Solar wind and transient structures

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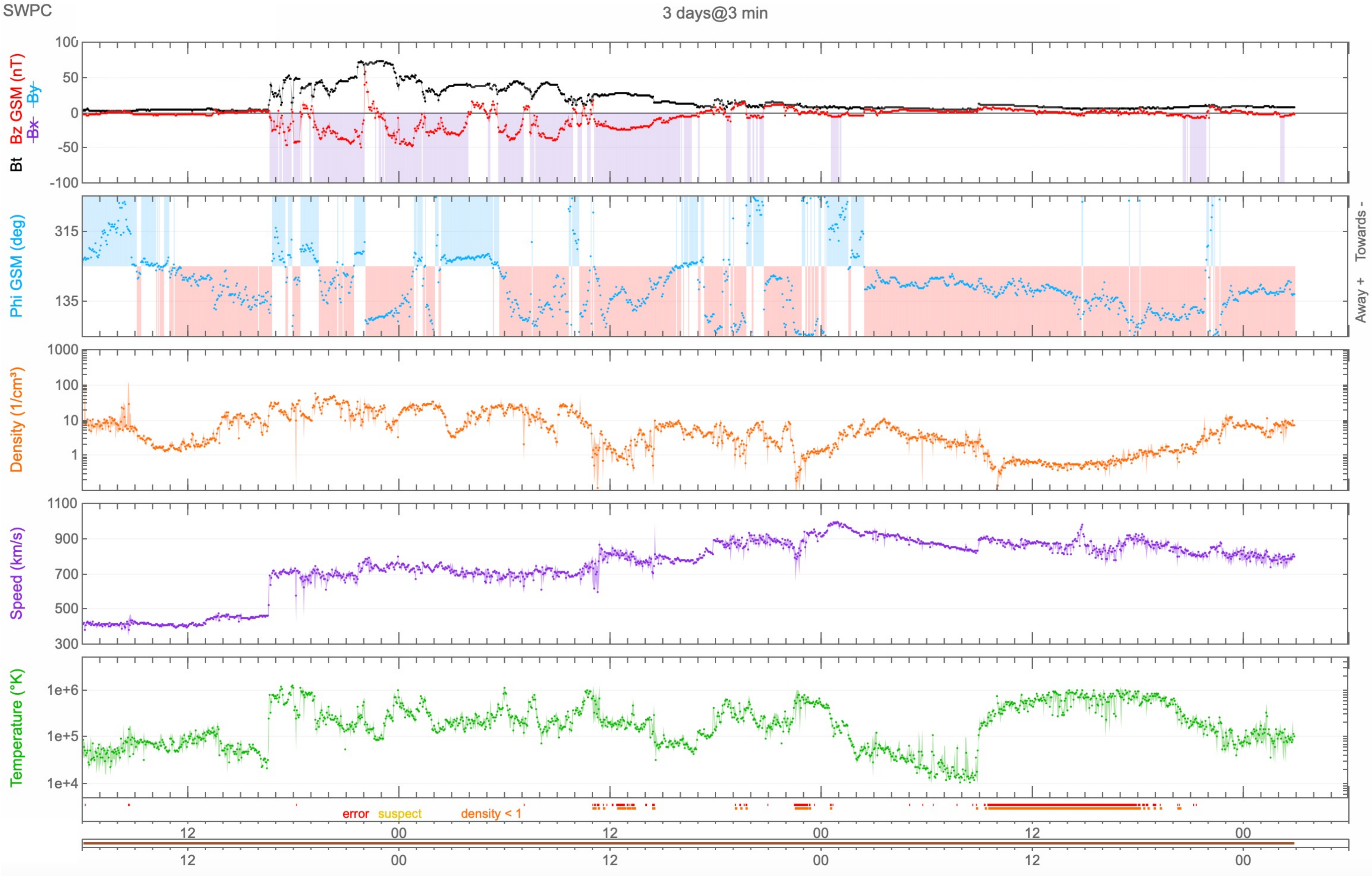

SWPC
3 days@3 min
Bt Bz GSM (nT) -Bx -By
Phi GSM (deg)
Towards -
Away +
Density (1/cm³)
Speed (km/s)
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error suspect density < 1
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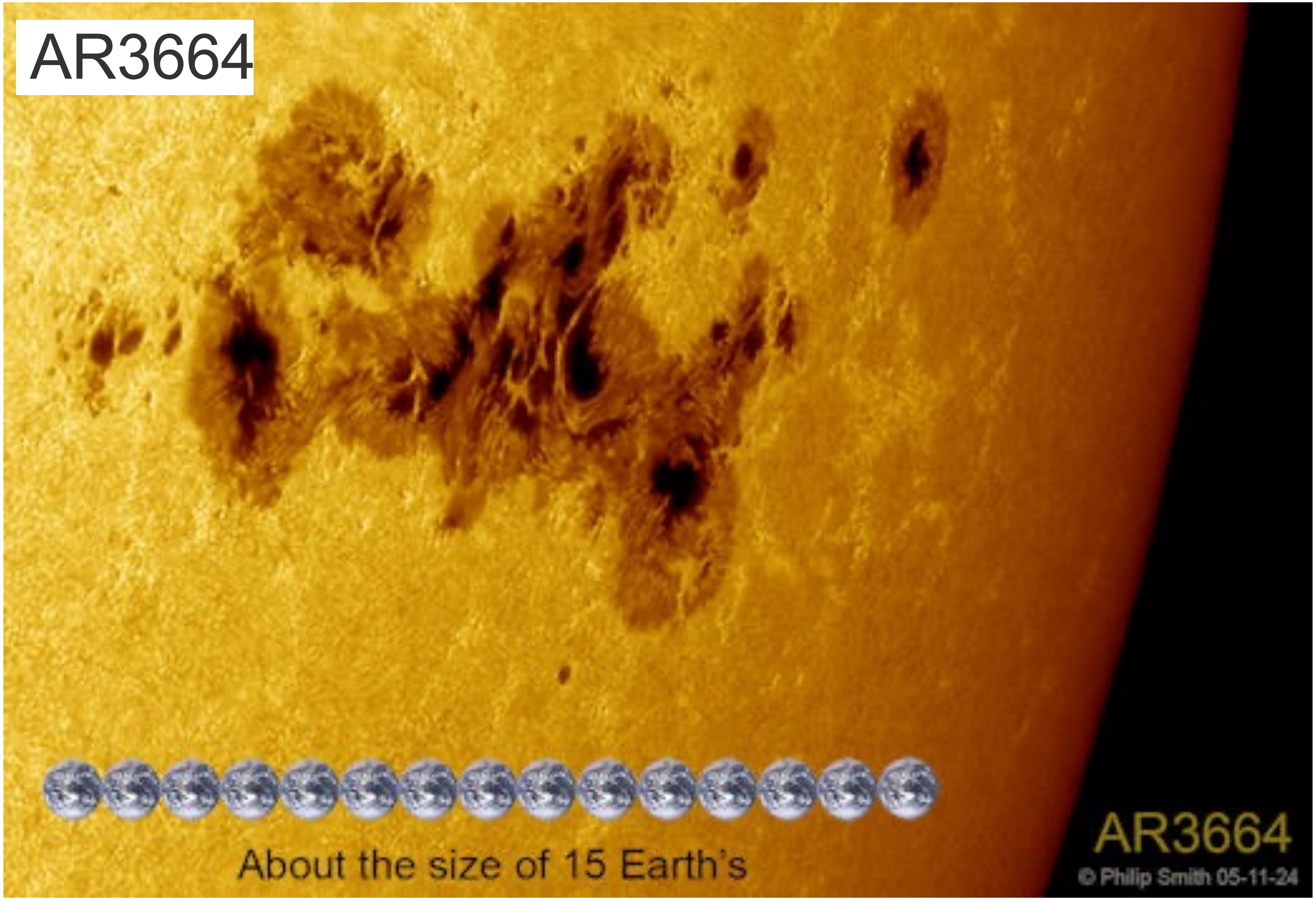
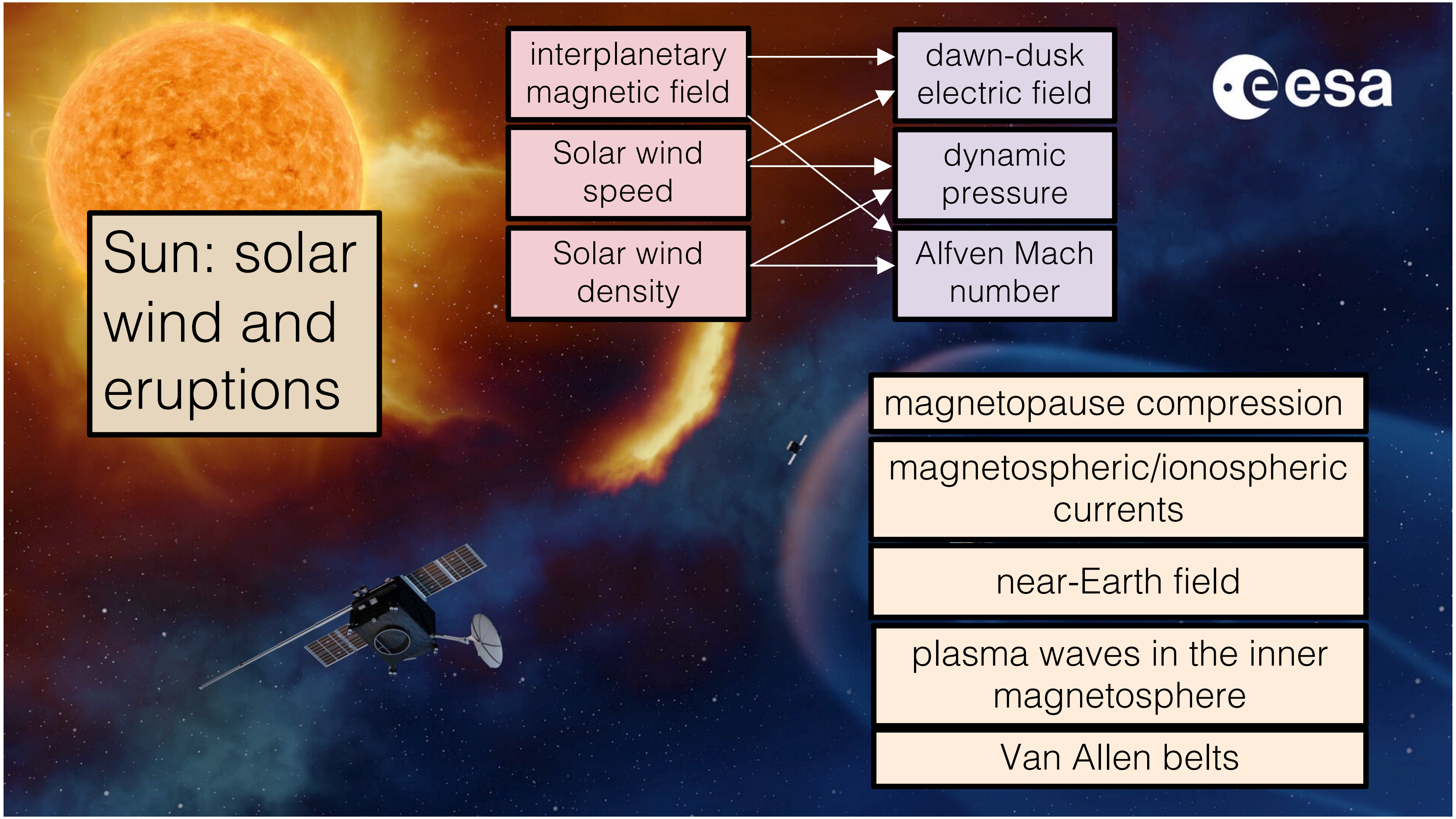

AR3664
About the size of 15 Earth's
AR3664
© Philip Smith 05-11-24


interplanetary magnetic field
Solar wind speed
Solar wind density
dawn-dusk electric field
dynamic pressure
Alfven Mach number
esa
Sun: solar wind and eruptions
magnetopause compression
magnetospheric/ionospheric currents
near-Earth field
plasma waves in the inner magnetosphere
Van Allen belts

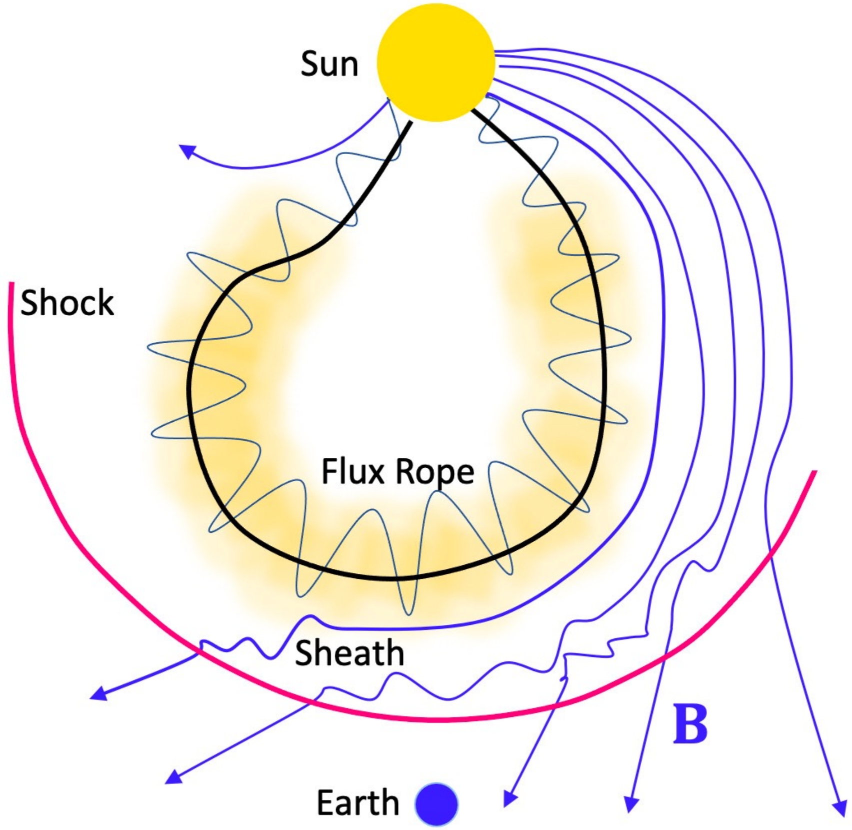
Two review papers on solar wind drivers

- 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)

Fully open access text book of the physics, theory and observations of radiation belts: Koskinen & Kilpua, Physics of Radiation Belts
https://link.springer.com/book/10.1007/978-3-030-82167-8

ICME: Structure & Scale Sizes

- Fast Forward **Shock**: Instantaneous (radial)
- **Sheath**: ~9 hours / 0.1 au
- **Ejecta**: ~1 day / 0.3 au

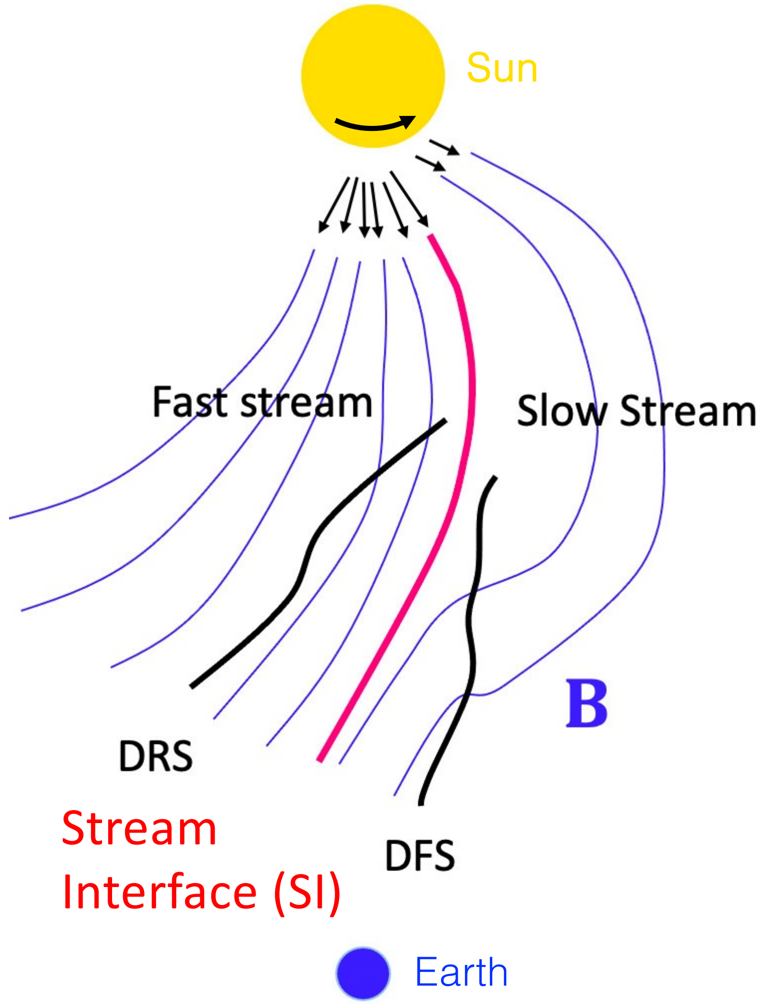


SIR: Structure & Scale Sizes

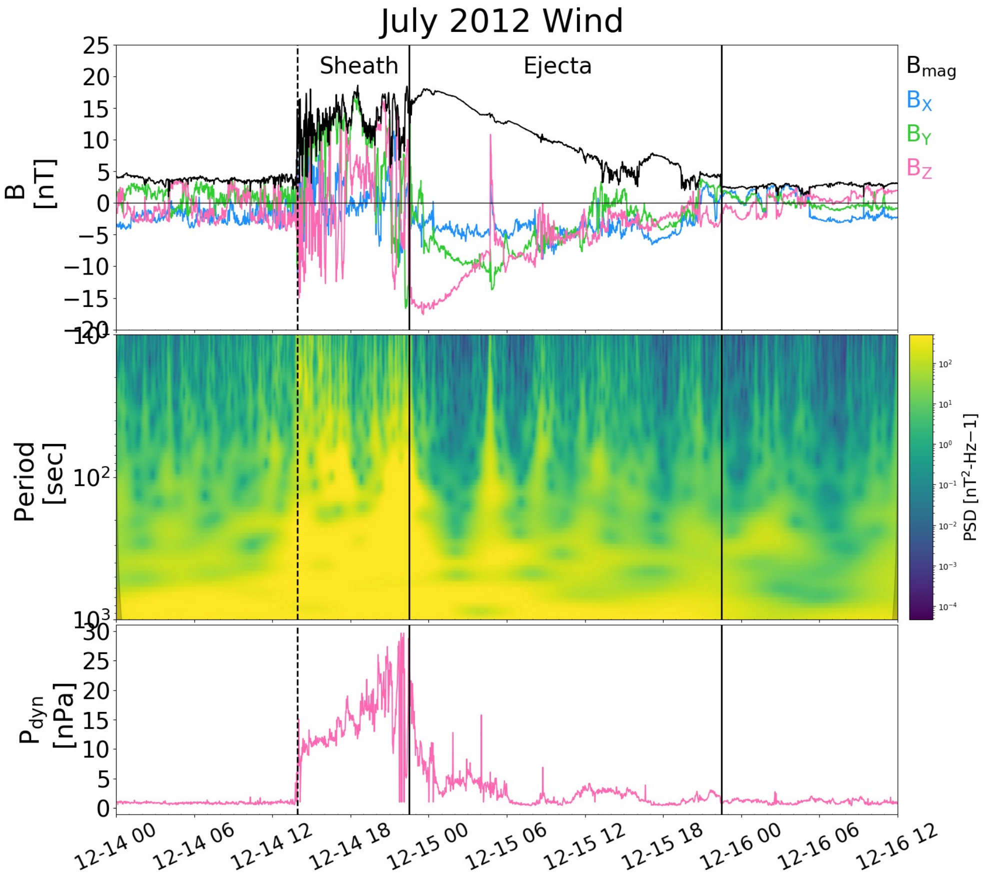
- Fast Forward **Shock***: instantaneous (radial)
- **SIR** (~1 day)
- Fast Reverse **Shock***: instantaneous
- **Fast stream**** (several days)

*typically not fully developed at Earth's orbit

**not all SIRs are followed by a fast stream, but there is a speed gradient



Sheath & Ejecta: Properties



Shock

- Simultaneous jump in plasma and field parameters

Sheath

- highly variable field
- high dynamic pressure

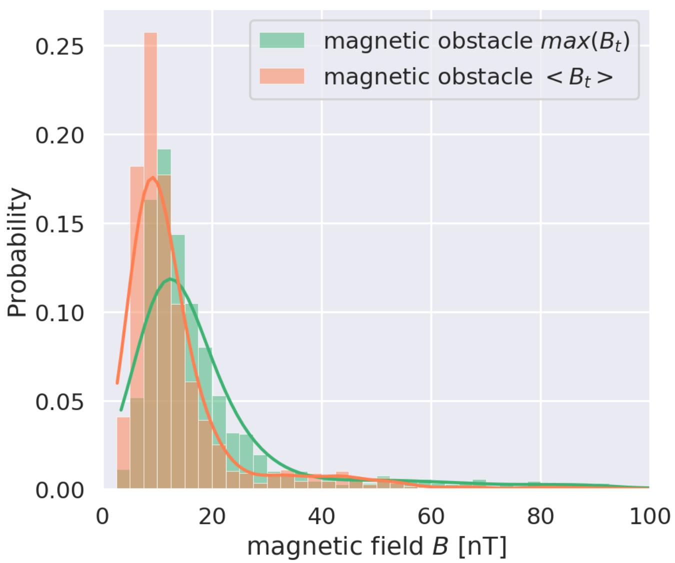
Ejecta

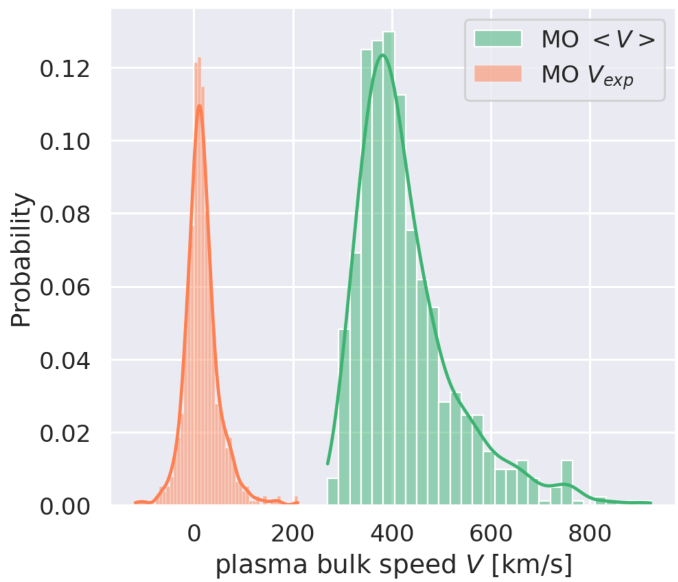
- Enhanced field
- smoothly changing field
- low dynamic pressure

ICME

Variability of ICMEs

- ICMEs exhibit a **large variety** of properties
- E.g., magnetic field vary from **a few to ~100 nT** (very rarely > 40 nT at 1 AU), and speeds from **~250 km/s to a few thousands of km/s**.
- Magnetic structure varies from coherent magnetic clouds to complex ejecta



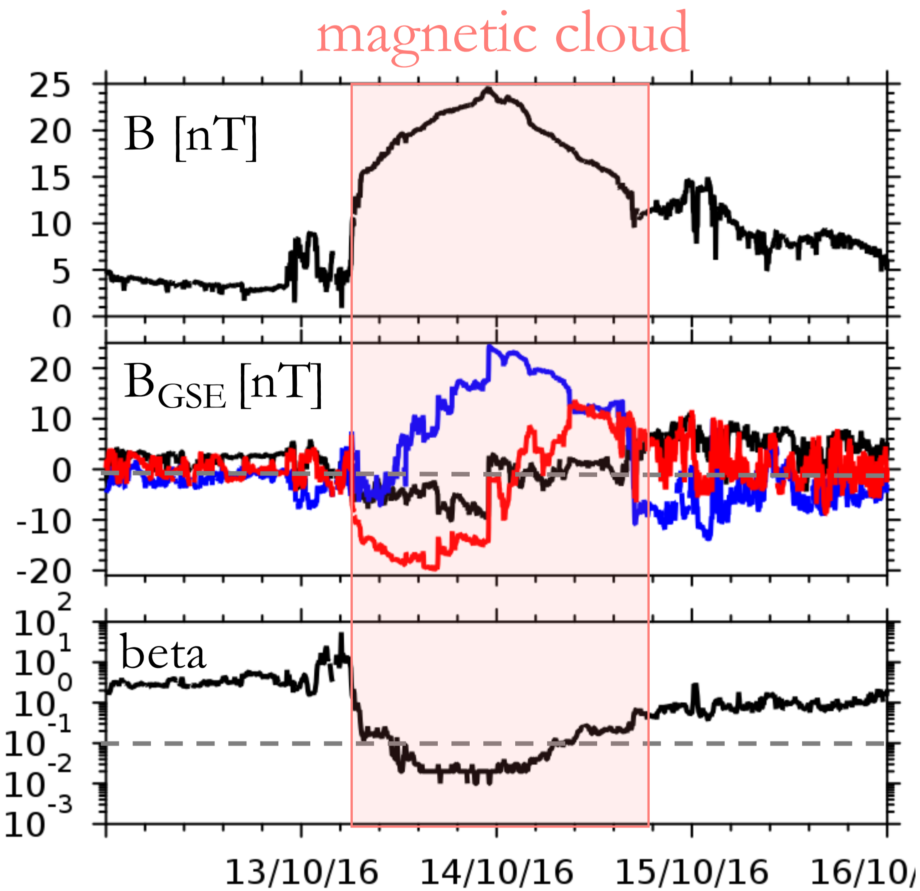


Left) Peak and average magnetic field magnitudes

Right) Average speed and expansion speed (leading to trailing edge speed gradient)

From the **ICMECAT catalogue**

Magnetic Cloud (MC): Observational Definition

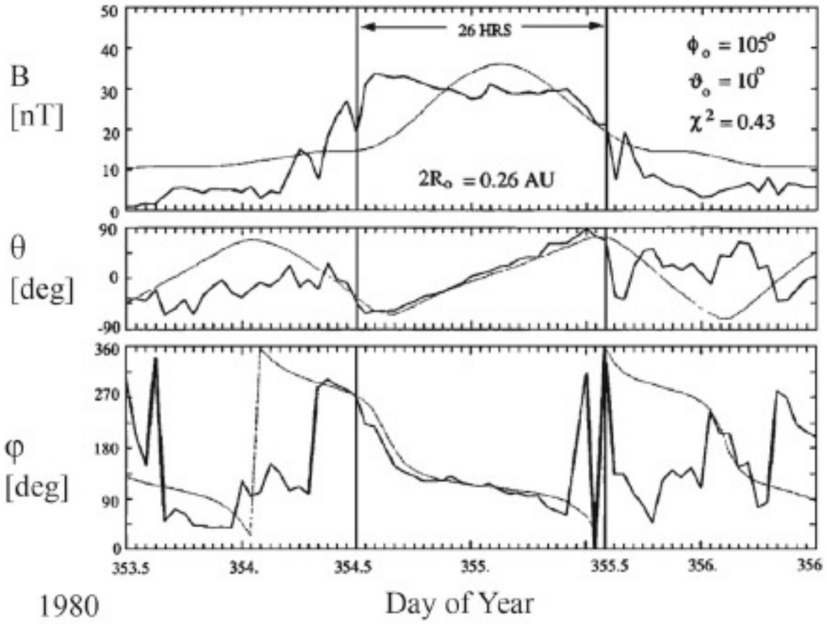


Observational signatures

- Enhanced magnetic field (typically ≳10 nT)
- Smooth rotation of the field diretion
- Low temperature/ depressed plasma beta (≲ 0.1)

(Burlaga et al. 1981)

Flux Rope: Physical Configuration

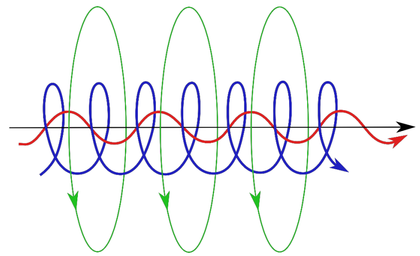


Lepping et al., 1990: Least-square method to **fit** the constant α solution (Lundquist solution) to the magnetic field data.

In the first approximation magnetic clouds (MCs) can be represent as force-free cylindrically symmetric **magnetic flux ropes*** (Burlaga, 1988).

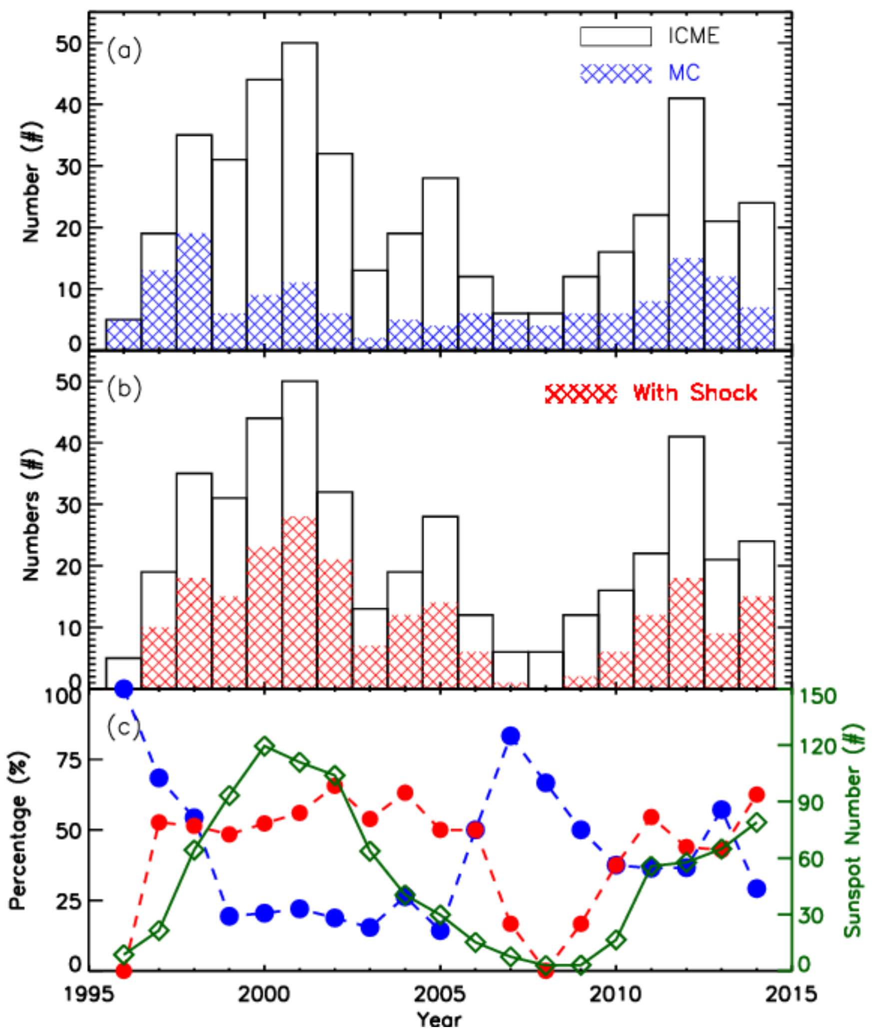
constant α solution of $\nabla\times\mathbf{B} \approx \alpha(r)\mathbf{B}$ → Helmholtz equation $(\nabla^2 + \alpha^2)\mathbf{B} = 0$ → solution given in terms of Bessel functions

$$\begin{cases} B_R = 0 \\ B_A = B_0 J_0\left(\dfrac{\alpha_0 r}{r_0}\right) & \text{axial field} \\ B_T = \pm B_0 J_1\left(\dfrac{\alpha_0 r}{r_0}\right) & \text{tangential field} \end{cases}$$



*structure where field lines wind about a common axis

Fraction of MCs from all ICMEs



About **one-third** of ICMEs are magnetic clouds

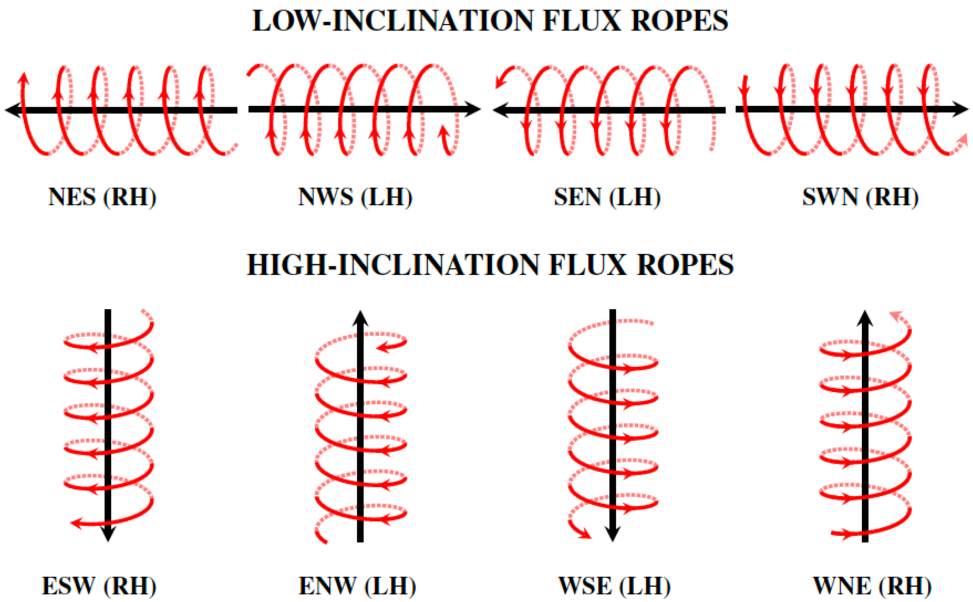
Fraction of MCs anti-correlates with solar activity
→ ICMEs have a more complex structure at solar maximum while near solar minimum nearly all ICMEs are MCs

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

Shen et al., 2015

Flux Rope (FR) Types



Palmerio et al., 2018

helicity sign (or chirality) tells the sense magnetic field winds
LH/-: clockwise rotation
RH/+: counter-clockwise rotation

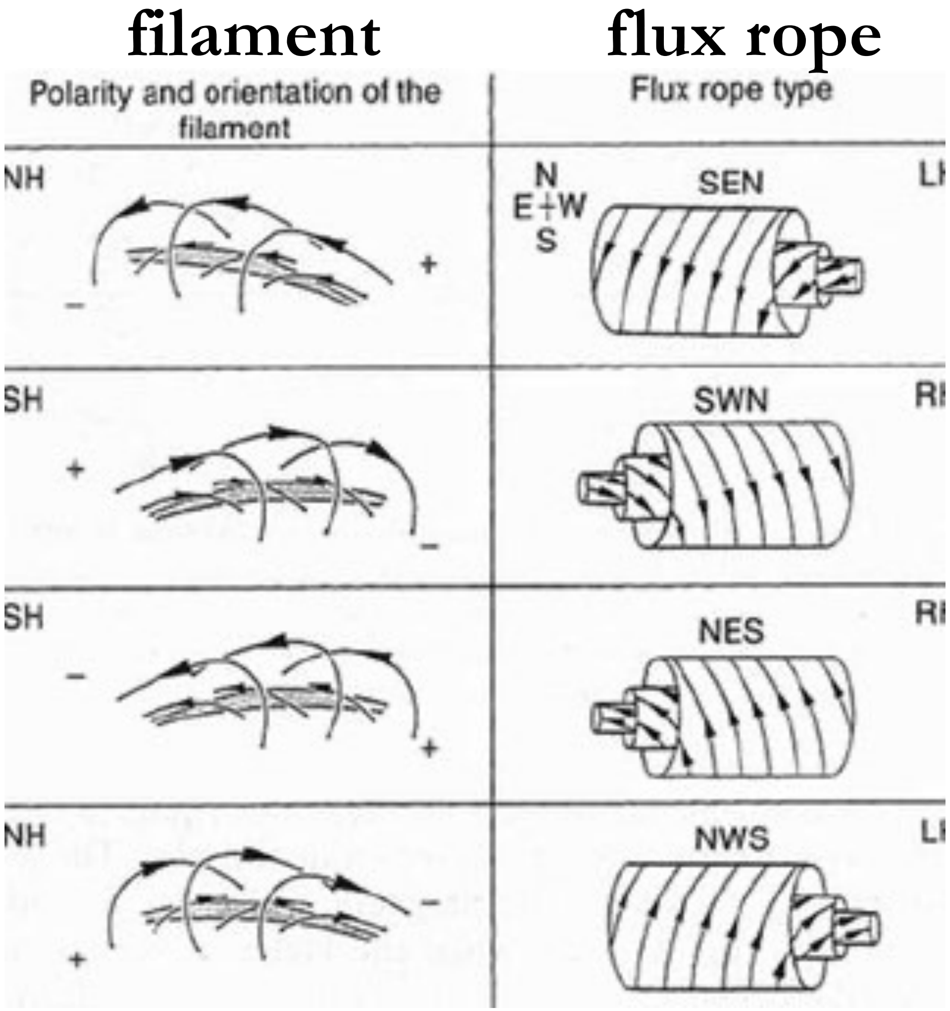
Observed **field rotation** within a FR varies depending on the

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

(e.g. Bothmer & Schwenn 1998; Mulligan, Russell, & Luhmann1998)

Flux rope types are based on the behaviour of the **north – south** (Bz) component (geoeffectivity)

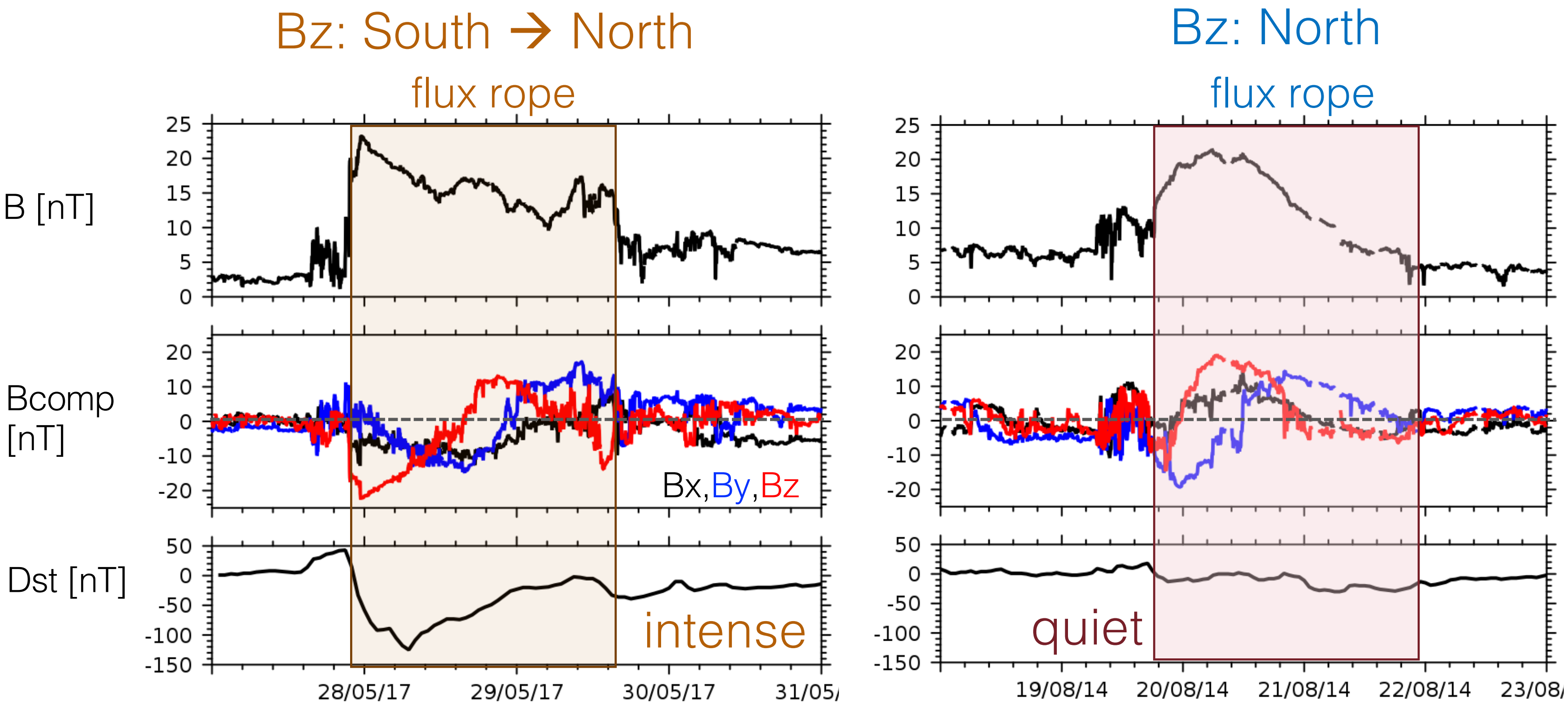
Flux Rope Types and solar source



Determined upon eruption from the **coronal source** region, varies with 22-year solar magnetic cycle (but **may change significantly** during interplanetary propagation!)

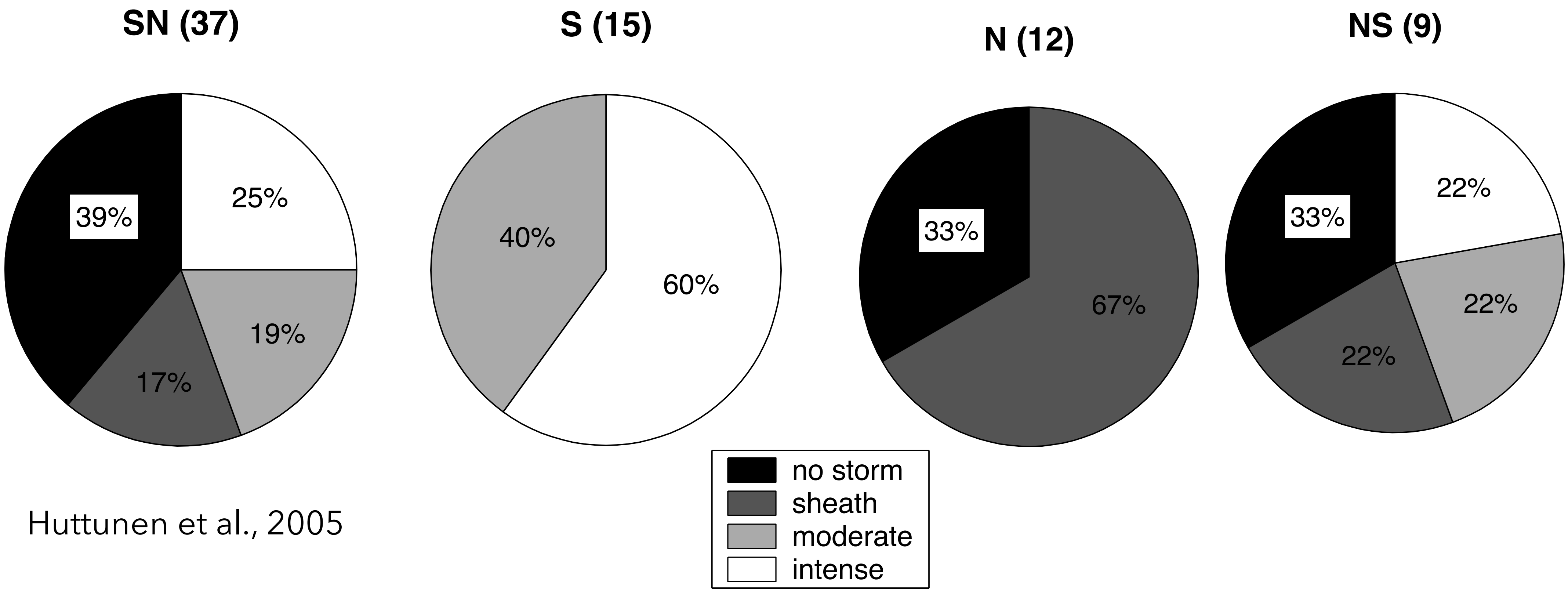
Bothmer & Schwenn 1998

Geoffectivity: Magnetic Clouds



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

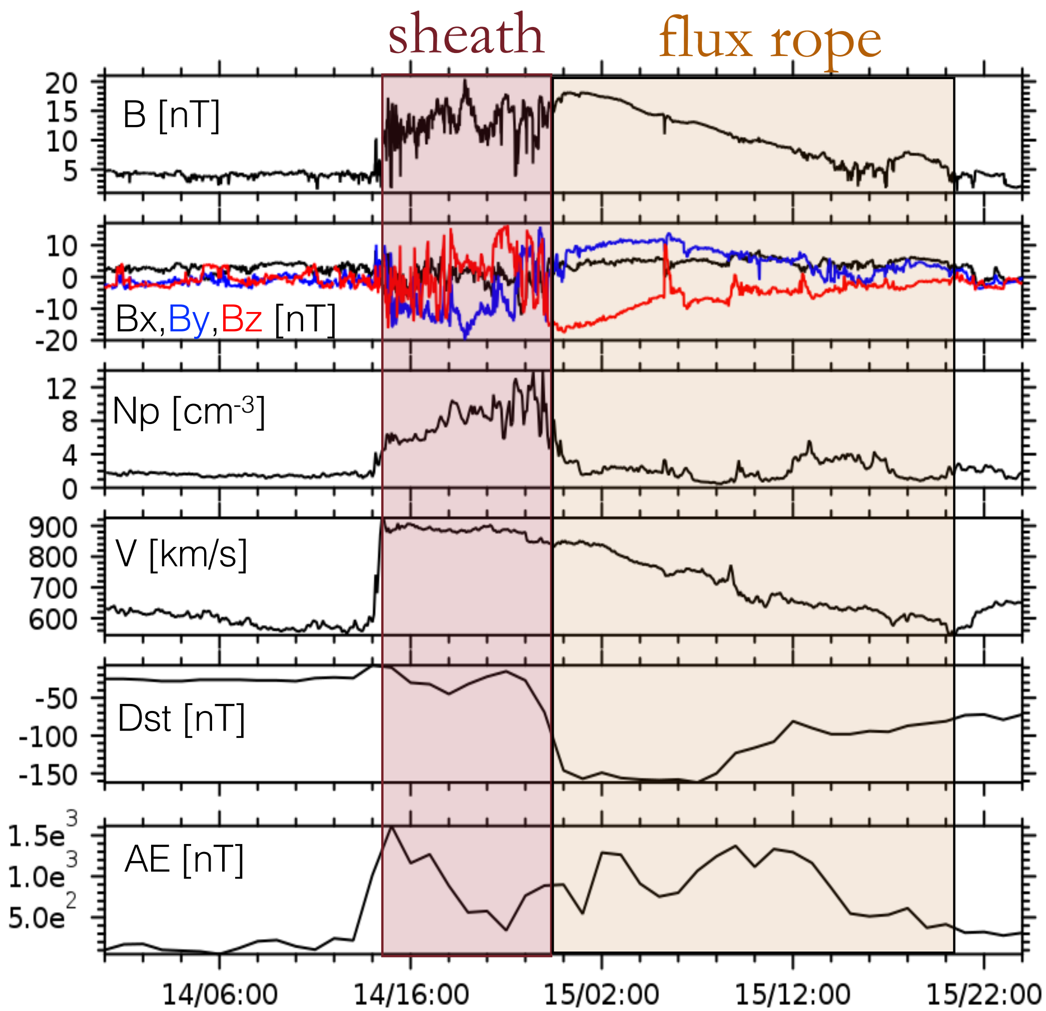
Flux Rope Types and Geoffectivity



Huttunen et al., 2005

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

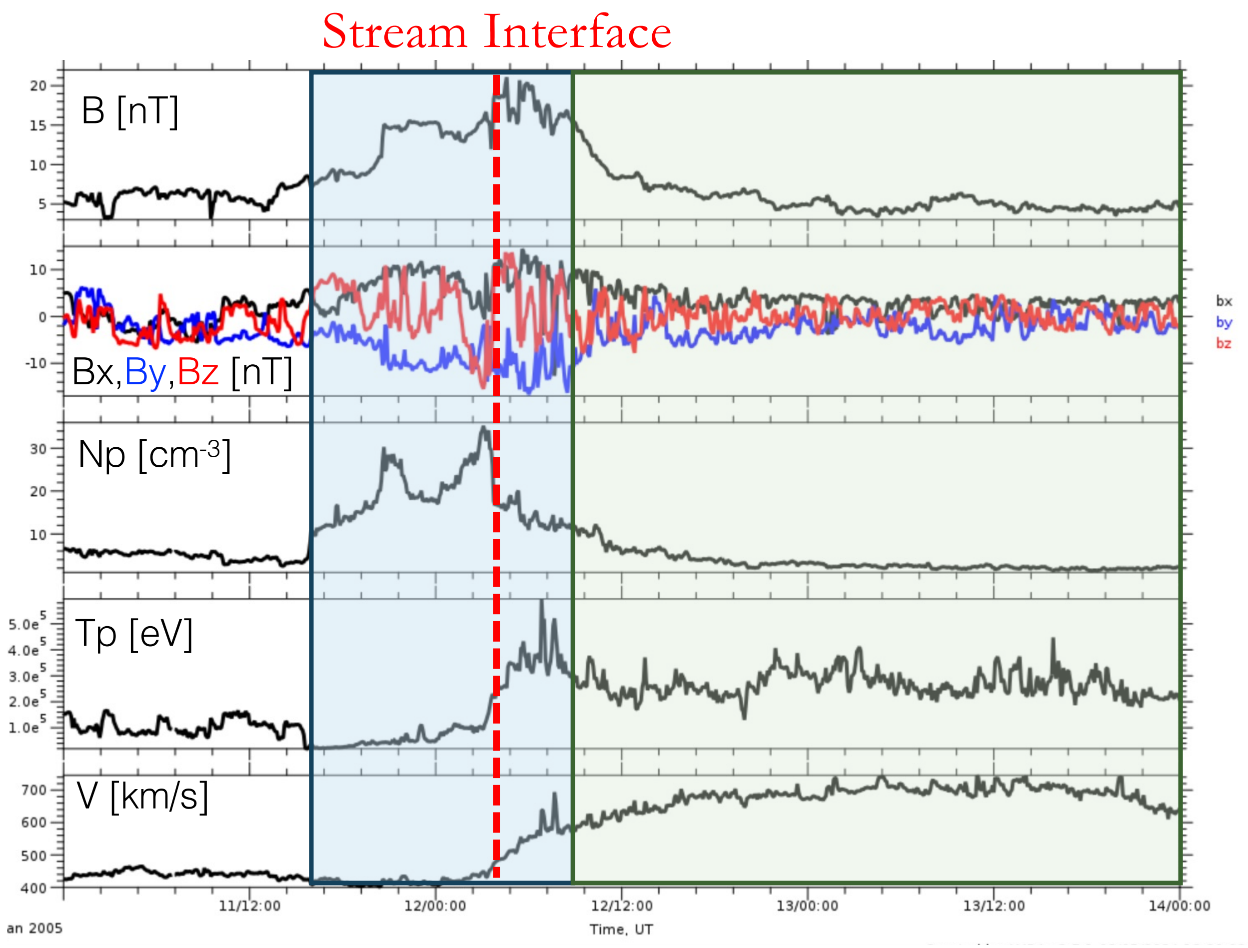
Geoffectivity of sheaths / magnetic clouds



Sheaths and magnetic clouds can cause storms **independent** of each other or **combined** storms

Sheaths tend to cause strong **high-latitude** activity (AE), magnetic clouds are more effective in enhancing **low latitude** currents (ring current, Dst)

SIR Properties



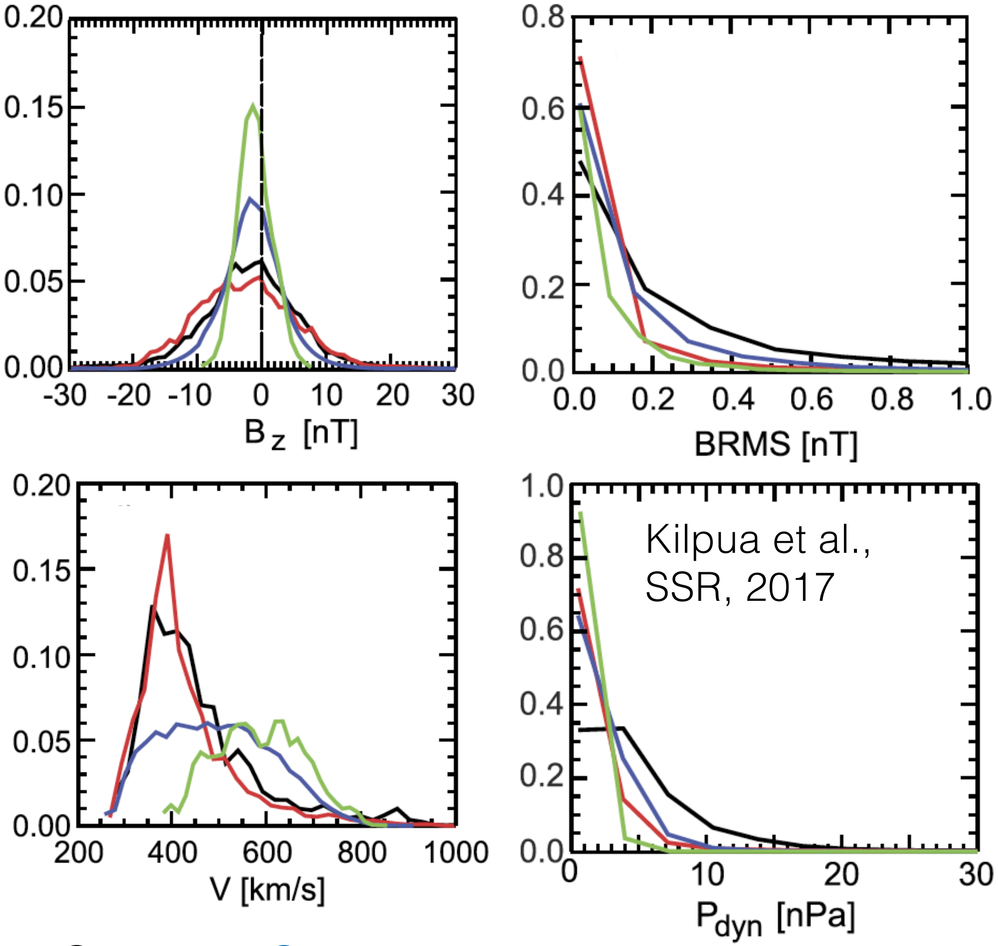
SIR

- highly variable field
- high dynamic pressure
- 'sheath'-like

Fast stream

- Alfvenic fluctuations
- Low dynamic pressure
- Low magnetic field

Storm drivers: ICME vs. SIR + HSS



Sheath SIR
Ejecta High Speed Stream (HSS)

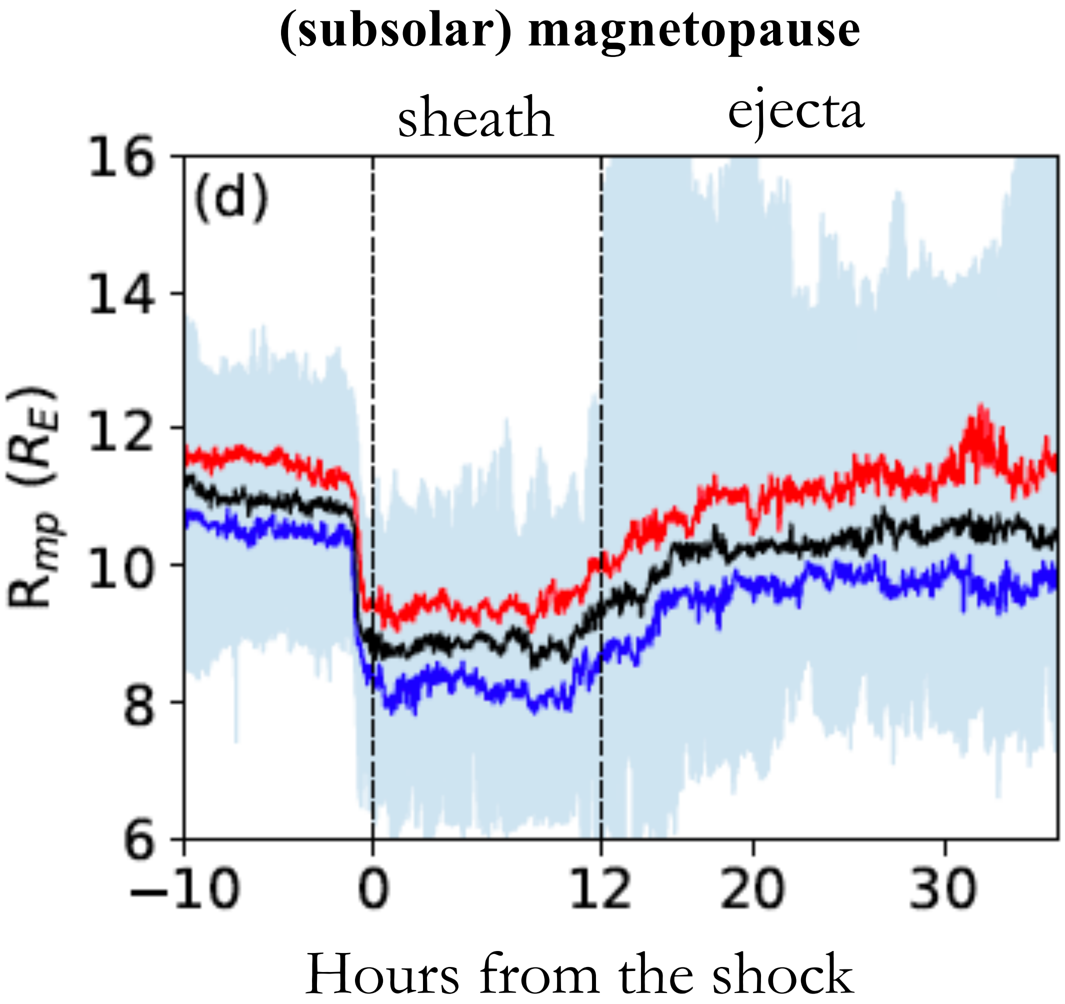
ICMEs and sheaths cause the strongest (southward) magnetic fields in the solar wind

Sheaths and SIRs have the highest dynamic pressure and field variability

→ large spread of solar wind parameters influencing the Earth

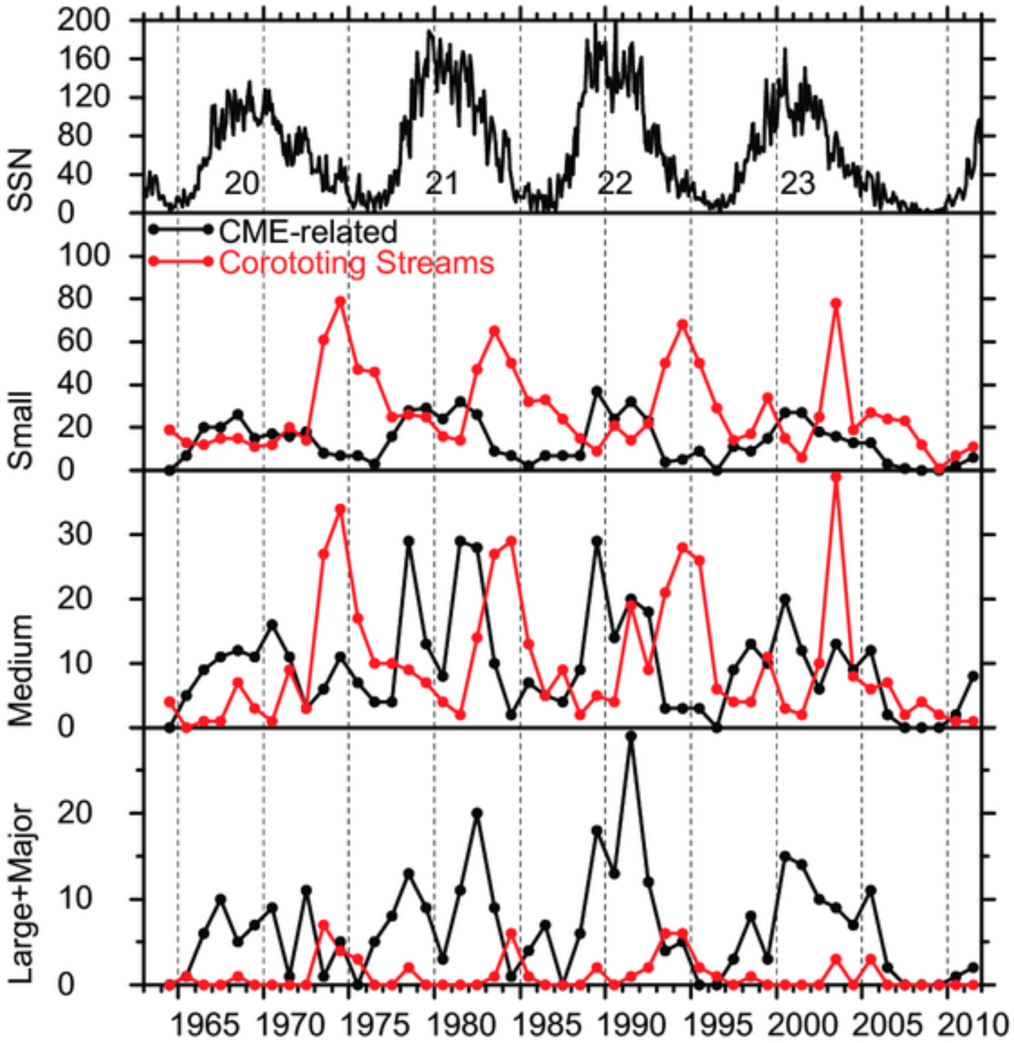
→ Different structures cause highly **different forcing**

Storm drivers: ICME vs. SIR + HSS



Sheaths compress strongly the magnetosphere!

Storm drivers: ICME vs. SIR + HSS

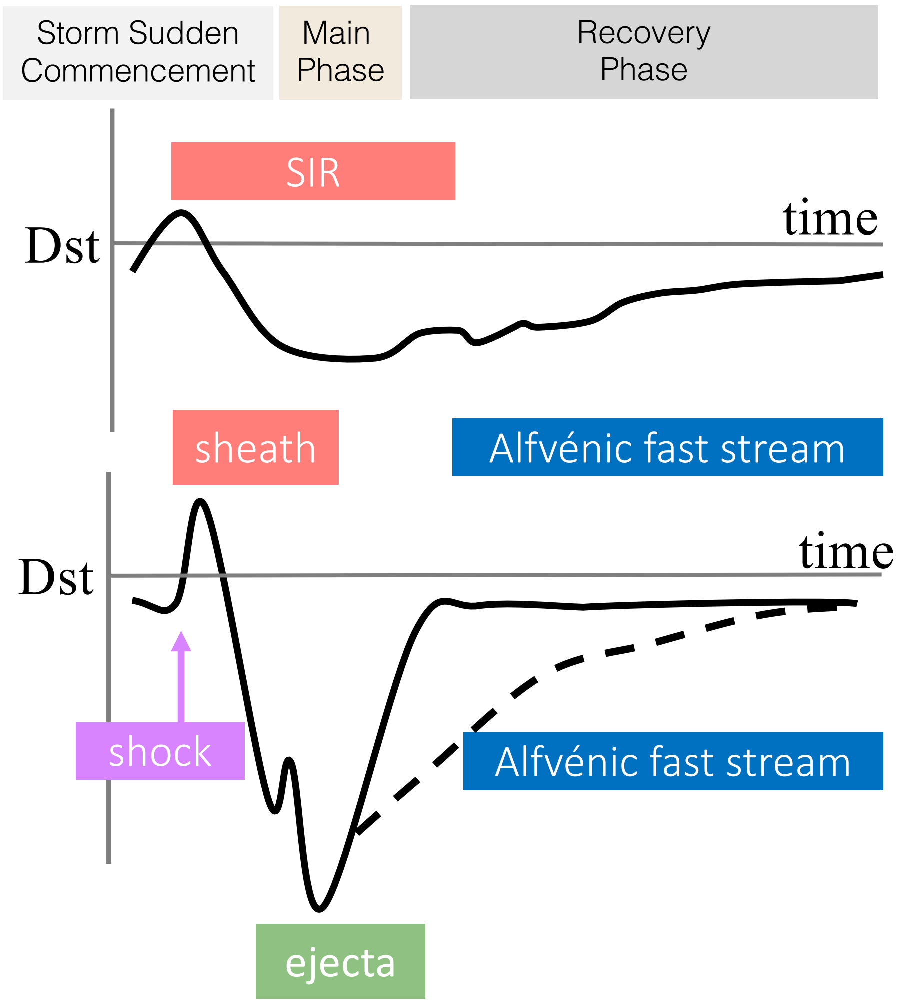


The rate of storms caused by **ICMEs** peaks near **solar maximum**. ICMEs drive **practically all large** and **major storms** because they can have the largest and most sustained southward IMF.

The rate of storms caused by **SIRs** peaks at the **declining phase** and solar **minimum**. SIRs drive mostly **small/medium storms**. The have typically weaker fields and the magnetic field direction fluctuates rapidly

Richardson and Cane, 2010

ICMEs, SIRs & storm phases



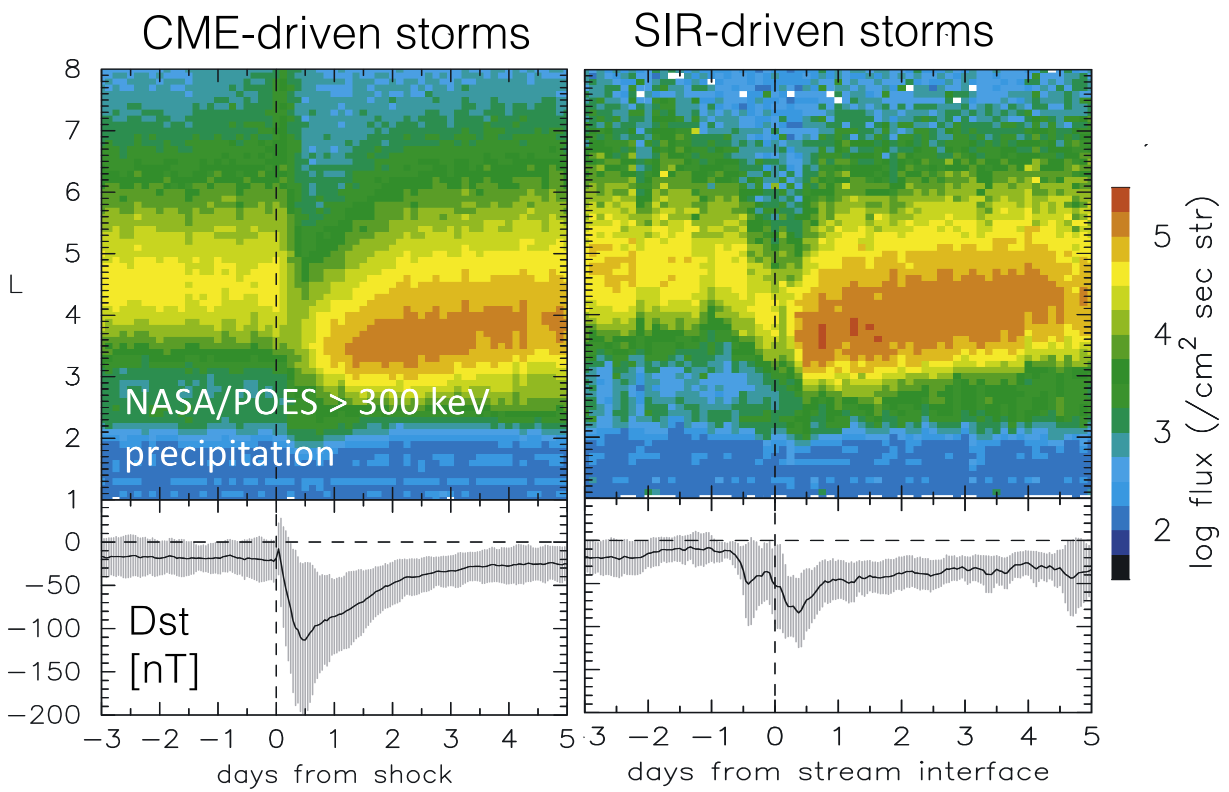
SIR-driven storm:

- Weak and moderate storms
- Relatively long recovery phases because SIRs are typically followed by a faster stream.

ICME-driven storm:

- 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.

Radiation belt response

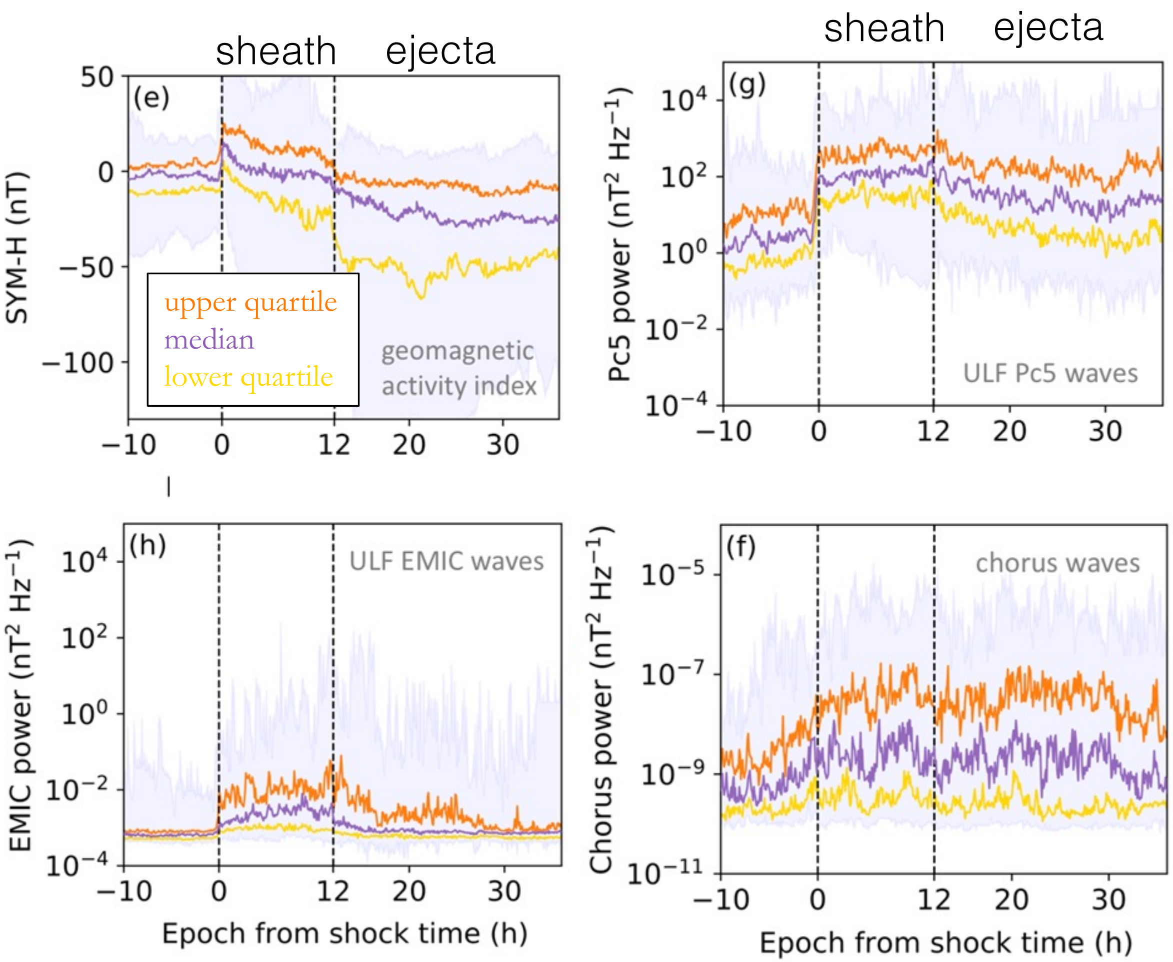


Kataoka and Miyoshi, 2006

For CME-driven storms fluxes recover slower (~ day later) than for SIR-associated storm.

SIR driven storms attain higher level of fluxes and the enhancement is broader.

Inner magnetosphere wave activity

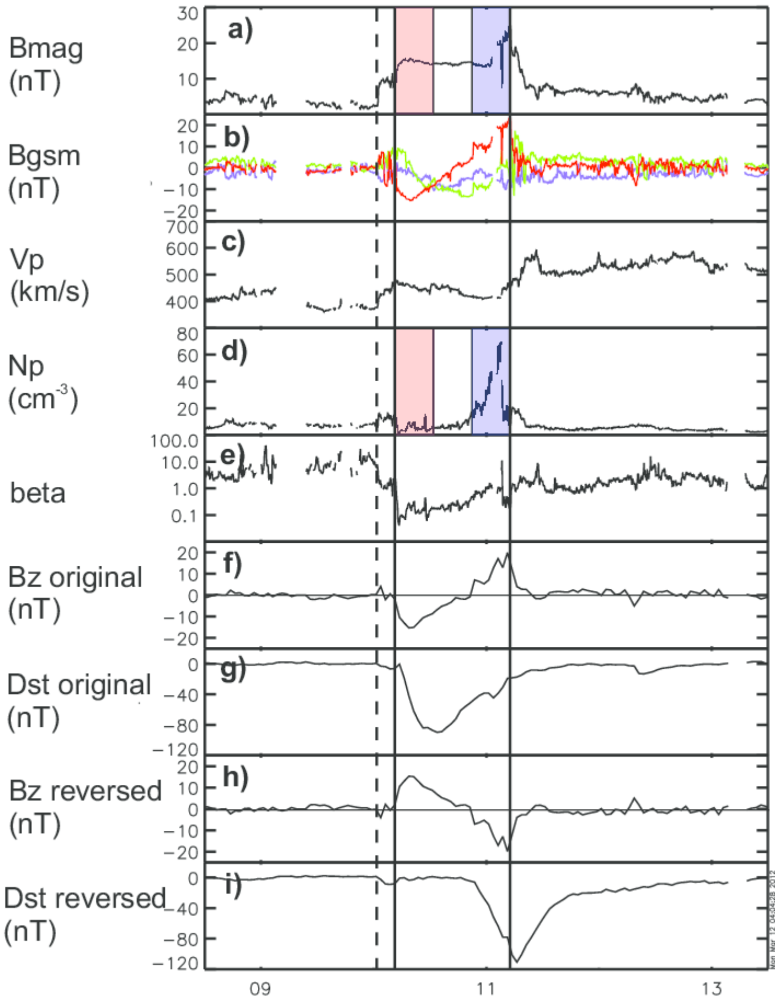


Kalliokoski et al., 2021

Sheaths in this data set are clearly less geoeffective than ejecta in terms of SYM-H (ring current), but induced similar level or higher wave activity in the inner magnetosphere

← 37 Sheath that were sampled to the same average duration (10.2 hours)

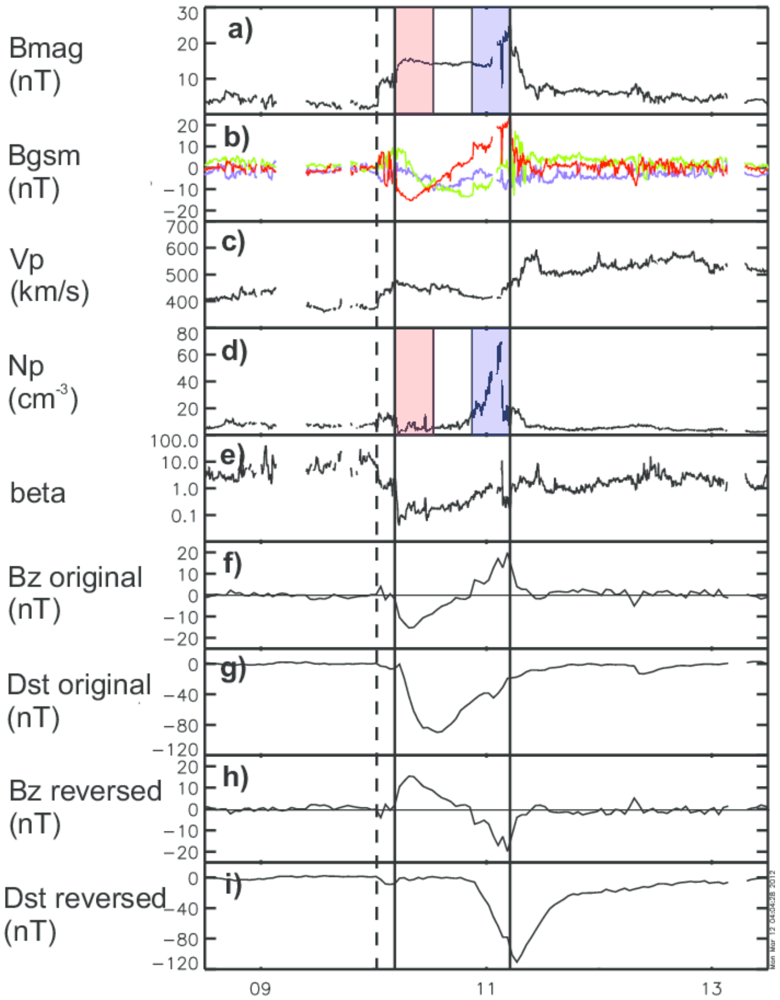
ICMEs at fast stream leading edges



- A significant fraction of ICMEs occur at the leading edge of fast streams
- Such ICMEs are typically **compressed** from behind and can have relatively **strong fields**.
- Geomagnetic response depends on the **flux rope type**

An ICME compressed at the leading edge of a fast stream (Kilpua et al., 2012, see also Fenrich & Luhmann, 1998)

ICMEs at fast stream leading edges

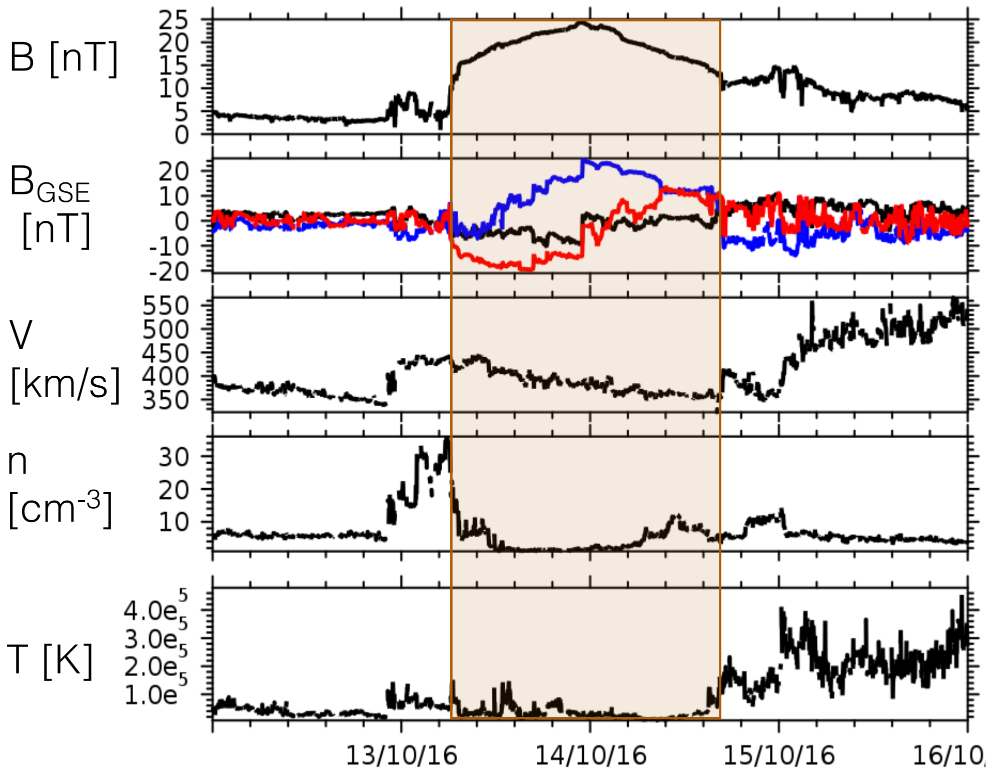


- **SN type:** northward fields enhance → no big effect
- **NS type**: southward fields enhance → stronger storm

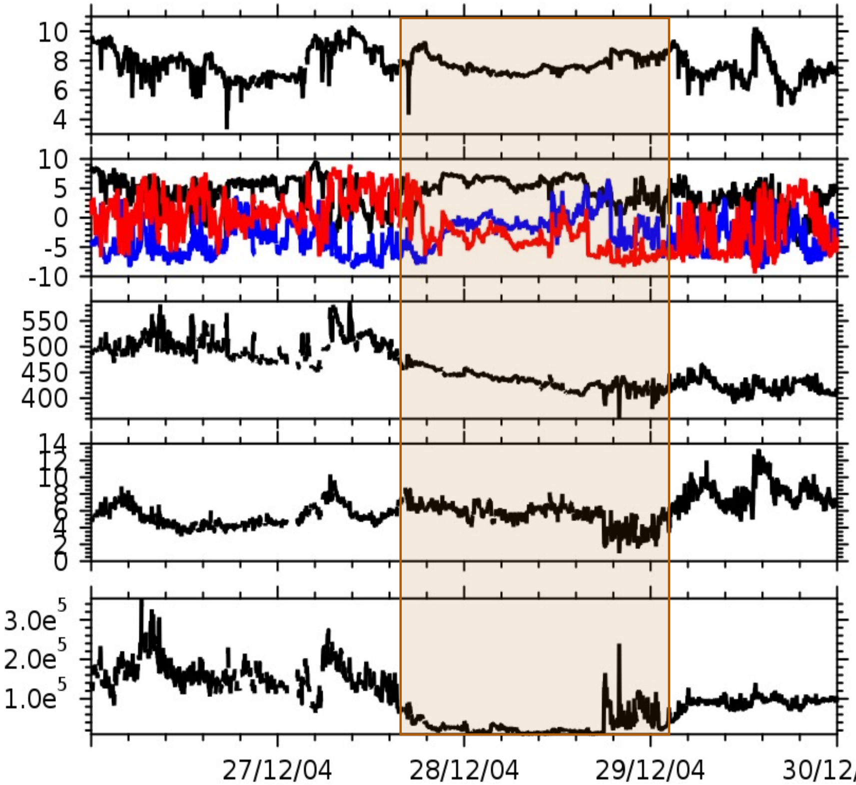
An ICME compressed at the leading edge of a fast stream (Kilpua et al., 2012)

Complexities

Expectation

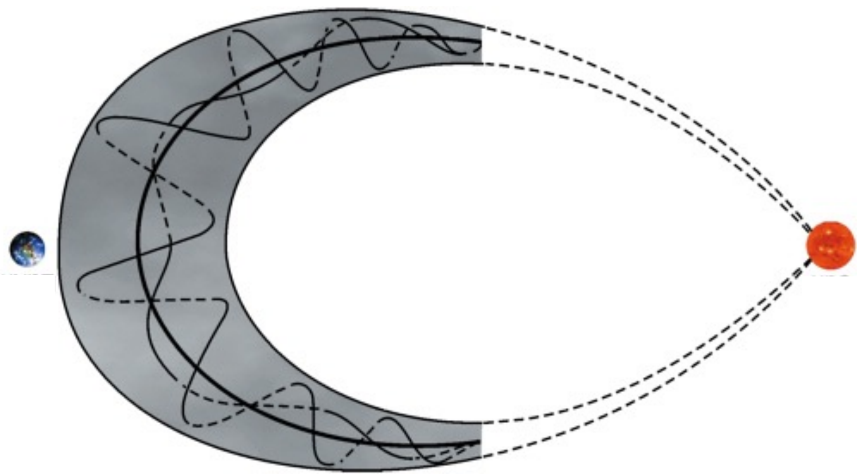


Reality…

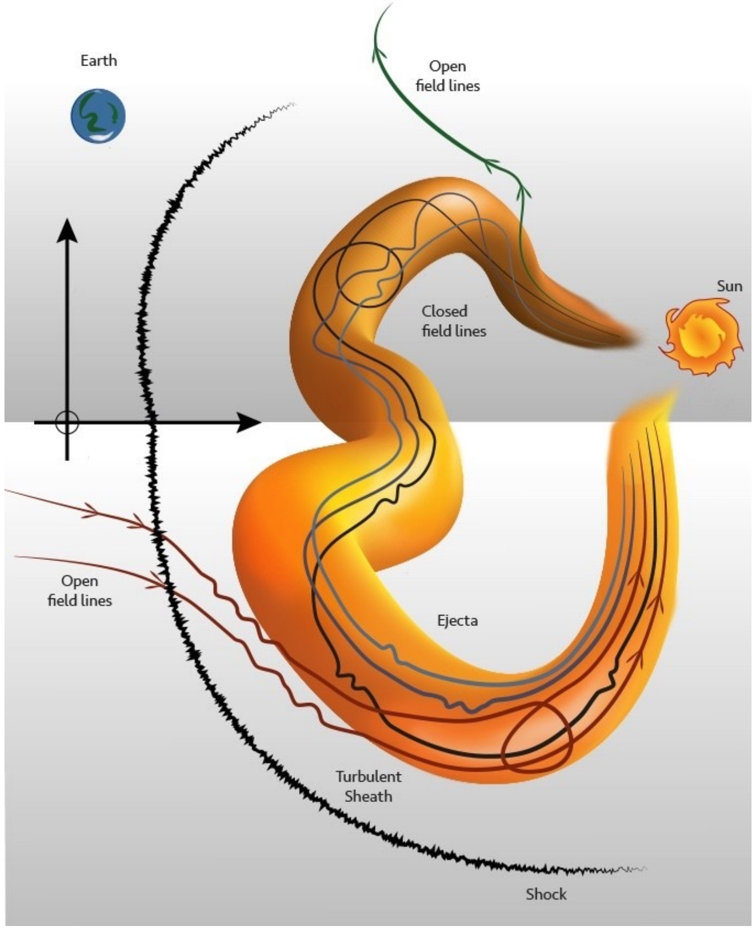


Complexities

Expectation

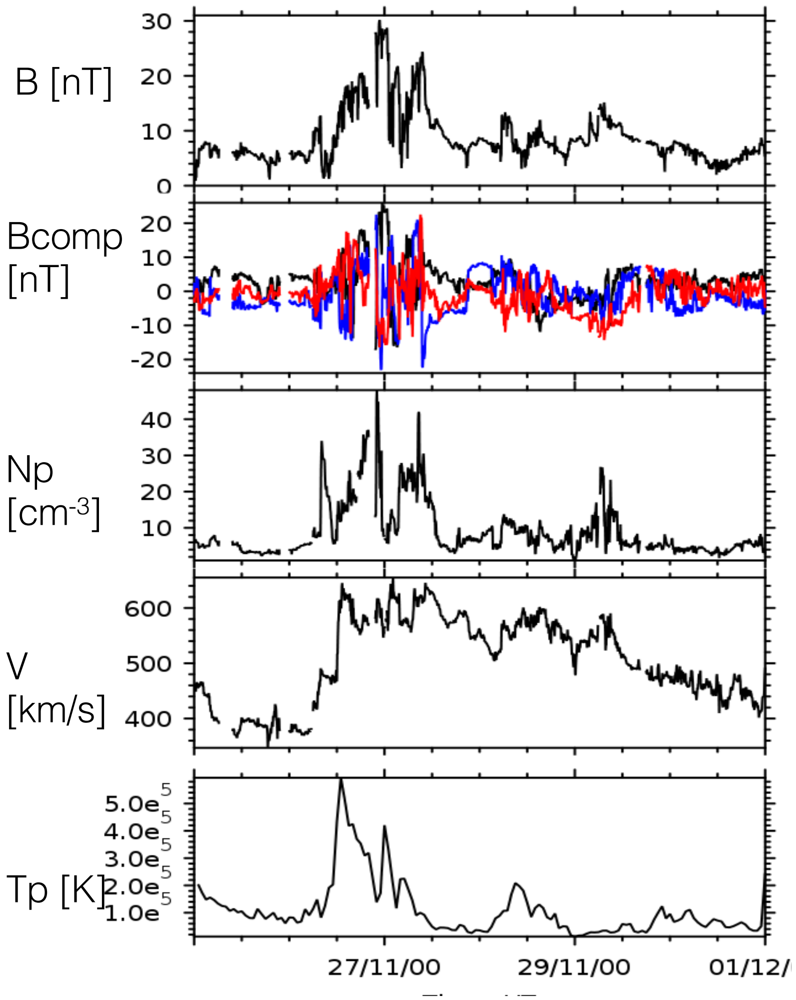


Reality…



Courtesy: Nada Al-Haddad

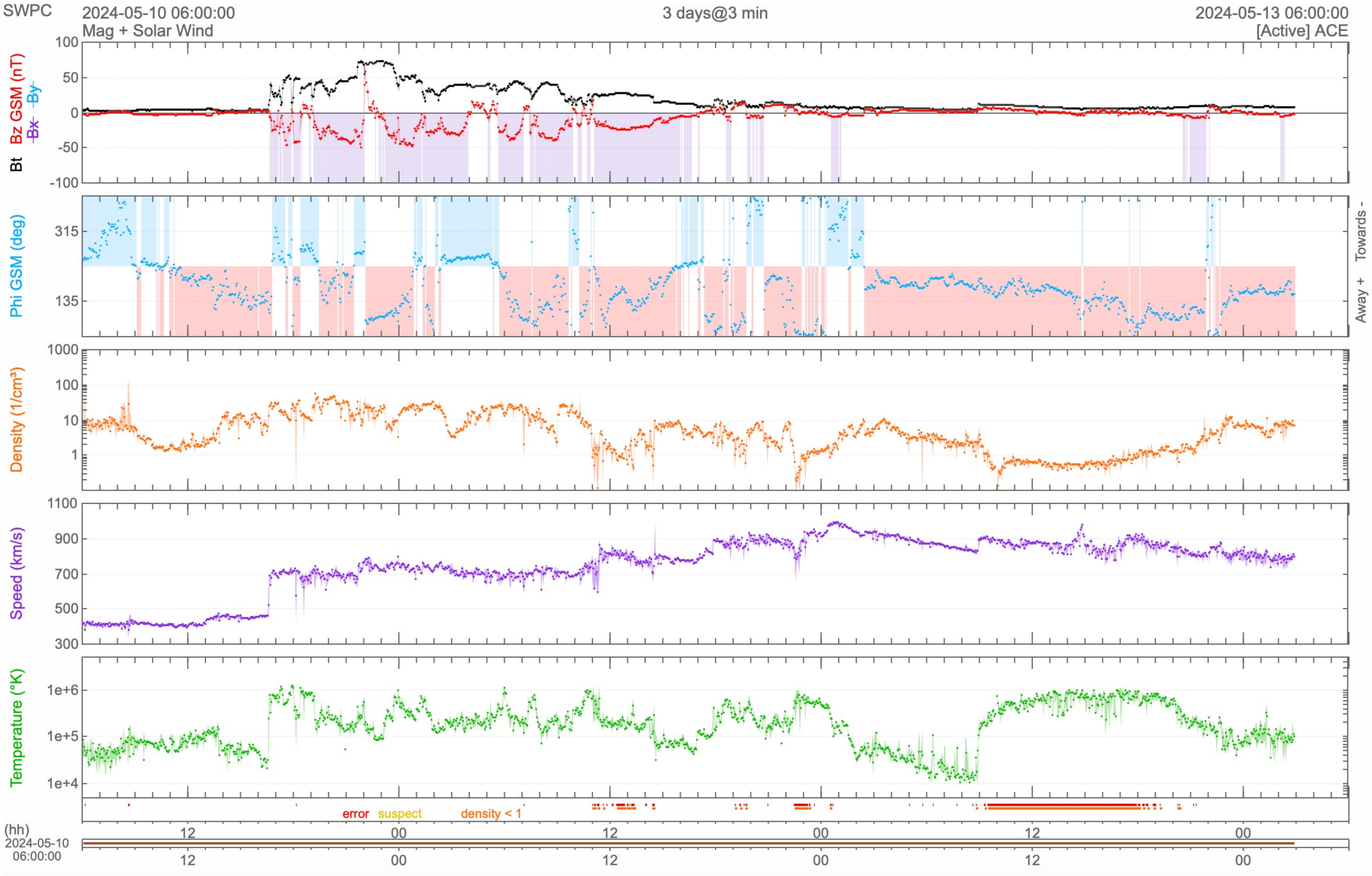
Complex Ejecta



Interactions between **multiple 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 the 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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3 days@3 min
2024-05-13 06:00:00
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Bz GSM (nT)
-Bx
-By
Phi GSM (deg)
Towards -
Away +
Density (1/cm³)
Speed (km/s)
Temperature (°K)
error
suspect
density < 1
(hh)
2024-05-10
06:00:00
12
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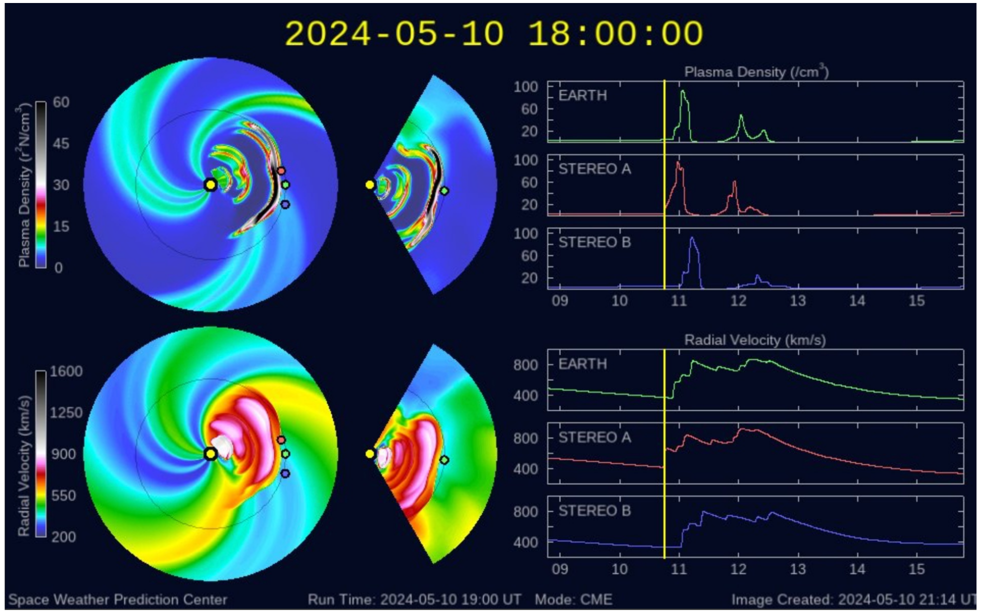
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Plasma Density (/cm³)
EARTH
STEREO A
STEREO B
Plasma Density (r²N/cm³)
Radial Velocity (km/s)
Space Weather Prediction Center
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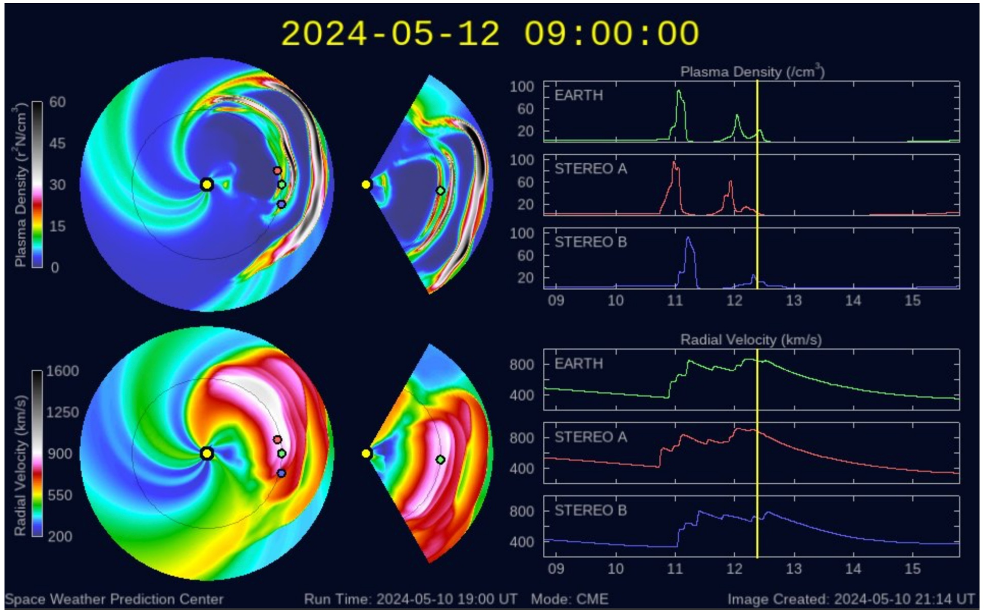
Mode: CME
Image Created: 2024-05-10 21:14 UT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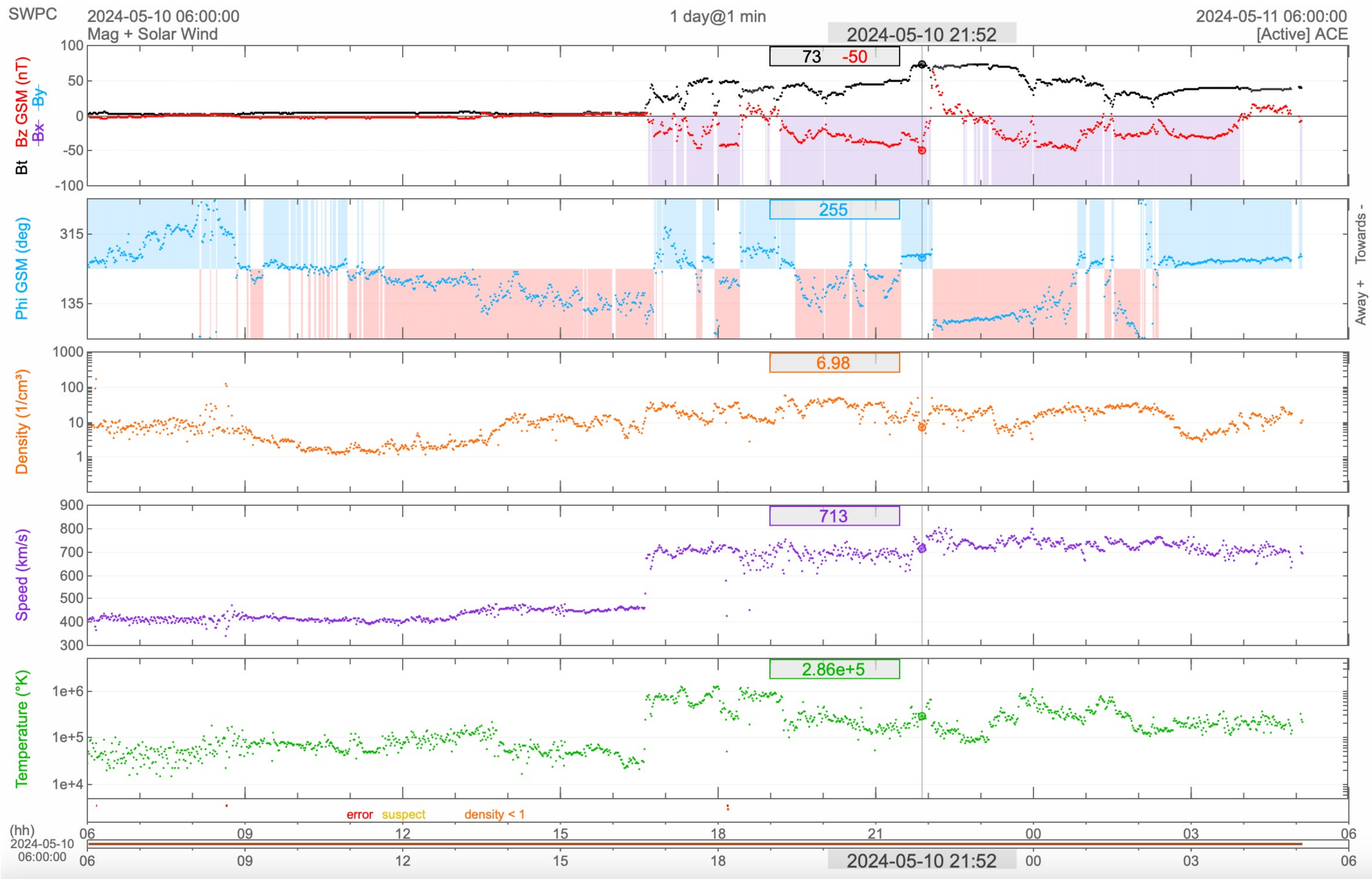
Plasma Density (/cm³)
EARTH
STEREO A
STEREO B
Plasma Density (r²N/cm³)
Radial Velocity (km/s)
Space Weather Prediction Center
Run Time: 2024-05-10 19:00 UT
Mode: CME
Image Created: 2024-05-10 21:14 UT


SWPC
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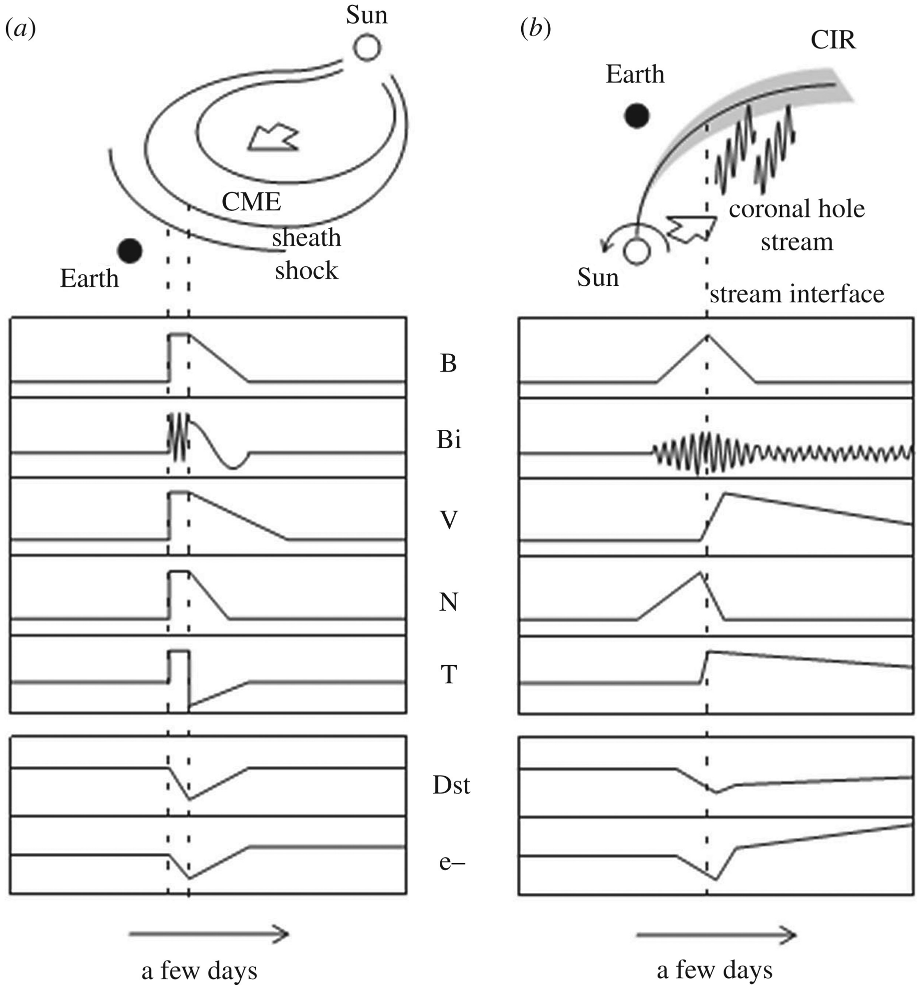
Mag + Solar Wind
1 day@1 min
2024-05-10 21:52
2024-05-11 06:00:00
[Active] ACE
73 -50
Bt Bz GSM (nT) -Bx -By
255
Phi GSM (deg)
Towards -
Away +
6.98
Density (1/cm³)
713
Speed (km/s)
2.86e+5
Temperature (°K)
error suspect density < 1
(hh)
2024-05-10
06:00:00
06 09 12 15 18 21 00 03 06

Summary



Kataoka and Miyoshi, 2006

- Key drivers: ICMEs (shock, sheath ejecta), SIR and fast streams
- ICME flux rope type affects strongly on its geoeffectivity
- Different drivers have highly different solar wind conditions → different geomagentic response