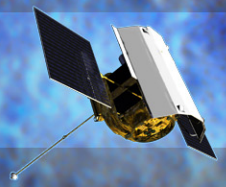


APL

MESSENGER

MErcury Surface, Space ENvironment, GEochemistry, and Ranging



MESSENGER Observations of Mercury's Magnetosphere

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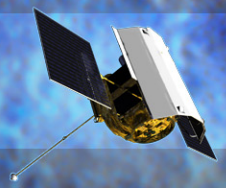


Overview

Major magnetospheric fields
- Magnetopause, magnetotail
- Core field structure

Residual Fields: Main contributors
- Cusp and equatorial plasma
- Birkeland currents

Other fields of internal origin
- Time-varying core fields (induced)
- Higher degree and order steady core fields
- Crustal fields

Focus: internal fields and quasi-steady external fields from MAG observations.

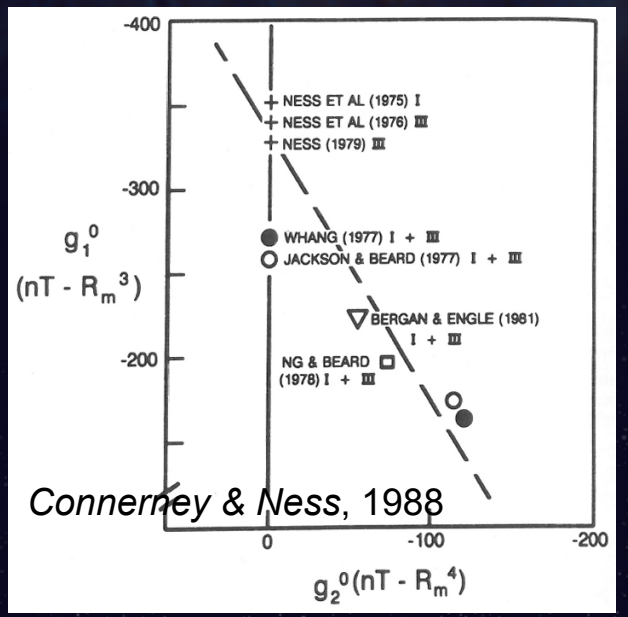
Not covered: short time-scale dynamics

Synthesis / Future Directions – comments and open discussion

Flybys: Mariner 10 and MESSENGER

Mariner 10: 1974, 1975

- Internal weak magnetic field detected on 1st and 3rd flybys
- Dipole moment estimates correlated with higher-degree and external field estimates
- Source (crustal, core) unresolved



Connerney & Ness, 1988

MESSENGER: 2008 & 2009

- Data from 1st and 2nd flybys (equatorial)
- Confirmed core dynamo origin
- No indication of longitudinal structure
- External fields and dipole moment still poorly characterized

MESSENGER Orbital Observations

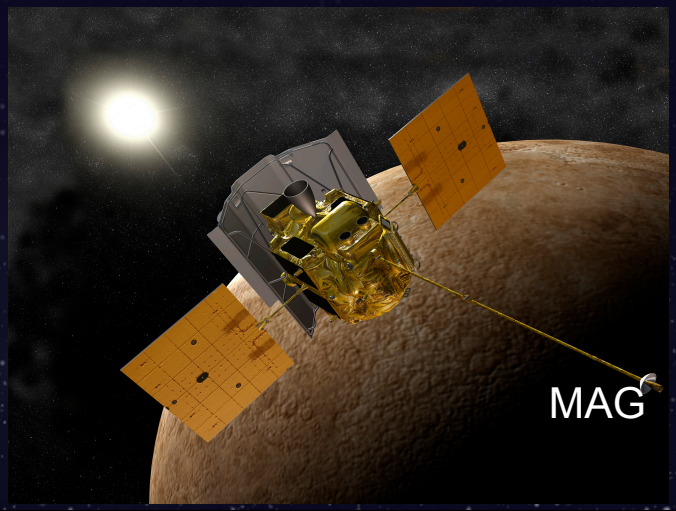
Small, dynamic magnetosphere

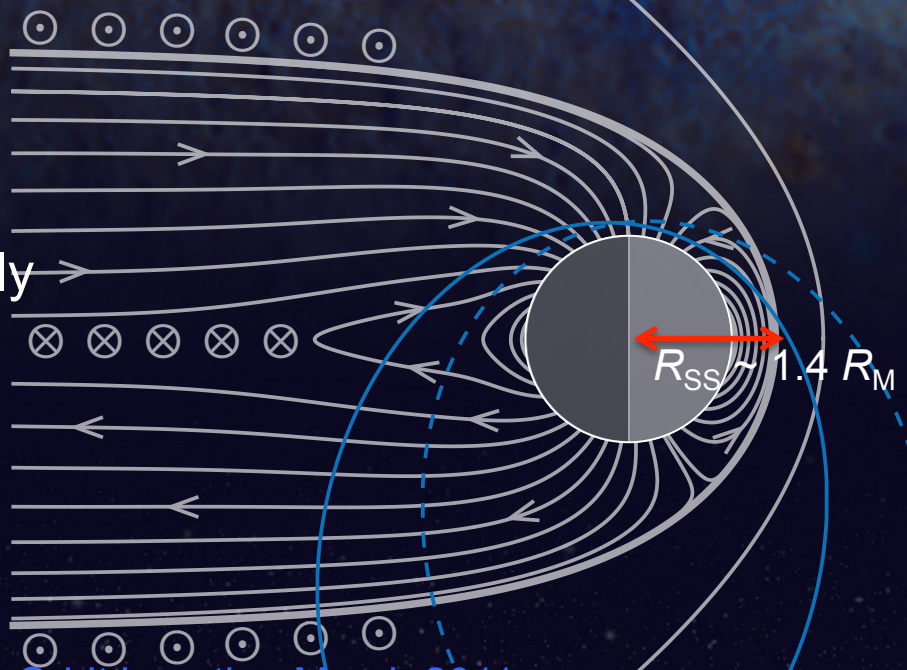
MESSENGER orbit

- all local times, longitudes
- strongly varying altitude

  < 800 km N. hemisphere only

MAG data acquired continuously



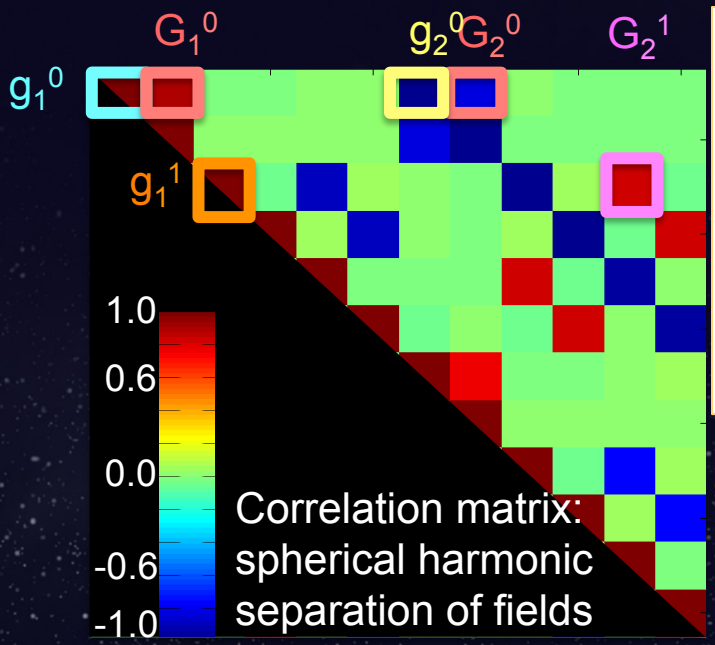


Orbit insertion March 2011
12/8 hr period, 0.2 h/day LT precession
initial periapsis ~200 km, apoapsis ~15,000 km
Periapses <100 km in late 2014 / early 2015
~1.0 - 1.6 hrs inside magnetosphere on each orbit
MAG data: 20/s inside magnetosphere

MESSENGER Orbit Geometry

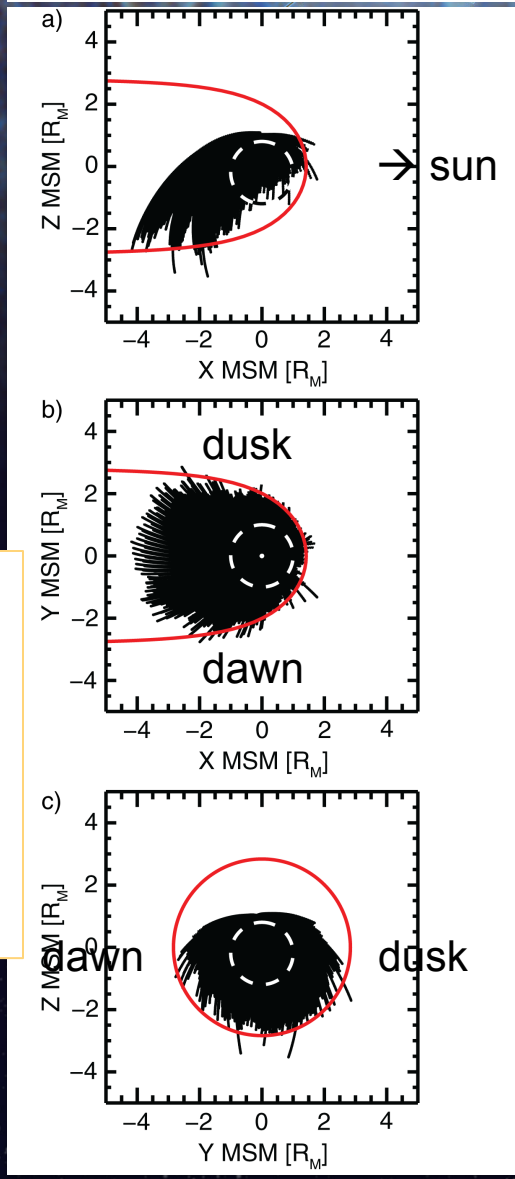
Correlations among

- internal, external latitudinal structure
- internal equatorially symmetric, antisymmetric terms
- internal, external *l*-*m* terms



- MUST account for external fields
- Spherical harmonics not optimal
- Must resolve/reduce internal field trade-offs

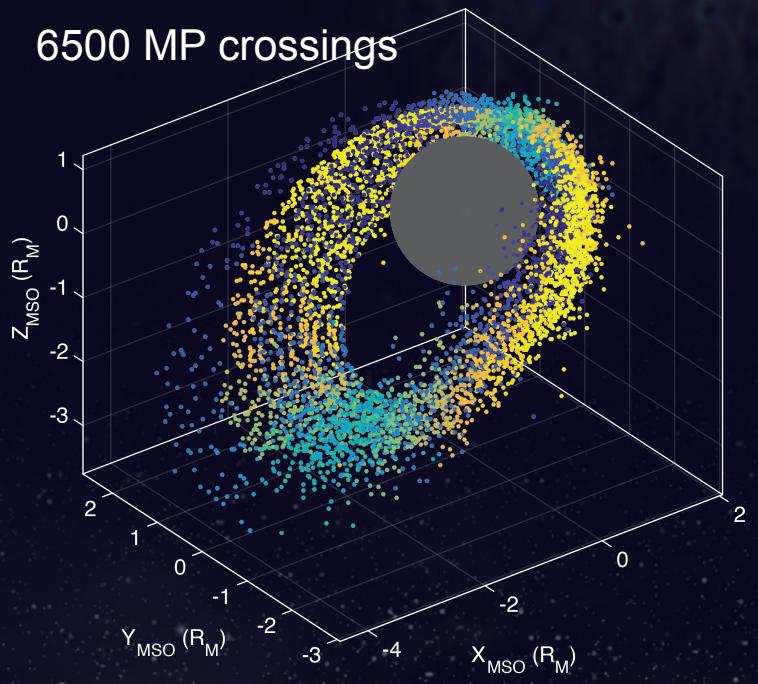
Data distribution inside magnetosphere



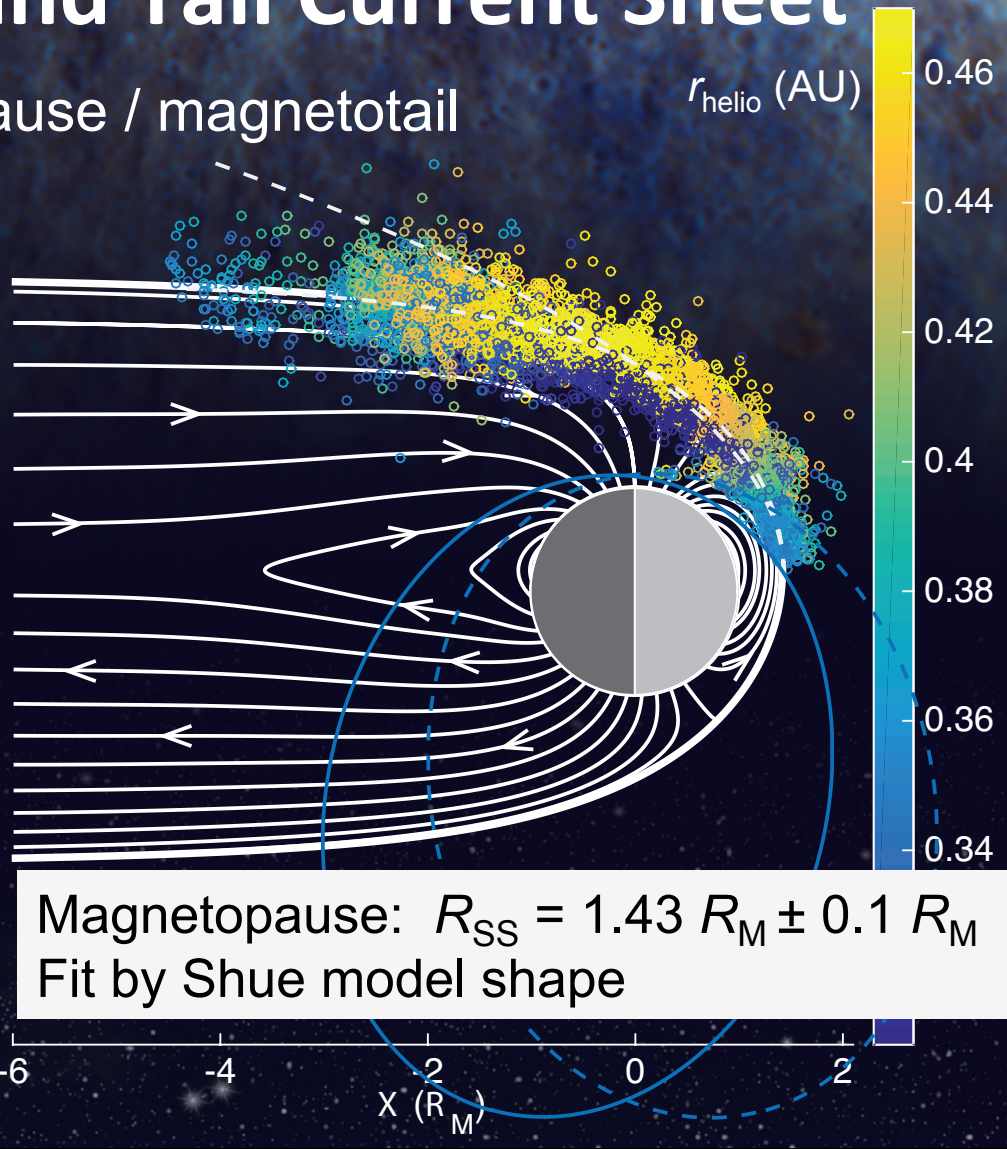
Magnetopause and Tail Current Sheet

Geometry specifies magnetopause / magnetotail fields: see Korth et al. talk

6500 MP crossings



Johnson et al., 2012; *Winslow et al.*, 2013
Philpott et al., 2014; *Al Asad et al.*, in prep.



Magnetopause: $R_{SS} = 1.43\ R_M \pm 0.1\ R_M$
Fit by Shue model shape

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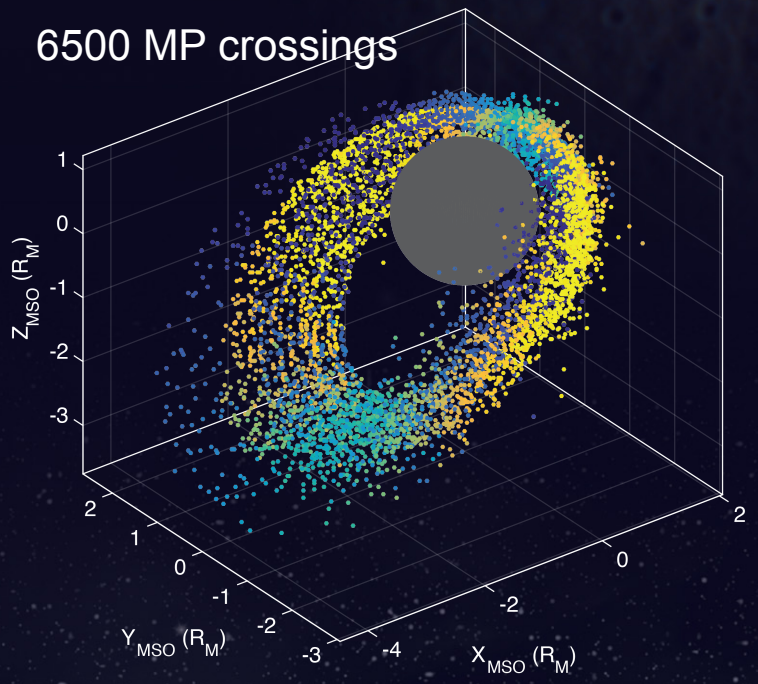

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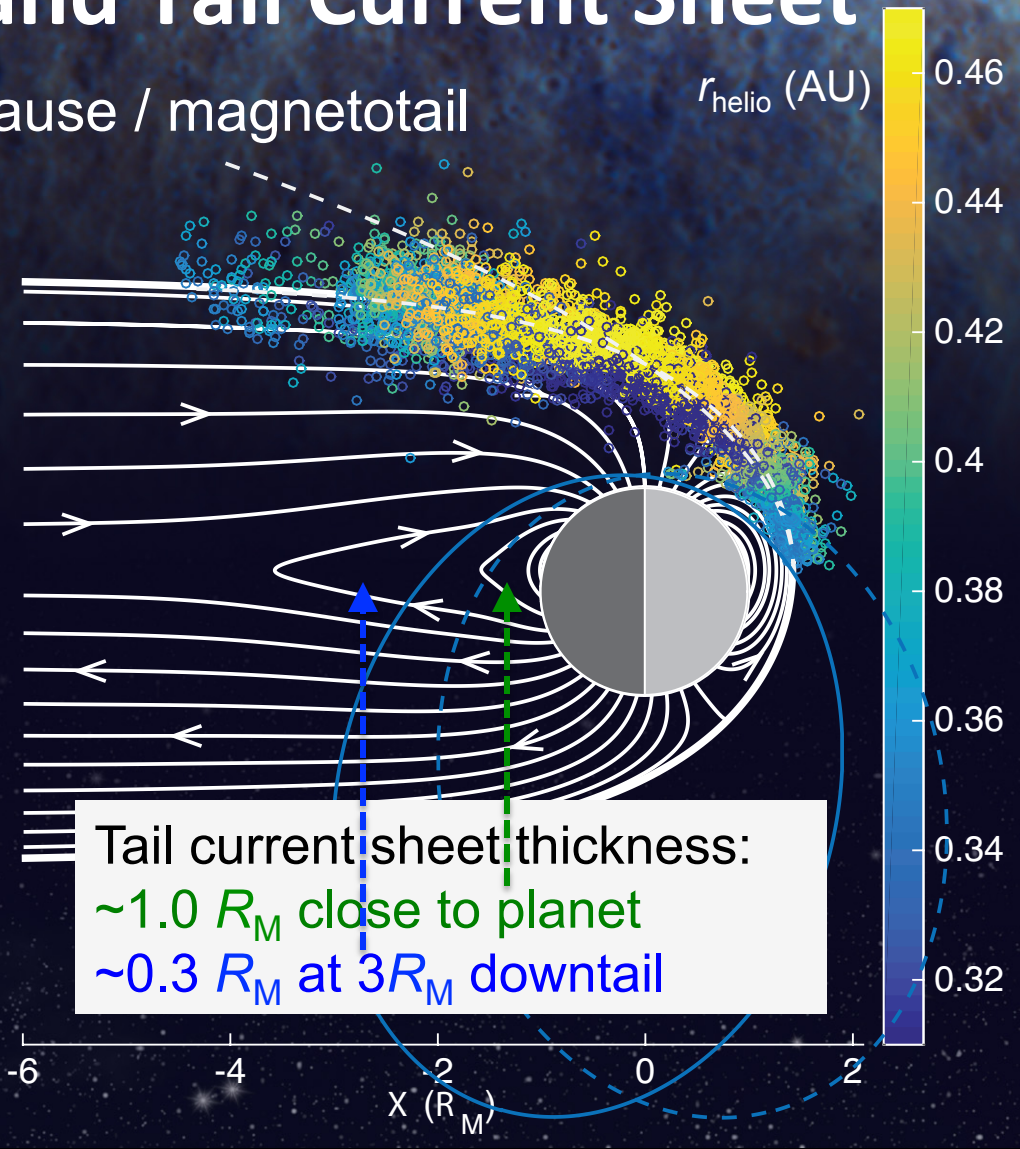
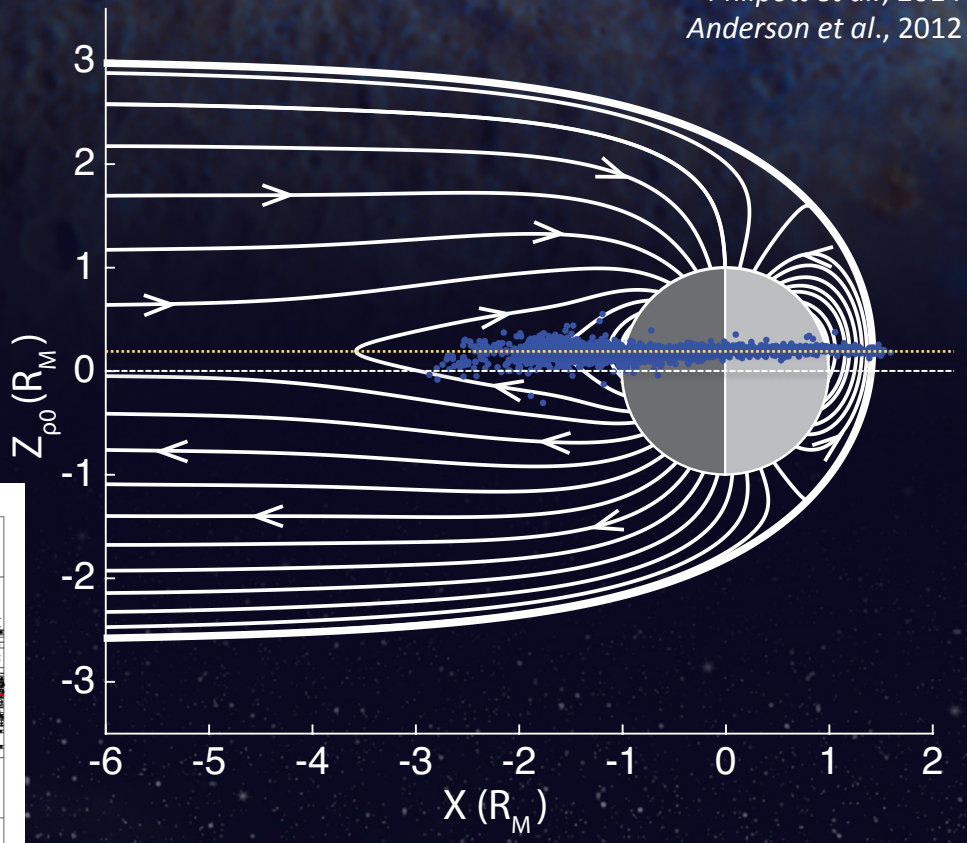


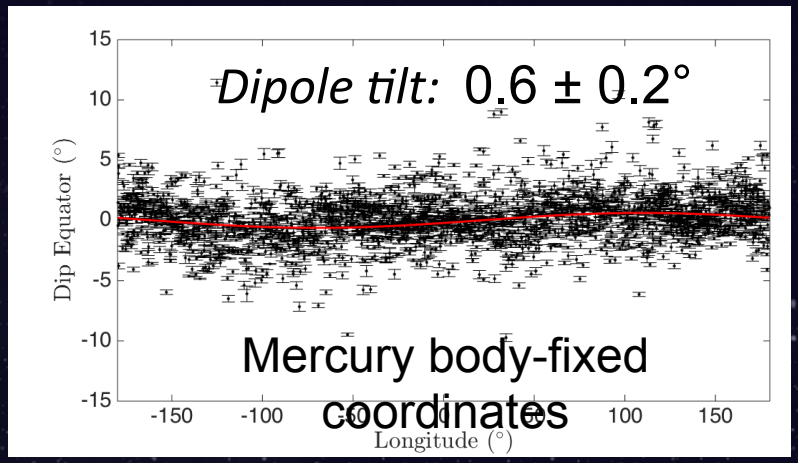
Magnetic Equator

Offset northward ~0.2 R_M

Z_0 = 469 ± 7 km

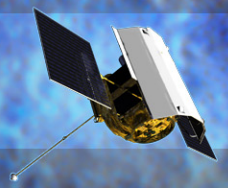
Philpott et al., 2014
Anderson et al., 2012





Interpretation:

Offset axial dipole field (OAD)



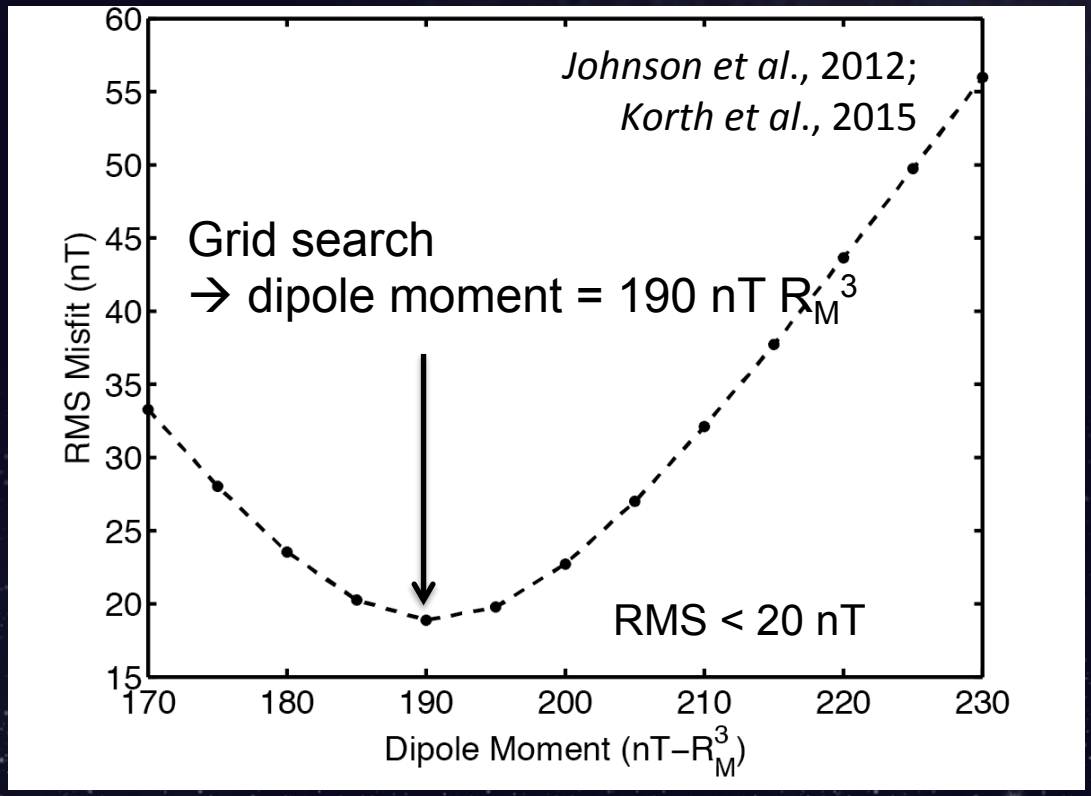
Magnetic Equator: Interpretation

- Field highly axisymmetric
- OAD interpretation resolves g_2^0-g_1^0 trade-off in internal field
- Equivalent body-centered SH expansion of offset dipole:
  - $g_2^0 / g_1^0 = 0.40$
  - $g_3^0 / g_1^0 = 0.12$
  - $g_4^0 / g_1^0 = 0.03$
- S. hemisphere magnetopause closer to surface c.f. N. hemisphere
- S. hemisphere cusp larger than N. hemisphere cusp

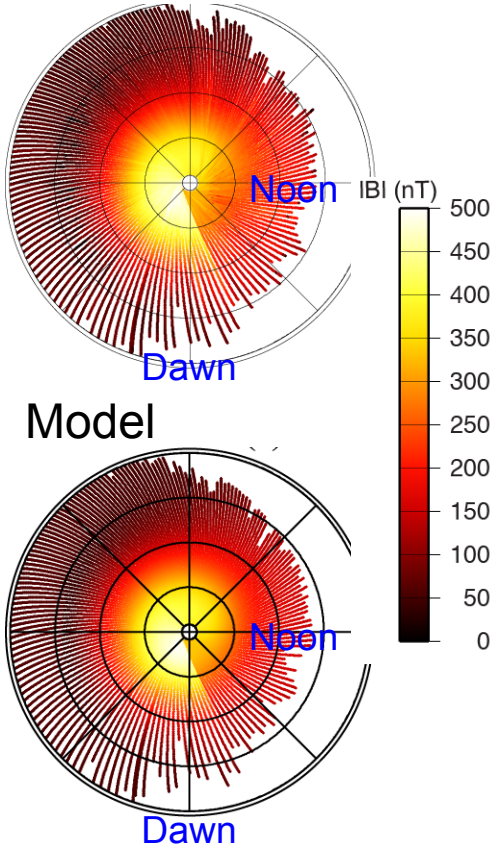
➔ Use OAD representation and magnetopause and magnetotail current sheet geometries in magnetospheric models (see Korth et al. talk) → estimate dipole moment

Magnetospheric Models: Dipole Moment

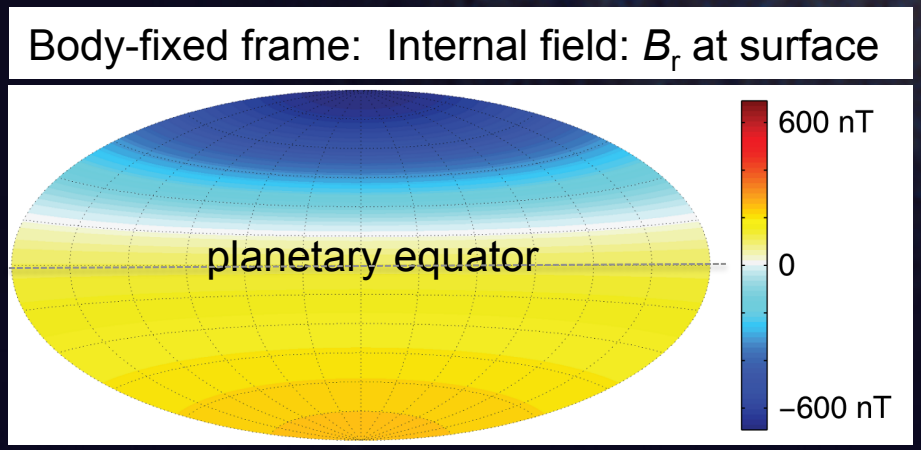
previous (pre-orbital) possible range

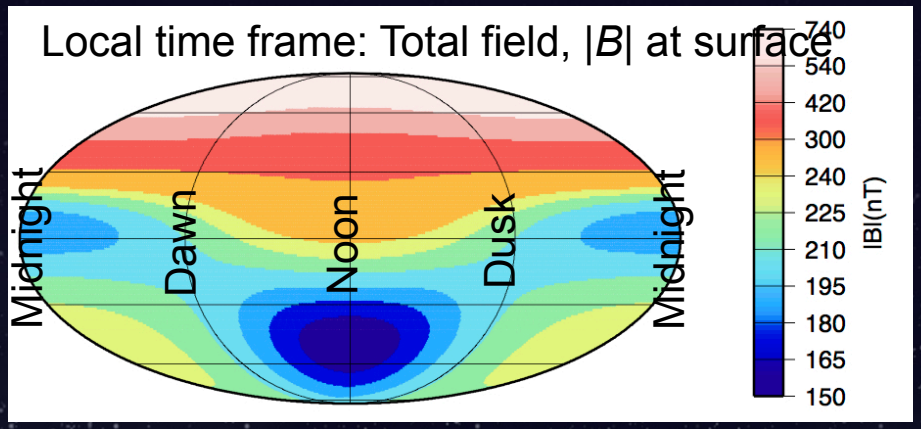


Data: 2nd Mercury year
30°S-90°N



Global Field Structure



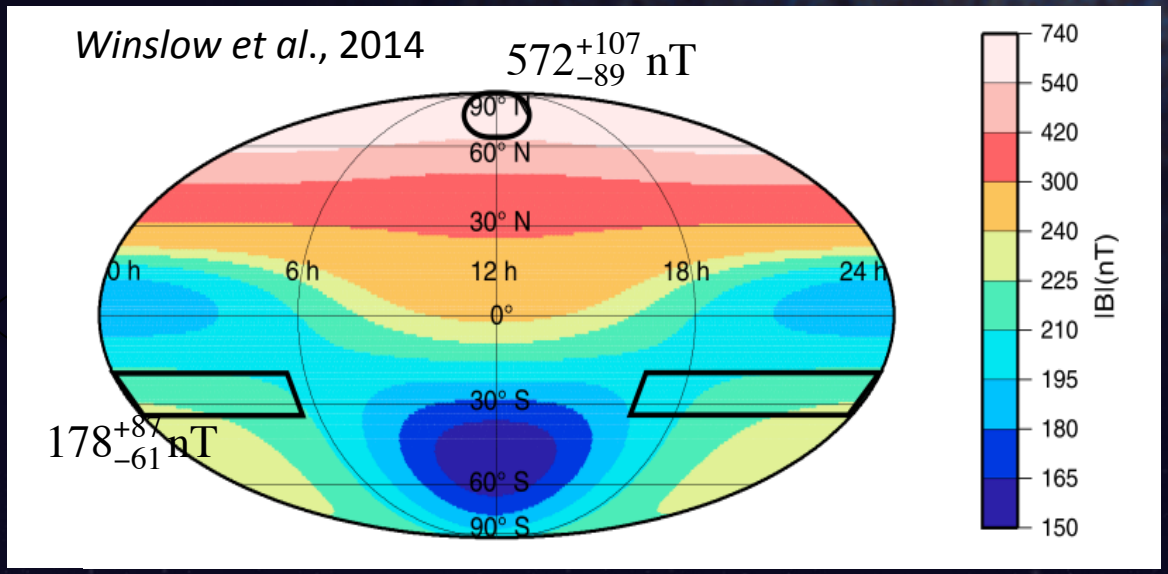


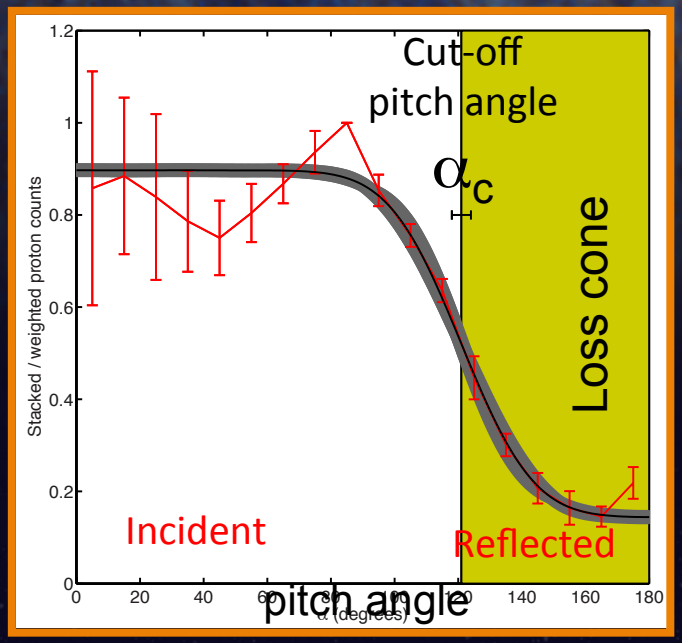
1. Weak dipole moment
2. Axisymmetric
3. Equatorially asymmetry

g_1^0 = -190 nT
g_2^0 = -76 nT
g_3^0 = -23 nT
g_4^0 = -6 nT

→ Accounts for ~90% of signal in the data
→ (2) and (3) new constraints on dynamo models

Proton Reflectometry: Surface Field Strength





Same principals as ER

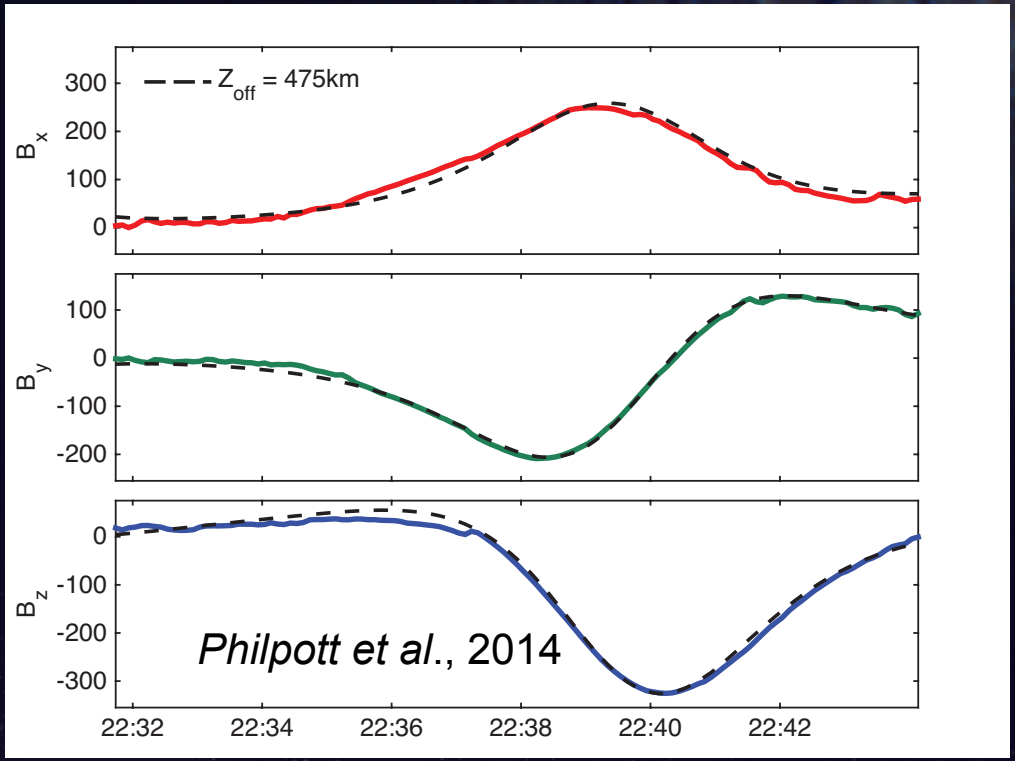
- Use FIPS data - only regional |B| estimates
- Cut-off pitch angle → surface field strength & particle flux

$$B_{surf} = \frac{B_{sc}}{\sin^2 \alpha_c}$$

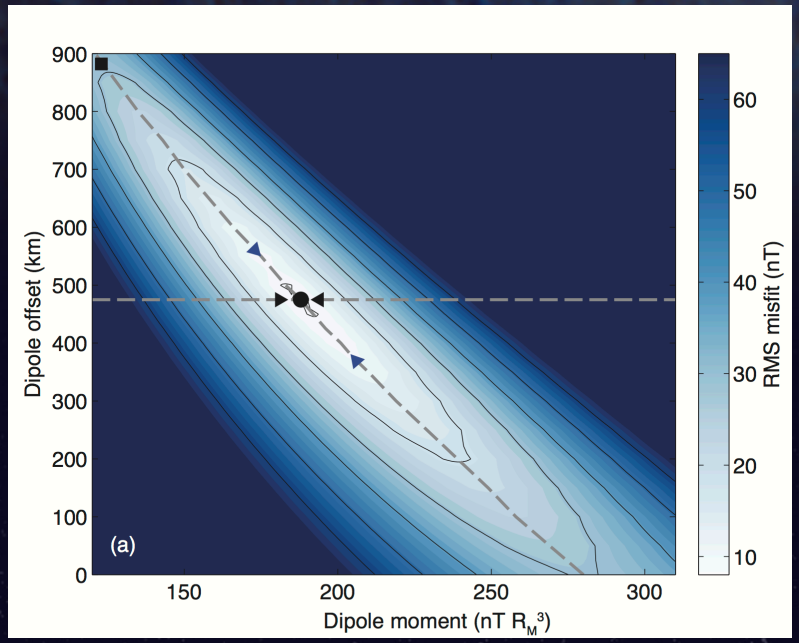
→ Confirms north-south asymmetry in global field

$$\frac{B_{N.Hem.}}{B_{S.Hem.}}$$

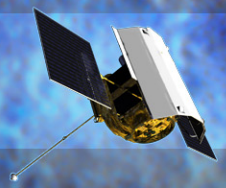
Secular Variation: Mariner 10 to MESSENGER



Re-analysis of data from Mariner 10 3rd flyby



Best fit m = 188 nT R_M^3; Z_d = 475 km
→ Consistent with no secular variation
→ Changes of up to 10% in g_1^0, 16% in g_2^0, 35% in g_3^0 permitted



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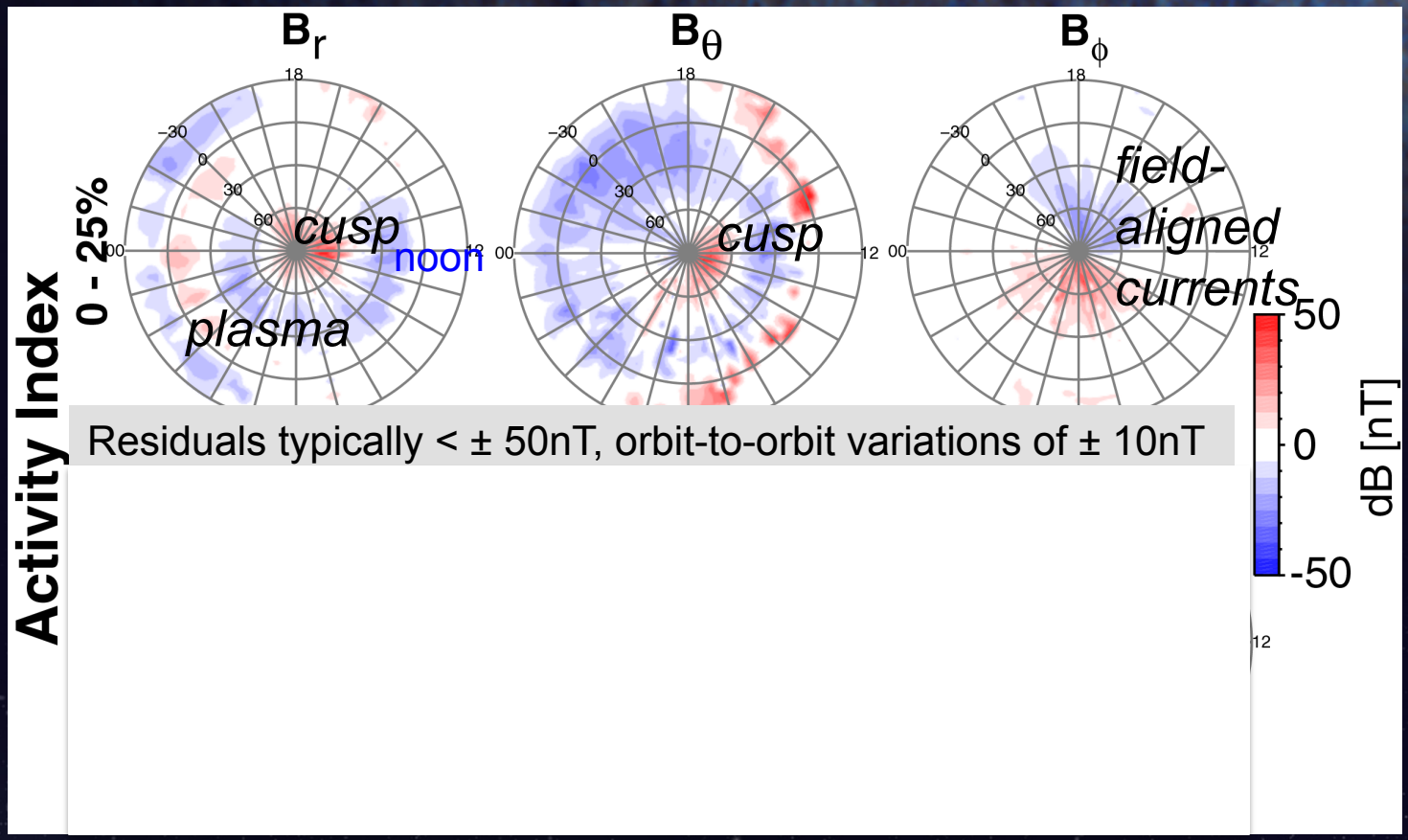
Synthesis / Future Directions – comments and open discussion

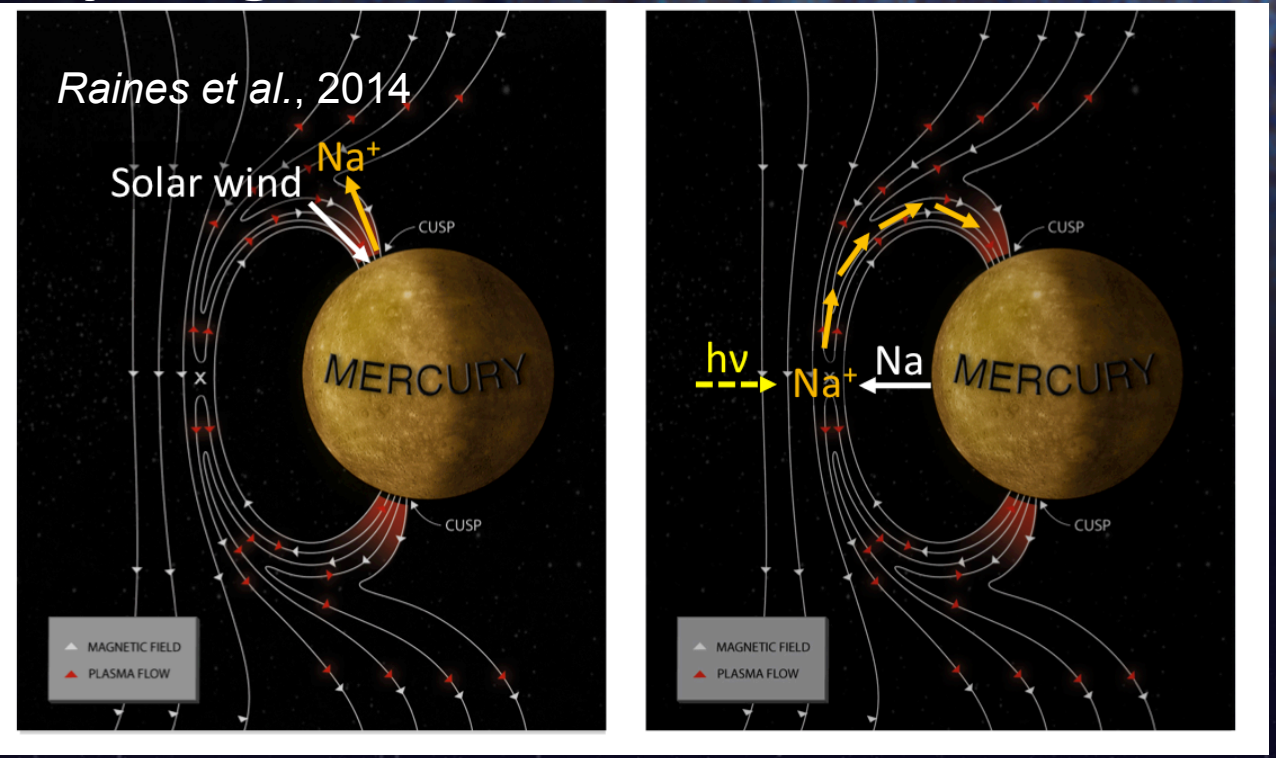
Residuals: Dominated by External Signatures



- Organized in local time and correlate with magnetospheric activity
  → see also Korth et al., Raines et al., talks
- Activity Index: variability at periods < 300s, *Anderson et al.*, 2013

Cusp Regions: Three Plasma Sources

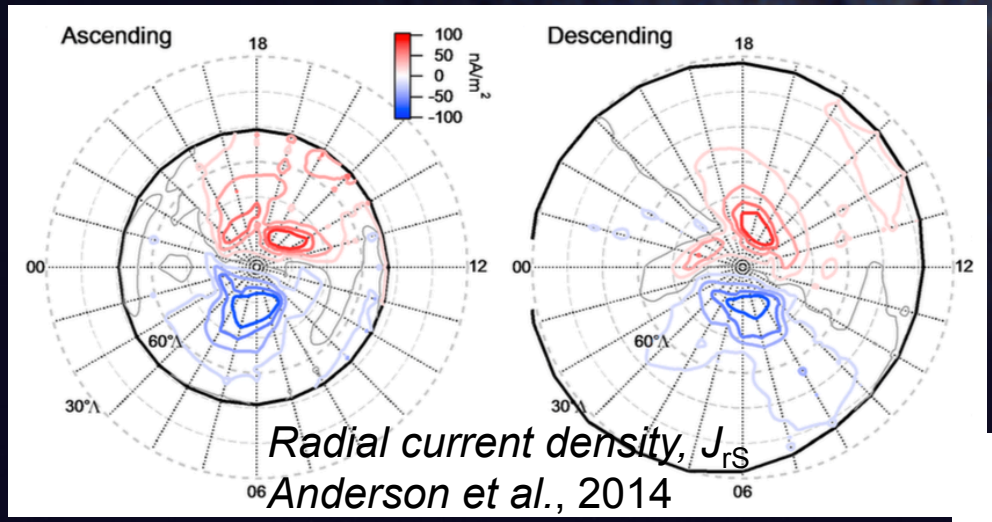
see Raines *et al.*, talk



1. Solar wind H^+ enter on newly reconnected field lines: some precipitate onto surface.
2. Upwelling Na^+ ions may be from surface sputtering.

3. Na ionized near the magnetopause; driven into the cusp by reconnection.

Birkeland Currents



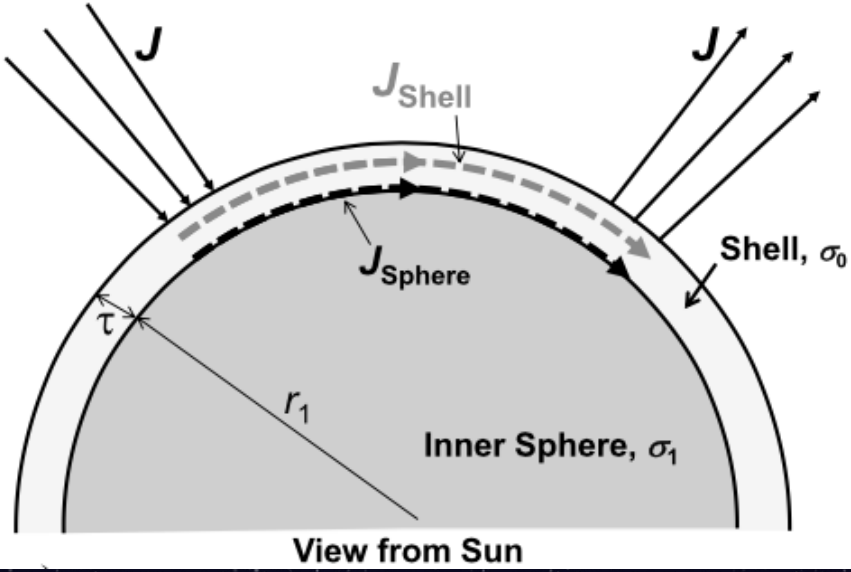
Radial current density, J_{rS}
Anderson et al., 2014

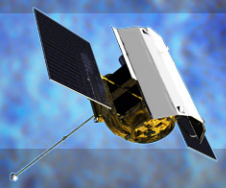
- Dominant quasi-steady large-spatial-scale residual fields
- Increase with decreasing altitude
- Strength correlates with activity index

- Between 50% and 90% of the current closes through the core at about 420 km depth.

see Korth *et al.*, talk

Anderson et al., 2014





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Synthesis / Future Directions – comments and open discussion

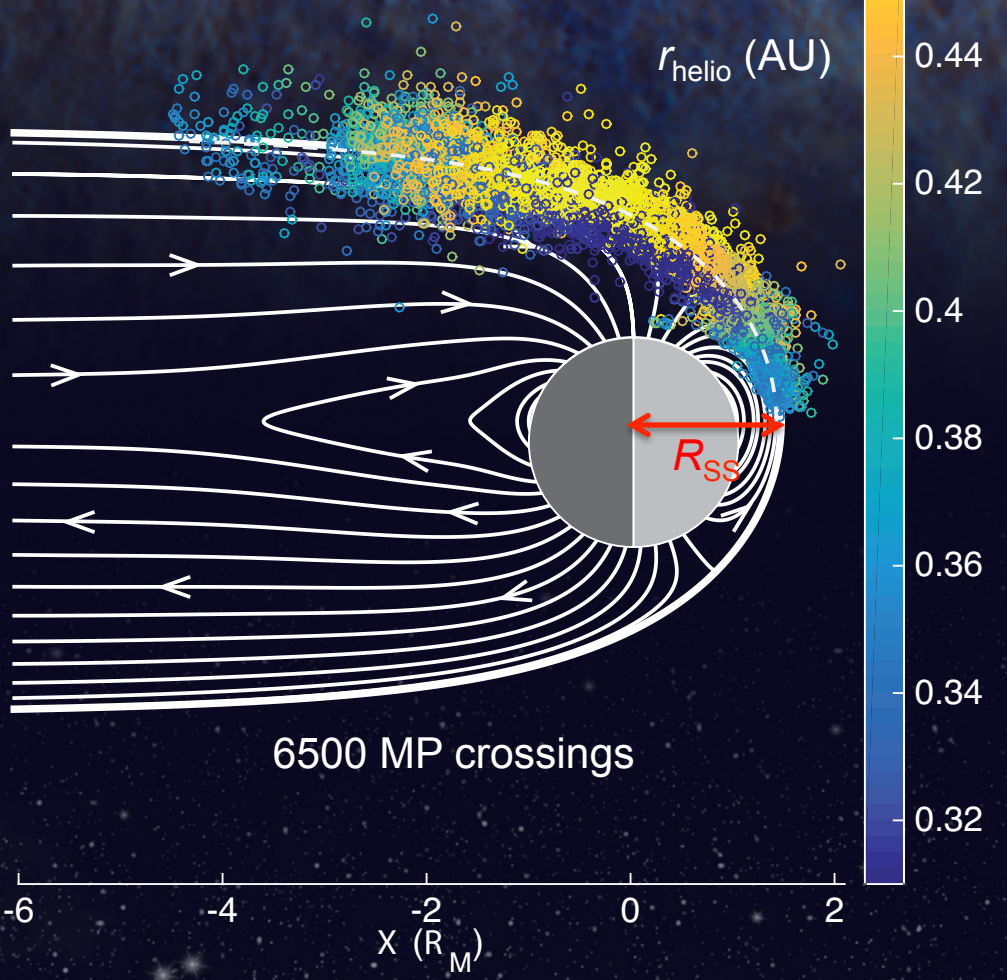
Magnetopause Position: Annual Variations

Magnetopause: R_{SS} = 1.43 R_M

further from planet at aphelion
closer to planet at perihelion

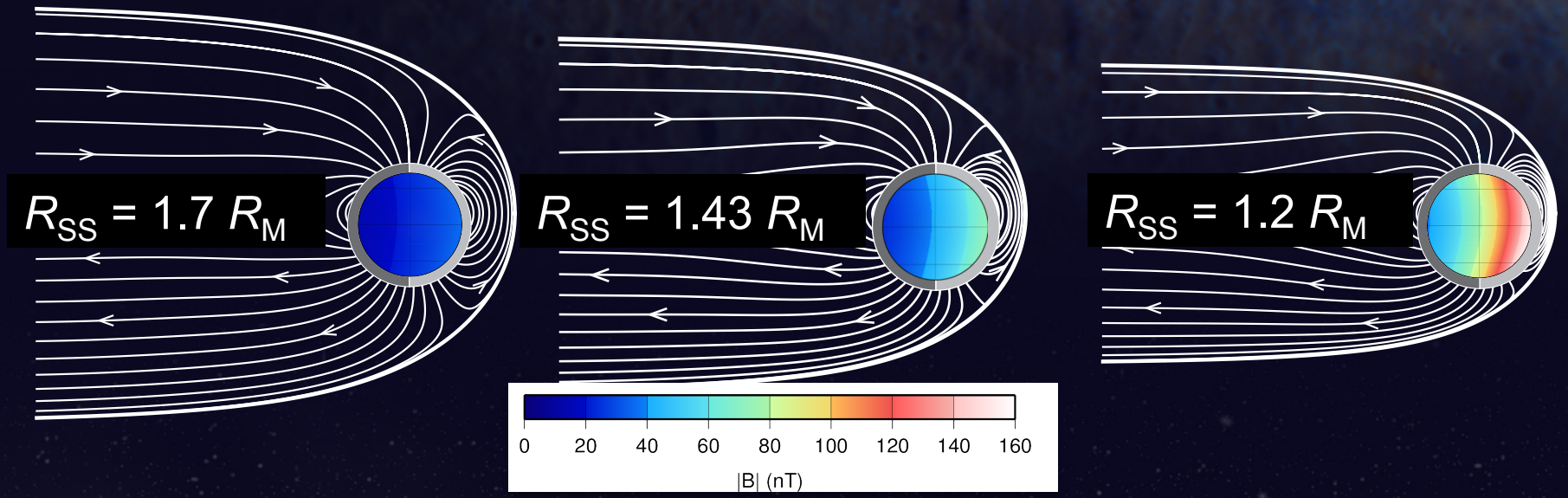
Annual variation in solar wind ram pressure, $\Delta P_{ram} \rightarrow \Delta R_{SS} = \pm 0.1\ R_M$

Larger orbit-to-orbit variations, especially during extreme events



Induced Fields

ΔP_{ram} → ΔR_{SS} → magnetopause field at core surface changes
→ currents at core surface → induced core field

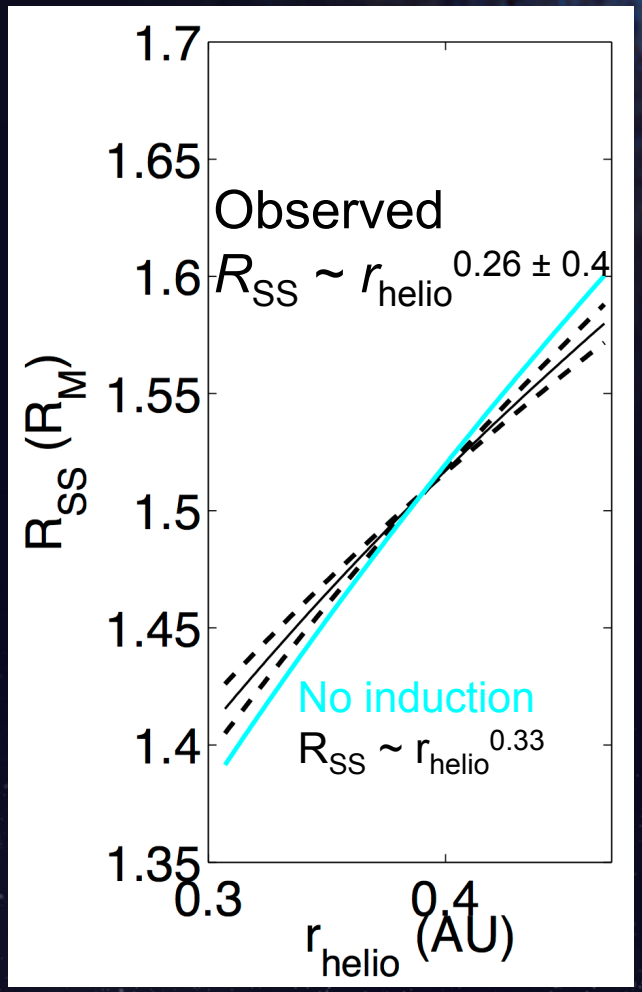


- induced field strength sensitive to core radius
- reduces dayside compression of magnetosphere by solar wind
- diagnostics: ΔR_{SS}, change in dipole moment
- annual signature (small)? aperiodic signals (larger but reconnection)

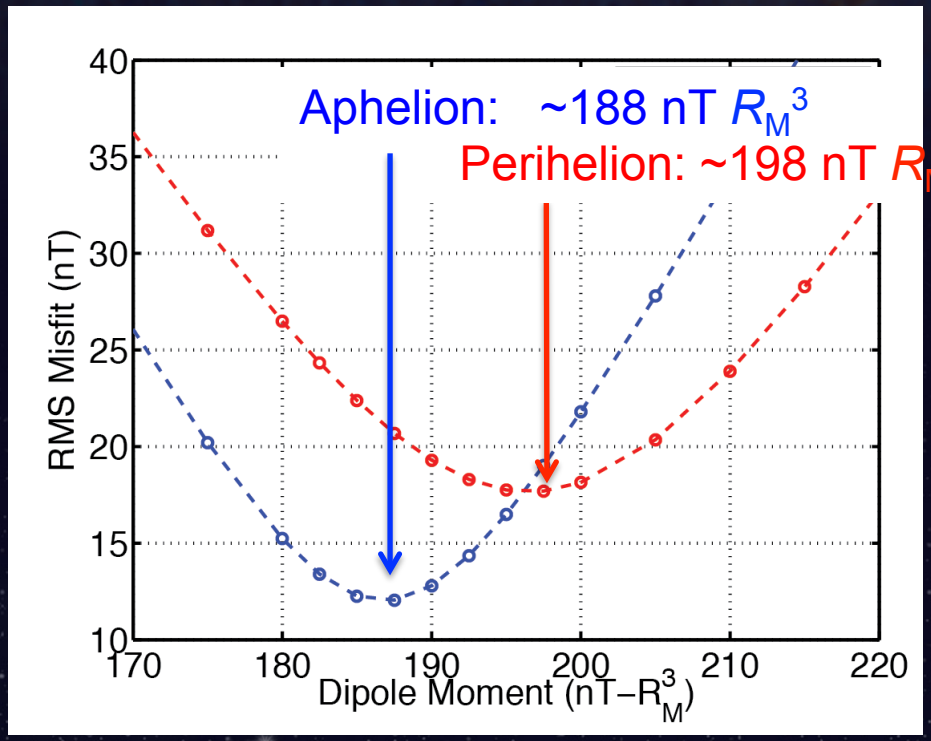
Annual Induction Signal

Induced dipole moment inferred from

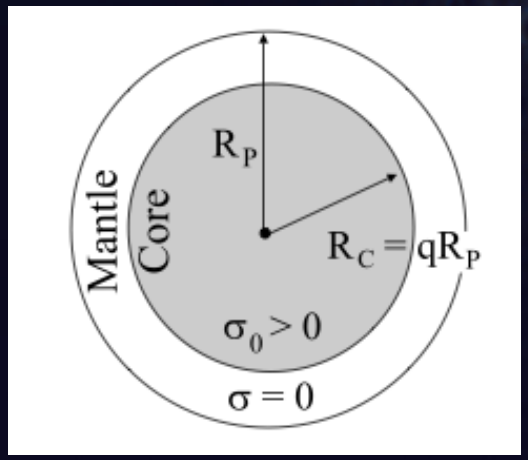
- R_{SS}-r_{helio} variation
- ***B*** inside magnetosphere



Johnson et al., in prep



Induction: Predictions and Implications



Grosser et al., 2004

Induced (core) field / Inducing (magnetopause) field

$$\frac{g_l^m}{G_l^m} = \frac{l}{l+1}\left(\frac{R_c}{R_p}\right)^{2l+1}$$

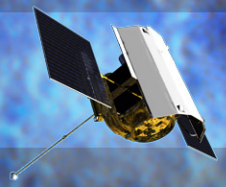
l = spherical harmonic degree
m = spherical harmonic order

Pre-MESSENGER R_c ~ 1800 – 2100 km
MESSENGER R_c = 2020 ± 30 km

Margot et al., 2012; *Hauck et al.*, 2013

- expand MP field in spherical harmonics: dominant terms G_1^0 and G_2^1
- annual ΔR_{SS} signal → Δg_1^0 ~10 nT, Δg_2^1 negligible
- ΔR_{SS} during extreme events → Δg_1^0 ~ 35 nT, Δg_2^1 ~ 20nT

→ Annual induction signature: rules out R_c < ~2000km



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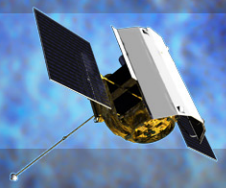


Regional Scale Core Fields?

Measured fields at MESSENGER: 100 – 500 nT

dipole, magnetopause, magnetotail fields: ~90% of signal

unmodeled currents, plasma

- dominate remaining 10% of signal at all altitudes!
- some signals quasi-steady with spatial scales ~12° - 40°
- Birkeland currents increase with decreasing altitudes
- orbit-to-orbit variations ±10nT

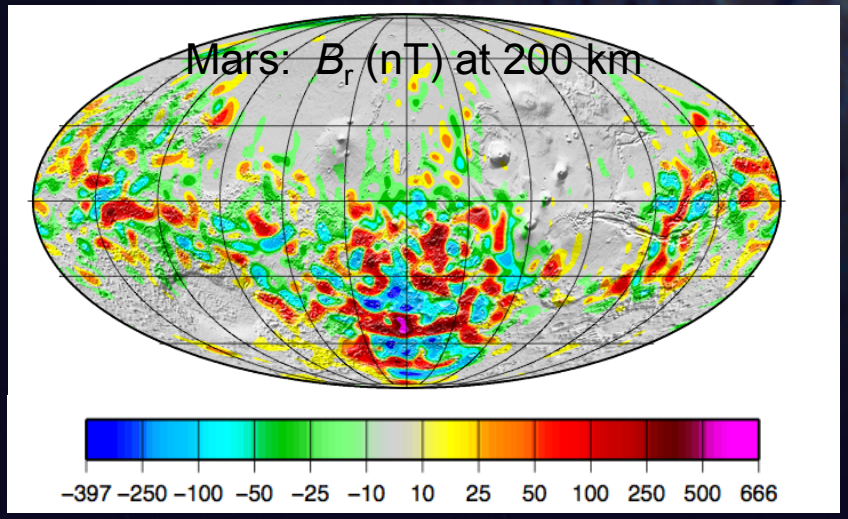
➔ Severe challenges to detecting higher *l,m* core fields

Observations not taken in source free region

Must use quiet orbits, account for these residual external fields

Work to date with MAG residuals and proton reflectometry ➔ ANY residual core fields are very weak

Identifying Crustal Fields: Similar Challenges

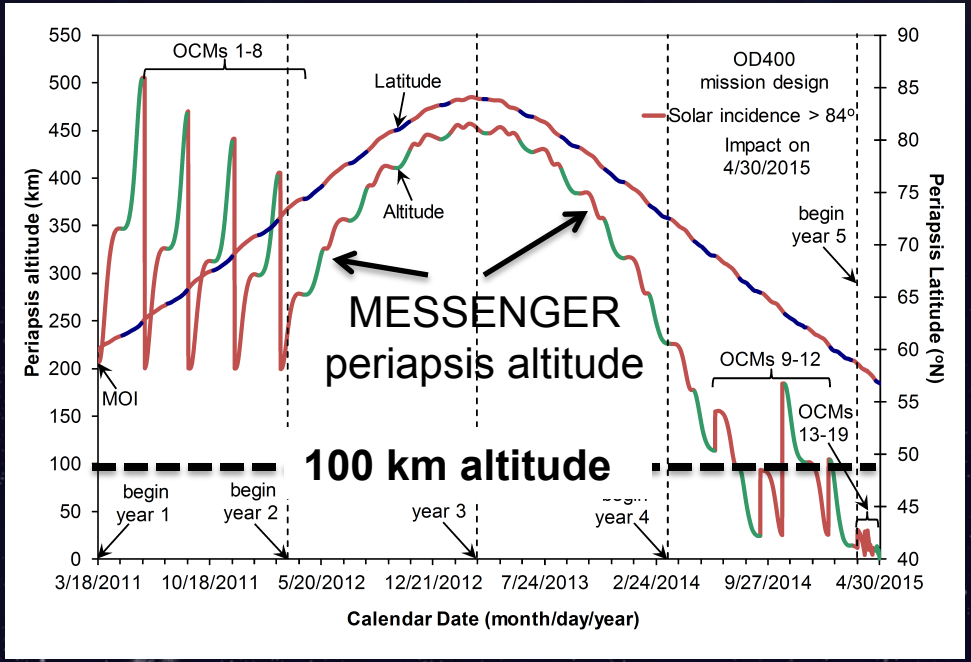


Earth, Mars, Moon crustal fields

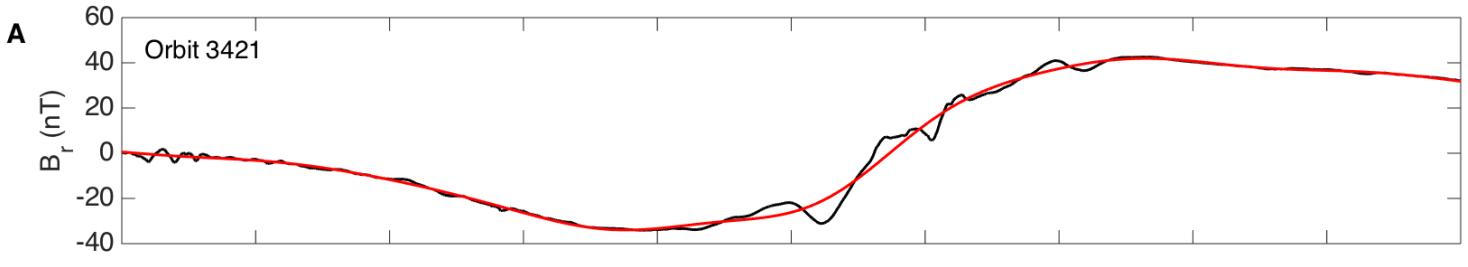
- dominate or major contributor
- easily separated from each other and from external fields

Mercury

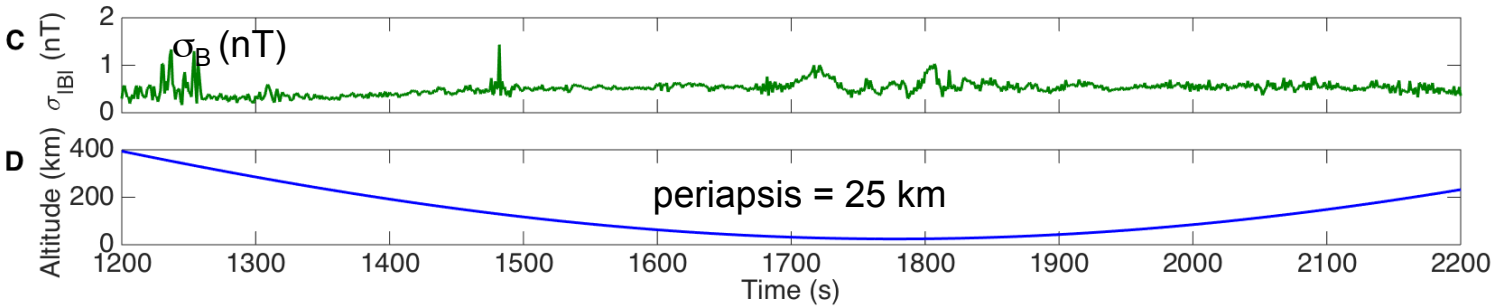
- regional-scale signals dominated by external effects
- BUT, at lowest altitudes might detect short-λ internal signals



Identifying signals at low altitudes

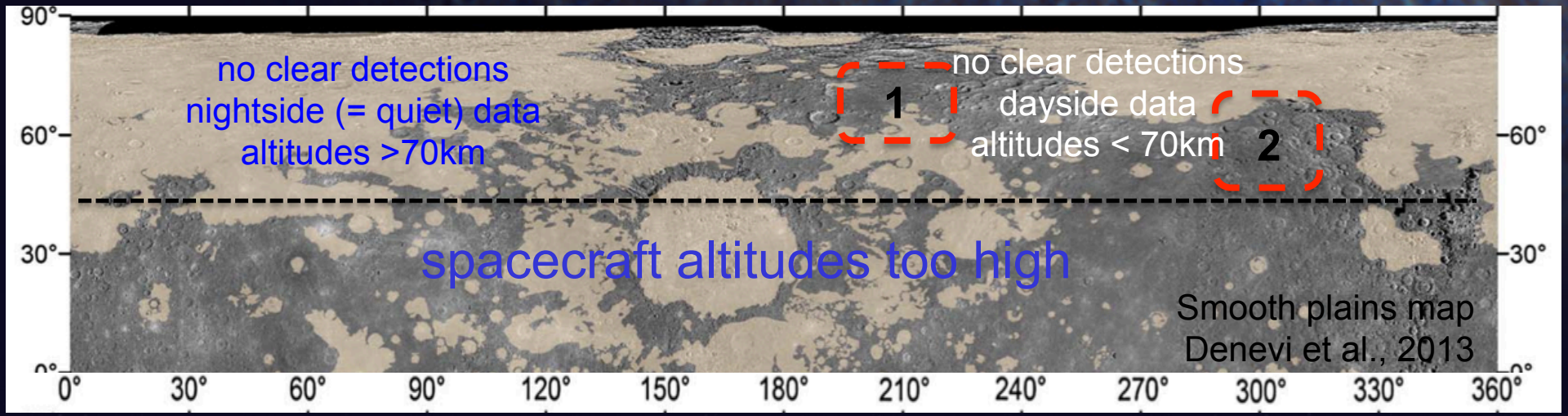


Approach: empirically remove ALL remaining long-λ signal(s) from each orbit, irrespective of origin(s)



Clear signals seen on some orbits at altitudes < ~50 km

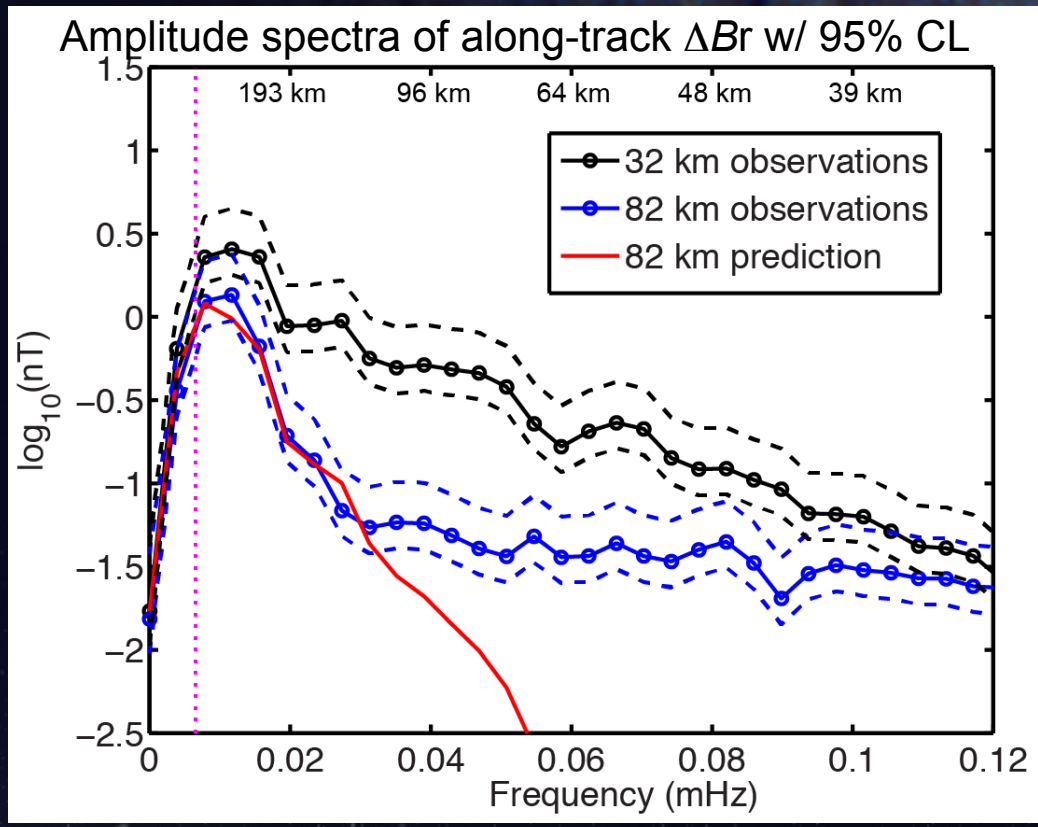
Detections from lowest altitudes in 2014

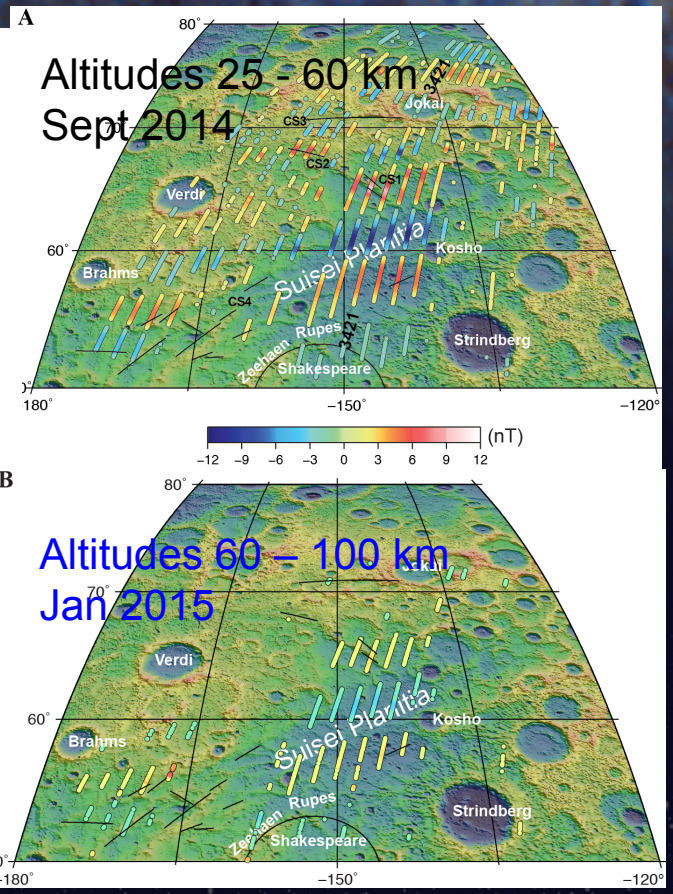


Signals weak: a few nT to ~20 nT

→ require nightside, low altitude data

Upward continuation of signals → internal origin

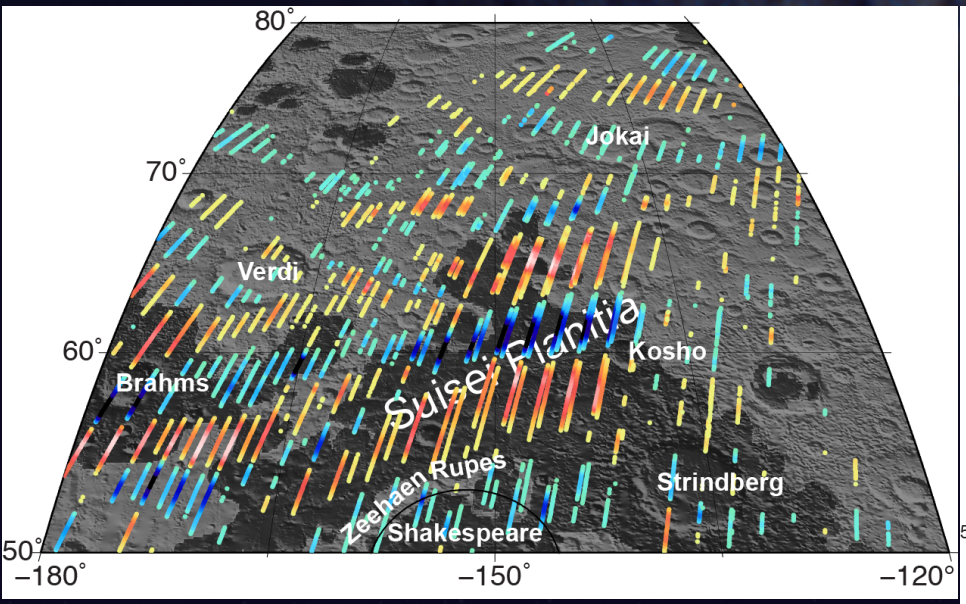


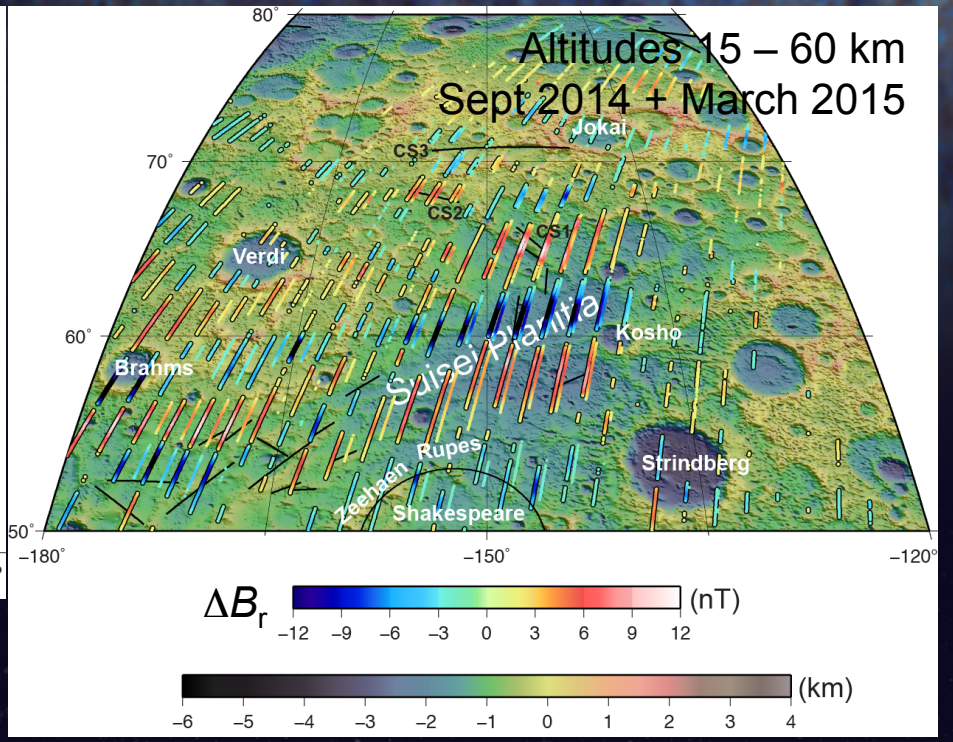


Amplitude ~ exp(-2 π z / λ) → internal source

Wavelength of spectral peak → suggests source depths = 7 – 45 km

Internal Origin: Repeated signals



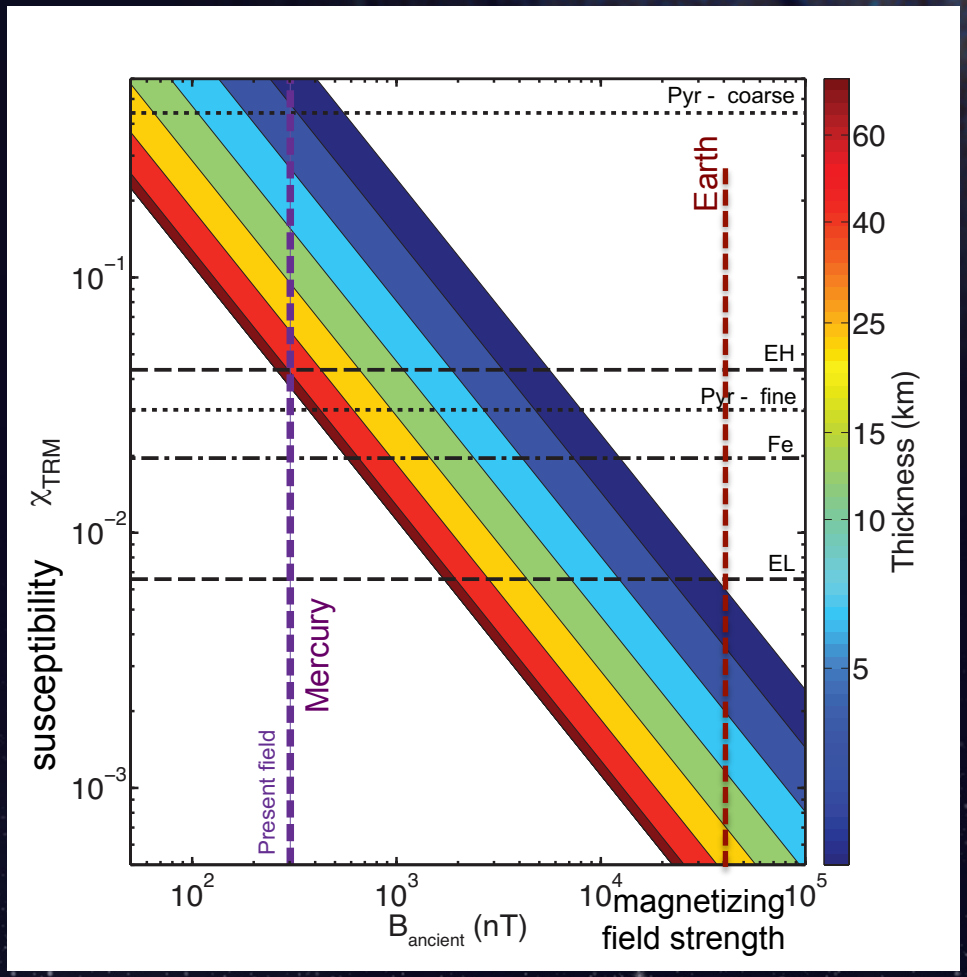


- No obvious association with impact craters, structures
- Stronger signals - smooth plains; weaker - inter-crater plains

➔ Magnetizations weak

➔ Average age remanence ~ age smooth plains: 3.7-3.9 Ga

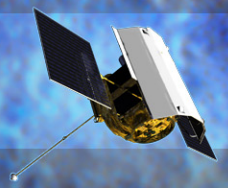
Ancient Field & Magnetic Mineralogy



$B_{crustal} \sim \chi_{TRM} * B_{ancient} * h_{layer}$

- Minerals: pyrrhotite, iron, high-iron (EH) and low-iron (EL) enstatite chondrites
- Susceptibilities, χ_{TRM} scaled for volume fractions consistent with 1.5 – 2 wt% Fe (Nittler et al, 2011; Evans et al., 2012; Weider et al., 2014)
- Induced and VRM contributions possible, but not the whole story
- Thermal preservation possible

➔ $B_{ancient}$ between current Mercury and Earth-like values



Overview

Major magnetospheric fields

- Magnetopause, magnetotail (see Korth et al., talk)
- Core field structure

Residual Fields: Main contributors

- Cusp and equatorial plasma
- Birkeland currents

Other fields of internal origin

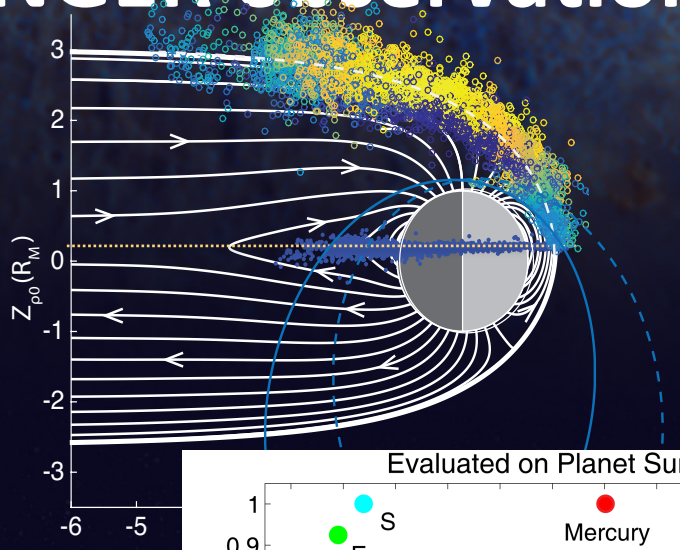
- Time-varying core fields (induced)
- Higher degree and order steady core fields
- Crustal fields

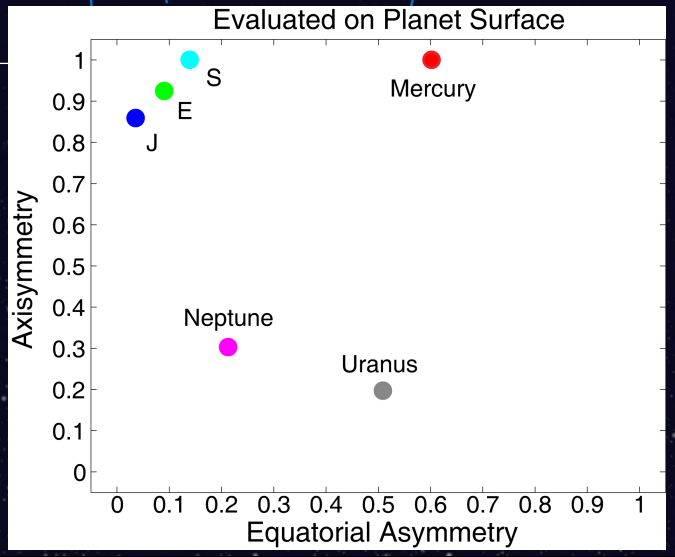
Synthesis / Future Directions – comments and open discussion

Summary I: Global Magnetospheric Structure from MESSENGER observations

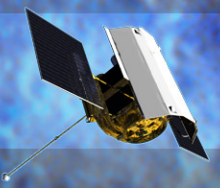
Global magnetospheric model predicts ~90% observed signal

- Magnetopause: R_{SS} = 1.43 $R_{M,}$ annual variation ± 0.1 $R_{M,}$ Shue model shape
- Some information on tail current sheet geometry
- Offset axial dipole internal field
- Secular variation over past 40 yr: best-fit result consistent with no SV





Mercury's core field unusual: strength, axisymmetry, equatorial asymmetry
→ Constraints on dynamo models



Summary II: Residual Fields from MESSENGER Observations

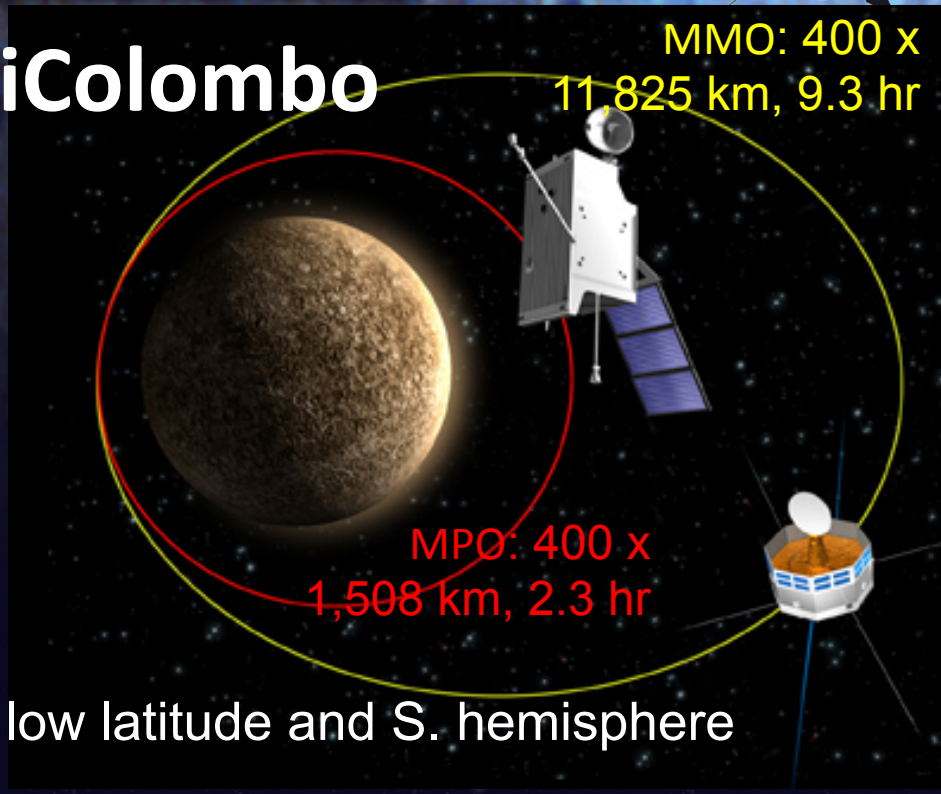
Dominated by unmodeled fields and plasma

- Characterization of N. cusp and equatorial plasma signatures
- Identification of Birkeland currents: close through core

Secondary (but important!) contributions from internal fields

- Identification of annual induction signal (dipole)
- Higher degree and order core fields not yet well characterized but weak
- Crustal fields identified: establish presence of an ancient field

Future: BepiColombo



- Improved global observations at altitudes < 1000 km
  - Equatorial asymmetry
  - Spatial power spectrum at spherical harmonic degrees > 4
  - Characterization of S. cusp
- Additional constraints on secular variation of internal field
- MMO → characterization of dayside low latitude and S. hemisphere magnetopause
- Dual spacecraft observations key to understanding solar wind driving of magnetospheric dynamics – many associated investigations including relative roles of induction and reconnection during extreme events
- If observations at very low altitude are possible these should be targeted at low latitudes / over S. hemisphere → global distribution of crustal fields