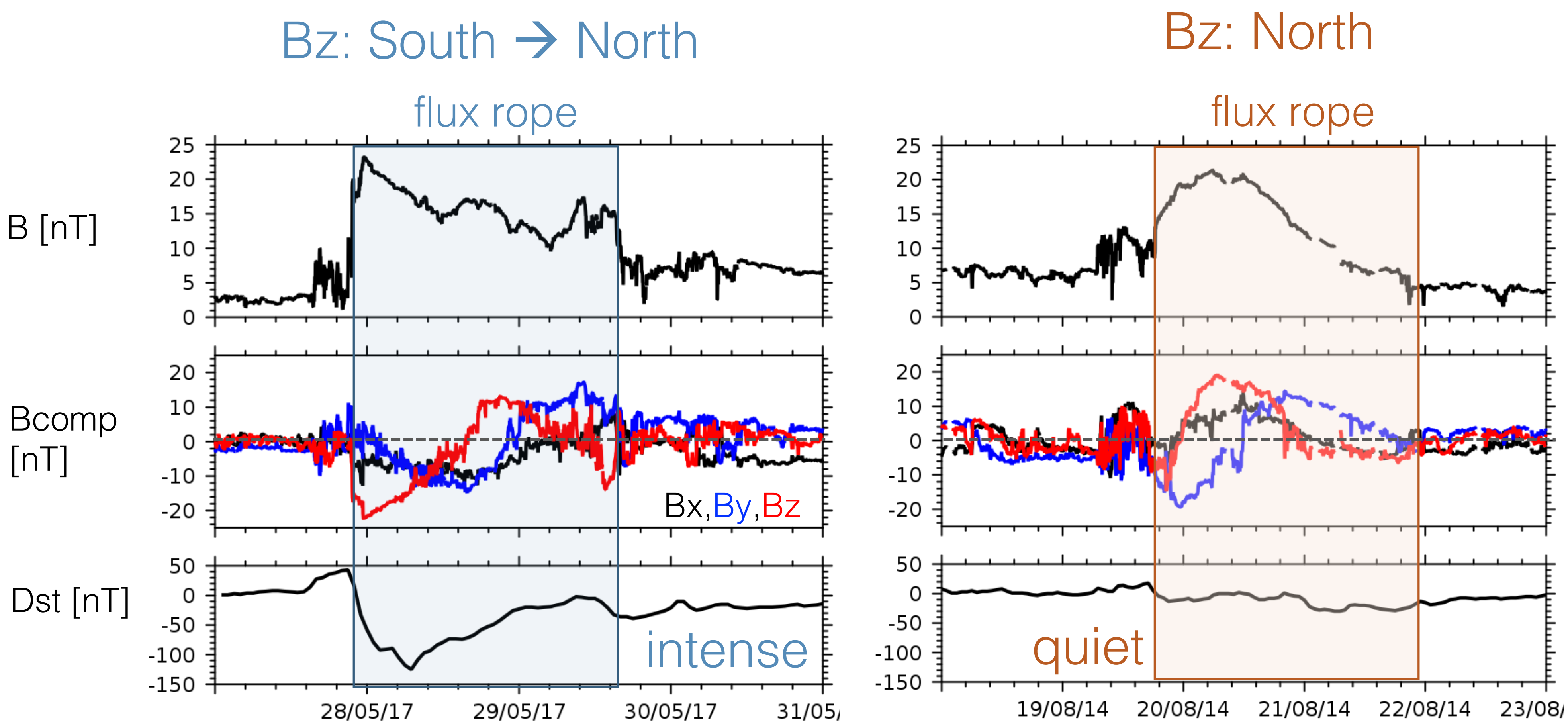

Depending on the flux rope type geomagnetic response can vary from quiet to a major storm.

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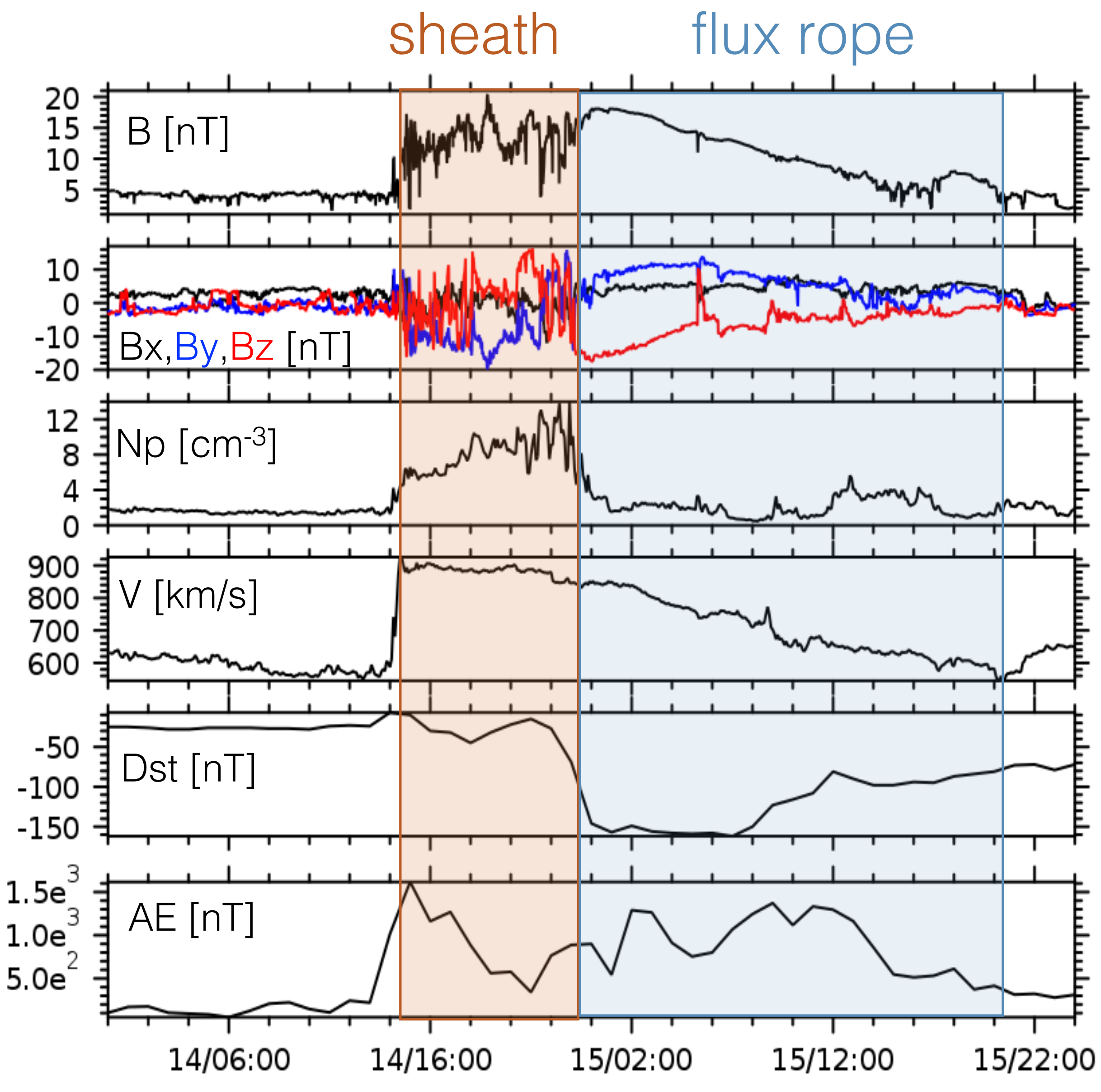

Sheaths and ejecta cause different types of storms

Sheaths tend to cause strong high-latitude activity

Ejecta are more prone to cause sustained and enhanced convection → strong ring current intensifications

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Summary

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- Key drivers: ICMEs (shock, sheath ejecta), SIR and fast streams
- These have highly different solar wind conditions → different geomagentic response
- Forcing of the magnetosphere can vary drastically on relatively short time-scales (large-scale structures half – 1 day in duration, but they have also substructuring on smaller time-scales)

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	Coronal Mass Ejections	SIRs/Fast streams
Occurrence	Varies in concert with solar activity, most common at solar maximum	Most common and prominent during the declining phase and solar minimum
Periocity	Relatively randomly	Repeat often in 27 days intervals
Source at the Sun	Active regions (strong and complex magnetic field)	Coronal holes
Geomagnetic storm characteristics	Intense storms that last typically a few days. Drivers of all super-intense storms	Regular and weak/moderate storms that typically last several days, even a week

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Driver	Duration	Solar wind conditions
Shock	instantaneous	Rapid jump in plasma and field parameters
Sheath	~9 hours	high dynamic pressure, large amplitude IMF variations, high variability (compressive)
Ejecta (flux rope/magnetic cloud)	~ 1day	low dynamic pressure, smooth field rotation, low variability
SIR	~1 day	high dynamic pressure, intermediate-amplitude IMF fluctuations, high variability, gradually increasing speed (compressive)
Fast stream	Several days	low dynamic pressure, Alfvenic, fluctuations (relatively lower amplitude and faster than in the sheath and SIR), high speed

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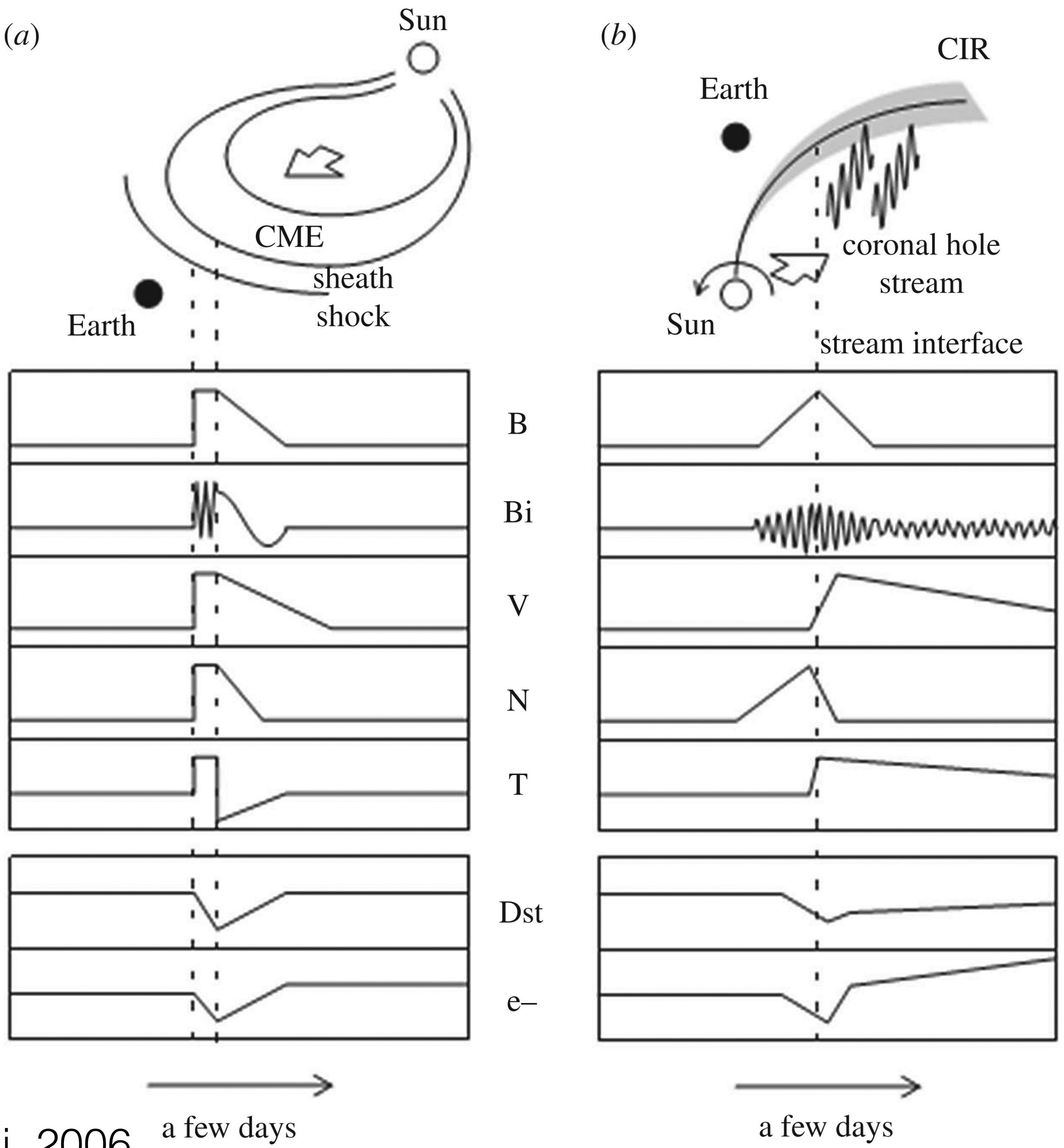

Kataoka and Miyoshi, 2006

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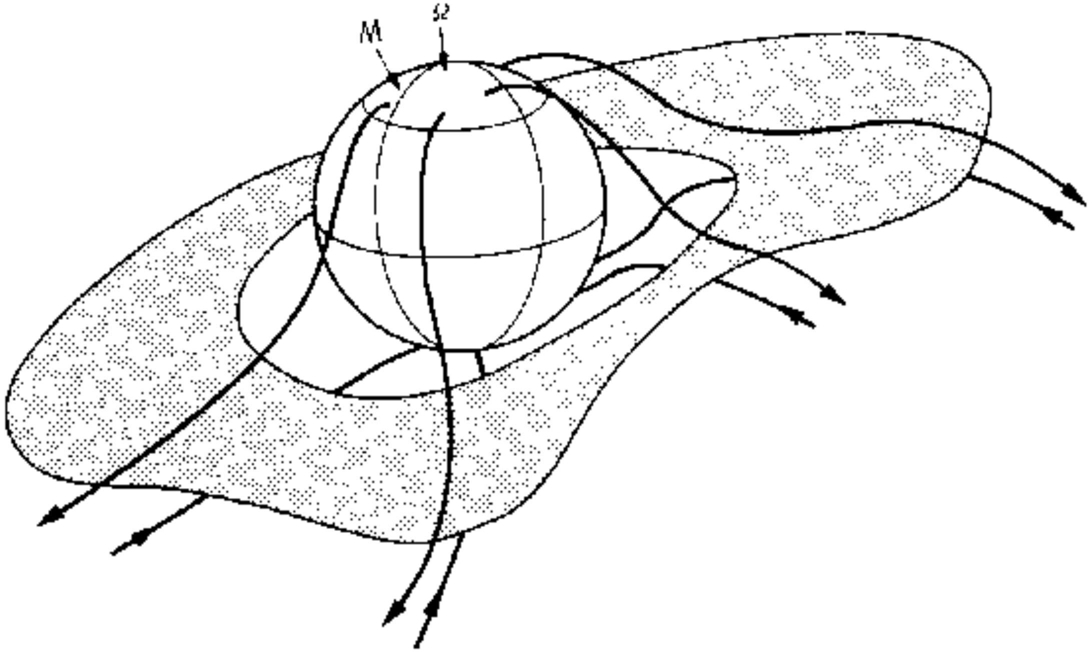

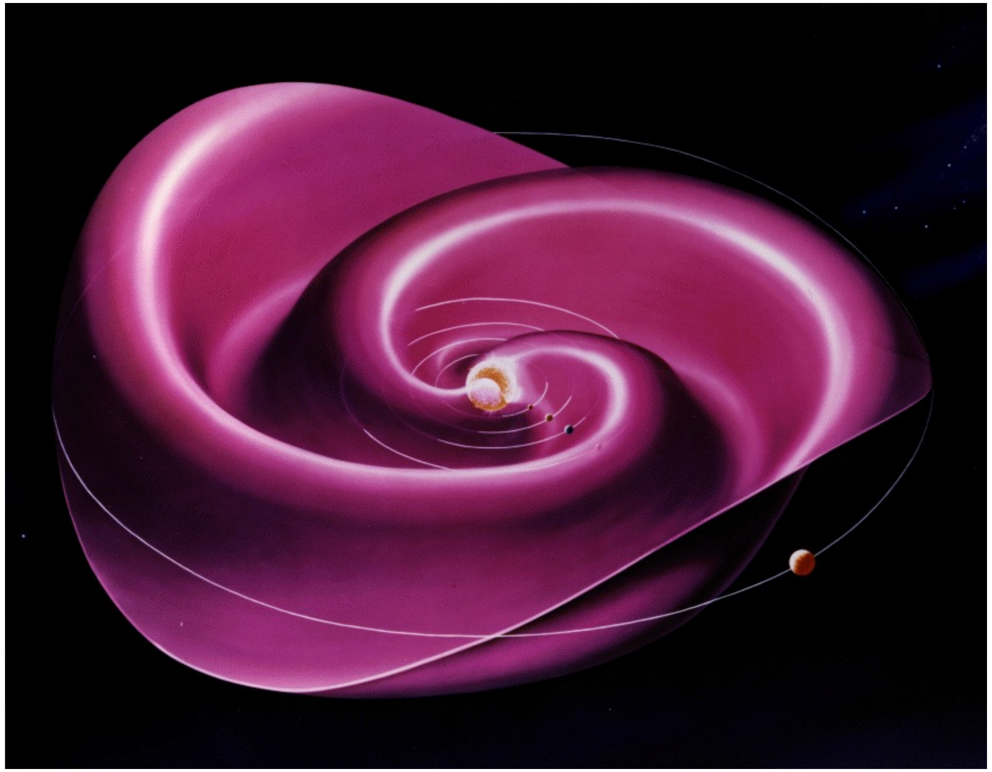

Magnetic field lines coming from the northern and southern solar hemispheres meet and a current sheet forms in between. This heliospheric current sheet (HCS) is a huge structure that is embedded in a high density plasma sheet.

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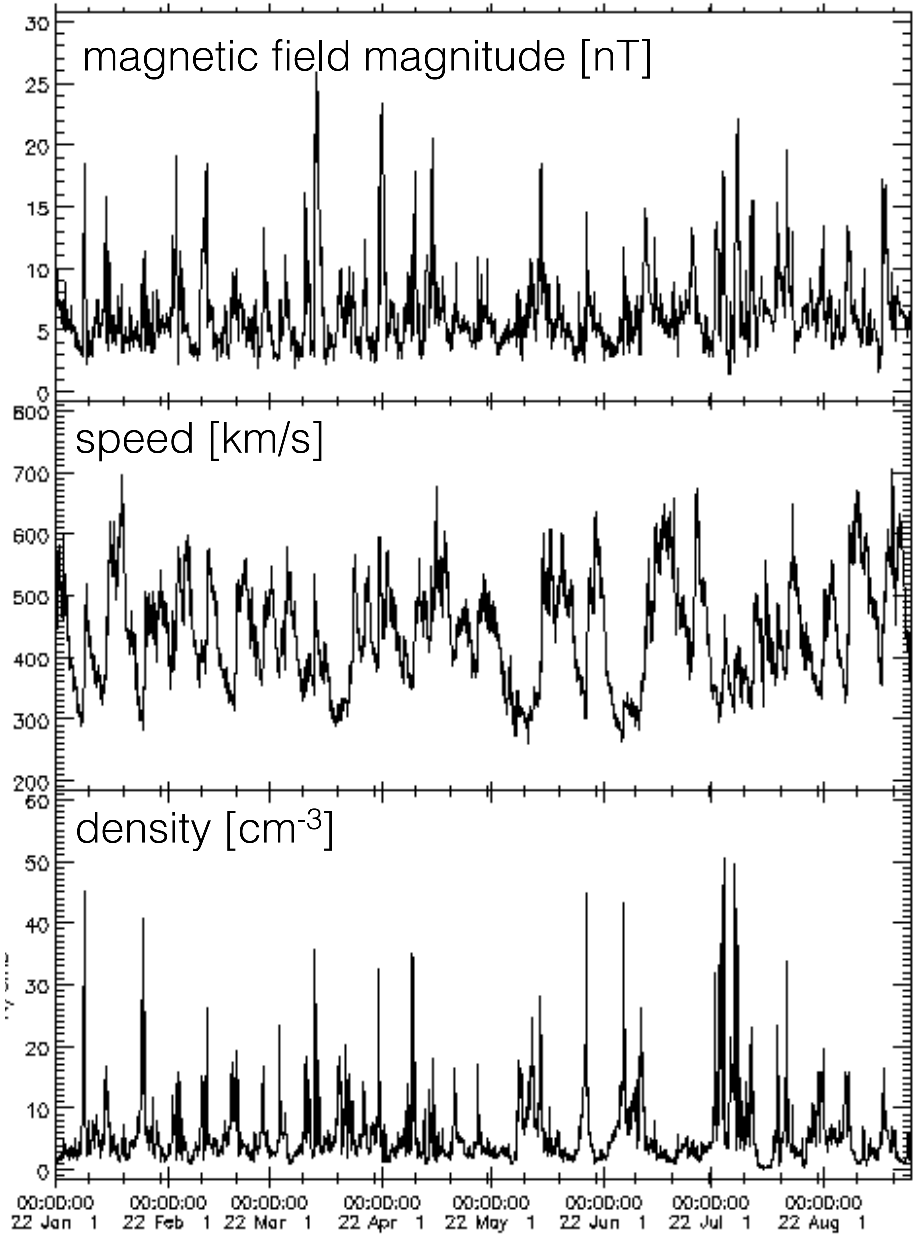

Recent solar wind measurements from the Lagrangian point L1 (OMNI data base)

Periodic variations (~27 days) of intense of solar wind magnetic field magnitude, speed and density also detected

Transient variations embedded (originating from solar eruptions)

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