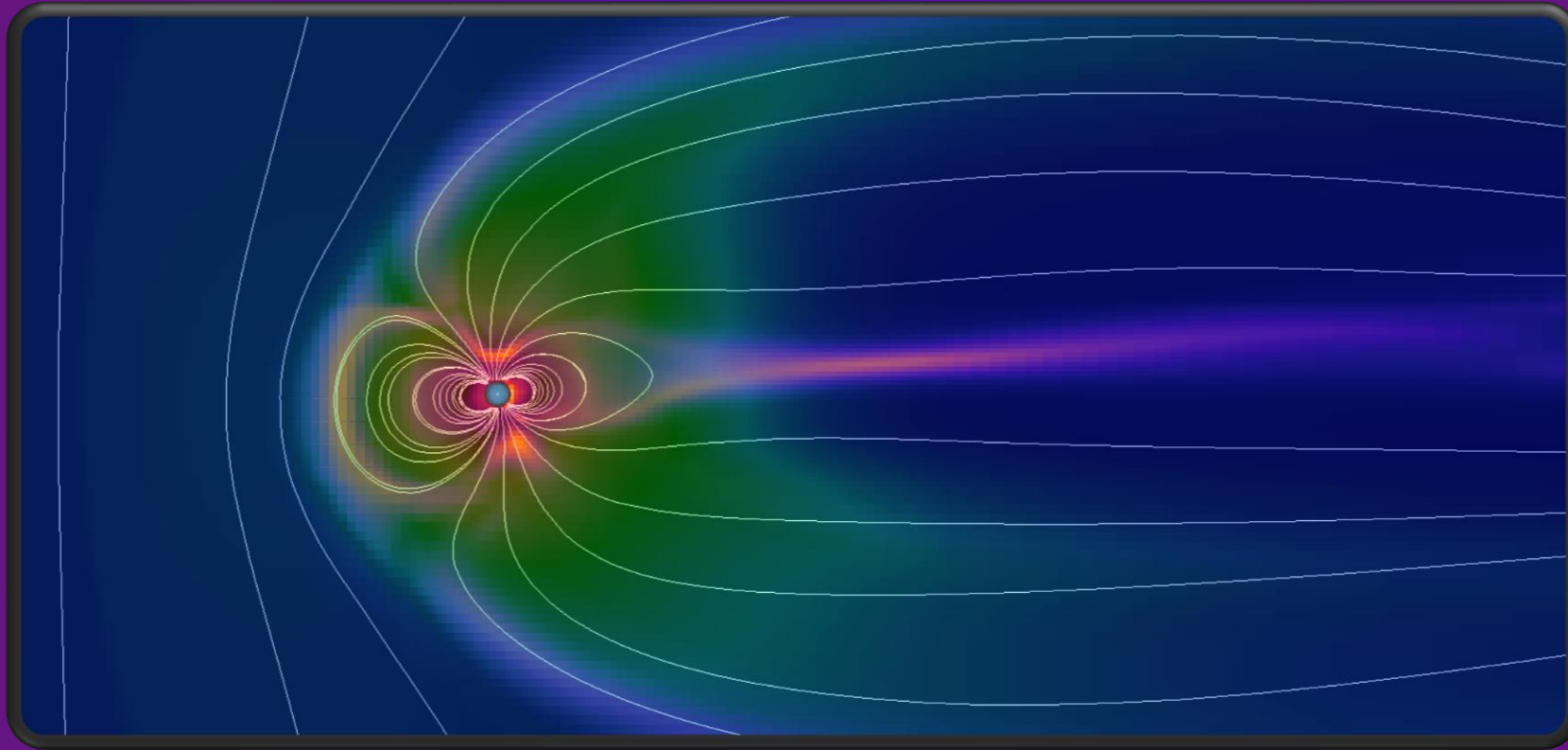


Modelling the Impact of Magnetic Storms on Planetary Environments

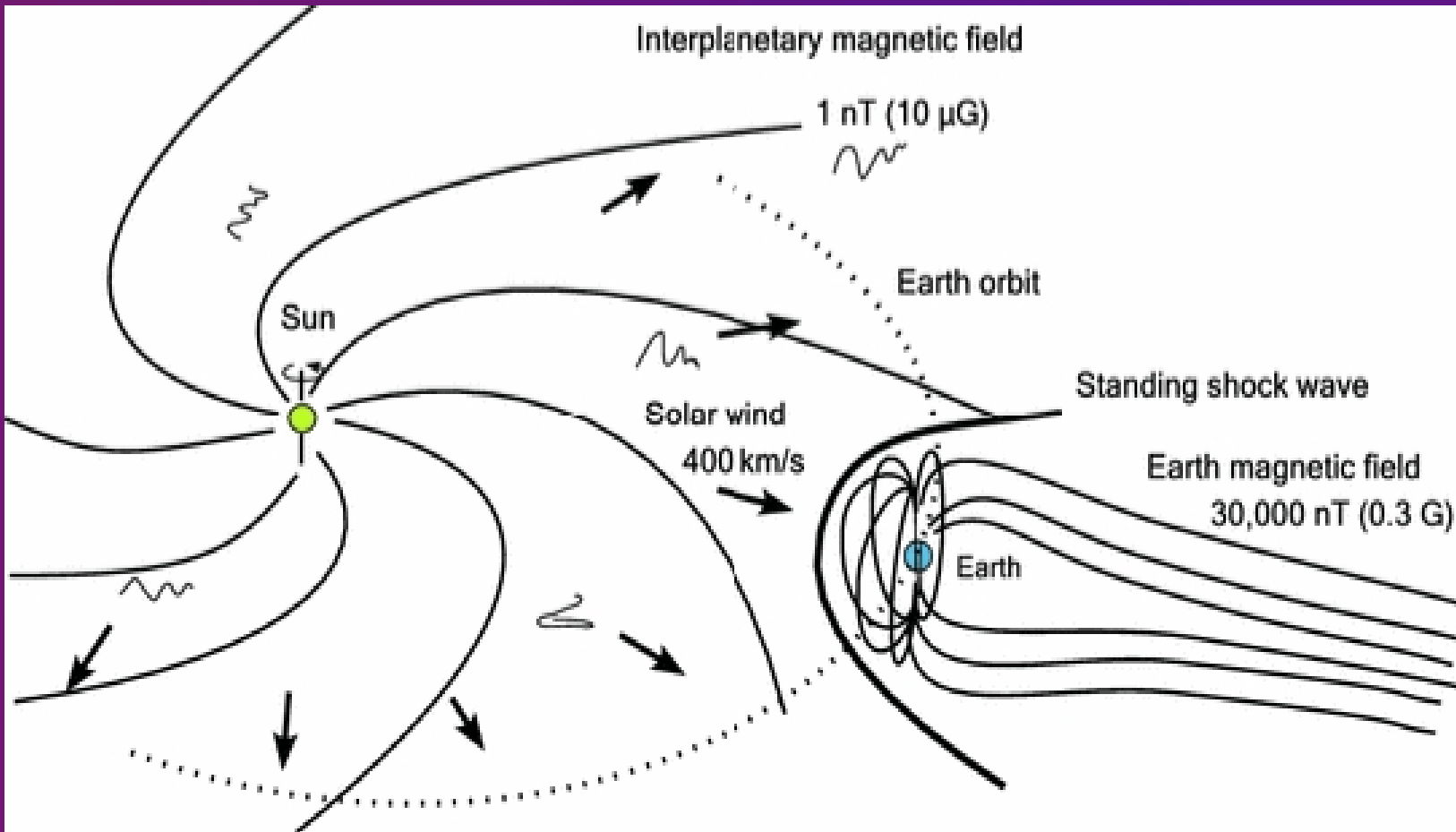


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Overview of this Presentation

- The physics of star-planet interactions.
 - CESSI – Star Planet Interaction Module (CESSI-SPIM)
- Modelling of the flux rope.
 - Interplanetary coronal mass ejection and SPIM
- Results
 - Temporal evolution of magnetosphere and magnetopause
 - Virtual satellite observations
 - Magnetospheric current systems
 - Mass flows
 - Helicity Injection
- Concluding remarks



What happens when a solar flare hits Earth?

- Observers**
A variety of observational spacecraft including the SOHO, STEREO and GOES are used to predict when the Sun will erupt and how powerful the eruption will be.
- International Space Station**
Radiation risks for astronauts on the ISS are minimal, but for future astronauts travelling to deep-space locations like Mars they could be more severe.
- Spacecraft electronics**
Hard X-rays from an incoming solar flare can damage the internal electronics of spacecraft and prevent instruments from working.
- GPS failure**
Increased solar activity can prevent GPS navigation satellites operating functionally and, as most are in a similar orbit, this is not able to provide backup for another.
- Atmosphere**
Soft X-rays from X-class flares can increase the ionisation of the atmosphere so that, while it might produce fantastic auroras, it also interferes with radio communication.
- Aircraft**
In the event of increased solar activity aircraft must avoid flying near the poles and at high latitudes to ensure that communications aren't affected.
- Power grid**
Increased solar activity can cause geomagnetic storms, which have been known to knock out power grids to entire cities in the past.
- Orbital decay**
Increased ionisation of the atmosphere caused by solar storms can increase the drag on satellites, decaying their orbit, as was the case with NASA's Skylab space station in 1979.
- Pipelines**
Telluric currents, those found in long pipelines, can be affected by solar flares when systems designed to protect pipelines from corrosion are overloaded.
- Telephone mast**
Even cell phones are not adverse to the effects of solar flares, as the increased activity can prevent devices communicating with telephone masts.

- Aurora formation [Liou et al. 1998]
- Space weather variations [Schwenn 2006; Pulkkinen 2007]
- Geomagnetic storms [Dal Lago et al. 2006]
- Effects on satellites and space missions [Kumar 2014]

<https://www.spaceanswers.com/news/effects-of-massive-solar-storm-to-bombard-earth-through-to-saturday-predict-experts/>

CESSI Star Planet Interaction Module

The Physics: Astrophysical Magnetohydrodynamics

$$\frac{\partial \rho}{\partial t} + \vec{\nabla} \cdot (\rho \vec{v}) = 0$$

$$\frac{\partial \vec{v}}{\partial t} + (\vec{v} \cdot \vec{\nabla}) \vec{v} + \frac{1}{4\pi\rho} \vec{B} \times (\vec{\nabla} \times \vec{B}) + \frac{1}{\rho} \vec{\nabla} P = \vec{g}$$

$$\frac{\partial E}{\partial t} + \vec{\nabla} \cdot [(E + P)\vec{v} - \vec{B}(\vec{v} \cdot \vec{B}) + (\eta \cdot \vec{J}) \times \vec{B}] = \rho \vec{v} \cdot \vec{g}$$

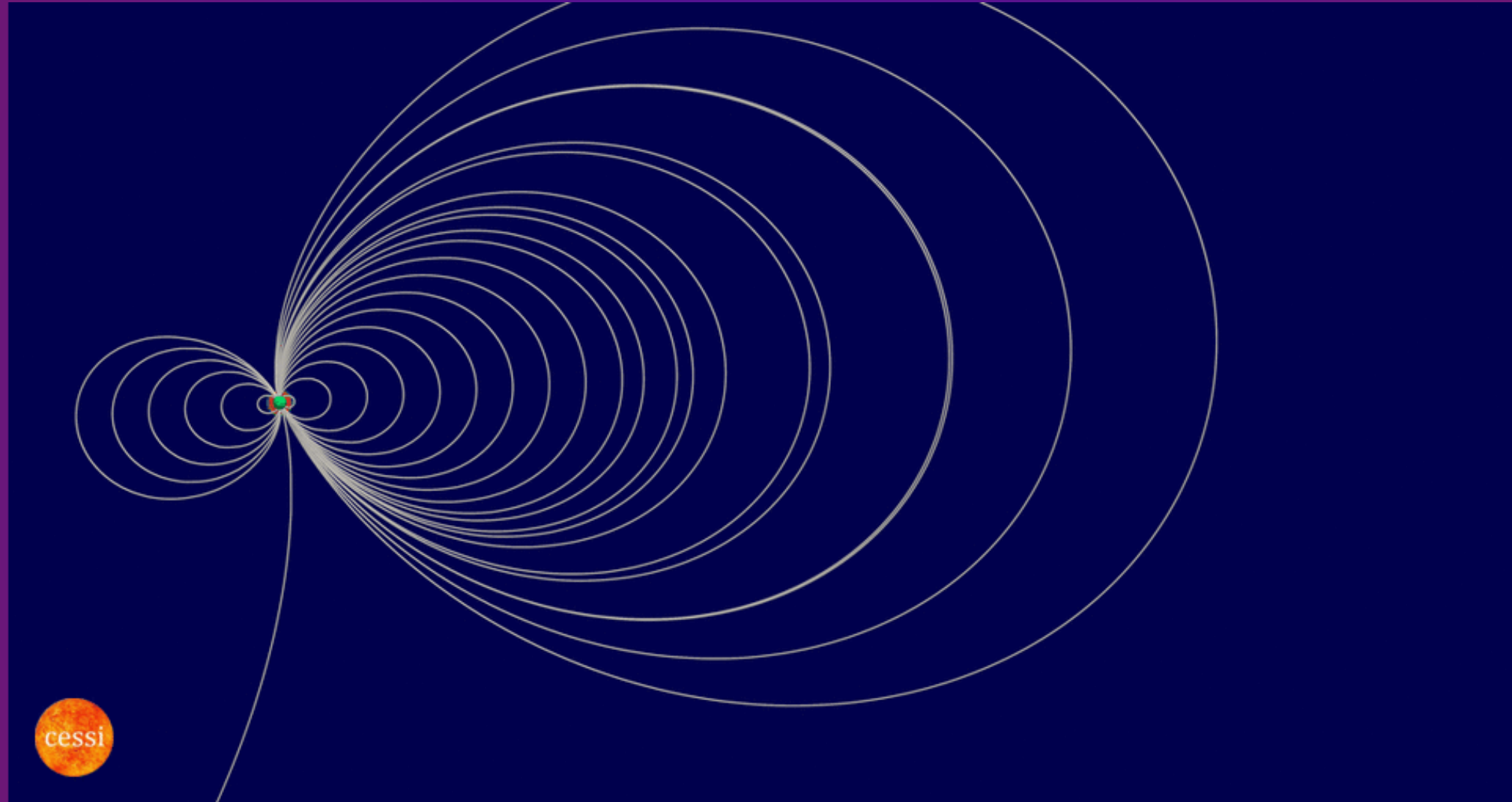
$$\frac{\partial \vec{B}}{\partial t} + \vec{\nabla} \times (\vec{B} \times \vec{v}) + \vec{\nabla} \times (\eta \cdot \vec{J}) = 0$$

Assumptions:

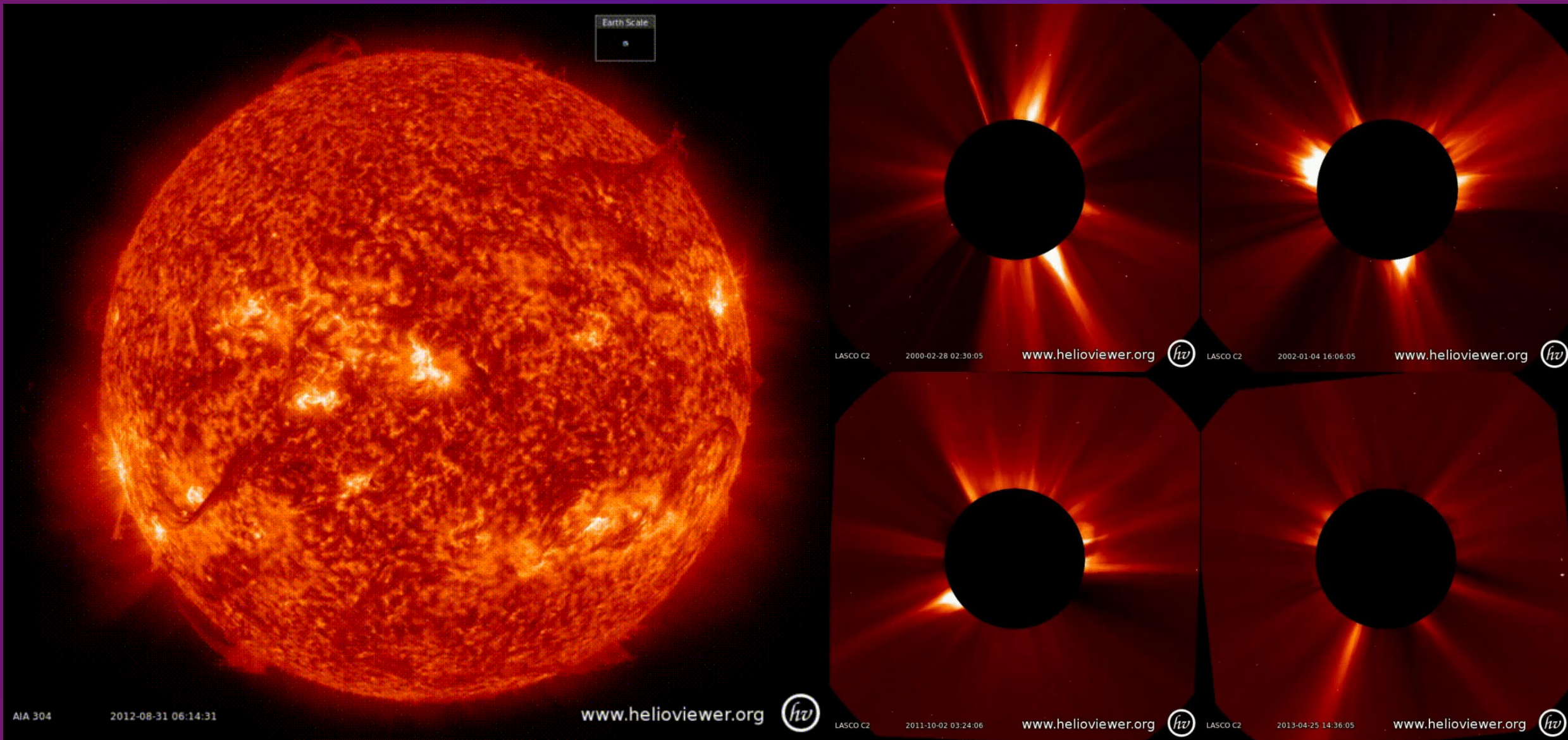
- “Far out” earth-like planet
- Intrinsic dipolar planetary magnetic field
- Stellar wind as magnetised shock
- Non-relativistic, compressible,
- Adiabatic fluid: Gamma = 5/3
- High Magnetic Reynolds number

Simulated on PLUTO V4.3

CESSI Star Planet Interaction Module

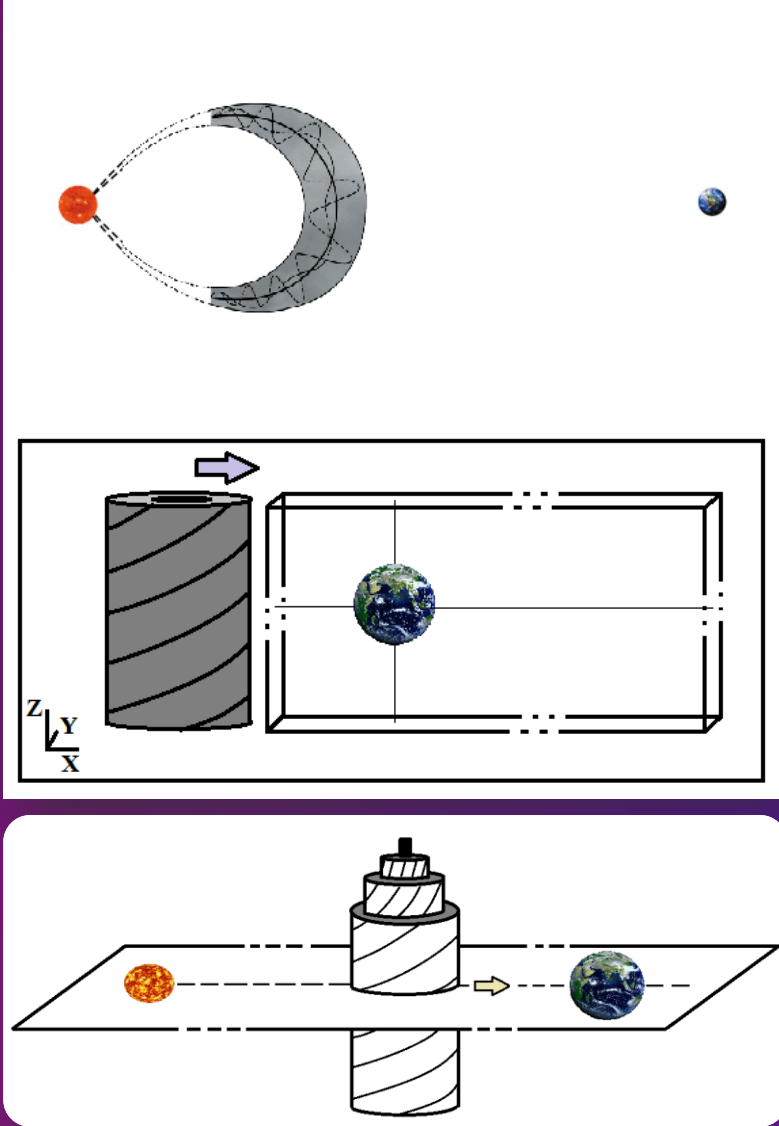


- Srijan Bharati Das et al 2019 ApJ 877 80
- Basak and Nandy 2021 MNARS 502 3



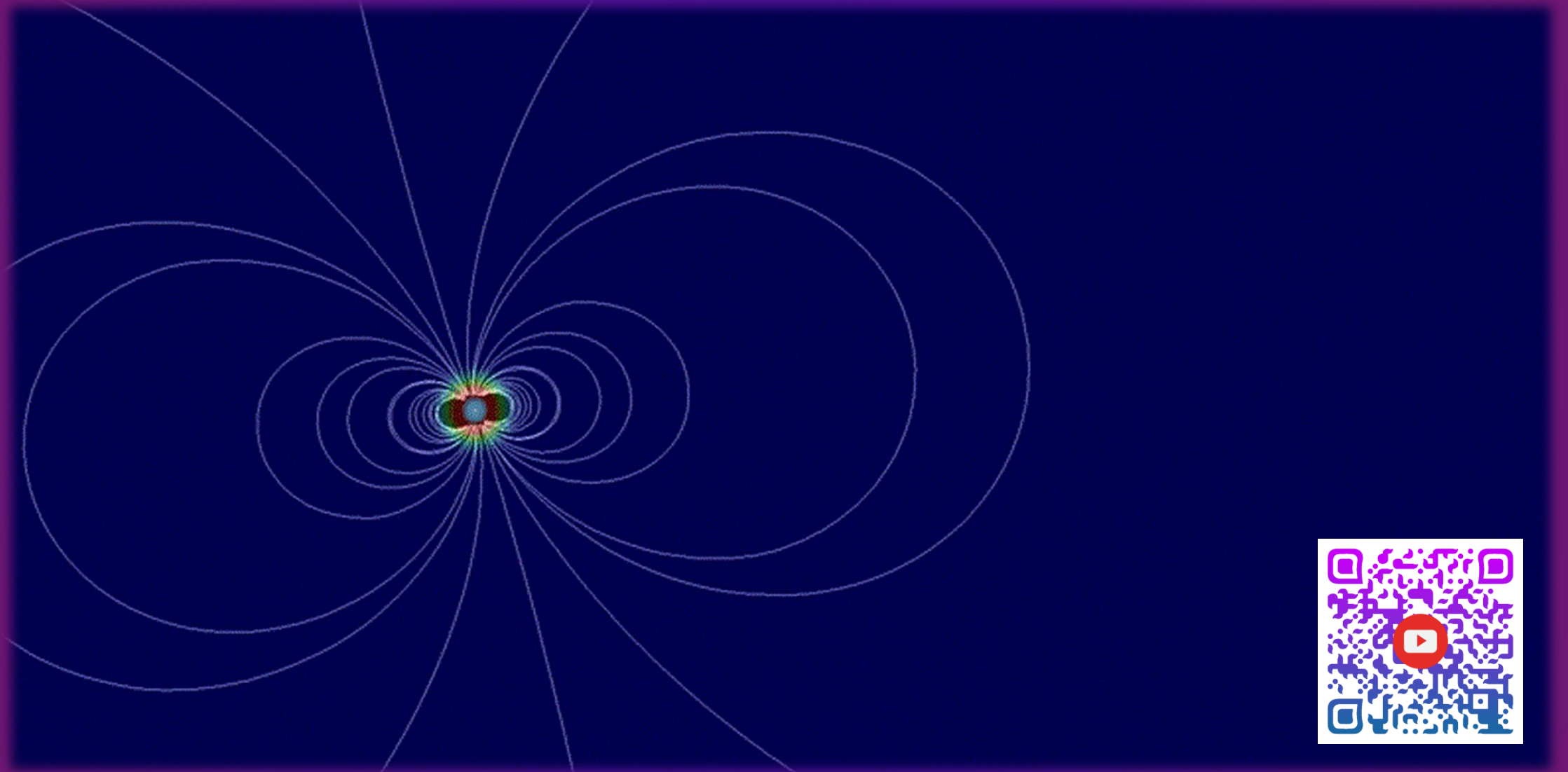
CME eruption events on (Left) 31/08/2012, (Middle-Top) 27/02/2000, (Right-Top) 04/01/2000, (Middle-Bottom) 02/10/2011, and (Right-Bottom) 25/04/2013. Data source: AIA304 (left), SOHO LASCO C2 (others). Image courtesy: Helioviewer. (<https://www.helioviewer.org/>)

Modelling a Interplanetary Coronal Mass Ejection Associated Flux Rope



- Cylindrical Gold-Hoyle (GH) flux rope with no axial curvature
- Flux rope expansion is assumed negligible during computation
- Flux rope central axis is normal to ecliptic plane, core passes through Earth
- Initial magnetosphere is in a dynamical steady state – computed by CESSI-SPIM
- At $t = 0$, shock wave crosses the left boundary followed by the ICME.

Time Evolution of The Magnetosphere

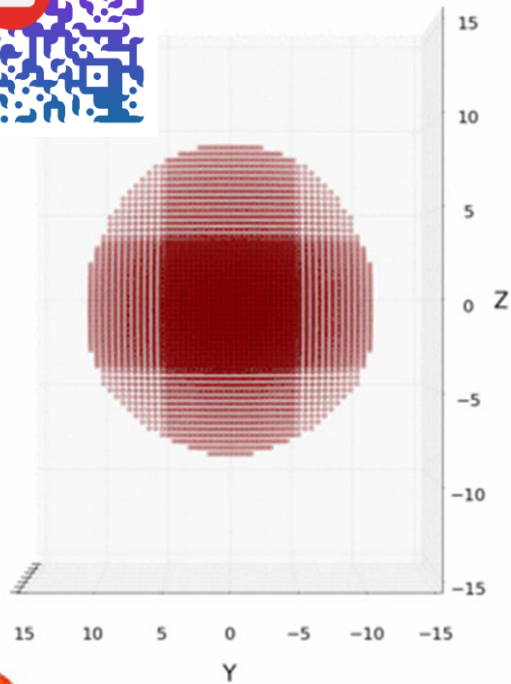


Deformation of the Magnetosphere

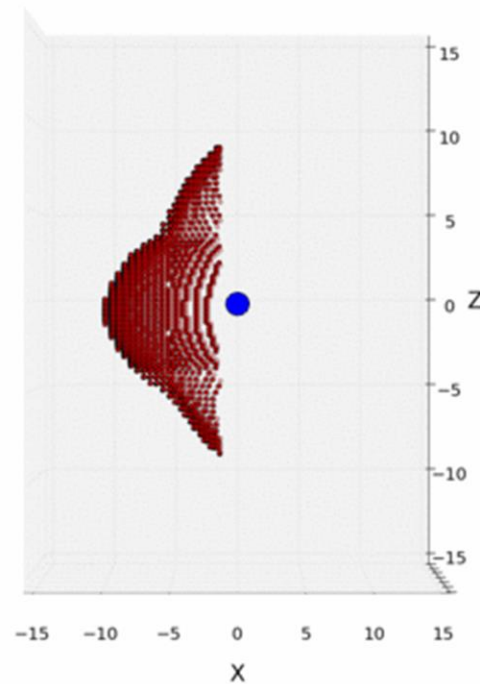
Dynamic Pressure \longleftrightarrow Magnetic Pressure



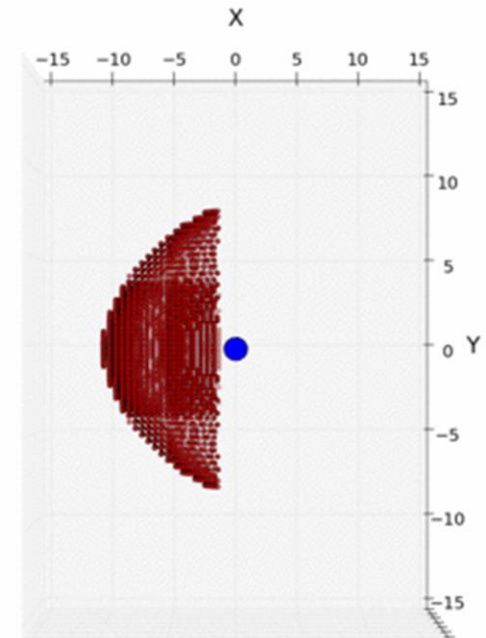
Noon View



Dusk View



North polar View

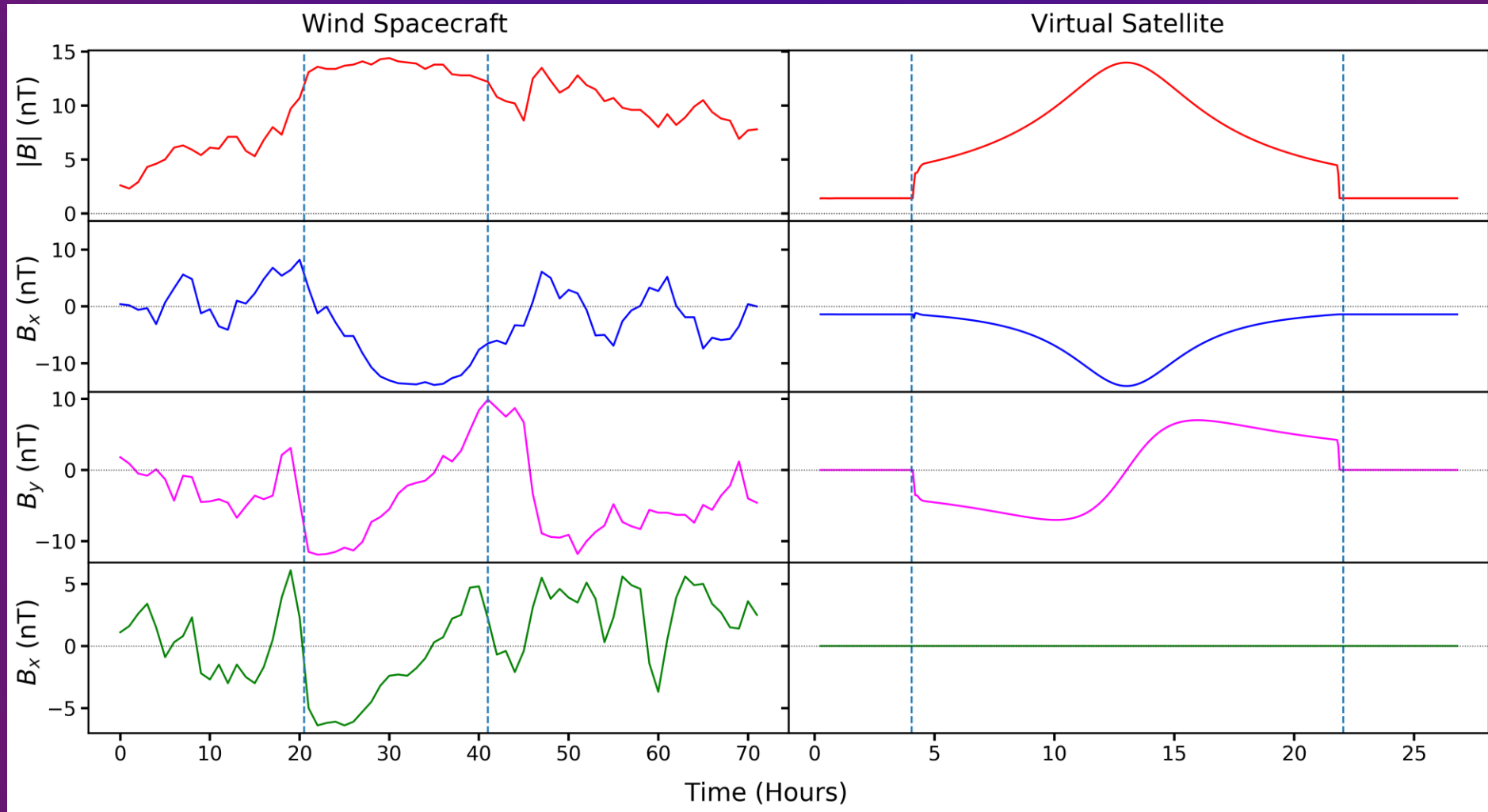


00D:00H:00M:00S



Virtual Satellite Observation of the ICME

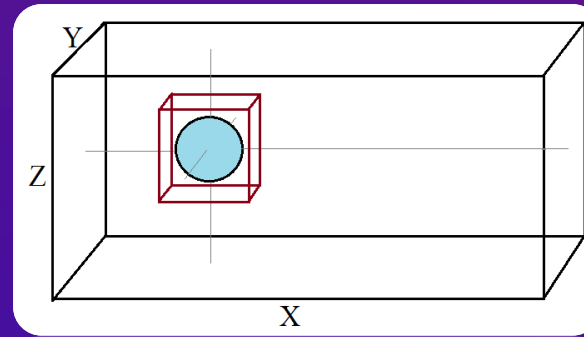
A fixed point in space, measuring B with time



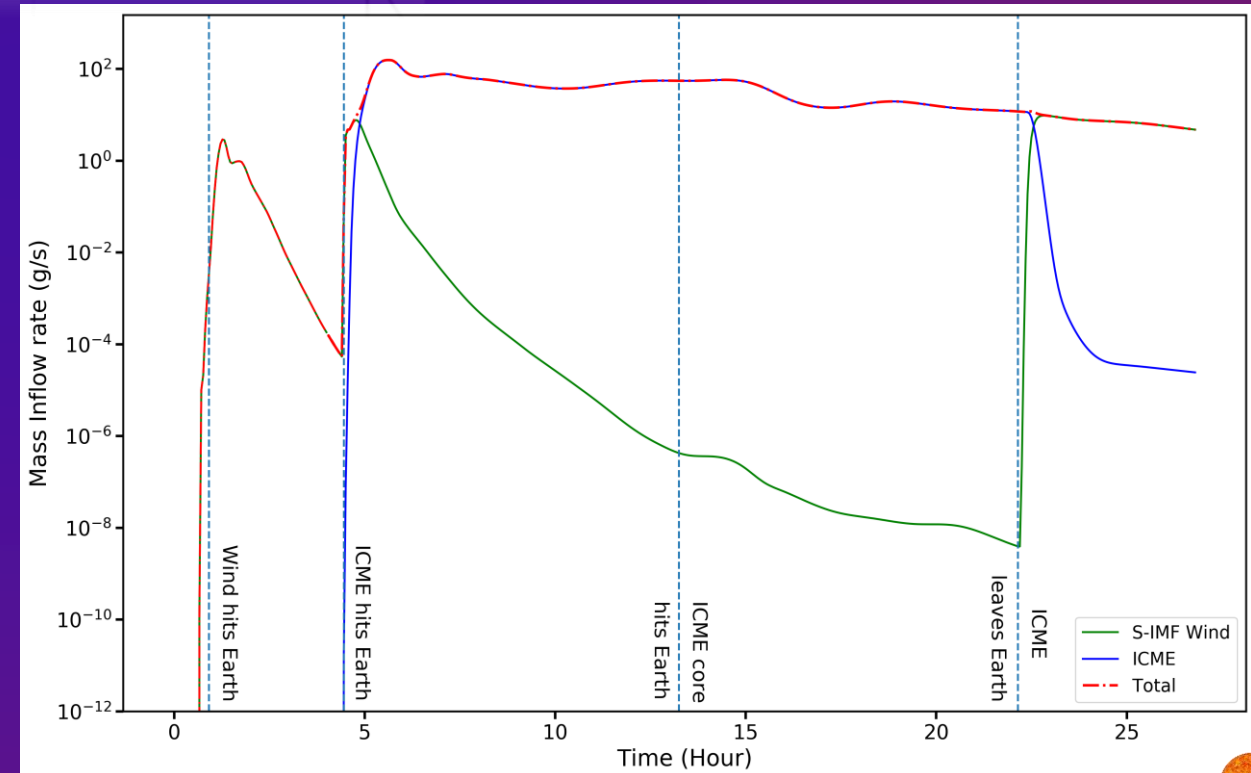
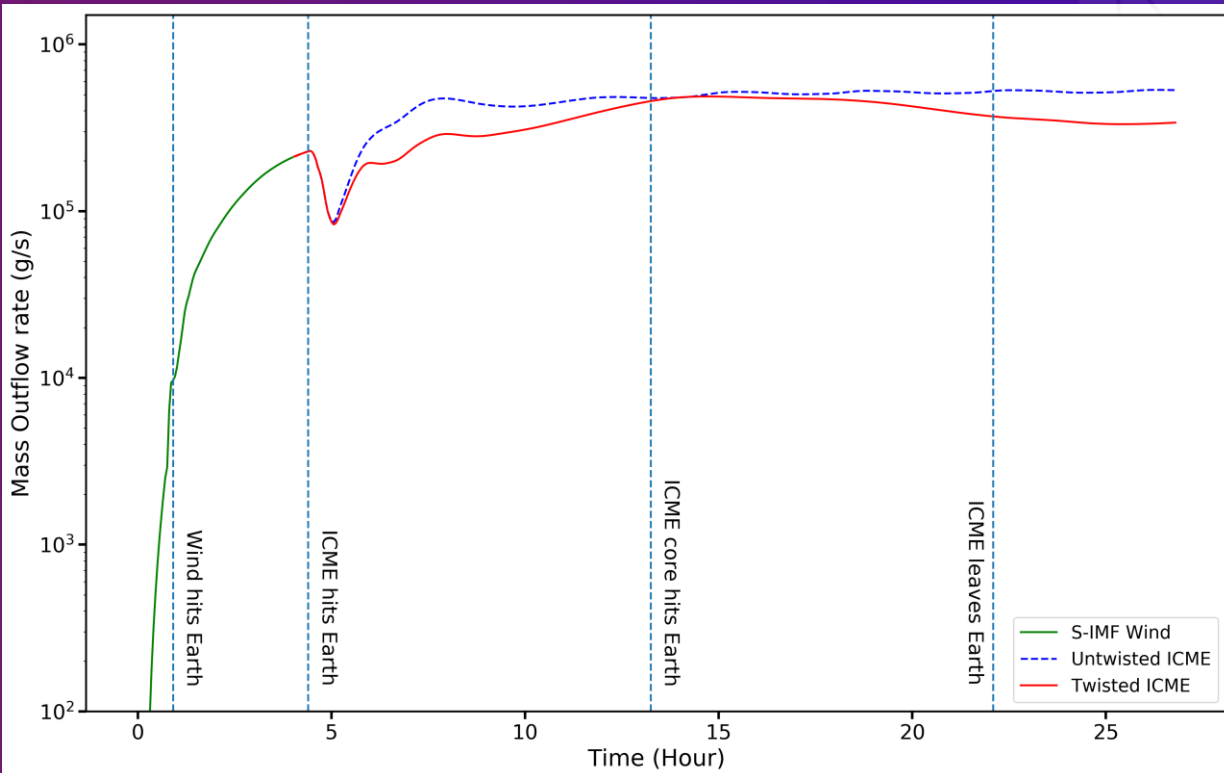
L1
Point

100
 R_{Earth}

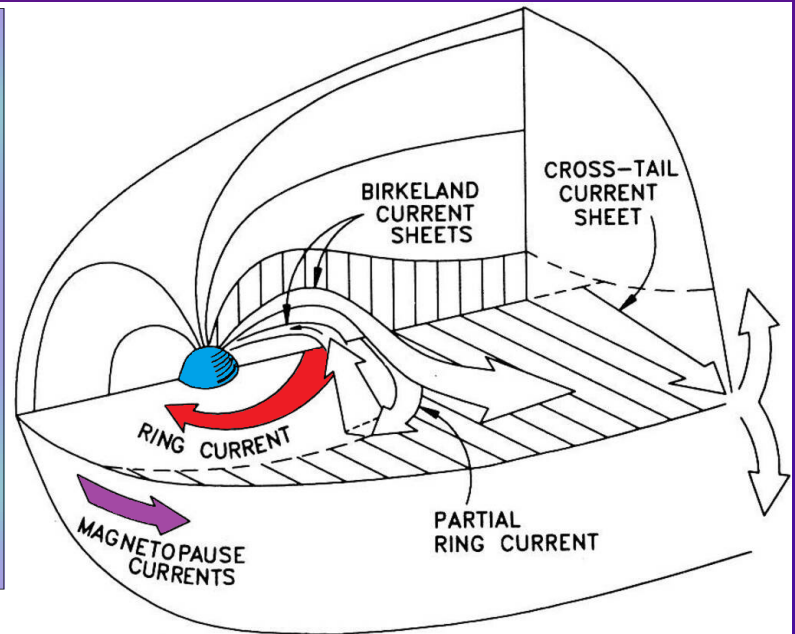
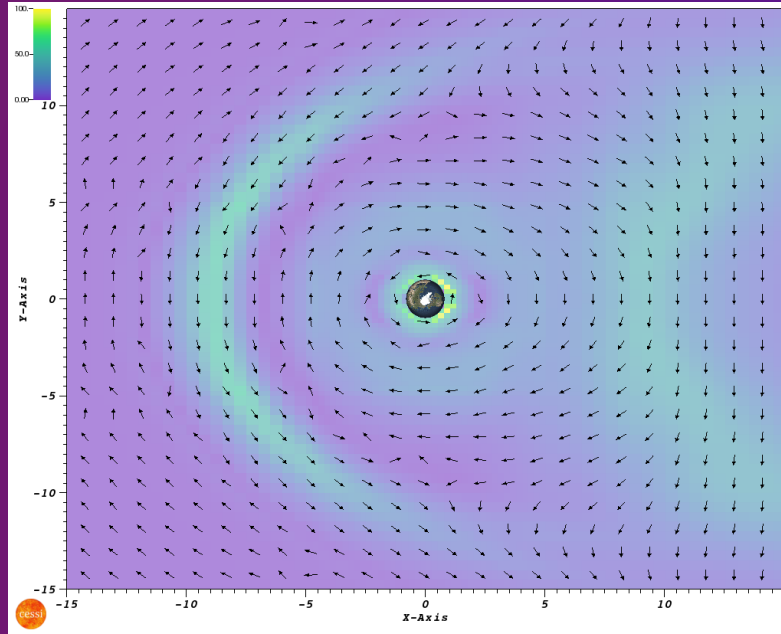
Mass Loss, Mass Gain



Box (R_{Earth}): 10 X 10 X 10

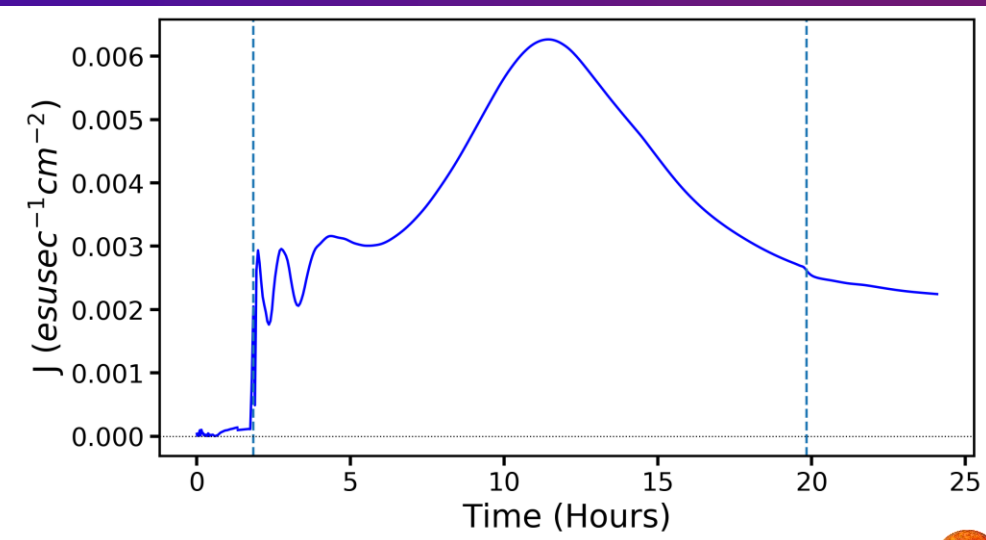
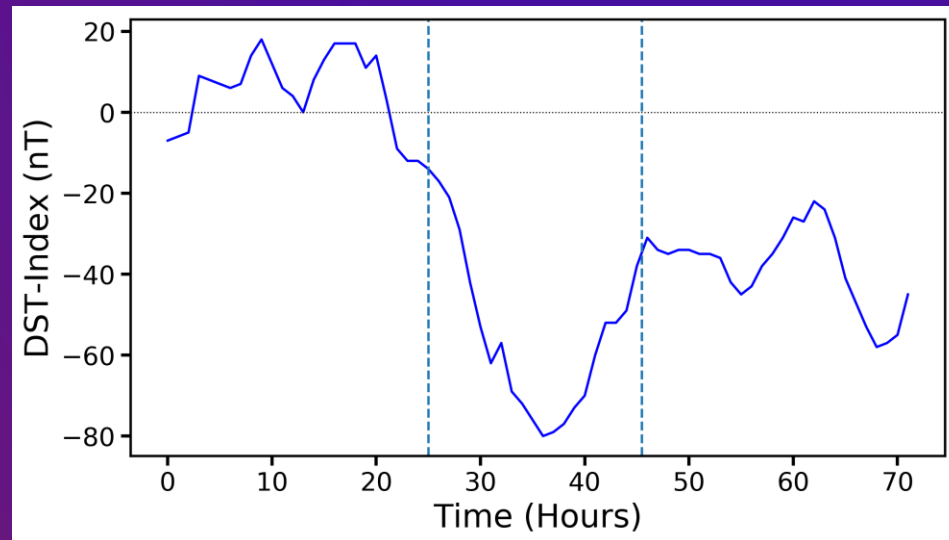


Ring Current and DST index

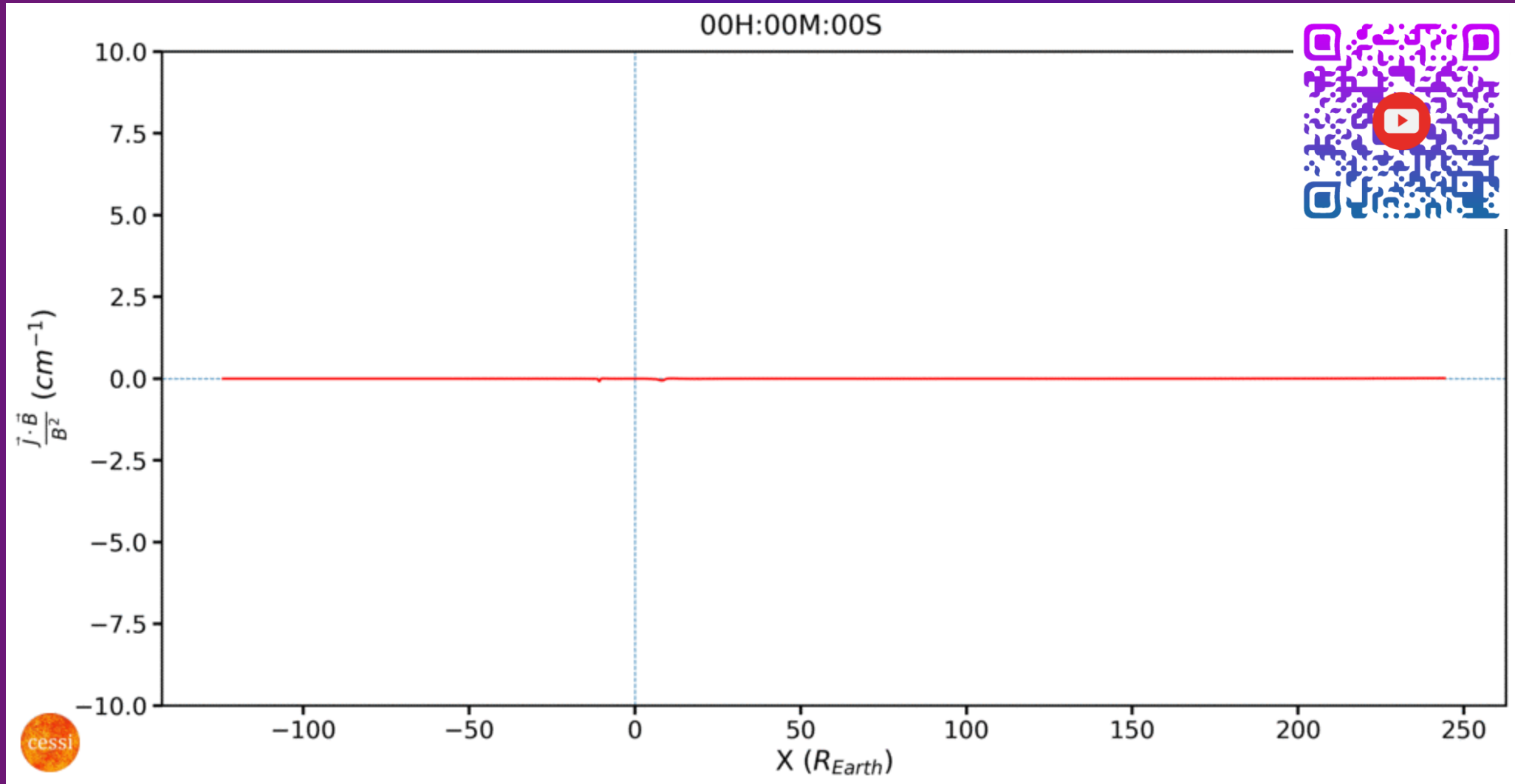


Disturbance storm time (DST) index gives information about the strength of the ring current around Earth caused by Solar Wind particles

Negative DST Index
↓
Weaker Geomagnetic Field
↓
Higher Ring Current



Helicity injection in Magnetotail



Concluding remarks

- In-situ observations support CESSI-SPIM results and make it a more important tool to probe and predict 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 Interplanetary Coronal Mass Ejection (ICME)
- Magnetic helicity of the flux rope distorts the shape of the magnetosphere and magnetotail current system. Current enhancement around Earth and magnetotail during the geo-storm.
- 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. Flux ropes can inject helicity in the magnetotail.



Thank You