Substorms at Mercury: Old Questions and New Insights

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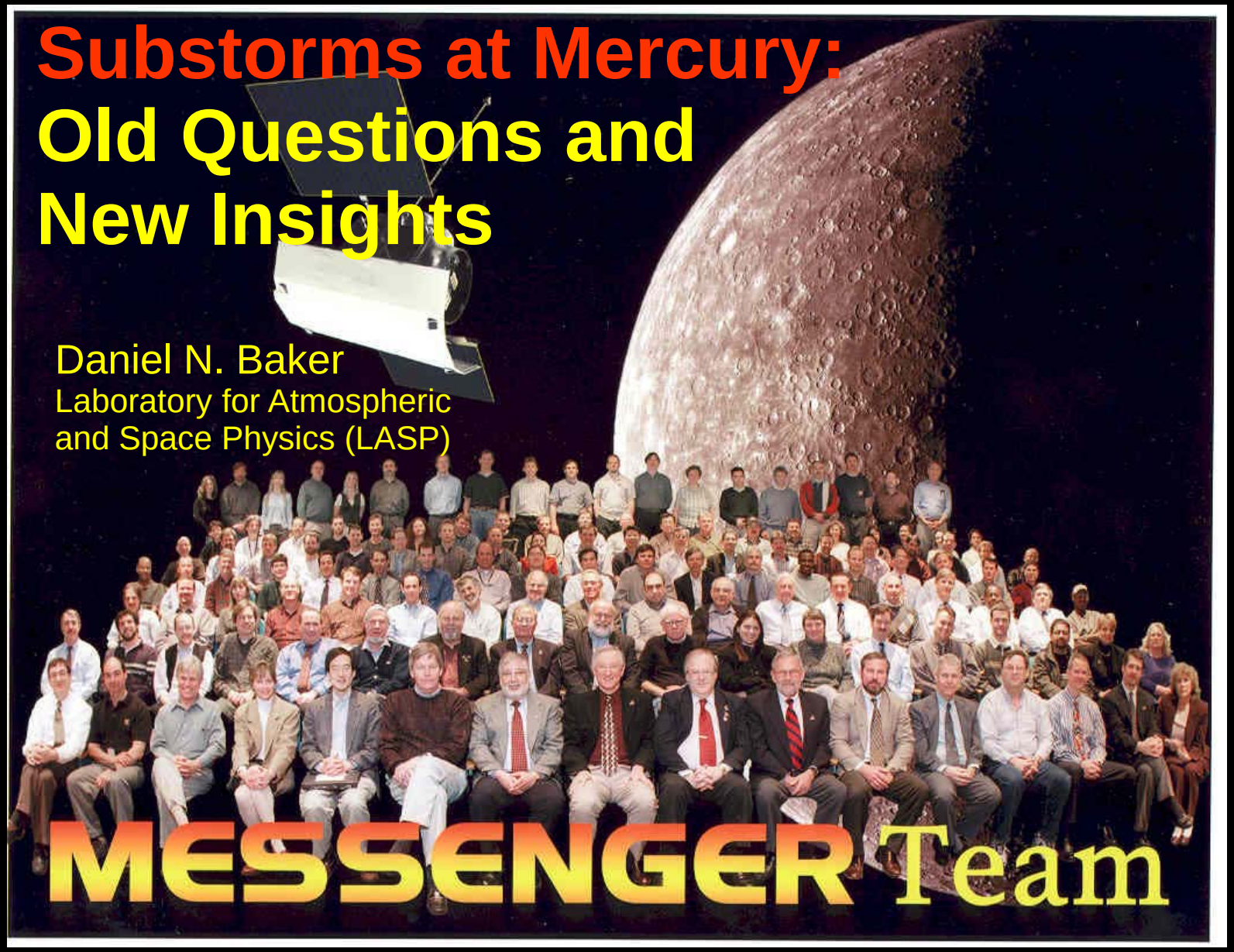
Laboratory for Atmospheric and Space Physics (LASP)



Outline of Presentation

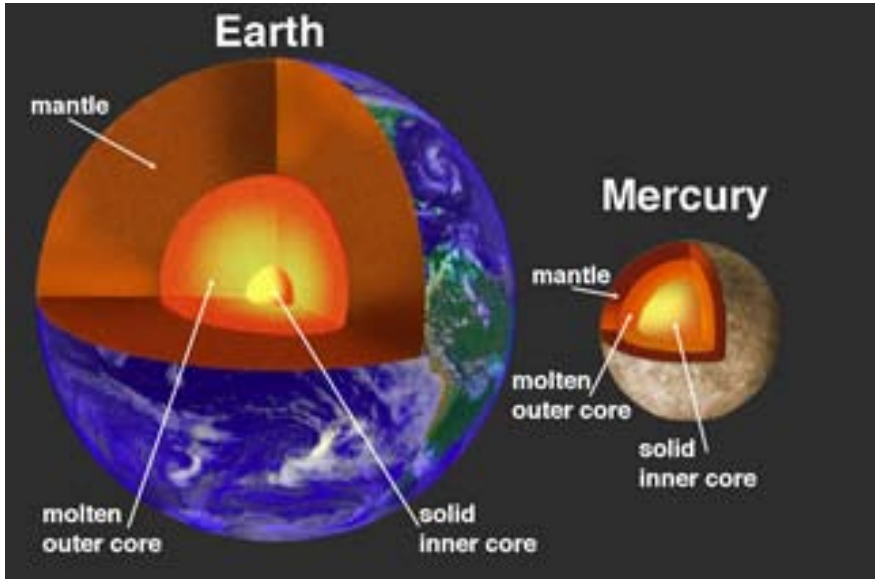
- Introduction
- Substorms in the Earth's Magnetosphere
- Prior Mercury Results: Mariner 10
- MESSENGER Flybys: 2008 - 2009
- Solar Conditions and Substorm Puzzles
- Summary and Future Directions

Exploring Mercury: History

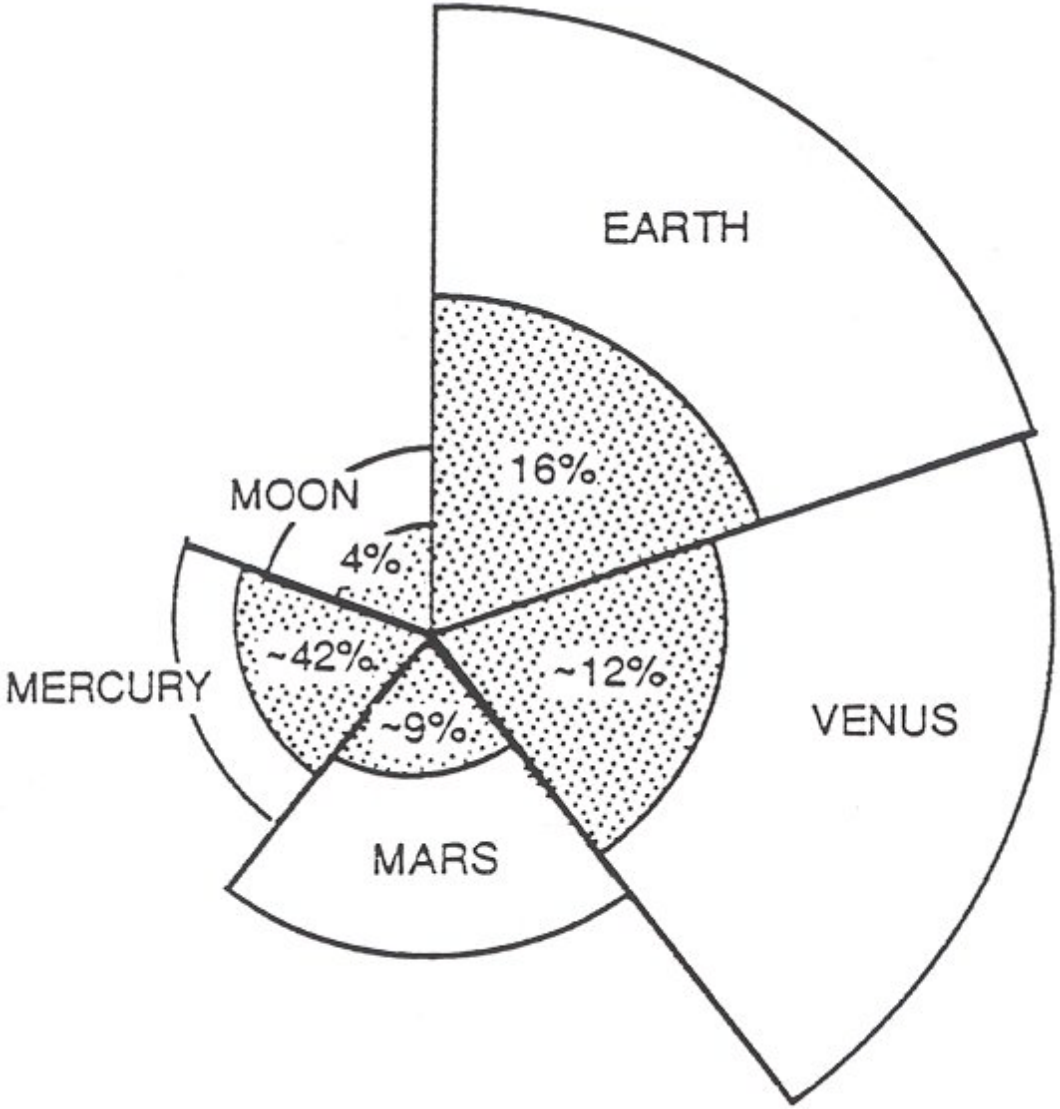
- Astronomical Observations and Radar Measurements
  - Determination of orbit, rotation period, radius and mass
- Mariner 10
  - Launched November 3, 1973
  - Arrived at Mercury March 29, 1974; Again in September 1974, and in March of 1975
  - Closest Approaches: 707 km (M1) and 327 km (M3)
  - Photographed the sunlit side of the planet and the south polar region
  - Detected planetary magnetic field
- Continuing Ground-based Observations
  - Atmospheric Constituents, Subsurface “Hot Spot” and Polar Deposits

Mercury In Perspective

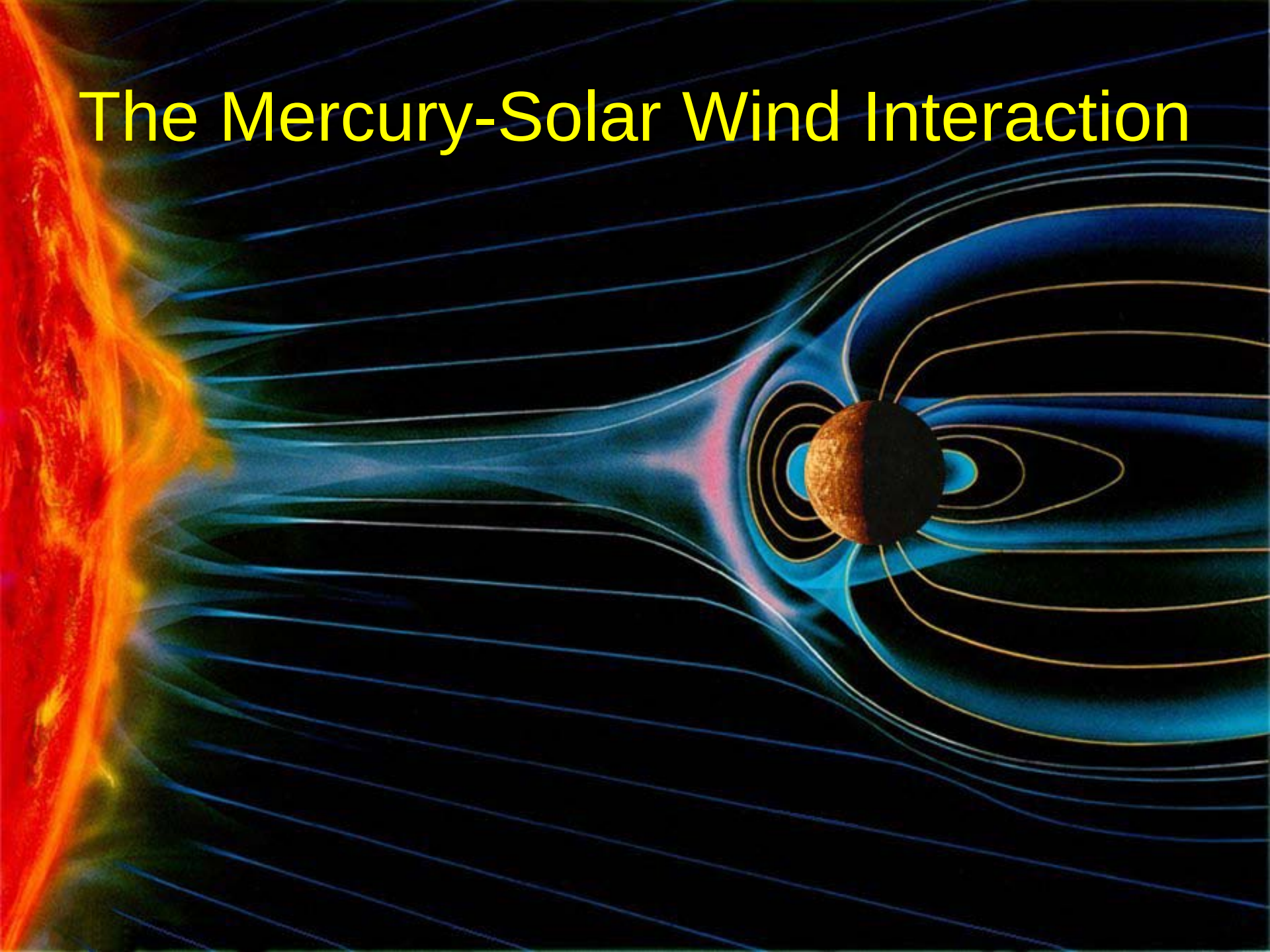
- **Smallest of the terrestrial planets**
- **Orbit:**
  - Period: 88 Days
  - Aphelion: 0.467 AU
  - Perihelion: 0.387 AU
- **Rotation period: 58.64 Days**
  - Orbit period:Rotation period = 3:2
- **Equatorial diameter: 4879 km**
- **Uncompressed density: 5.3 g/cm^3**
  - Metal:Silicates ~ 2.3:1
- **Surface temperature: 100˚K - 700˚K**
- **Ancient surface similar to that of the moon**
- **Weak dipole magnetic field: 300 nT**



Planetary “Core Values”



The Mercury-Solar Wind Interaction



Mercury: Fundamental Magnetosphere/Atmosphere Questions

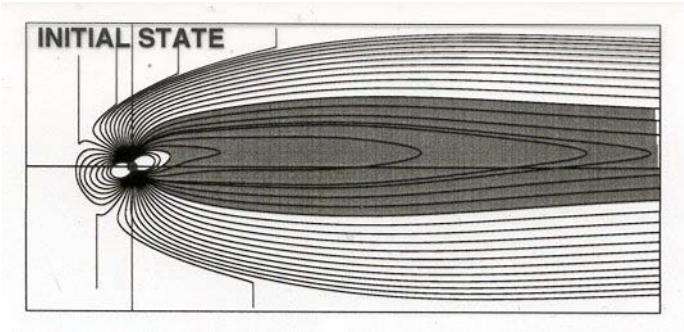
- Magnetic Field
  - Origin: dynamo or remanence?
  - Harmonic structure?
  - Surface or geological magnetic anomalies?
  - Spatial and temporal variations?
- Magnetosphere
  - Shape and structure?
  - Properties of constituent plasmas?
  - Radiation belt structure and dynamics?
  - Fundamental interaction with solar wind?
  - Ionosphere, atmosphere or surface interactions?
- Ionosphere/Atmosphere
  - Atmospheric (exospheric) constituents?
  - Sources and losses of particles?
  - Atmosphere-surface interactions?
  - Existence and possible causes of ionosphere?

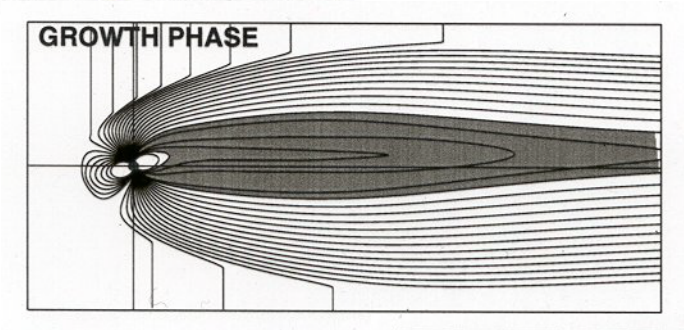
Solar Driving of Substorm Cycle

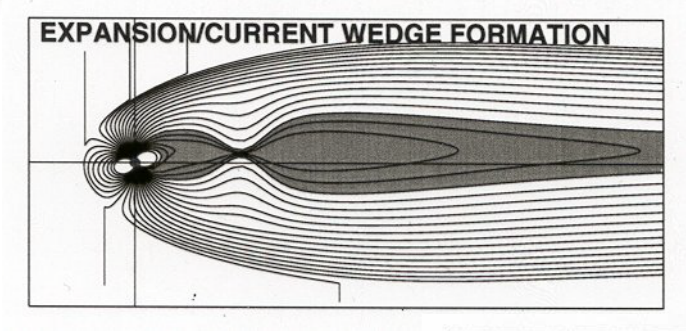
Courtesy of NASA

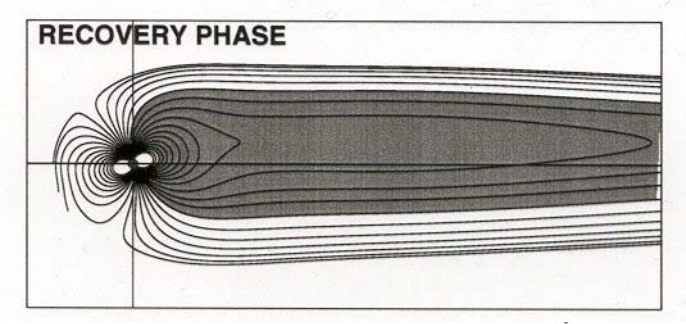
Substorm Magnetotail Sequence

The ”Dungey Cycle”



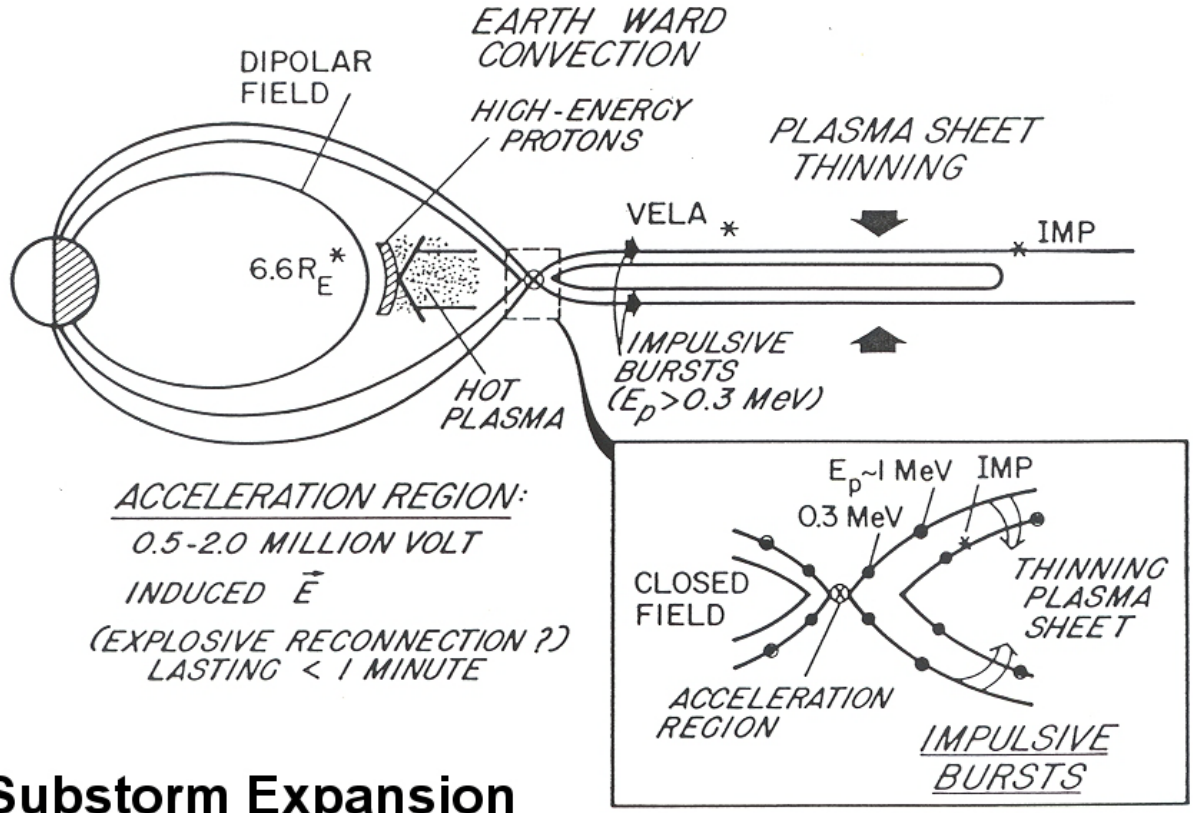






[Baker et al., 1998]

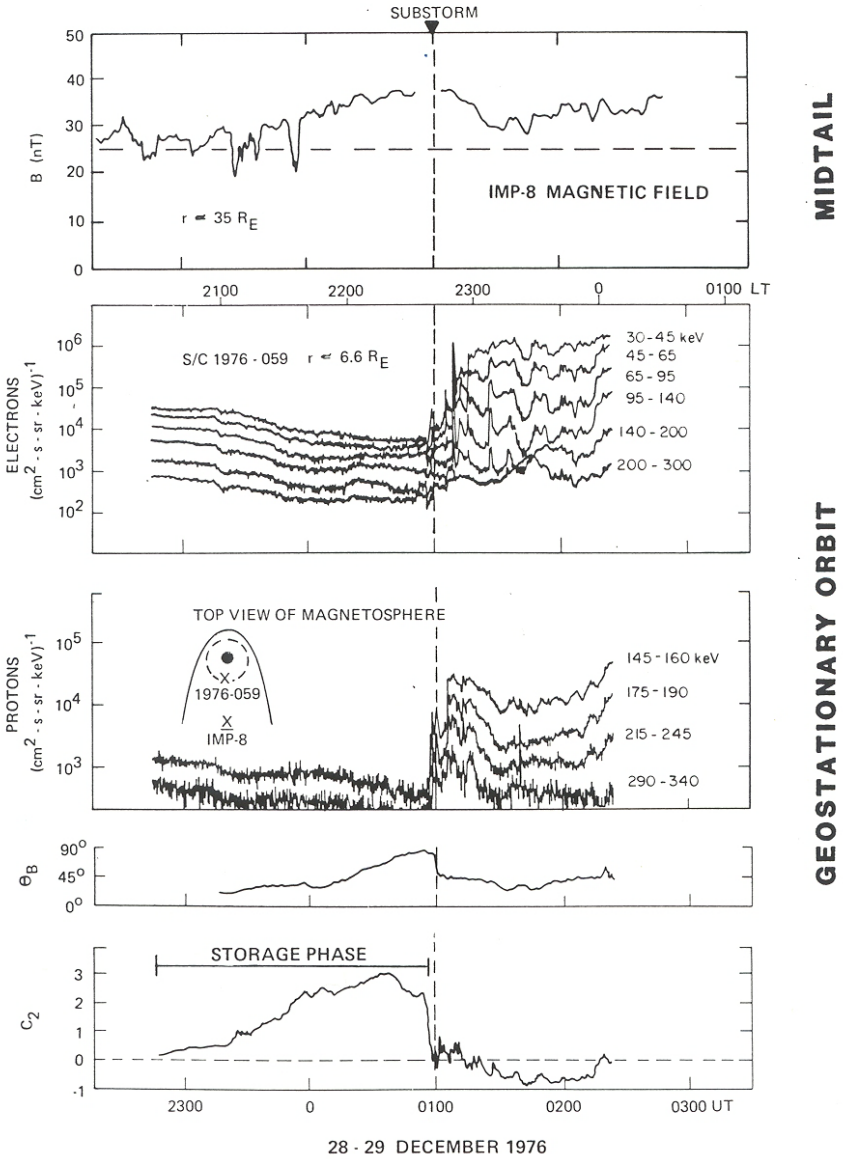
Neutral Line Substorm Model



Substorm Expansion

[Baker et al., 1979]

Substorm Particle Injection

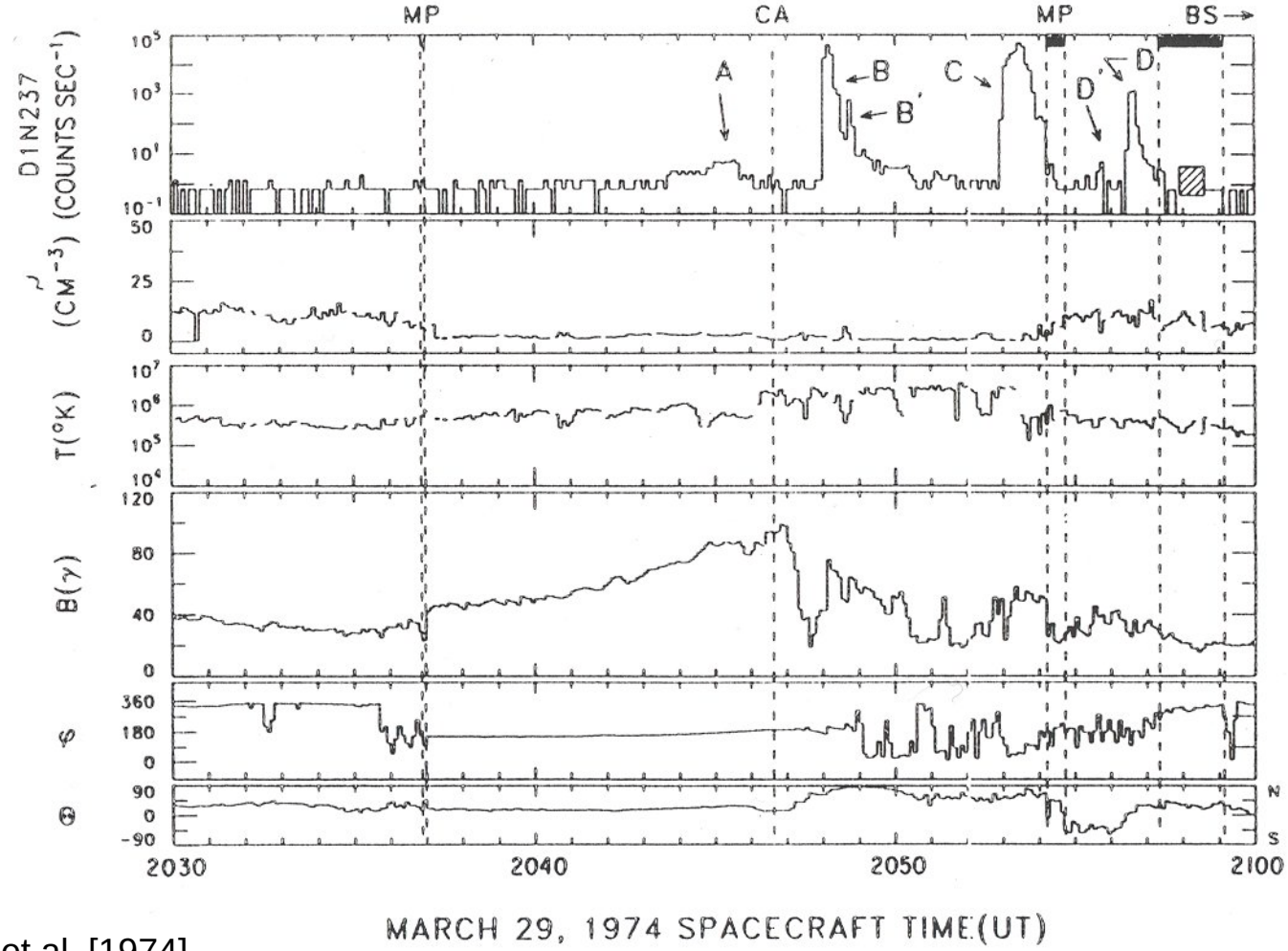


Magnetic energy increase in magnetotail

30 - 300 keV particle enhancements near geostationary orbit

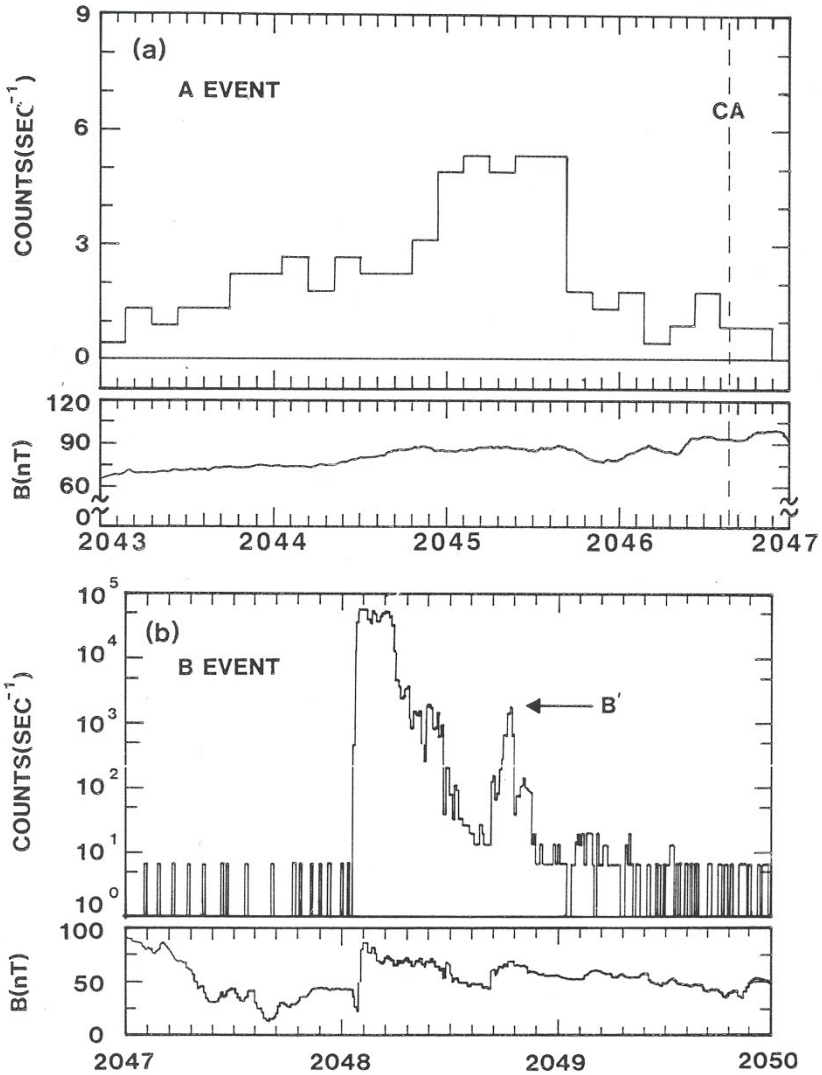
Magnetic field "dipolarization" near GEO orbit

Mariner 10: Mercury Encounter I

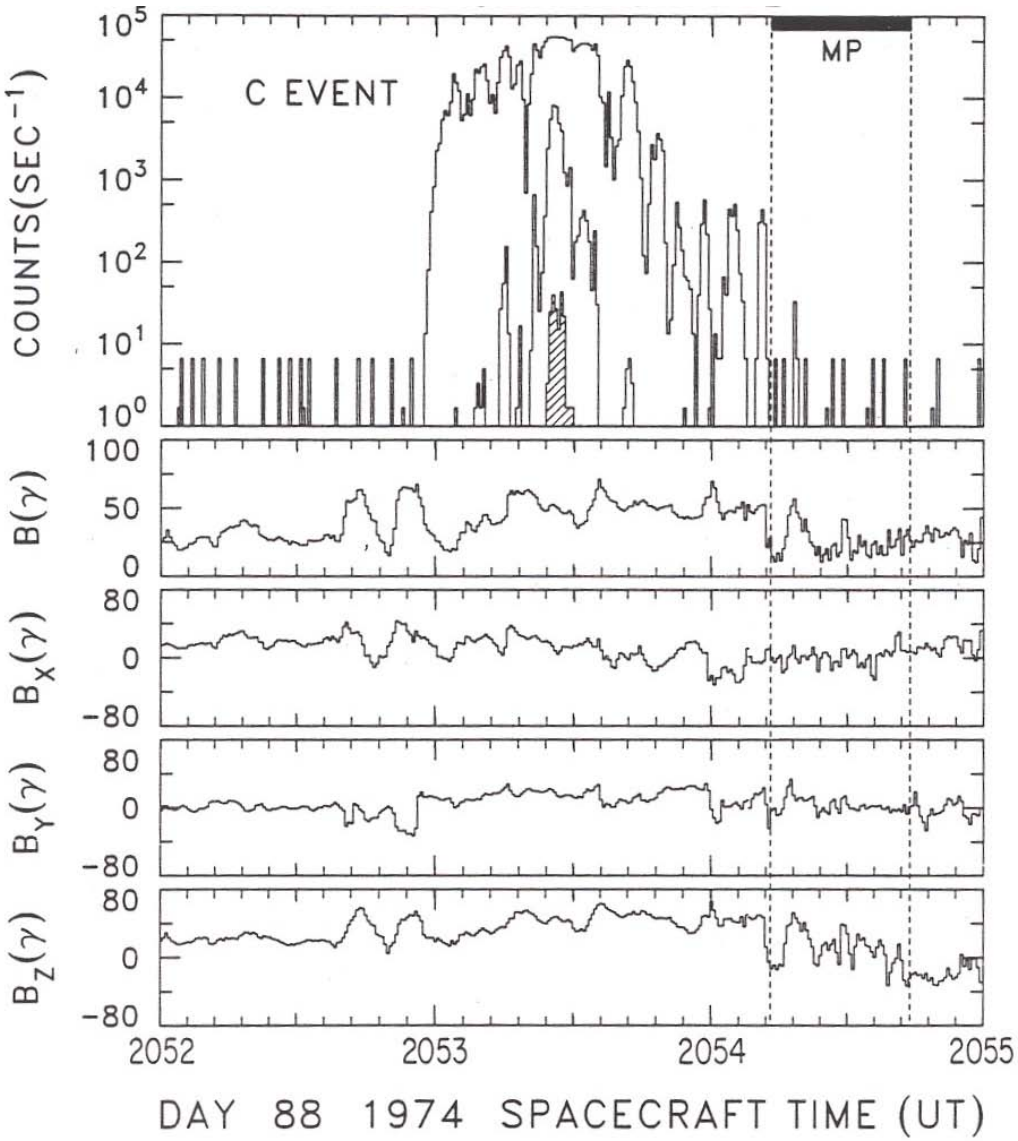


Simpson et al. [1974]

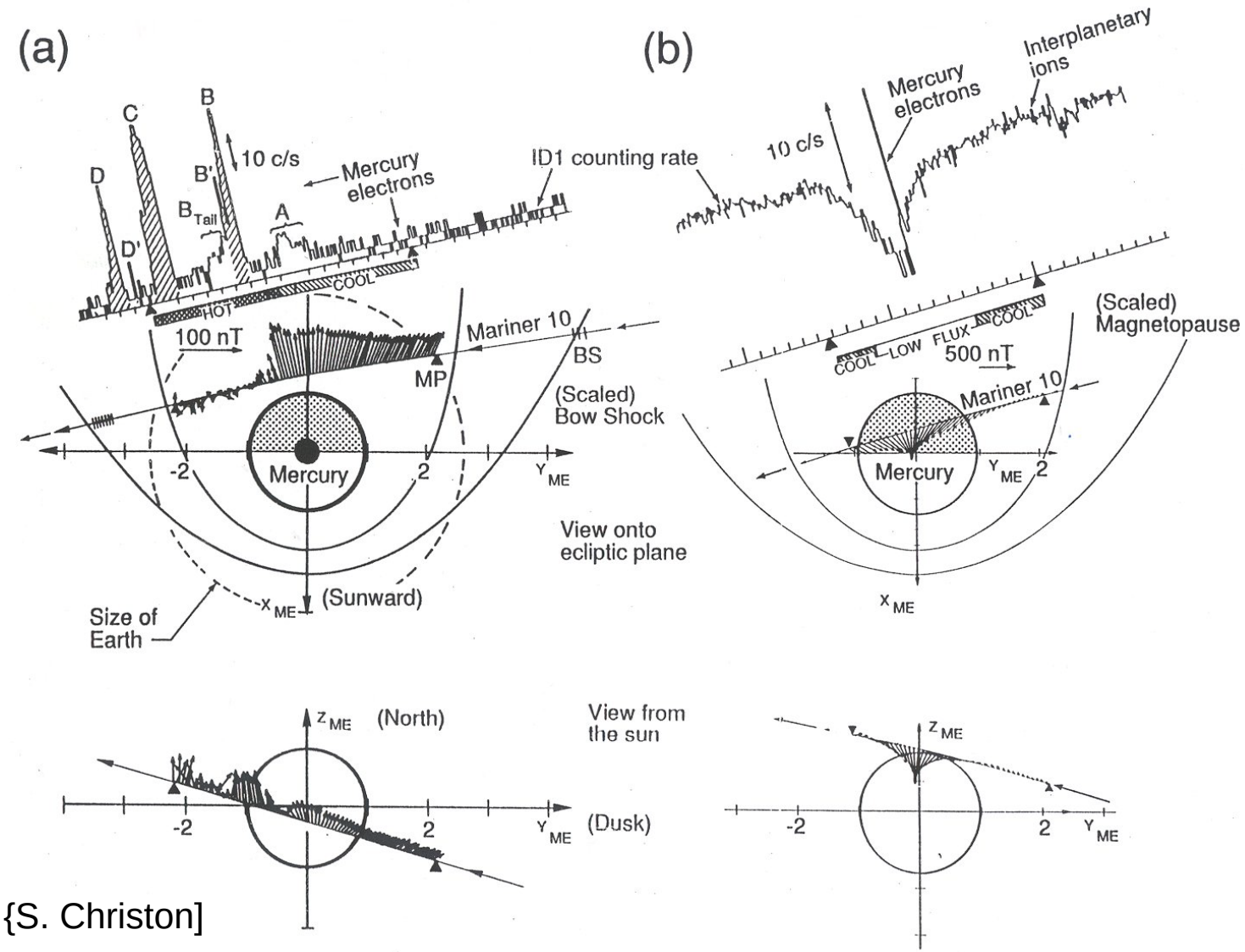
Mariner 10-Energetic Particle Bursts



Mariner 10 – Event C

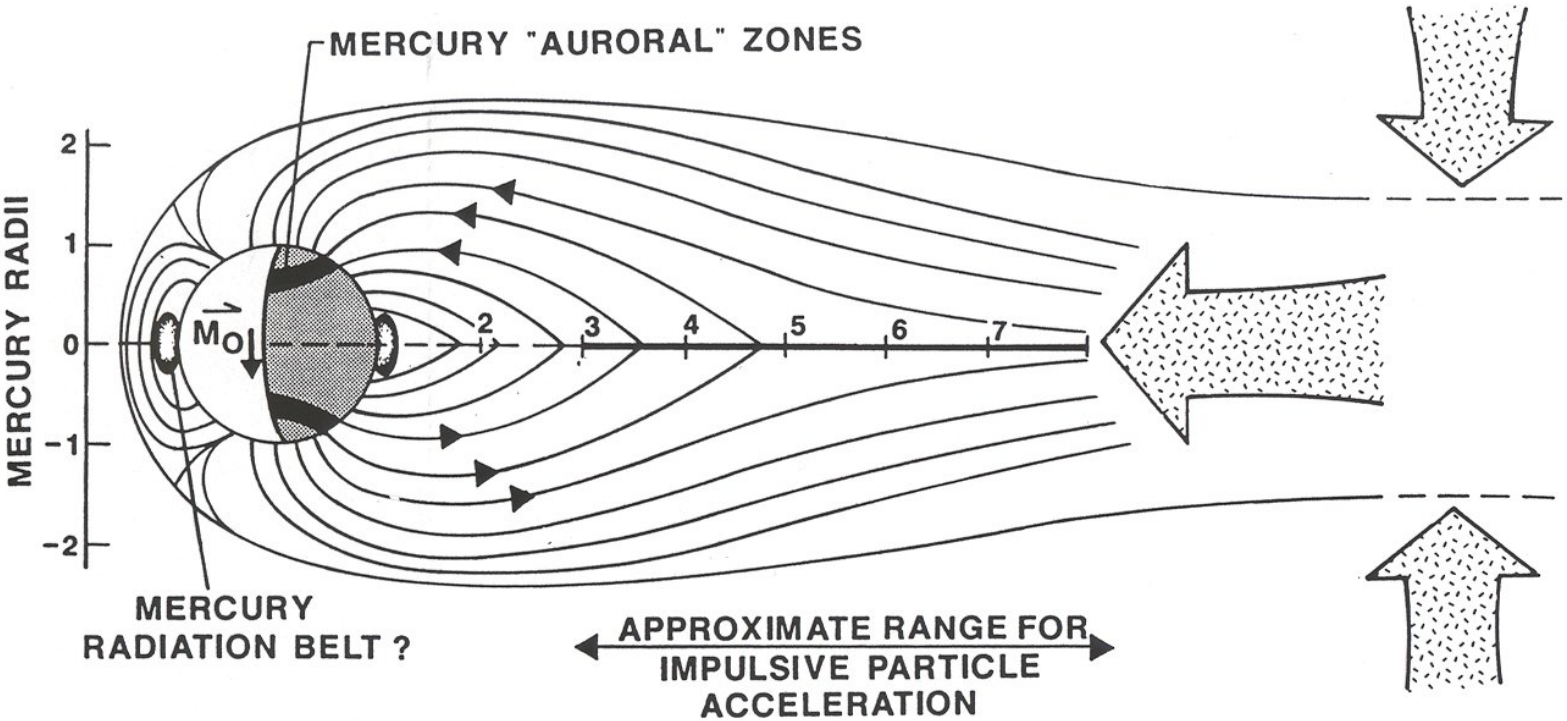


Mariner 10 Flybys I & III



{S. Christon]

Mercury Particle Acceleration

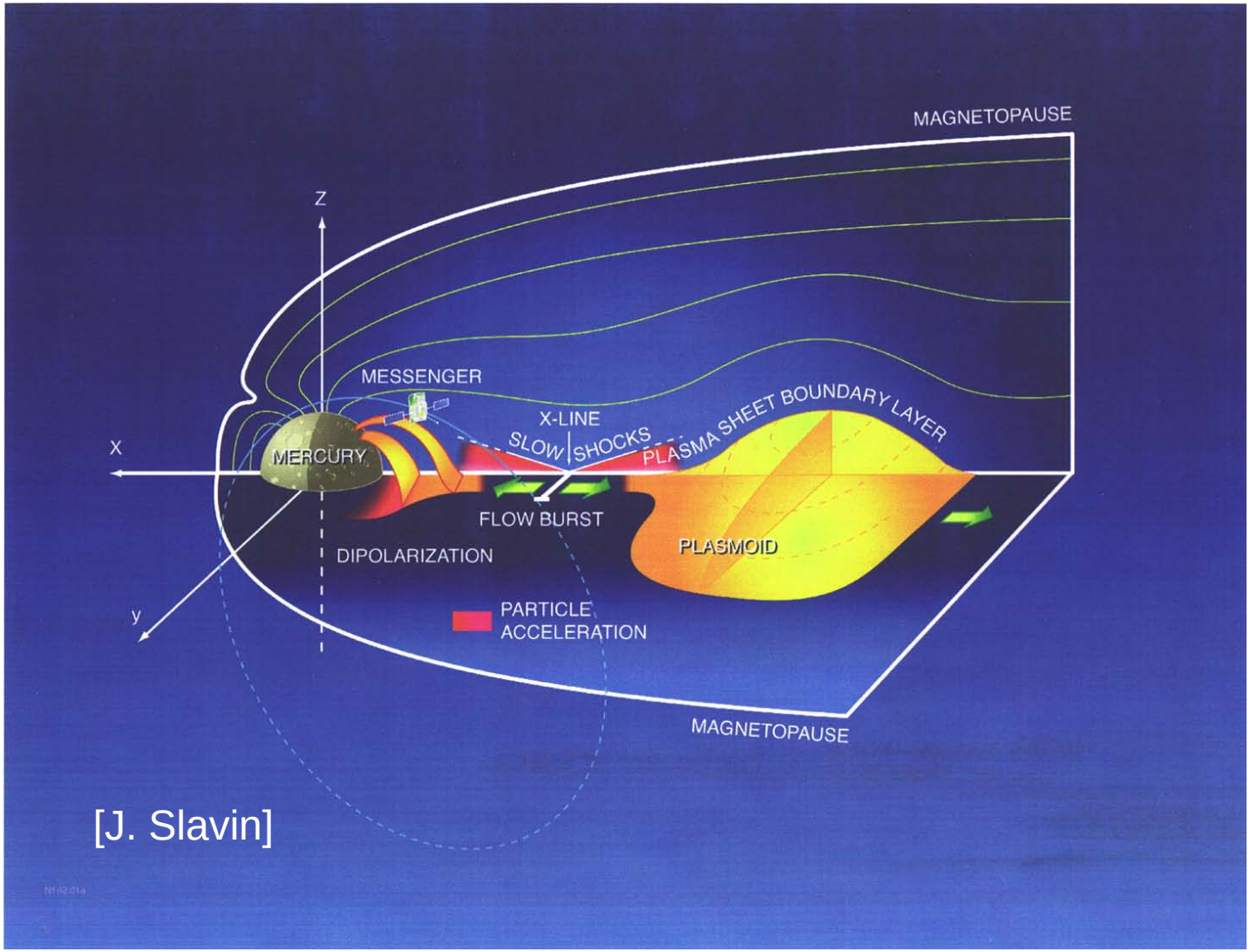


Baker et al., 1986

Magnetospheric Energy Budgets

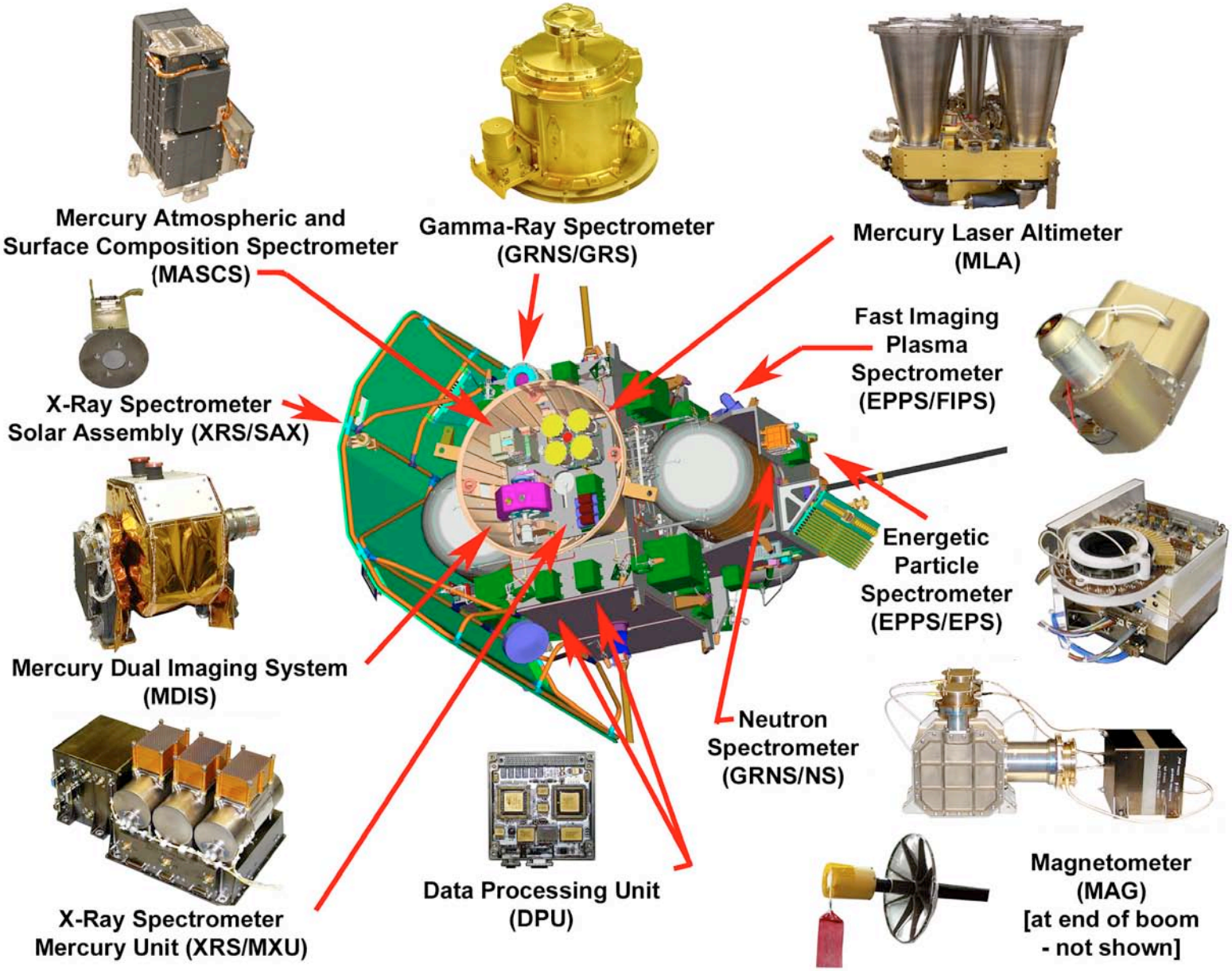
	Energy Source	Power Level
SW Input	Kinetic Energy Flux	10^{11}-10^{13} W
	Electromagnetic Coupling	10^{9}-10^{12} W
Substorm Dissipation	Earth-Scaling [Siscoe, 1975]	10^{9}-10^{10} W
	Particle Bursts [Eraker, 1986]	10^{11}-10^{14} W
	Auroral Bands [Baker, 1987]	10^{-5}-10^{-3} W/cm^2

Magnetospheric Substorm Model

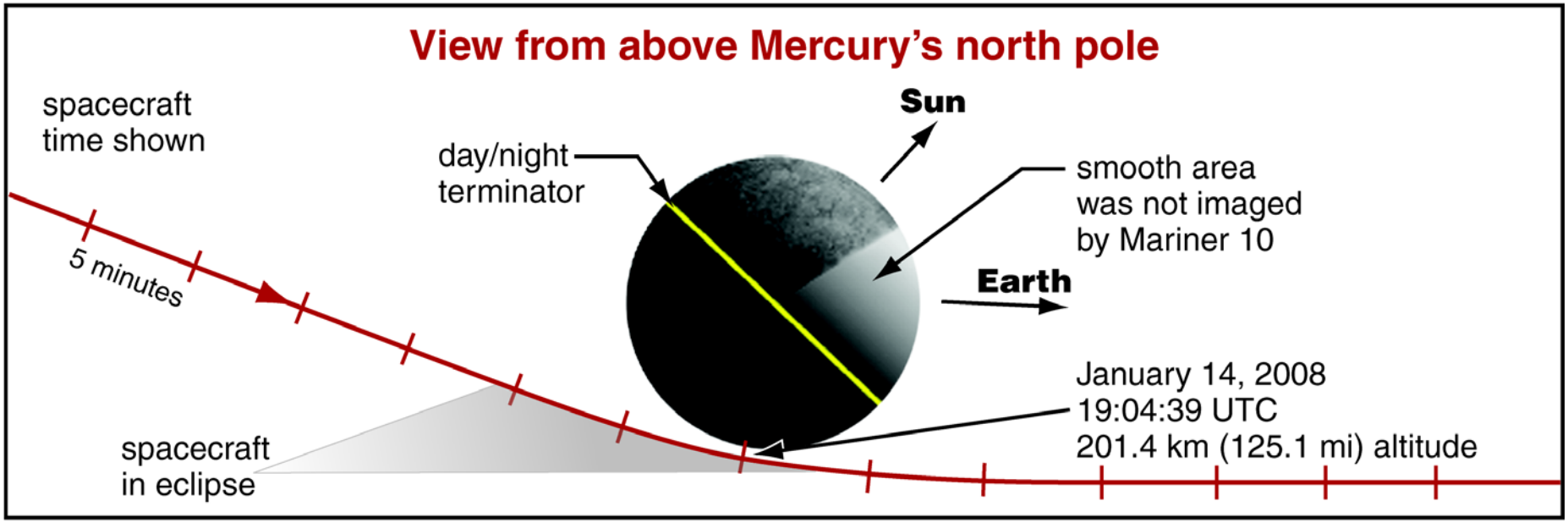


[J. Slavin]

MESSENGER: Comprehensive Payload

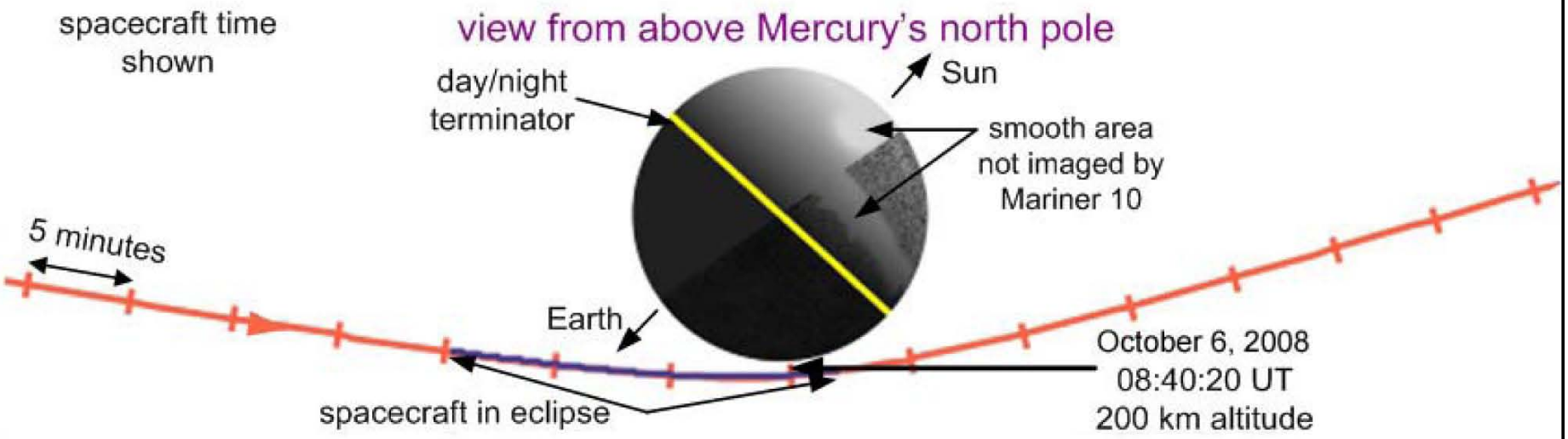


Flyby 1 Geometry



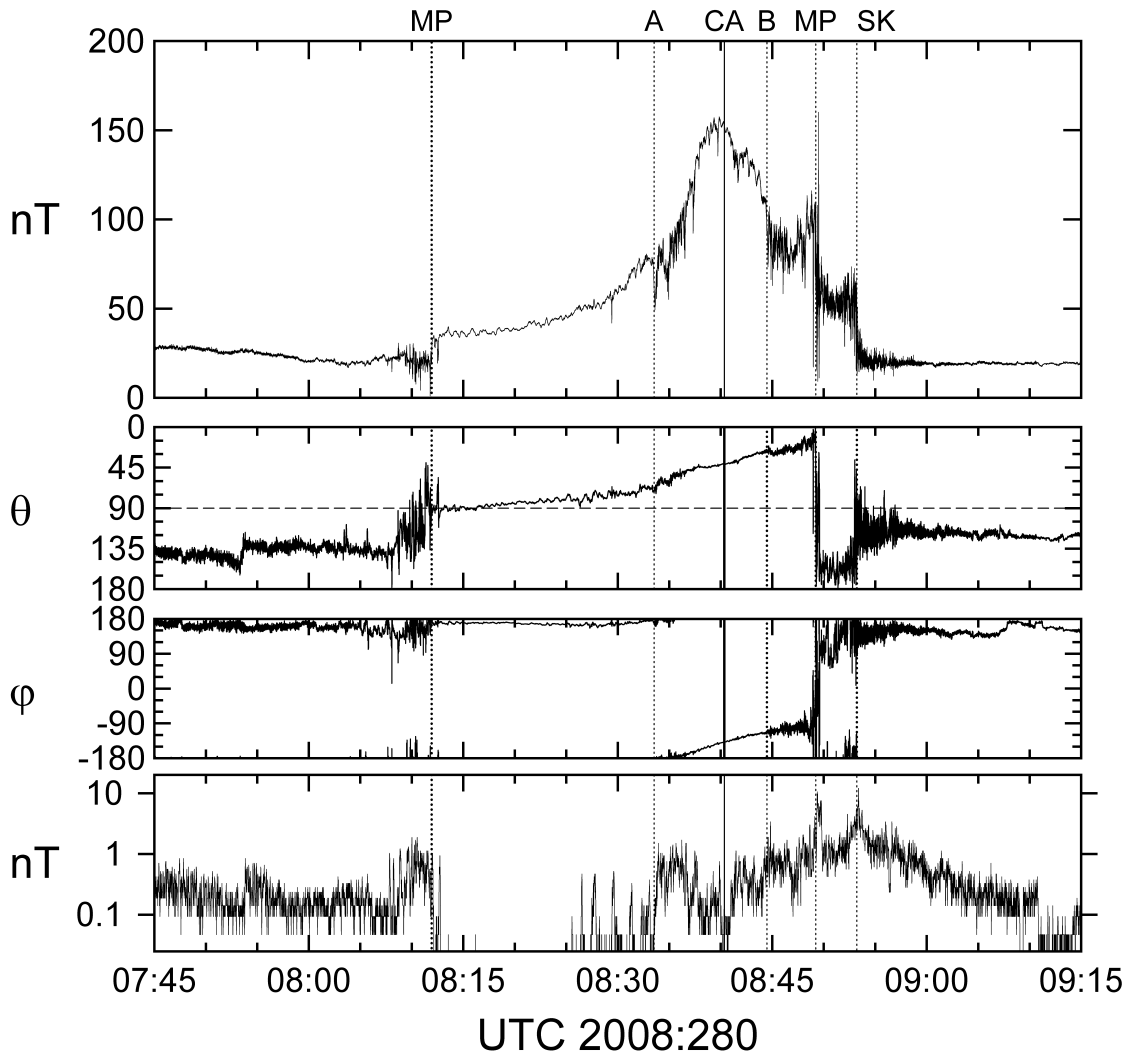
M1: Plasma and Fields

Flyby 2 Geometry

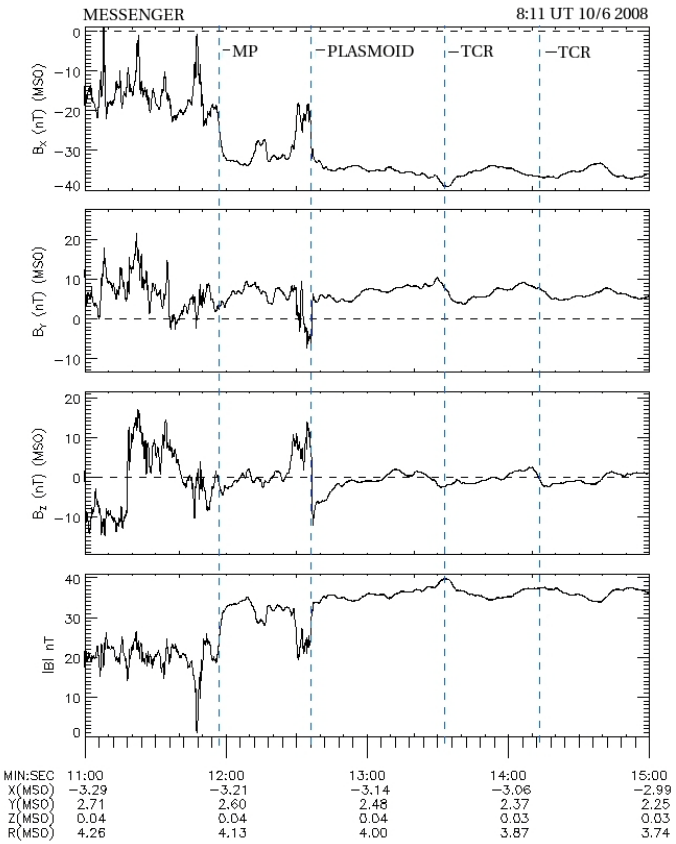


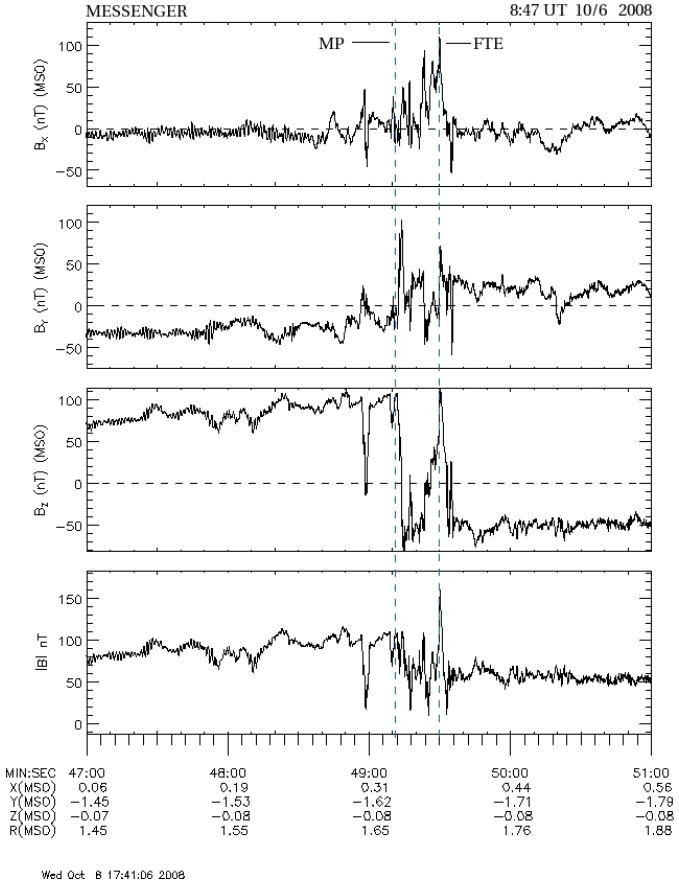
View of the second Mercury flyby trajectory from above the planet's northern pole. The yellow line marks the position of the day/night or dawn/dusk terminator. Closest approach time listed is in local spacecraft time, not accounting for the one-way light time for the signals to reach the Earth.

M2 Magnetic Field Overview



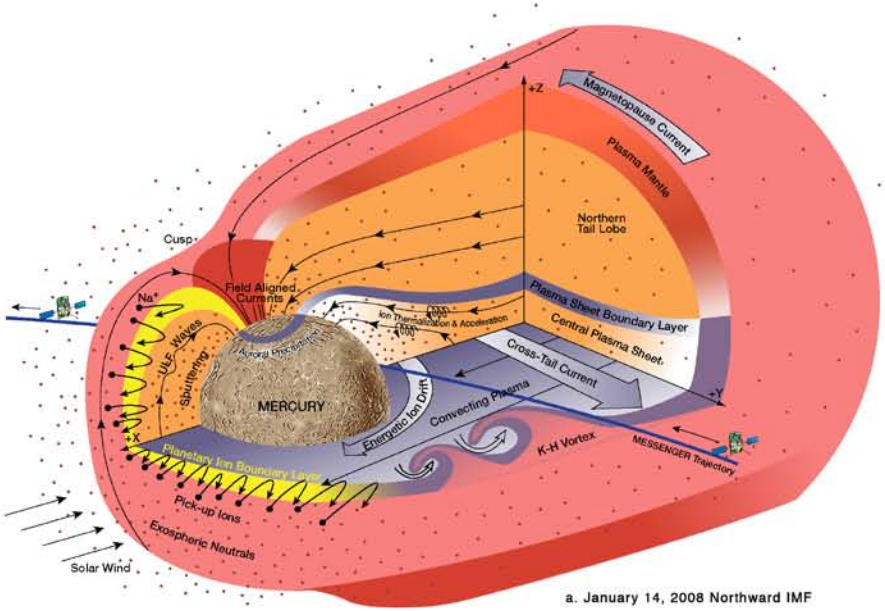
Plasmoids and Magnetic Flux Ropes



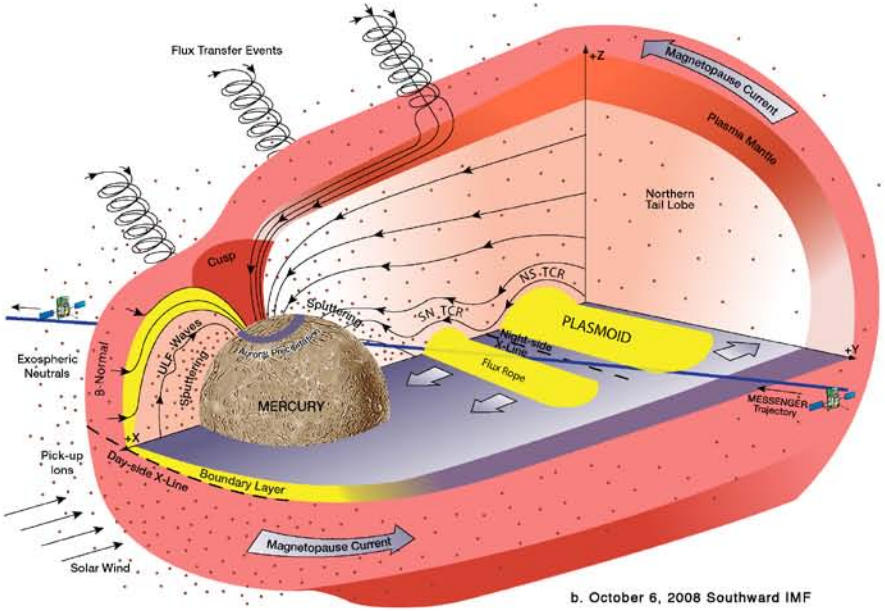


MESSENGER observed Strong *Dayside & Nightside* Reconnection Signatures

Mercury's Magnetosphere Post-Flyby View



a. January 14, 2008 Northward IMF



b. October 6, 2008 Southward IMF

Northward IMF

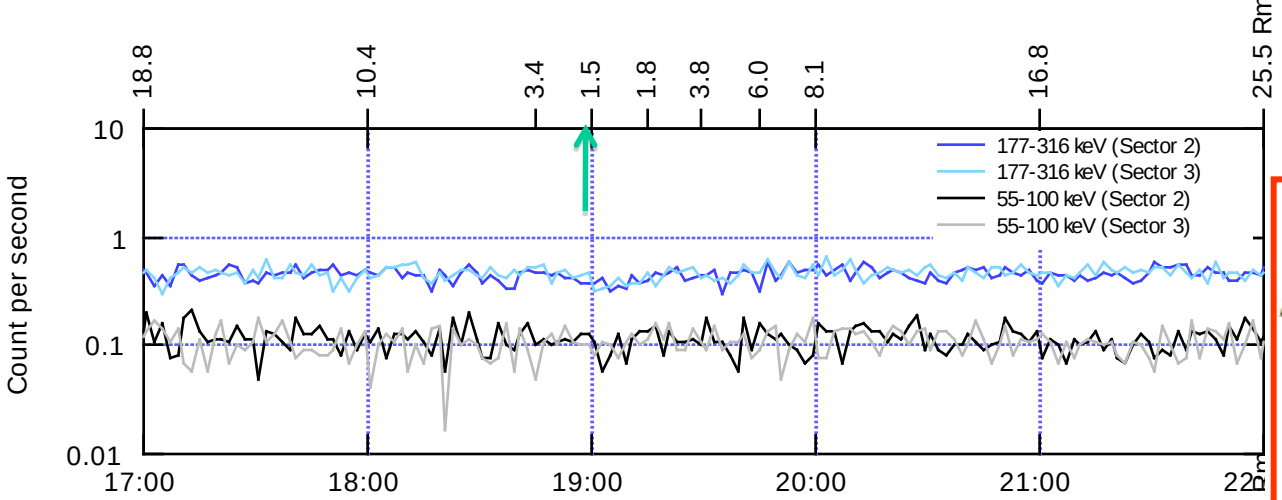
- Magnetopause Boundary Layer
- Kelvin-Helmholtz Waves on Flanks

[Slavin et al., 2009, 2010]

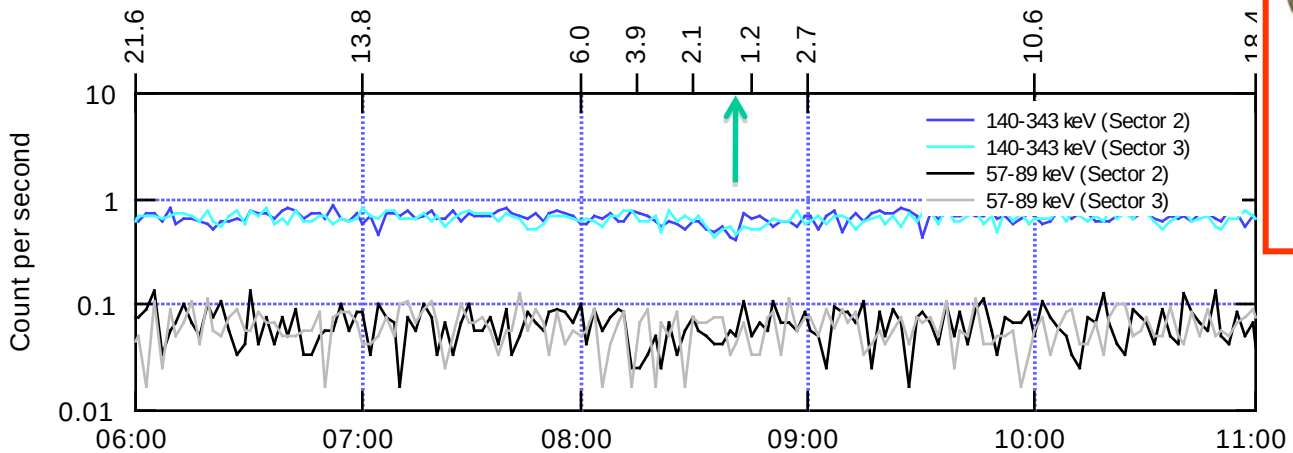
Southward IMF

- Magnetopause B-normal is ~ 10 times Earth values; Dungey Cycle Time is ~ 2 min;
- Large Flux Transfer Event when IMF $B_z < 0$
- Plasmoid and TCRs imply NMNL X ~ -2.6 R_M

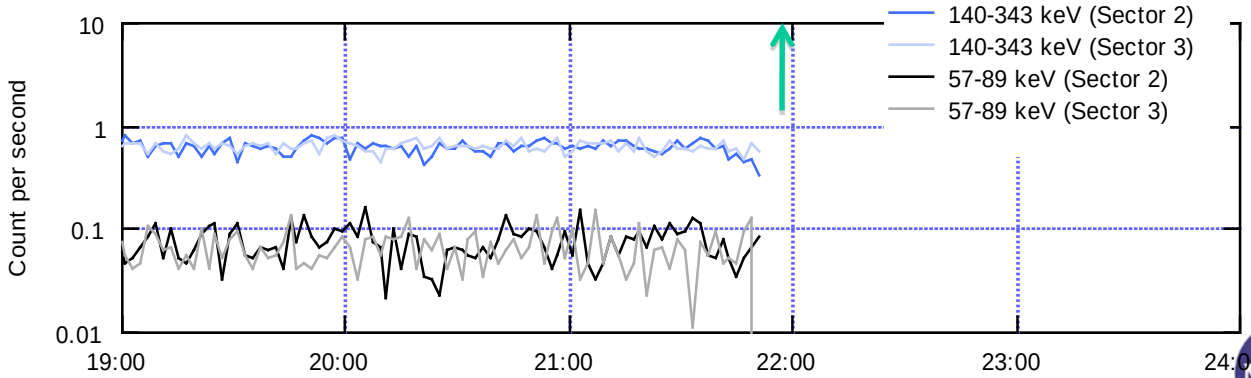
M1
1/14/2008



M2
10/6/2008

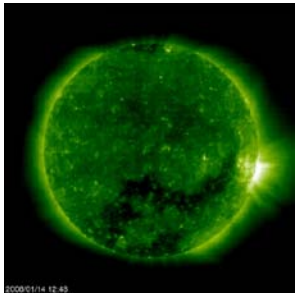


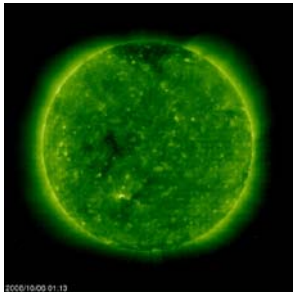
M3
9/29/2009

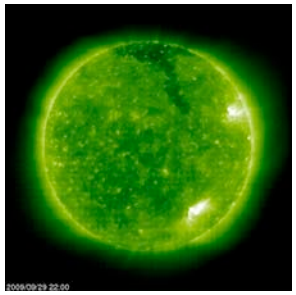


[See G. Ho et al., PSS, 2010]

MESSENGER Encounters: Deep Solar Minimum



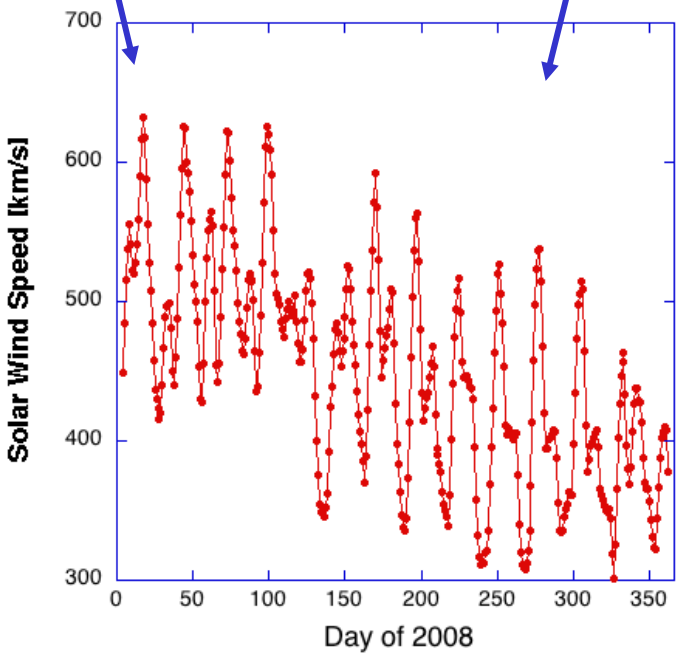


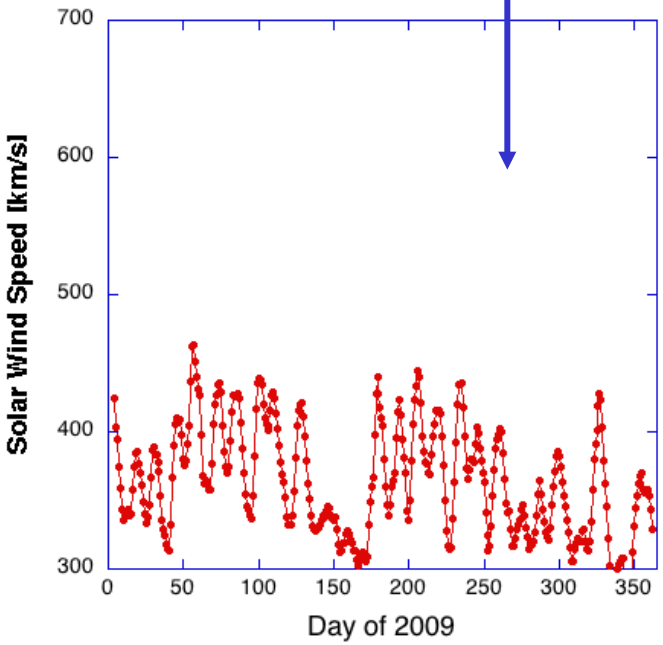


M1

M2

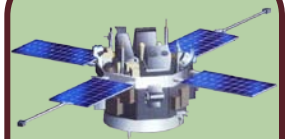
M3





Real-Time Solar Wind Forecast Model

Daily synoptic maps



Real-time Solar Wind Data

Real-time Inputs

WSA

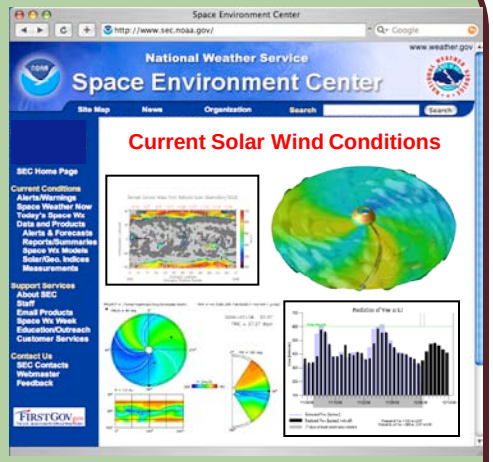
- Pre-processing of synoptic maps
- Potential field source surface (PFSS) + Heliospheric current sheet (HCS)
- Mapping to ENLIL inner boundary or L_1

ENLIL

- Generation of inner boundary from WSA
- Propagation of SW structures with MHD code in heliosphere
- Post-processing of simulation for L_1 prediction

AR Linear filter to predict SW speed at L_1 → **V** Validation of SW parameters at L_1

Coupled Coronal Heliospheric model (WSA 1.5-ENLIL 2.5)



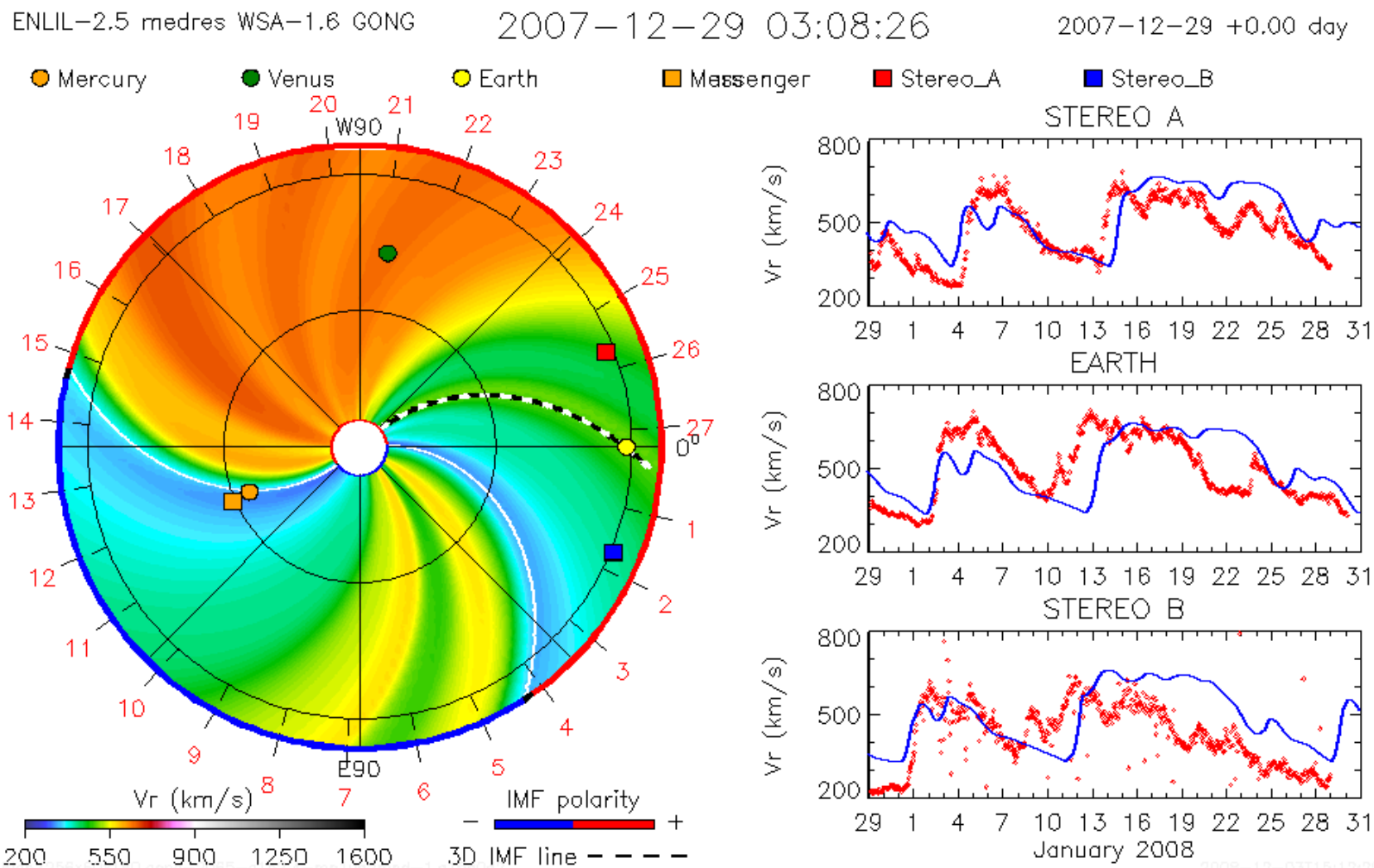
Space Weather Forecast (SWPC)

Output Products, User Benefits

LASP

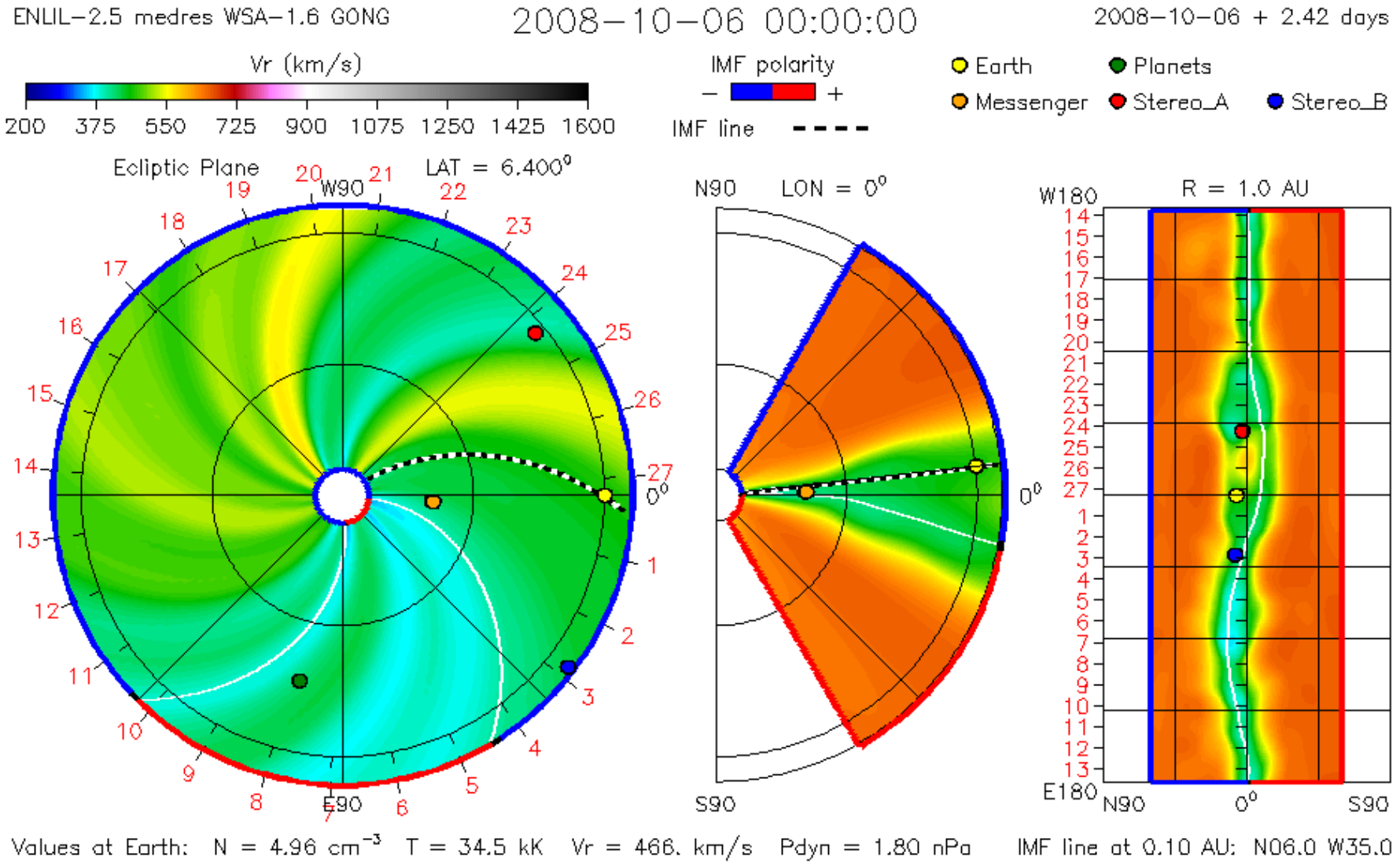
NASA

M1 Model Comparison: STEREO & ACE



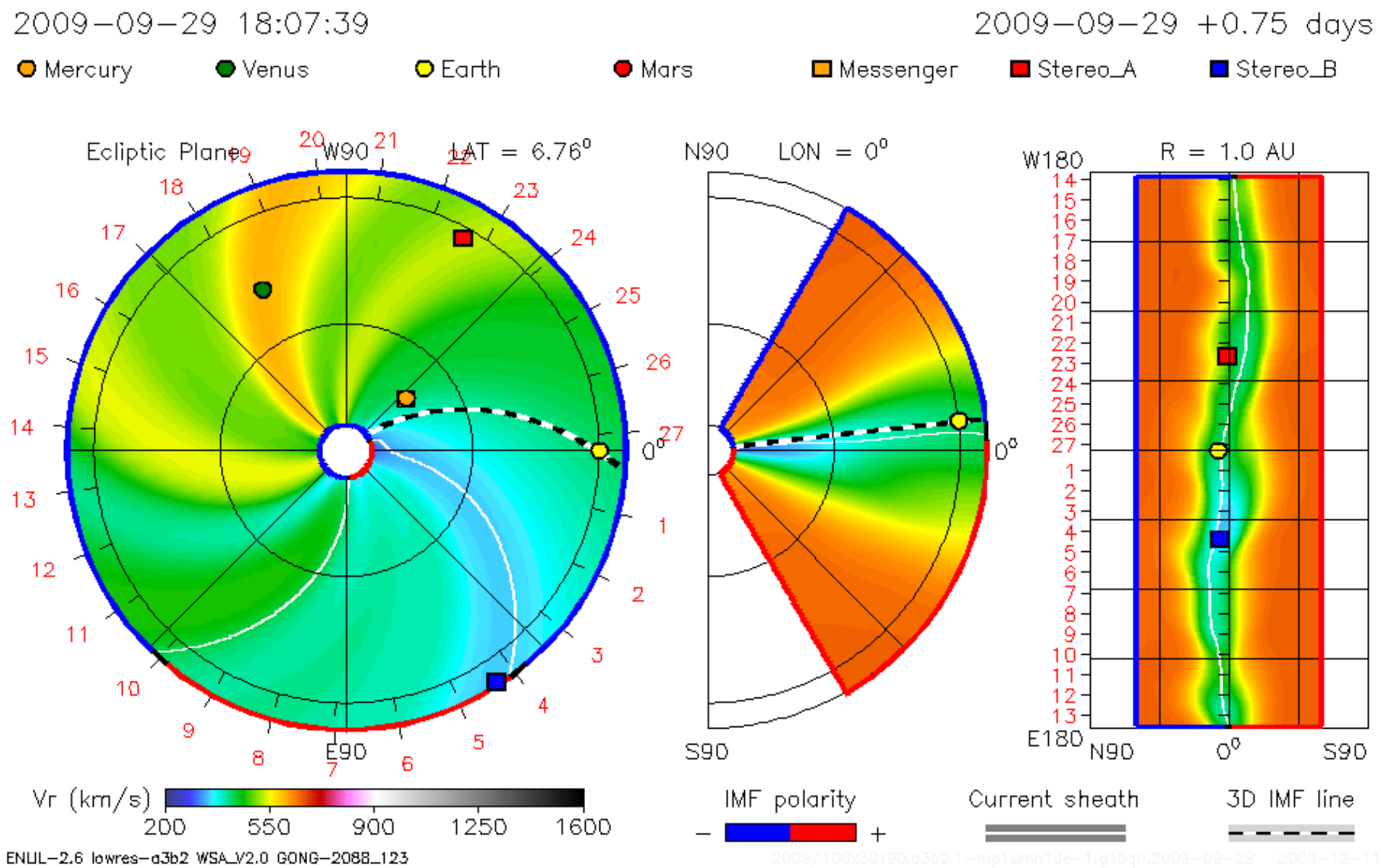
[Baker et al., JGR, 2009]

M2 Encounter Snapshot

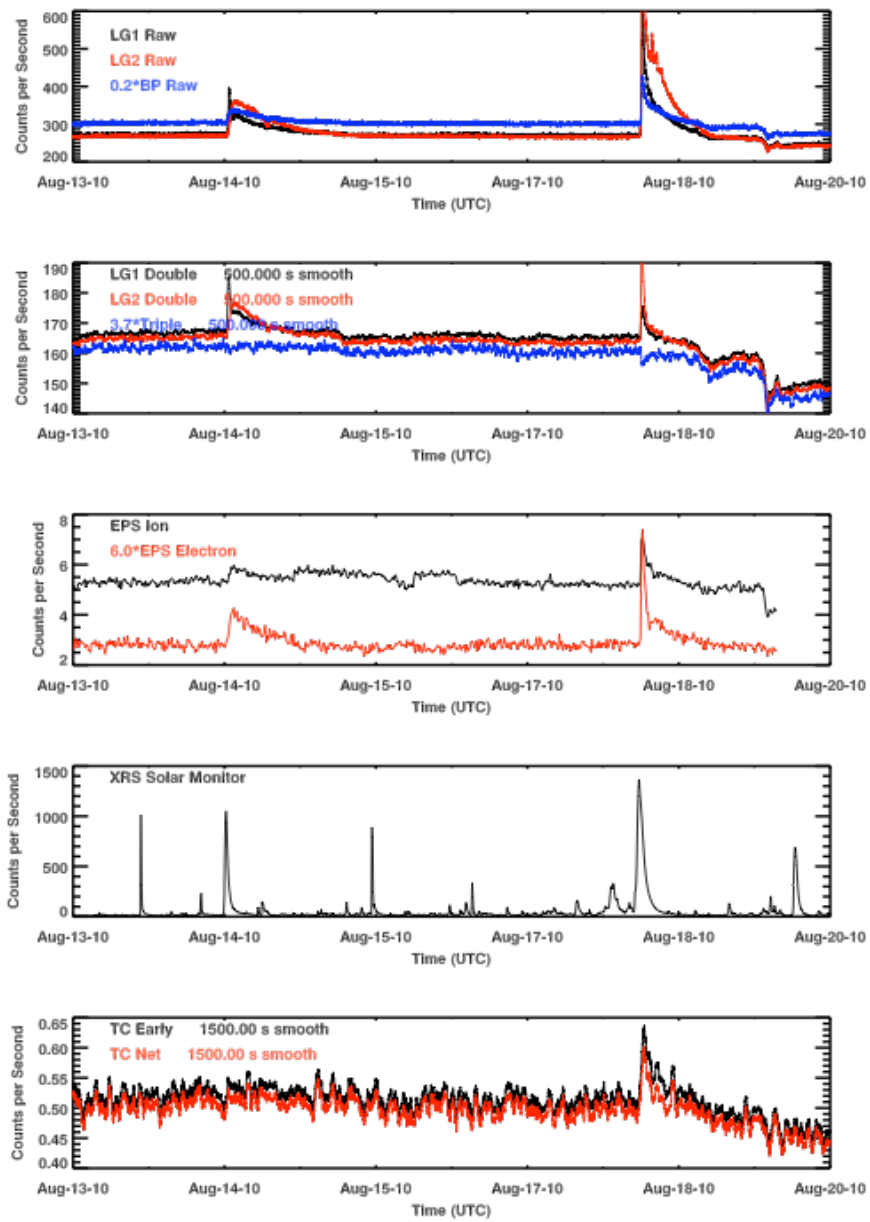


[Baker et al., PSS, 2010]

M3 Encounter Snapshot

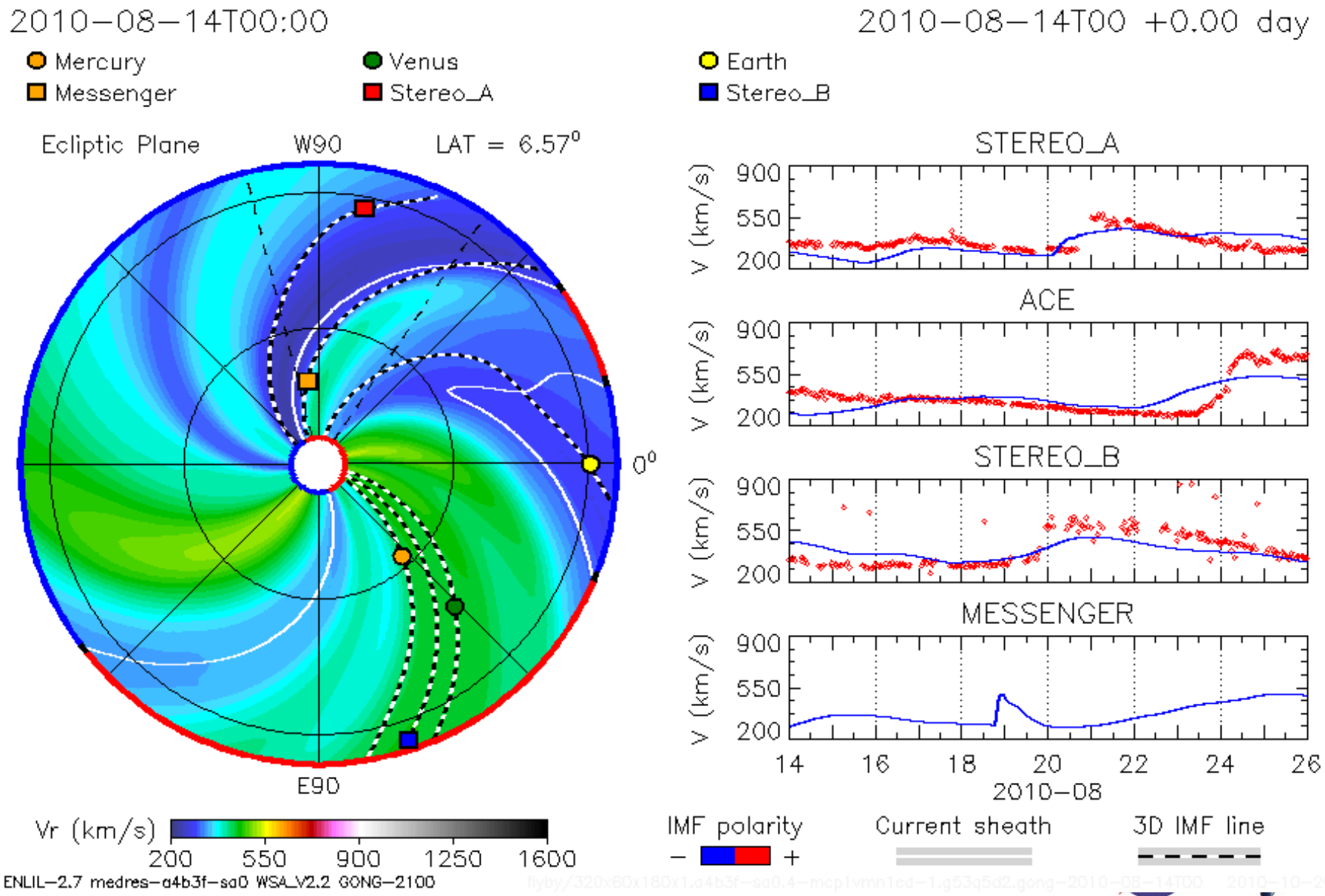


Flare and Particle Events – August 2010



CME-driven activity
In recent times from
the reawakening Sun

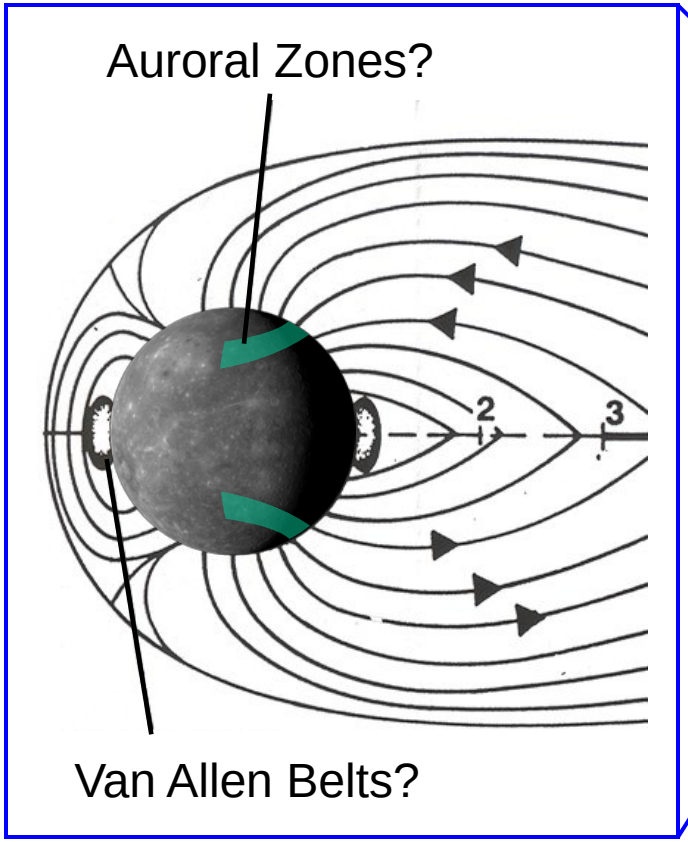
August 2010 - Animation



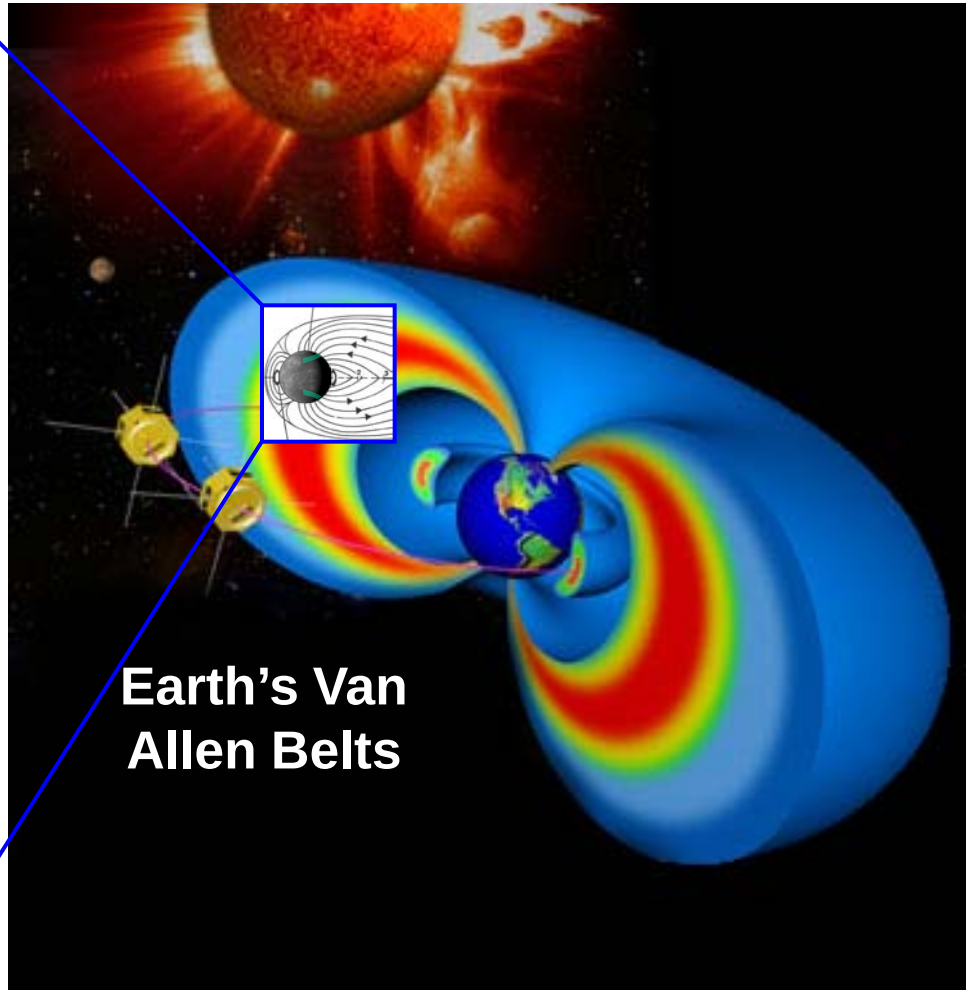
Mercury’s Tenuous Atmosphere

[W. McClintock et al.]

Comparing Earth and Mercury



[Adapted from Baker et al., 1986]



Summary

- Since the Mariner 10 flybys of Mercury in the 1970s we have believed that magnetospheric substorms were an essential dynamical feature of the system.
- MESSENGER's instruments operated well during the first two flybys of Mercury and obtained further data sequences during the third Mercury flyby on 29 September 2009. M3 flyby had operational anomaly and missed some desired data.
- The M2 and M3 passages occurred during more active magnetospheric conditions than for M1: Much evidence of substorm-like behavior and substantial surface interactions.
- Through all of this there have been no detections of the kinds of field dipolarizations with energetic particle bursts we had expected to see!?
- Orbit insertion in 2011 should provide a whole new perspective on Mercury substorms