Magnetohydrodynamical Understanding of the Interactions Between Coronal Mass Ejections and Earth's Magnetosphere.

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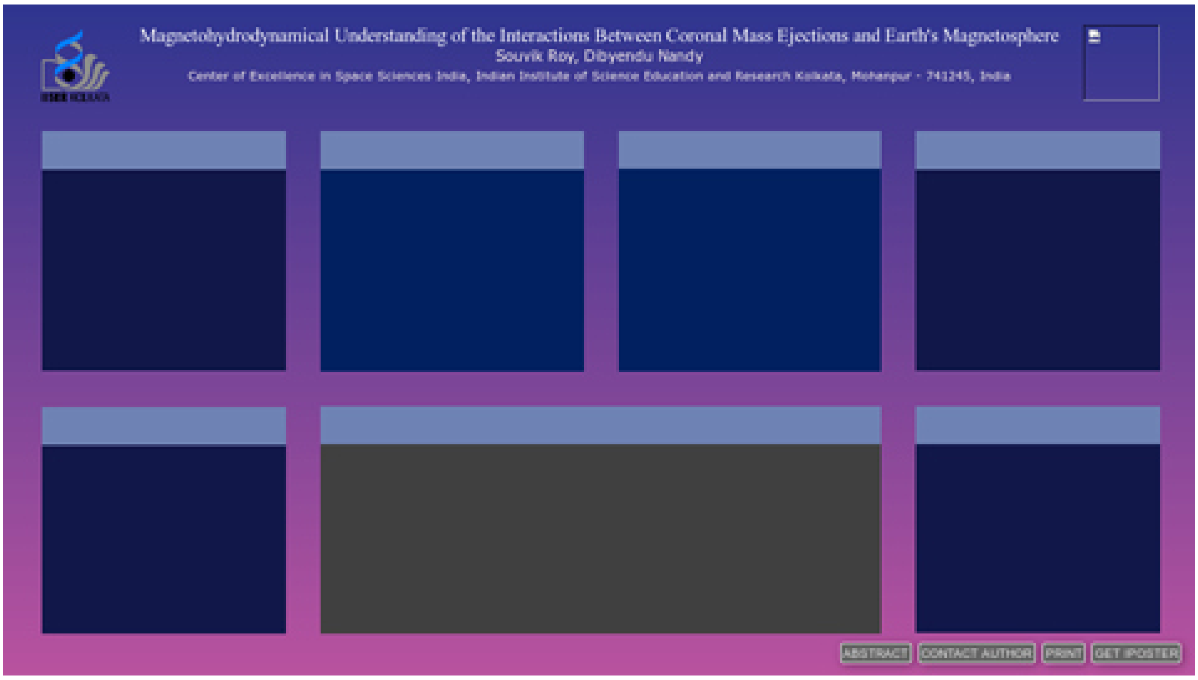
Abstract

Coronal mass ejections (CMEs), the large scale transient eruptions from the Sun, interact with the Earth's magnetosphere while travelling into the heliosphere. The energetic interplanetary CME (ICME) at 1AU not only creates geomagnetic storms and disrupts the magnetic field structure around the Earth but also impacts the plasma environment, causes strong aurorae, and disturbs the radio and electrical transmission massively. We use 3D compressible magnetohydrodynamic simulation of a star-planet system and study the interesting magnetohydrodynamic processes like bow-shock, magnetopause, magnetotail, planet-bound current sheets, magnetic reconnections, atmospheric mass loss as well as particle injection, etc., when an ICME flux rope crosses the Earth at 1 AU. We use the uniformly twisted force-free flux rope model proposed by Gold and Hoyle in 1960 to initiate the ICME and vary the flux rope properties using actual observational data. We observe a change in magnetopause's shape and the stand-off distance to the magnetopause. We notice twist helicity injection inside the magnetotail current system. We discover comparative increment in both the rates of atmospheric mass out-flow and solar wind in-flow in the vicinity of Earth during the geo-storm. Such studies will help us understand how energetic magnetic storms from a host star impact planetary magnetospheres and atmospheres with implications for planetary and exoplanetary habitability.

Magnetohydrodynamical Understanding of the Interactions Between Coronal Mass Ejections and Earth's Magnetosphere



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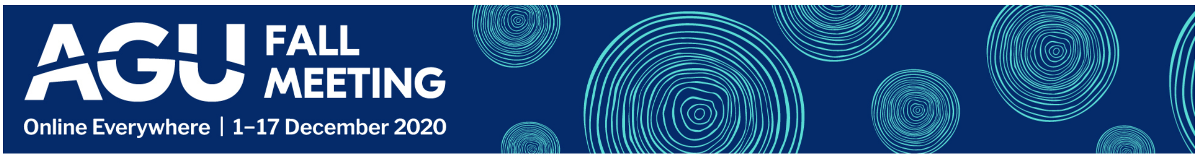
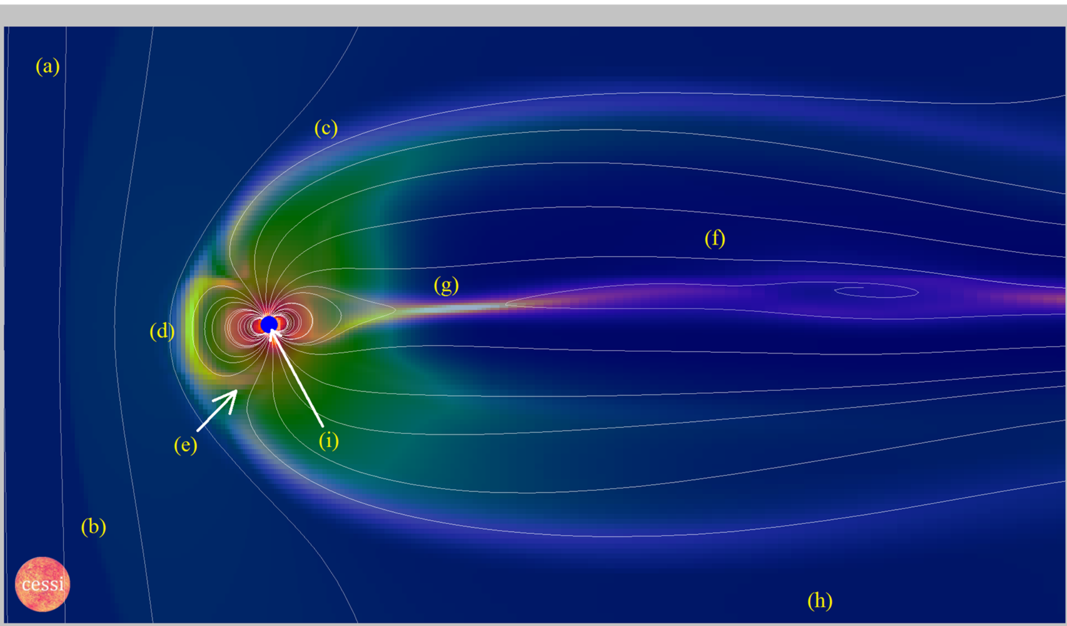


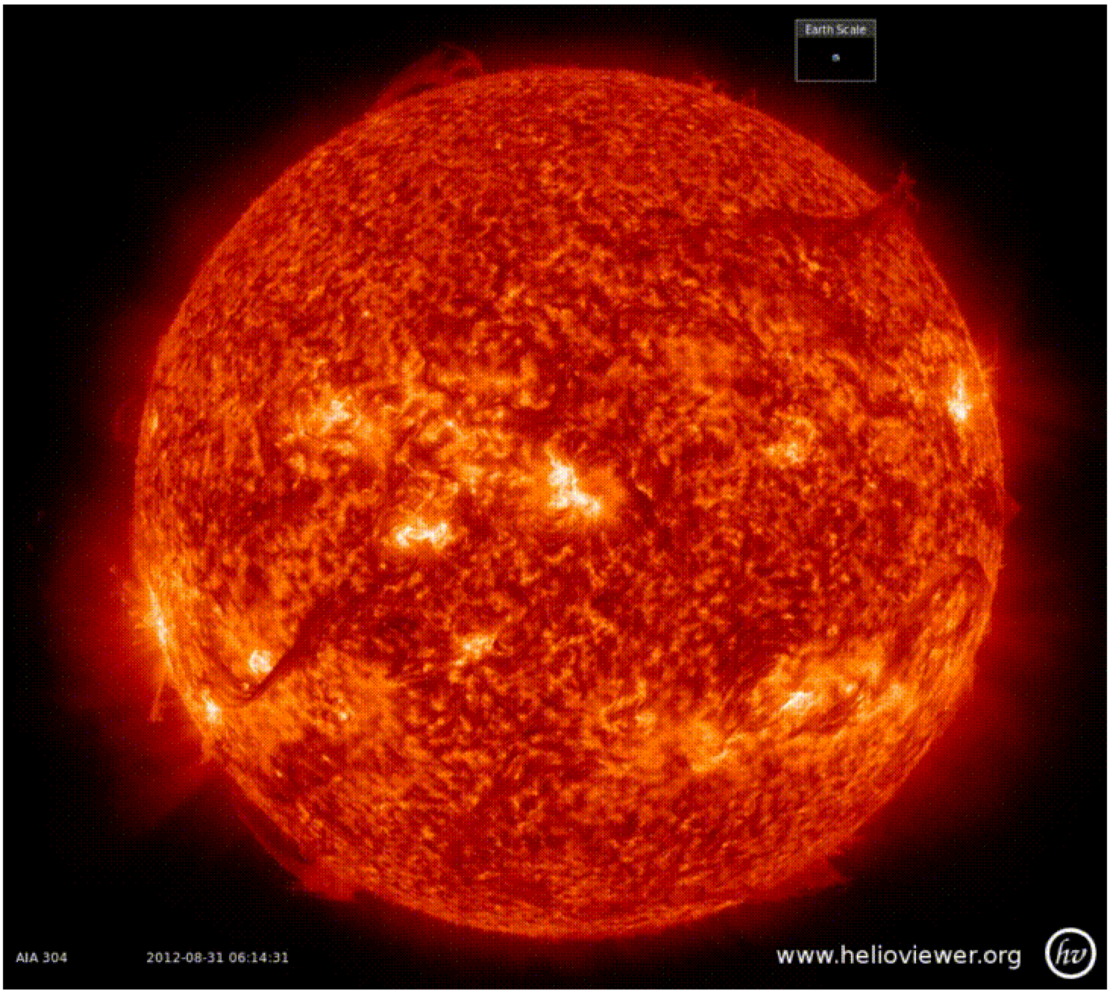
1. INTRODUCTORY IDEAS



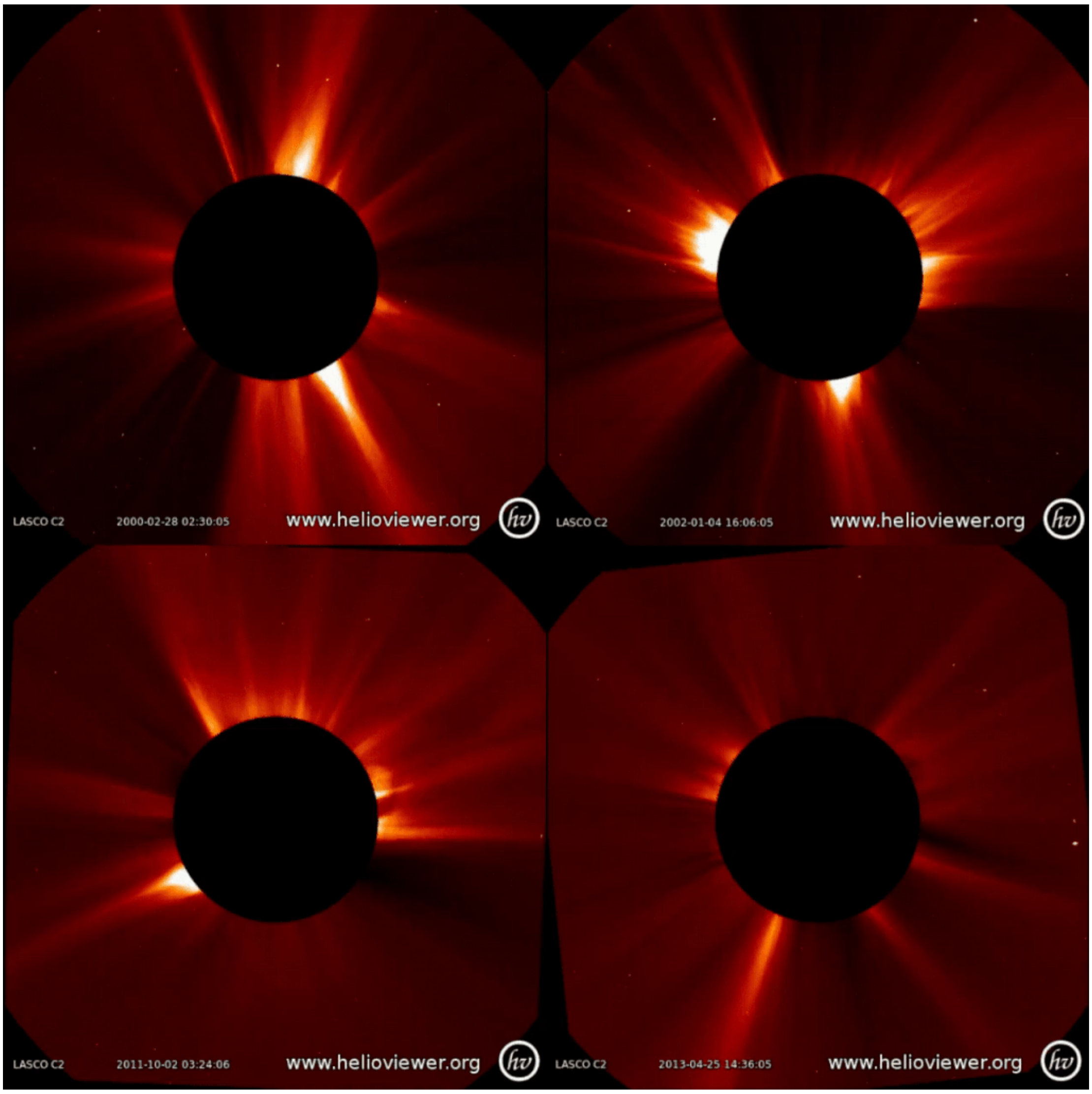
(a) Interplanetary magnetic field, (b) Bow shock, (c) Magnetopause, (d) Day-side reconection zone, (e) Polar cusp, (f) Magnetotail, (g) Night-side reconection zone, (h) Magnetosheath, (i) Earth

F1.1: Schematic diagram of the magnetic field and plasma configuration around Earth.

Host stars play a critical role in shaping the planets such as Earth. Due to the magnetic properties of the Sun and Earth, the interactions between the solar wind and the Earth's magnetosphere give rise to various plasma phenomena and impact the space environment.

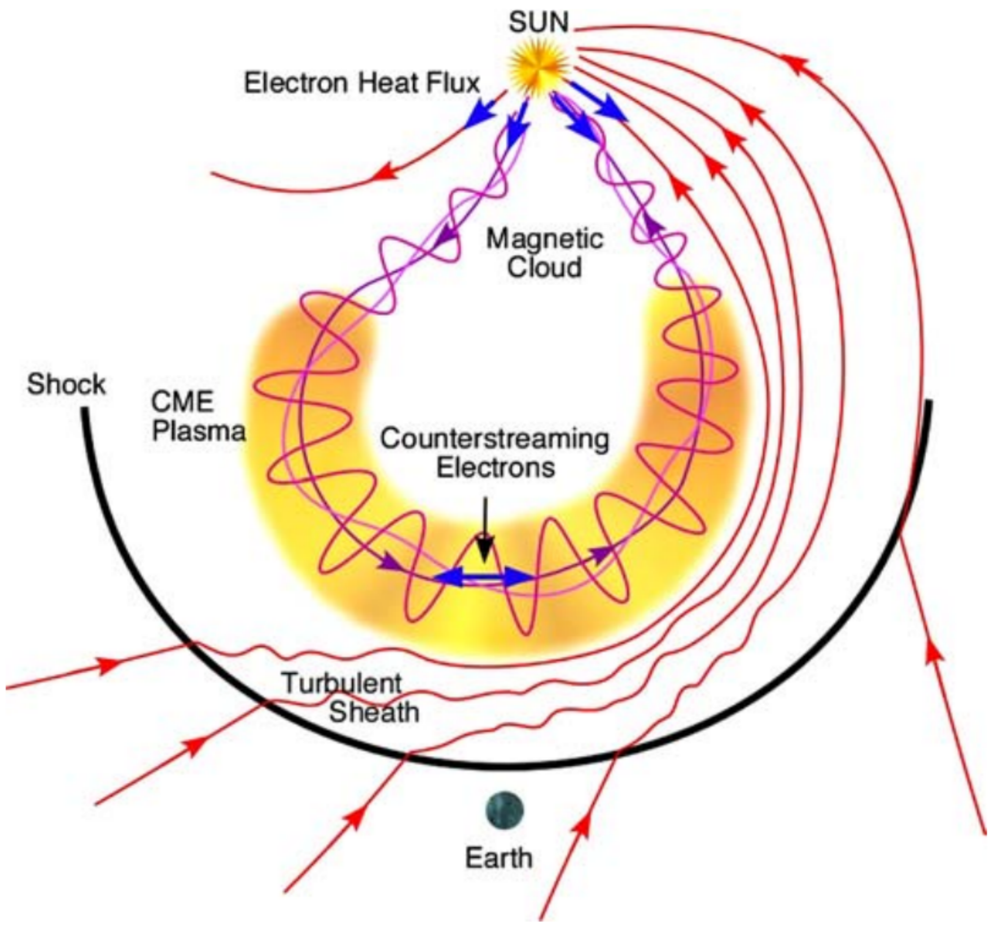


F1.2: CME eruption event on 31st of August, 2020. Data source: AIA304. Image courtesy: Helioviewer (https://www.helioviewer.org/)



F1.3: CME eruption events on (Left-Top) 27/02/2000, (Right-Top) 04/01/2000, (Left-Bottom) 02/10/2011, and (Right-Bottom) 25/04/2013. Data source: SOHO LASCO C2. Image courtesy: Helioviewer. (https://www.helioviewer.org/)

Other than the solar wind and the solar energetic particles, CMEs or the coronal mass ejections are one of the most effective ways (mass ~ 10^{12} kg, magnetic field ~ 2 mT and velocity ~1000-2000 km/s) for the Sun to influence planetary space environments. The heliospheric counterpart of CME (> 50 R_{Sun}), an interplanetary coronal mass ejection or ICME remains highly energetic and supersonic at 1AU and impacts the magnetosphere of Earth with the helical magnetic flux rope and the embedded high energetic plasma.

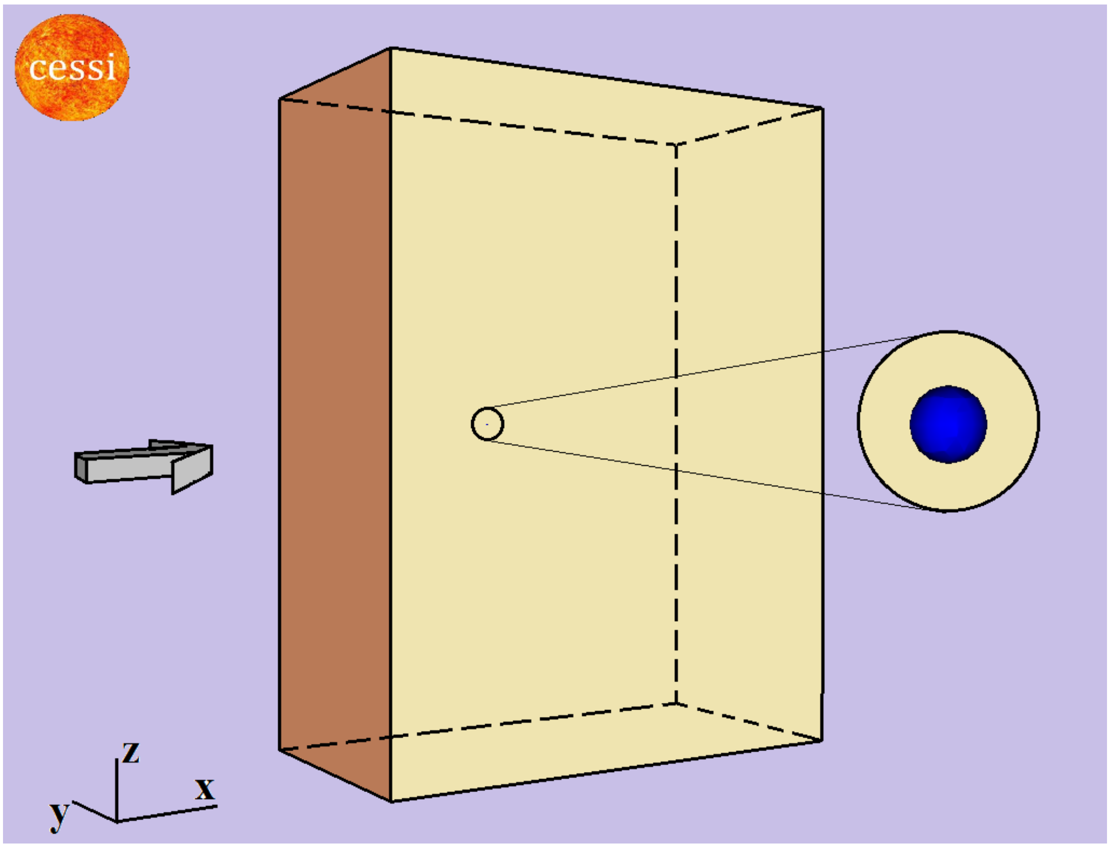


F1.4: The global schematic structure of an ICME. The ICME is led by a shock, followed by a hot and turbulent sheath, which in turn is followed by a magnetic cloud containing a flux rope. Image courtesy: Zurbuchen, T. and Richardson, I. (2006) (https://doi.org/10.1007/978-0-387-45088-9_3)

To study these magnetic connections, not only between the Sun-Earth but a general star-planet system, a computational module has been developed at the Center of Excellence in Space Sciences India (http://www.cessi.in/) aka *CESSI* named CESSI – Star-Planet Interaction Module (CESSI-SPIM). In this study, we present the outcomes of the interactions between an idealised ICME and Earth's magnetosphere using CESSI-SPIM simulations.

2. INITIALIZATION AND MODELLING

CESSI-SPIM:



F2.1: Schematic diagram (not to scale) of the CESSI-SPIM domain for SPI simulations. The arrow dictates the direction of the solar wind.

(Inset) Planet Earth inside computational domain at a position (0,0,0).

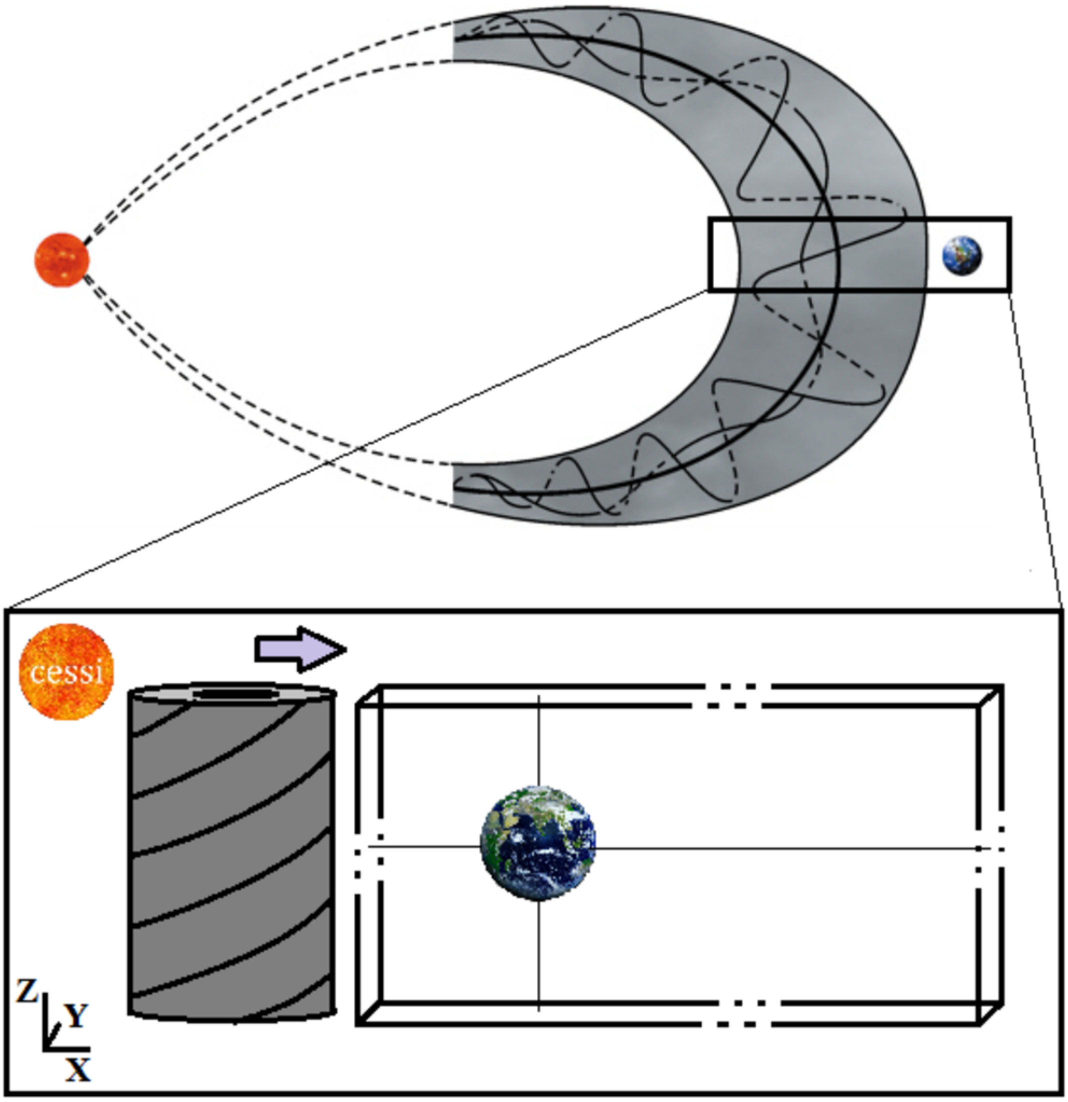
In the typical length scale of a general star-planet system Magnetohydrodynamical approximation of plasma is generally valid. Using CESSI-SPIM, we perform 3D MHD simulations in PLUTO (Mignone, et.al., (2007) (https://doi.org/10.1086%2F513316)) architecture. For further details, see Das, et. al., (2019) (https://doi.org/10.3847/1538-4357/ab18ad)

Modelling the ICME:

We use S-IMF solar wind and ICME flux rope as consecutive inputs and simulate Earth's magnetosphere. We choose uniformly twisted force-free **Gold Hoyle** model for the flux ropes (Gold, T. and Hoyle, F. (1960) (https://doi.org/10.1093/mnras/120.2.89)), where the field components in cylindrical coordinates look like.

$$B_r = 0,$$
$$B_\phi = \frac{Tr}{1+T^2r^2}B_0,$$
$$B_z = \frac{1}{1+T^2r^2}B_0.$$

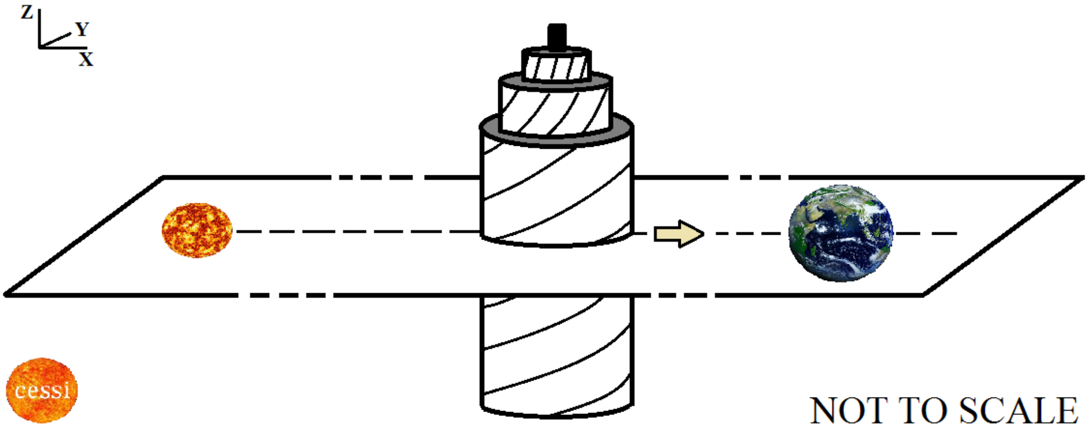
Here, B_0 is the magnetic field of the ICME core and T is a constant parameter, representing the twist in the form of $\tau = \frac{T}{2\pi}$.



F2.2: Schematic diagram (not to scale) of the SPIM domain for ICME simulations. ICME Image courtesy: Burlaga, L.F., Lepping, R.P. and Jones, J.A. (1990) (https://doi.org/10.1029/GM058p0373)

Important assumptions of the ICME model:

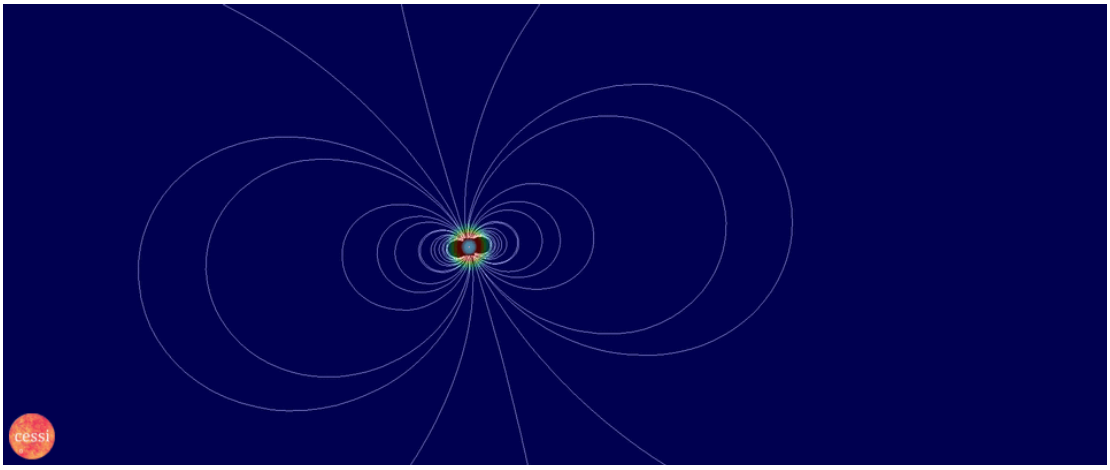
- Flux rope is a combination of the coaxial cylindrical surface of the helical magnetic field with zero axial curvature.
- The central axis of the flux rope is normal to the Sun-Earth ecliptic plane and travels along the sun-earth line without changing its orientation and physical properties.
- Flux rope is guided by a shock wave and the velocity and density is uniform inside the flux rope.
- The initial magnetosphere, as seen by the ICME, is in a dynamical steady state.



F2.3: Schematic diagram (not to scale) of the ICME flux rope with respect to Earth's ecliptic plane and Sun-Earth line.

ICME Parameters:

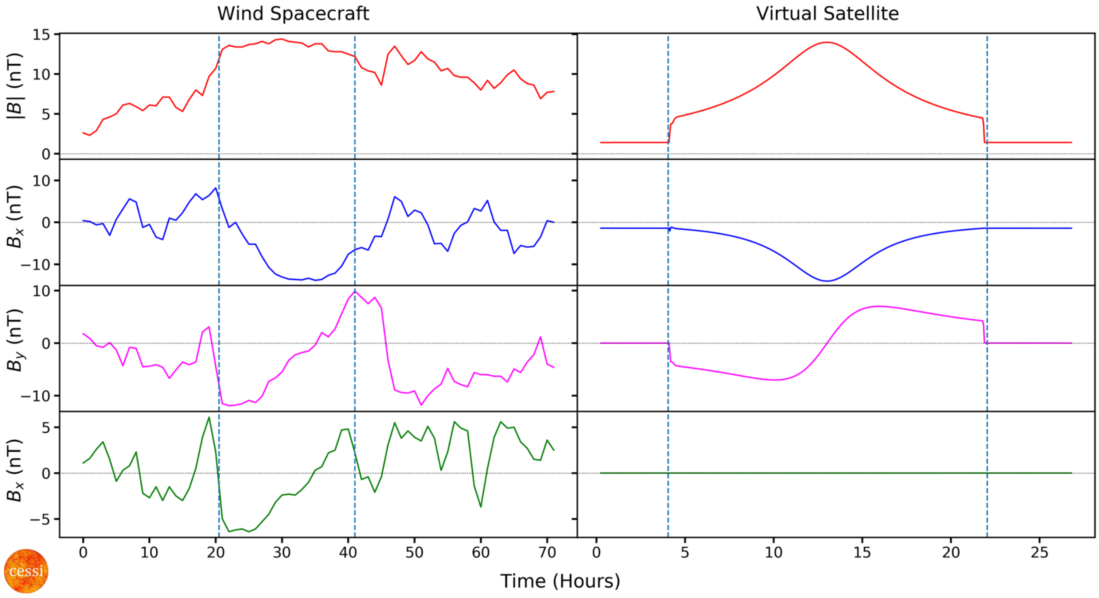
- Axial magnetic field (B_0) = -14 nT
- Velocity of the flux rope (V_{FR}) = 380 km/s
- Radius of the flux rope (R_{FR}) = 0.08 AU
- Density of the plasma in flux rope (ρ_{FR}) = 1.5 x 10^{-19} kg/m^3
- Twist (τ) = 37 rad/AU



F2.4: S-IMF solar wind and ICME flux rope shaping the Earth's magnetosphere on CESSI Star Planet Interaction Module (SPIM)

3. PSEUDO SATELLITE, MAGNETOPAUSE AND CURRENT

Pseudo-Satellite Observing the Event:

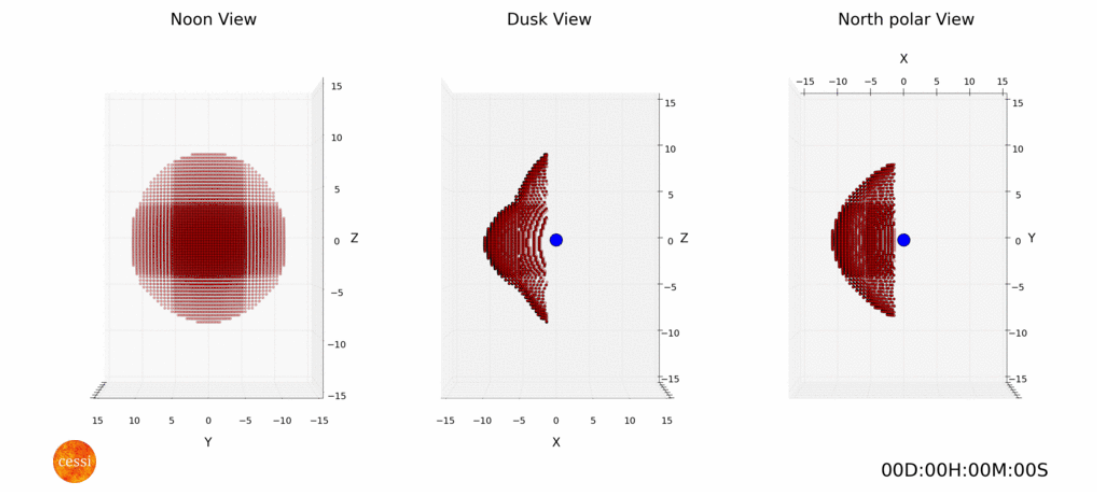


F3.1: Comparison of the magnetic field structure of an actual ICME event (Left) and the modelled flux rope (Right). The vertical lines specify the crossing timebound of the flux rope in both the plots. The ICME event on the left starts from 28/05/2010 00:00:00 hours. Data courtesy: NASA's Space Physics Data Facility (SPDF) (https://spdf.gsfc.nasa.gov/index.html)

To measure the incoming solar wind inside the computational domain, we put a point-sized pseudo satellite at -100 R_{Earth} on the Sun-Earth line, similarly like the actual spacecraft measuring solar wind parameters at the L1 point. We compare our result with an identical ICME event using data from Wind spacecraft. Expectedly, the magnetic field inside the domain follows the Gold-Hoyle structure except for the observed B_x component. It remains zero with time because of the orientation of the flux rope axis to the ecliptic plane and the pseudo satellite's position.

Time Evolution of Magnetopause:

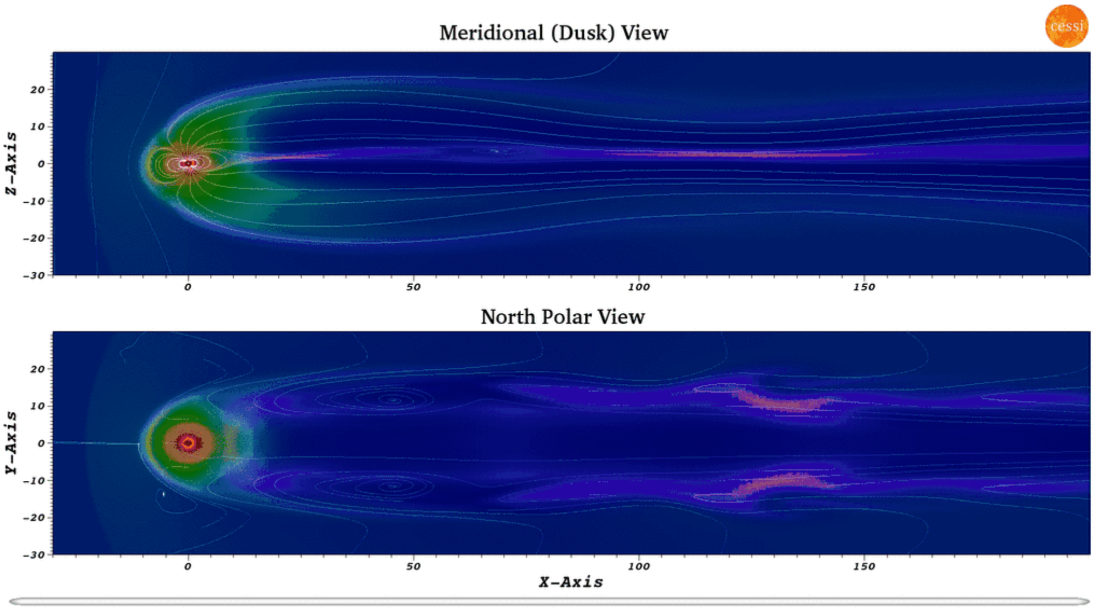
Solar plasma forcing on the magnetosphere creates a pressure balanced boundary on the dayside of Earth - known as the magnetopause, beyond which the solar wind particles can't penetrate. The ICME pushes the boundary further towards Earth. Because of the twisted structure of the ICME, we see a distorted magnetopause during the geo-storm, and the deformation actually replicates the field profile of the ICME as it crosses the earth.



F3.2: Time evolution of the raptured three-dimensional magnetopause during the geo-storm as viewed (Left Column) from the Sun, (Middle Column) above the meridional plane and (Right Column) above the ecliptic plane. The blue sphere represents the Earth.

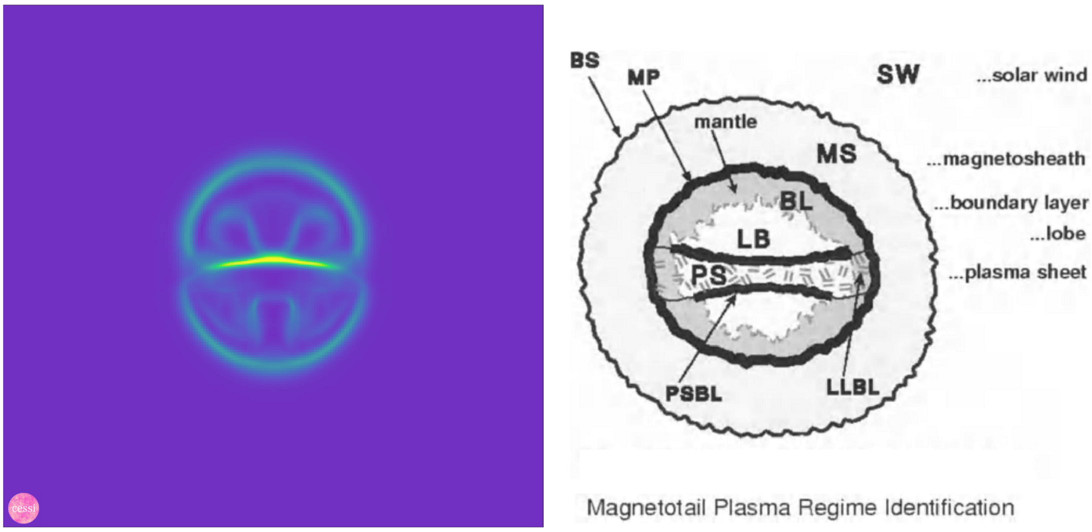
Current Distribution around Earth:

To understand the trace of the trapped particles around Earth, it's important to map the current distribution around it. An image of the current distribution of the dynamical but steady magnetosphere is given in the first section. Here we present how the consistent current distribution changes abruptly over time in the presence of the ICME's.



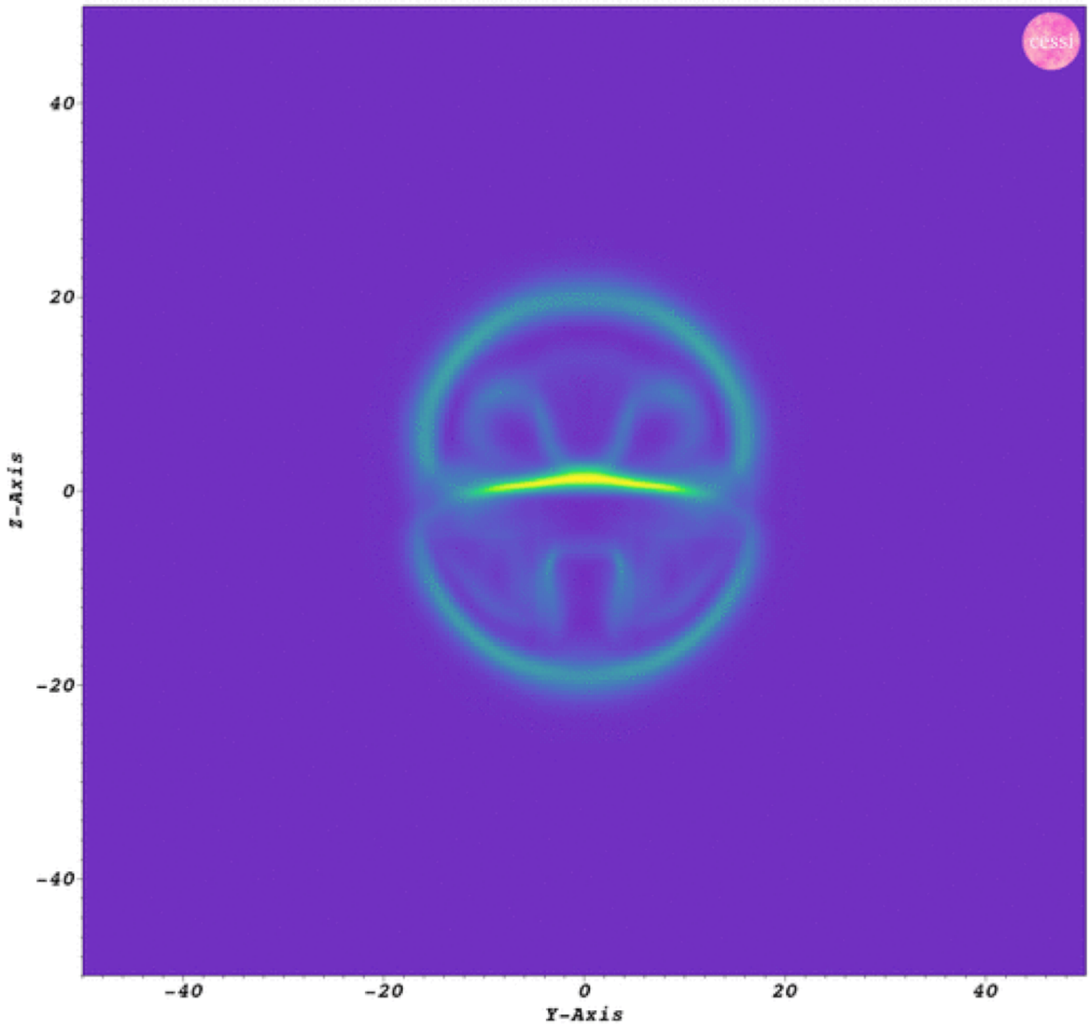
F3.3: Time evolution of the current distribution around the Earth and the magnetotail as viewed from (Top) above the meridional plane and (Bottom) above the ecliptic plane.

The magnetotail of Earth also holds a crossectional ϴ-shaped current system because of the solar wind oppression. The magnetotail is completely different from the solar wind in terms of the plasma properties inside it. The figures below show the current and plasma configuration in the magnetotail and how the configuration changes with time during the geo-storm. The flux rope is imposing torsional twist in the magnetotail current system.



F3.4: (Left) Cross-sectional image (YZ plane) of the current systems inside magnetotail.

(Right) Schematic drawing (not to scale) of the magnetotail cross-sectional plasma regimes. Image Source: Christon, S. P., et al. (1998) (https://doi.org/10.1029/98JA01914)

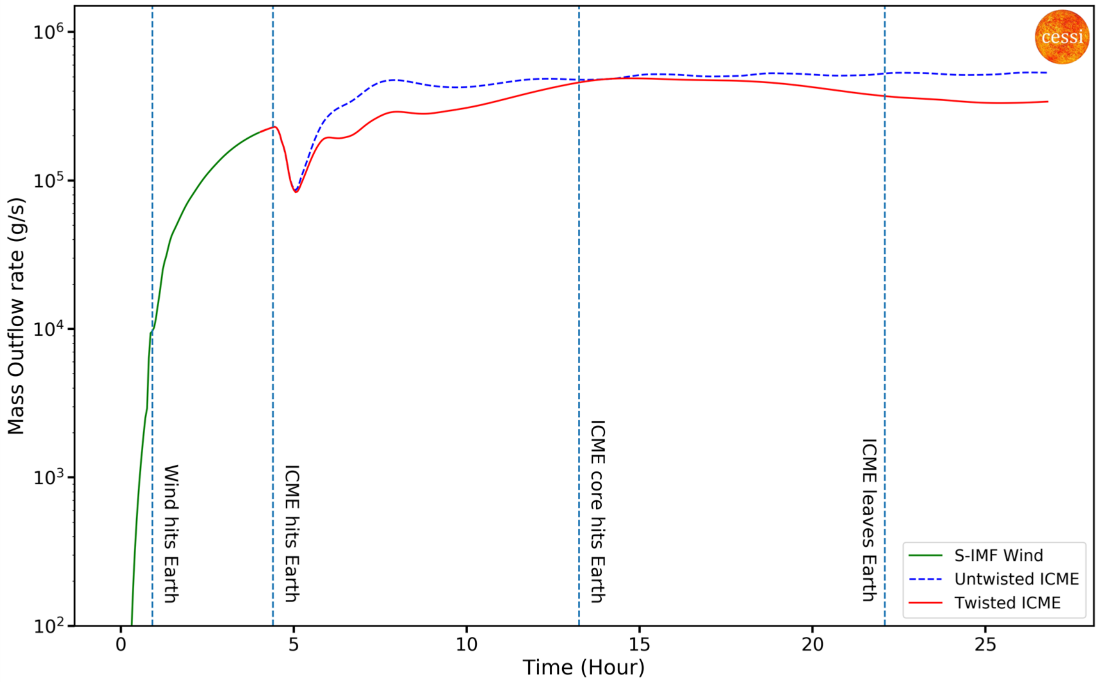


F3.5: Cross-sectional current systems inside magnetotail as a function of time during the ICME's passage. The flux rope is imposing torsional twist in the current system.

4. ATMOSPHERIC MASS LOSS AND GAIN

We estimate the relative mass flow rate in the plasma atmosphere of our Earth. We take a box of length 10 R_{Earth}, around Earth and sum up the mass flux contributions from all the surfaces.

Mass Out-Flow:



F4.1: Change in Earth's mass out-flow rate as a function of time

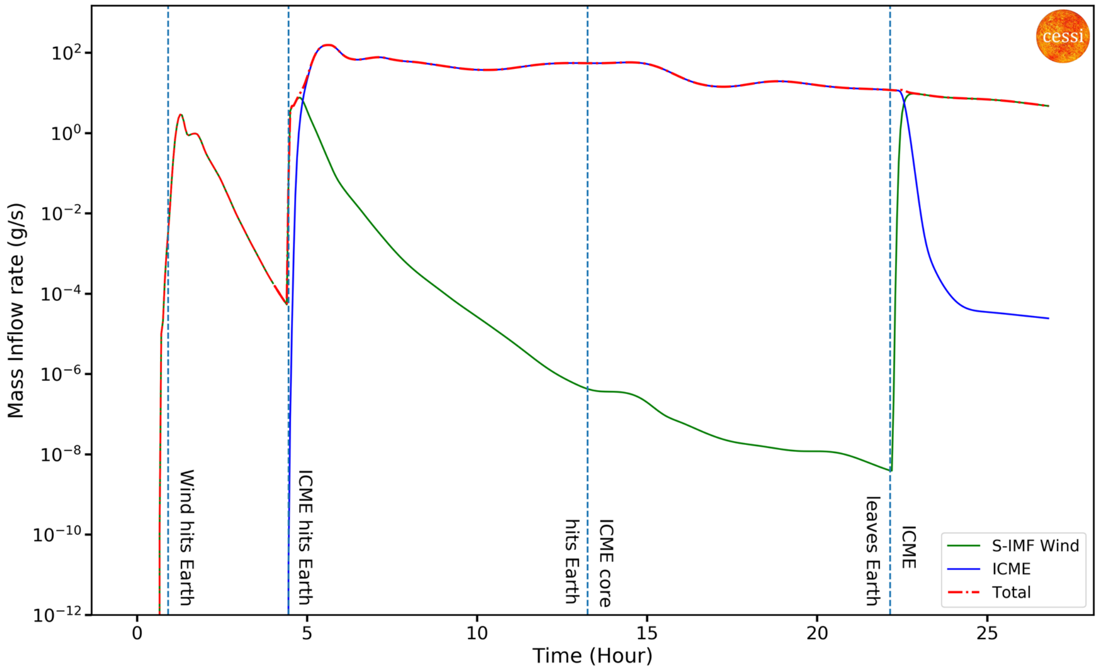
The rate of planetary mass outflow directly indicates how star-planet interaction processes mediated by magnetic reconnection and subsequent advection by the solar wind could result in atmospheric mass losses. We observe a sharp increase in the mass outflow rate as soon as the S-IMF wind hits the Earth, and it further increases during the ICME passage.

We simulate the dynamics of the interaction with both twisted and untwisted flux rope to explore the role of twist of magnetic field orientation in the process. As shown in figure 4.1 we find that when the magnetic field of the twisted flux rope is not exactly anti-parallel to the magnetospheric field the mass loss rate is lower compared to the case when the untwisted flux rope with purely anti-parallel fields interacts with the magnetosphere.

Mass In-Flow:

Other than depleting the atmosphere, the incoming wind also injects plasma into it, mostly via the polar cusps. We compare the mass inflow rate and it shows -

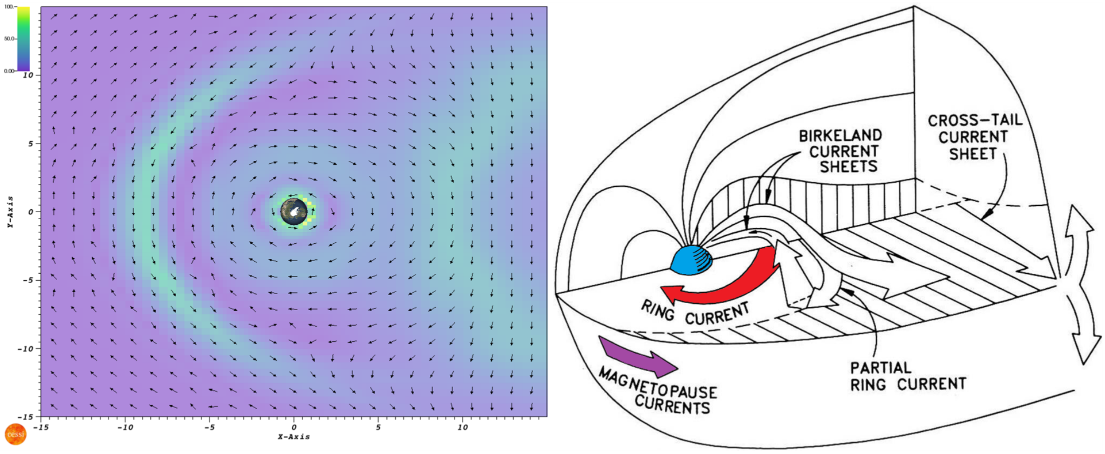
- initially, the S-IMF injects plasma into Earth and later magnetotail injects trapped solar wind plasma into the atmosphere.
- With time the initial inflow rate decreases.
- in presence of ICME, the mass injection rate further increases to become maximum.
- at a later time, it starts decreasing slowly again.



F4.2: Change in solar wind in-flow rate into Earth as a function of time

5. DST INDEX, RING CURRENT AND HELICITY INJECTION

Dst index and Ring Current:

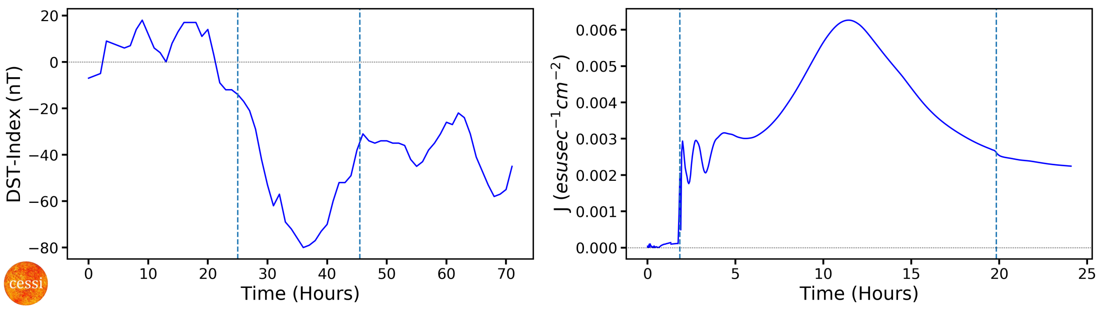


F5.1: (Left) North polar view of the ecliptic plane shows the ring and magnetopause current flow in Earth's Magnetosphere. The arrows follow the direction of $\vec{J}$ whereas the background colour plot indicates the magnitude of the current.

(Right) Cartoon on current flowing systems in Earth's magnetosphere. Image Courtesy: Stern, D. P. (1994). (https://doi.org/10.1029/94JA01239)

The Disturbance storm time (Dst) index is the measurement of Earth's magnetic activity during geo-storm. It represents the axially symmetric disturbance field as a function of storm time and gives information about the strength of the ring current around Earth caused by solar wind particles. Any variation in the Dst index clearly indicates the occurrence of magnetic storms.

Here on one side, we present the in situ measurement of time-averaged Dst index during a geo-storm event on 28th of May 2010 and on another side, we plot the magnitude of current density inside the magnetopause using our simulation data. The current density is calculated at a point on the sun earth line, at a distance 6 R_{Earth} from the Planet.



F5.2: (Left) In-situ measurement of Dst index during an ICME event. Time axis starts from 28/05/2010 00:00:00 hours. Data courtesy: NASA's Space Physics Data Facility (SPDF) (https://spdf.gsfc.nasa.gov/index.html)

(Right) The magnitude of current density from the simulation data, calculated inside the magnetopause, at a distance 6 REarth from Earth.

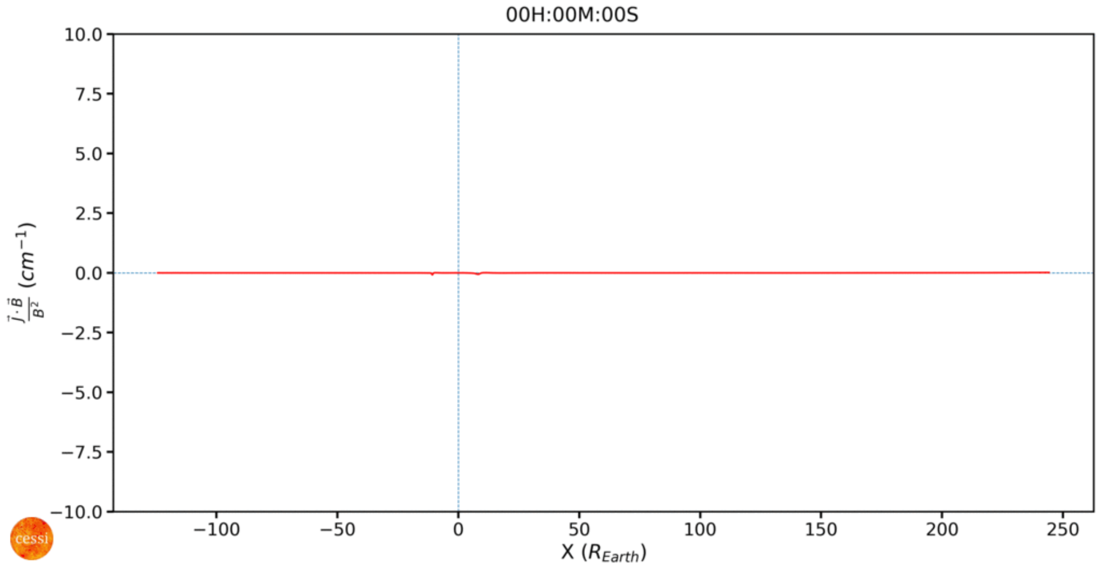
The ring current around Earth produces a magnetic field that directly opposes Earth's magnetic field. The negative Dst value, which indicates that the Earth's magnetic field is weakened, actually implies that the ring current is increased during the storm. And our simulation's result also shows the same with respect to the modelled ICME.

Helicity Injection:

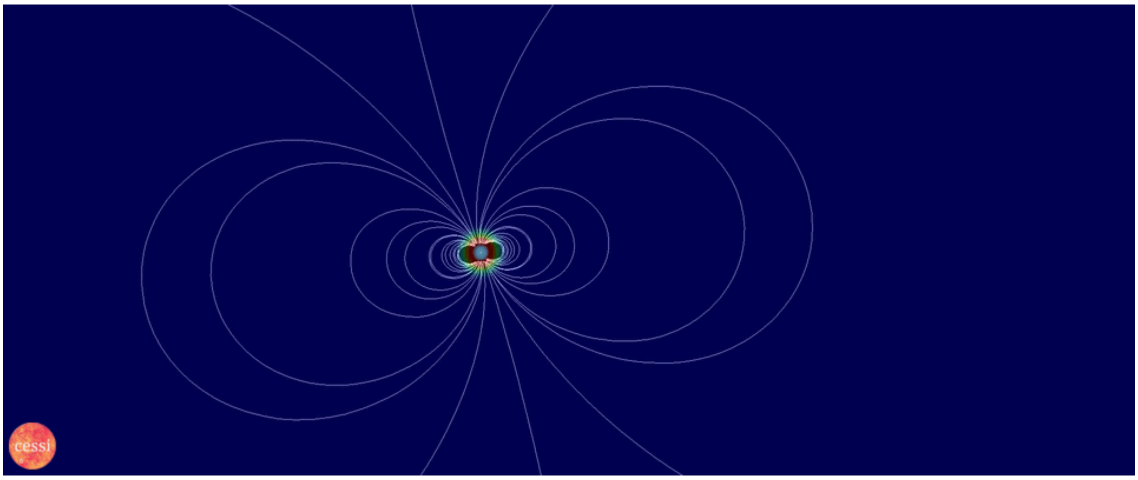
Because of the helical magnetic structure, ICME can inject helicity into planetary magnetotail. We present the temporal evolution of the force-free field parameter α, given by,

$$\vec{\nabla} \times \vec{B} = \alpha \vec{B}.$$

We evaluate $\frac{\vec{J} \cdot \vec{B}}{B^2}$ as a function of time, which is directly proportional to α, at each point on the Sun-Earth line (X-axis). The result indicates that injection of helicity in Earth's magnetotail is possible during a geomagnetic storm.



F5.3: Temporal evolution of $\frac{\vec{J} \cdot \vec{B}}{B^2}$ (∝α) on each point of the Sun-Earth line (X-Axis) of the computational domain.



6. CONCLUSION AND ACKNOWLEDGEMENT

Conclusion:

- In-situ observations support CESSI-SPIM results and make it a more important tool to probe and predict the space weather conditions in future.
- Solar wind forcing leads to a steady and dynamic magnetosphere and ICME is a perturbation to the steady-state.
- The day-side magnetopause is pushed further towards the Earth by the ICME
- Magnetic helicity of the flux rope distorts the shape of the magnetosphere.
- Noticeable current enhancement around Earth and magnetotail during the geo-storm. This increases the high energy particle flux in Earth's vicinity.
- Magnetotail current system also gets torsionally twisted by the flux rope structure.
- ICME comparatively enhances the in and outflow rate of mass around Earth.
- The mass-loss rate is comparatively high when the core is passing.
- In-situ Dst index measurement correlates with current enhancement inside magnetopause.
- ICME can inject helicity in the magnetotail.

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ABSTRACT

Coronal mass ejections (CMEs), the large scale transient eruptions from the Sun, interact with the Earth's magnetosphere while travelling into the heliosphere. The energetic interplanetary CME (ICME) at 1AU not only creates geomagnetic storms and disrupts the magnetic field structure around the Earth but also impacts the plasma environment, causes strong aurorae, and disturbs the radio and electrical transmission massively. We use 3D compressible magnetohydrodynamic simulation of a star-planet system and study the interesting magnetohydrodynamic processes like bow-shock, magnetopause, magnetotail, planet-bound current sheets, magnetic reconnections, atmospheric mass loss as well as particle injection, etc., when an ICME flux rope crosses the Earth at 1 AU. We use the uniformly twisted force-free flux rope model proposed by Gold and Hoyle in 1960 to initiate the ICME and vary the flux rope properties using actual observational data. We observe a change in magnetopause's shape and the stand-off distance to the magnetopause. We notice twist helicity injection inside the magnetotail current system. We discover comparative increment in both the rates of atmospheric mass out-flow and solar wind in-flow in the vicinity of Earth during the geo-storm. Such studies will help us understand how energetic magnetic storms from a host star impact planetary magnetospheres and atmospheres with implications for planetary and exoplanetary habitability.