Solar wind - magnetosphere interactions

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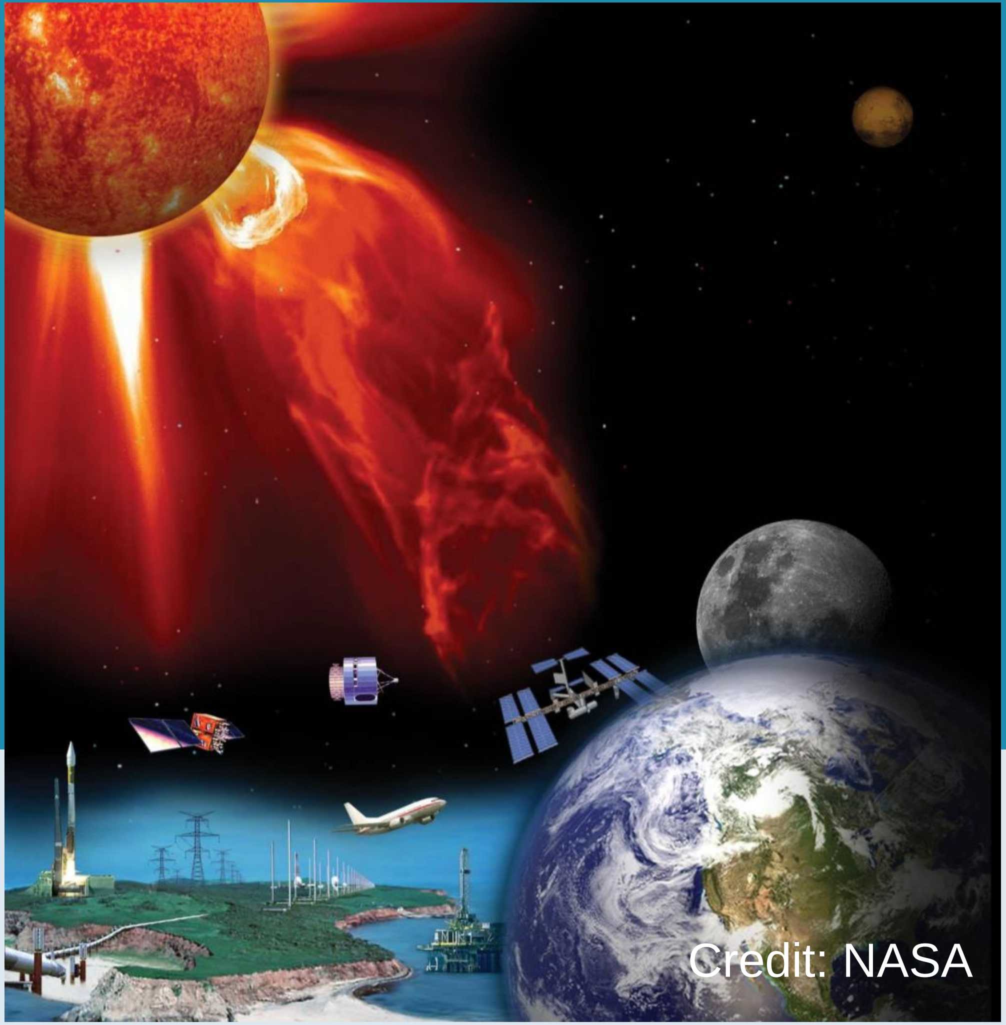


2nd PITHIA NRF – T-FORS school, 05/02/'24

Outline

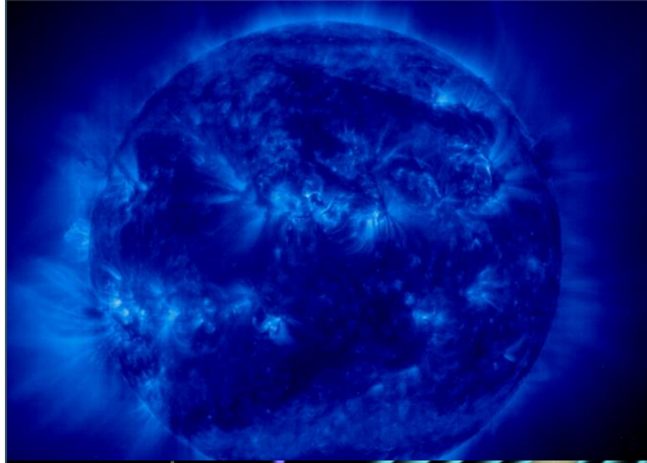
- Influence of the Sun on Earth: **Space Weather!**

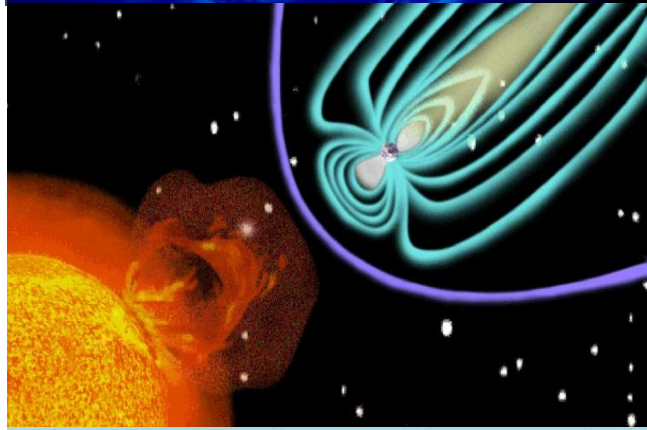
  (definition, effects & socio-economic impact…)

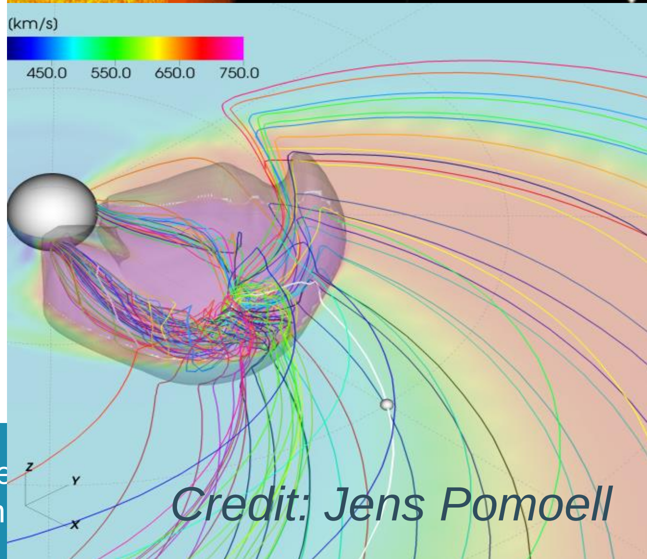
- **The magnetosphere of the Earth**

- **Solar wind - magnetosphere interactions**

  & space weather prediction models:
  data-driven models with *predictive* capabilities,
  enabling forecasting and mitigation







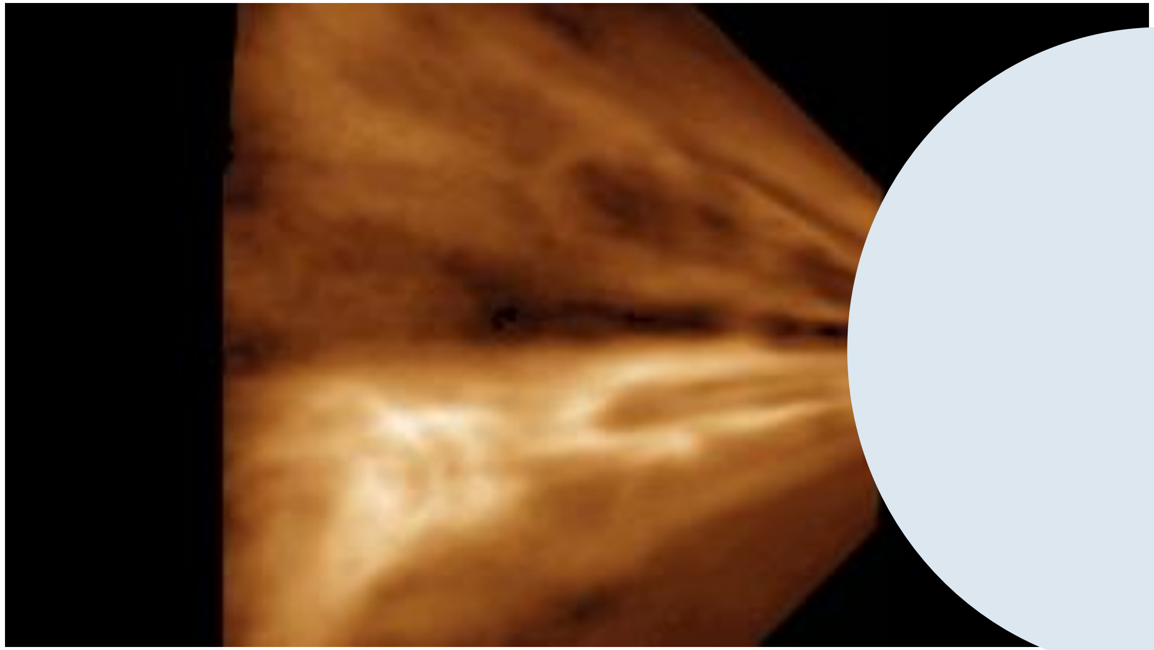
Credit: Jens Pomoell

The solar wind

- Stream of particles leaving the Sun (~10^9 kg/s)
- Fills the entire solar system (heliosphere)

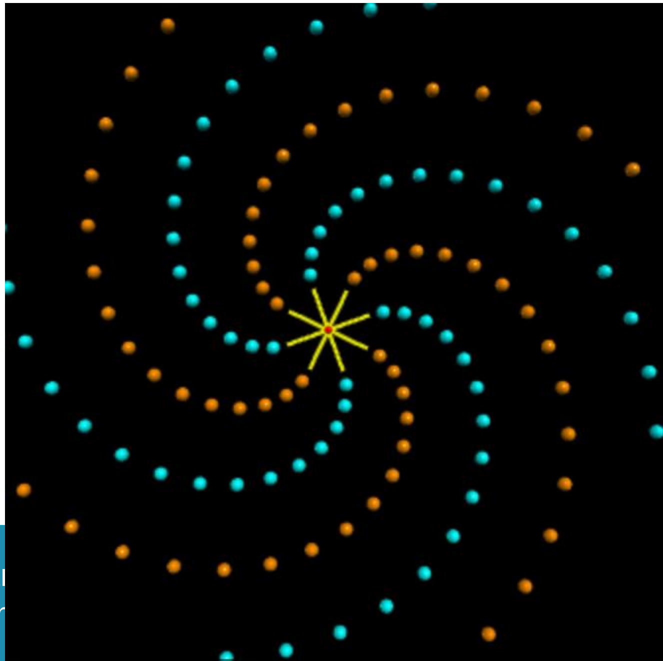
- "Low" energy particles (0.5 - 10 keV)
- ***Slow*** and ***fast*** wind: 300 – 750$^+$ km/s
  (also different chemical composition)

- Drags out the solar magnetic field:
  - *Interplanetary magnetic field (IMF)*
  - *Spiral structure due to solar rotation*

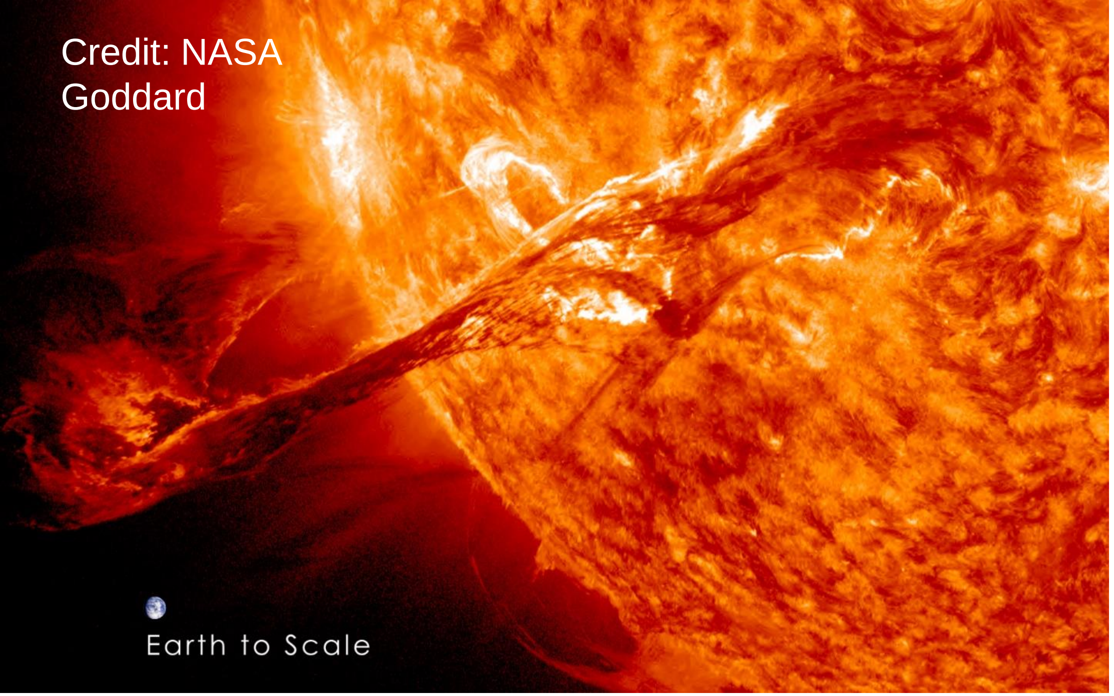


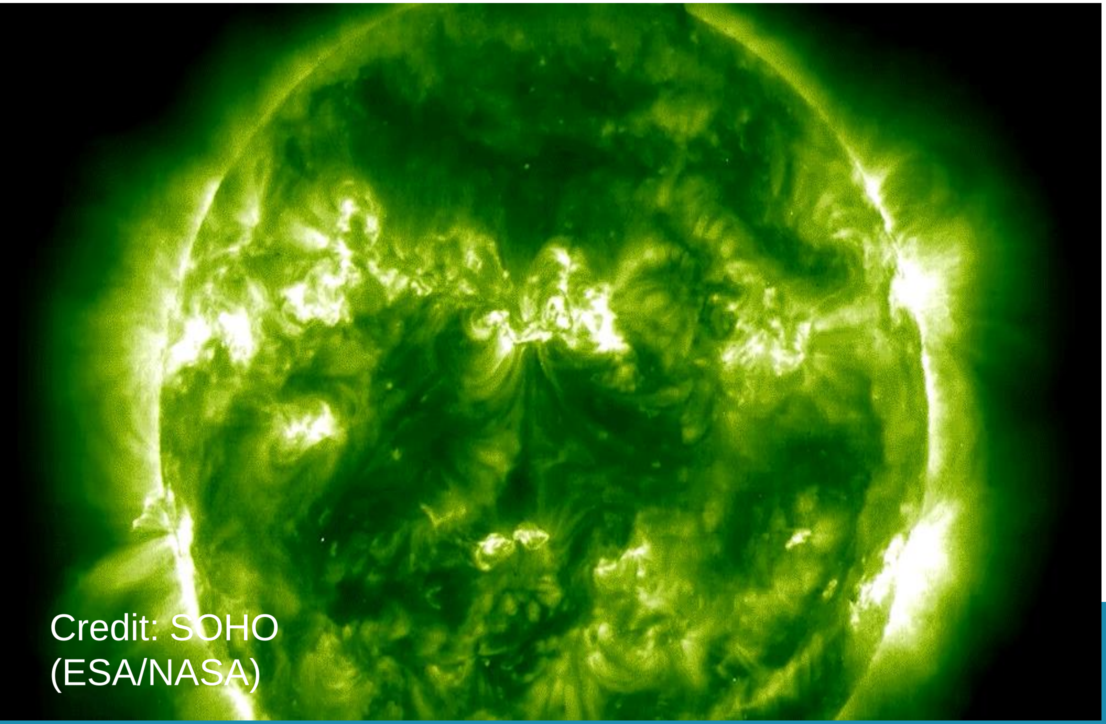
Processed solar wind images (comoving-frame averaging) of STEREO A (COR2).

DeForest+(2018)



Ecliptic view
Source: N. Wijsen





Solar storms

Coronal mass ejections (CMEs)

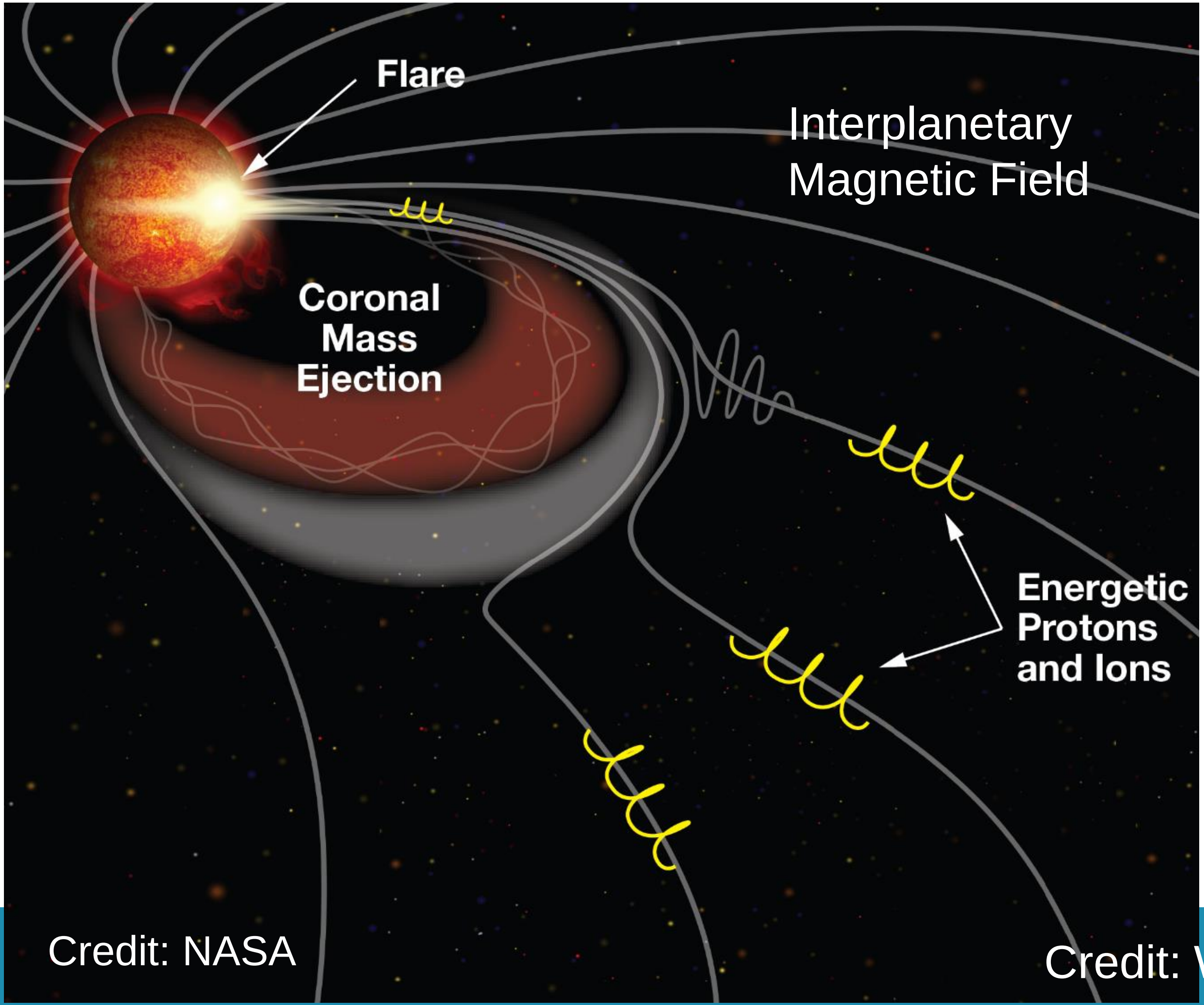
- *Enormous clouds of hot plasma launched into space*
- Propagation speed: typ. 450 km/s but range from 350 to 3000⁺ km/s

(> 10 million km/hour!)

Solar Flares

- *Intense release of high-energy radiation (EUV, X-rays, Gamma-rays)*
- *Accelerate particles!*

Solar energetic particles (SEPs)



Credit: NASA

- CMEs **can** act as powerful particle accelerators too!
- Electrons, protons, ions
- Energies: keV - GeV

  1 MeV proton → 14 000 km/s

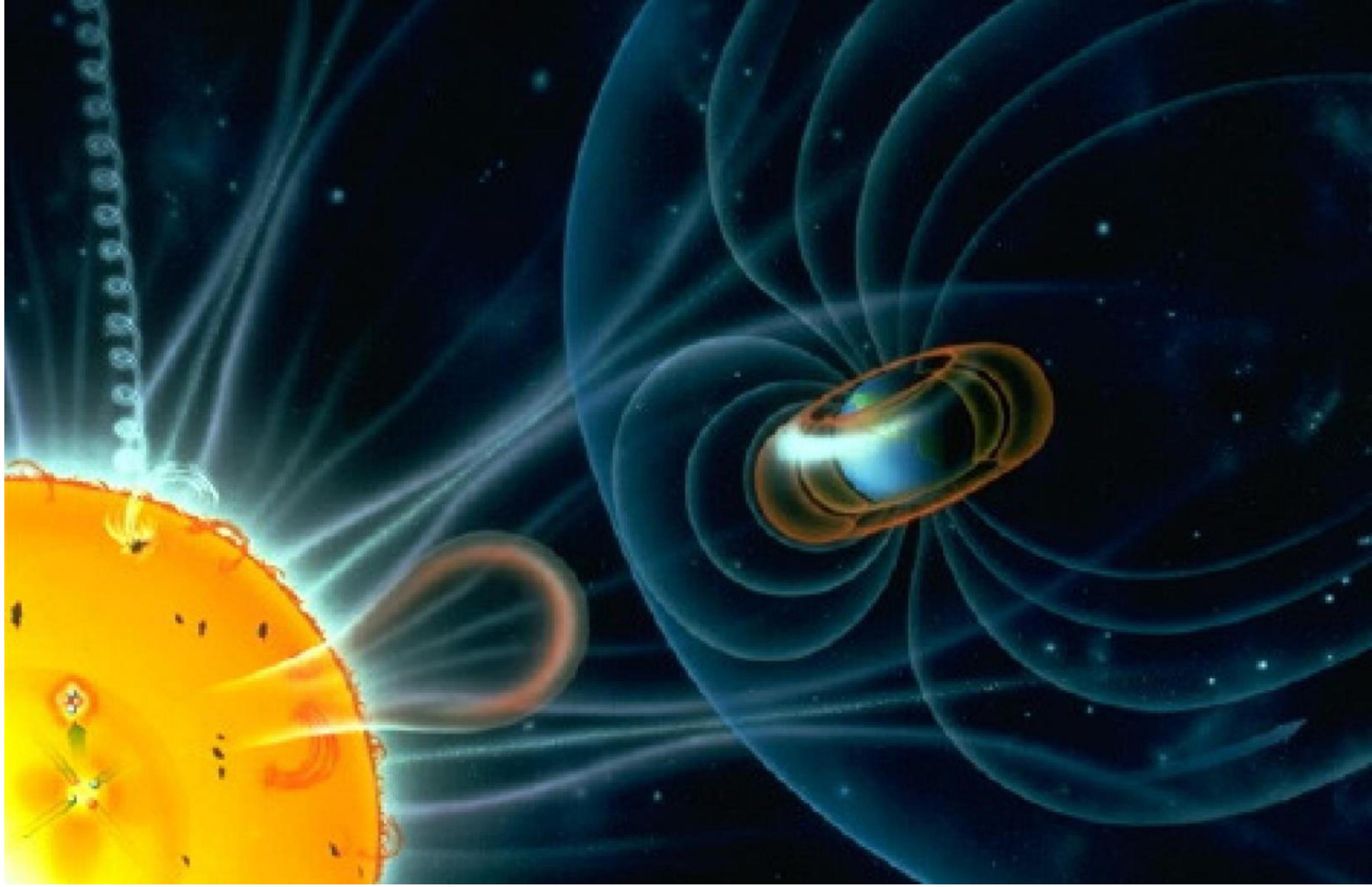
  1 GeV proton → 262 000 km/s

  Much more energetic than the solar wind!

- Charged particles: spiral around IMF

Credit: Wijsen (2020)

‘Space Weather’



cf. USA NSWP

Strategic Plan:

“Space Weather refers to conditions on the sun and in the solar wind, magnetosphere, ionosphere, and thermosphere that can influence the performance and reliability of space-borne and ground-based technological systems and can endanger human life or health.”

Solar flares and CMEs

When a CME is ejected in the direction of the Earth, we see a so-called **‘halo CME’**
(about 10% of all the CMEs, more than 1 per week during solar maximum)

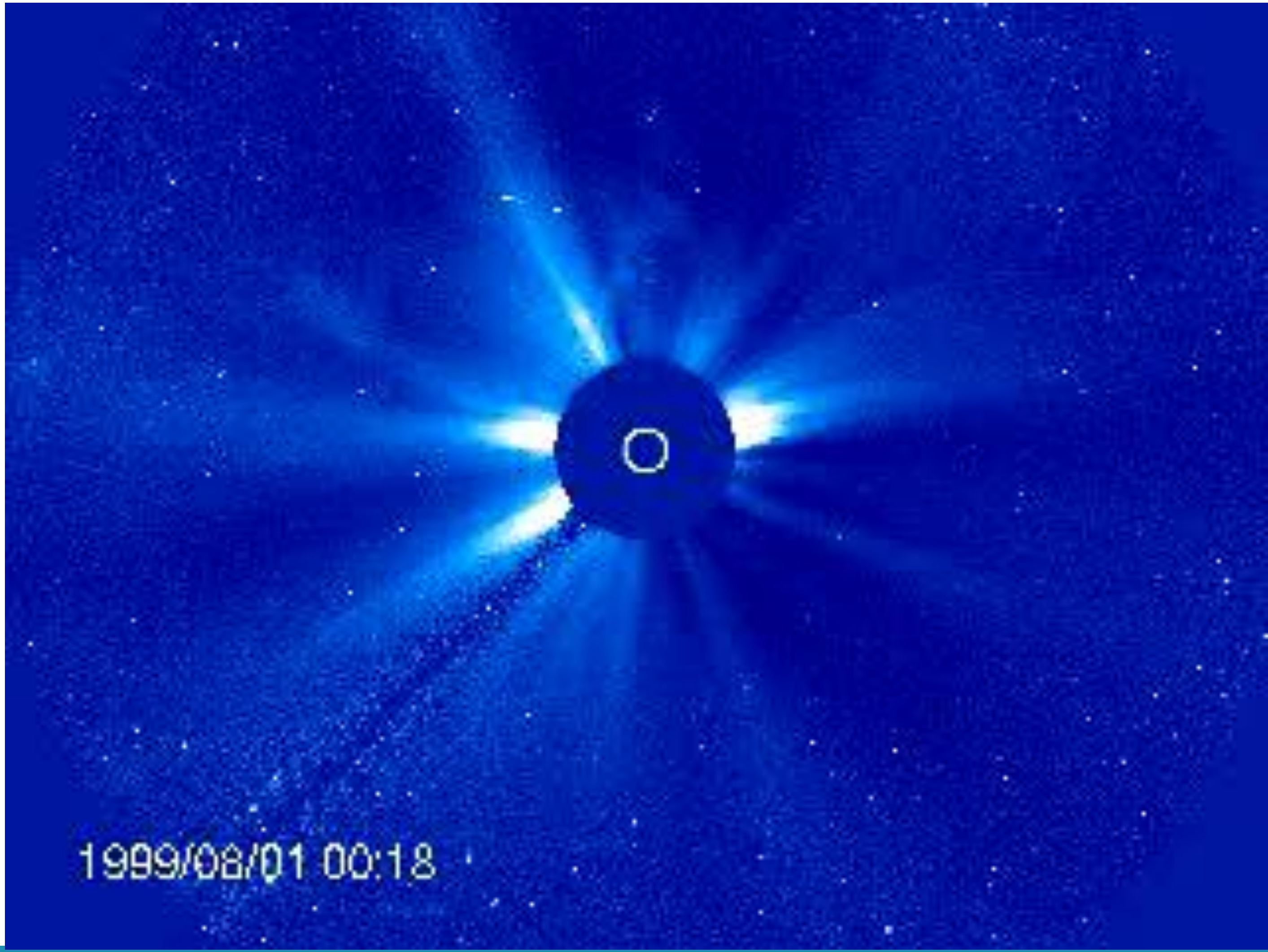
(halo) CMEs:

V_{cme} = 100 - 3000 km/s, typ. 450 km/s

Mass = 10^{13} - 10^{16} g

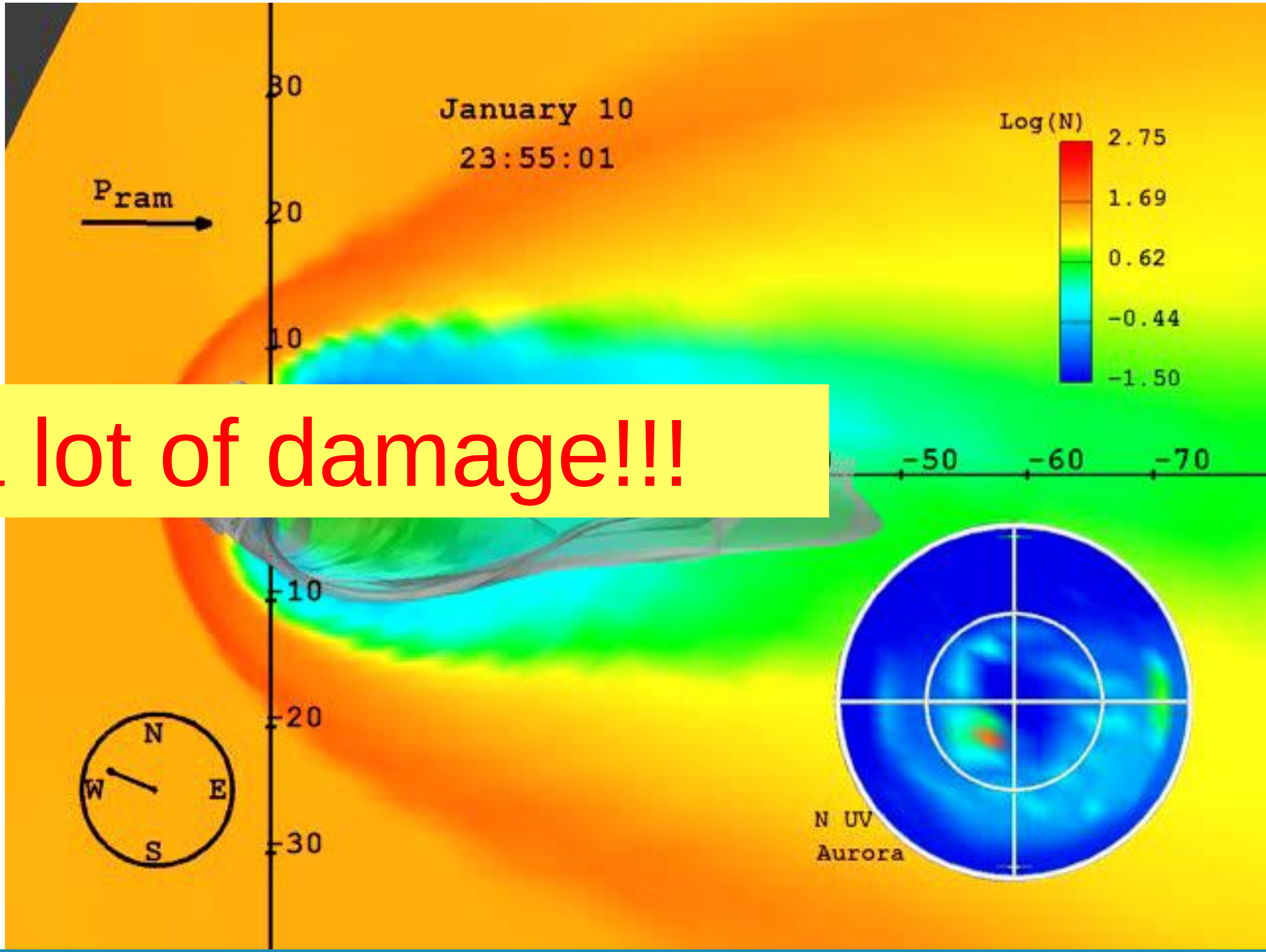
Energy = 10^{27} - 10^{33} erg

(1st: OSO7 (’71) see Bruecker et al. ’72)



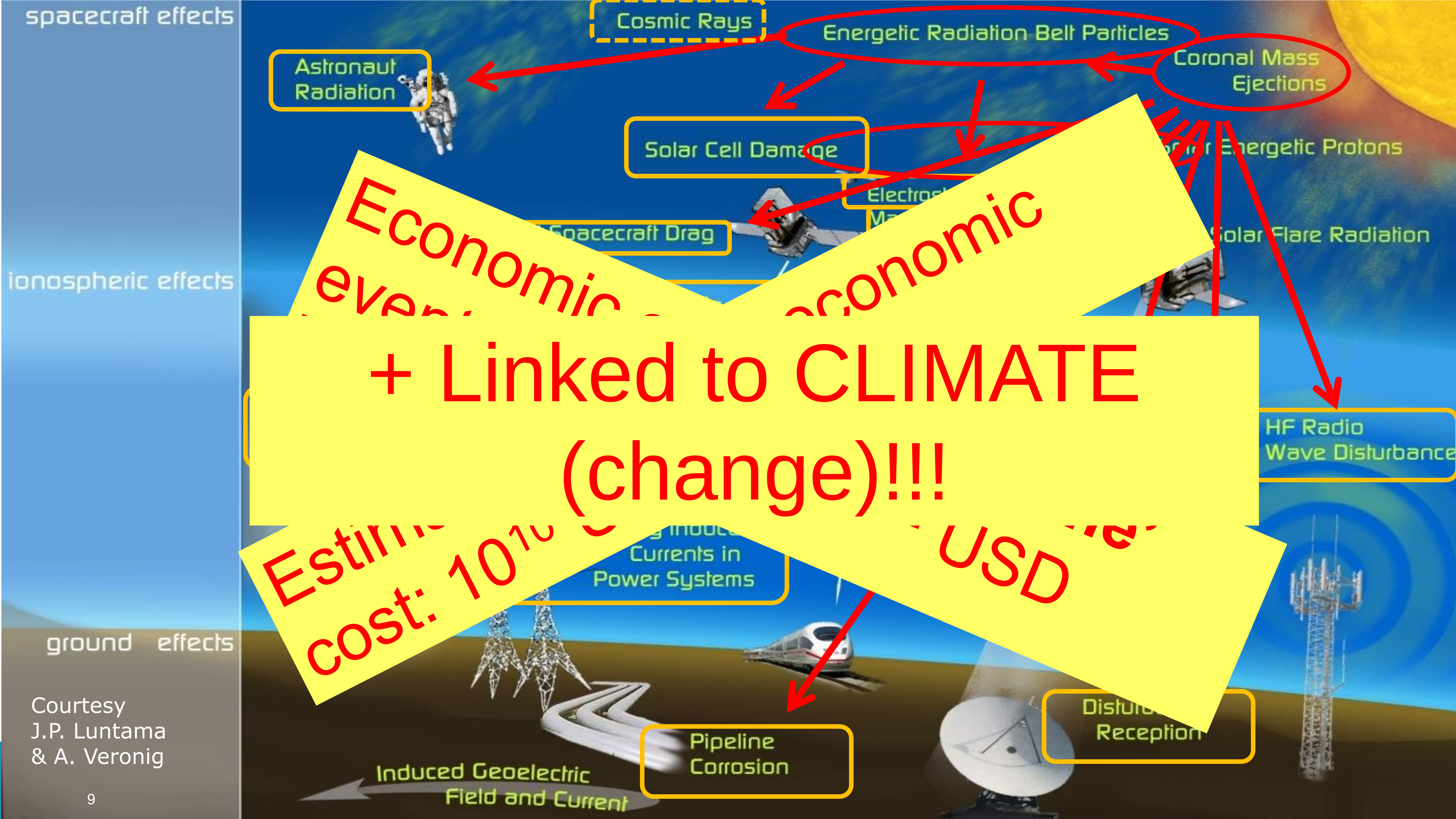
SoHO-Lasco C3

Geomagnetic storms

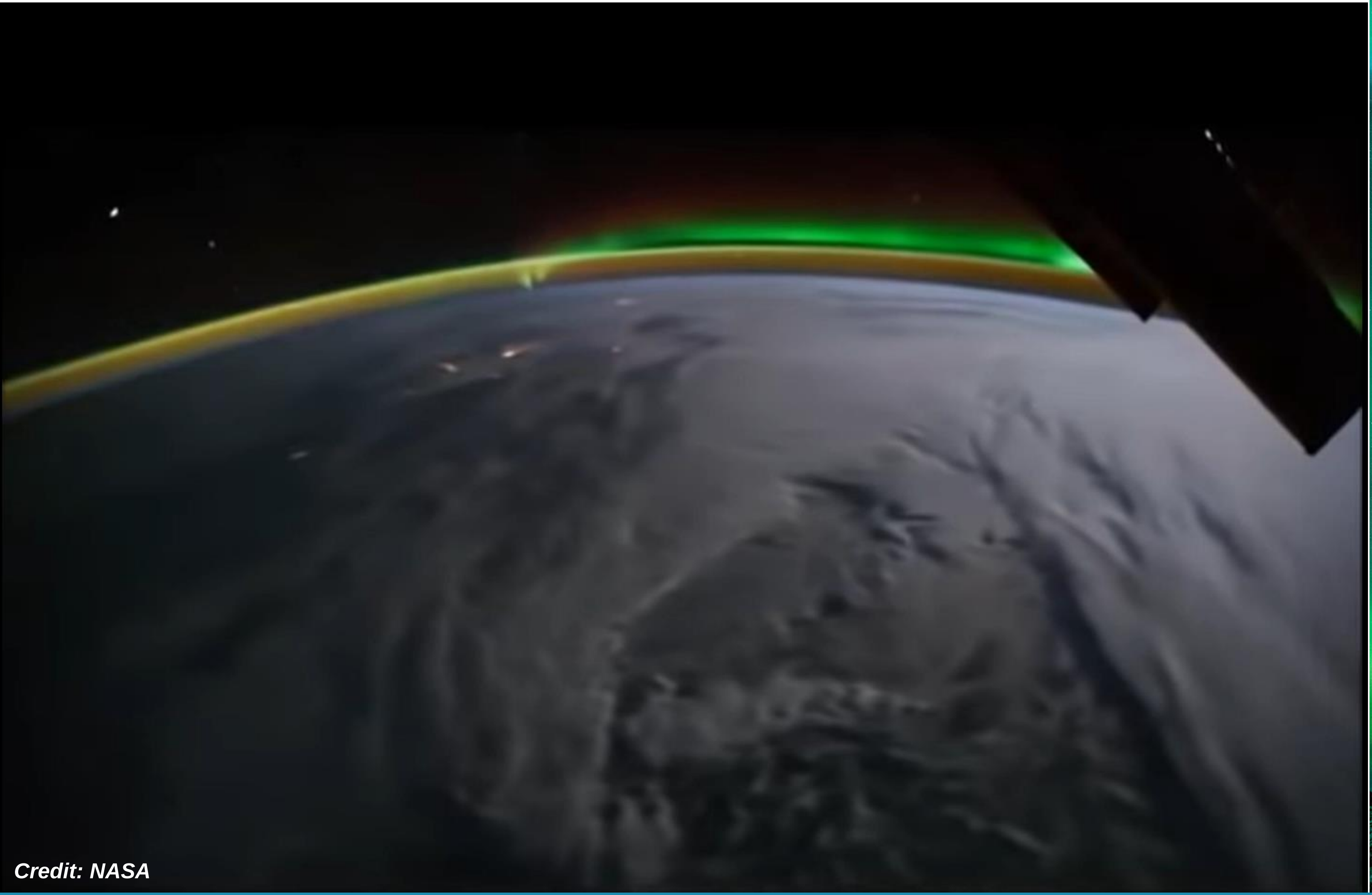


These cause a lot of damage!!!

Simulation of SW interaction with magnetosphere


spacecraft effects
ionospheric effects
ground effects
Cosmic Rays
Astronaut Radiation
Energetic Radiation Belt Particles
Coronal Mass Ejections
Solar Cell Damage
Spacecraft Drag
Solar Flare Radiation
HF Radio Wave Disturbance
Currents in Power Systems
Pipeline Corrosion
Reception
Induced Geoelectric Field and Current
Economic
economic
cost:
USD
+ Linked to CLIMATE (change)!!!
Courtesy J.P. Luntama & A. Veronig

Aurora

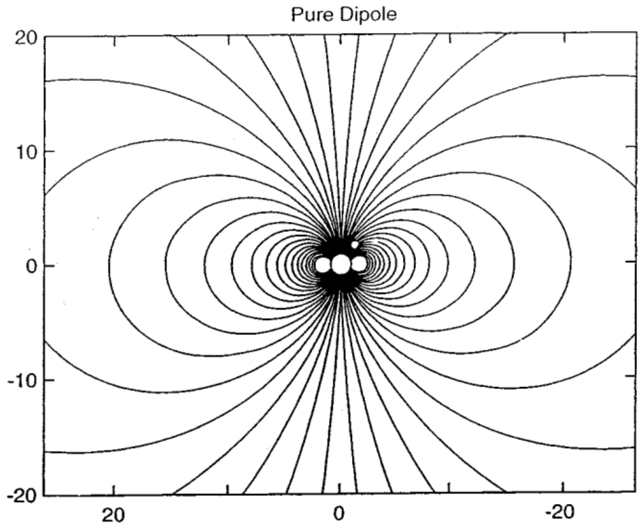


Credit: NASA

Image courtesy of Johnny Henriksen/Spaceweather.com

Dipole magnetic field in a wind

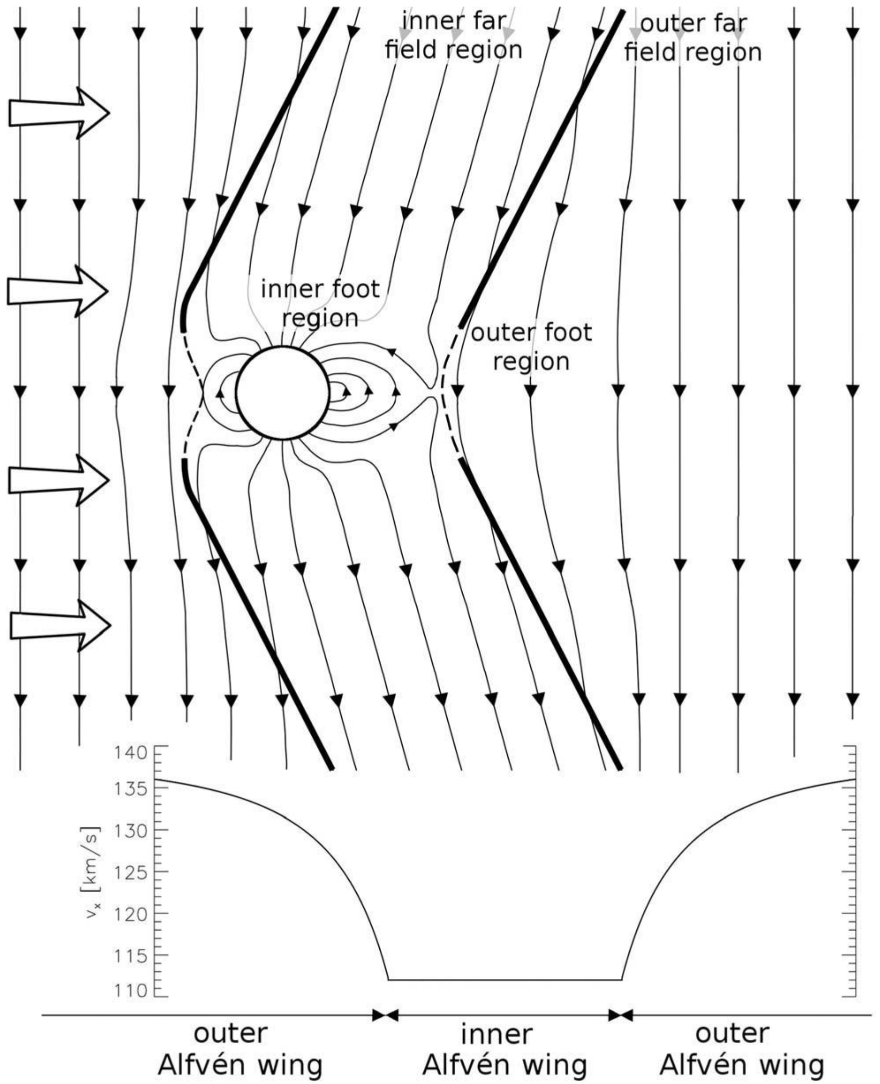
The magnetic field of the Earth is ***essentially a dipole***.
The interaction of the solar wind with it, is ‘*complicated*’.



Field lines of a magnetic dipole in a plane containing the dipole axis.
From Russel (2000).

Ganymede, located in the magnetosphere of Jupiter, possesses an internal dipole field and is embedded in a **sub-Alfvénic plasma flow** (coming from the left on the sketch), but also subsonic in contrast to the situation at Earth.

Top: Sketch of Ganymede and its magnetic field lines (thin lines), where the external magnetic field and the dipole moment are parallel to each other. The boundary between the inner part of the **Alfvén wings** and the outer part is represented by bold lines. *Bottom*: Plasma velocity profile across the Alfvén wing. From Chané et al. (2012)

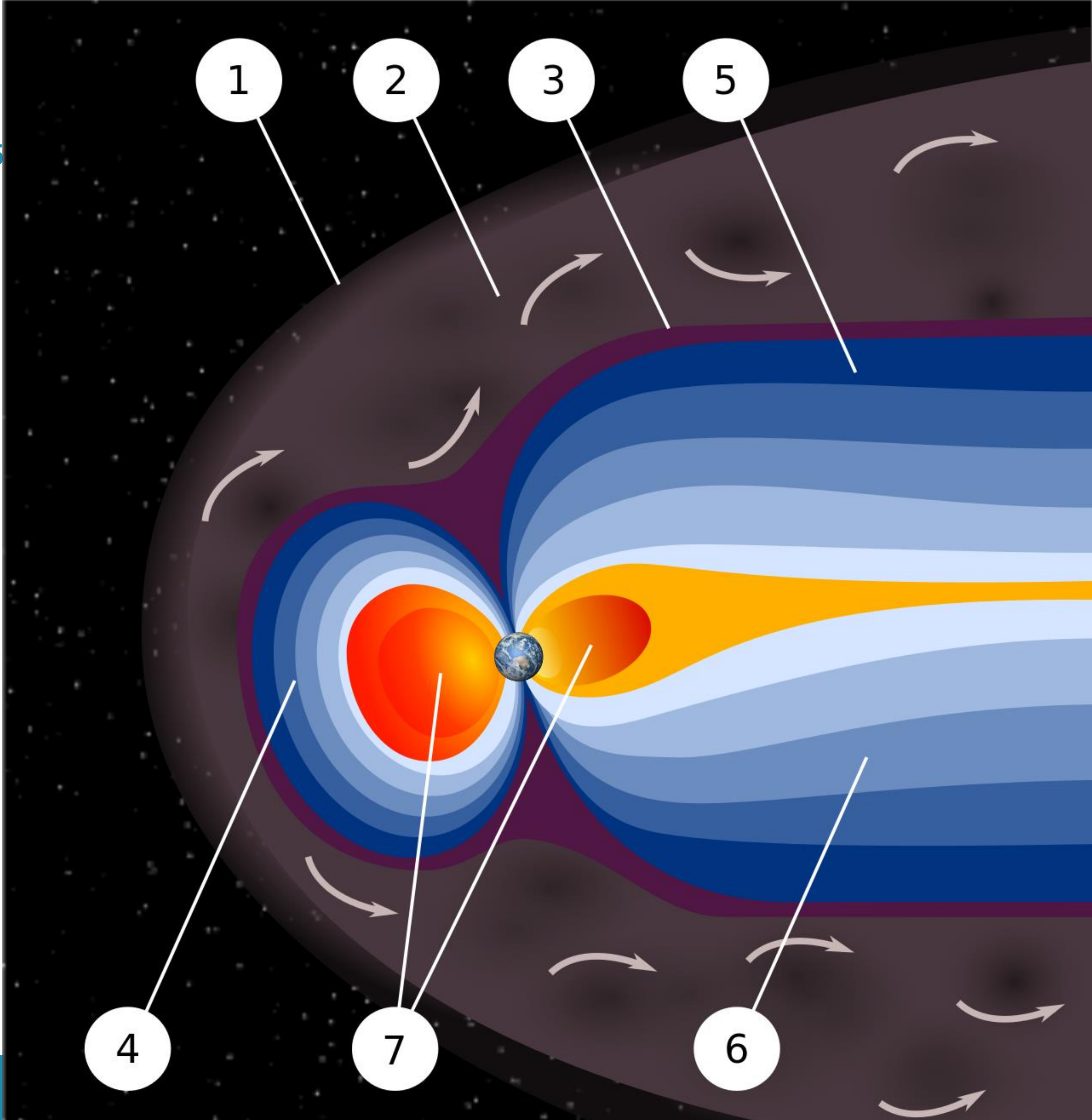


The magnetosphere 1/5

An artist's rendering of the structure of a magnetosphere:

1) **Bow shock:**

- The solar wind at the orbit of the Earth is **usually strongly super-Alfvénic and super-fast**, causing a *bow-shock* to be formed upstream of the Earth to deviate the solar wind around it
- **outermost layer** of the magnetosphere
- due to interactions with the bow shock, the solar wind plasma becomes ***anisotropic*** which leads to various plasma ***instabilities upstream and downstream of the bow shock***

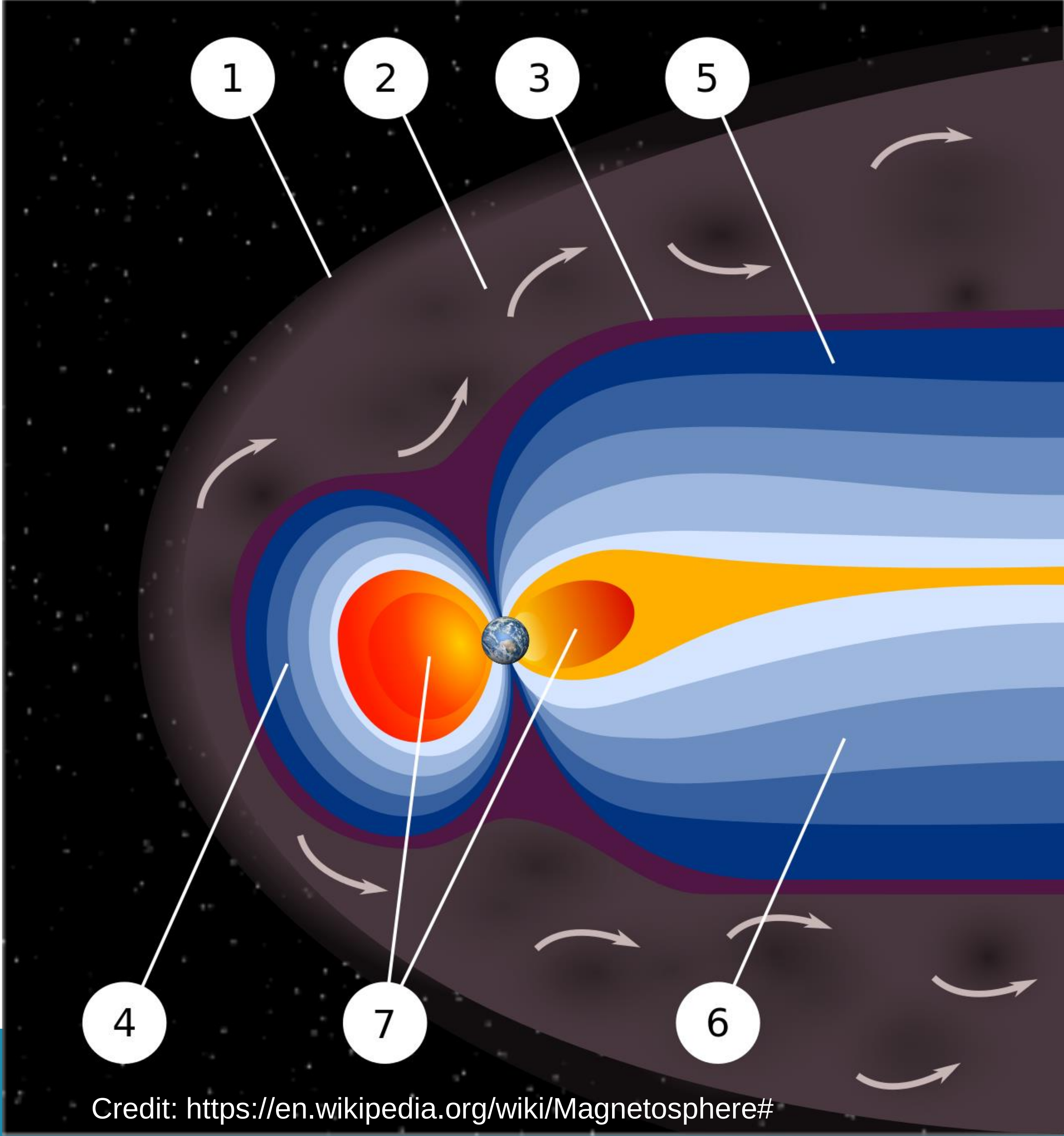


Credit: https://en.wikipedia.org/wiki/Magnetosphere#

The magnetosphere 2/5

2) **Magnetosheath:**

- between the bow shock and the magnetopause
- contains mainly shocked solar wind (+ a little magnetospheric plasma)
- exhibits high particle energy flux
- the direction and magnitude of the magnetic field varies erratically

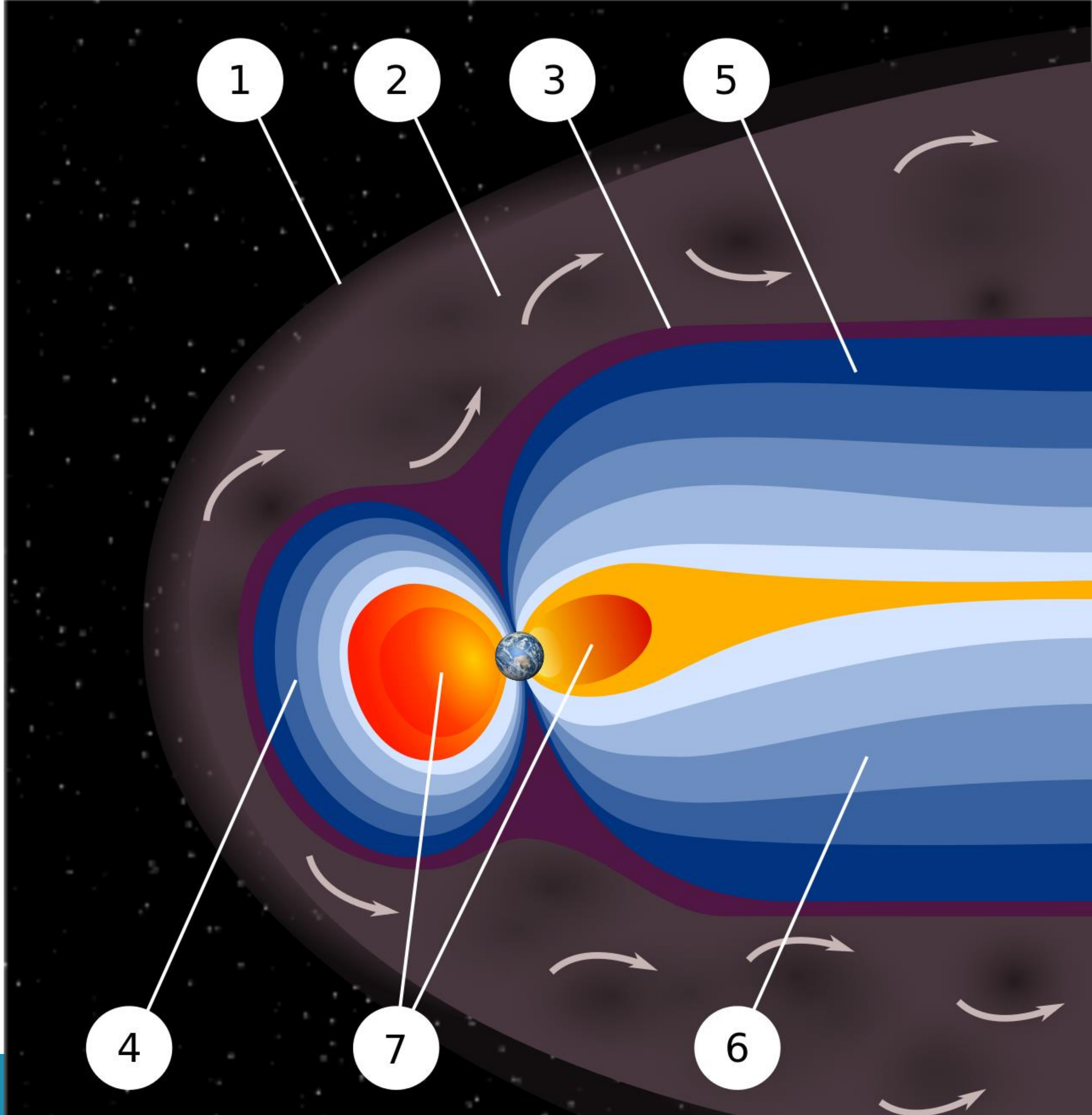


Credit: https://en.wikipedia.org/wiki/Magnetosphere#

The magnetosphere 3/5

3) **Magnetopause:**

- where pressure from magnetospheric field is balanced by that from solar wind
- where the shocked solar wind from the magnetosheath meets the magnetospheric field and plasma
- **structure varies** depending upon the *Mach number, plasma beta, and the magnetic field*
- **size and shape vary** as the dynamic pressure from the solar wind fluctuates



Credit: https://en.wikipedia.org/wiki/Magnetosphere#

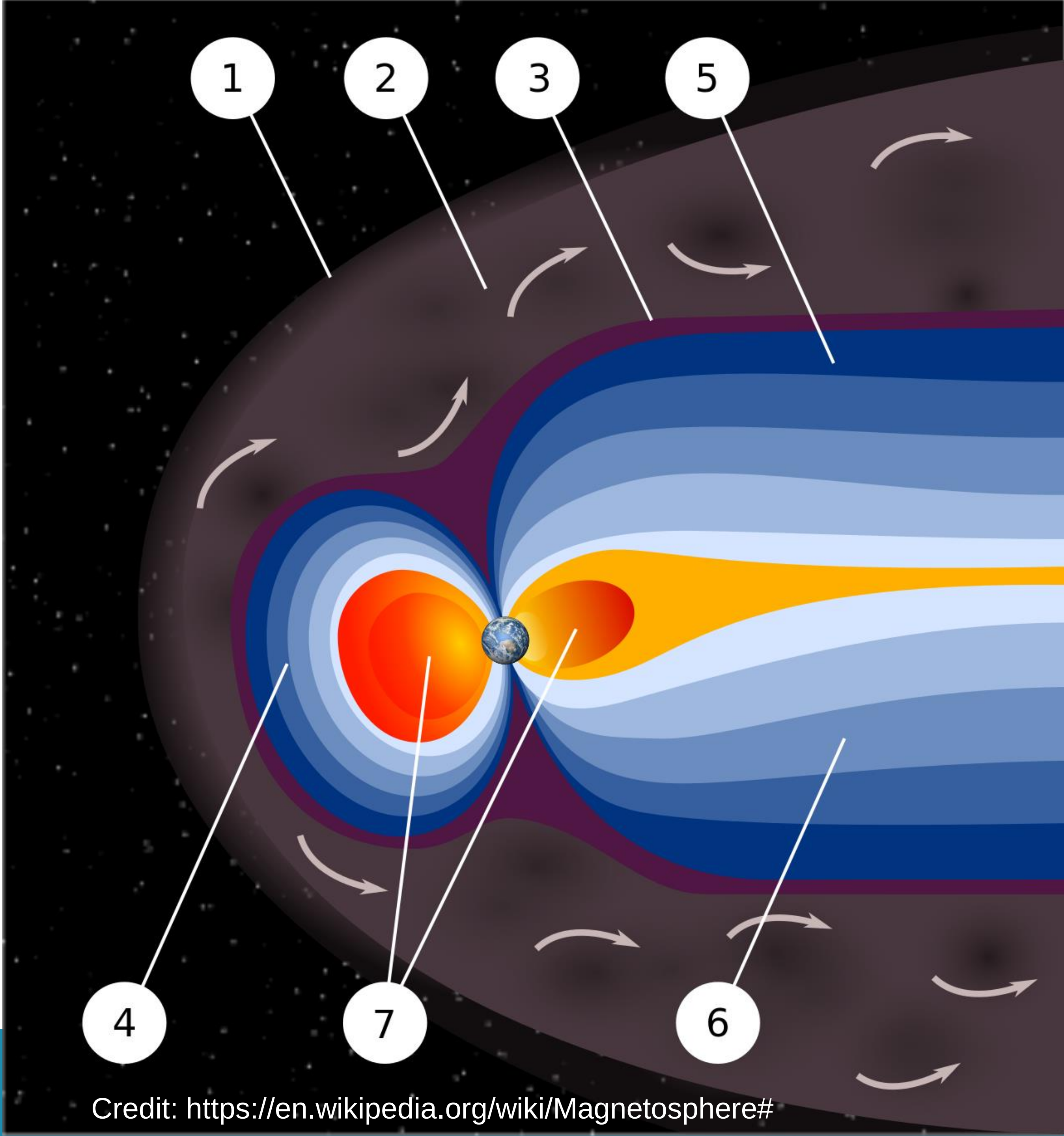
The magnetosphere 4/5

4) **Magnetosphere:** compressed magnetic field, and, opposite to it the **Magnetotail,** extending far beyond the Earth

5) **Northern tail lobe** where the magnetic field lines point towards Earth

6) **Southern tail lobe** where the magnetic field lines point away from Earth

The tail lobes are separated by a **plasma sheet** (weak **B**, higher density)

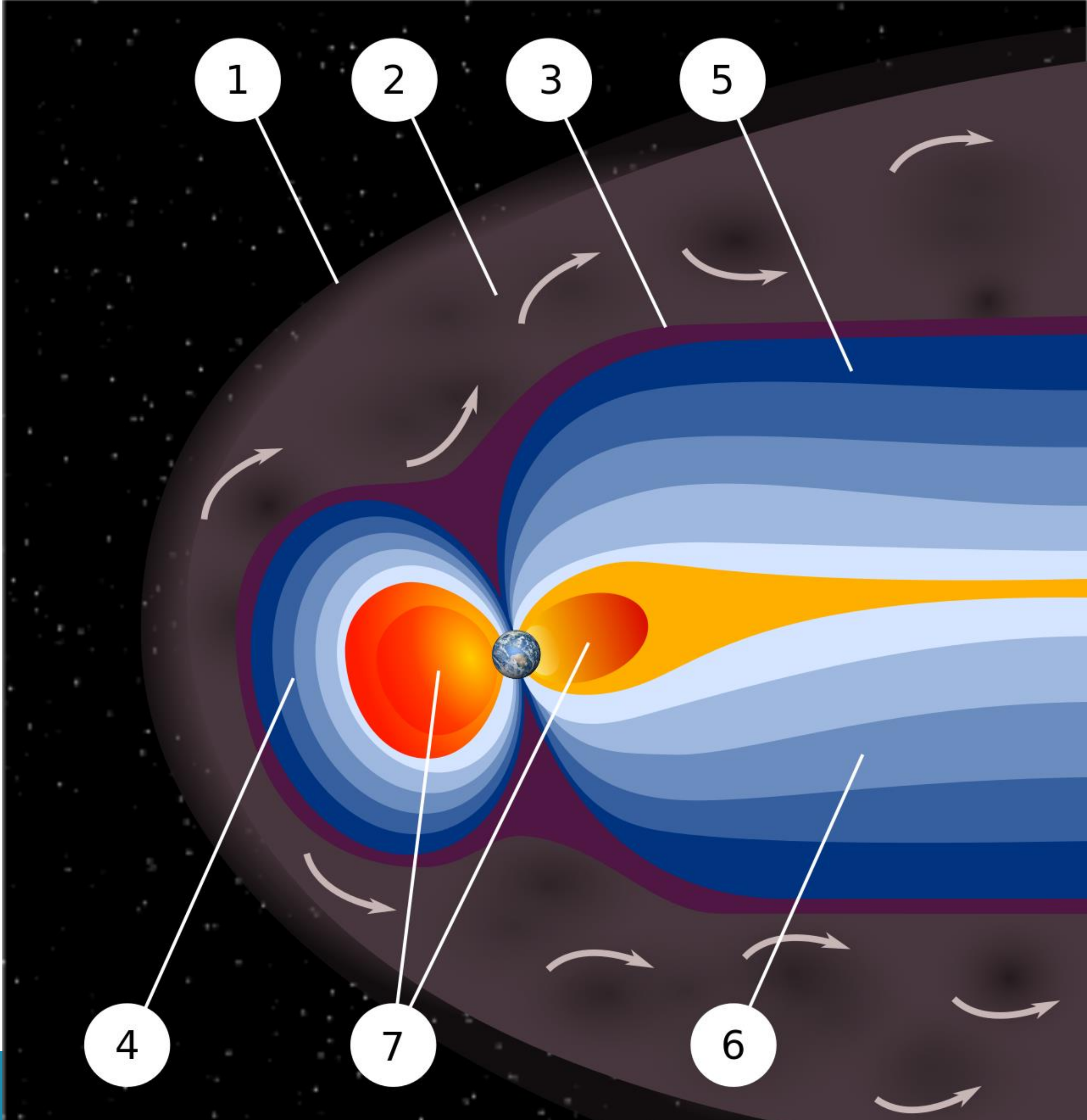


Credit: https://en.wikipedia.org/wiki/Magnetosphere#

The magnetosphere 5/5

7) **Plasmasphere,** or ***inner magnetosphere***

- consists of low-energy (cool) plasma
- is located above the ionosphere
- its outer boundary is known as the **plasmapause** (defined by an order of magnitude drop in density)
- *particle motion is determined entirely by the geomagnetic field*
- *co-rotates* with the Earth



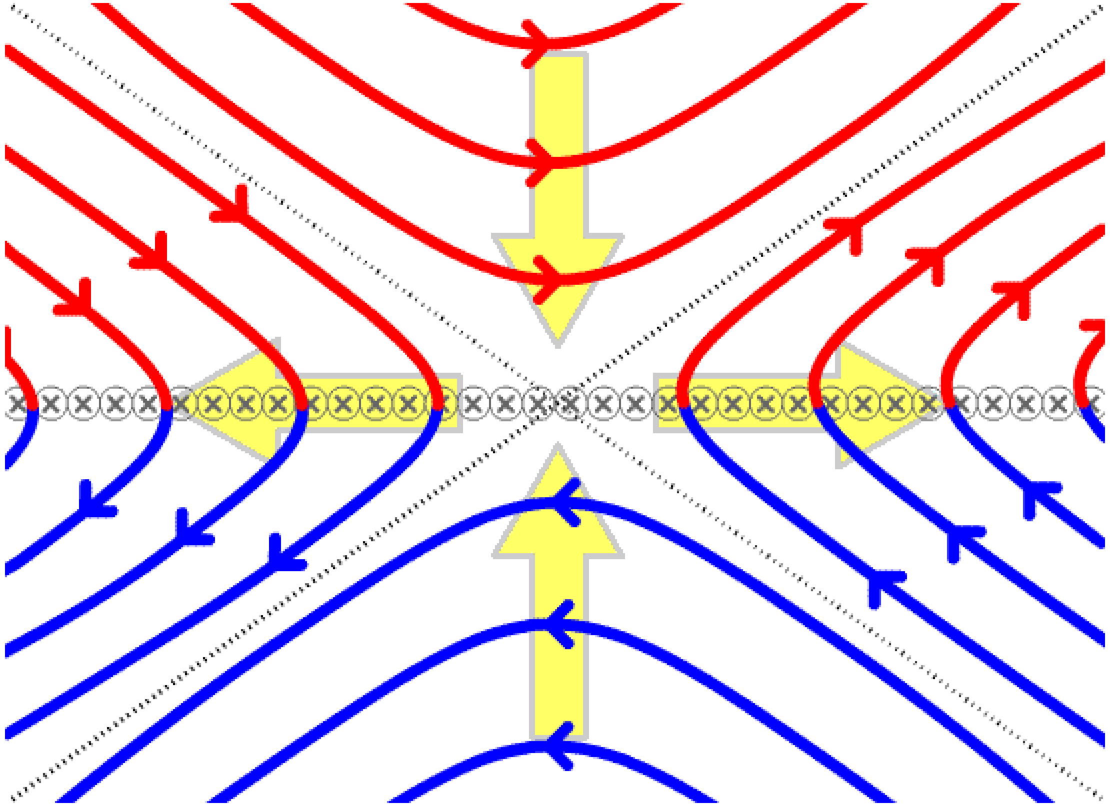
Credit: https://en.wikipedia.org/wiki/Magnetosphere#

Magnetic reconnection

- **Rearranges magnetic topology and converts magnetic energy** to kinetic energy, thermal energy, and particle acceleration.
- **involves plasma flows** at a substantial fraction of the Alfvén wave speed *(= fundamental speed for mechanical information flow in a magnetized plasma).*
- magnetic reconnection is a **generic process,** the concept of which was discovered in parallel by **solar physicists** and researchers studying the **interaction between the solar wind and magnetized planets.**

  This reflects the **bidirectional nature of reconnection:** it can either disconnect formerly connected magnetic fields (cf. solar flare/CME) or (re-)connect formerly disconnected magnetic fields, ***like magnetic fields of the solar wind and Earth***.

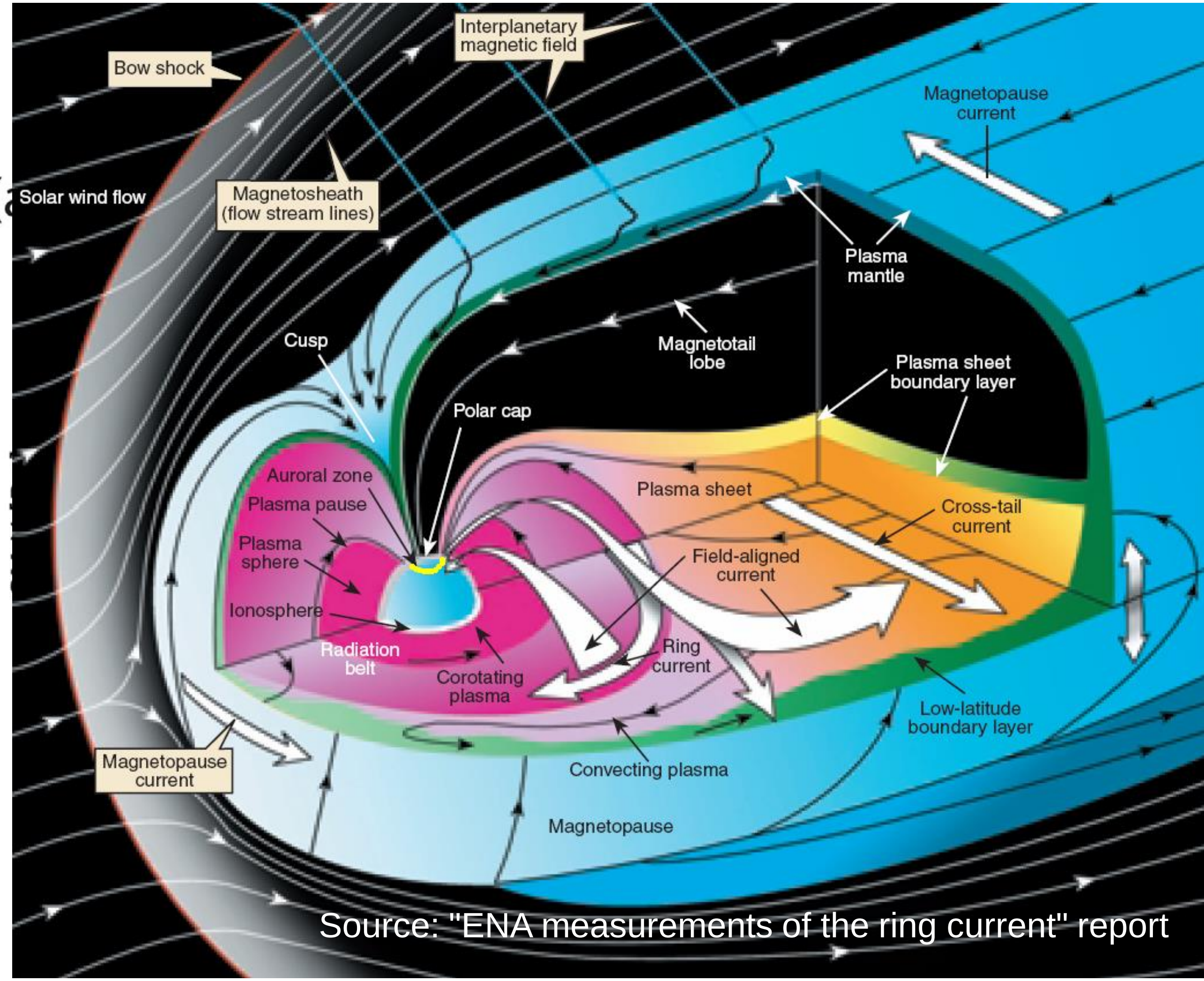
Credit: https://en.wikipedia.org/wiki/Magnetic_reconnection



A cross-section through four magnetic domains: two separatrices divide space into four magnetic. Field lines and plasma flow inward from above and below the central separator, reconnect, and spring outward along the current sheet.

Magnetosphere: dimensions

- On the dayside, **B** is significantly compressed by the SW to ± 65,000 km
- Earth's bow shock is about 17 km thick and located about 90,000 km from Earth (±15R_E)
- Earth's magnetopause allows solar wind particles to enter causing **Kelvin–Helmholtz instabilities** as the plasma travels along the edge of the magnetosphere at a different velocity from the magnetosphere
- This results in **magnetic reconnection**, ***enabling solar wind particles to enter the magnetosphere***.
- The magnetotail length exceeds 6,300,000 km is the primary source of the **polar aurora.**



Source: "ENA measurements of the ring current" report

Centre for mathematical Plasma Astrophysics

KU LEUVEN

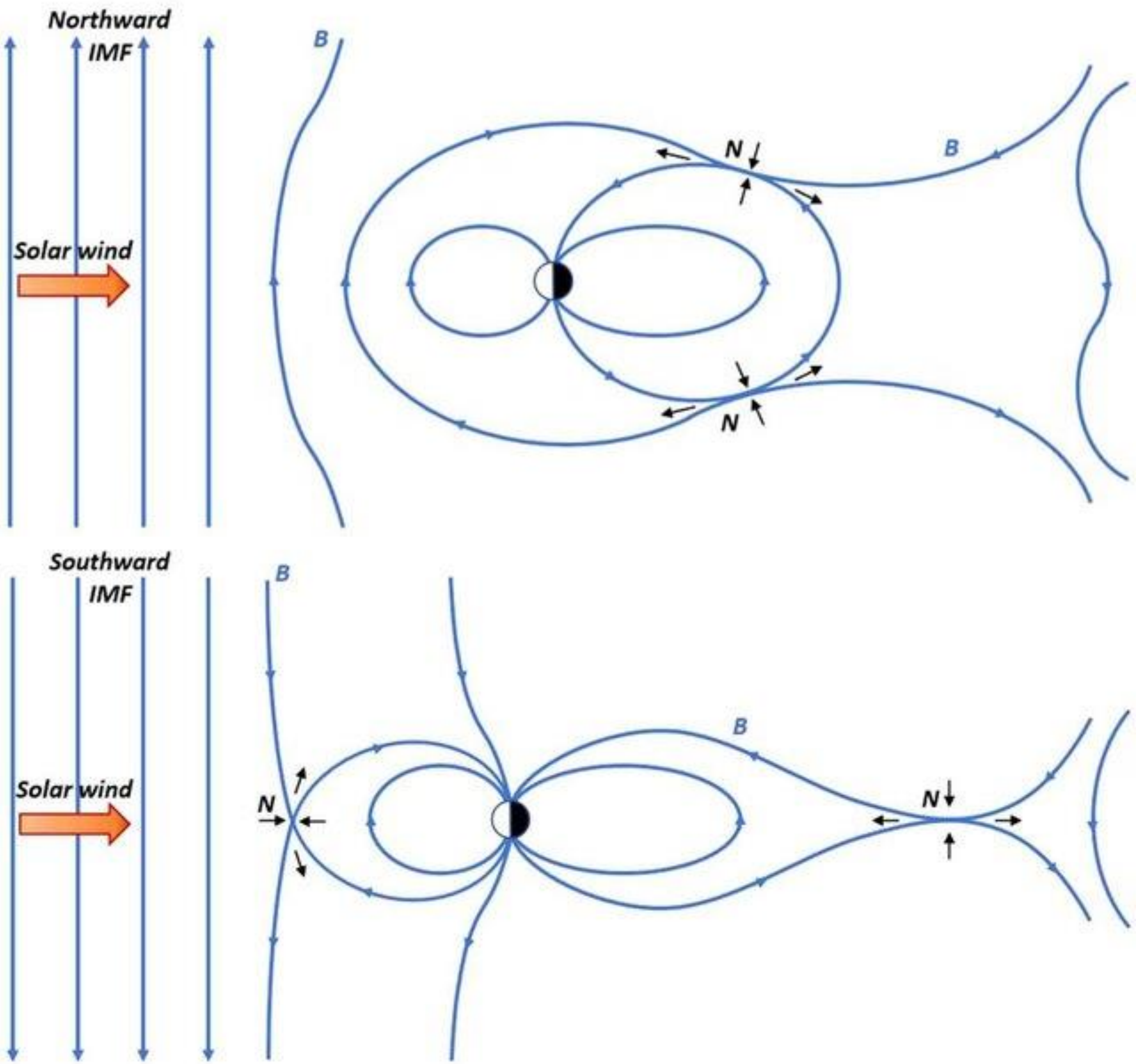
Effect of IMF

Early 2D representations of reconnection between the magnetic fields (blue traces) of the solar wind and the Earth's magnetosphere, as first described by Dungey (1961, 1963).

Top: **An instance of pure northward IMF**, showing magnetic reconnection at high latitudes just downstream of the Earth.

Bottom: A **pure southward IMF condition,** showing magnetic reconnection occurring at null points (N) in the subsolar region and within the magnetotail, with associated magnetic field motion and plasma inflow and outflow (represented by black arrows).

Adapted from Russell (2000) by Trattner et al. (2021), courtesy of Spinger Nature



Aurore and energetic particles

Artist impression of impulsive SEP event

Credit: NASA

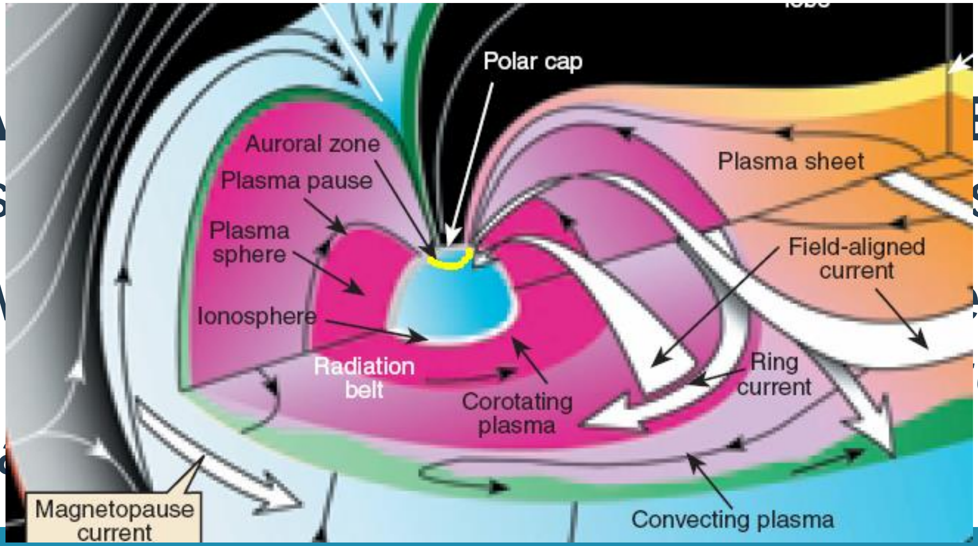
Solar wind - magnetosphere interaction

Lesson learned *(so far):*

- The Earth's magnetic field *shields the planet and its atmosphere from the solar wind*.
- However, this magnetic shielding is *not perfect*. A fraction of the mass, energy, and momentum from the solar wind can transfer to the magnetosphere and ionosphere through processes that are often referred to as **solar wind-magnetosphere interactions**
- *Pulkkinen et al. (2023)* performed 131 simulations of geomagnetic storms using the UMICH SWMF and **focusing on modeling the parameters that are characterizing the condition of the magnetosphere like the geomagnetic indices, which are directly related to solar wind drivers, magnetopause locations, and the cross-polar cap potential**.

Geomagnetic indices: Dst

- **Disturbance storm time** (**Dst**, Kyoto Dst) index, introduced by Sugiura [1963], gives information about the strength of the **ring current** that is caused by solar protons and electrons and has a *large effect on the electrodynamics of geomagnetic storms*.
- The **ring current** around Earth produces *a magnetic field that is directly opposite Earth's magnetic field*, i.e., if the difference between solar electrons and protons gets higher, then Earth's magnetic field *becomes weaker*.
- **A** … **Earth's magnetic field is weakened**. This is … storms.
- W … es: *a* … *ontal va* …



The ring current system consists of **a band, at a distance of 3 to 8** R_E which lies in the equatorial plane and circulates clockwise around the Earth (when viewed from the north). The particles of this region produce a magnetic field in opposition to the Earth's magnetic field and so an Earthly observer would observe a decrease in the magnetic field in this area. The negative deflection of the Earth's magnetic field due to the ring current is measured by the **Dst index**.

Local horizontal variation

Magnetic latitude of observatory

$$Dst(t) = \sum_{i=1}^{4} D_i(t) / \sum_{i=1}^{4} \cos(\lambda_i)$$

Doumen & Maharana (2024)

Geomagnetic indices: K_p-index

- Introduced by Bartels [1939] to **quantify geomagnetic activity** with an integer in the **range 0–9** with 1 = calm and 5 or more = a geomagnetic storm
- Derived from the largest fluctuations (in nT, relative to a quiet day) of the horizontal components of the magnetic field of the Earth in **3h-intervals**

Scale	Level	Effect			K_p equivalent	Average frequency (1 cycle = 11 years)	Days during solar cycle 24[7]
		Power system	Spacecraft operations	Other systems			
G1	Minor	Weak power grid fluctuations can occur.	Minor impact on satellite operations possible.	Migratory animals are affected at this and higher levels; aurora is commonly visible at high latitudes (northern Michigan and Maine).	5	1700 per cycle (900 days per cycle)	256
G2	Moderate	High-latitude power systems may experience voltage alarms, long-duration storms may cause transformer damage.	Corrective actions to orientation may be required by ground control; possible changes in drag affect orbit predictions.	HF radio propagation can fade at higher latitudes, and aurora has been seen as low as New York and Idaho (typically 55° geomagnetic lat.).	6	600 per cycle (360 days per cycle)	86
G3	Strong	Voltage corrections may be required, false alarms triggered on some protection devices.	Surface charging may occur on satellite components, drag may increase on low-Earth-orbit satellites, and corrections may be needed for orientation problems.	Intermittent satellite navigation and low-frequency radio navigation problems may occur, HF radio may be intermittent, and aurora has been seen as low as Illinois and Oregon (typically 50° geomagnetic lat.).	7	200 per cycle (130 days per cycle)	18
G4	Severe	Possible widespread voltage control problems and some protective systems will mistakenly trip out key assets from the grid.	May experience surface charging and tracking problems, corrections may be needed for orientation problems.	Induced pipeline currents affect preventive measures, HF radio propagation sporadic, satellite navigation degraded for hours, low-frequency radio navigation disrupted, and aurora has been seen as low as Alabama and northern California (typically 45° geomagnetic lat.).	8-9	100 per cycle (60 days per cycle)	9
G5	Extreme	Widespread voltage control problems and protective system problems can occur, some grid systems may experience complete collapse or blackouts. Transformers may experience damage.	May experience extensive surface charging, problems with orientation, uplink/downlink and tracking satellites.	Pipeline currents can reach hundreds of amps, HF (high frequency) radio propagation may be impossible in many areas for one to two days, satellite navigation may be degraded for days, low-frequency radio navigation can be out for hours, and aurora has been seen as low as Florida and southern Texas (typically 40° geomagnetic lat.).	9	4 per cycle (4 days per cycle)	0

Doumen & Maharana (2024)

Auroral Electrojet (AE, AL, AO, AU) indices

- **AE index** is a ***proxy of the response of the ionosphere to the substorms*** which are quite *stochastic* and *have high temporal variability*. It is derived from geomagnetic variations in the horizontal component observed at selected (10-13) observatories along the auroral zone in the northern hemisphere.
- **AU and AL indices** are, respectively, defined by the *largest* and the *smallest* (normalized) values selected from all the stations. The symbols, AU and AL, derive from the fact that these values form the upper and lower envelopes of the superposed plots of all the data from these stations as functions of UT.
- The difference, **AU - AL, defines the AE index**, and the mean value of the AU and AL, i.e. (AU+AL)/2, defines the **AO index**.

The term "AE indices" is usually used to represent these four indices (AU, AL, AE and AO).

Maharana et al. (2024)

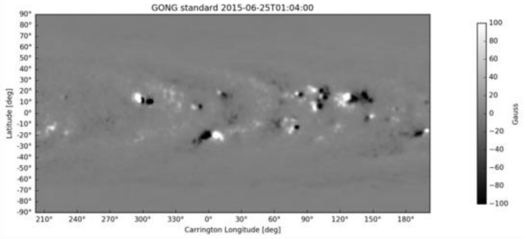
EUHFORIA

‘European heliospheric forecasting information asset’

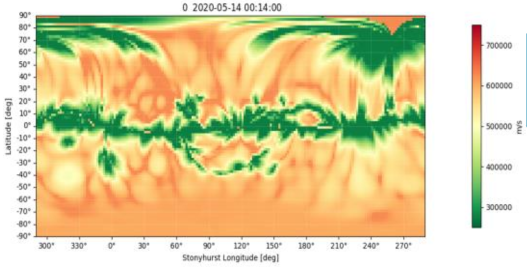
Corona:
Semi-Empirical WSA model

Heliosphere:
3D time dependent ideal MHD model

Synoptic Magnetogram (1 R_{sun})



v_r

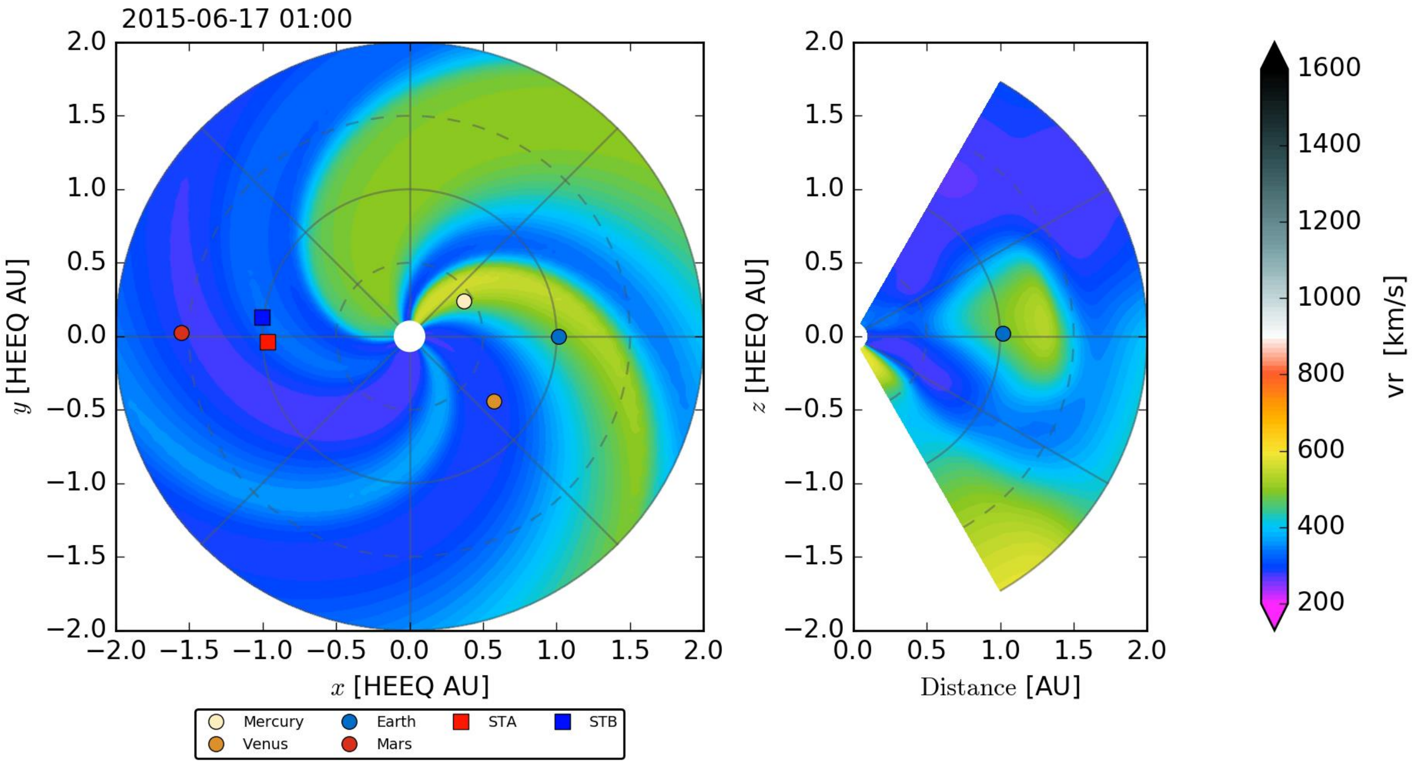


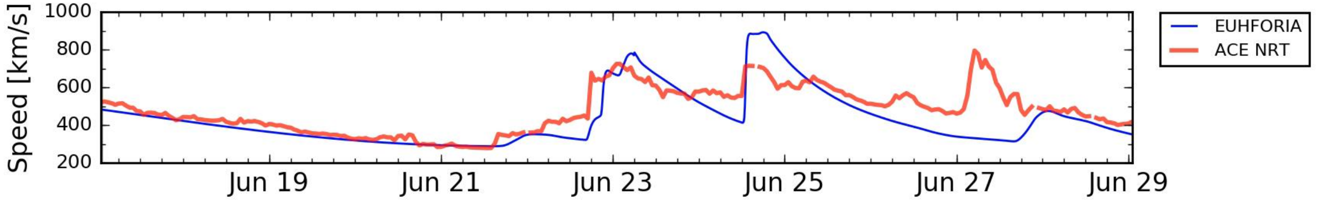
PFSS (1 - 2.6

SCS (2.3 R_{sun} -

MHD parameters (0.1 AU) using empirical relations

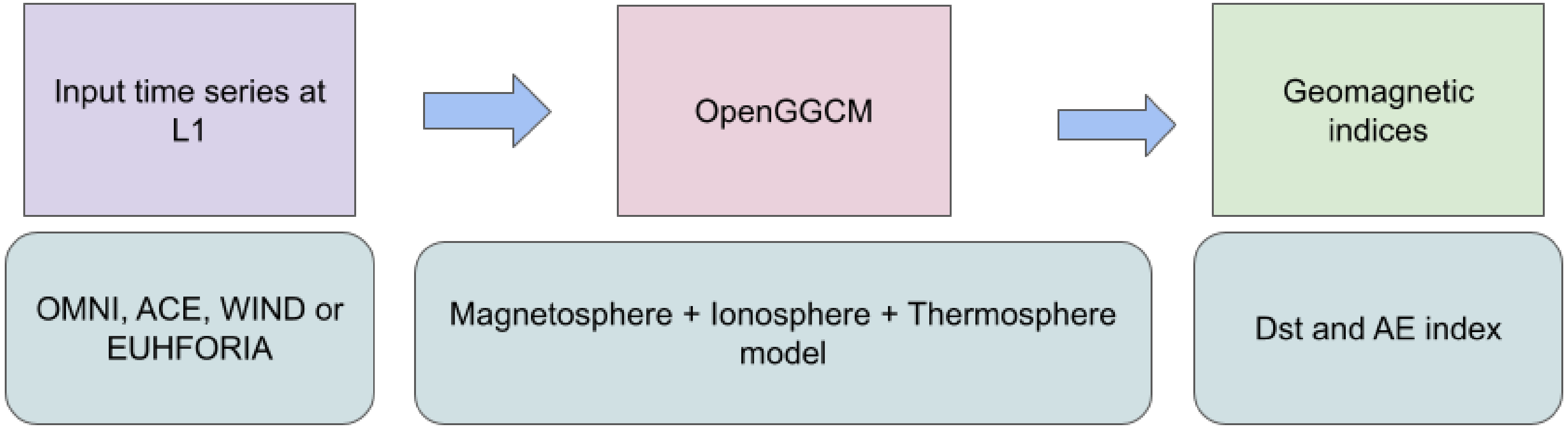
Solar wind relaxation





Credit: Anwesha Maharana

EUHFORIA – OpenGGCM coupling



Flowchart demonstrating the coupling of OpenGGCM with EUHFORIA

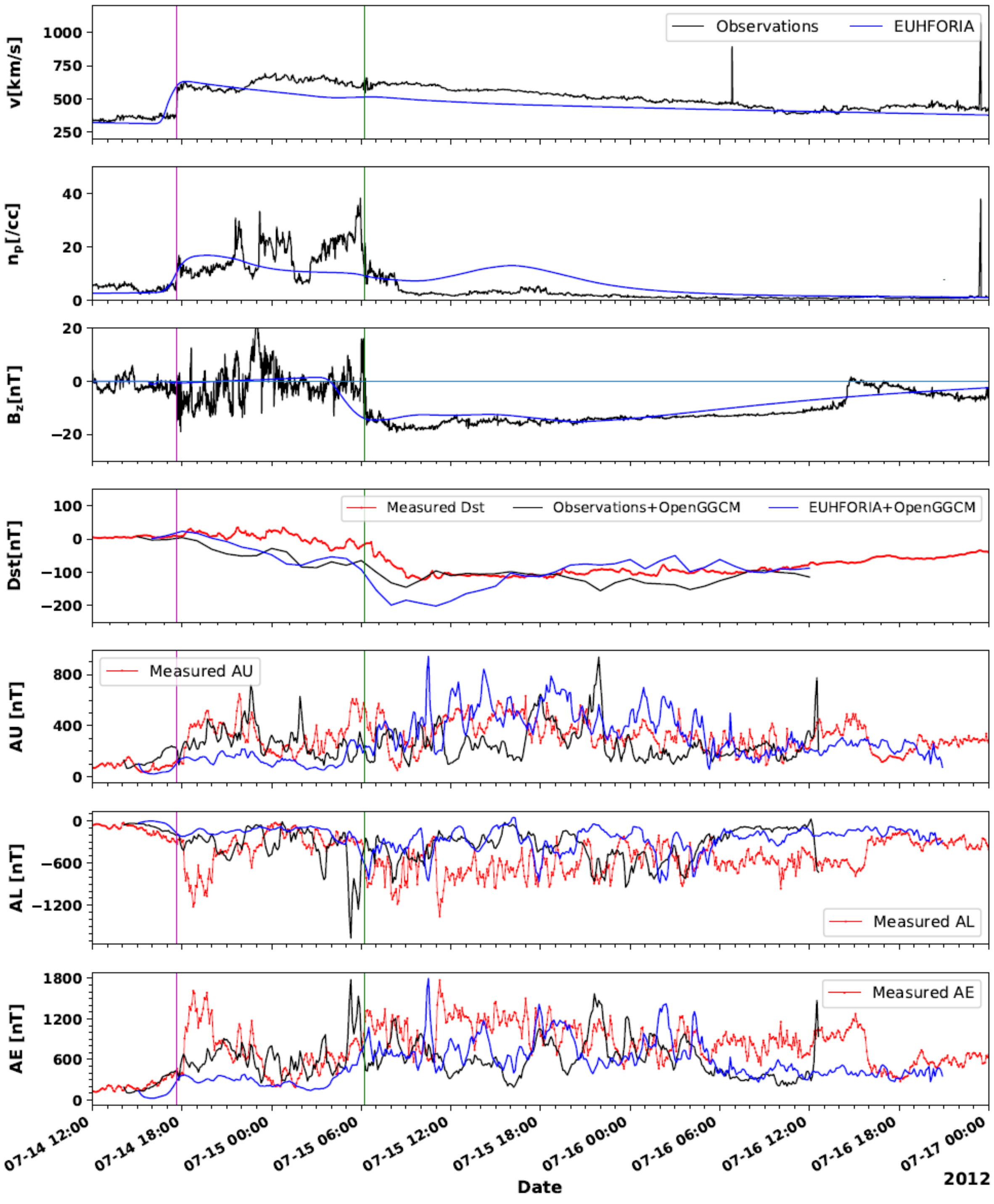
Maharana et al. (2024)

Geo-effectiveness

*Characteristics and predicted geomagnetic indices of **Event 1** (July 12, 2012). **Using a spheromak CME.***

Panels 1-3 show the plasma parameters – speed (v), proton number density (np), and the magnetic field parameter – z-component of magnetic field (Bz) as obtained from the Wind spacecraft in situ observations (in black) and the EUHFORIA simulation of the event based on Scolini et al. (2019) (in blue), respectively. The horizontal blue line in Panel 3 corresponds to $B_z = 0$.

*Panels 4–7 show the geomagnetic indices – **Dst index, AU index, AL index, and AE index** as measured in Earth's magnetosphere and ionosphere (in red), and as obtained from OpenGGCM simulations using input from the OMNI database (in black) and EUHFORIA simulation (in blue). The magenta and green vertical solid lines depict the arrival of the CME shock and the beginning of the magnetic cloud passage at Earth, respectively.*



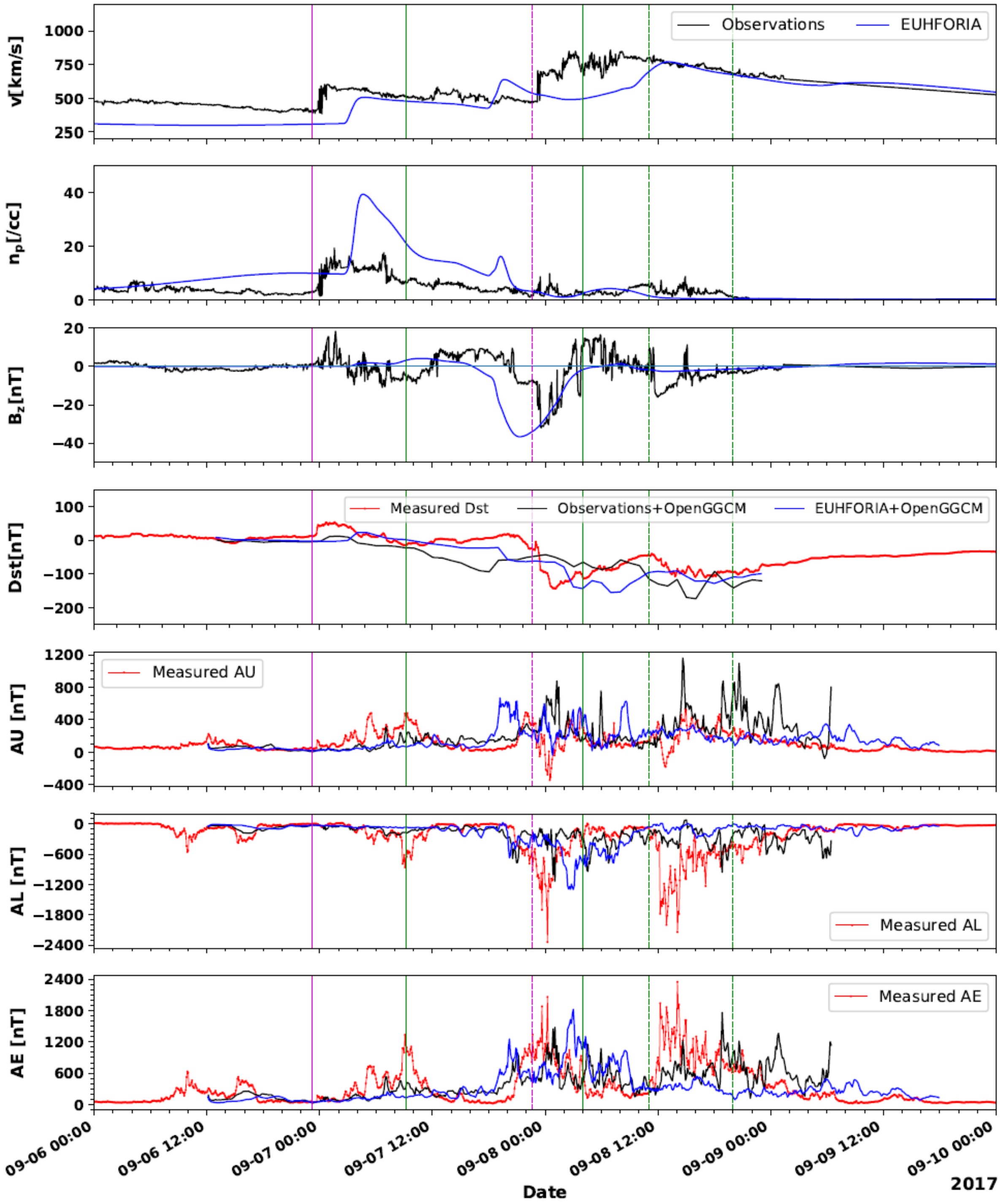
Maharana et al. (2024)

Geo-effectiveness

*Characteristics and predicted geomagnetic indices of **Event 2** (September 4–6, 2017). **Using a spheromak CME.***

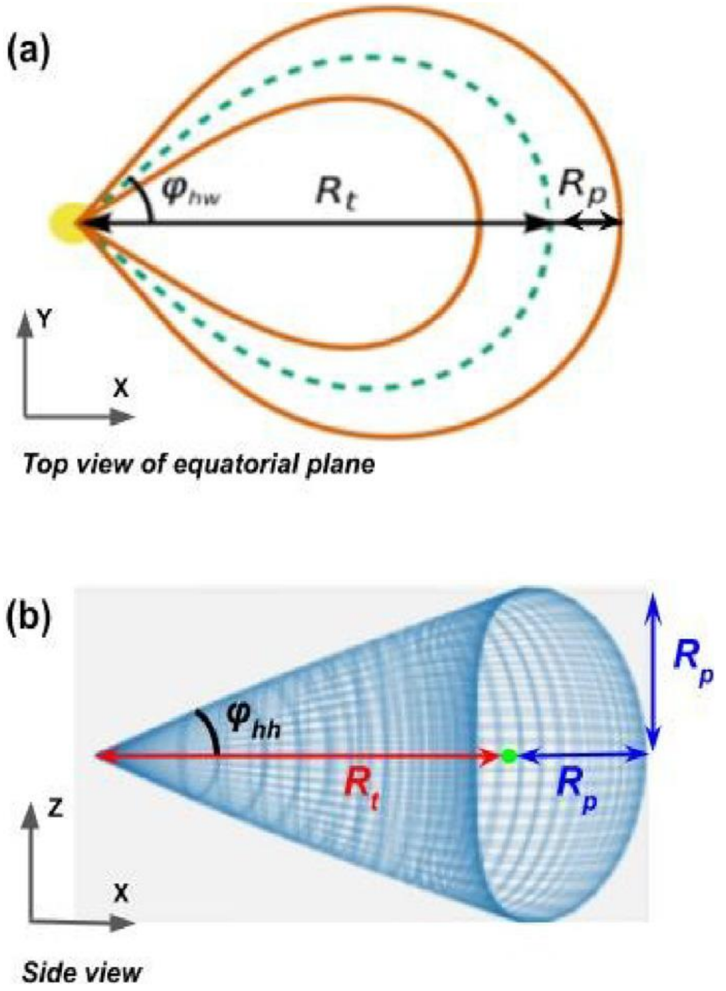
Panels 1-3 show the plasma parameters – v, np, and Bz as obtained from the Wind spacecraft in situ observations (in black) and the EUHFORIA simulation of the event based on Scolini et al. (2020) (in blue), respectively.

Panels 4-7 show the geomagnetic indices – Dst index, AU index, AL index, and AE index as measured in Earth's magnetosphere and ionosphere (in red), and as obtained from OpenGGCM simulations using input from the Wind spacecraft (in black) and EUHFORIA simulation (in blue). The magenta solid and dashed lines depict the arrival of two shocks (S1 and S2) associated with this event. The two green solid lines depict the boundary of the passage of the magnetic ejecta E1 at Earth and the dashed lines correspond to the boundary of E2 at Earth.



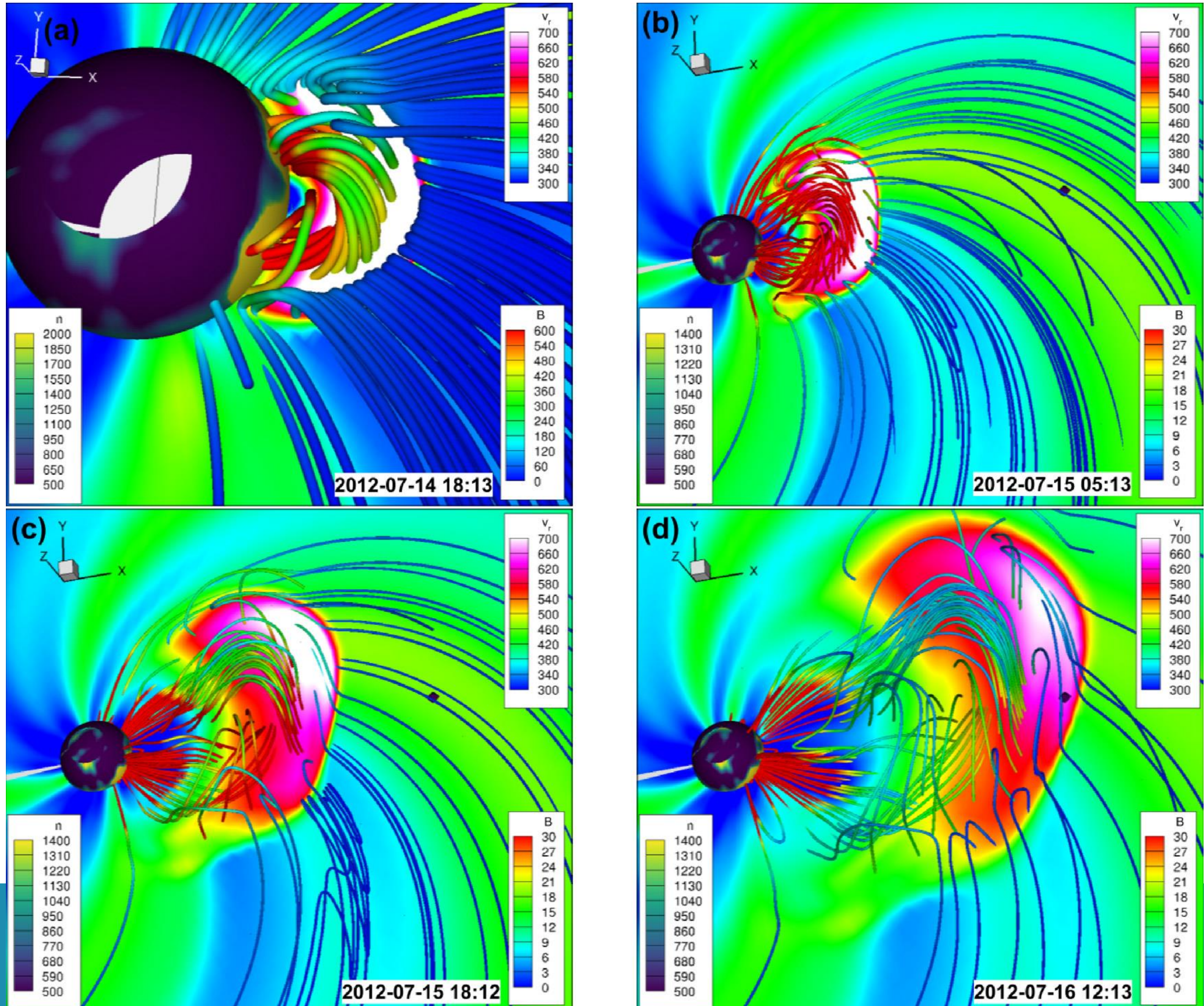
Maharana et al. (2024)

FR CME models and empirical geo-effect models



FRi3D flux rope geometry.

3D visualization of the EUHFORIA simulation results of the CME that erupted on 12 July 2012 using the FRi3D model, evolving in the heliospheric domain of EUHFORIA.

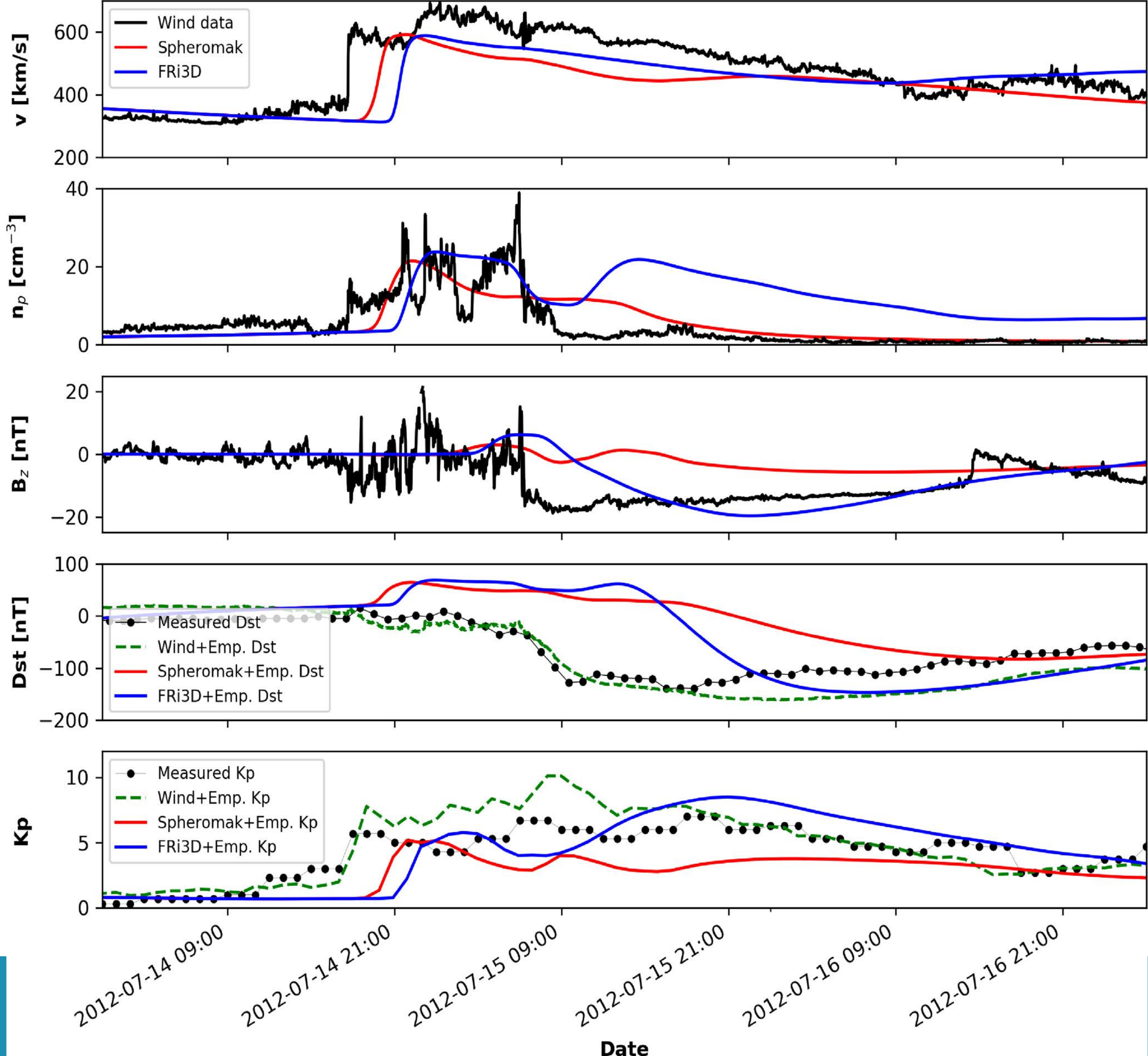


Maharana et al. (2022): FRi3D model

Geo-effectiveness

Using a spheromak and FRi3D CME.

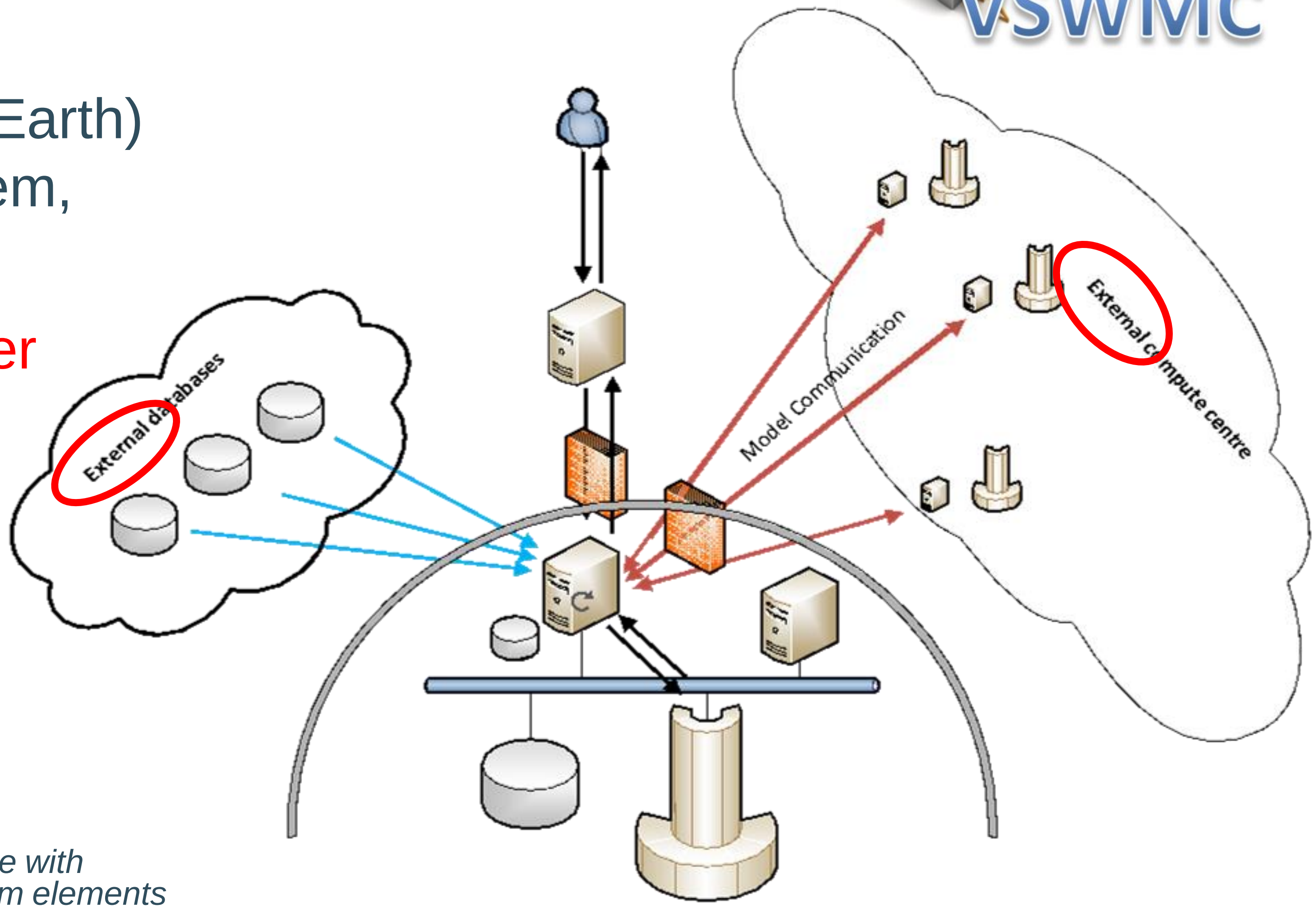
*Comparison of the geoeffectiveness predictions employing the empirical **Dst formalism of O'Brien and McPherron (2000a,b)** and the empirical **Kp-index formalism of Newell et al. (2007, 2008)** with observations. The empirical Dst (panel 4) and Kp index (panel 5) computed using the measured Wind data (green dashed line), and EUHFORIA simulated solar wind data using the spheromak (in red solid line) and FRi3D (in blue solid line) are compared with their measured values. The solar wind parameters (v; n_p; B_z) at Earth are additionally plotted to show their correlation with the geomagnetic indices. **For example, B_z and n_p strongly influence Dst and Kp index respectively.***



Maharana et al. (2022): FRi3D model

Virtual SWE Modelling Centre

- An **open end-to-end** (Sun to Earth) space weather modeling system,
- enabling to *interactively* run & "couple" various space weather models in an integrated tool,
- with the models located either locally or geographically distributed (≠ CCMC)



Basic set-up of federated service with geographically distributed system elements

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EUHFORIA in the e-Science Centre

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Home > All Scientific Metadata > Data Collection-related Metadata > Data Collections > EUHFORIA: EUropean Heliospheric FORecasting Information Asset | Help & Support

EUHFORIA: EUropean Heliospheric FORecasting Information Asset

Description

EUHFORIA (EUropean Heliospheric FORecasting Information Asset) consists of two main parts: a semi-empirical coronal model, the purpose of which is to determine the plasma environment of the solar wind at the location of the inner boundary of the heliospheric module, and the heliospheric model, which provides the dynamics of the background solar wind with superposed CMEs into the inner heliosphere by numerical evolution of the MHD equations. EUHFORIA runs at the Virtual Space Weather Modeling Center (VSWMC) on the ESA Space Weather Network (ESA-SWE) website (https://swe.ssa.esa.int). VSWMC is an interactive modeling system developed for space weather research from the Sun to the Earth. It allows users to run different tools stand-alone or in combination with models that are locally or geographically dispersed.

Interact

Interaction Method	Description	Data Format	Link
Direct data download	The ESA-SWE website requires an account to run. Once received, go to the VSWMC webpage and select: "NEW RUN". From the list of model chains that appear, you can choose those that contain	image/png text/plain	Latest VSWMC at ESA-SWE Landing Page (link opens in new tab)

Identifier

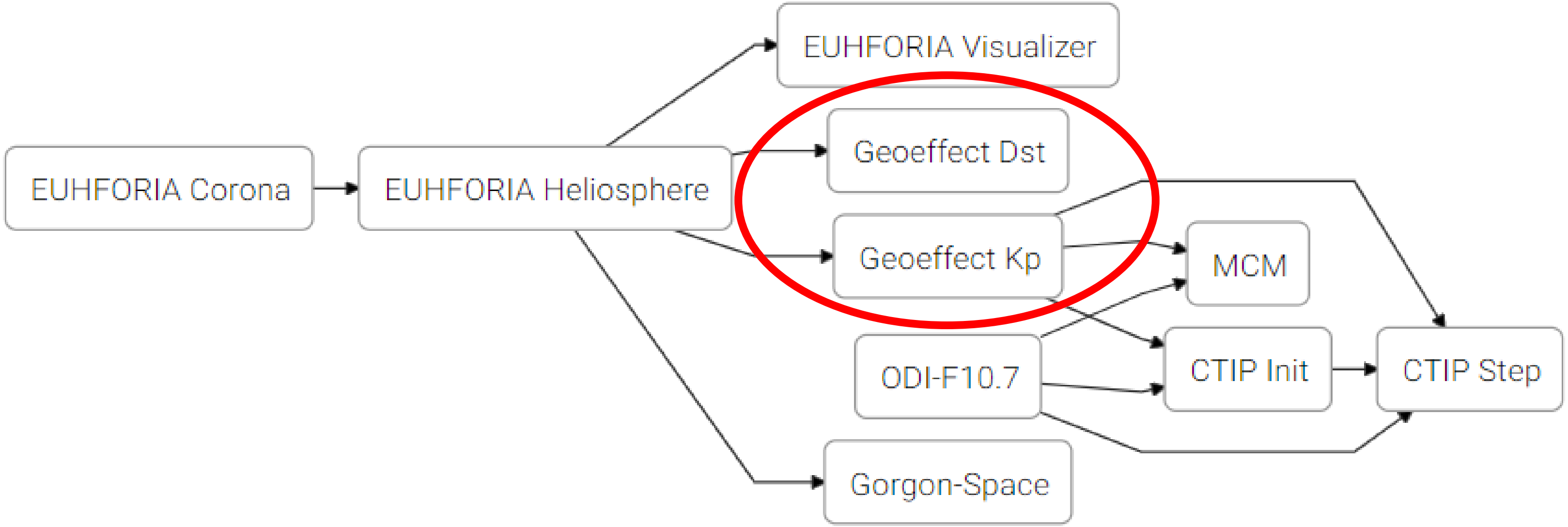
Local ID	DataCollection_EUHFORIA
Namespace	kul
Version	2
Created	Tuesday 28th Feb. 2023, 01:30:00
Last Modified	Monday 24th April 2023, 18:56:00

Download

DataCollection_EUHFORIA.xml

Model chains in the VSWMC

For example:



EUHFORIA Corona
: Provides MHD parameters at 0.1AU based on a PFSS/SCS magnetogram extension and the semi-empirical WSA model.

EUHFORIA Heliosphere
: Steady solar wind model based on magnetogram, using HEEQ coordinates. CMEs can be superposed on this wind.

Visualizer
: Visualization of EUHFORIA-like output

Geoeffect Dst
: Simple model based on an empirical equation to determine the Dst index form solar wind parameters at L1.

Geoeffect Kp
: Simple model based on an empirical equation to determine the Kp index form solar wind parameters at L1.

ODI-F10.7
: Provides F10.7 solar flux index values from the ODI F10.7 dataset.

Gorgon-Space
: 3D MHD magnetosphere model using a 3D cartesian grid.

CTIP Init
: Calculate globally the initial state of the thermosphere and the ionosphere by solving self-consistently the coupled equations of momentum, energy and continuity for neutral particles and ions.

CTIP Step
: Calculate globally the time-dependent state of the thermosphere and the ionosphere by solving self-consistently the coupled equations of momentum, energy and continuity for neutral particles and ions.

MCM
: A full atmosphere model developed in the framework of the H2020 SWAMI project. It covers from the surface up to 1500 km.

Empirical *Dst* model

- AK2 model derived by *O'Brien and McPherron [2000]*
- Corrected Dst index:

$$Dst^*(t) = Dst(t) - b\sqrt{P_{dyn}(t)} + c$$

Force exerted on magnetosphere by solar wind

- *Simple differential equation for evolution of* Dst*:

$$\frac{\mathrm{d}Dst^*}{\mathrm{d}t} = Q(t) - \frac{Dst^*}{\tau}$$

Decay time (3 - 20hrs)

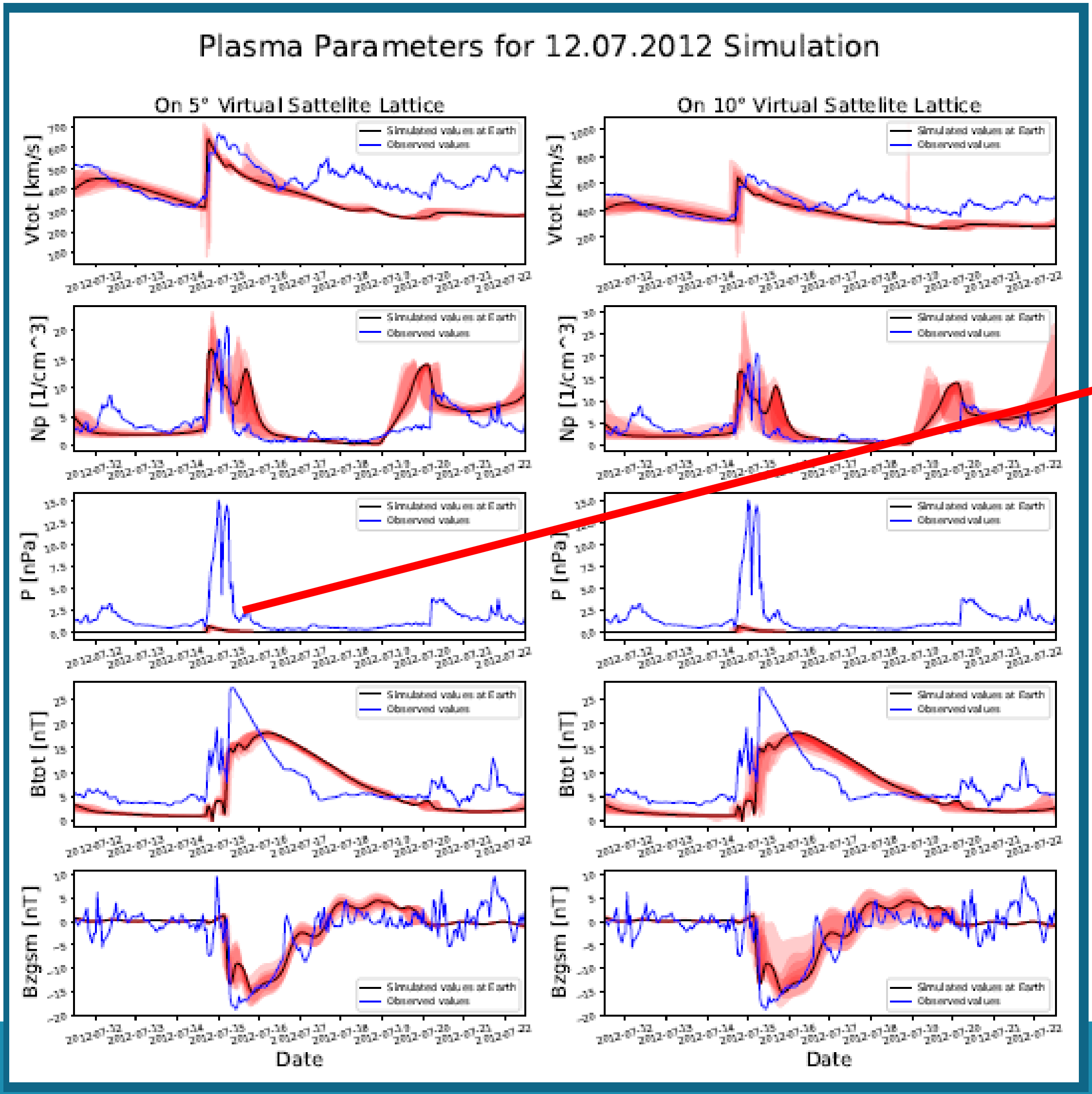
proportional to the rate of energy injection into the ring current

- Integrated using a simple forward difference:

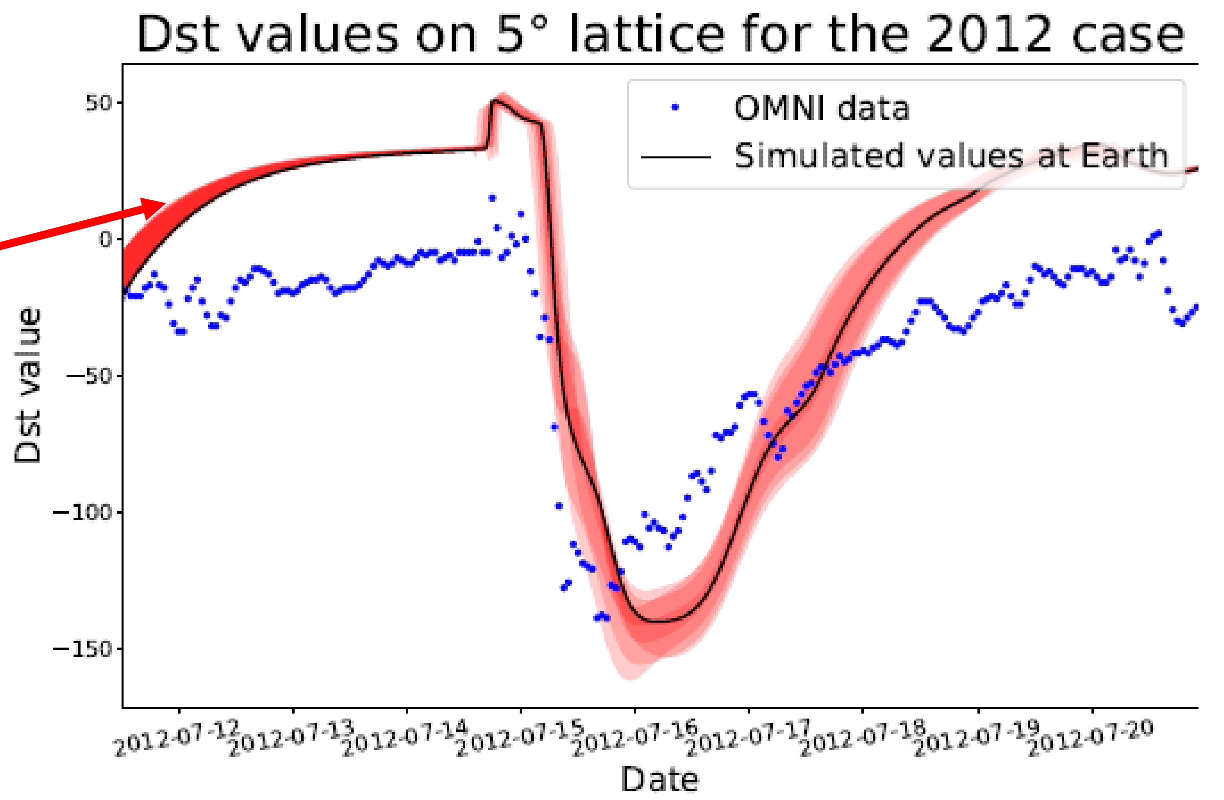
$$Dst^*(t+\Delta t) = Dst^*(t) + \left(Q(t) - \frac{Dst^*(t)}{\tau(t)}\right)\Delta t$$

Doumen & Maharana (2024)

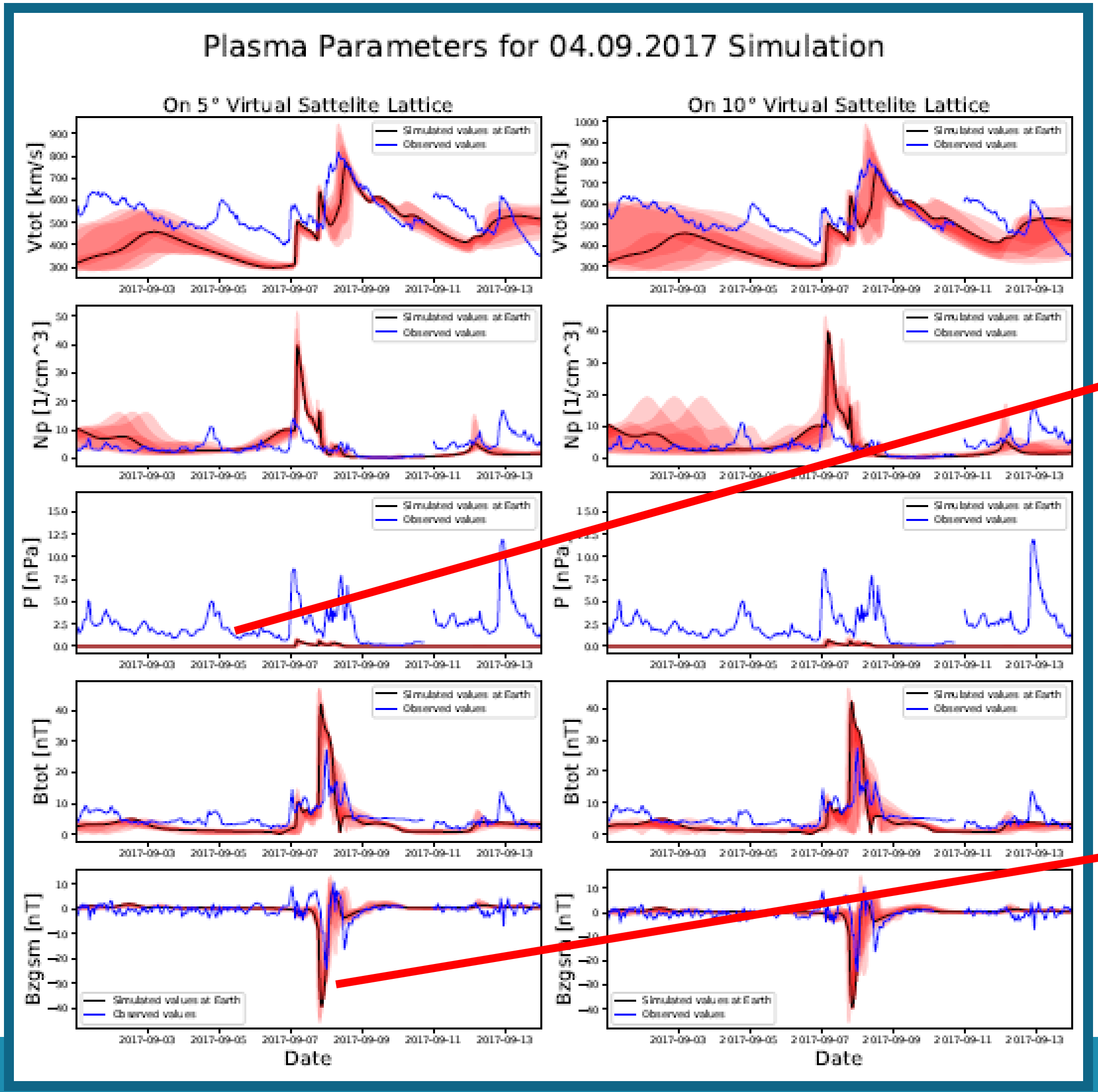
Empirical *Dst* model with synthetic EUHFORIA data



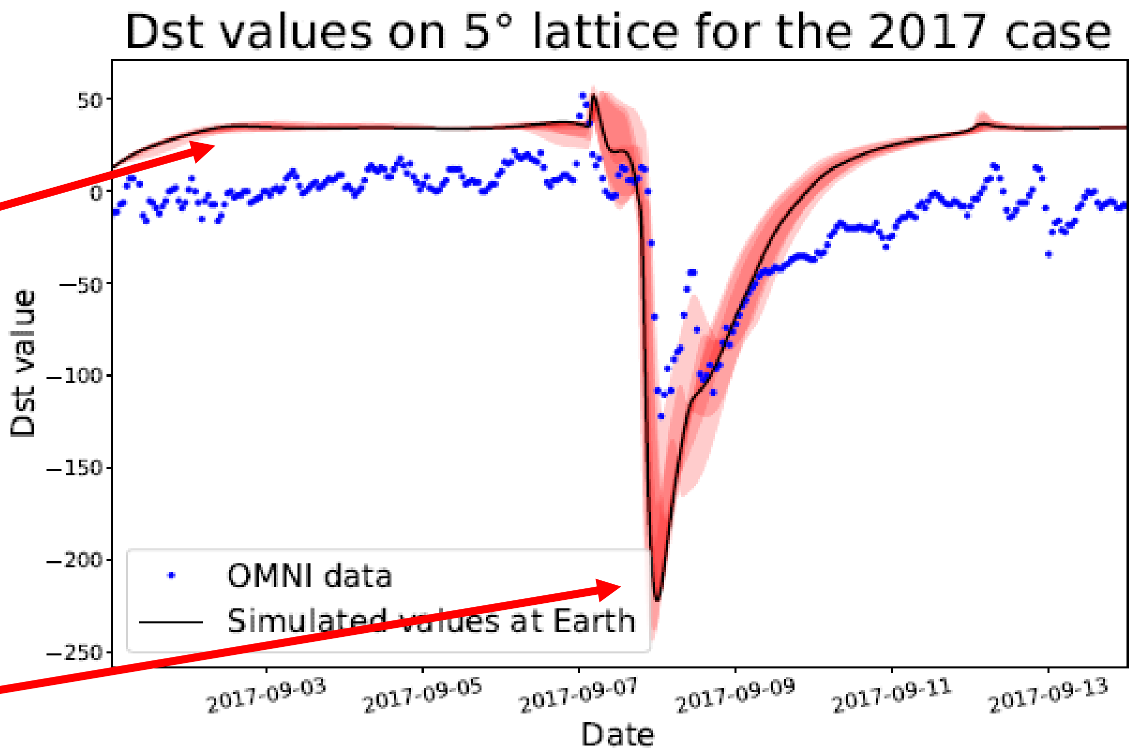
Doumen & Maharana (2024)



Empirical *Dst* model with synthetic EUHFORIA data



Doumen & Maharana (2024)



Empirical K_p model

- Equation derived by *Newell et al. [2008]*
- Considered 496 binary combinations of 32 solar wind coupling functions
- Find the least variance linear prediction:

the rate magnetic flux is opened at the magnetopause

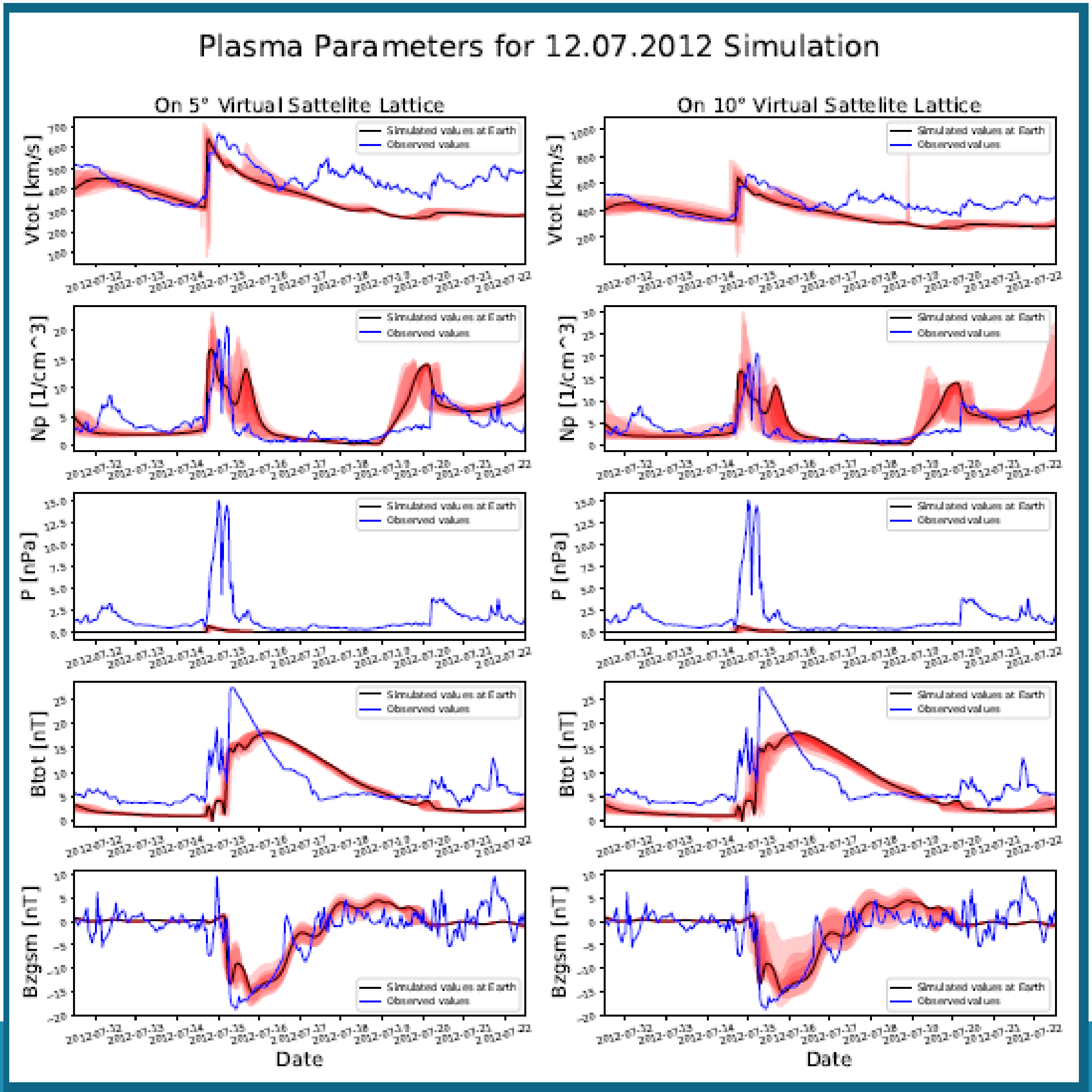
$$Kp = 0.05 + 2.244 \times 10^{-4} d\Phi_{MP}/dt + 2.844 \times 10^{-6} n^{1/2} v^2$$

where $$\frac{d\Phi_{MP}}{dt} = v^{4/3} B_T^{2/3} \sin^{8/3}(\theta_c/2)$$

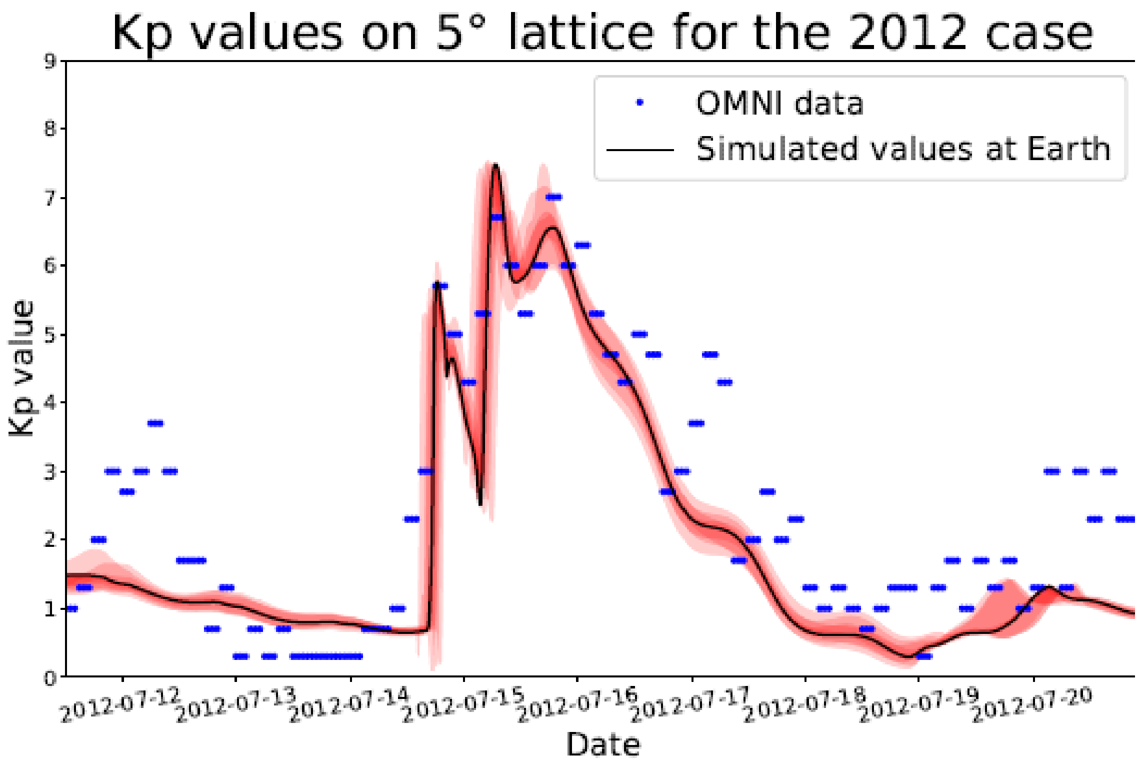
and $$\theta_c = \arctan(B_y/B_z).$$

Doumen & Maharana (2024)

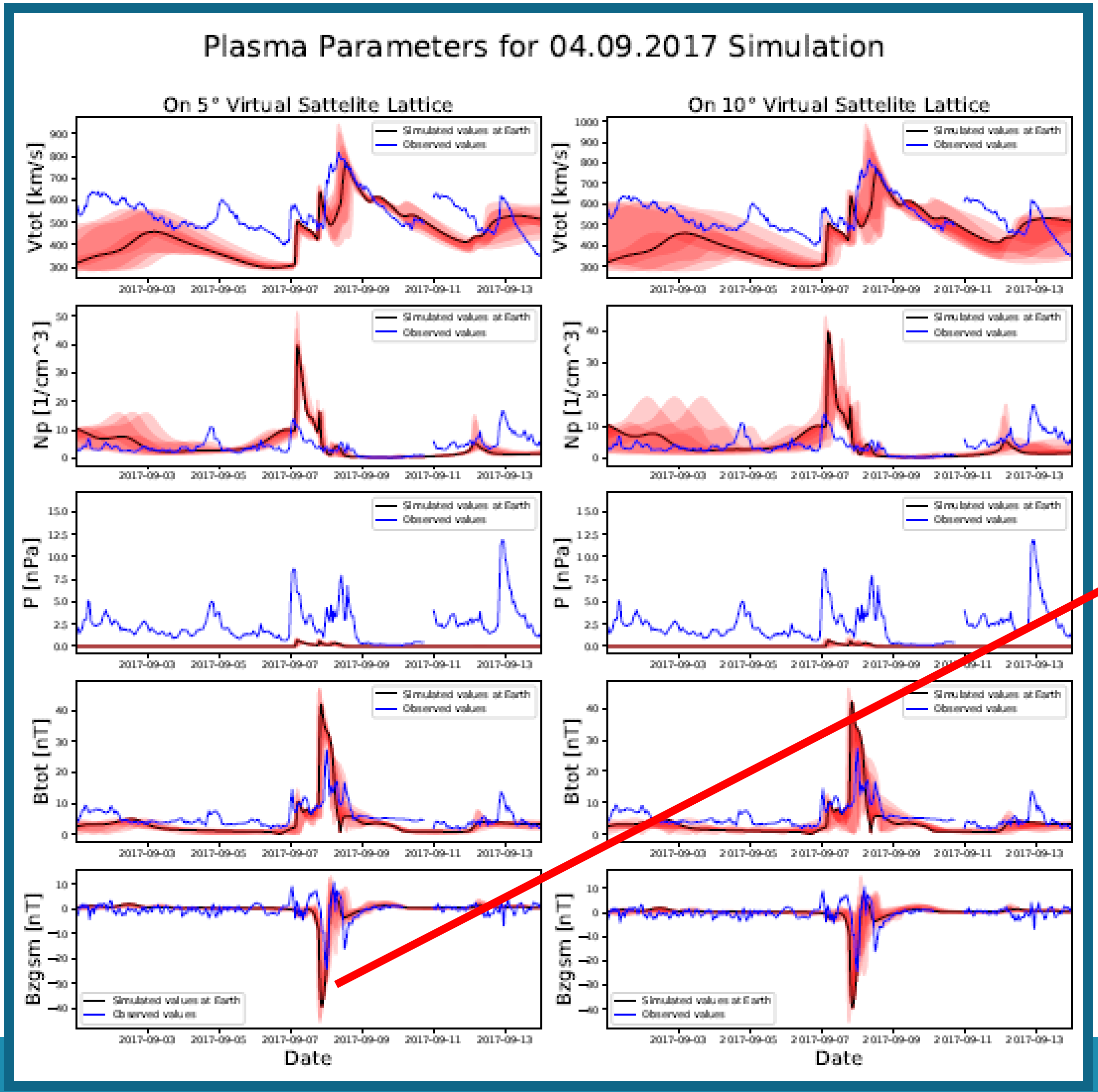
Empirical K_p model with synthetic EUHFORIA data



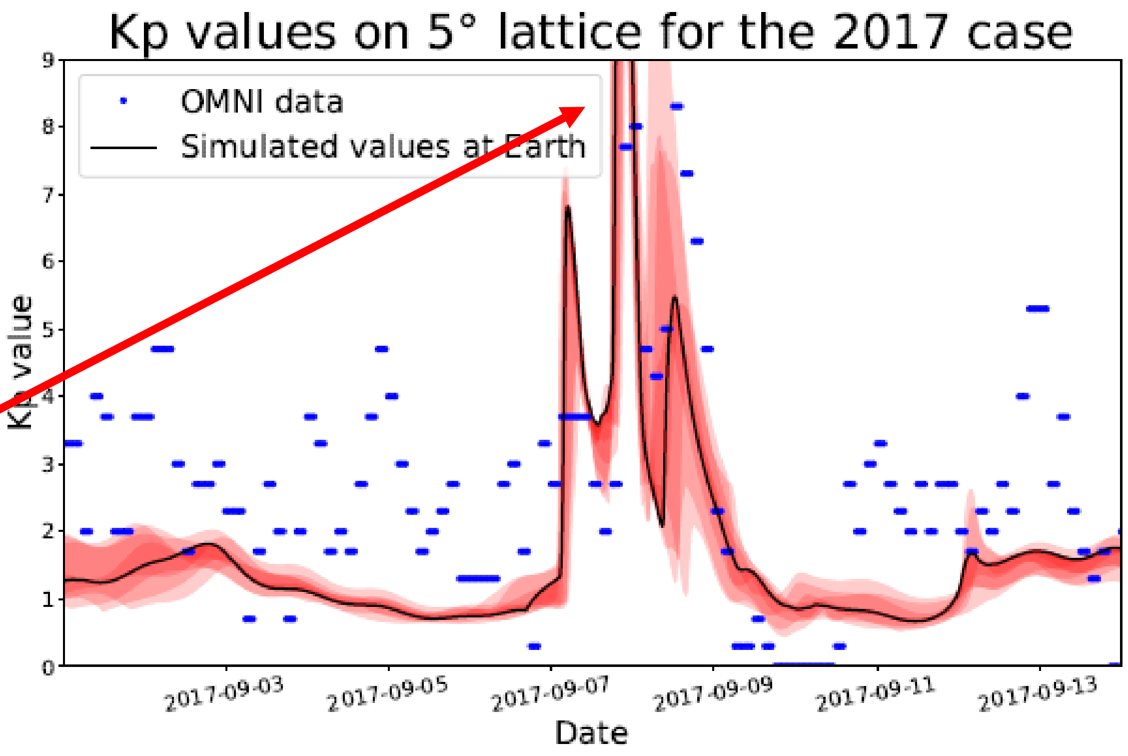
Doumen & Maharana (2024)



Empirical K_p model with synthetic EUHFORIA data



Doumen & Maharana (2024)



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Other empirical geo-effect models

- **SNGI** from the Sheffield NARMAX geomagnetic indices models
  - Based on work of Ayala Solares et al. [2016]

- **Feed-Forward Neural Networks** like those by Wintoft and Wik [2021]
  - RNN can learn mappings that are temporally correlated
  - Three types of ***Recurrent Neural Networks***
    - Elman network
    - Gated Recurrent Unit (GRU) network
    - Long Short-term Memory (LSTM) network
  - Example: Elman network:

$$y_t = \boldsymbol{V} \boldsymbol{h}_t$$

$$h_t^j = f(\boldsymbol{W} \boldsymbol{x}_t + \boldsymbol{U} \boldsymbol{h}_{t-1})^j$$

  - GRU network has 3X more weights, LSTM 4X

Doumen & Maharana (2024)

Take-home messages

Key Points:

- Space weather has a large socio-economic impact
- Space weather modelling is **multi-scale and multi-physics** and **extremely challenging,** *especially the solar wind – magnetosphere interactions*
- For some problems there exist **models with predictive value**
- Models for sub-problems can be **chained to enable Sun-to-Earth simulations,** ***much earlier by using synthetic data from simulations***

Conclusion: ***a lot of modelling work remains, and novel numerical techniques need to be developed, e.g., to speed up the simulations***

THANK YOU! EUHFORIA is also available in euhforiaonline.com

Acknowledgements: EU H2020 project **EUHFORIA 2.0** *(Project 870405)* + ESA project ITT AO/1-10125/19/NL/HK (Heliospheric Modelling Techniques)

Some references:

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Other references: **EUHFORIA web page**: euhforia.com/