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Magnetospheric Magnetic Field Observations and Modeling at Mercury

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Boulder, CO 2010

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Magnetic Field Observations

- The totality of our observations of Mercury's magnetic field comes from 5 flyby encounters.
- Only M10-III was out of the equatorial plane of the planet.
- All trajectories were inbound on the dusk/night flank and outbound in the dawn/morning quadrant.
- MESSENGER M3 flyby returned data only inbound in the tail.
- MESSENGER M2 flyby is the only flyby returning data through CA from the equatorial western hemisphere.

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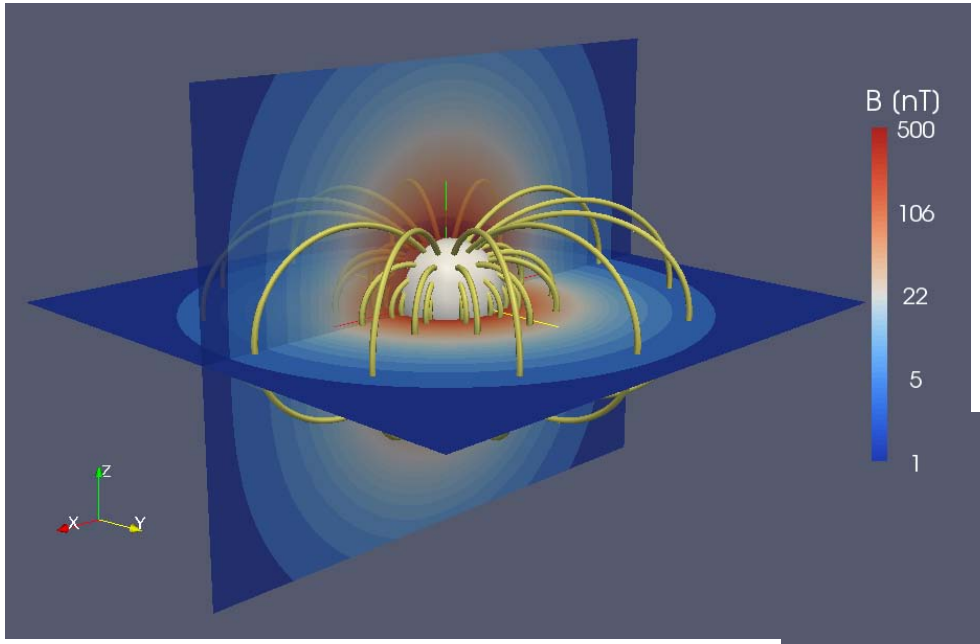
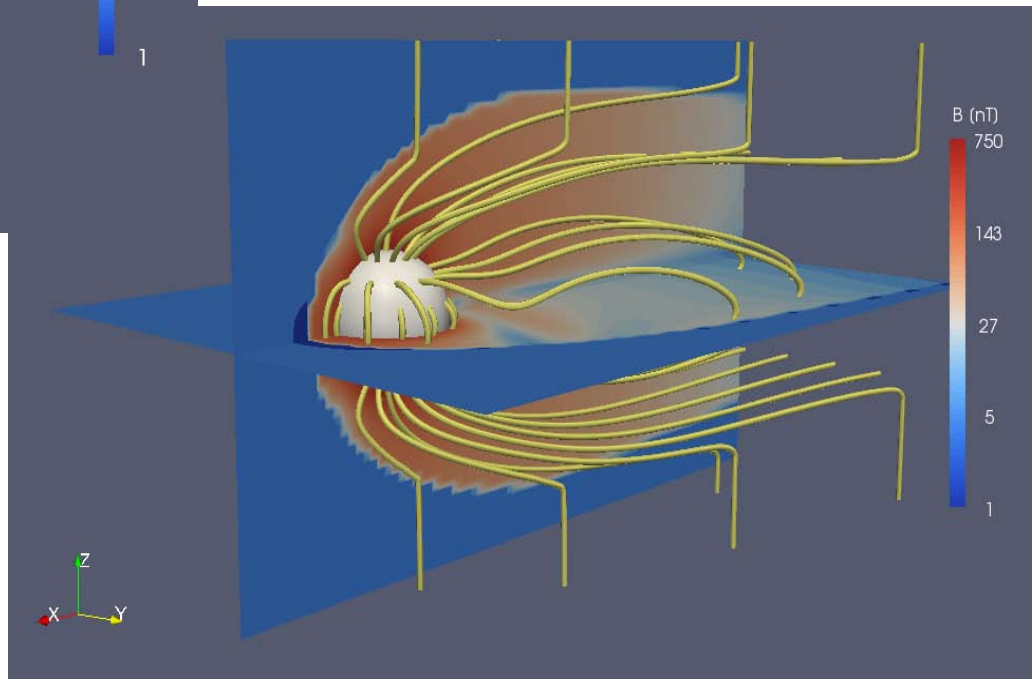
External Currents: 0th Order



Internal field: largely dipolar, aligned with spin axis

From H. Korth (2009)



Magnetic field in solar wind environment

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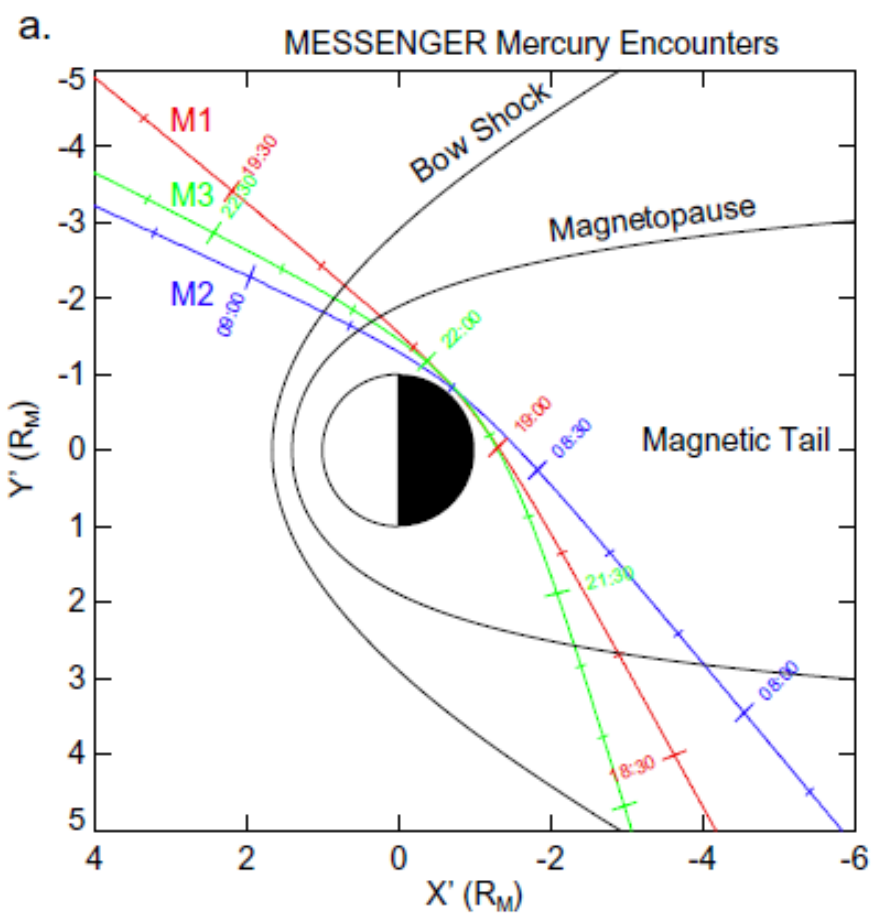
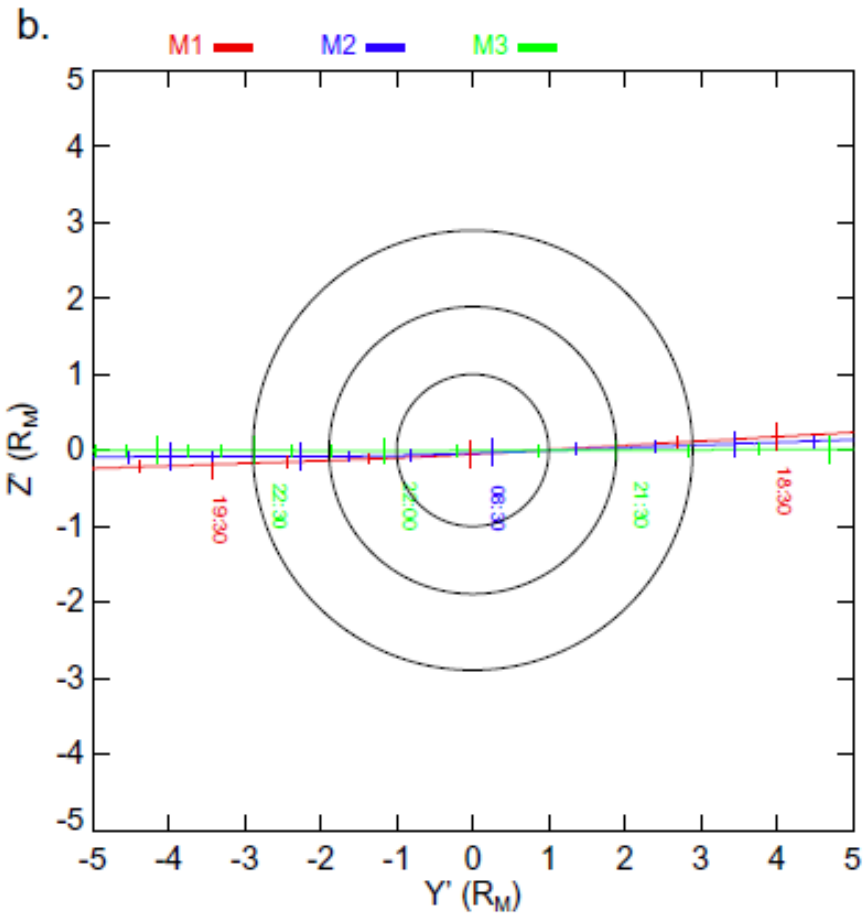
MESSENGER Mercury Flybys

MESSENGER flybys all equatorial

M3 data acquisition was only inbound





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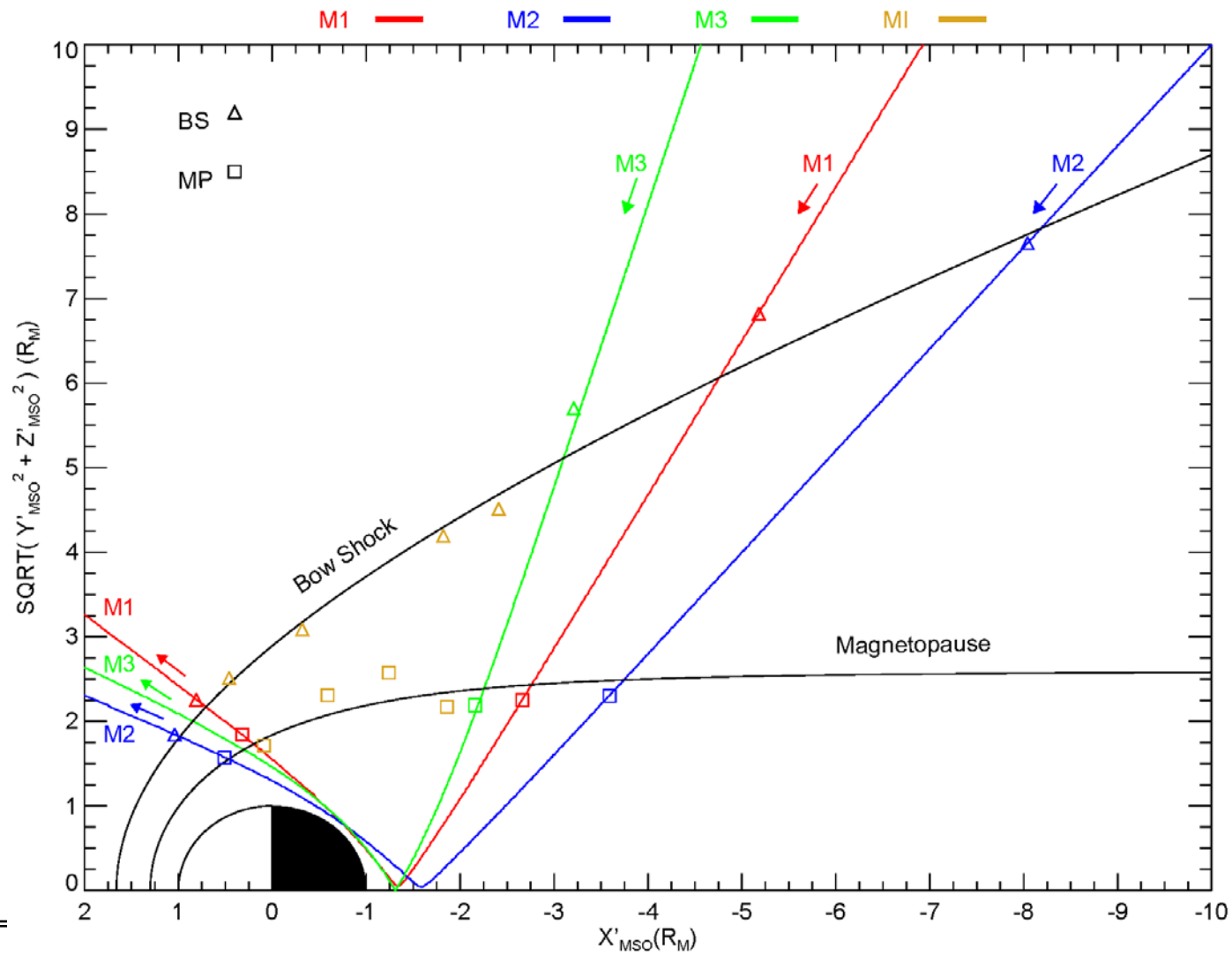
MESSENGER Mercury Flybys

Models for bow shock (▲) and magnetopause (■) locations are not too bad

Understanding the distribution and intensities of magnetospheric currents is nearly independent of knowledge of these boundary locations



Slavin et al., 2010

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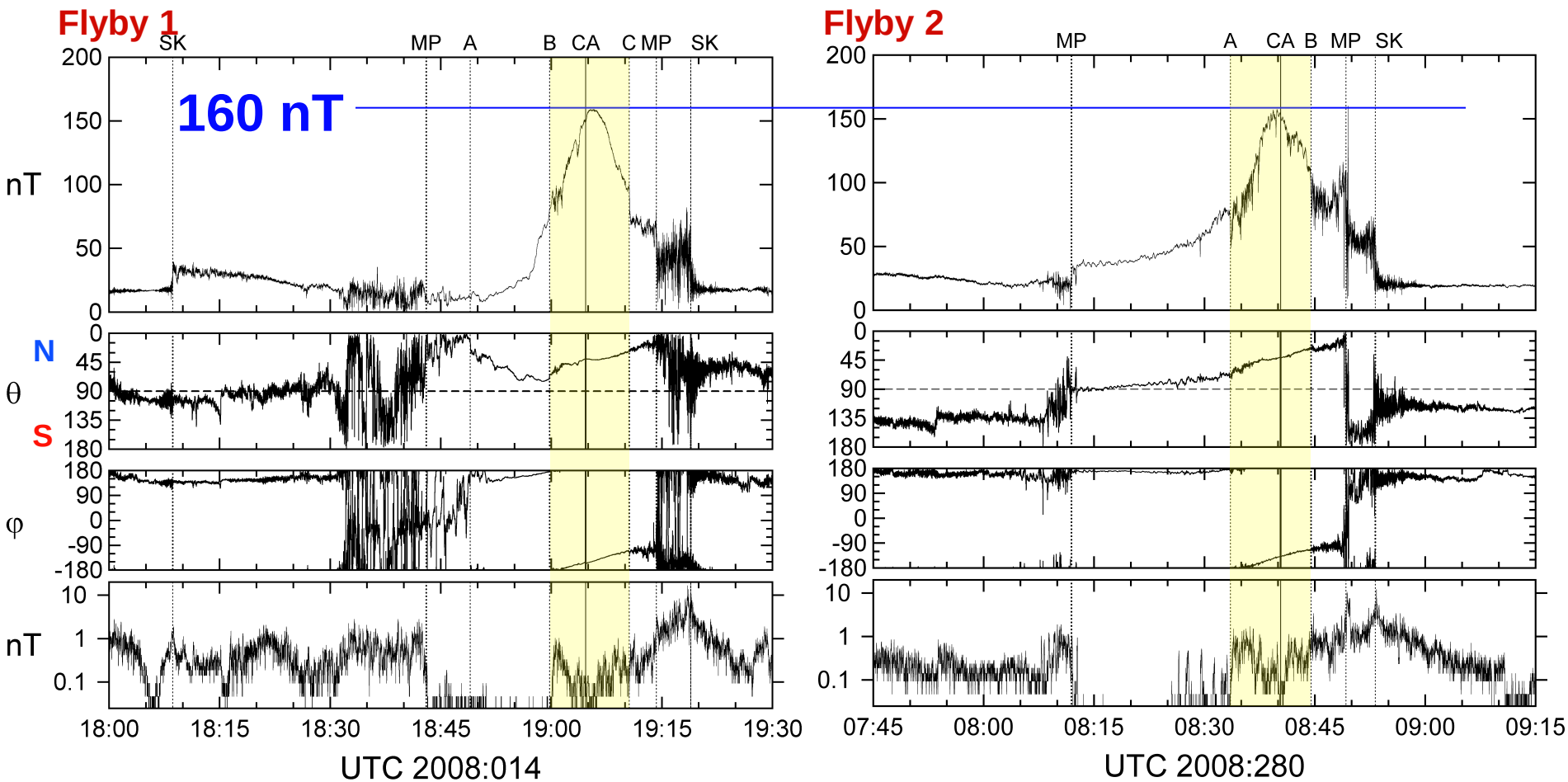
Comparison of M1 & M2

Identical field maxima at opposite longitudes: constrains dipole tilt

Signatures of internal magnetospheric processes near CA on both flybys



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Internal Field Inversions

- Discriminate against external currents by restricting data to ‘inner magnetosphere’
  - Not in obviously radial (i.e. lobe) or reduced magnitude (i.e. plasma sheet) tail field
  - Inside dayside boundary layer
- Apply various approaches for external currents and higher order terms to understand uncertainties
  - External field: (1) none; (2) SHA external field evaluation; (3) empirical external model
  - Inversion orders: (1) centered dipole; (2) quadrupole (displaced dipole), (3) regularized higher order

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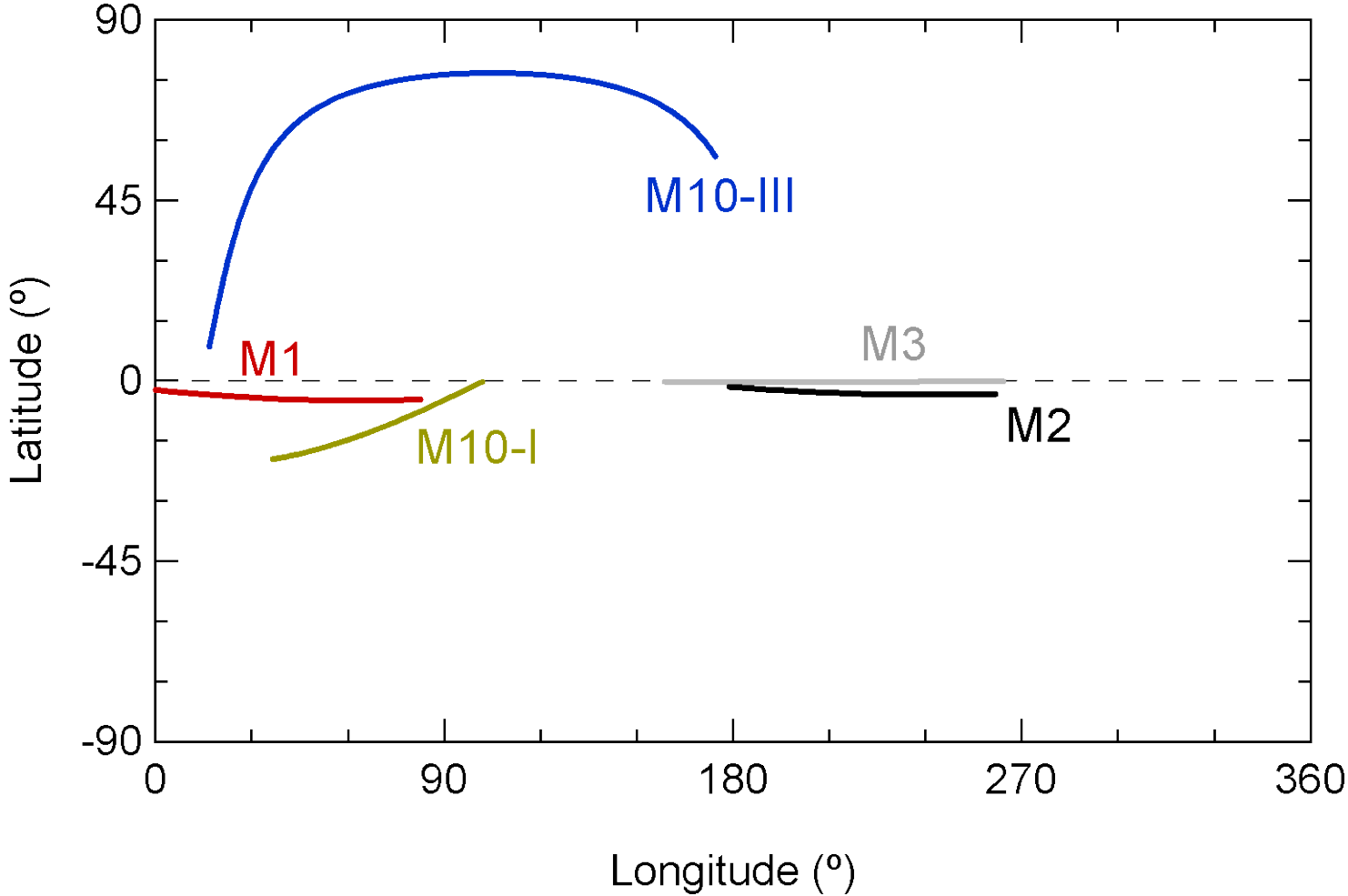
Inner Tracks: Body Fixed

Only M10-III is over the pole. M3 data not useful for internal field.

Only M2 returned data from western hemisphere: ~180° from M1.



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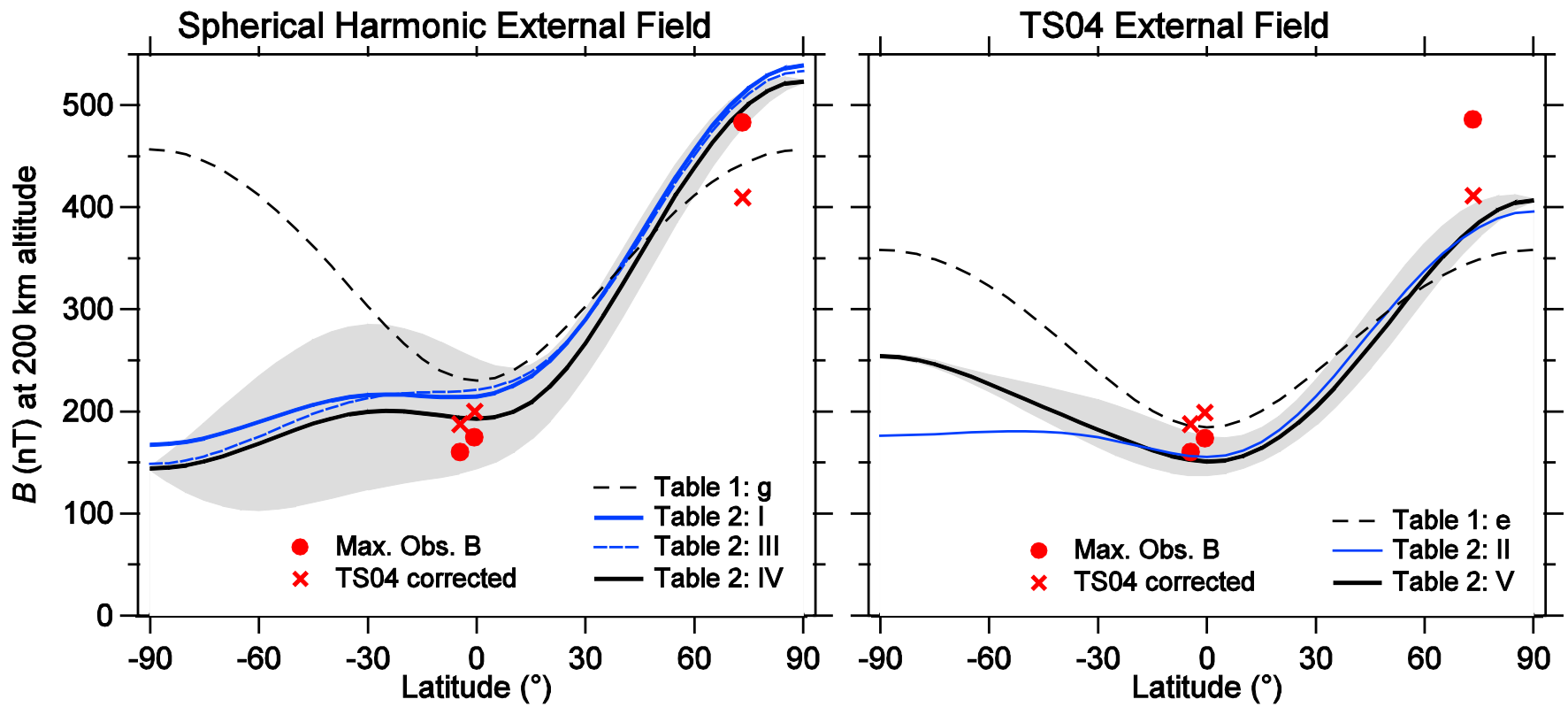
Pole-Equator Inconsistency

- M10-III field over pole indicates a field at 200 km that is more than 2x the equatorial field at 200 km
- Maximum pole-equator field difference for a dipole field is 2x
- Either (a) something enhances the polar field or (b) something suppresses the equatorial field.



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Summary of Inversions

Planetary dipole moment ranges from 173 to 249 nT-R_M^3

Higher order fits consistent with northward displacement of a dipole

Internal model	External field	g_1^0	g_1^1	h_1^1	g_2^0	g_2^1	g_2^2	h_2^1	h_2^2	Residual (nT)	Condition number
1 Dipole	None	-216	-6	14						42	2
2 Dipole	TS04	-240	-1	5						29	2
3 Dipole*	SHA	-249	-12	16						30	7
4 Quad.	None	-173	-7	15	-108	-9	-1	16	-17	19	3
5 Quad.	TS04	-213	-4	7	-66	9	4	5	-4	14	3
6 Quad. *	SHA	-182	-15	9	-108	10	2	6	-15	15	12
7 Reg.†	TS04	-222	12	2	-24	9	9	-6	8	24	n/a
External terms		G_1^0	G_1^1	H_1^1	G_2^0	G_2^1	G_2^2	H_2^1	H_2^2		
3 Dipole*	SHA	47	26	8	10	-15	-3	-2	-8		
6 Quad. *	SHA	7	-4	-15	-9	-9	-3	2	0.4		

* Results for the spherical harmonic analysis (SHA) treatment for the external field are from Uno (2009).
† Results for the regularized solution are from Uno (2009). Higher-order terms are given by Uno (2009). The g_n^0 terms in the regularized solution are as follows: g_3^0 = -1; g_4^0 = -4; g_5^0 = -6, g_6^0 = 0; g_7^0 = 1; g_8^0 = 0.

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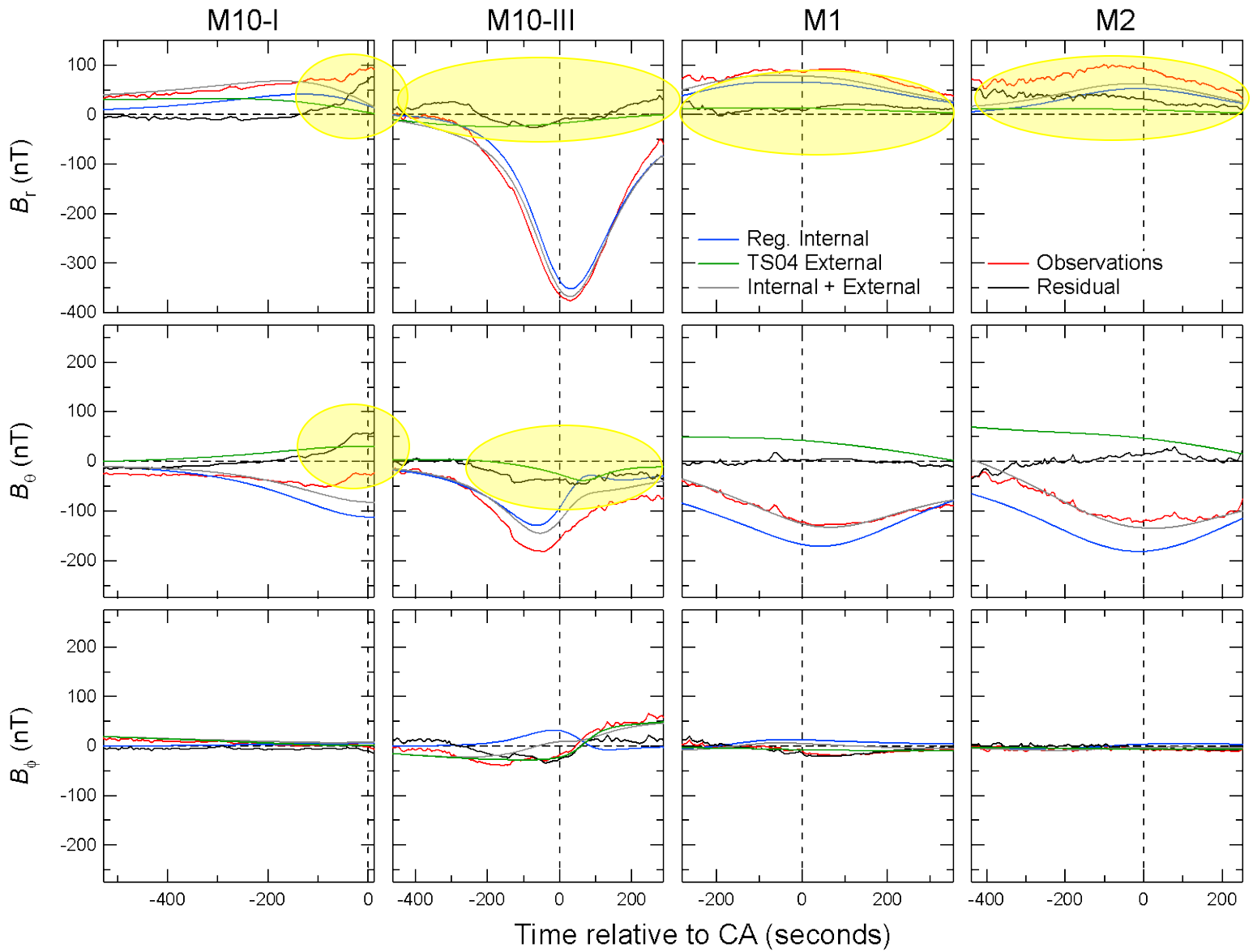
Residuals: δB_r M1,2 > 0



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View in Physical Space

- Projection views in Z-X and Y-X planes
  - Trajectory traces
  - Plane projections of **B** or δ**B** shown as lines from trajectory
- First series in Mercury Body Fixed (MBF) coordinates
  - Residuals are not correlated with proximity to planet
  - Radial components of M1 and M2 are both radially outward on opposite sides of planet
- Second series in Mercury Solar Orbital (MSO) coordinates
- Radical approach:
  - Fit a centered, axial dipole to the M10-III data: 270 nT-R_M^3
  - Evaluate residuals in MSO coordinates and interpret in terms of external currents

Raw data:

Northward **B** in equator, southward **B** over pole make sense for dipole.

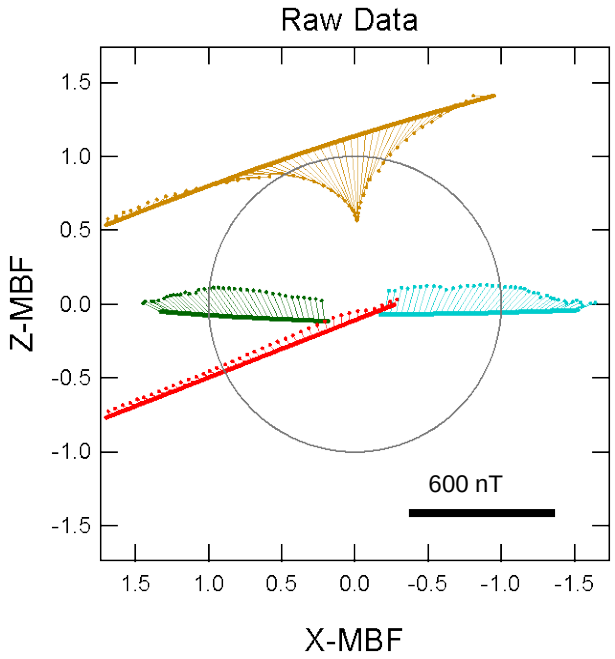
Radially outward **B** in equator does not fit dipole.

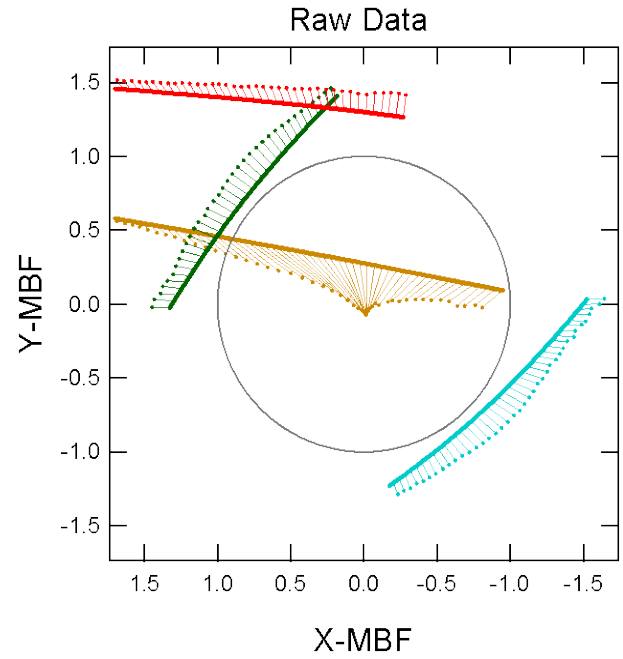
Horizontal **B** over pole.

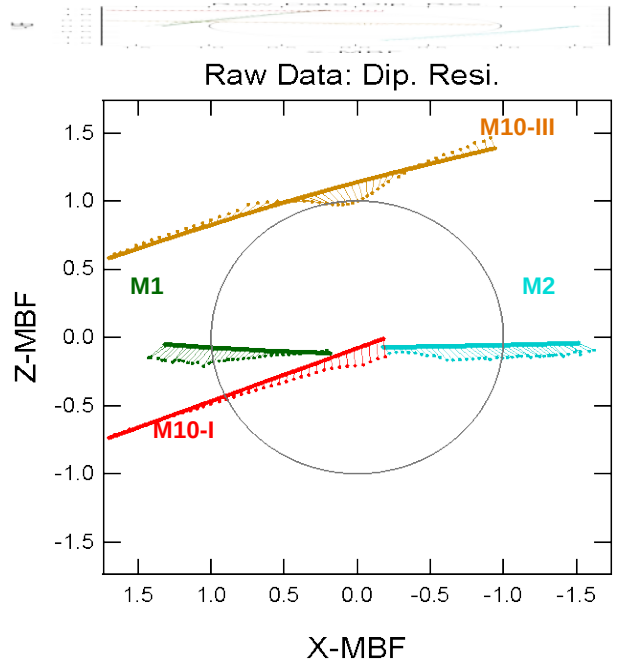
Dipole only:

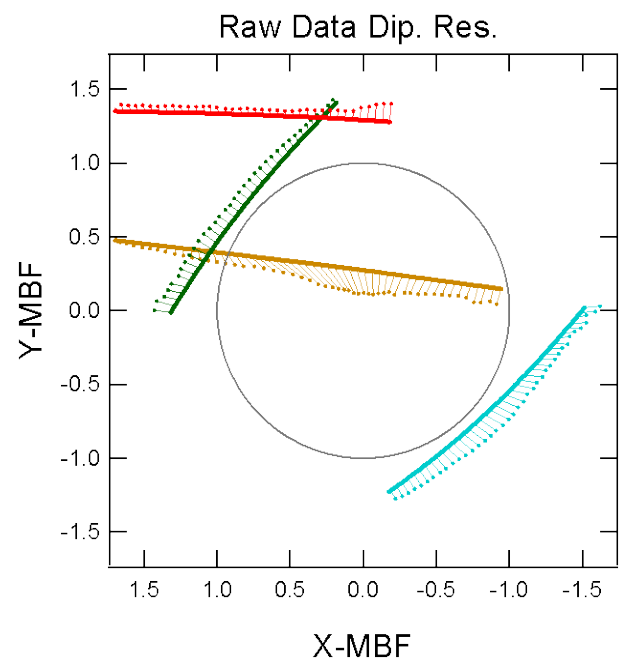
Dipole field is too weak over the pole and too strong at equator.

Dipole cannot fit radial equatorial fields or account for horizontal **B** over pole.



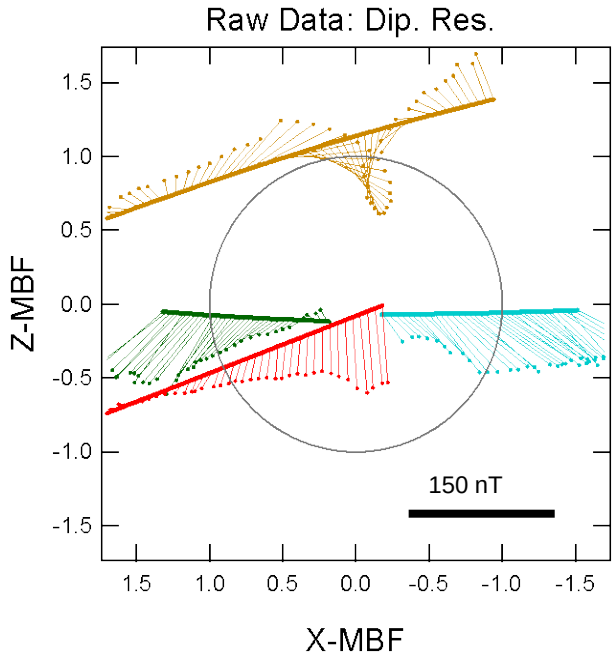


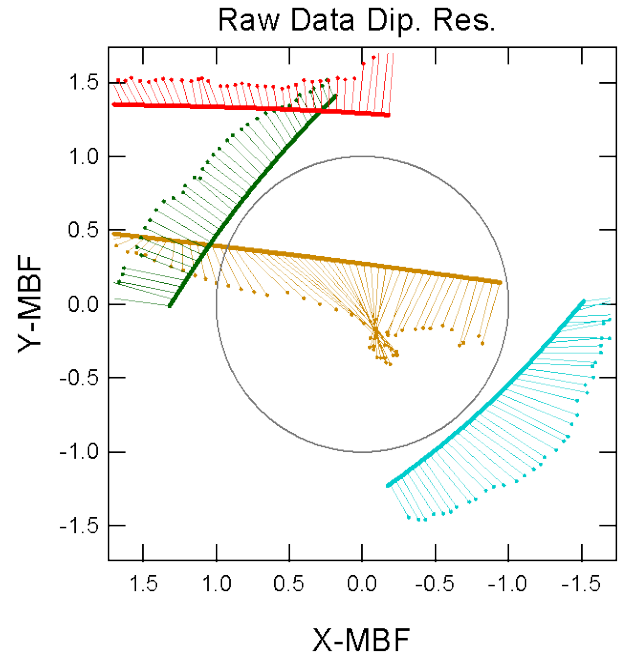




Dipole-only:

Zoom: 4x higher scale for δ**B**

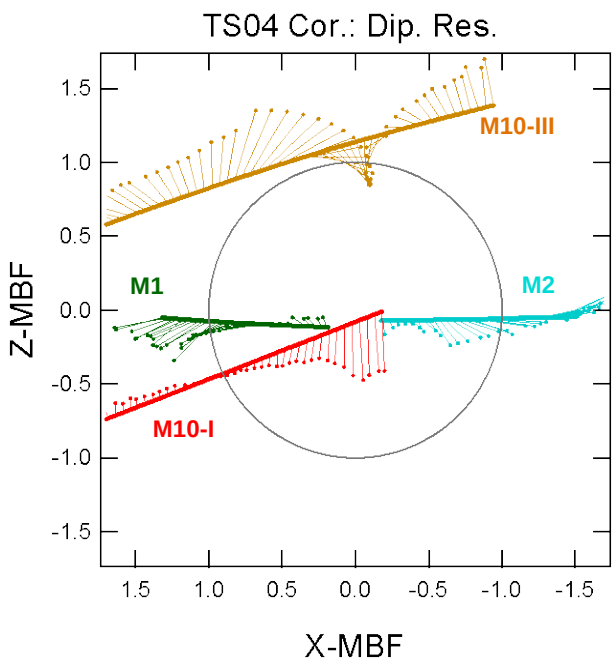


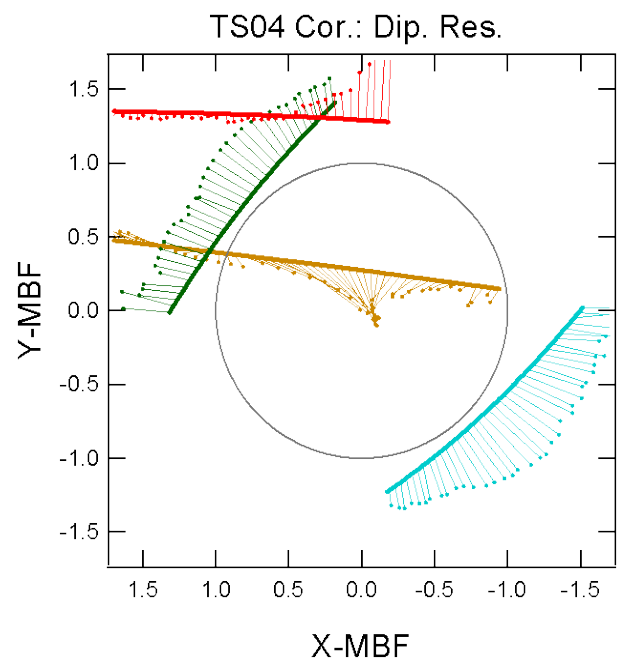


TS04 & Dipole:

Equatorial southward δ**B** smaller, equatorial radial δ**B** only a bit smaller.

Polar horizontal δ**B** smaller but northward δ**B** is worse.

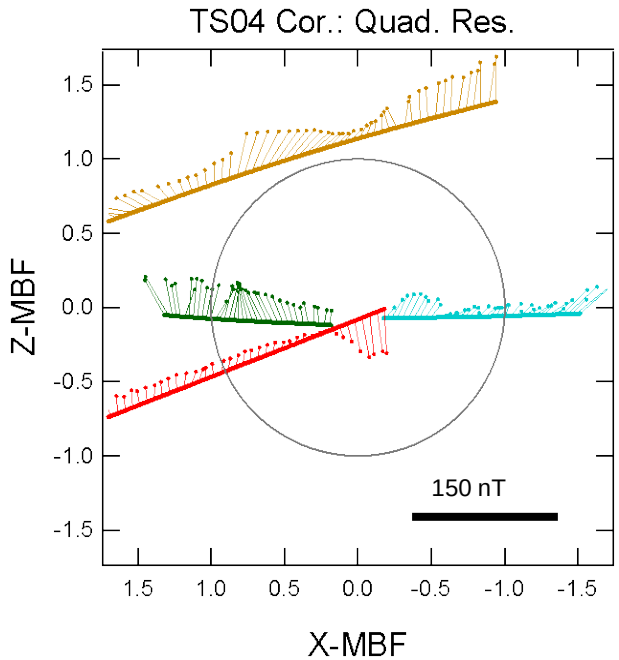


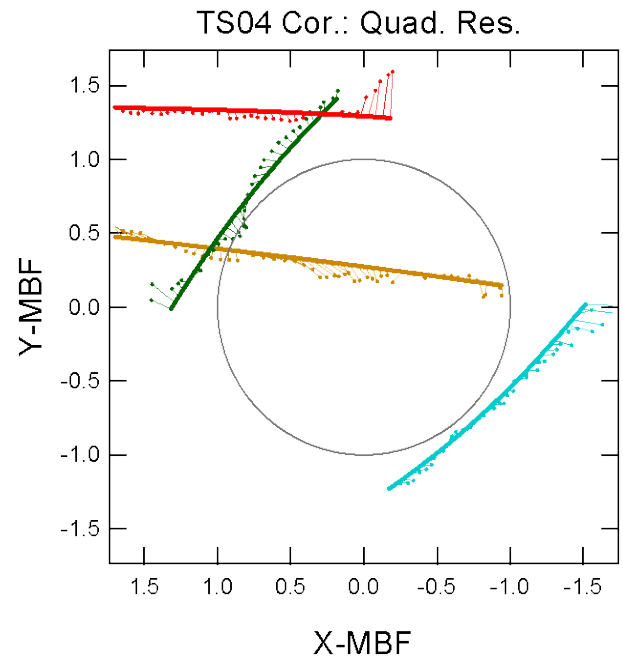


TS04 & Quadrupole:

Radially outward δ**B** in equator is pretty good.

Northward δ**B** is persistent.

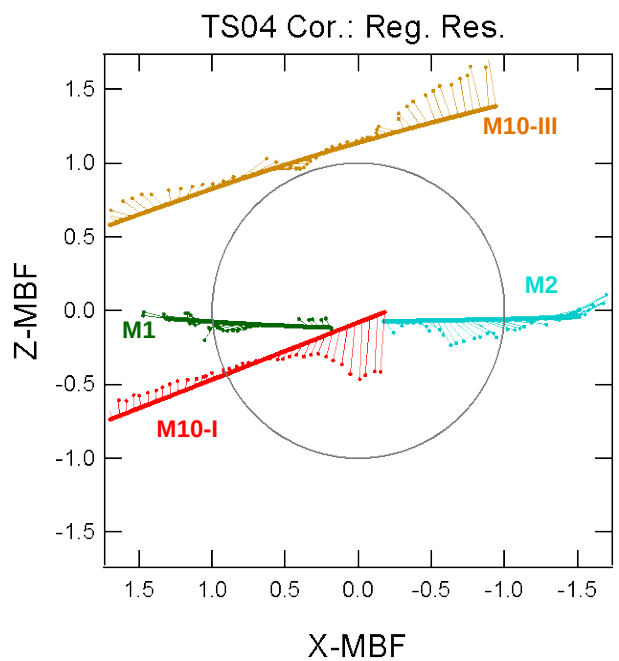


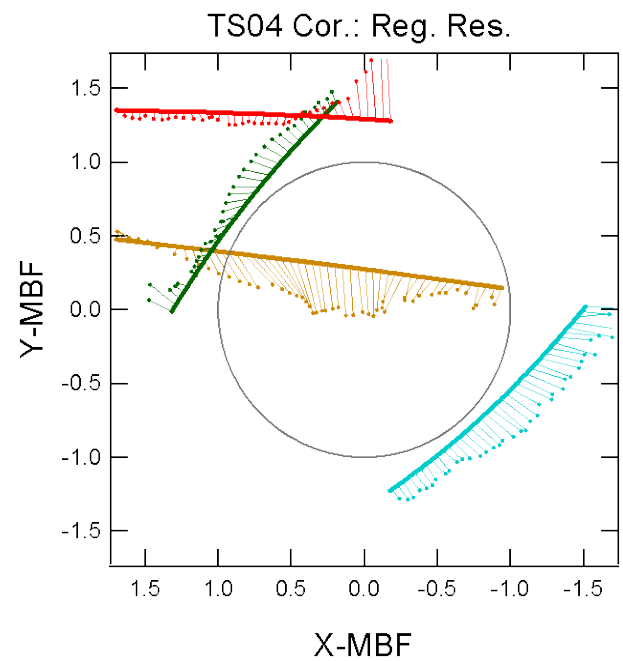


TS04 & Regularized Inv.

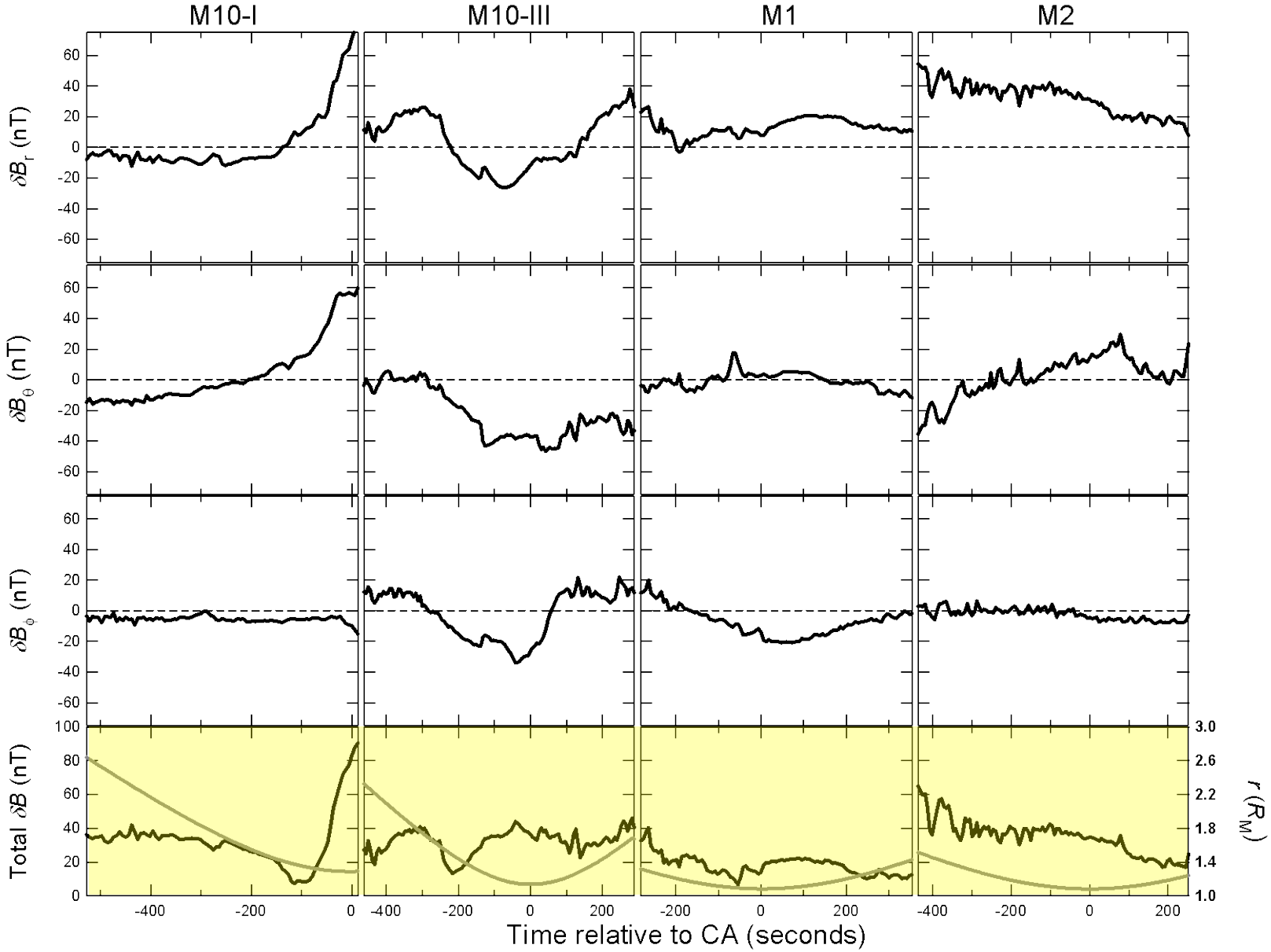
Radially outward δ**B** in equator is persistent.

Northward δ**B** is pretty good but horizontal δ**B** over pole is worse.





TS04 & Regularized Inv.



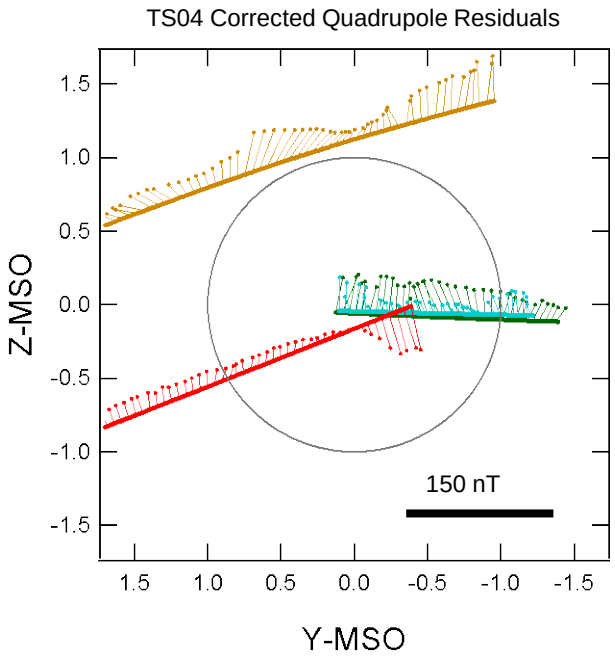
Key point: The residuals are NOT correlated with distance from planet. Suggests that the primary source of the remaining residuals is not the internal field.

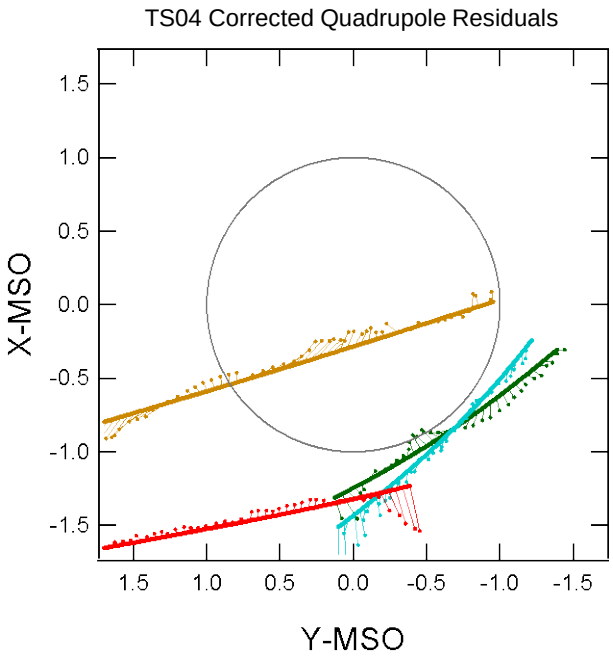
MSO coordinates

TS04 & Quadrupole:

Equatorial passes are all in the near tail. δ**B** are not consistent.

Northward δ**B** is the primary M10-III res.

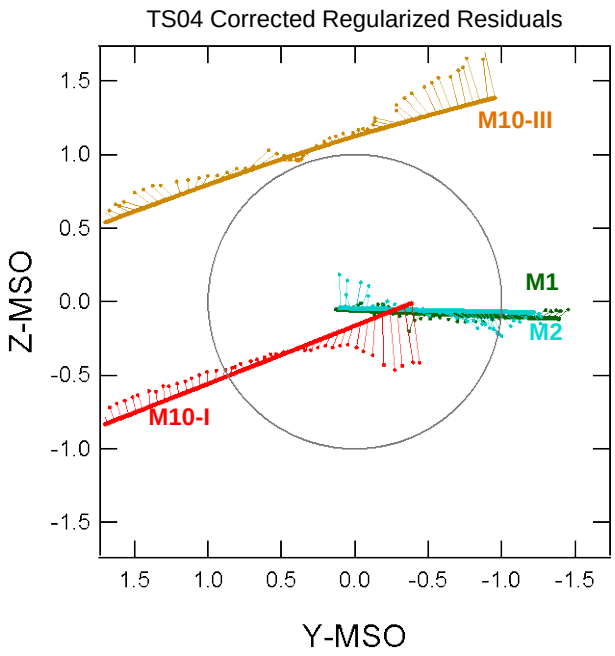


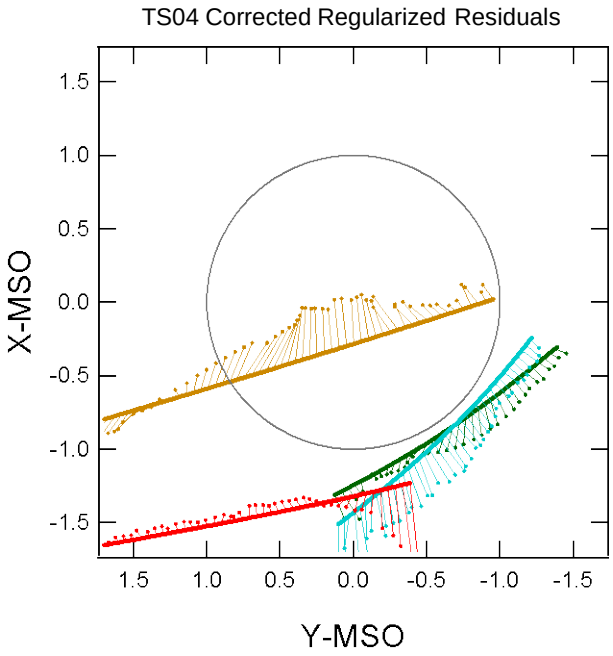


TS04 & Regularized Inv.

Equatorial passes inconsistent here as well.

M10-III primary δ**B** is sunward closest to planet.





View to Sun

View above N pole

MSO coordinates

M10-III dipole:

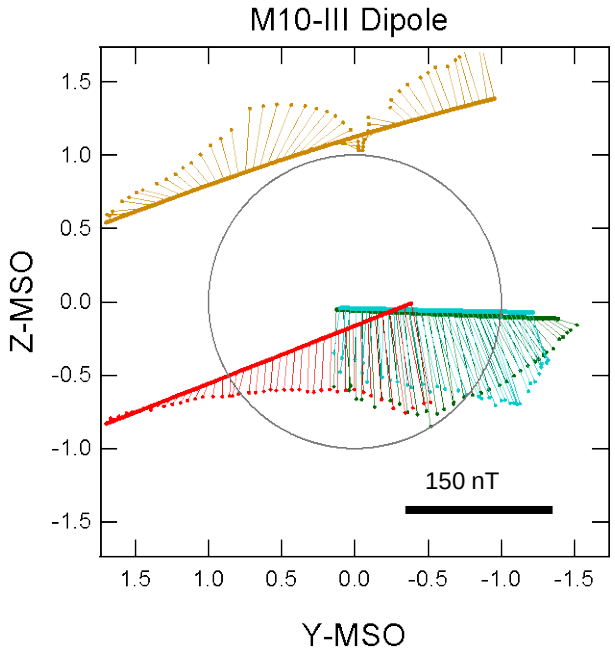
Equatorial passes all indicate residual southward and tailward δ**B**.

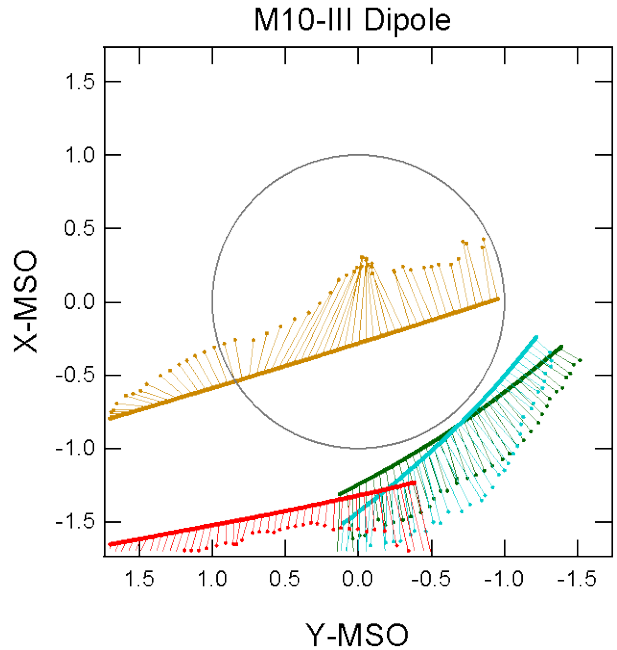
Polar δ**B** are northward and sunward.

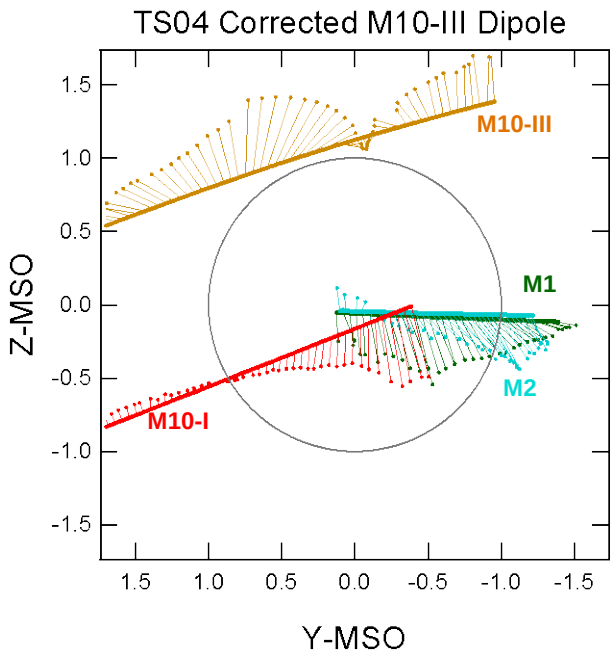
TS04 & M10-III dipole:

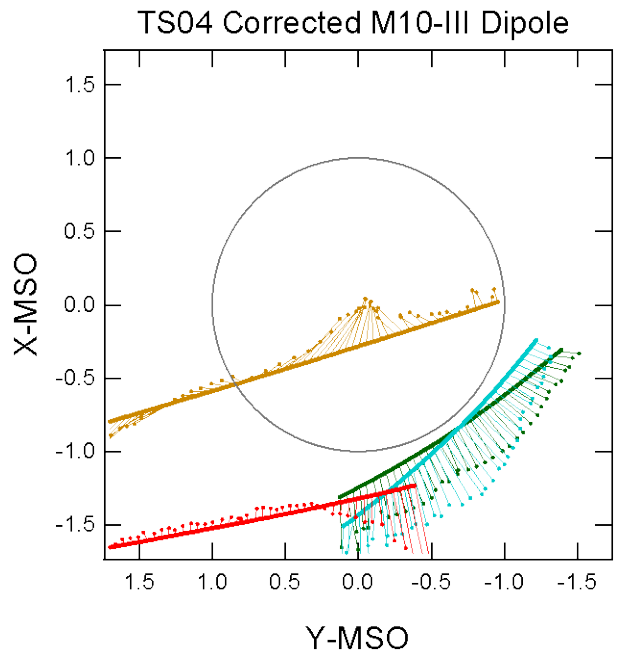
Polar sunward δ**B** is smaller but northward δ**B** persists.

Near tail southward and radial δ**B** are improved: but still strong.









View to Sun

View above N pole

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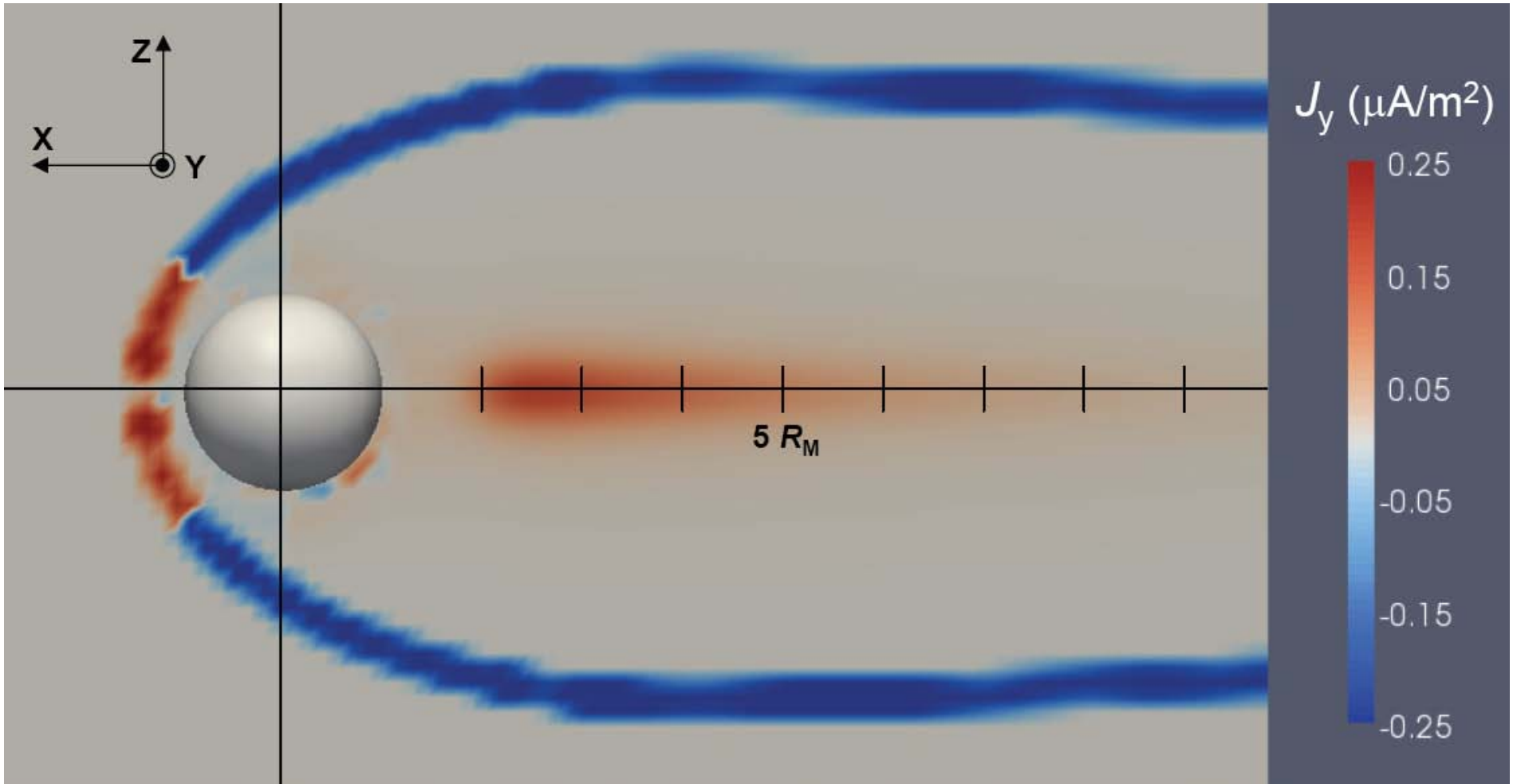
TS04 MP and Tail Currents

Equatorial δB indicate currents to within 0.5 R_M

TS04 cross-tail current is too far tailward



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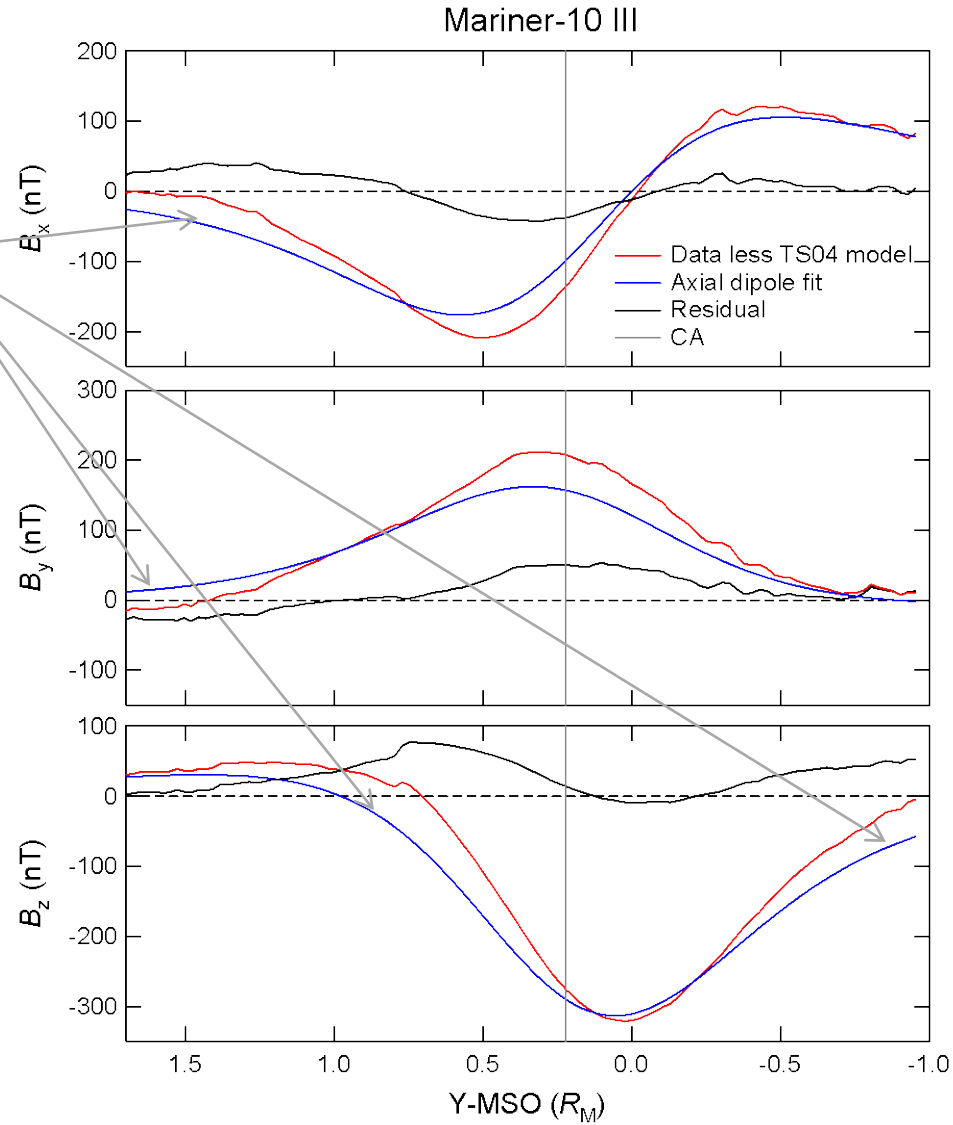
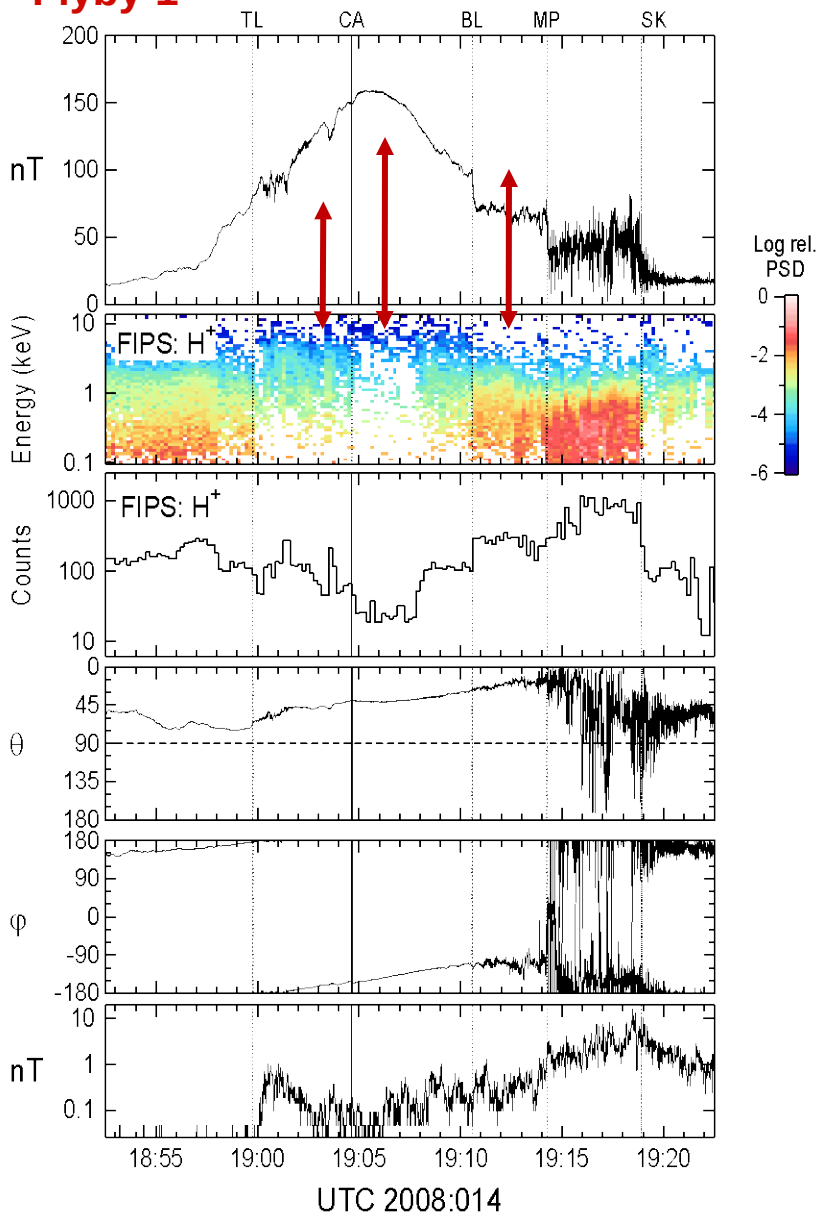
M10-III Residuals (TS04-Dipole)

- TS04-Dipole field has ‘wings’ not present in M10-III observations.
- Observed magnetic field is more confined to polar regions.
- Could this be due to internal plasma pressures projected to mid-latitudes?

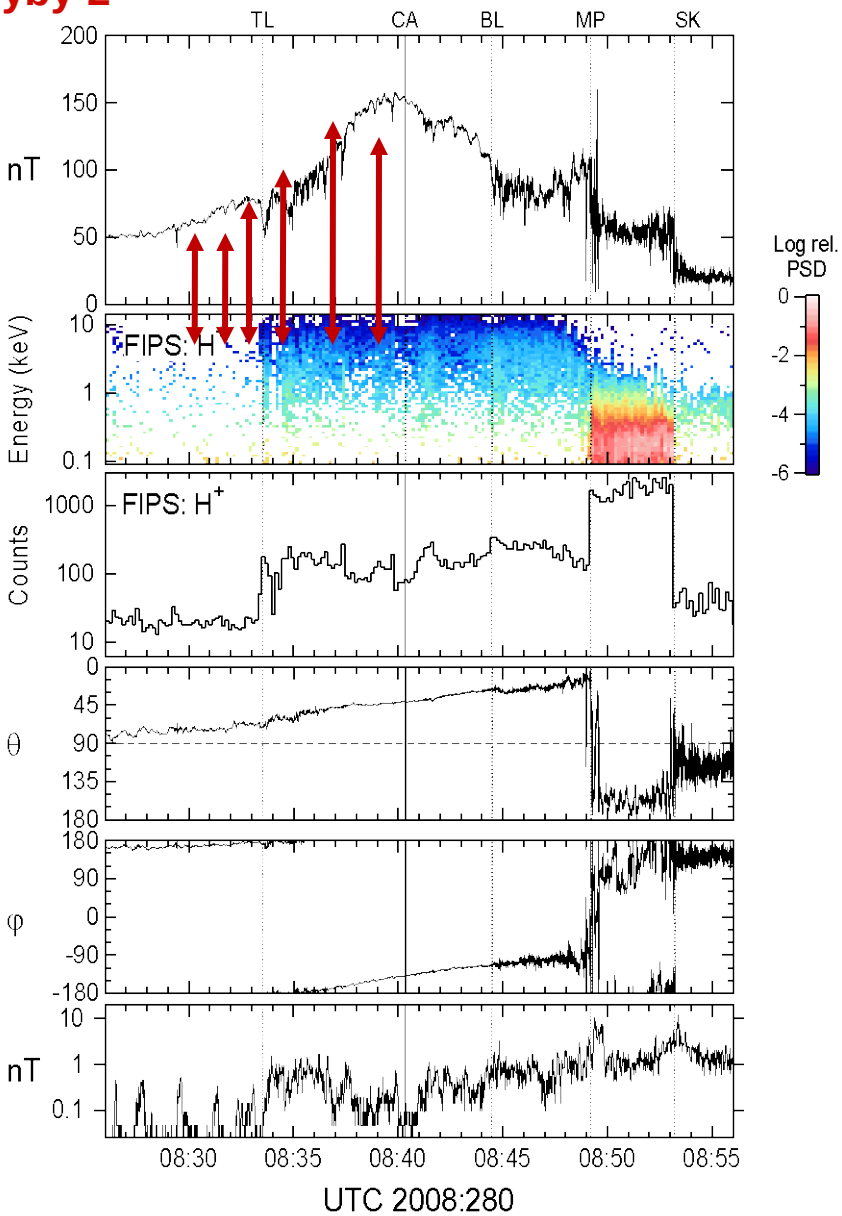


Signatures of internal plasma pressures in inner magnetosphere (between TL and BL) on both M1 and M2

Flyby 1



Flyby 2



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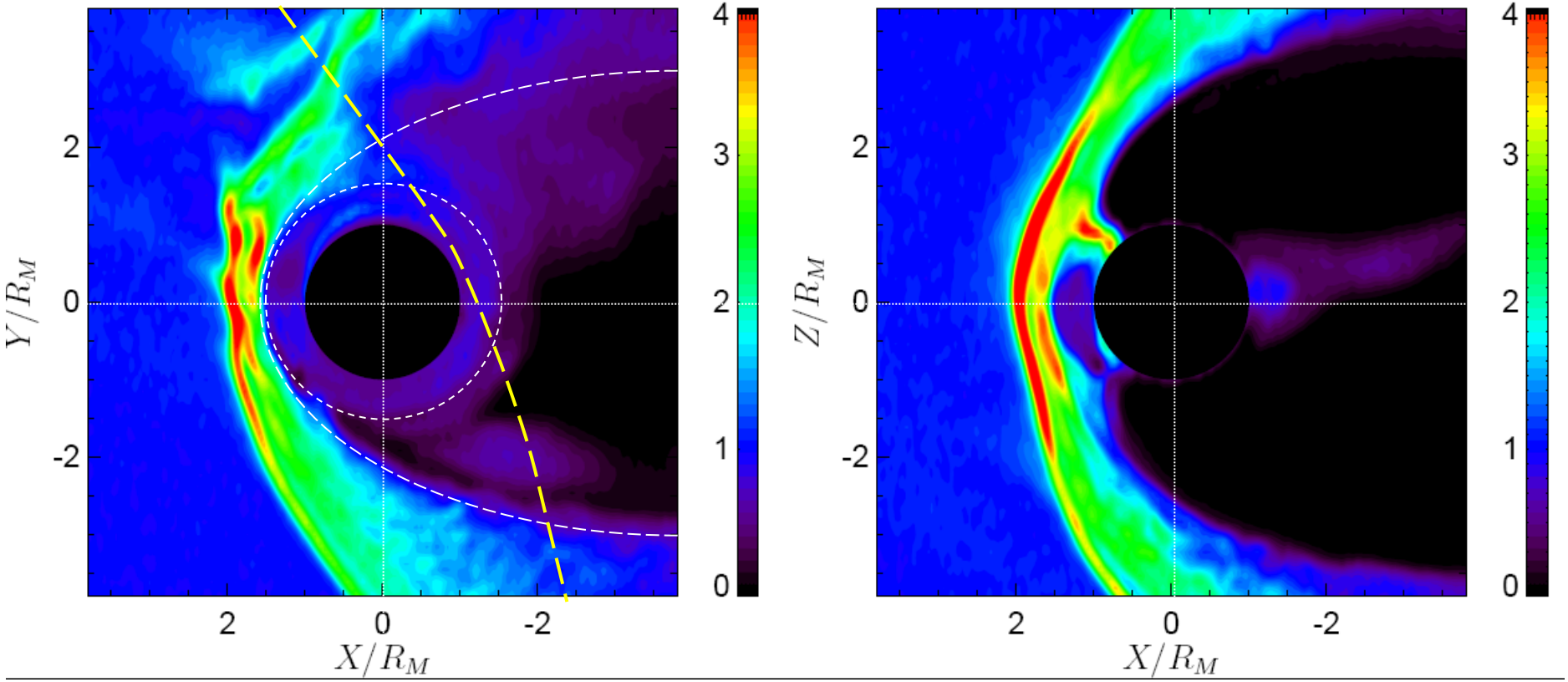
Simulation context

Plasma density: n/n_{sw}

Travnicek et al.



Significant solar wind plasma densities are predicted

Consistent with MAG and FIPS observations

Note also plasma pressures at mid-latitudes

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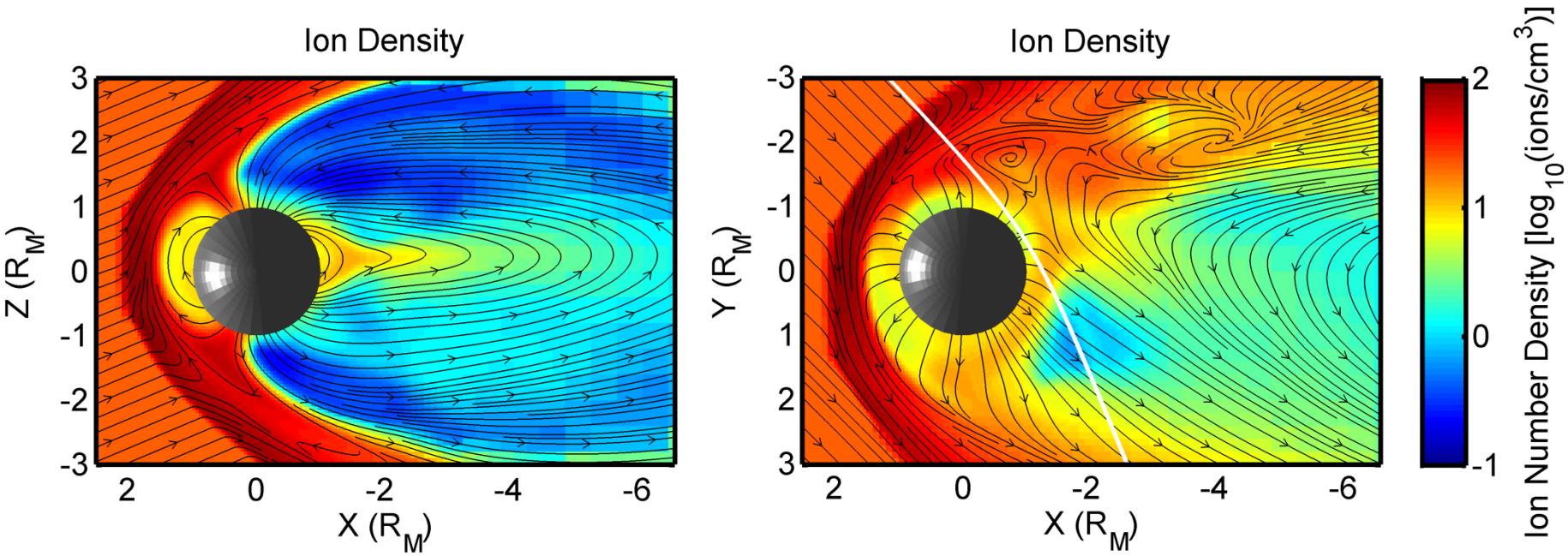
Benna et al.



Similar enhanced densities near planet, strong near-tail current and mid latitude plasma densities are predicted by MHD models.

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Steps Forward

- Further spherical harmonic inversions
  - Unlikely to make further progress
  - Potential (SH) formalism is not valid if there are currents, plasma pressures within the measurement domain
- Use MHD or hybrid code for external model iterate with internal model
  - Benna and Purucker ; Travnicek and Shriver
  - Key tests: Is there a dayside boundary layer? Is the cross-tail current in the right place (elevation and near-planet)?
- Improved, customized empirical field model for Mercury
  - Various authors
  - Key features: near-planet cross-tail current; ‘annulus current’; diamagnetic effect of mid-latitude plasma distributions

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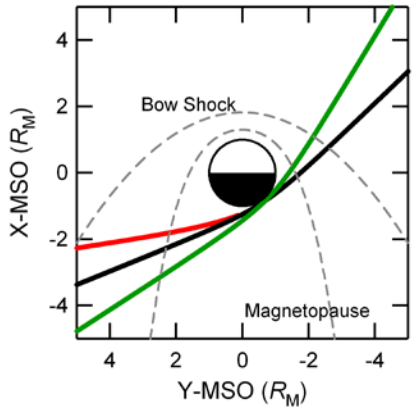
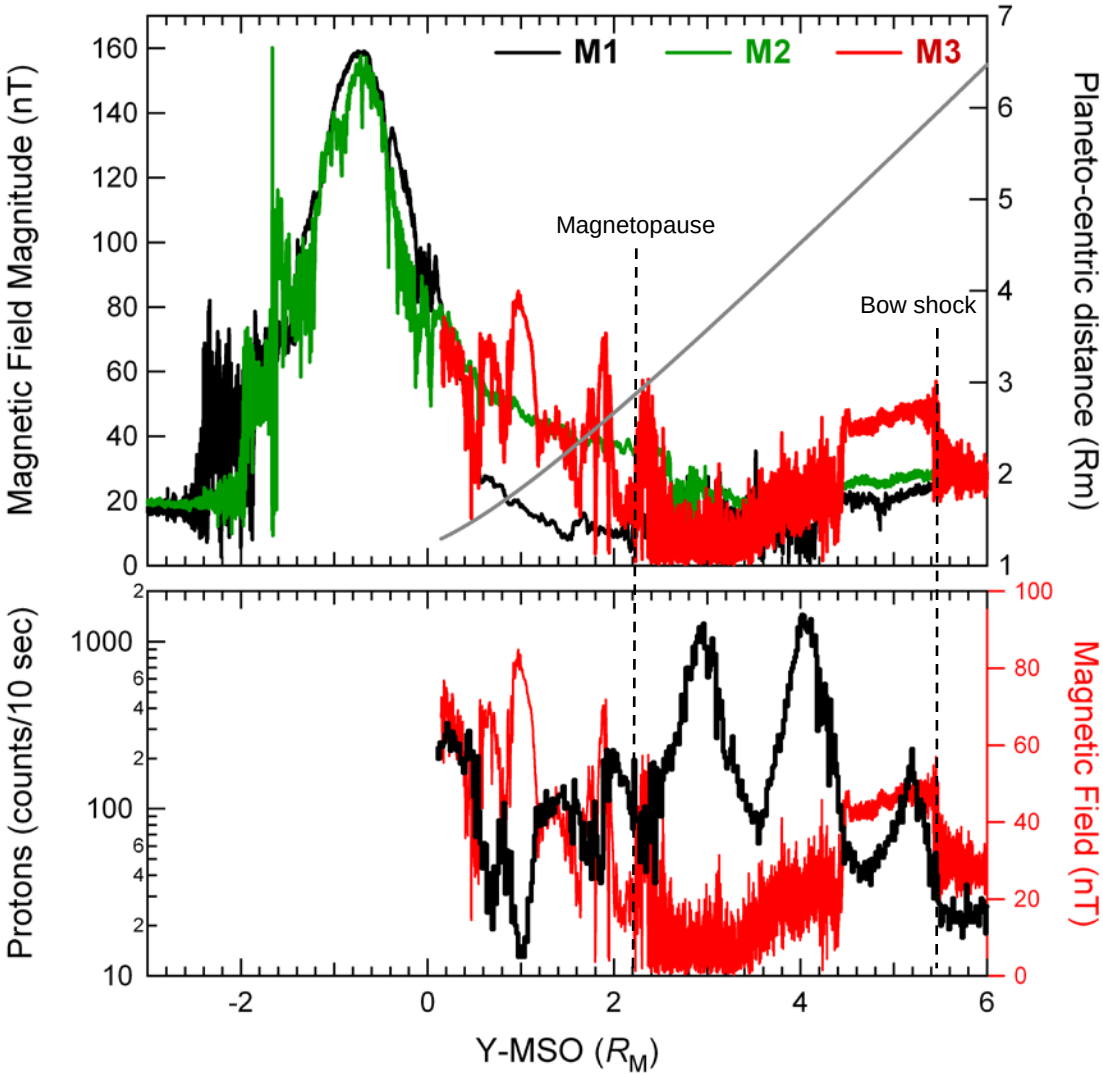
M3: A Tail of Extreme Dynamics





Passage across magnetotail: dusk to midnight

Highly dynamic tail magnetic field: factor of five variations in magnitude

Field variations in magnetotail anti-correlate with protons

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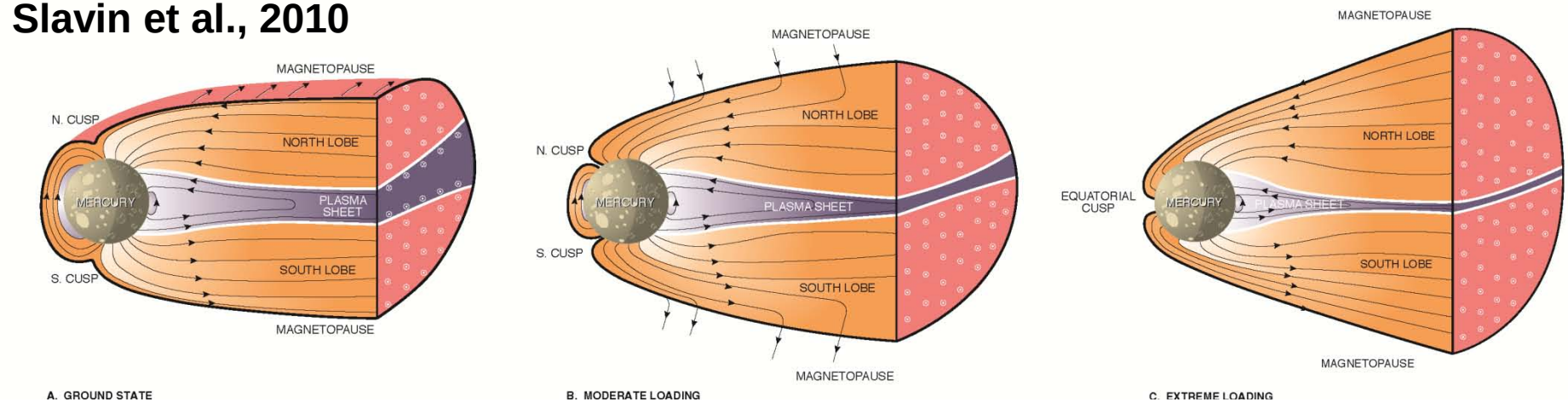
M3: A Tail of the Vanishing Dayside

Slavin et al., 2010



Normal loading | **Strong: inflated tail** | **Extreme: saturated tail**

- **Total planetary magnetic flux: $\Phi_M = 2\pi B_{eq} R_M^2$**
  - B_{eq} = 250 nT ↔ **Φ_M = 9.5 MWb**
- **Tail magnetic flux: $\Phi_{TAIL} = 0.5\,\pi B_{TAIL} R_{TAIL}^2$**

  B_{TAIL} = 50-60 nT (nominal); 70 - 83 nT (maxima); Φ_{TAIL} = 3.0 MWb

  R_{TAIL} ~ 2.5 R_M (no flaring); ~ 3.5 R_M (flaring); **Φ_{TAIL} = 9.5 MWb**
- **Tail may have become completely saturated: Mercury's magnetosphere may achieve extreme tail loading/unloading**

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M3: A Sobering Lesson

- Severe tail dynamics may imply a radically different magnetosphere
- Short time dynamics: minutes
  - Which physical/empirical model does one use?
  - What IMF/solar wind parameters should one use?
- Internal field inversions will probably need to focus on orbits with ‘clean’ data
  - Consistent with minimal dynamics
  - Low solar wind/IMF driving
  - Stable solar wind/IMF conditions
- Need to identify from the MESSENGER data which orbits are ‘clean’

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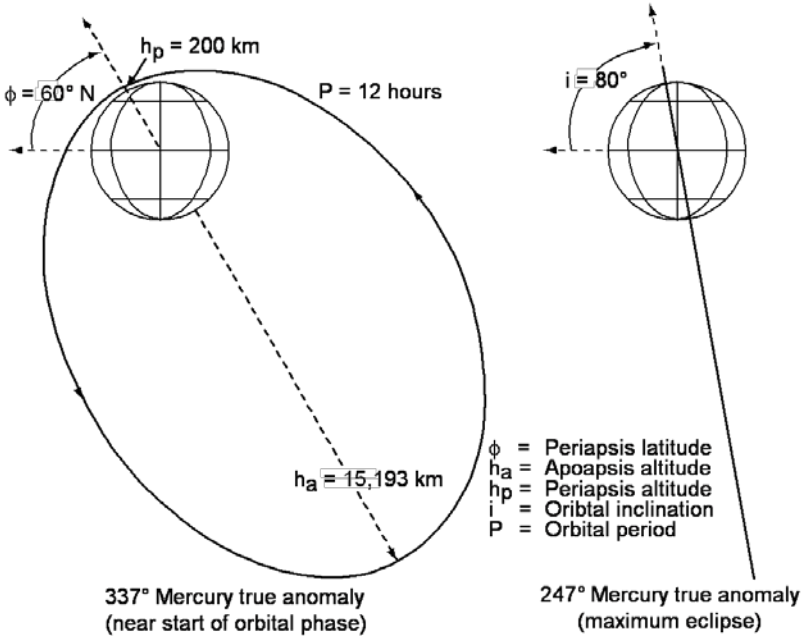
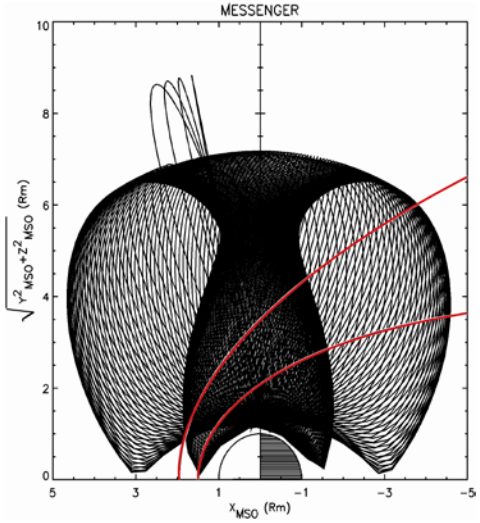
Orbital Mission Phase

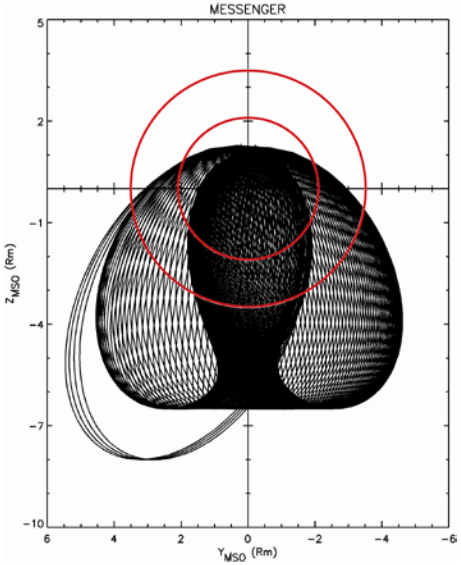
Three flybys down, 730 to go!



View from 'dusk'



View from Sun



There will be plenty of data over the north pole and around the equator at two cuts of radial distances.

If MOI and orbit operations go as planned we should have the luxury of being selective with the data we use for internal field studies.