EXPLOSIVE EVENTS: CME'S, FLARES, AND SUBSTORMS

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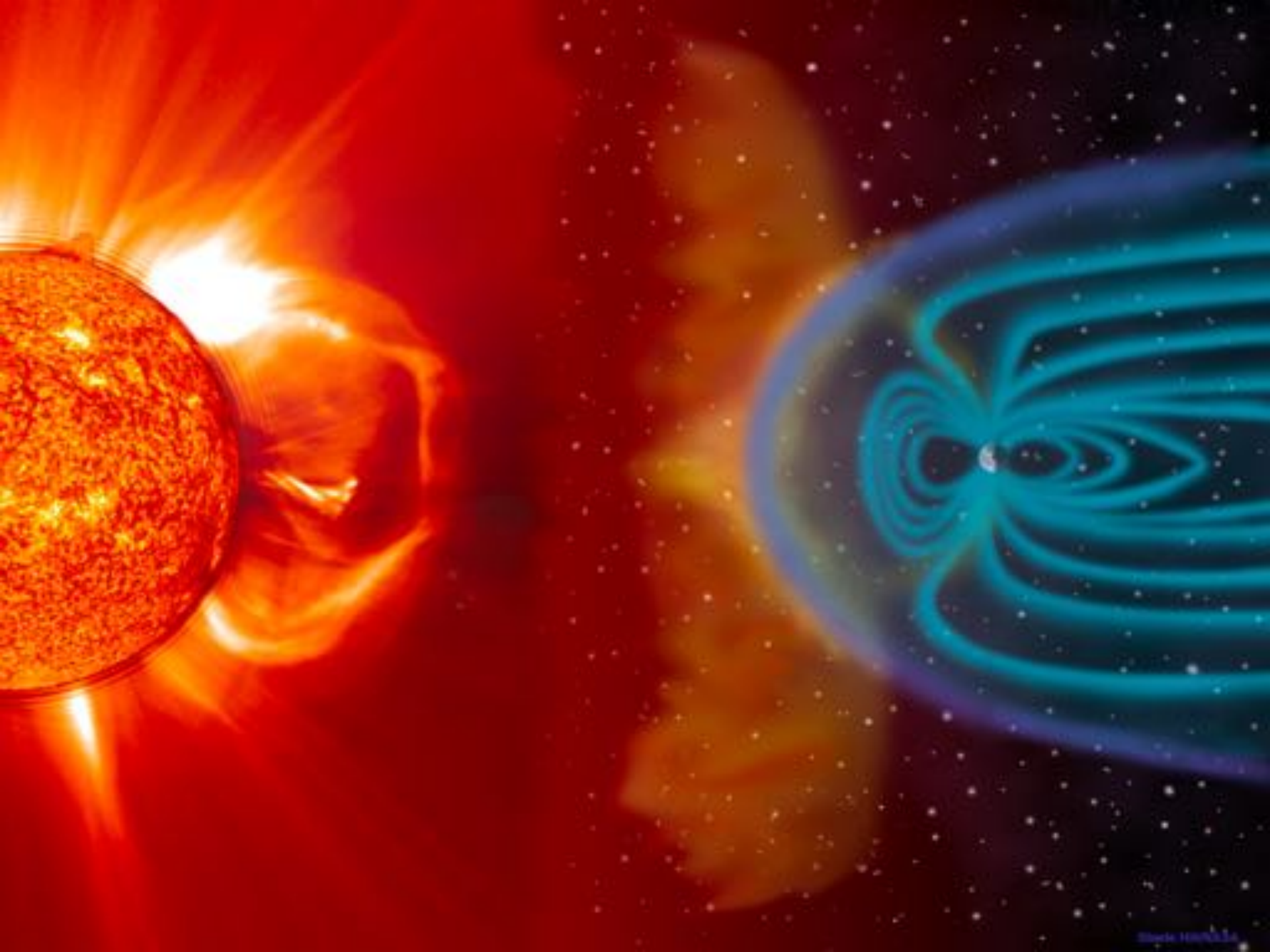
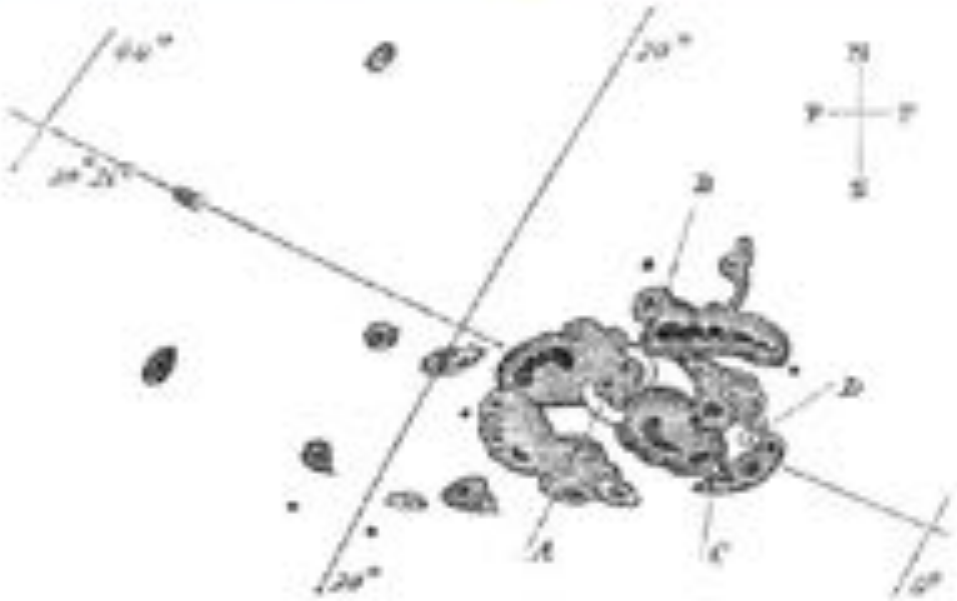
Acknowledgments: D. Longcope, N. Murphy



Societal impacts of space weather

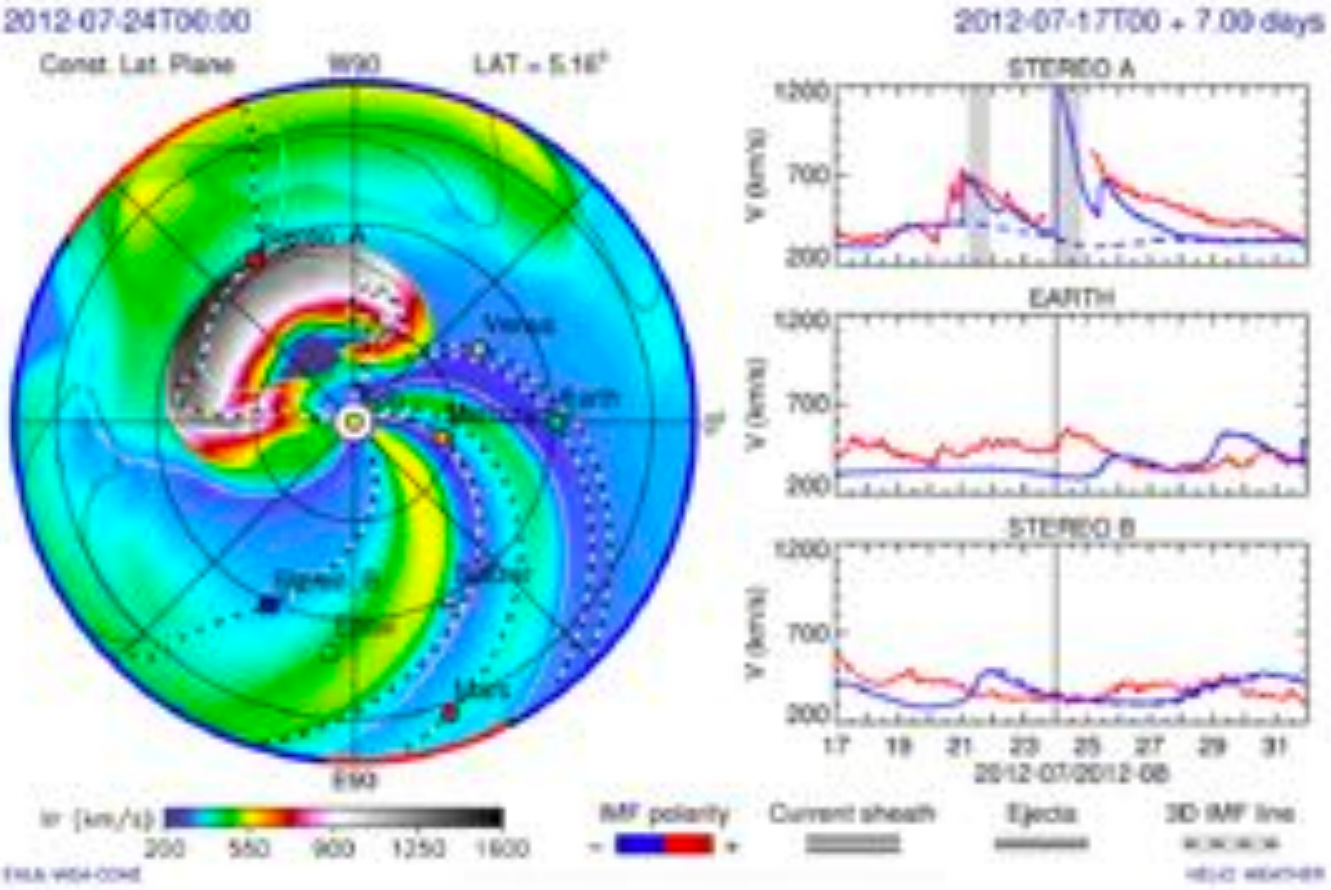
- Power grid failures
- Disruption to spacecraft operations
  - Energetic particles disrupt electronics
- Diversion of airplanes from poles
- Radio interference
- Reduced accuracy of Global Positioning System (GPS)
  - Radio emission during flares reduces signal-to-noise
- Radiation danger to astronauts
- Disruption of telegraph services
- Reduced efficacy of space wombat echolocation

The Carrington Event of 1859



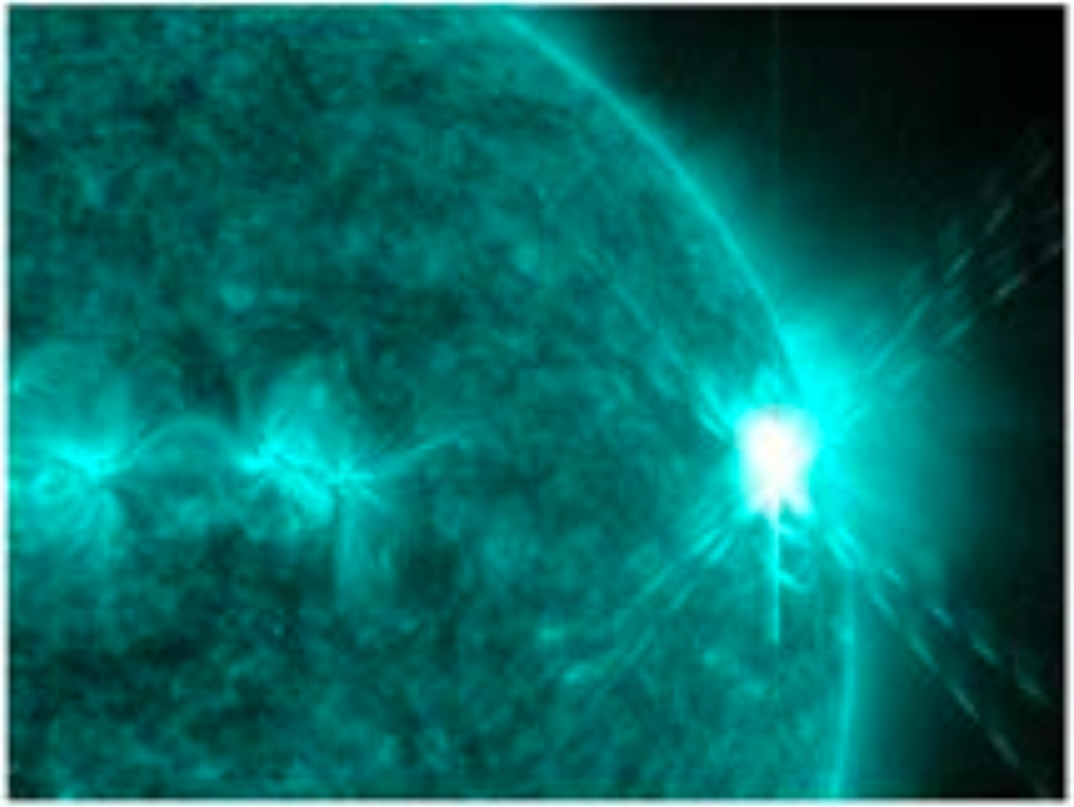
- First observed solar flare
- The associated coronal mass ejection (CME) took just 17.6 hours to reach Earth
  - Usually takes several days
  - Previous CME cleared the way
- Global effects
  - Aurora observed at low latitudes
  - Telegraph messages could be sent without a power supply
- Potential trillion dollar costs were it to happen today

A near miss in July 2012

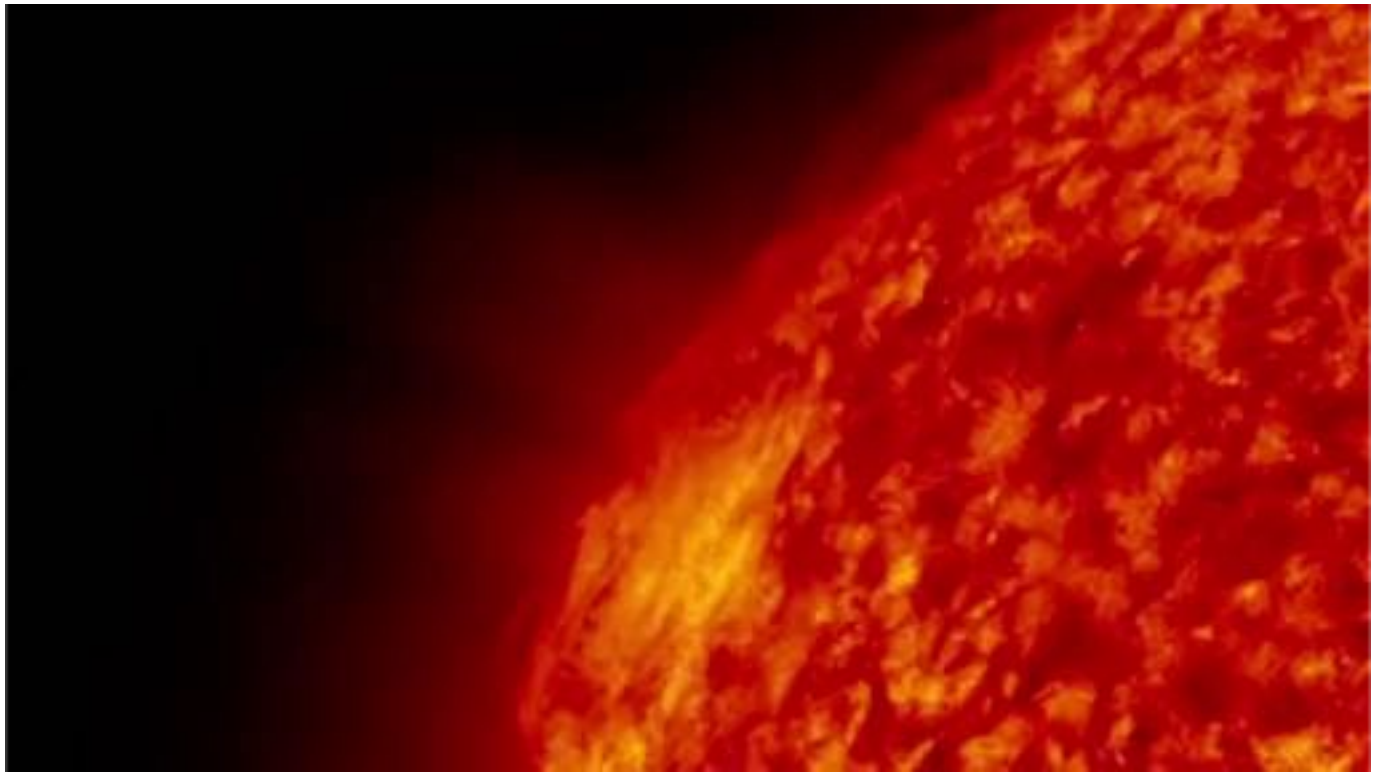


- A Carrington-scale event passed STEREO-A which is in an Earth-leading orbit
- Several prior CMEs cleared the way
- Could have caused major disruptions to power grids

Solar flares

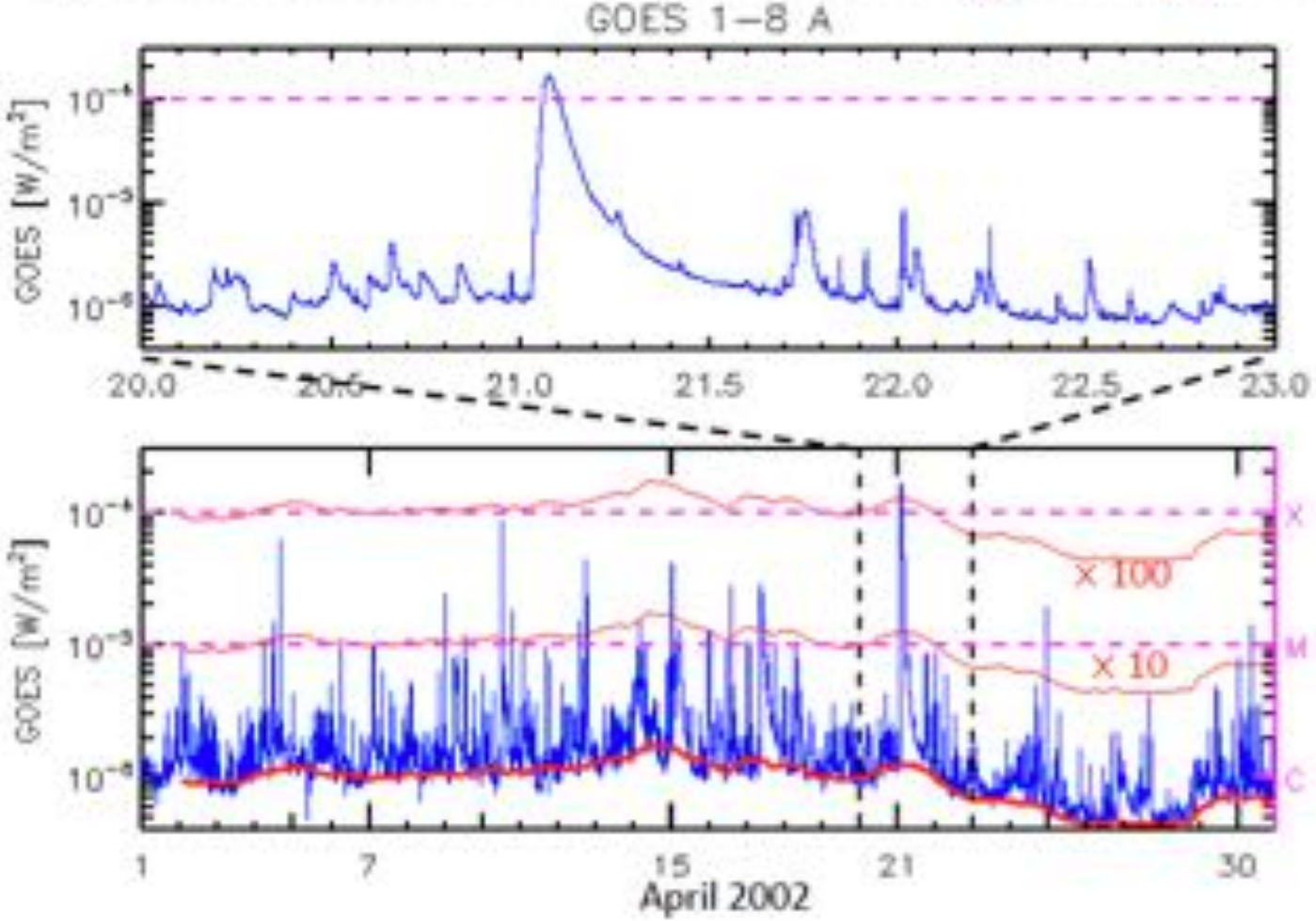


- Magnetic energy released suddenly
- Efficient plasma heating and particle acceleration
- Energy transport downward into chromosphere
  - Energetic particle beams and/or thermal conduction fronts
- Radiation emitted from radio to gamma rays



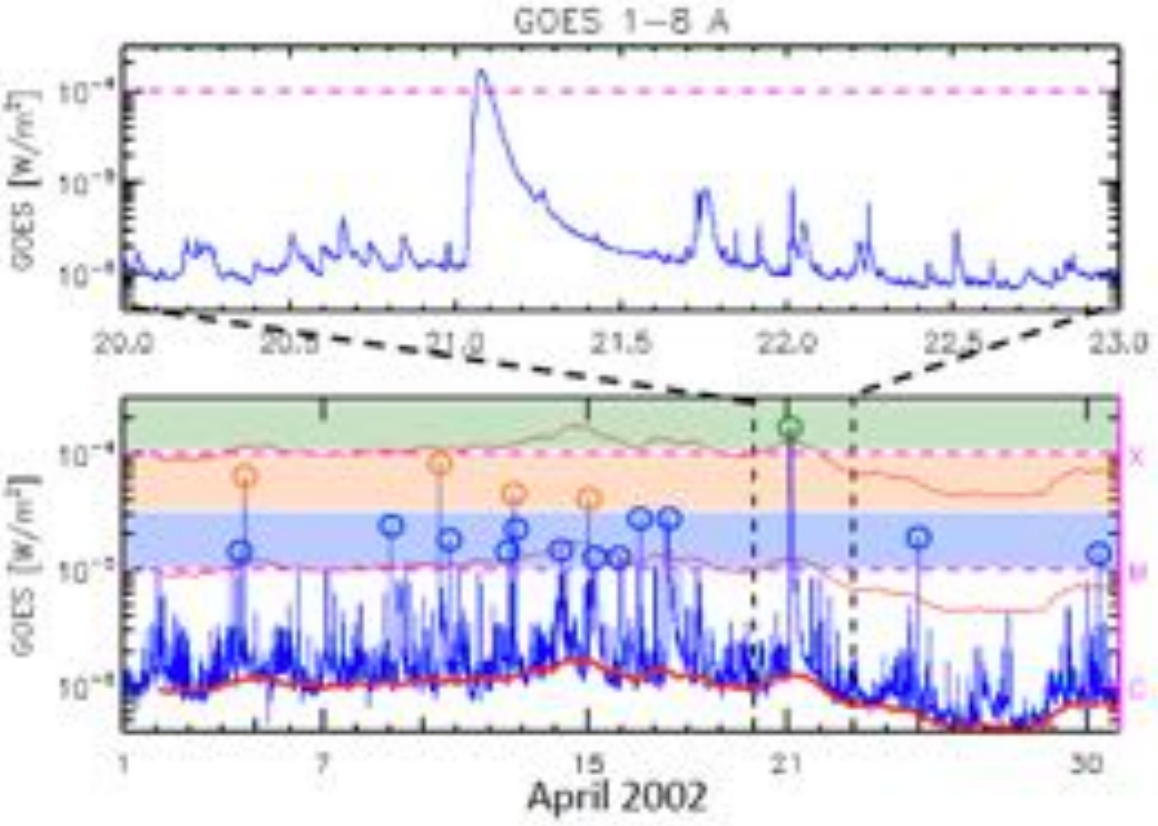
What is a solar flare?

Operational def'n: Flare: sudden brightening in X-rays

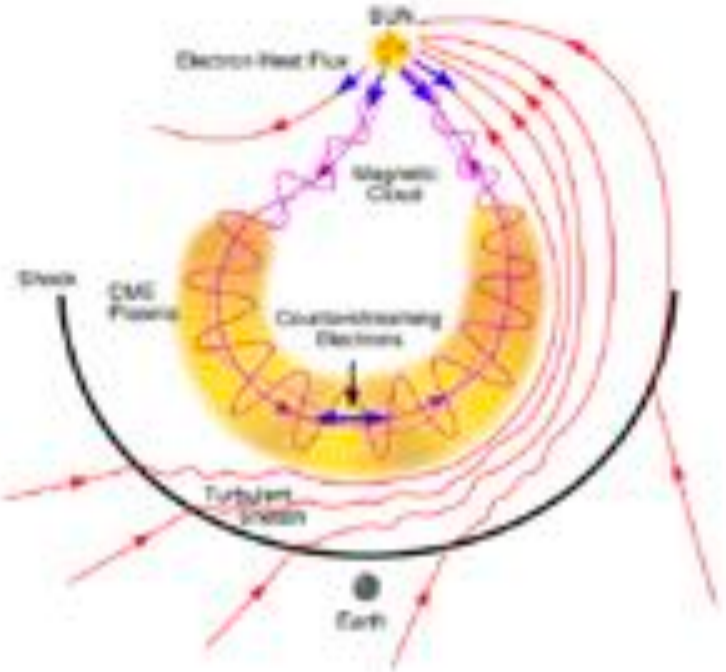


What is a solar flare?

A member of a population



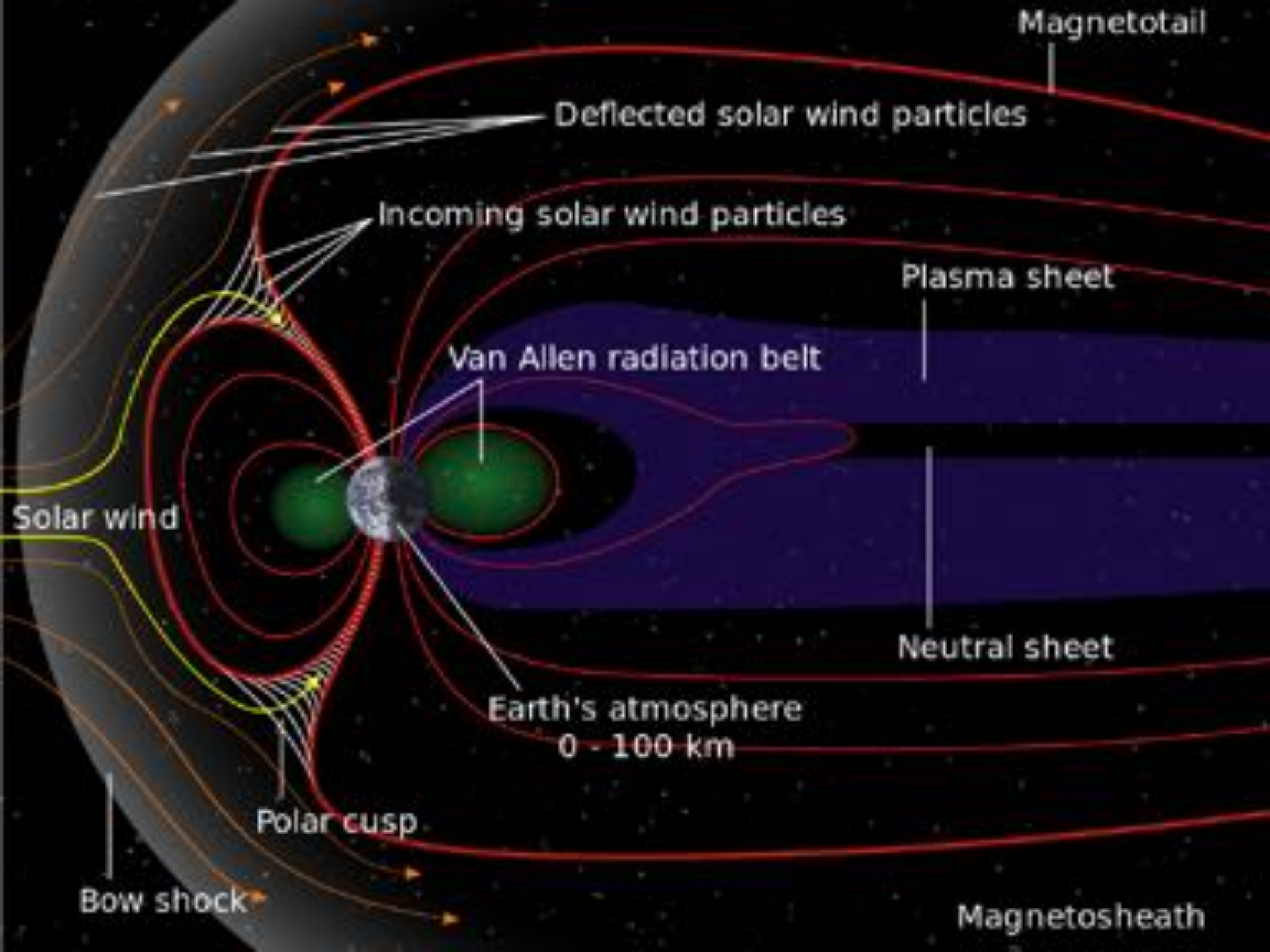
Coronal mass ejections (CMEs)



- Expulsion of magnetized plasma into the solar wind
- Velocities of hundreds to thousands of km s^{-1}
- Usually contain a magnetic flux rope
- A shock preceding the flux rope can accelerate particles
- CMEs are the main driver of geomagnetic storms

The Earth's magnetic field

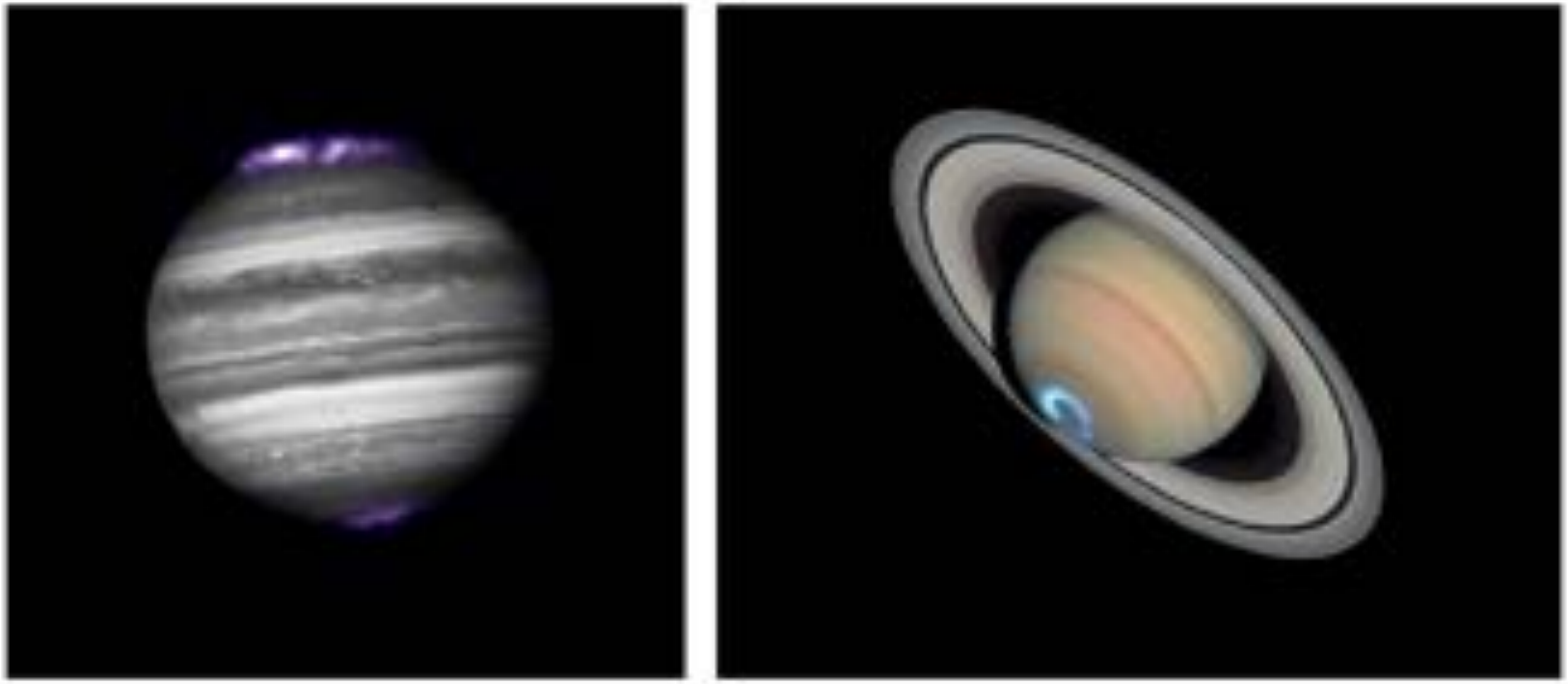
- The Sun sends high velocity magnetized plasma, solar energetic particles, and/or EUV & X-ray radiation toward Earth. Then what?
- The particle and plasma components impact Earth's magnetosphere
- The EUV/X-ray radiation and particle component affect Earth's thermosphere and ionosphere


Magnetotail
Deflected solar wind particles
Incoming solar wind particles
Plasma sheet
Van Allen radiation belt
Solar wind
Neutral sheet
Earth's atmosphere
0 - 100 km
Polar cusp
Bow shock
Magnetosheath

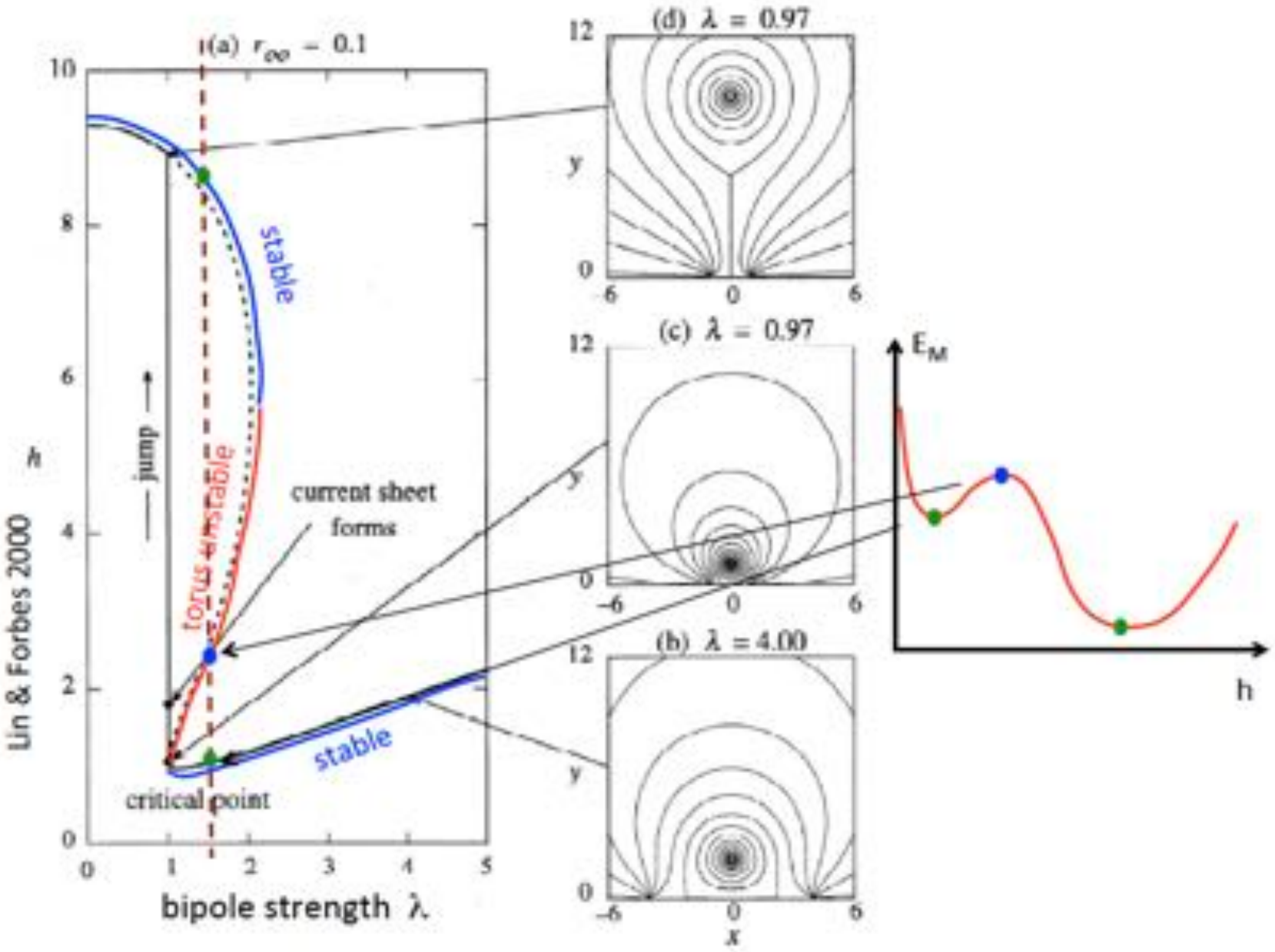
Substorms in the Earth's Magnetosphere

Photograph of the aurora by Dirk Obudzinski, near the Yukon River in Circle, Alaska (August 29, 2000).

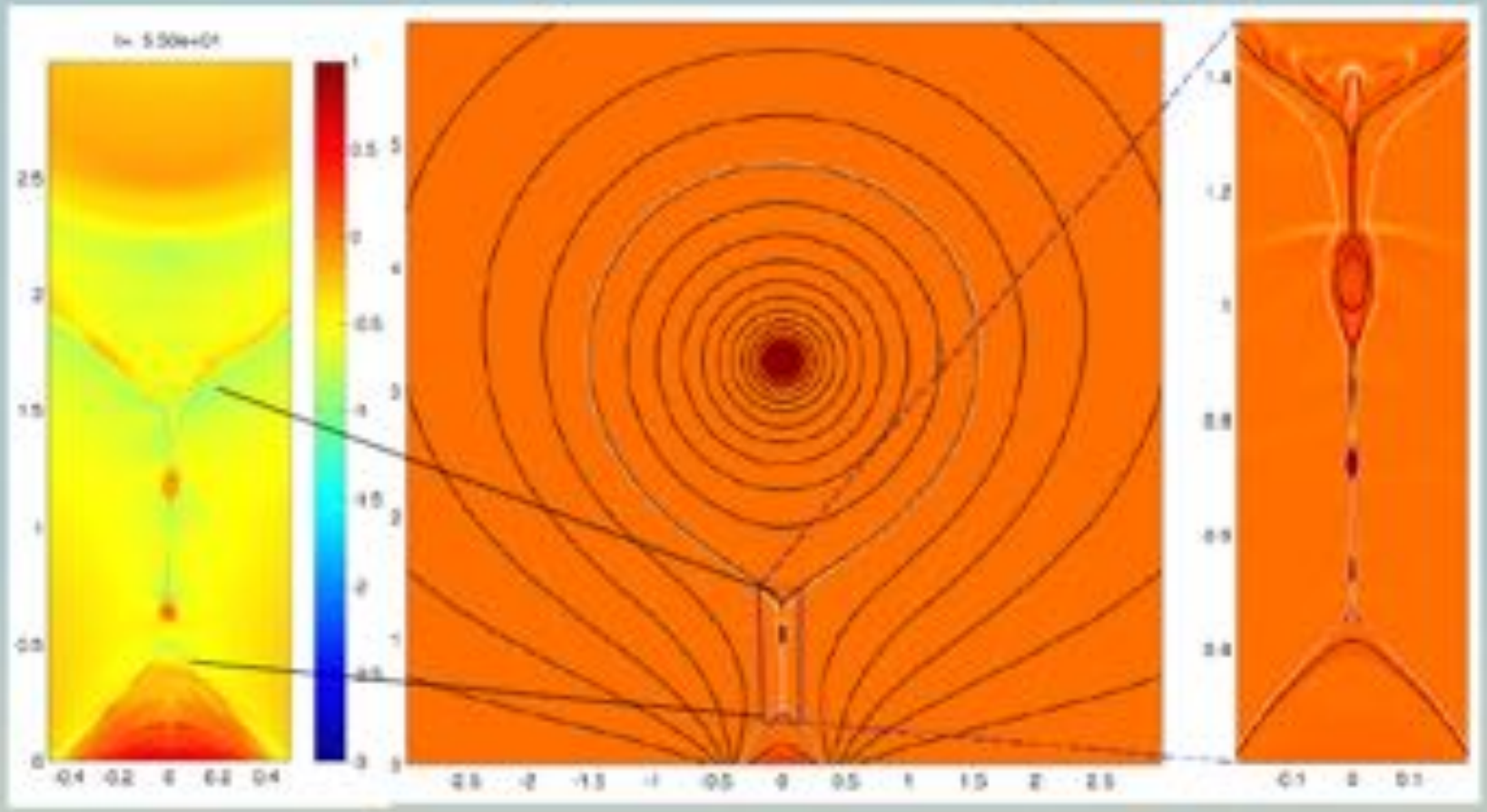
Aurora around Saturn & Jupiter



- Left: X-ray aurora observed by Chandra around Jupiter
- Right: UV aurora observed around Saturn
- Aurora recently observed in radio around brown dwarf
- Can observations of aurora help characterize the magnetic field and space environment of exoplanets?

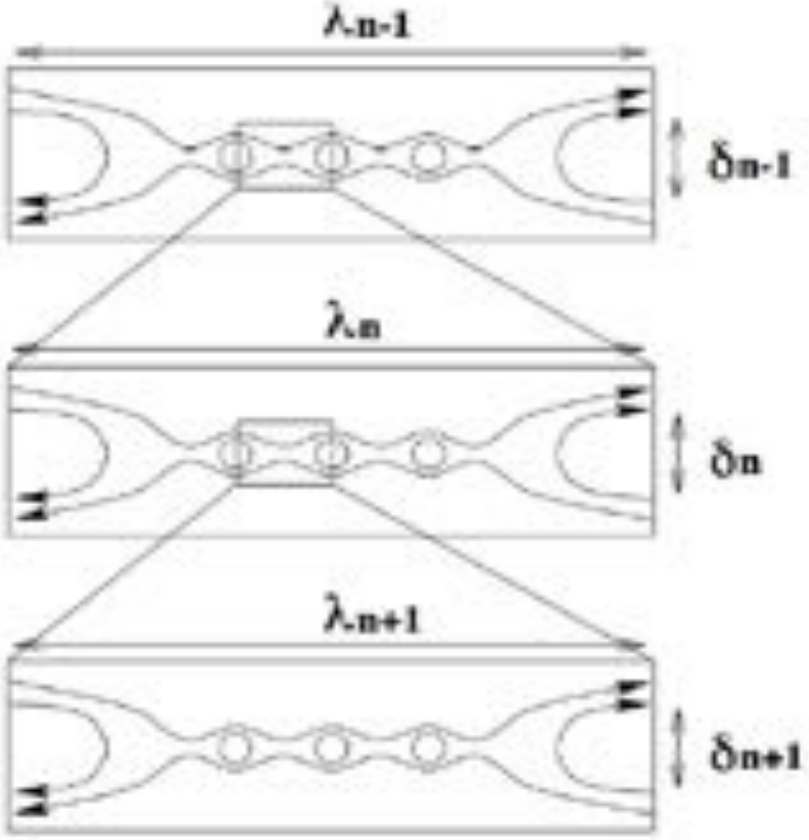

(a) r_{∞} = 0.1
Lin & Forbes 2000
h
bipole strength λ
stable
jump
torus-unstable
current sheet
forms
critical point
stable
(d) λ = 0.97
(c) λ = 0.97
(b) λ = 4.00
y
x
E_M
h

Flux map and density map from simulation



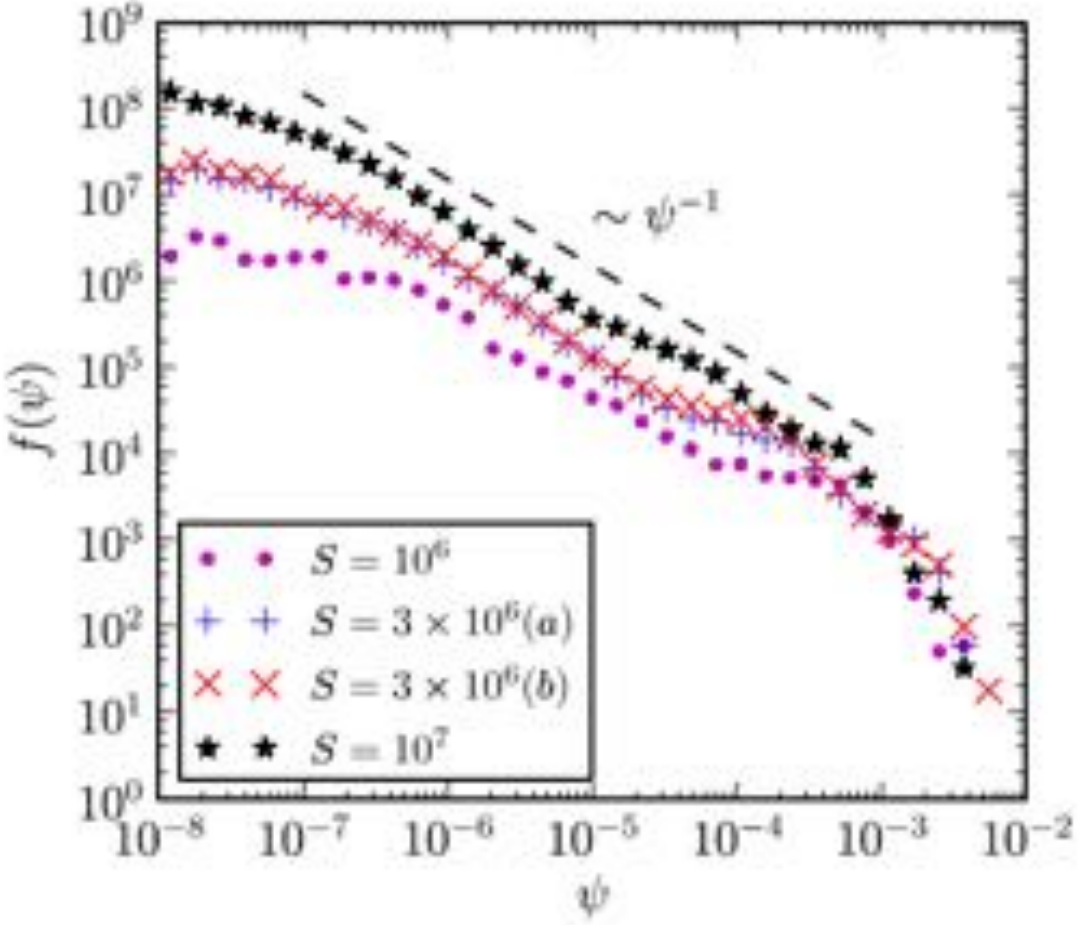
Distribution of the Plasmoids

- Multiple levels of cascade suggest self-similarity across different scales, which often leads to power-laws.
- Uzdensky *et al.* (2010) gave a heuristic argument that predicts $f(\psi) \sim \psi^{-2}$



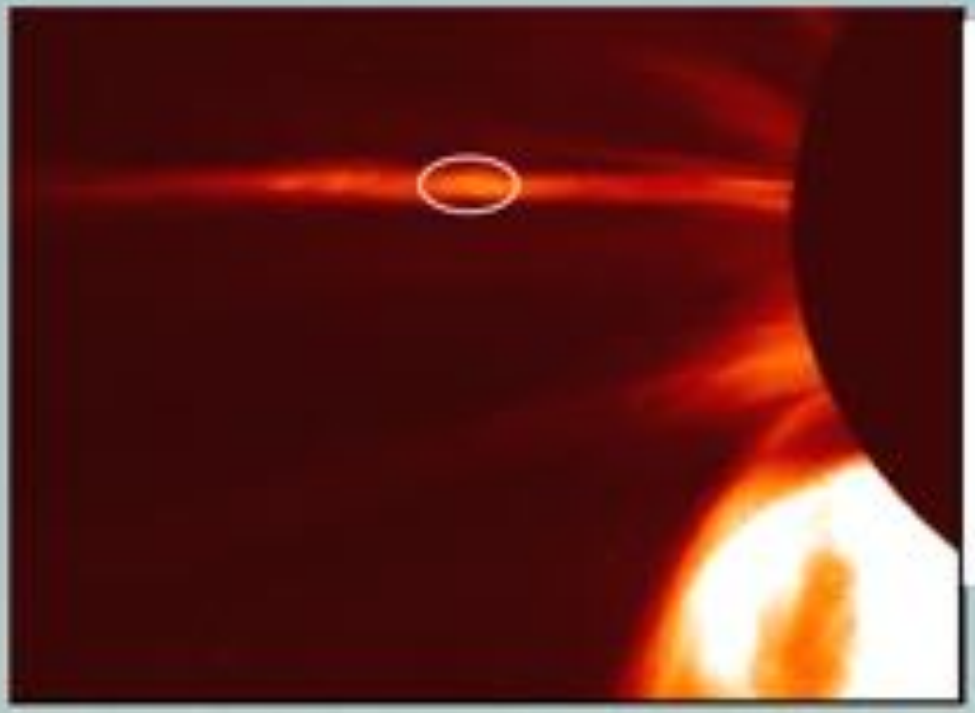
Shibata & Tanuma (2001)

Plasmoid Distribution from Simulations

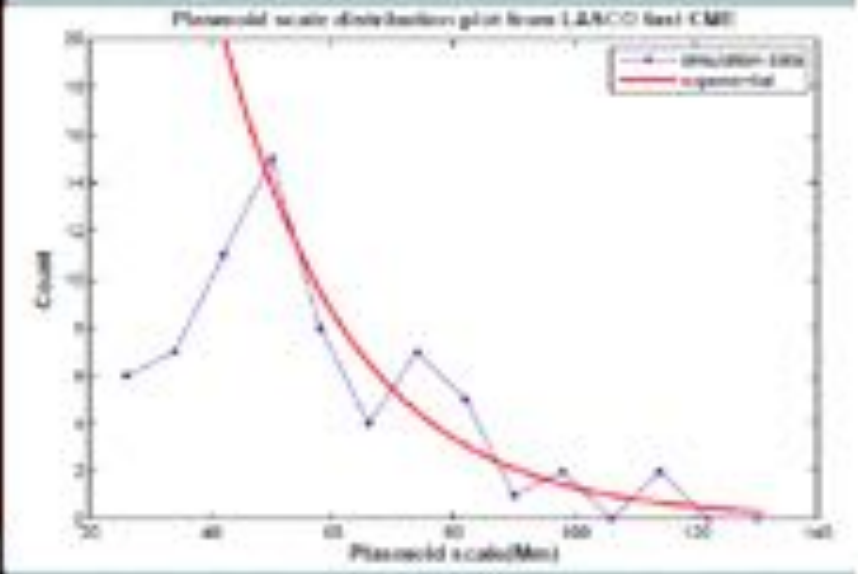


Huang and B., PRL, 2012

Plasmoid distribution plot (fast CME event)

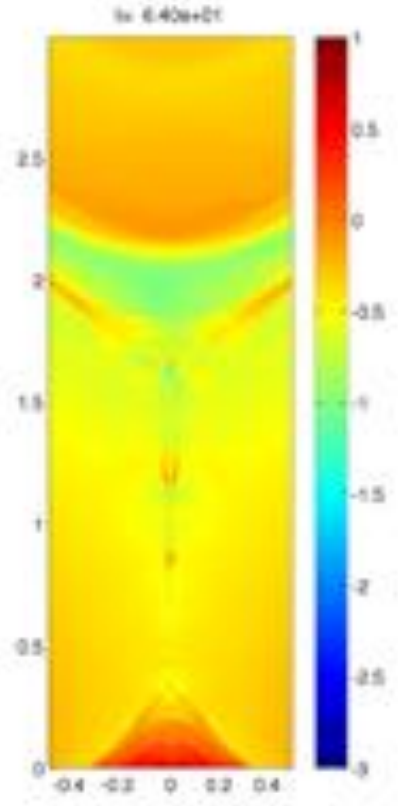


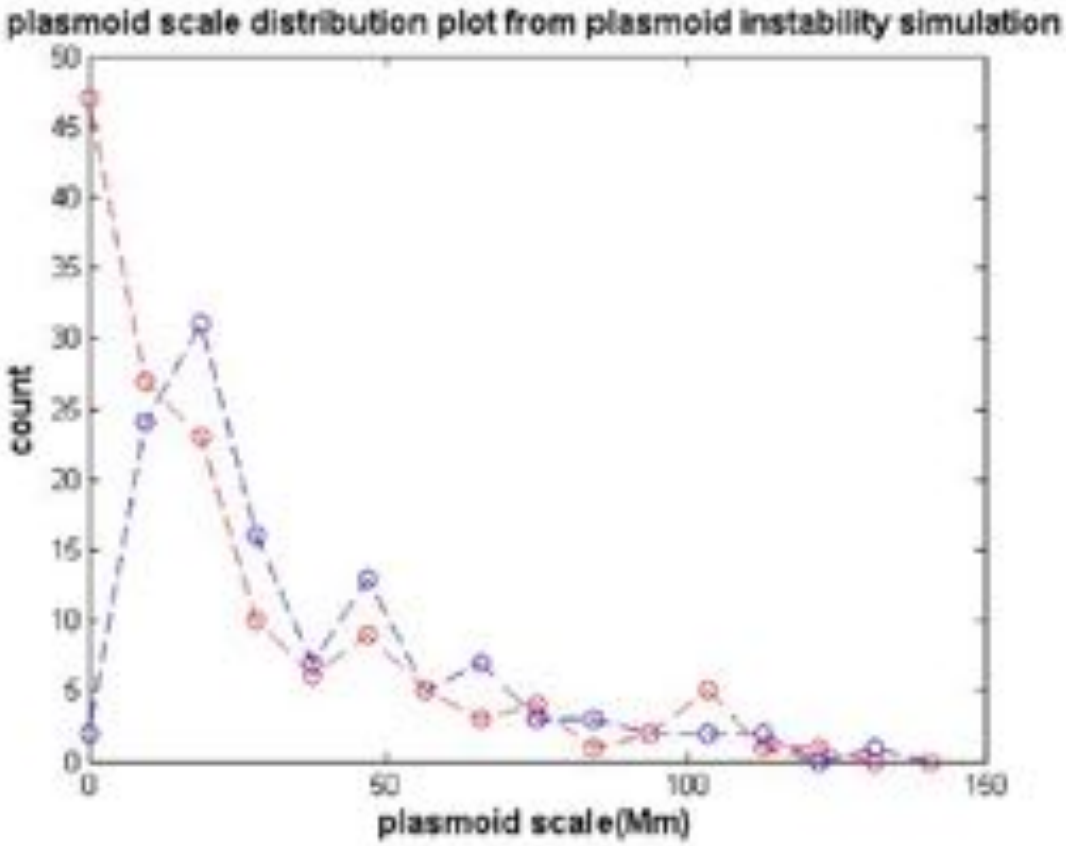
LASCO C2 white light ray structure and plasmoid



We observe near 72 plasmoids in LASCO in 2002/01/08 halo fast CME events, their scale distribution plot is shown in the right panel.

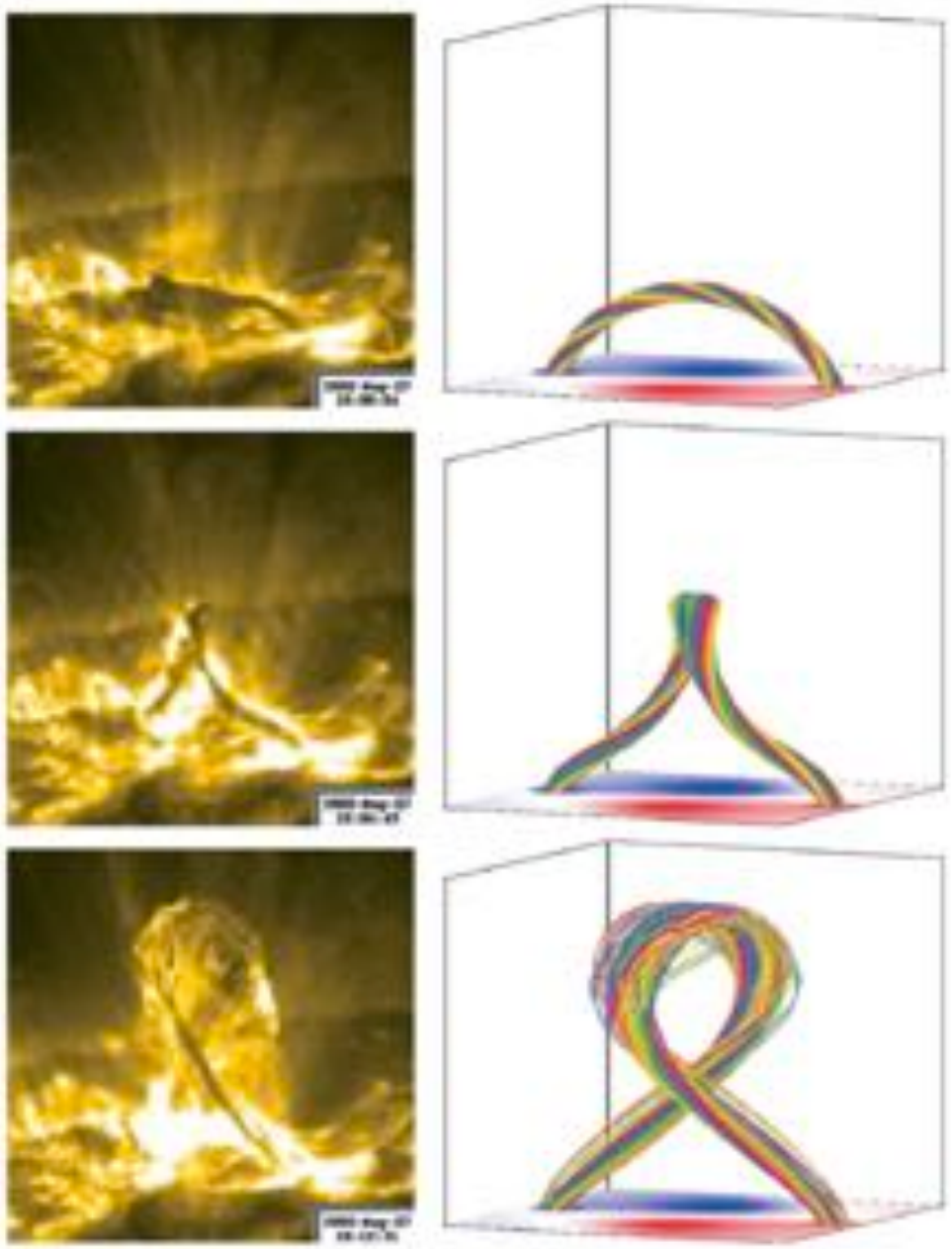
Visual Inspection and Magnetic Diagnostics Yield Very Different Distributions for Small Plasmoids





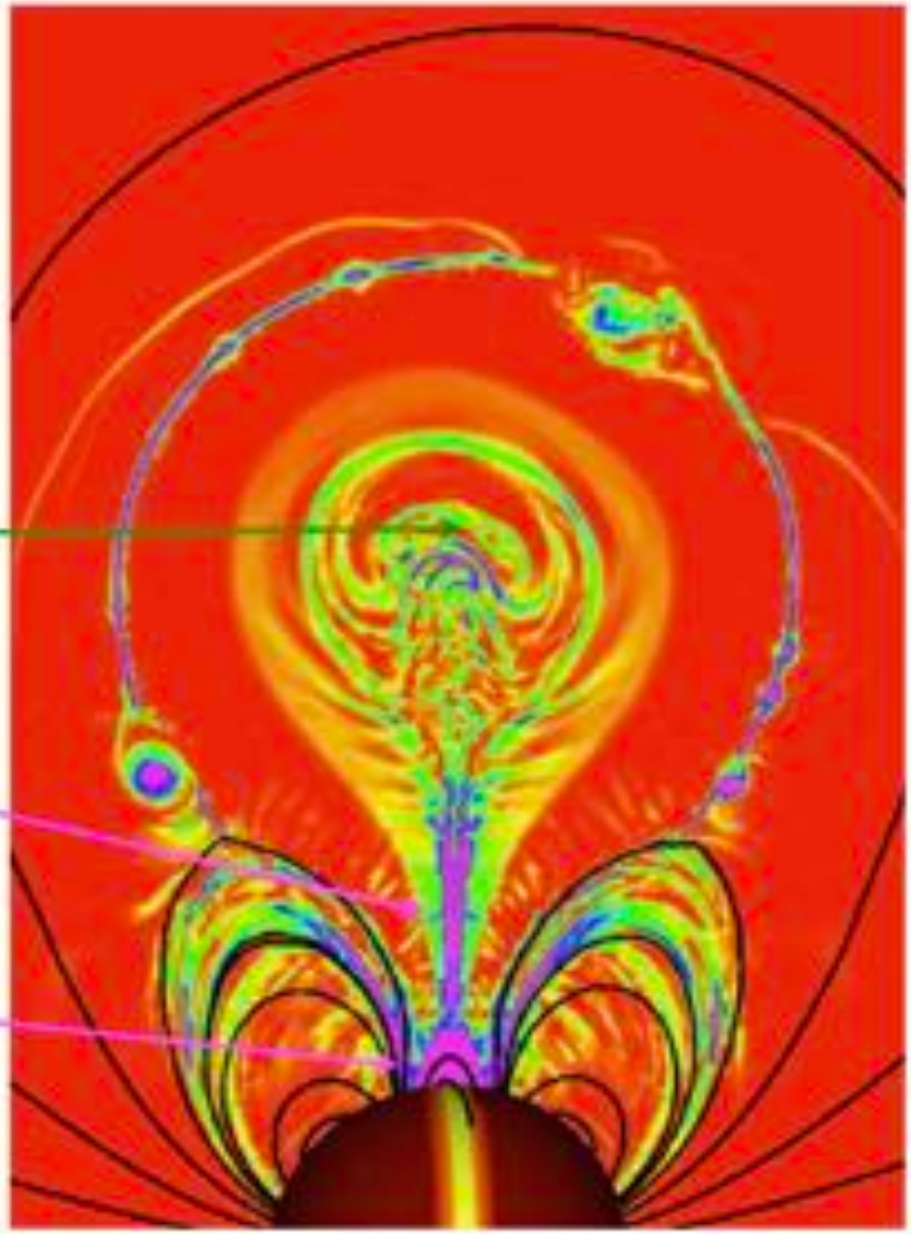
Courtesy of Lijia Guo

A CME is an MHD instability



Torok & Kliem 2005

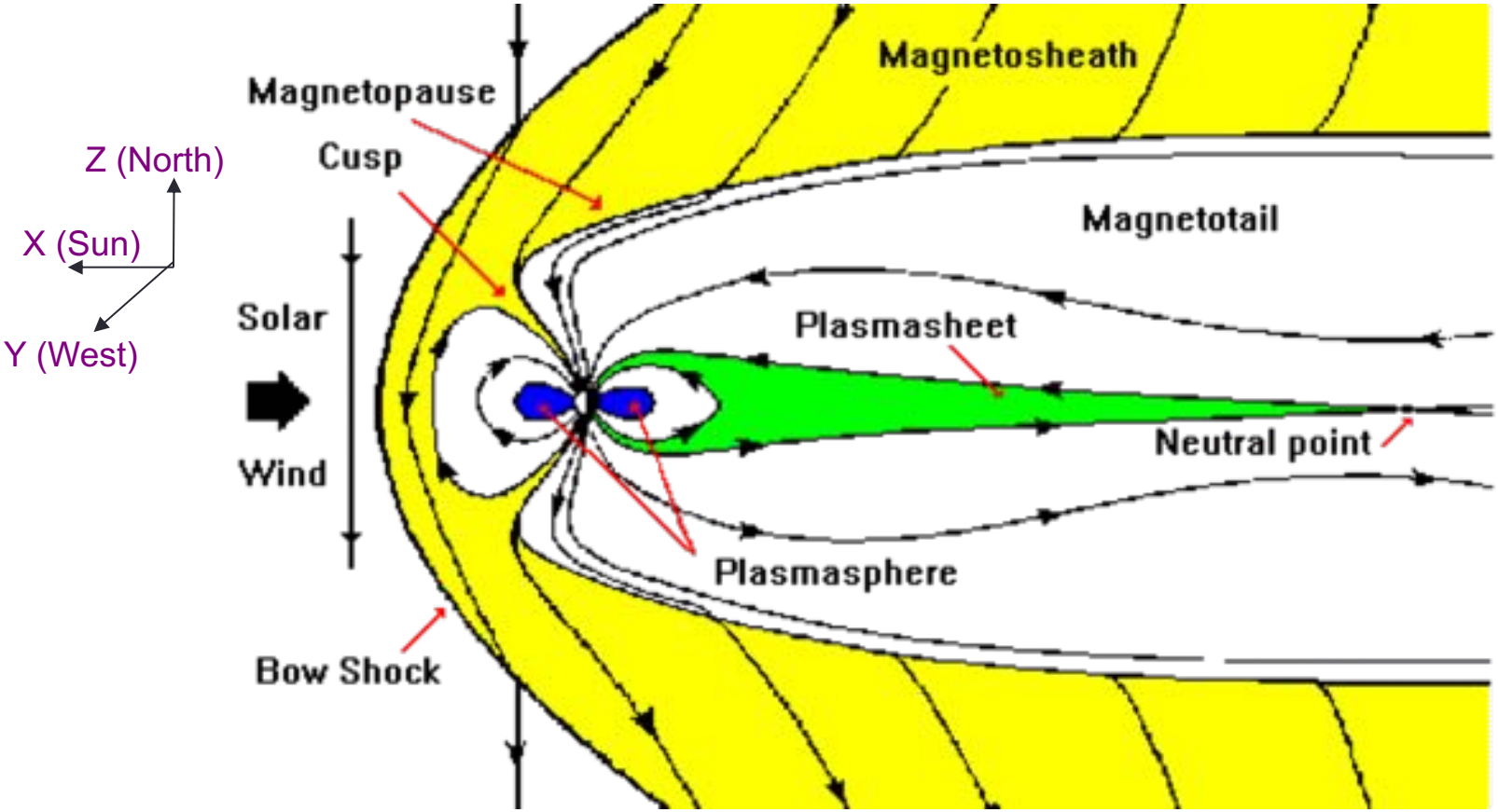
How they relate…
the basic picture



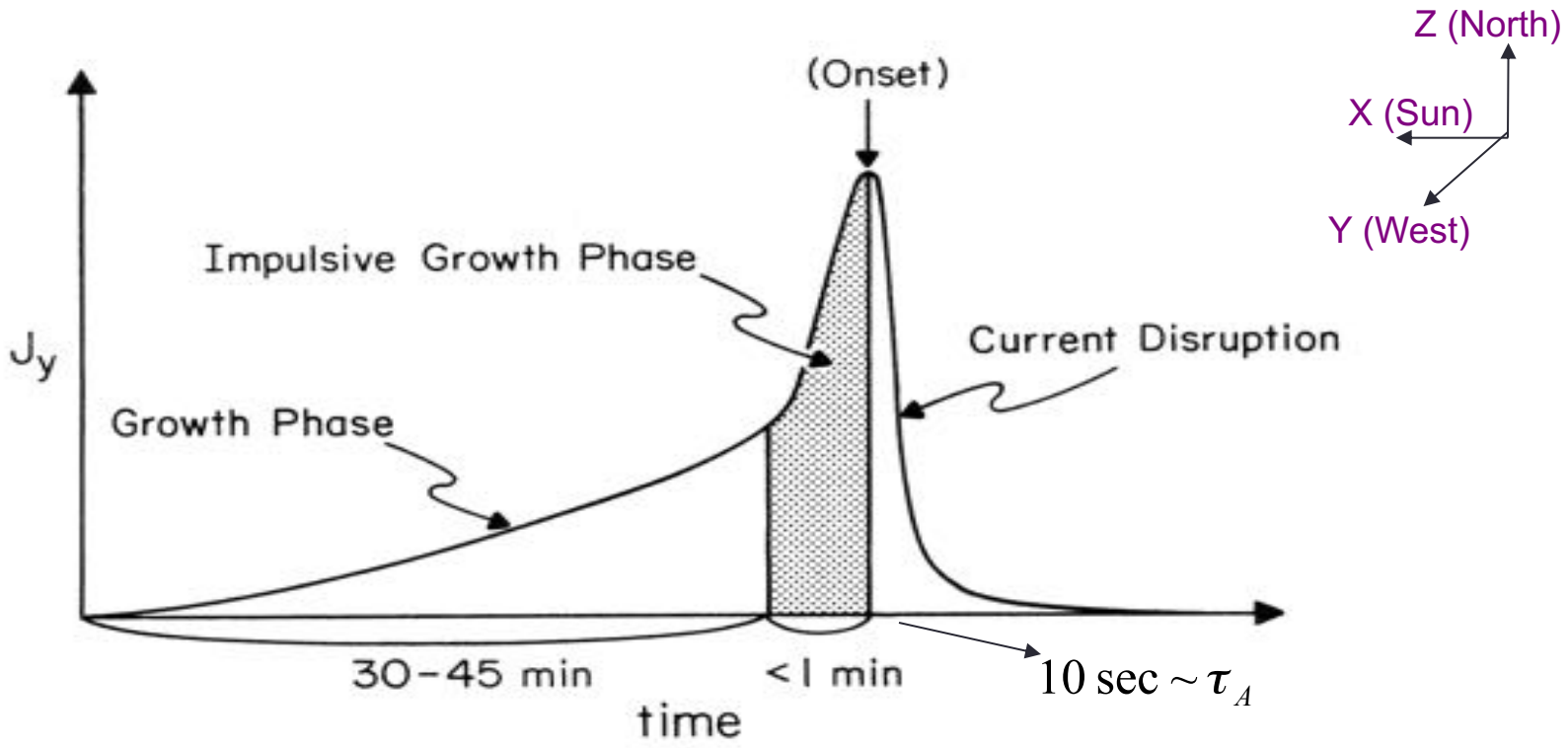
CME model ingredients

- Current = twist in flux rope
- Increasing twist (current) → instability
- Eruption converts energy: magnetic → kinetic
- Frozen-flux leads to current sheet (CS)
- Reconnection @ CS eliminates overlying flux
  - Can lead to instability
  - Can permit further eruption
  - Will produce flare signatures (later)

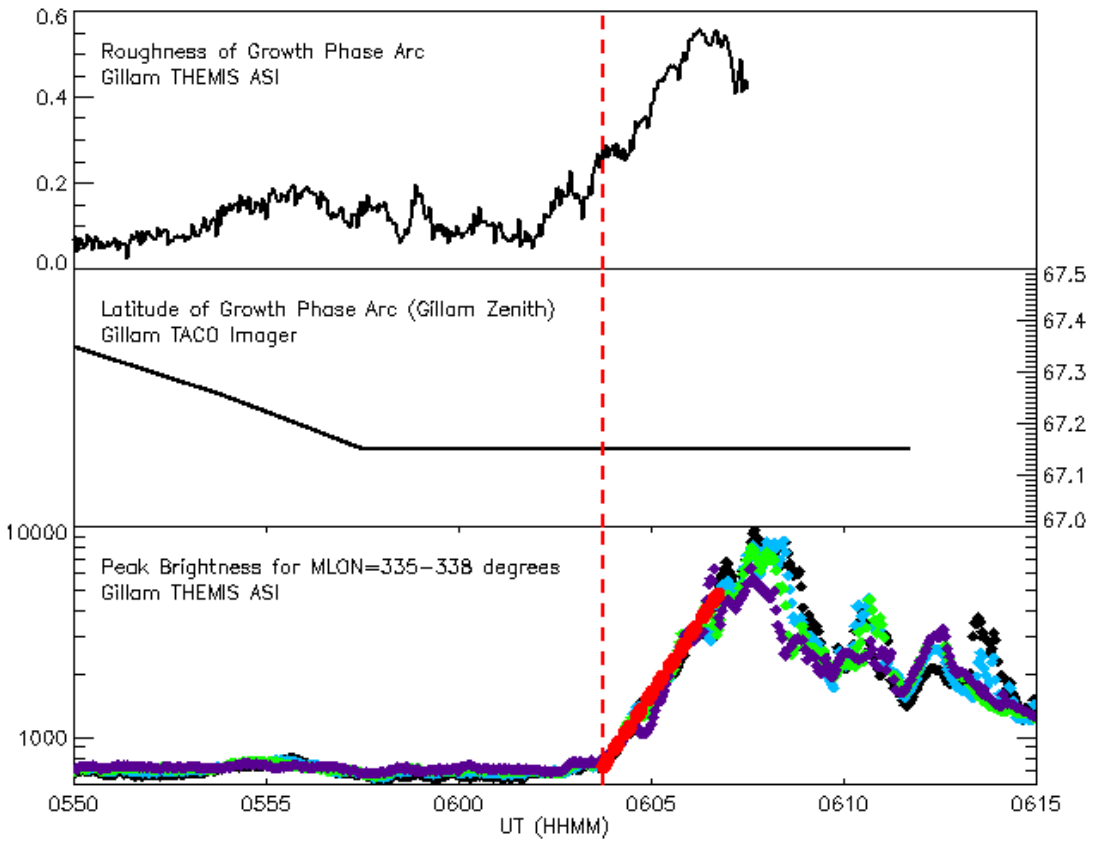
Substorm Onset: Where does it occur?



Substorm Onset: When does it occur?

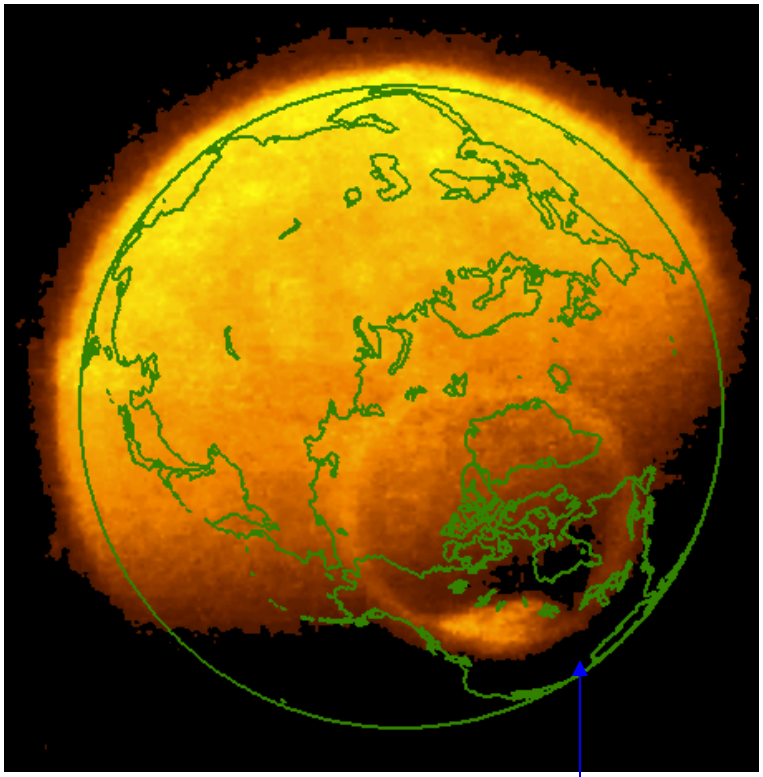


(Ohtani et al., 1992)

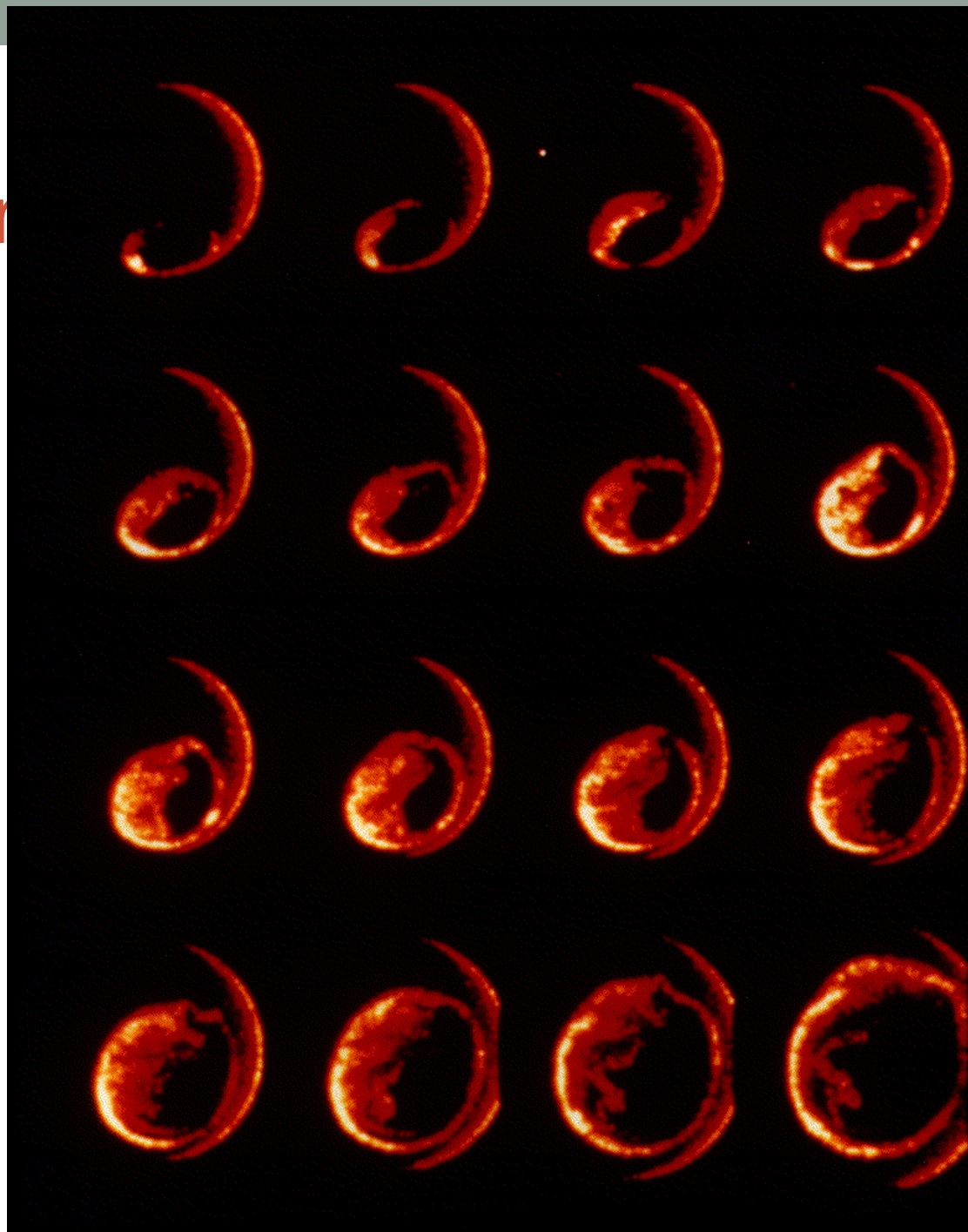


Courtesy: E. Donovan (THEMIS)

Substorm Onset: Aur

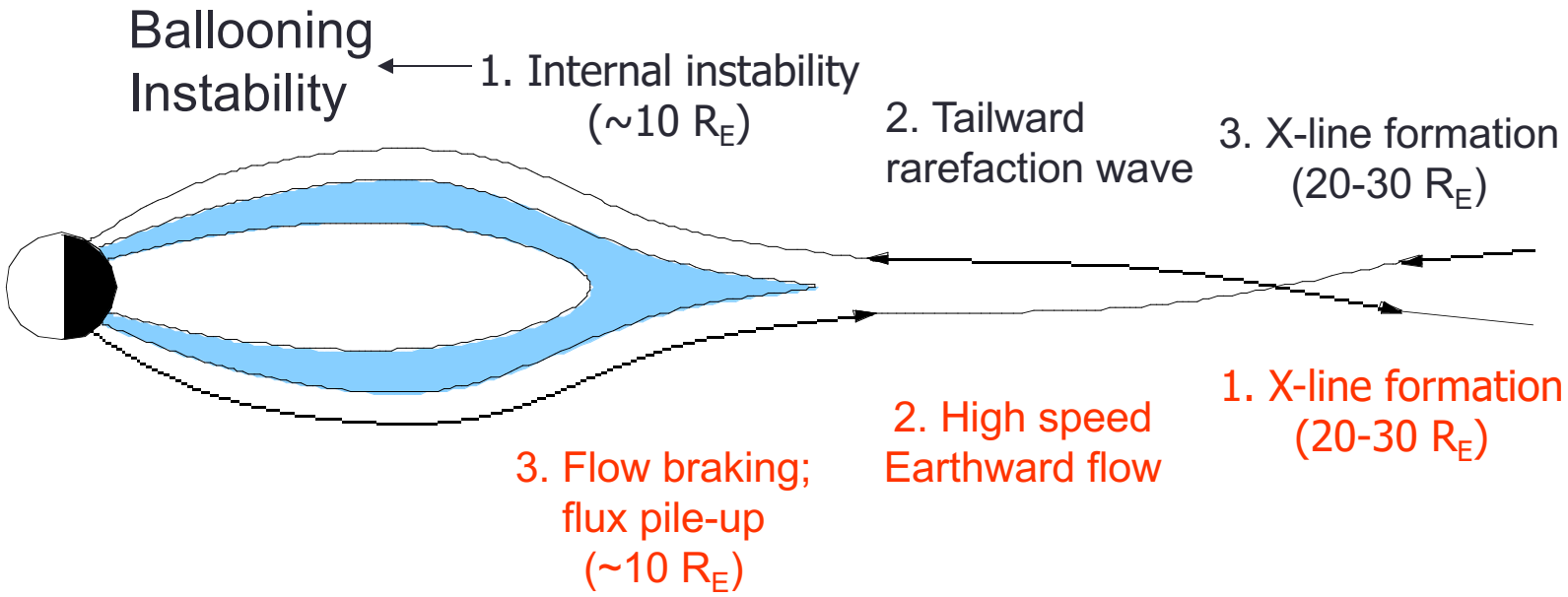


Auroral bulge



Substorm Onset: How is it triggered?

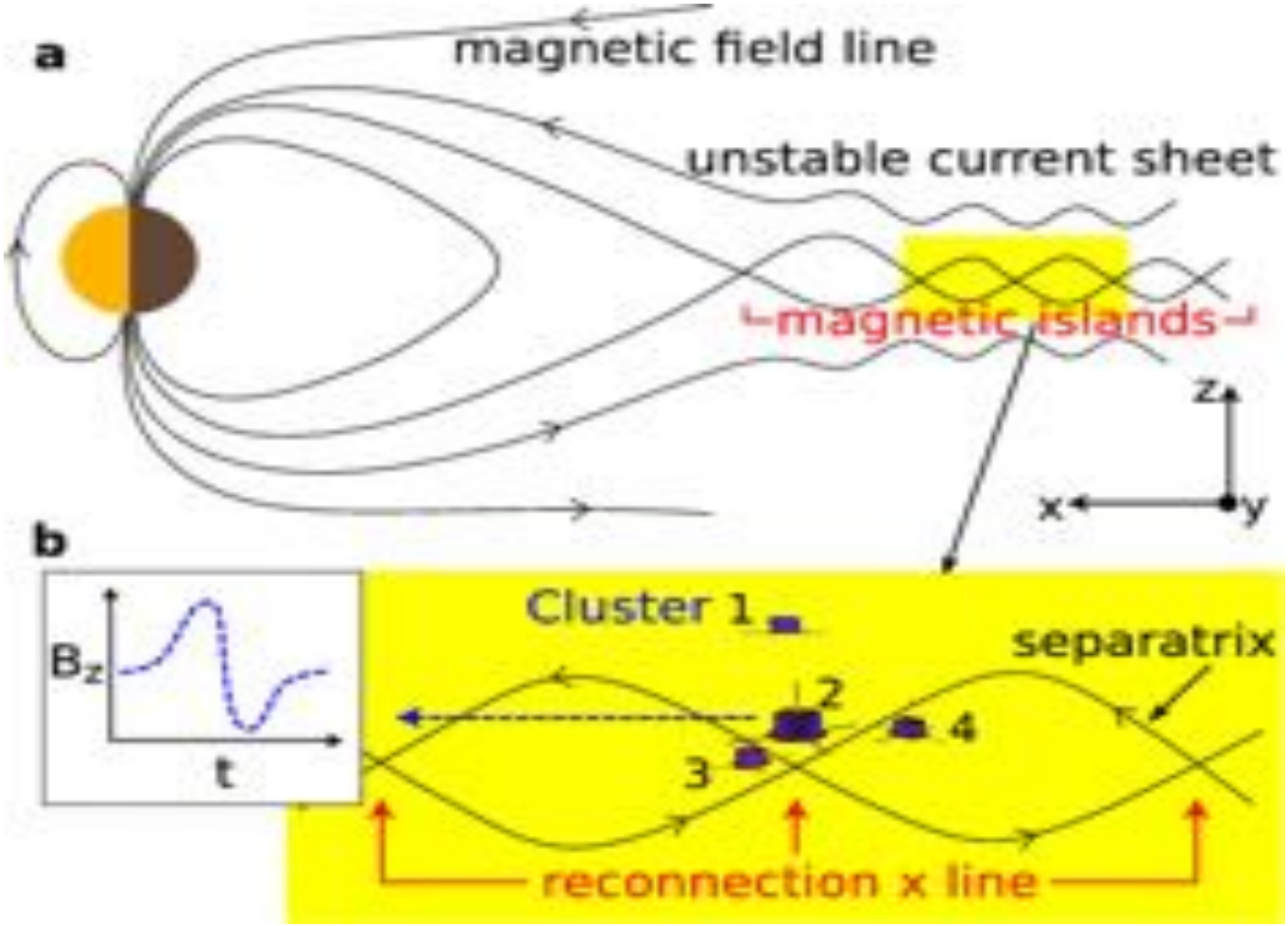
Near-Tail Instability [e.g. Roux et al., 1991, Lui et al., 1992; Erickson et al., 2000]



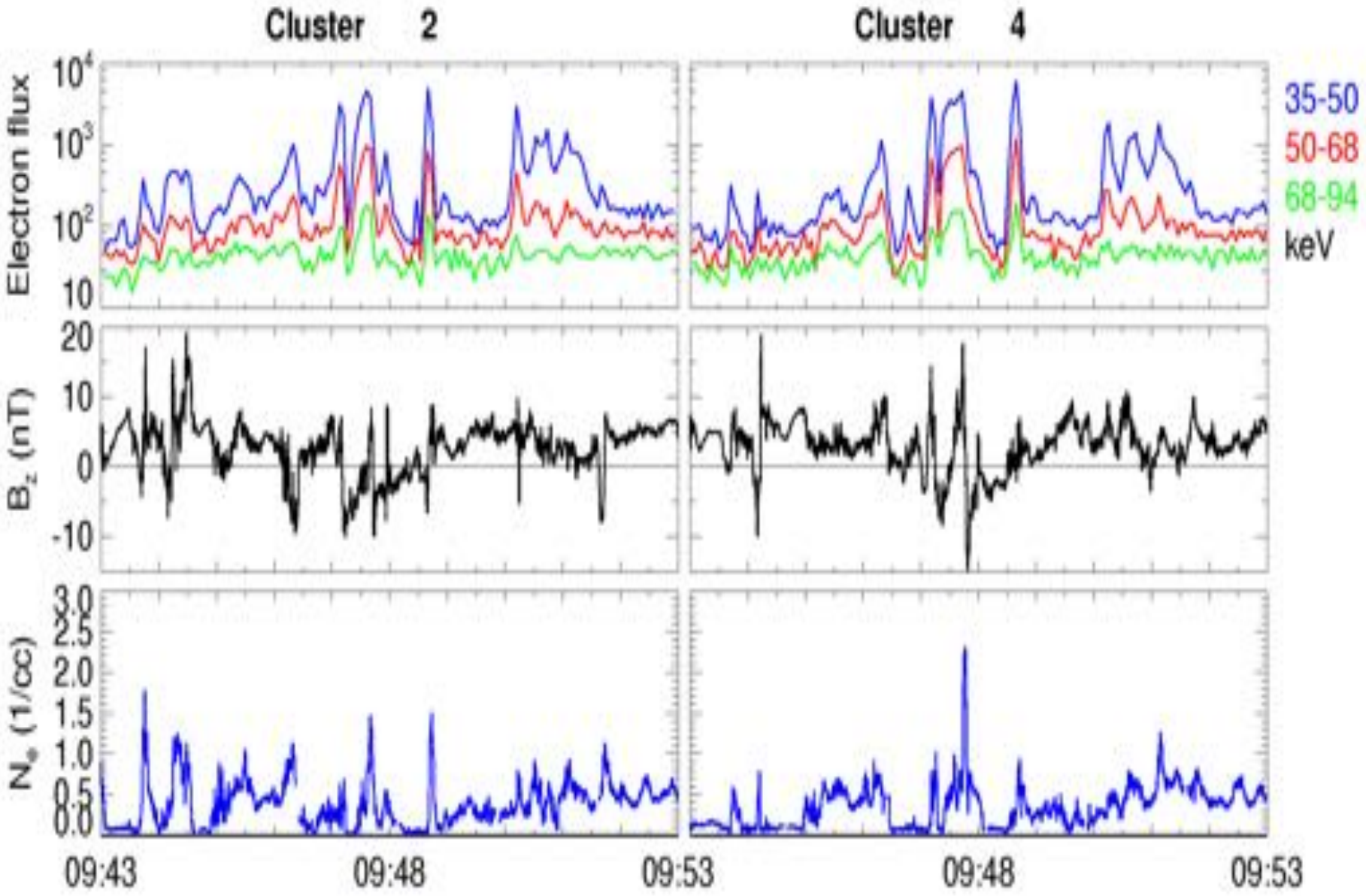
Mid-Tail Reconnection [e.g. Shiokawa et al., 1998]

Fluxes of energetic electrons peak within magnetic islands

[Chen et al., Nature Phys., 2008]



e bursts & bipolar Bz & Ne peaks ~10 islands within 10 minutes



Substorm Onset: The "2-minute" problem

"This year's substorm conference (ICS-4, 1998) was one of the most successful yet with over 250 in attendance. All existing paradigms were discussed at length and during the wrap-up session it was realized that ***only the time of the events within 2 minutes of onset were still seriously under debate***. Since it seems somewhat foolish for a couple of hundred scientists to travel half way around the world to argue over ***two minutes*** of geomagnetic activity, the substorm problem was declared solved and no more substorm conferences are being planned."

--- Y. Kidme (Kamide?)

(AGU-SPA Newsletter, April 1, 1998)

Open questions in heliophysics and space weather

- How do solar and planetary dynamos operate?
- How are the chromosphere, corona, and solar wind heated?
- What accelerates the slow and fast solar winds?
- How does reconnection release magnetic energy in solar and space plasmas?
- Can we predict major flares and CMEs?
- Can we predict if and when ejecta and energetic particles will impact Earth?
- How can we predict the direction of the interplanetary magnetic field (IMF) at Earth using remote observations?
- How frequent are superflares around the Sun and other stars?
- How can we apply results from space plasmas to astrophysical situations?