Do Mercury's Dipolarization Fronts Originate From Flux Ropes? MHD-AEPIC Simulations of Mercury's Magnetosphere

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Mercury's Magnetosphere

Mercury has the most comparable magnetosphere to Earth, as both are rocky planets with externally-driven dipole fields. However, they also have significant differences:

- Weaker field ($\sim 1\%$ of Earth), resulting in comparably large ion kinetic scales
- Large conductive core and insulating crust but no ionosphere
- Intense solar wind conditions with low Alfven Mach number, conducive to dayside reconnection

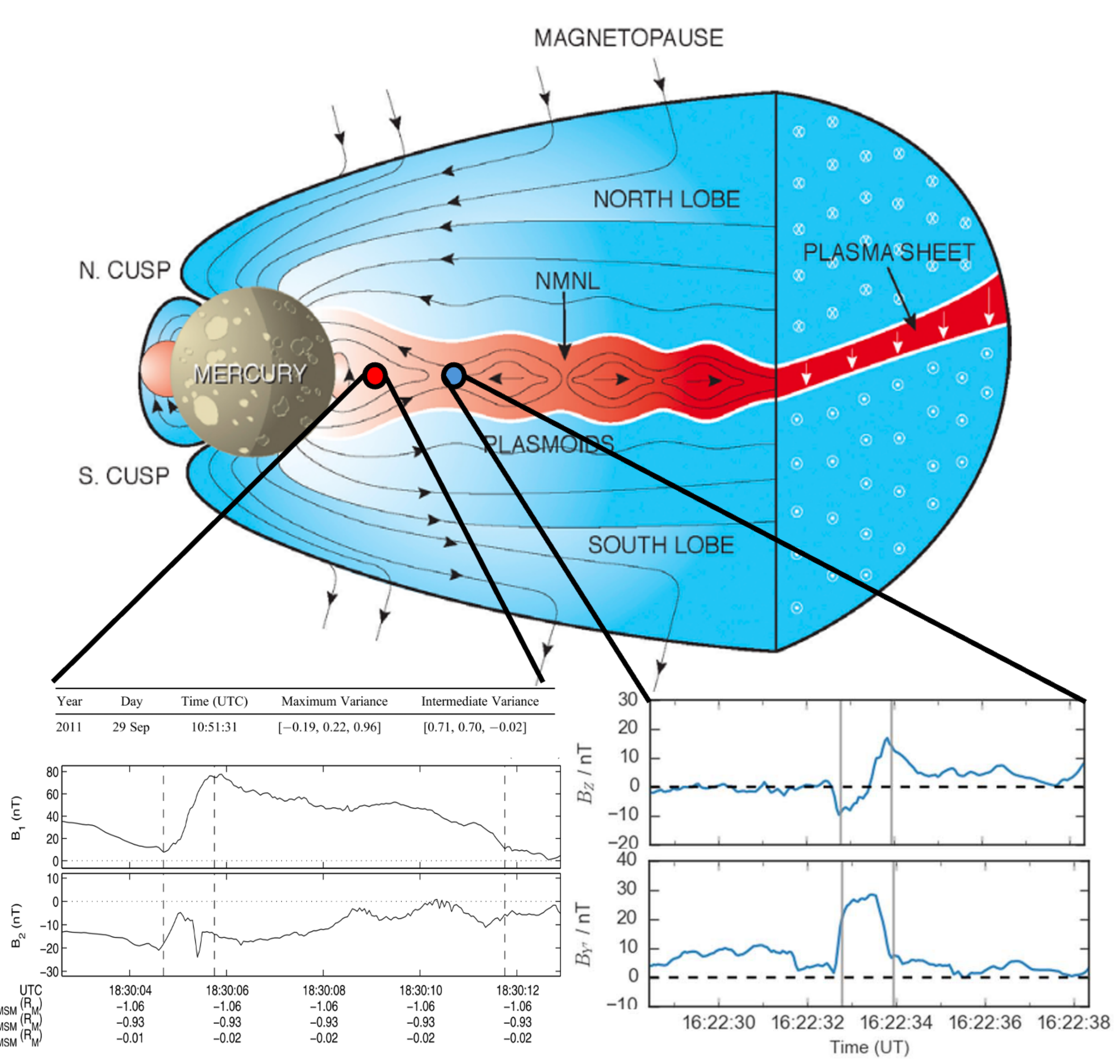

Figure 1: Top: Mercury's magnetosphere during substorm activity, from Slavin et al. 2012. Bottom: dipolarization front example from Sundberg et al. 2012, and flux rope example from Smith et al. 2017.

Reconnection products, including dipolarization fronts (DFs) and flux ropes (FRs), were frequently observed moving planetward by MESSENGER:

- DFs characterized by B_z dip followed sudden ~ 20 nT increase, fast planetward flows, and depleted (low entropy) flux tubes, electron injections
- FRs have bimodal B_z variation, B_y axial field, with pressure balance between $J \times B$ and ∇p

Are flux ropes and dipolarization fronts the same reconnection product seen at different times?

Simulation Methodology

MHD-AEPIC simulation couples global MHD magnetosphere to embedded particle-in-cell region for magnetotail. $R_M/64 \simeq 40$ km grid and $m_p/m_e = 100$ partially resolves electron scales, capturing non-ideal effects and differential motion.

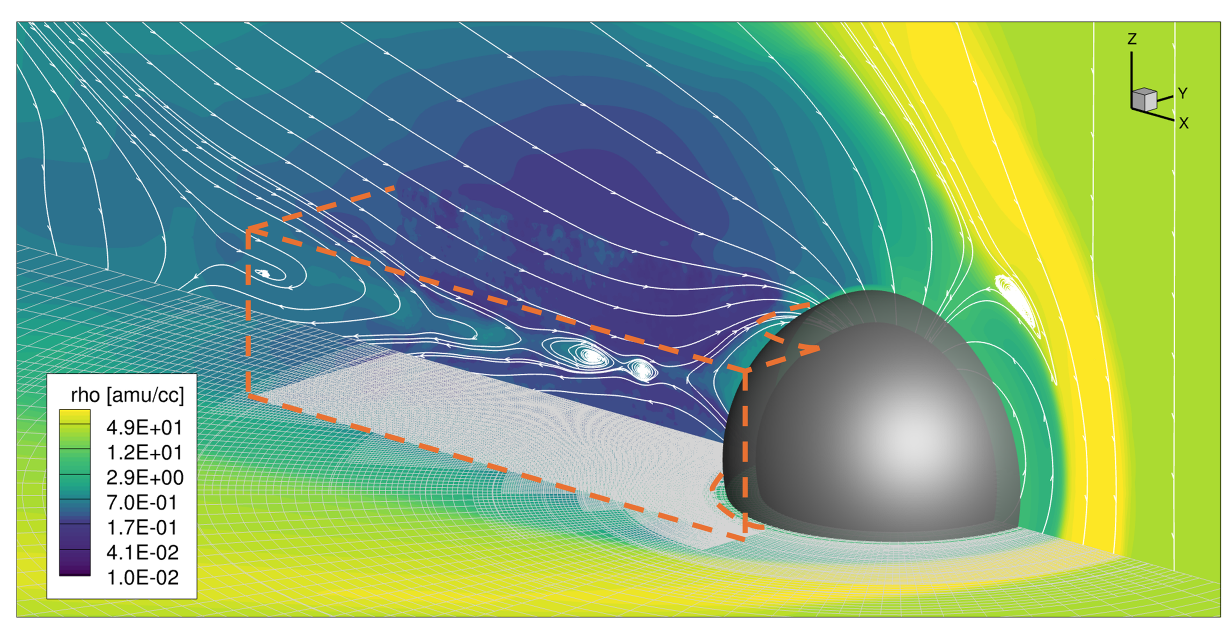

Figure 2: PIC domain (orange border) shown at time slice when flux ropes present in the magnetotail. Shading is plasma mass density.

Nominal run is ideal MHD steady-state startup, 60 s Hall-MHD, 60 s FLEKS initialization, followed by 80 s primary run used to identify examples. Fluid data from FLEKS region saved at 0.05 s cadence. Run 1 is $B_{IMF} = 23\hat{y}$ nT, Run 2 is $B_{IMF} = -23\hat{z}$ nT.

n [amu/cc]	T [K]	V_x [km/s]	$\lvert B_{IMF}\rvert$ [nT]
36.0	87,000	-500	23

Figure 3: Upstream boundary conditions for both simulation runs.

35 DFs are identified from timeseries taken along $X = -1.5R_M$, using automated algorithm from Dewey+ 2020. DF point cloud is propagated forward and backward in time to categorize origin of flow associated with dipolarization signature.

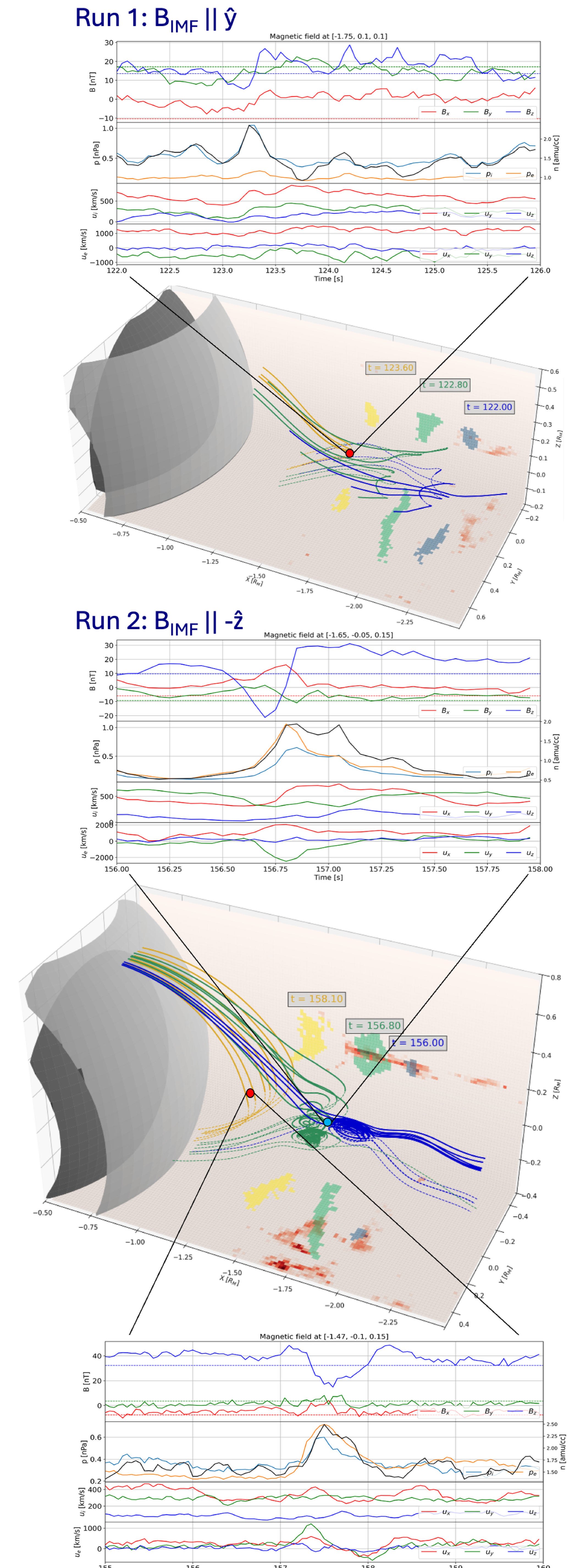

Figure 4: Example of flux ropes evolving into DF from both run. Blue, green, yellow shading and lines represent early to later times. Red shading in diagrams shows reconnection score at earliest time from Li et al. (2023) Extracted timeseries show $\vec{B}, p, \vec{v}$ at given point.

Flux ropes drift dawnward, re-reconnect with dipole field, and further energize electrons

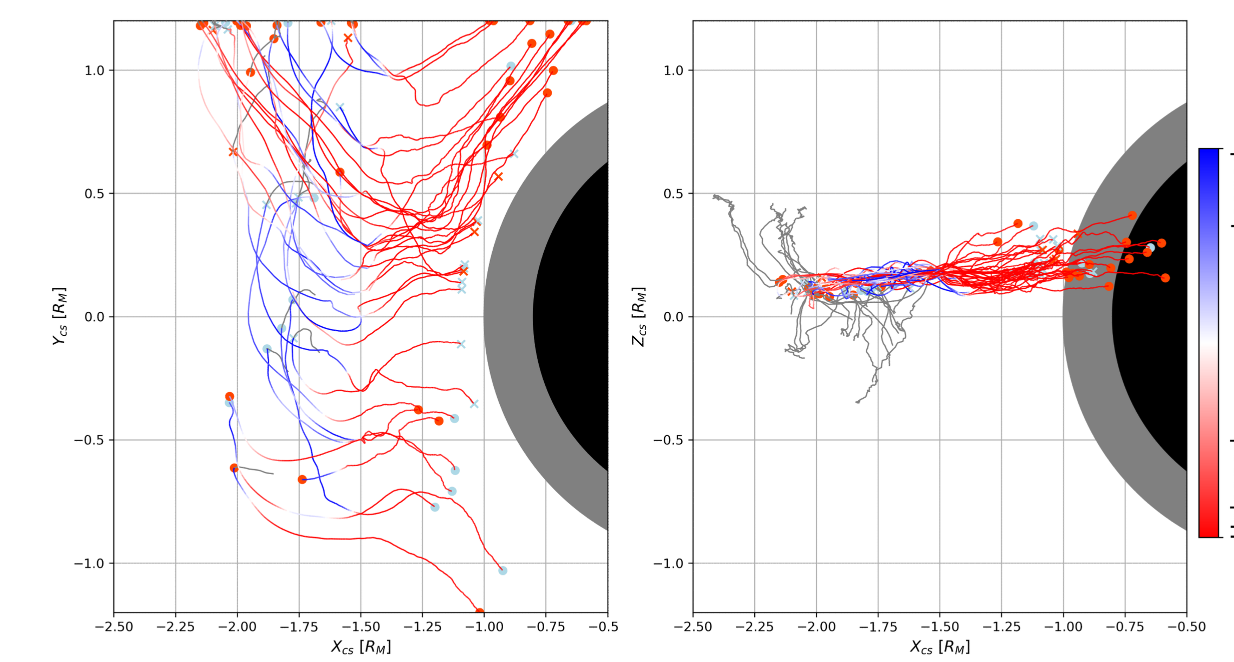

Figure 5: XY and XZ planes, showing trajectory and topology of tracked DF point clouds.

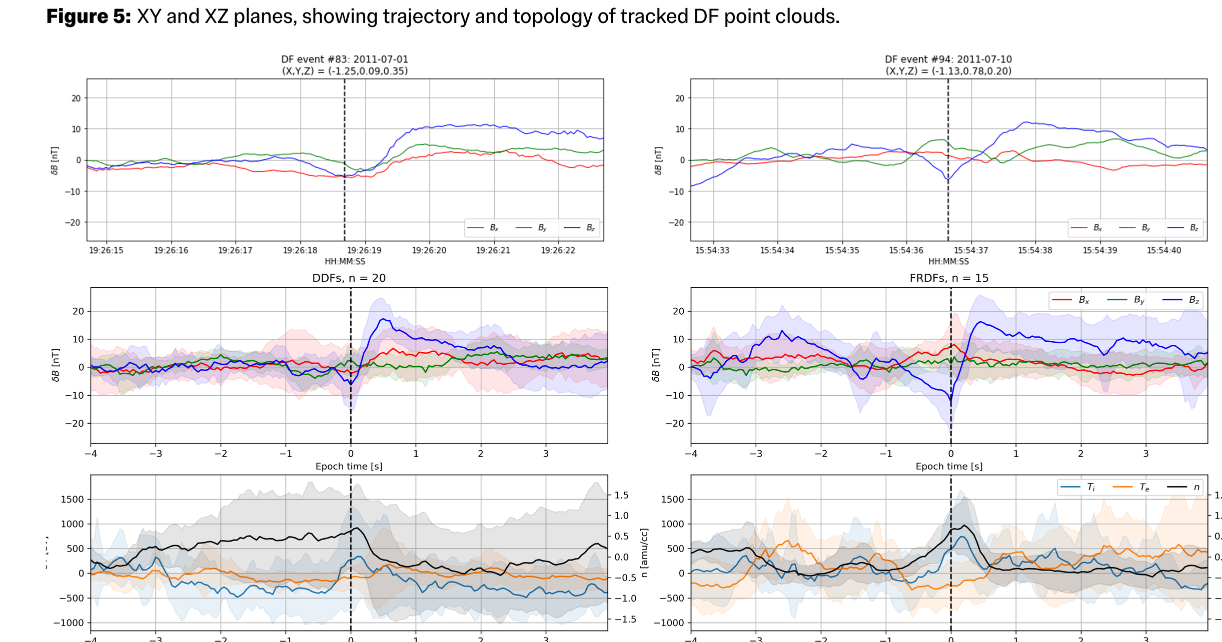

Figure 6: 2 MESSENGER events, compared to superimposed epoch averages of DDFs and FRDFs from simulation.

Key Takeways

1. Mercury forms flux ropes (or plasmoids) even when IMF has no B_y component
2. Flux rope dissipation is key formation mechanism for $\sim 50\%$ of dipolarization fronts
3. Flux rope dawnward drift leads to asymmetry in DDFs/FRDFs, and rereconnection heats electrons

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