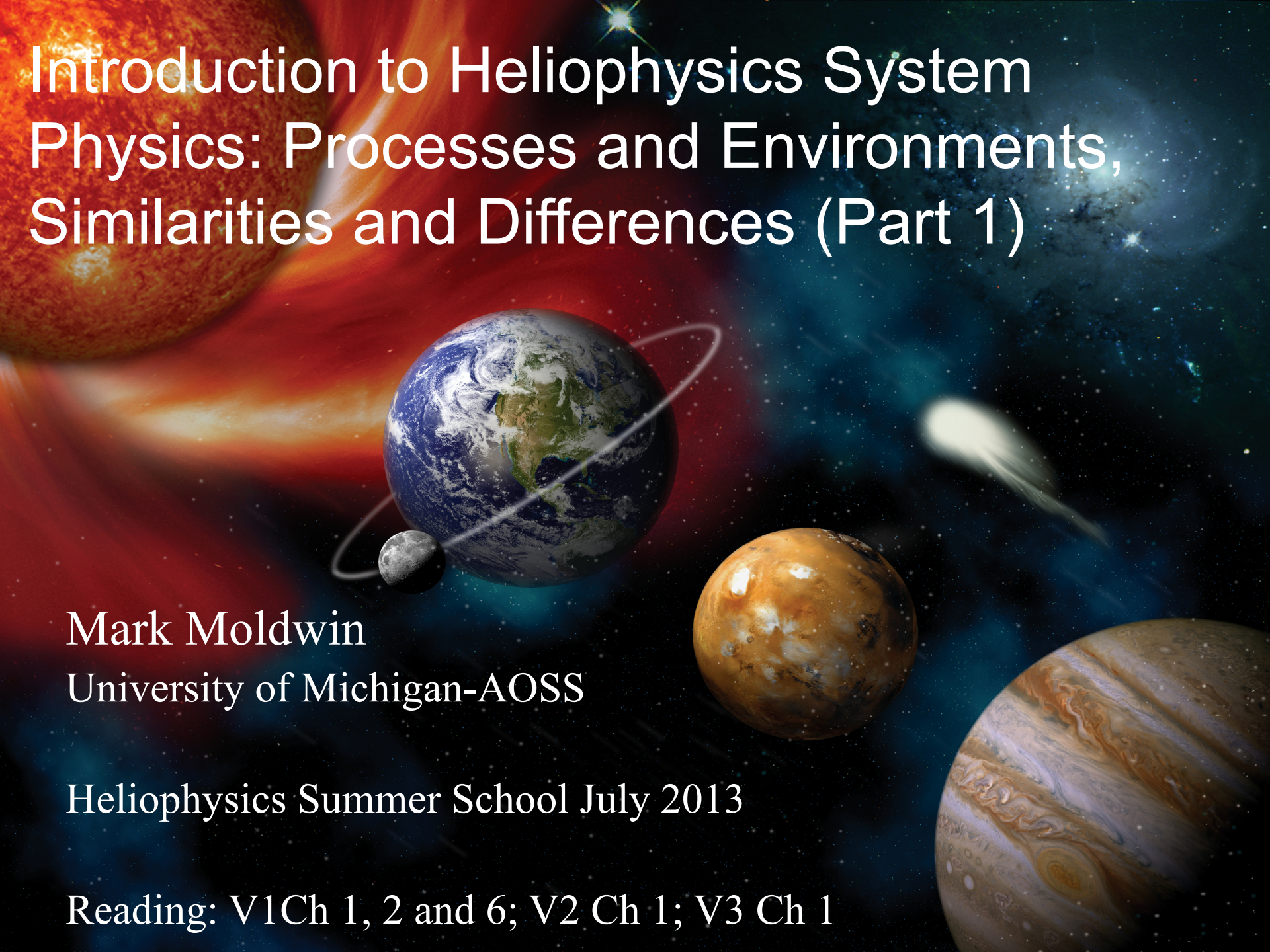
Introduction to Heliophysics System Physics: Processes and Environments, Similarities and Differences (Part 1)



Mark Moldwin
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Heliophysics Summer School July 2013

Reading: V1Ch 1, 2 and 6; V2 Ch 1; V3 Ch 1

What is your Background?

- I know the domains of heliophysics
  - (1 agree; 2 kinda; 3 disagree)
- I have taken graduate level space plasma physics courses.
- I have an undergrad degree in physics
- I have read the 3 Heliophysics Texts
  - (1 cover2cover; 2 skim; 3 what books?)

What are Scientists Interested in Finding?

- Structure and Dynamics
- Causes/Physical Processes

- Compare and Contrast
- Analogies (explaining new observations/ models/ideas in context of previous knowledge)
- Develop Simple Conceptual Understanding

Goal of this Morning's Lecture

- Flux Tubes and Current Sheets are the "quanta"-structures of plasma physics
- These are universal structures that span all scales and tell us about universal processes that create them.
- Reconnection happens at thin current sheets
- What are the similarities and differences of the the Sun's, Earth's and other solar system and astrophysical space plasma environments?

Universal Magnetic Structures

- Magnetized plasmas form a FINITE set of structures seen over wide range of scales
- For this discussion, I posit that there are only three groups – flux tubes, cavities, current sheets.
- What does this tell us about magnetized plasmas? Why only three?

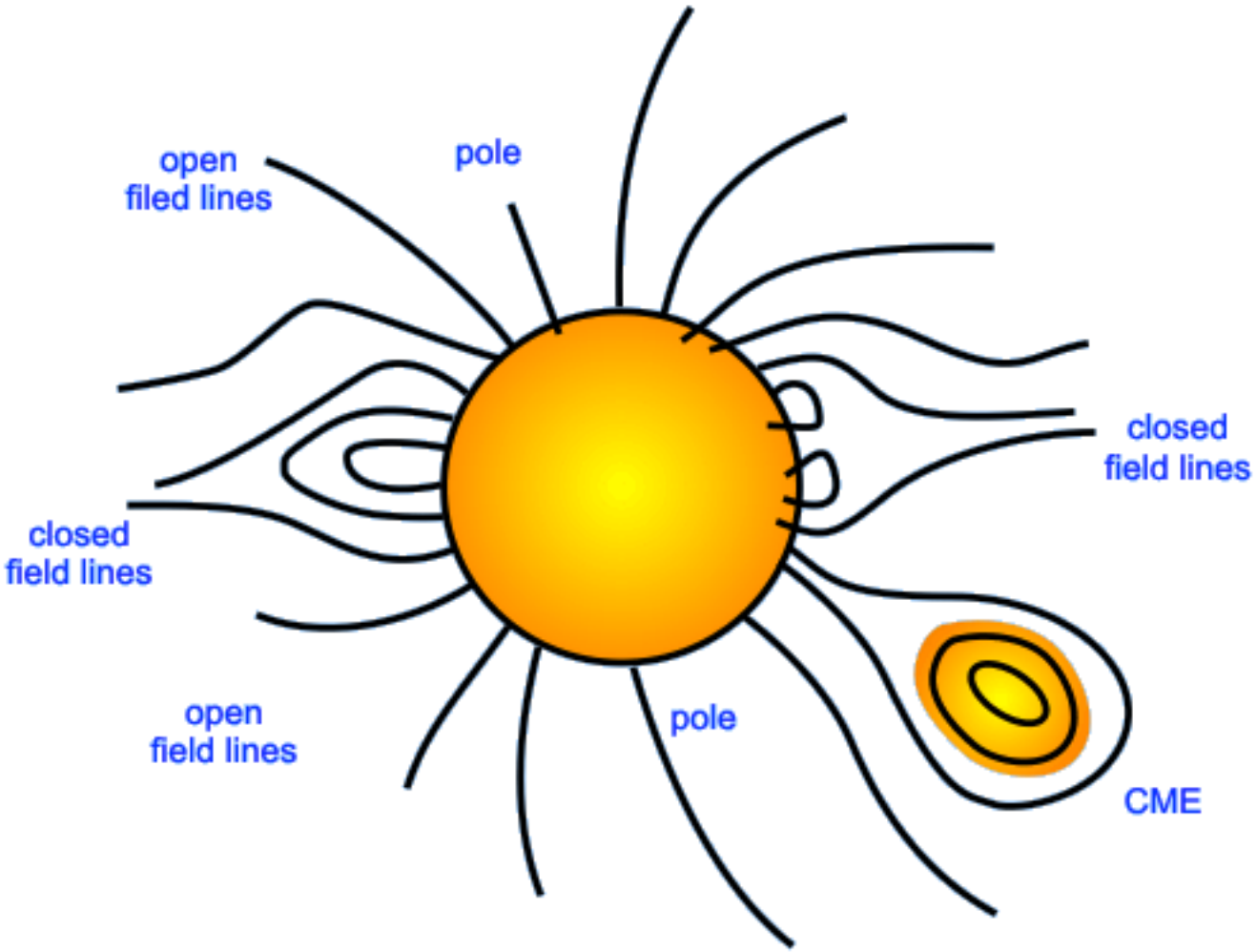
Can you define and give examples of these structures?

- Cavities
- Current Sheets
- Flux Tubes
- Introduce yourself to your neighbors and quickly answer above question as best you can.

Examples of Three Groups

- Cavities: Magnetospheres, heliosphere
  - (Vol 1, Figure 2.7)
- Current Sheets: Heliospheric Current Sheet, magnetospheric current sheets
  - (Vol 1, Section 2.6)
- Flux Tubes: the smallest fundamental plasma structure
  - (Vol 1, Chapter 6)

Heliosphere/Cavity; HCS/current sheet; CME/ flux tube

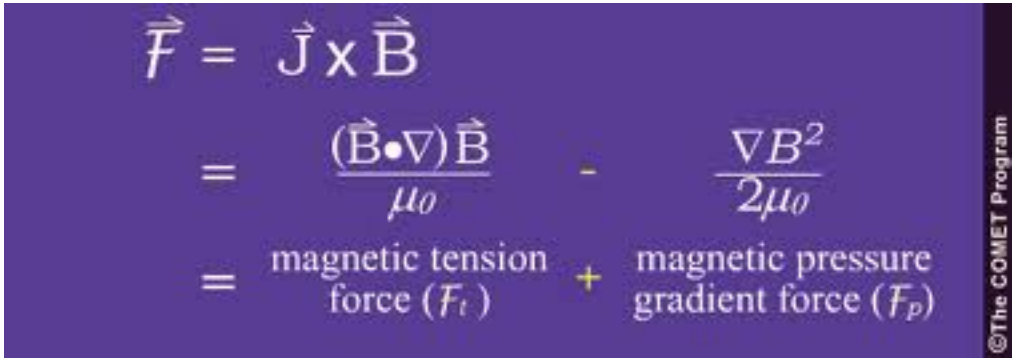


What is a Flux Tube?
(Vol 1,Section 6.4)

- Ideal MHD's frozen-in flux condition
  - (V1, S3.2.3)
- Equation of motion has the pressure gradient and Lorentz term on RHS (V1, Eqt 6.5)

$$\rho\left(\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v}\cdot\nabla)\mathbf{v}\right) = -\nabla p + \mathbf{j}\times\mathbf{B}$$

- Magnetic force has two components - magnetic pressure term acting perpendicular to field and a tension term along field.
  - (V1, Eqt 3.10)



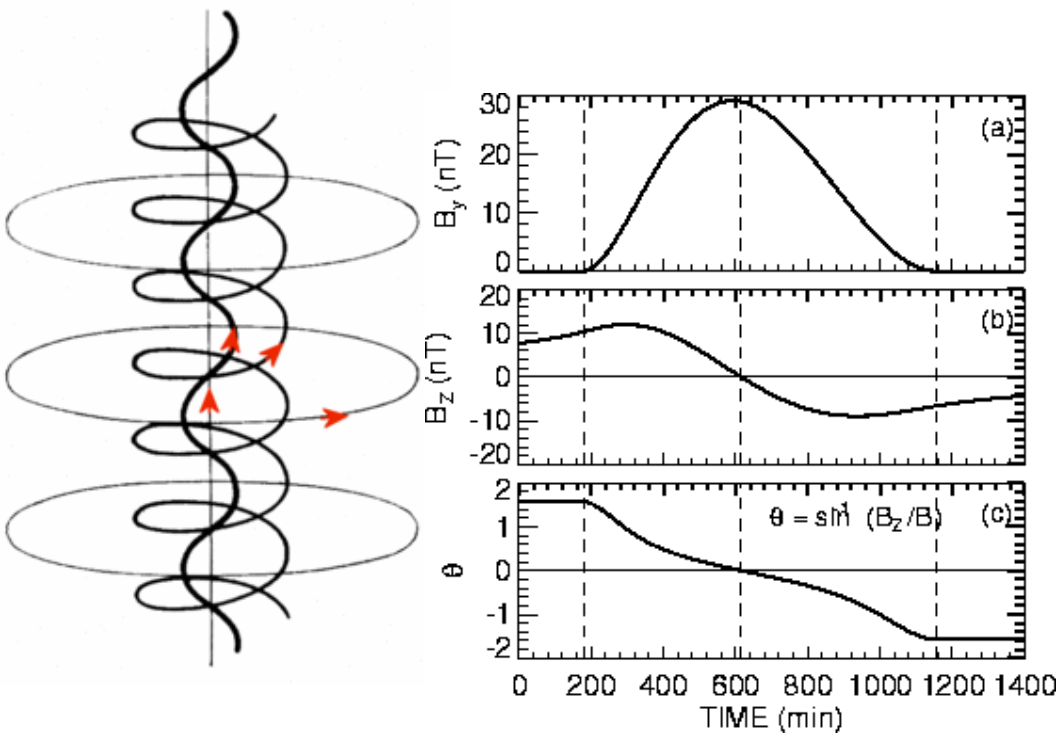
- Can think of flux tubes as mutually repulsive rubber bands
- They are the "elementary particles" of MHD

What are Flux Ropes?

- Field aligned currents cause the field to twist – hence the term “rope”

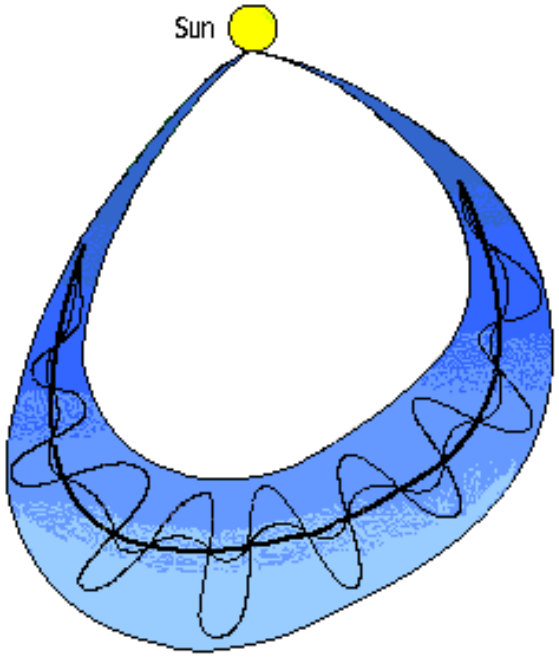
- Some are created by magnetic reconnection (V1, Section 2.4). Due to topology change allow exchange of Energy/momentum/mass between flux tubes (V1, Section 2.5)

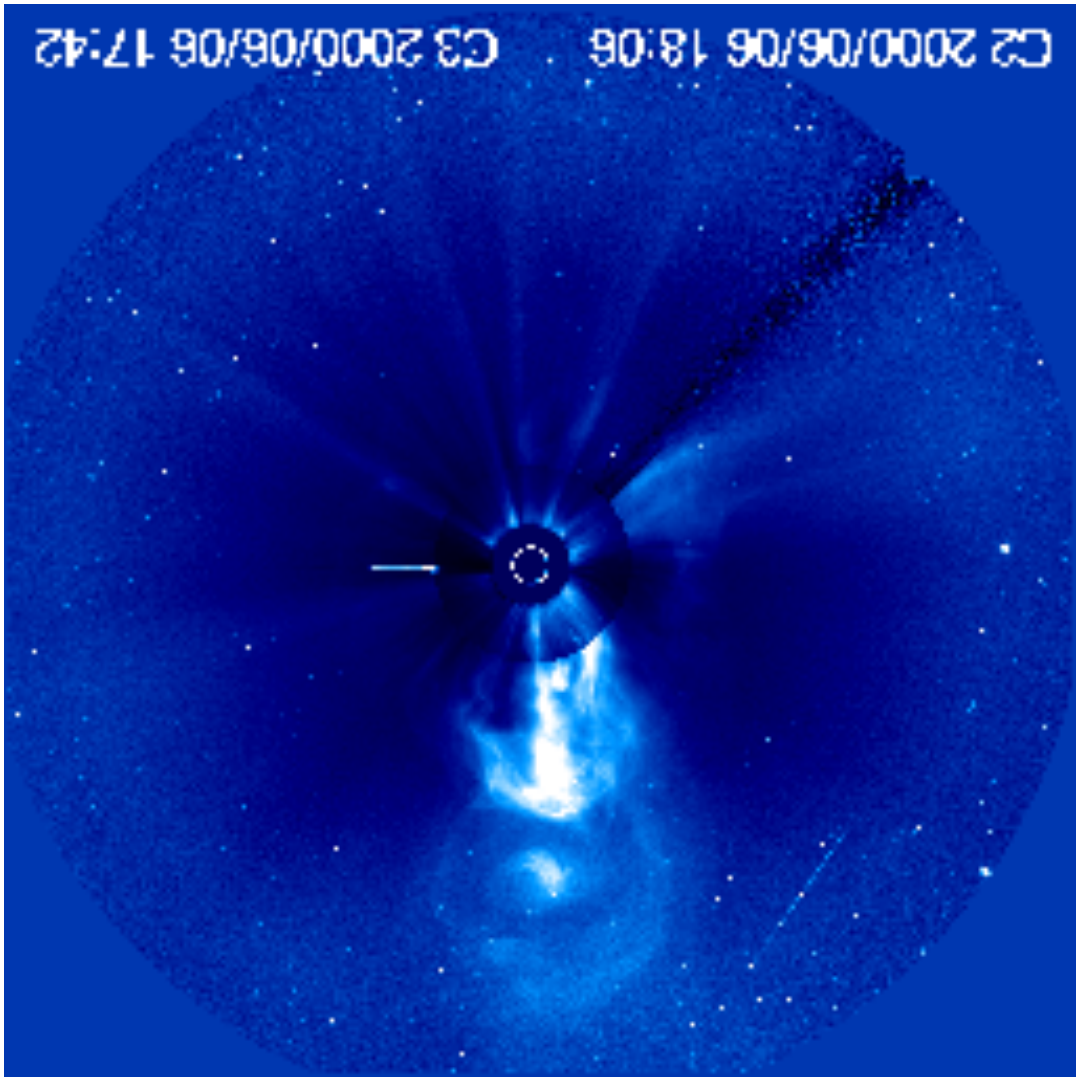
Flux Ropes



- The center of the rope is the core field
- Edges of rope often have current sheets to separate it from surrounding plasma

CMEs often have flux rope structure

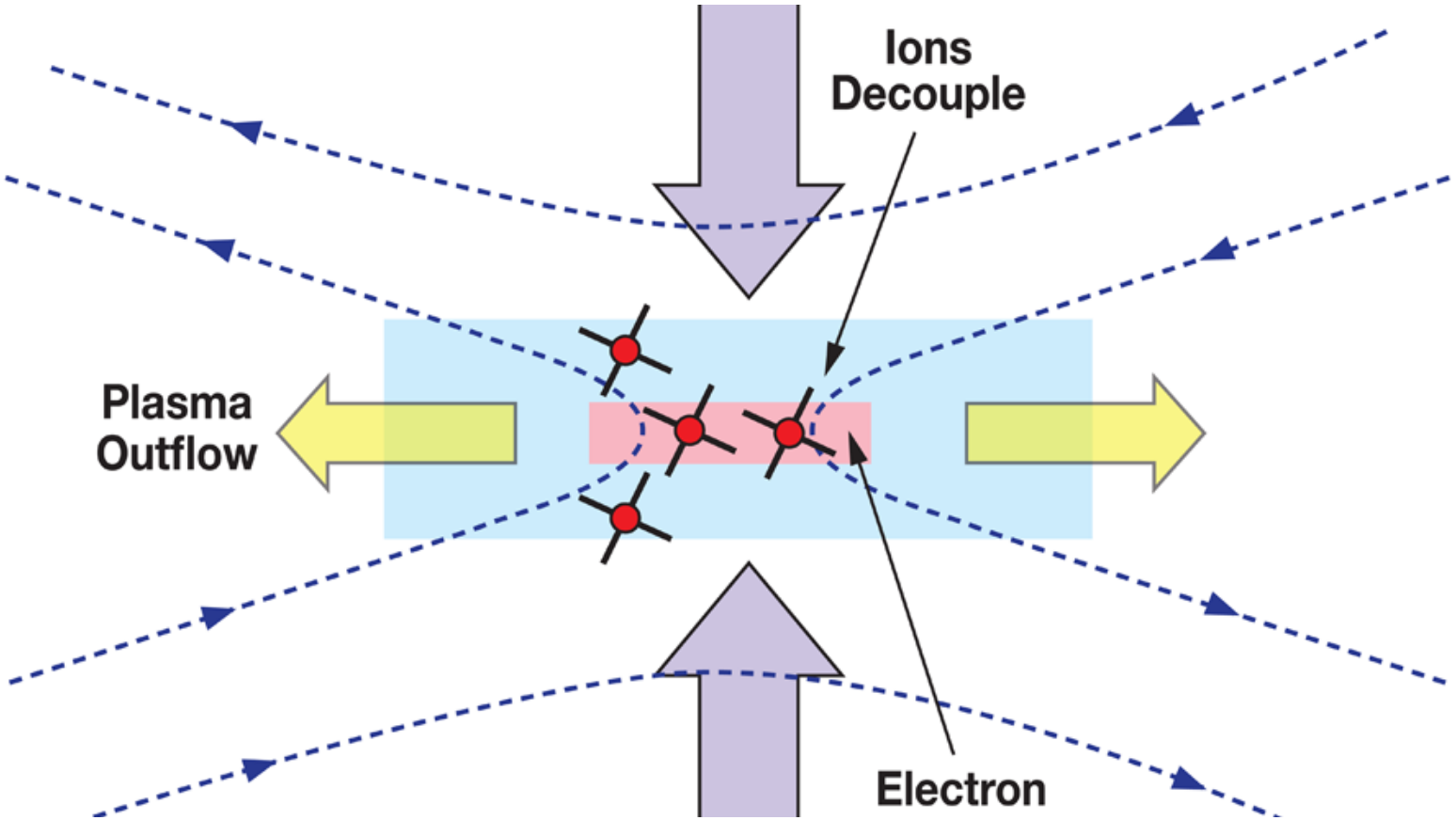




Role of Flux Tubes/Ropes: Defining and Connecting Domains

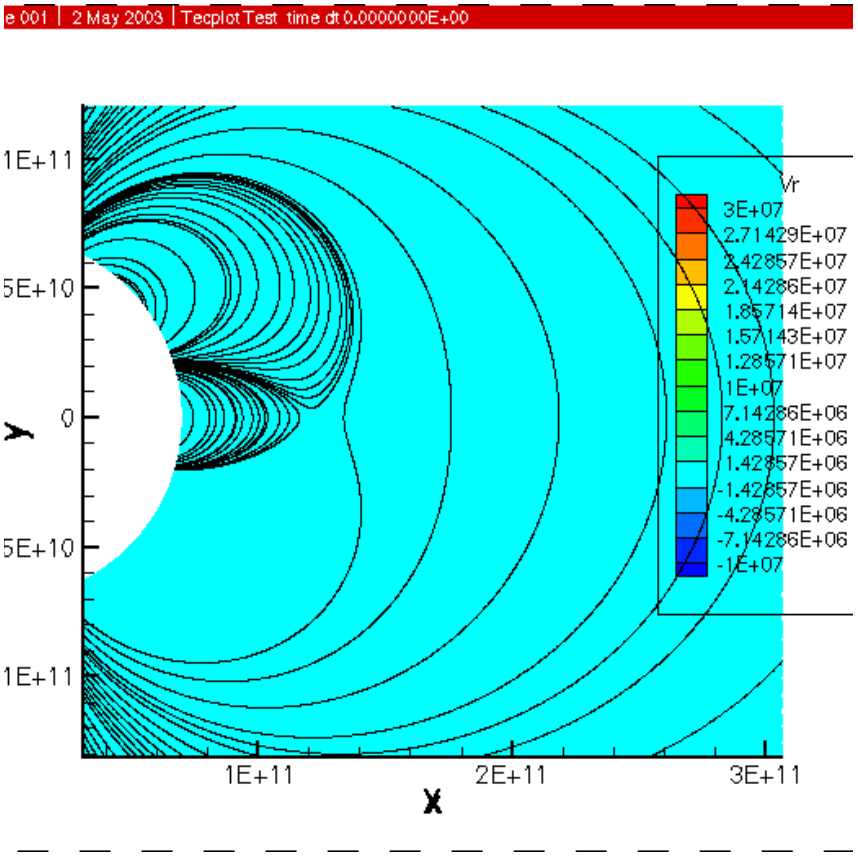
- What are inside “cavities”?
- What distinguishes/separates one “domain” or “region” of space from another? (i.e., the plasmasphere from the plasmasheet? Or a CME from the solar wind?)
- How can one domain interact with another?

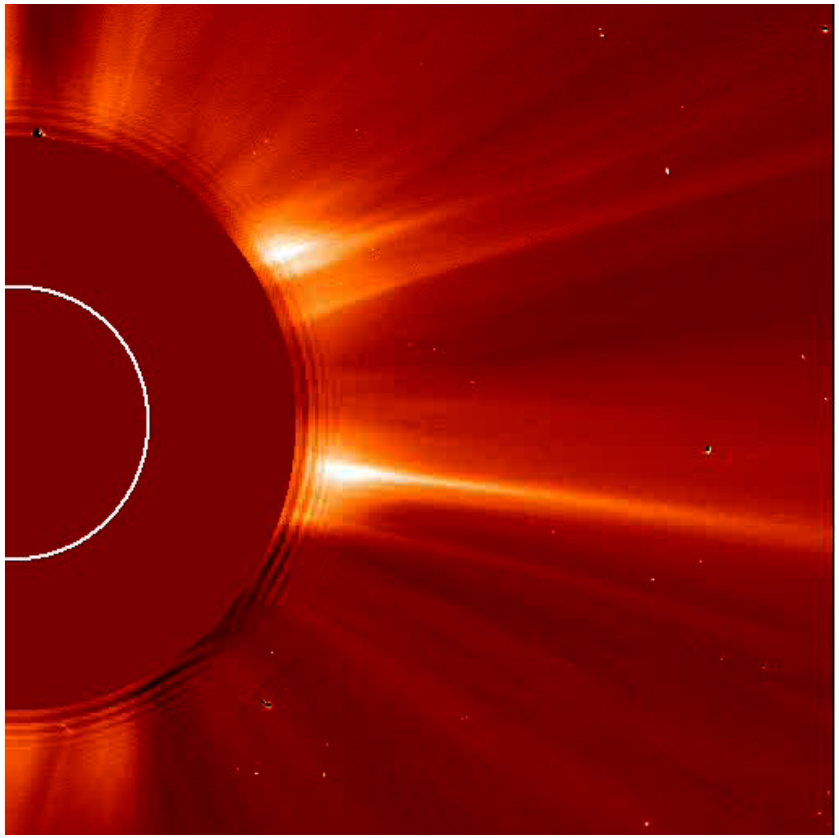
Magnetic Reconnection



NASA MMS EPO

CME formation involves thin current sheets and RXN

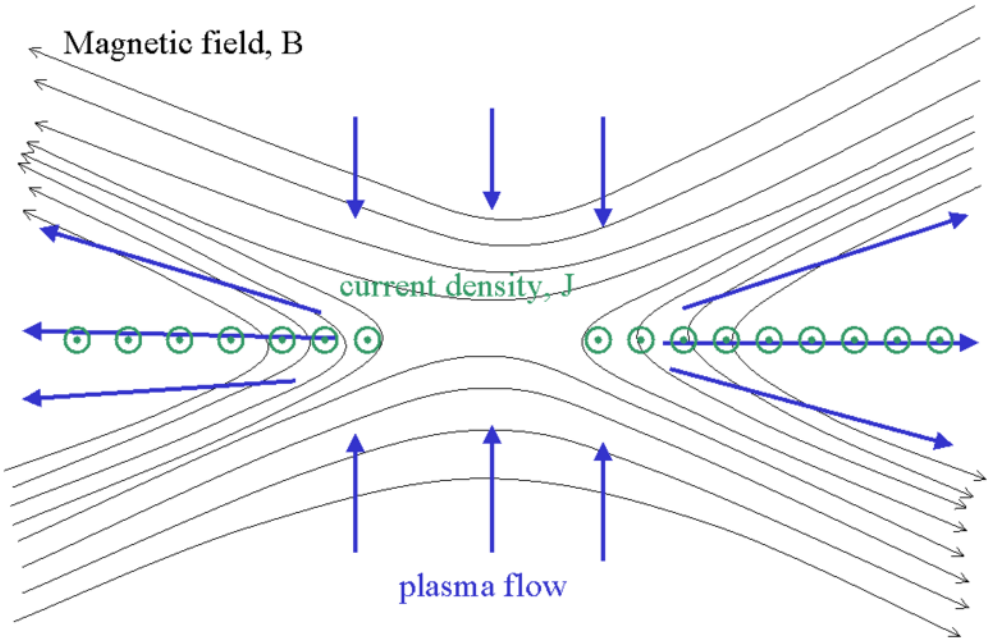




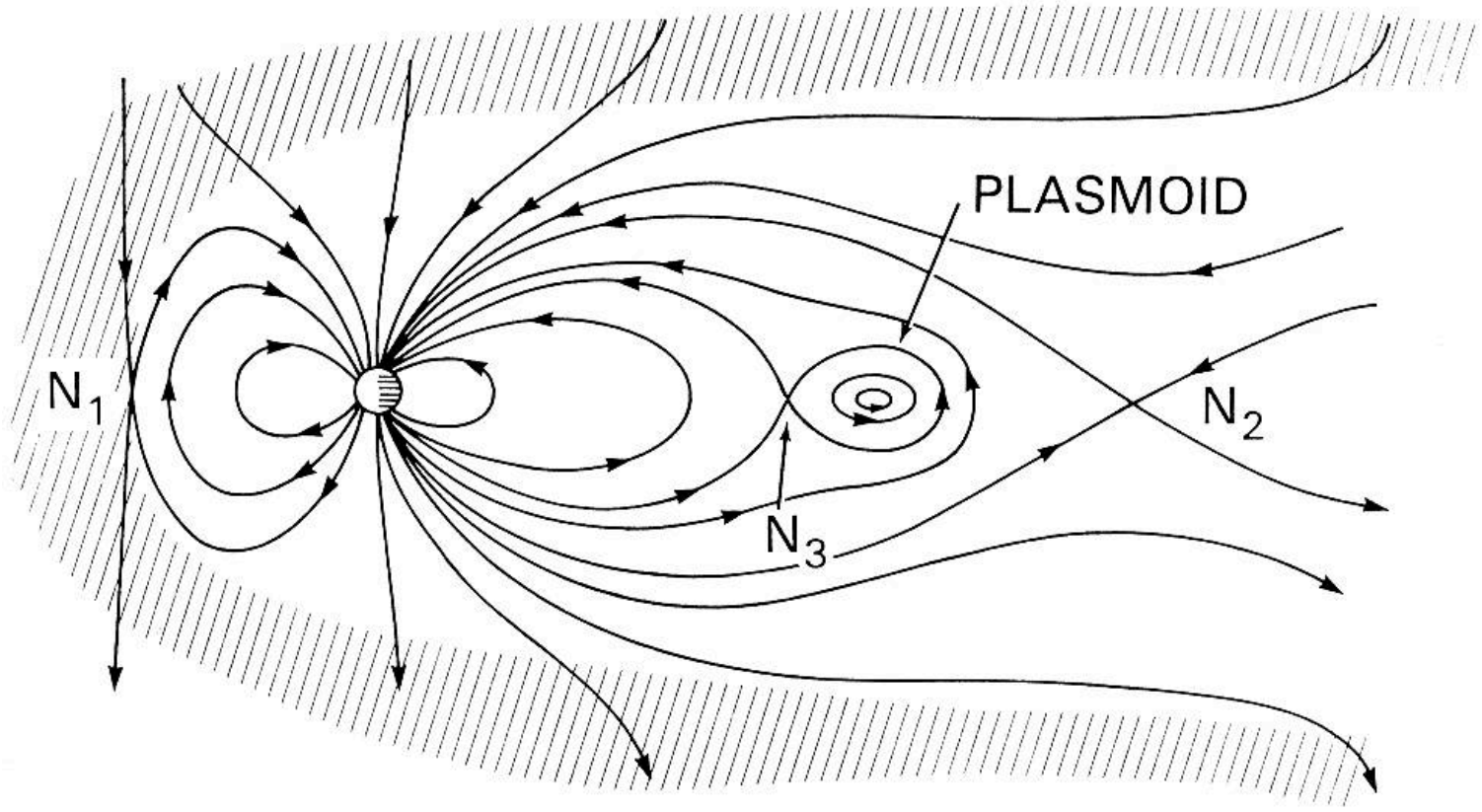
MacNeice et al. 2004

Reconnection across HCS

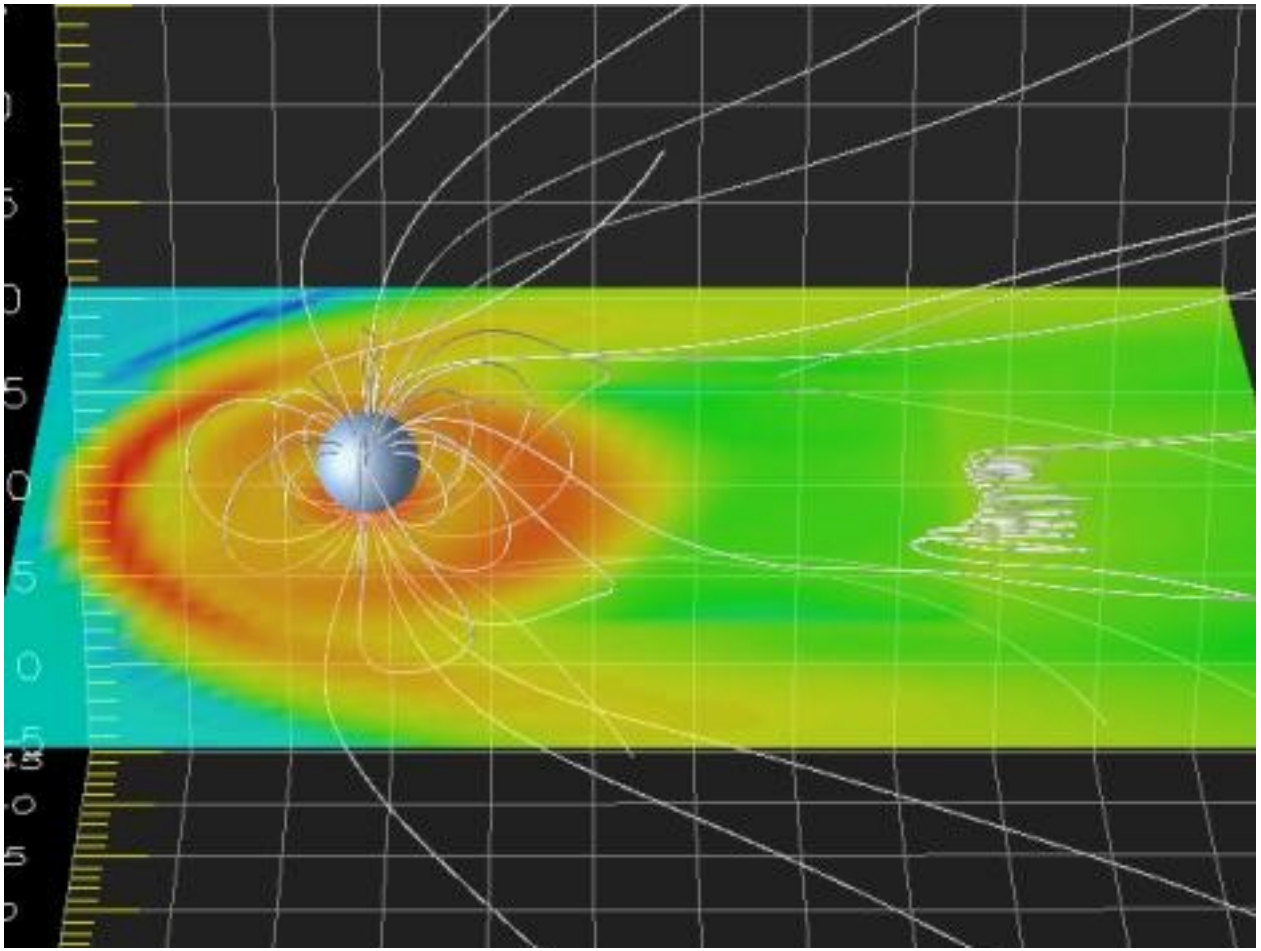
- Gosling, Phan et al. have presented numerous observations of signatures in the solar wind consistent with classic Petschek-like reconnection jets



Creation of Plasmoid by Magnetic Reconnection in Earth's Magnetotail

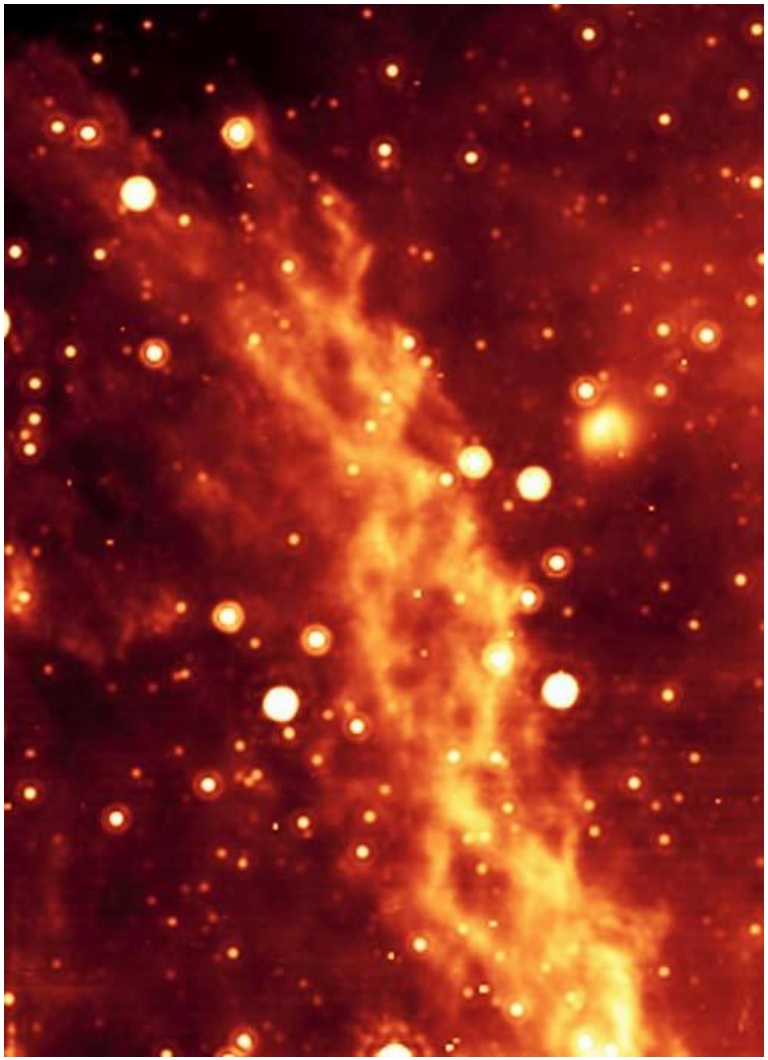


Formation of Plasmoid



Magnetotail current sheet forms – similar to Post-CME current sheet. Localized reconnection forms plasmoid, tearing mode can lead to tangling, multiple plasmoids, as in post CME flare.

Double Helix Nebule



- IR image
- Near center of Milky Way
- About 80 LY long

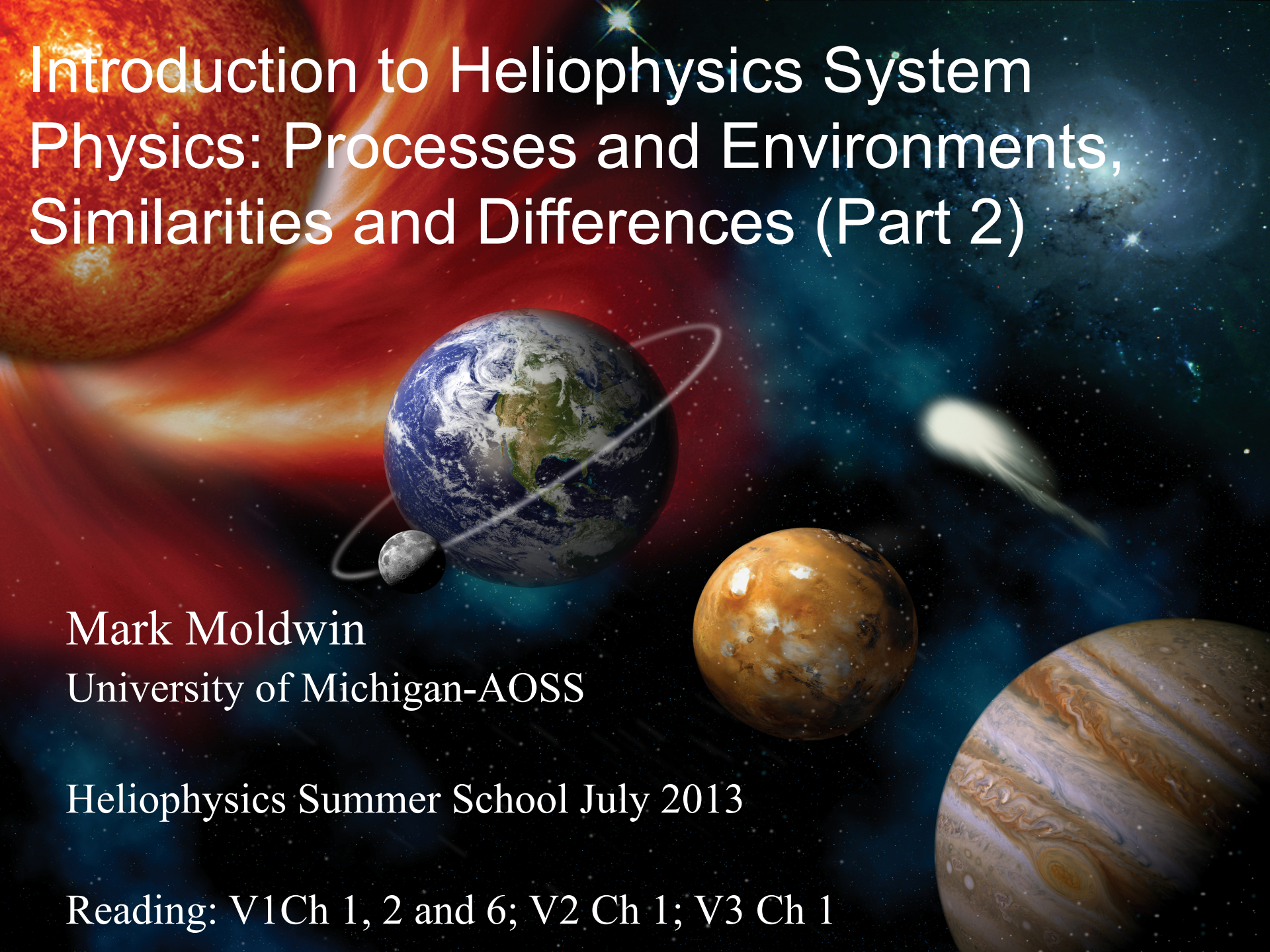
Morris et al. Nature, 2007

Take Home Message

- Three Universal Magnetic Structures
  - Cavities, current sheets and flux tubes
- Observed throughout space
- Reconnection couples flux tubes and plays significant role in energy, mass, and momentum transfer in Sun-Earth relationship (CMEs and storms, role of RXN across HCS)

- Want to understand Heliosphere – need to understand magnetic reconnection

Introduction to Heliophysics System Physics: Processes and Environments, Similarities and Differences (Part 2)



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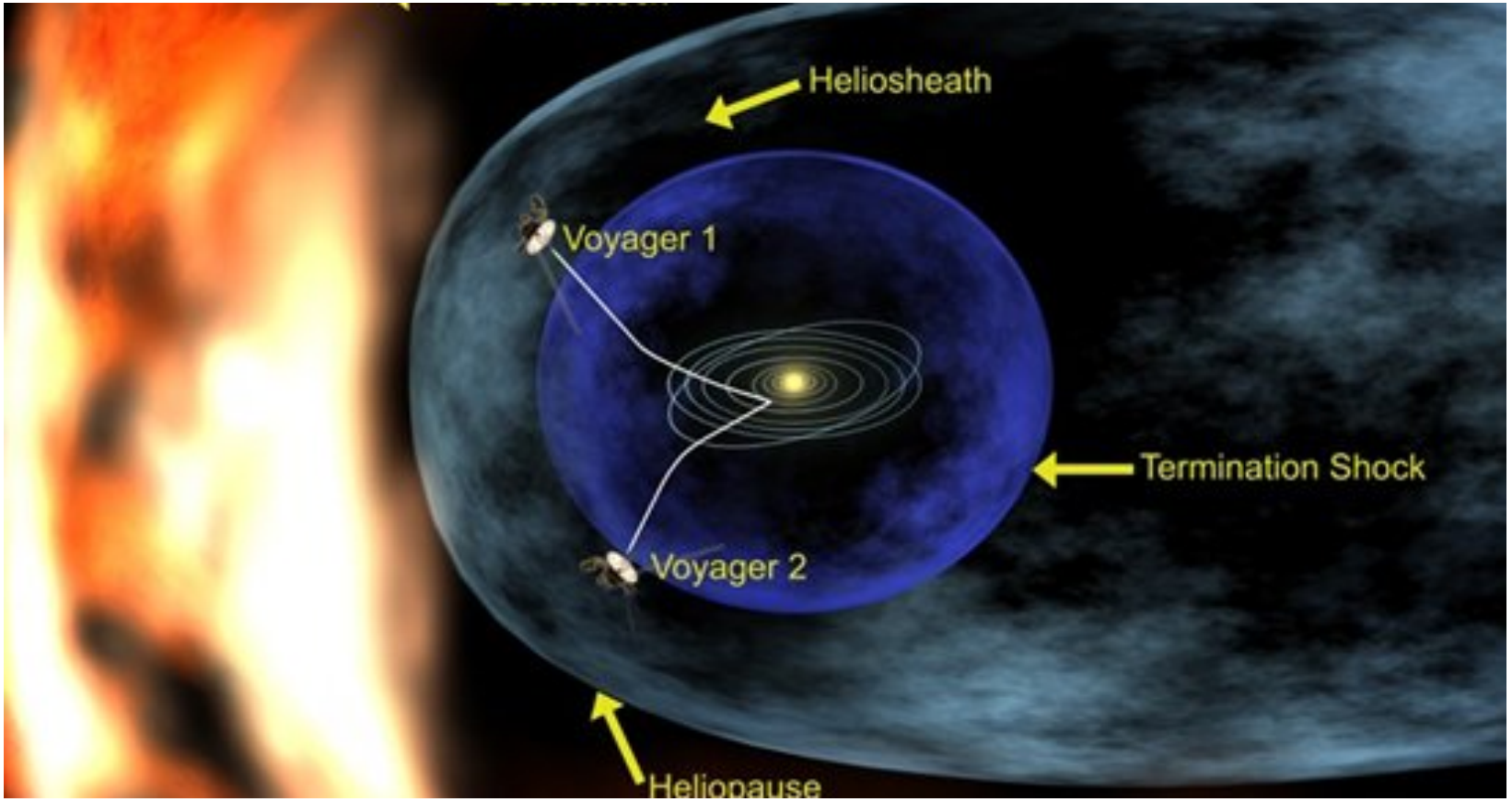
Goal of this Lecture

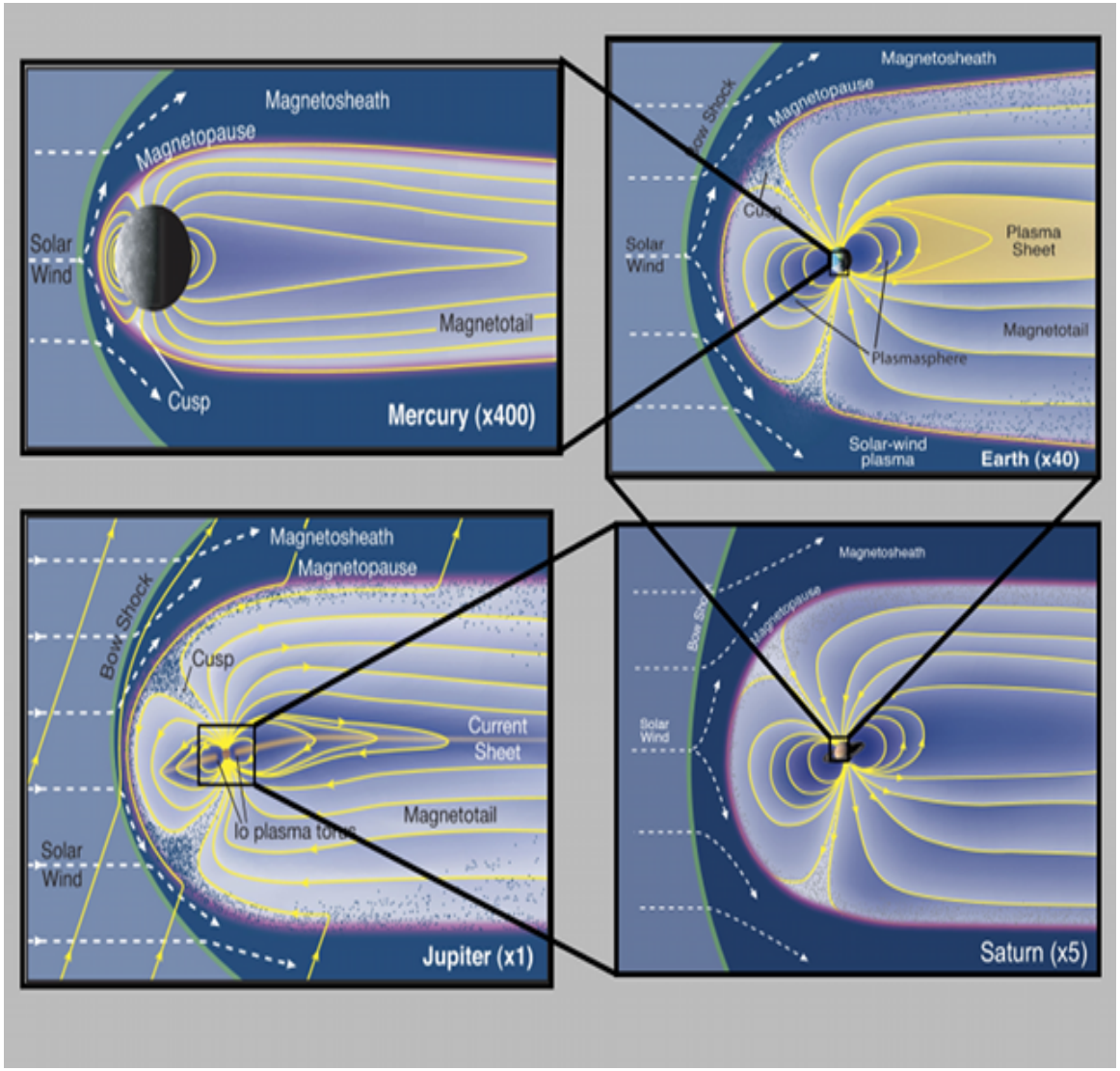
- The scales of the universal structures tell us about the energy content of the structure and its surroundings
- There are a small set of plasma scales that order the physics.
- Reconnection is a CROSS-SCALE process. The physics is at the electron scale, but the dynamics is driven by the global scale (RXN changes the global structure – global structure changes RXN)

Cavities – Magnetosphere and Heliosphere

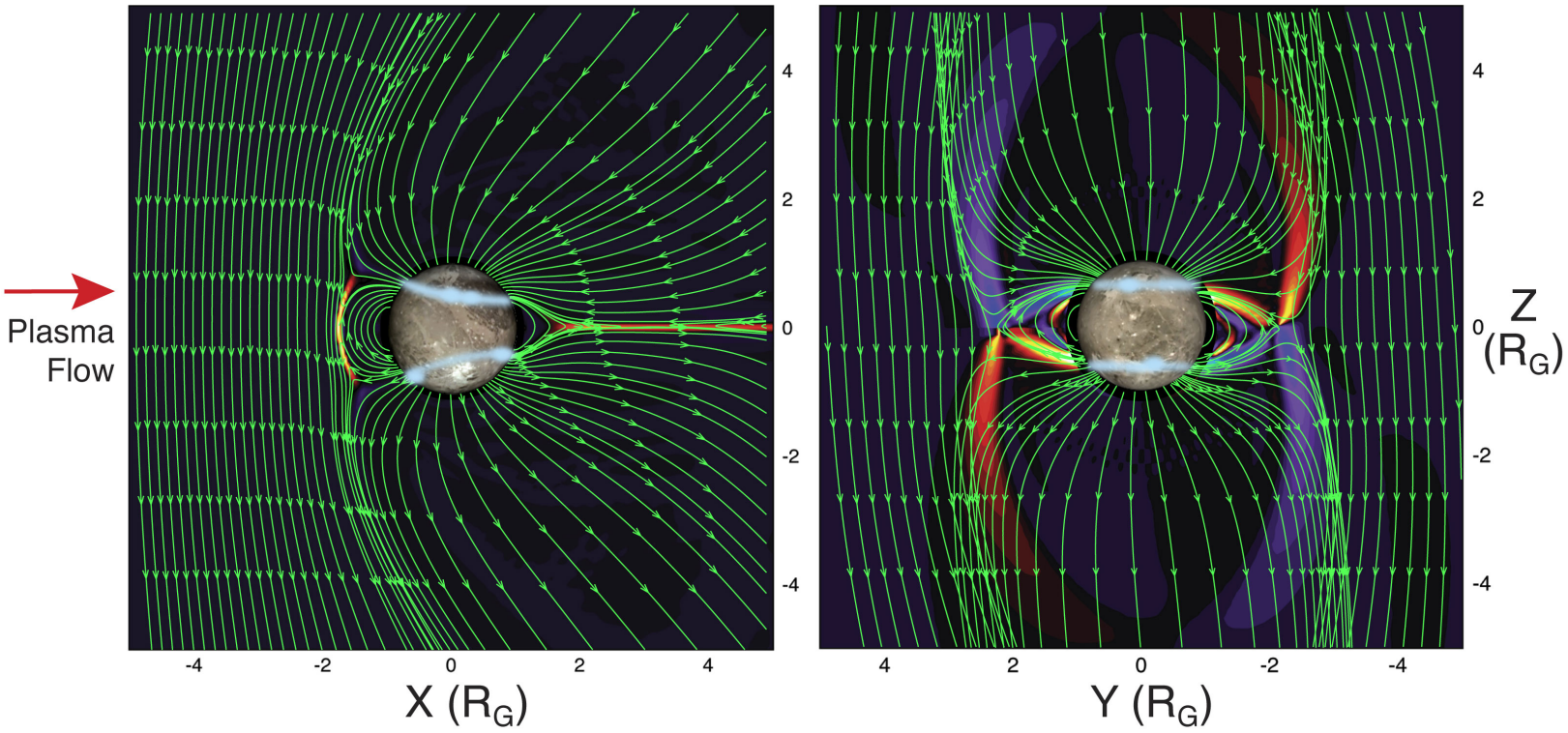


Astrosphere around L.L Orionis from HST

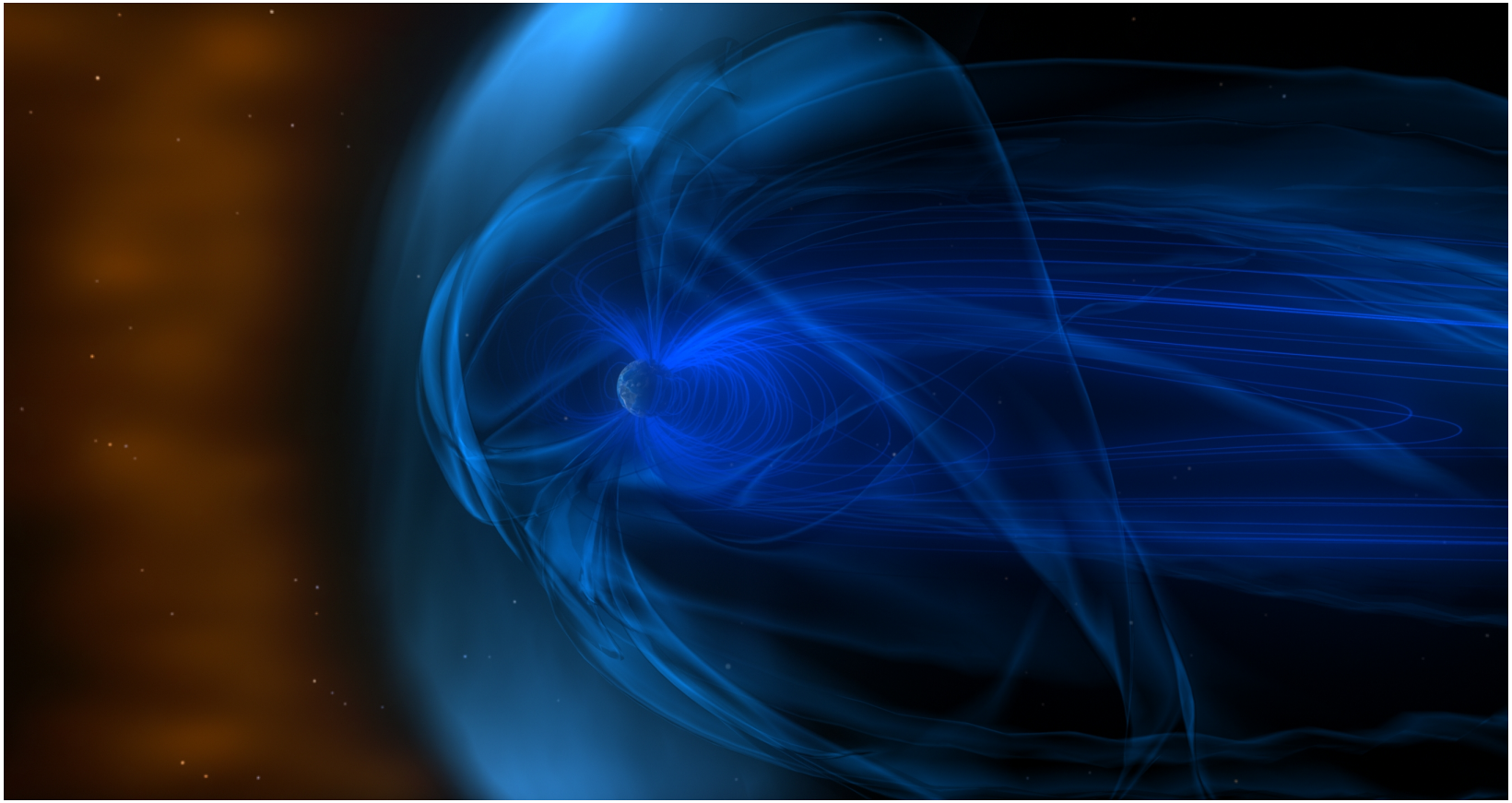
Planetary Magnetospheres



Matryoshka Nesting Dolls



What is this? An astrosphere, the heliosphere, a planetary magnetosphere (if so which one?), or a satellite's magnetosphere?

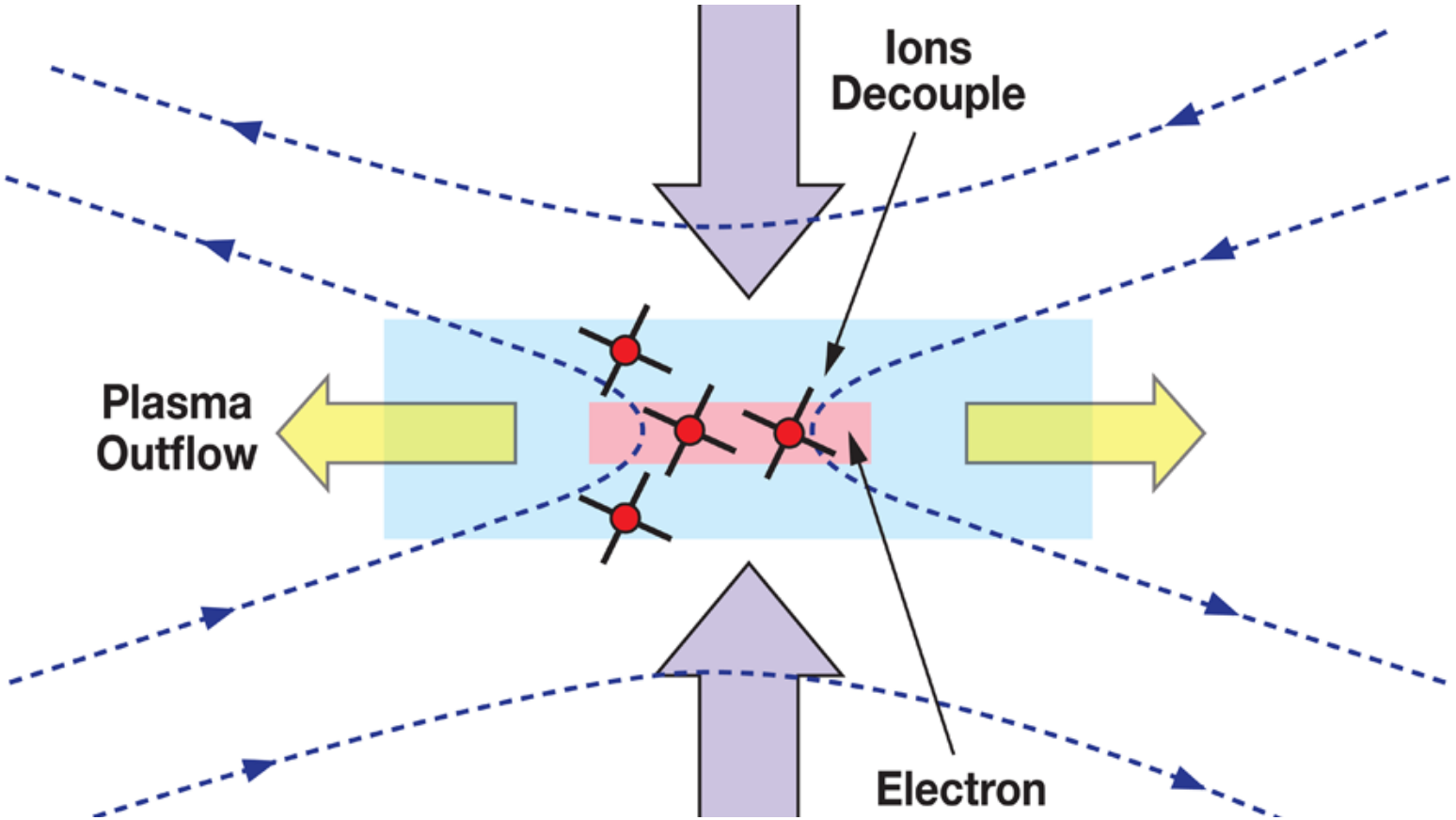


Coupling Processes

- What determines the structure of magnetospheres?
- What determines the dynamics of magnetospheres?

- How does mass, momentum and energy flow through the coupled system?

Magnetic Reconnection

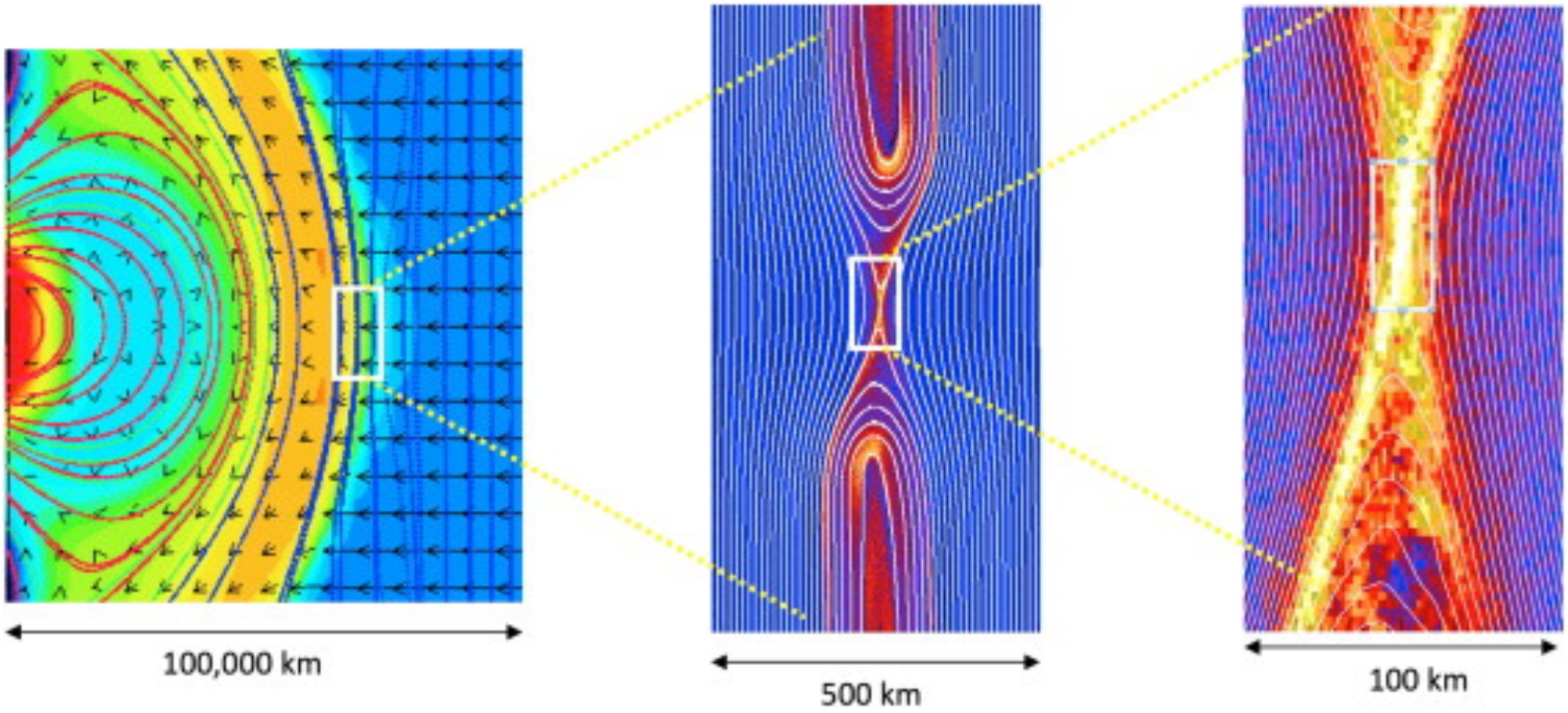


NASA MMS EPO

Cross-Scale Coupling

- If magnetospheres are self-similar, does scale matter? (See V1 Section 10.6 for discussion of magnetospheric scaling parameters).

- What are the scales important for reconnection?



Moore et al., JASTP 2013

Plasma Scales

- **Electron and ion gyroradius**, the radius of the circular motion of an electron or ion in the plane perpendicular to the magnetic field:

$$r_g = \frac{m v_\perp}{|q| B}$$

- **Ion inertial length**, the scale at which ions decouple from electrons and the magnetic field becomes frozen into the electron fluid rather than the bulk plasma:

$$d_i = c / \omega_{pi}$$

ω_{pi} Ion plasma frequency

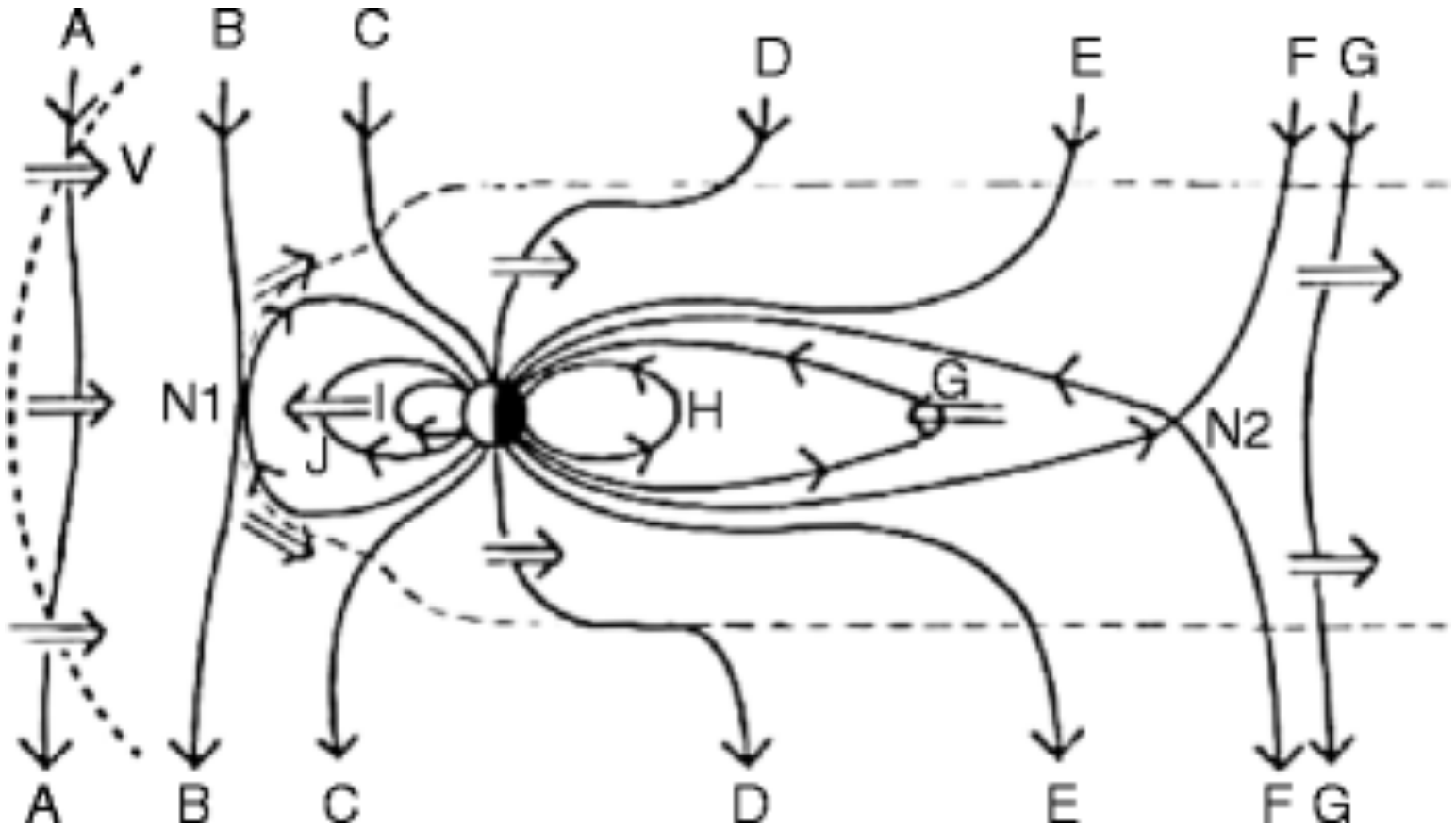
$$\omega_{pi} = \left(4\pi Z^2 q^2 / m_i \right)^{\frac{1}{2}}$$

- Other scales: Debye, skin depth, bounce, drift, mean-free path
- Which one is important?

Effects of RXN

- Conversion of magnetic energy to plasma kinetic and thermal energy
- Change in field topology
  - Coupling of different flux tubes
  - Allows exchange of mass

Dungey Cycle



Magnetic Energy $= \frac{B^2}{2\mu_0}$

(See V1, Eqt 3.31)

- Spatial Scales of RXN
  - Solar (micro-flares to CME), Magnetosphere (patchy dayside RXN to Plasmoid formation)
- Time Scales of Energy Release
  - Explosive (flares, substorms)
  - Quasi-steady state (magnetospheric convection due to distant X-line)

Take Home Message

- Three Universal Magnetic Structures
  - Cavities, current sheets and flux tubes
- Flux tubes are the basic structure
- Reconnection couples flux tubes and plays significant role in energy, mass, and momentum transfer in Sun-Earth relationship (CMEs/flares/geomagnetic storms/substorms)

- Want to understand Heliosphere – need to understand magnetic reconnection

- Complication comes in that RXN involves cross-scale coupling from micro $\leftrightarrow$ macro