Magnetic Fields in Solar System Planets

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- **Magnetic fields are ubiquitous in the Solar System.**

- **All the planets with the possible exception of Venus have or have had magnetic fields.**

- **Even some moons and small bodies have or have had magnetic fields.**
  Ganymede, Vesta, Gaspra

- **Planetary-scale magnetic fields are a window to a planet's interior and provide shielding of the planet's atmosphere and surface for life.**

- **Planetary magnetism poses some of the most challenging problems in planetary physics today. The magnetic characteristics of some planets and moons are difficult to explain.**

How do we measure the magnetic fields of Solar System objects?

Magnetometers on flyby and orbiting spacecraft.

Electron reflectometers on orbiting spacecraft. Lunar and Martian crustal remanent magnetic fields have been mapped by Lunar Prospector and Mars Global Surveyor, respectively.

How do we measure the magnetic fields of extra solar system bodies?

Electron cyclotron maser emission, resulting from an interaction between the planetary magnetosphere and the solar wind in the magnetic polar regions, has been detected from all of the gas giants and the Earth in the solar system.

Ultraviolet emission from planetary auroral regions.

Asymmetric transit light curve due to the bow shock in front of the magnetospheres of hot Jupiters.

Mercury's Magnetic Field

Highly axisymmetric.

Approximately spin aligned.

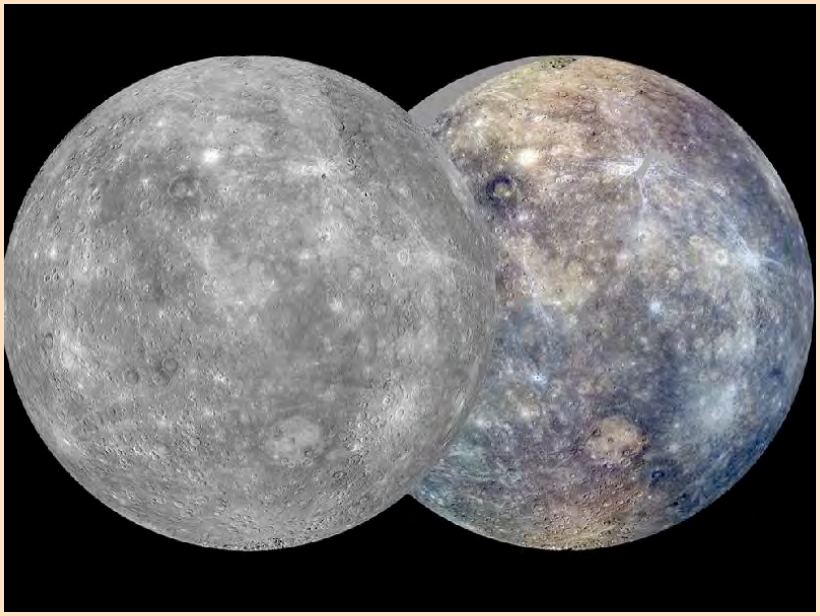
Southward directed.

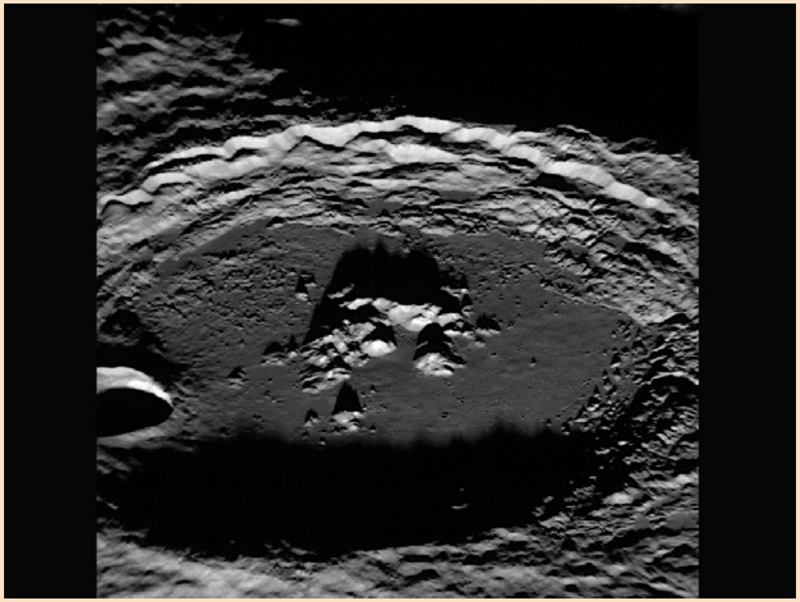
Dipole centered on the spin axis and offset from the center of the planet by 484 km to the north.

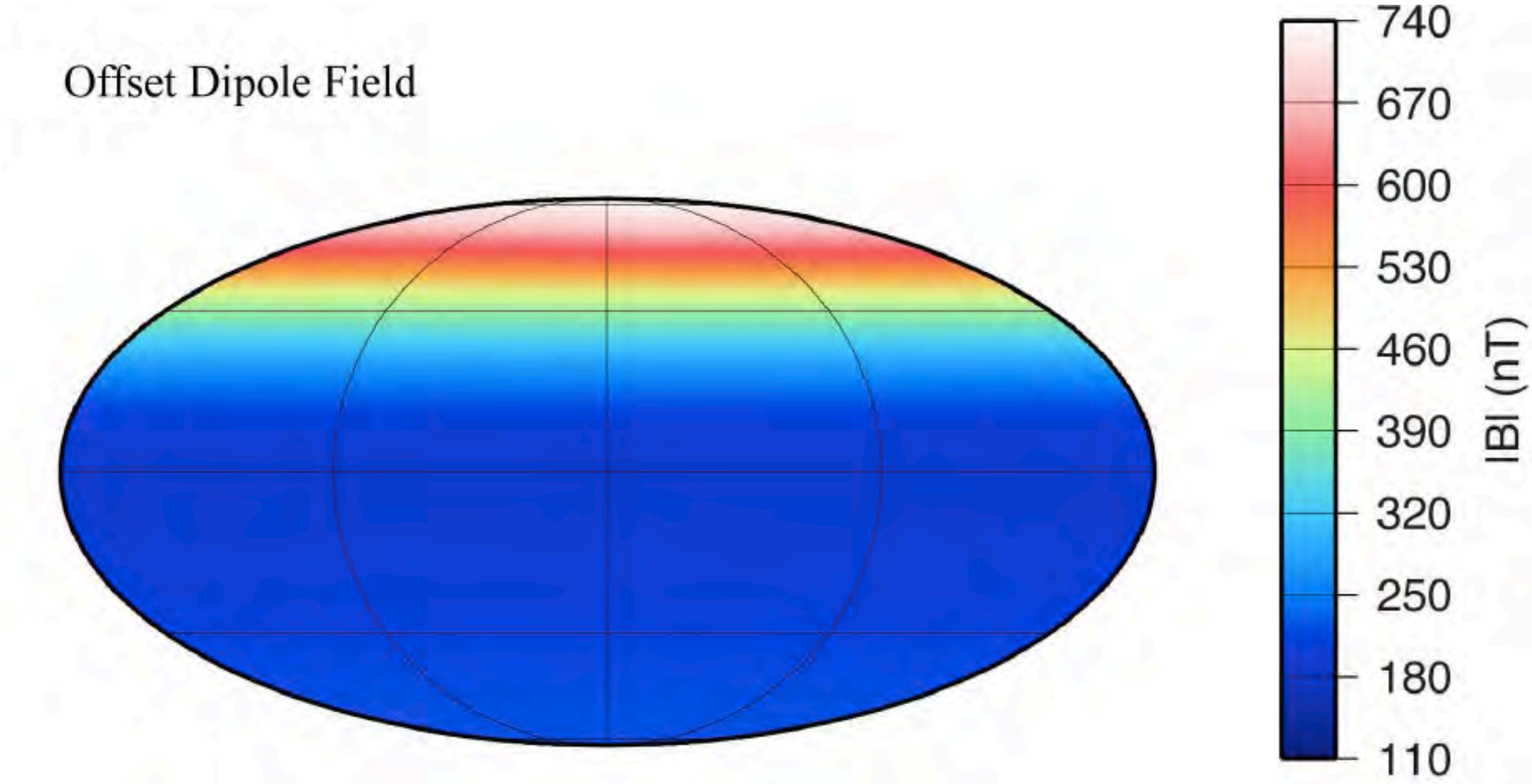
Significant quadrupolar component, g_{10}= -195 nT, g_{20} = -74 nT, g_{20} = 0.38 g_{10} .

Dipole moment 195 nT-R_M^3.

Weakest intrinsic magnetic field in the solar system.







The surface field at the north pole of Mercury is a factor of 3.4 larger than at the south pole.

Mercury

- **Why is the magnetic field so weak? Earth's dipole moment is about 1000 times stronger than Mercury's. Mercury's dipole moment is less than half that of Ganymede even though Ganymede, stripped of its ice shell, has a radius only about 75% of Mercury's radius.**

- **Why is the dipole displaced from the center of the planet?**

- **Why is the magnetic field dominated by a dipole and quadrupole while other multipoles are small?**

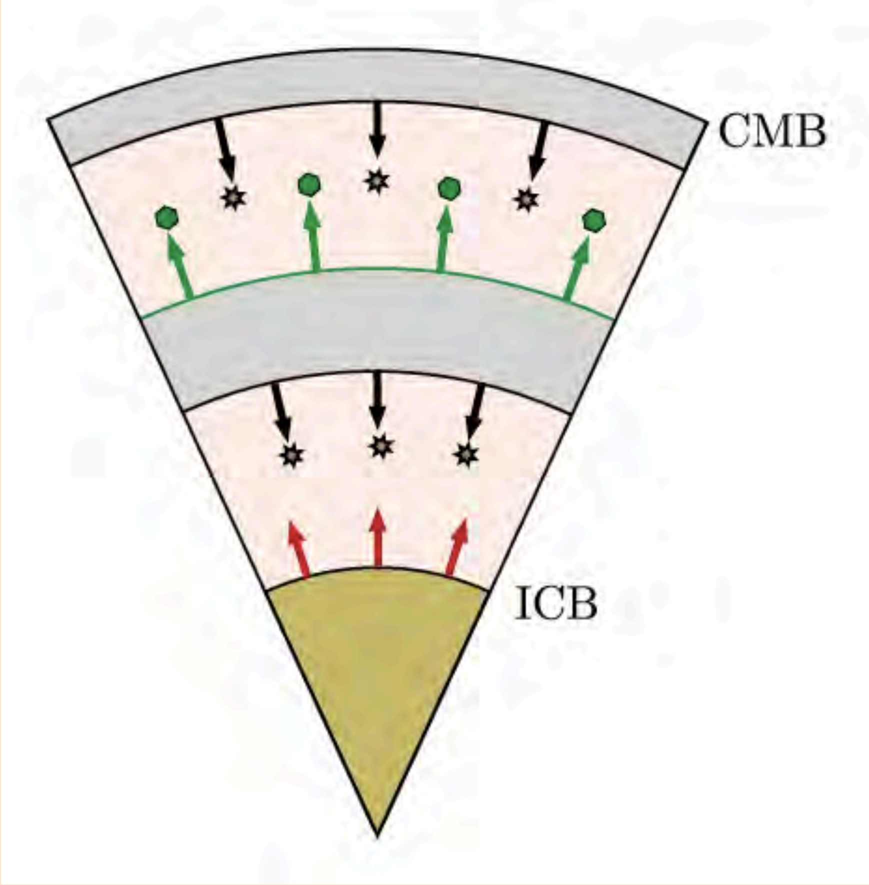
- **Why is the field so highly axisymmetric and nearly spin aligned?**

Mercury’s Weak Magnetic Field

- Attenuation of the internally generated field by an electrically conducting stable layer at the top of the core (Christensen, 2006; Christensen and Wicht, 2008; Manglik et al., 2010).
-
- Dynamo action in a thin layer of Mercury’s liquid core can produce weak external dipole fields (Stanley et al., 2005; Takahashi and Matsushima, 2006).
-
- Dynamo action in a thick layer of Mercury’s liquid core can produce weak external dipole fields (Heimpel et al., 2005).

Mercury's Weak Magnetic Field

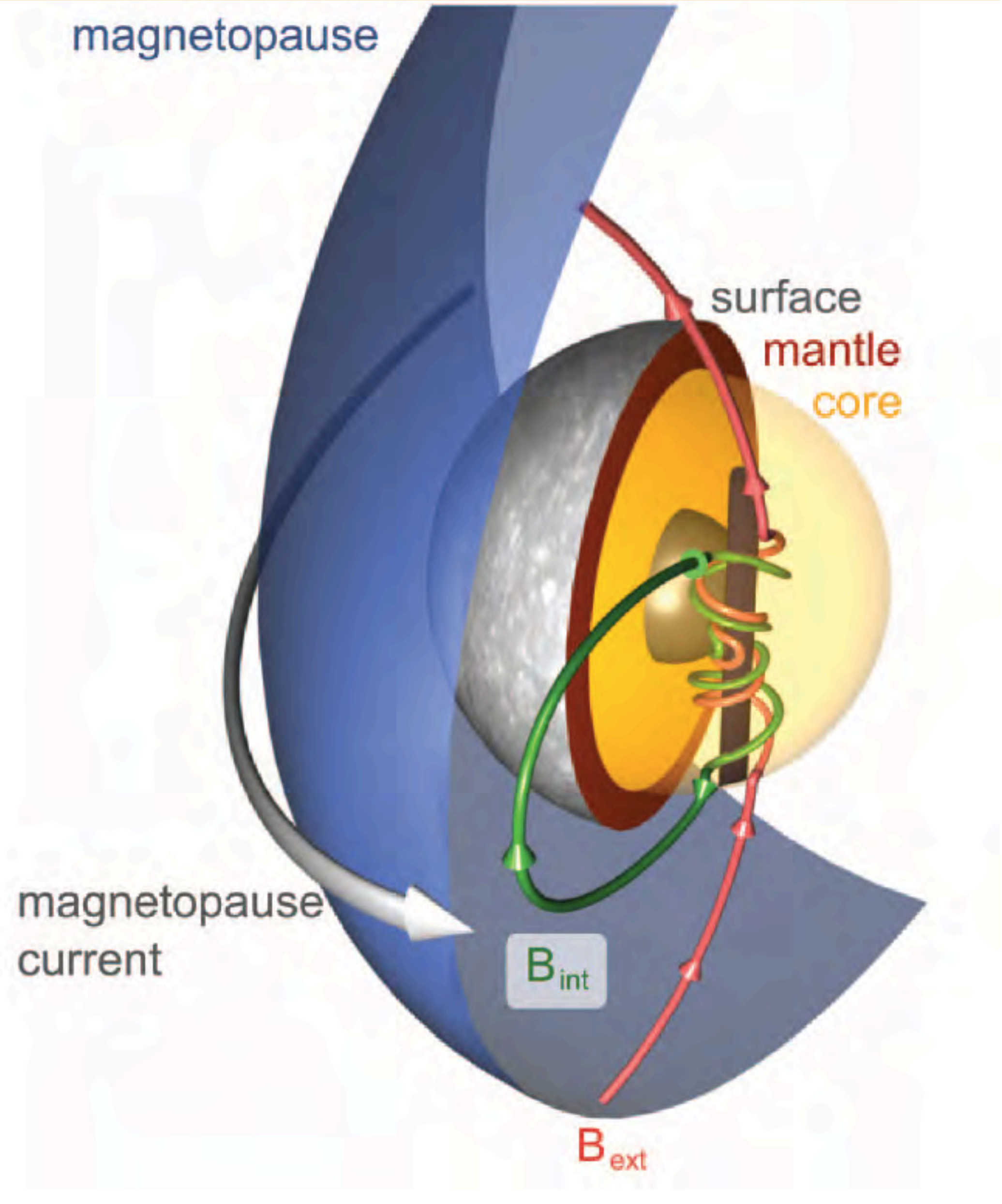
- Conditions in Mercury's core (p,T, S concentration) could lead to a different source of buoyancy driving its dynamo. Vilim et al. (2010) show that core states which include an Fe snow zone midway through the core produce the observed field strength. However, the model produces a large octupole.



Mercury’s Weak Magnetic Field

- Mercury’s dynamo creates a magnetosphere around the planet.
- Chapman-Ferraro currents in the magnetopause generate a magnetic field that opposes the dynamo-generated field.
- This feedback weakens the overall field.

(Glassmeier et al., 2007; Gomez-Perez and Solomon, 2010; Gomez-Perez and Wicht, 2010)



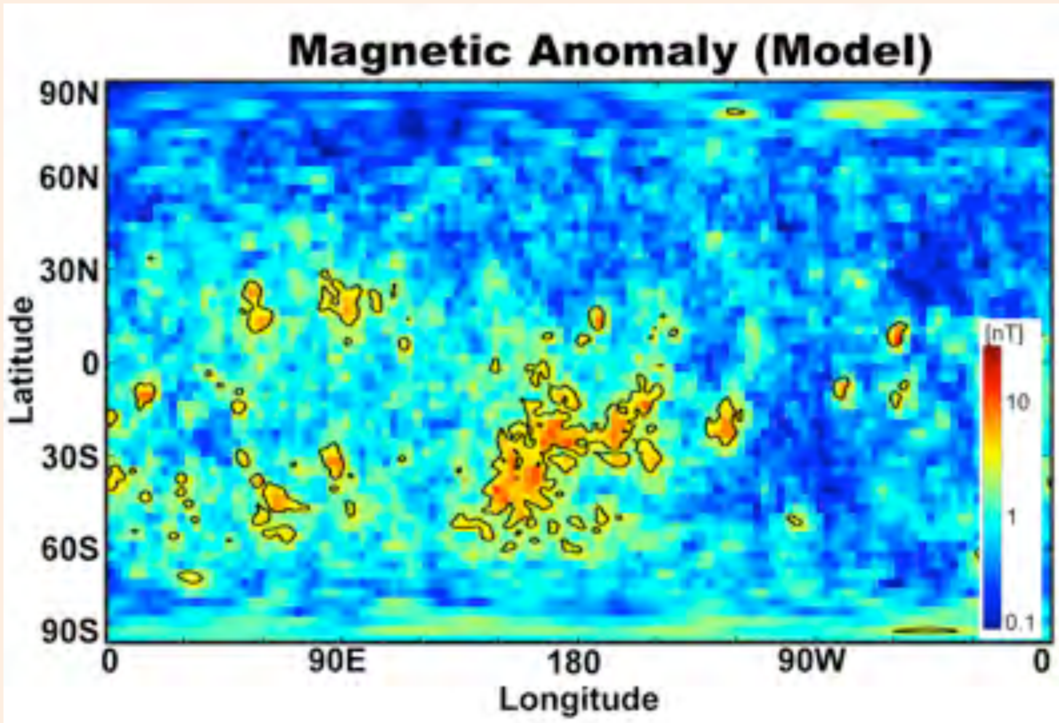
(Heyner et al., 2011)

Moon

- The Moon does not have a magnetic field at present but parts of its crust are magnetized.

- Lunar magnetic anomalies are generally isolated and small-scale.

- Some of the largest magnetic anomalies are antipodal to major impact basins, particularly Imbrium and Orientale. Magnetic fields within the impact basins themselves are rather weak.



The Enigmatic Lunar Dynamo

It has long been thought that the crustal magnetization of the Moon was acquired during an early period of lunar history when the Moon had an active dynamo.

When did dynamo action begin and how long did it last? Paleomagnetic measurements indicate that a core dynamo probably existed on the Moon 4.2 billion years ago. Magnetization of 3.56 Ga mare basalts suggest that the dynamo lasted for at least 640 Myr (Shea et al., 2012; Suavet et al., 2013).

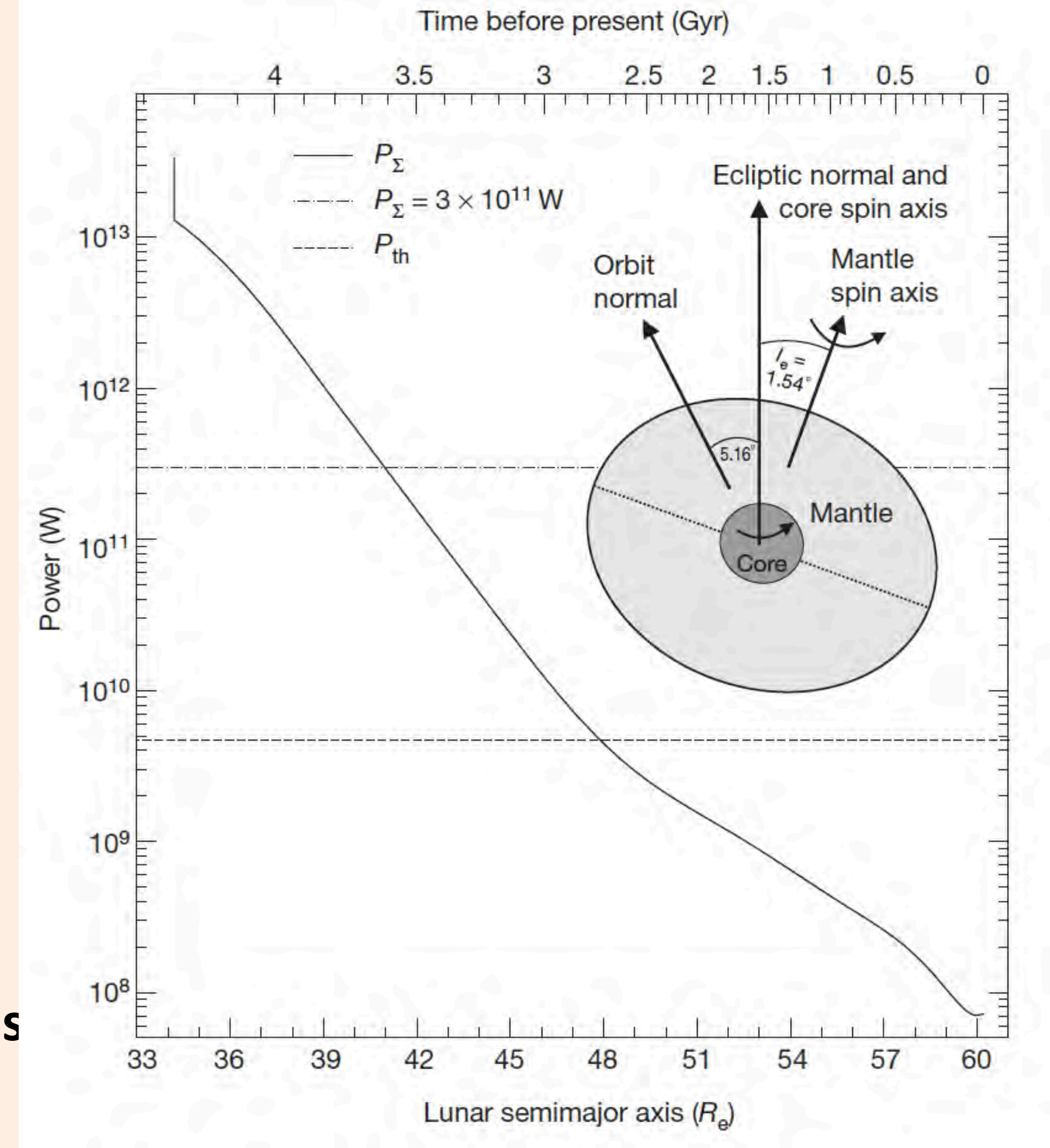
It has been claimed that a thermally convectively driven lunar dynamo would not last for more than a few hundred million years.

What drove the lunar dynamo for so long?

Why isn't more of the lunar crust magnetized?

Precession-Driven Lunar Dynamo

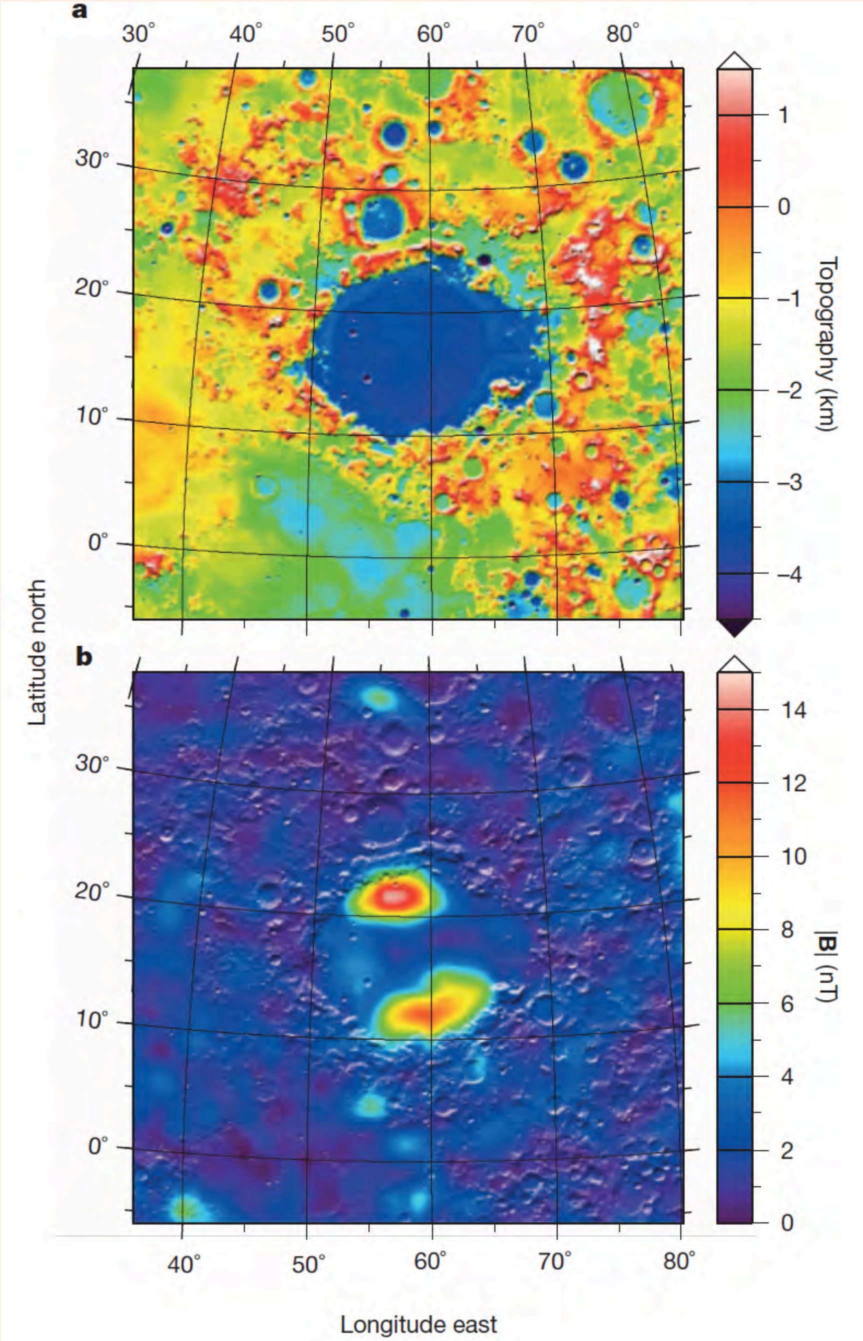
In order to circumvent the limitations of a convectively driven early lunar dynamo, Dwyer et al. [2011] proposed that the dynamo could be driven by mechanical stirring associated with the differential precession of the Moon's core and mantle during an extended period of lunar orbital evolution. Though Dwyer et al. [2011] showed that the precession driven dynamo was energetically feasible, no actual dynamo simulations testing the hypothesis were carried out.



Impact-Driven Lunar Dynamo

Le Bars et al. (2011) have proposed that the lunar dynamo was driven by impact-induced changes in the Moon's rotation rate. Basin forming impact events are energetic enough to have unlocked the Moon from synchronous rotation, and subsequent large-scale flow in the core, excited by the tidal distortion of the core–mantle boundary, could have powered a lunar dynamo. Predicted surface magnetic field strengths are on the order of several µT, consistent with paleomagnetic measurements, and the duration of these fields is sufficient to explain the central magnetic anomalies associated with several large impact basins.

Mare Crisium

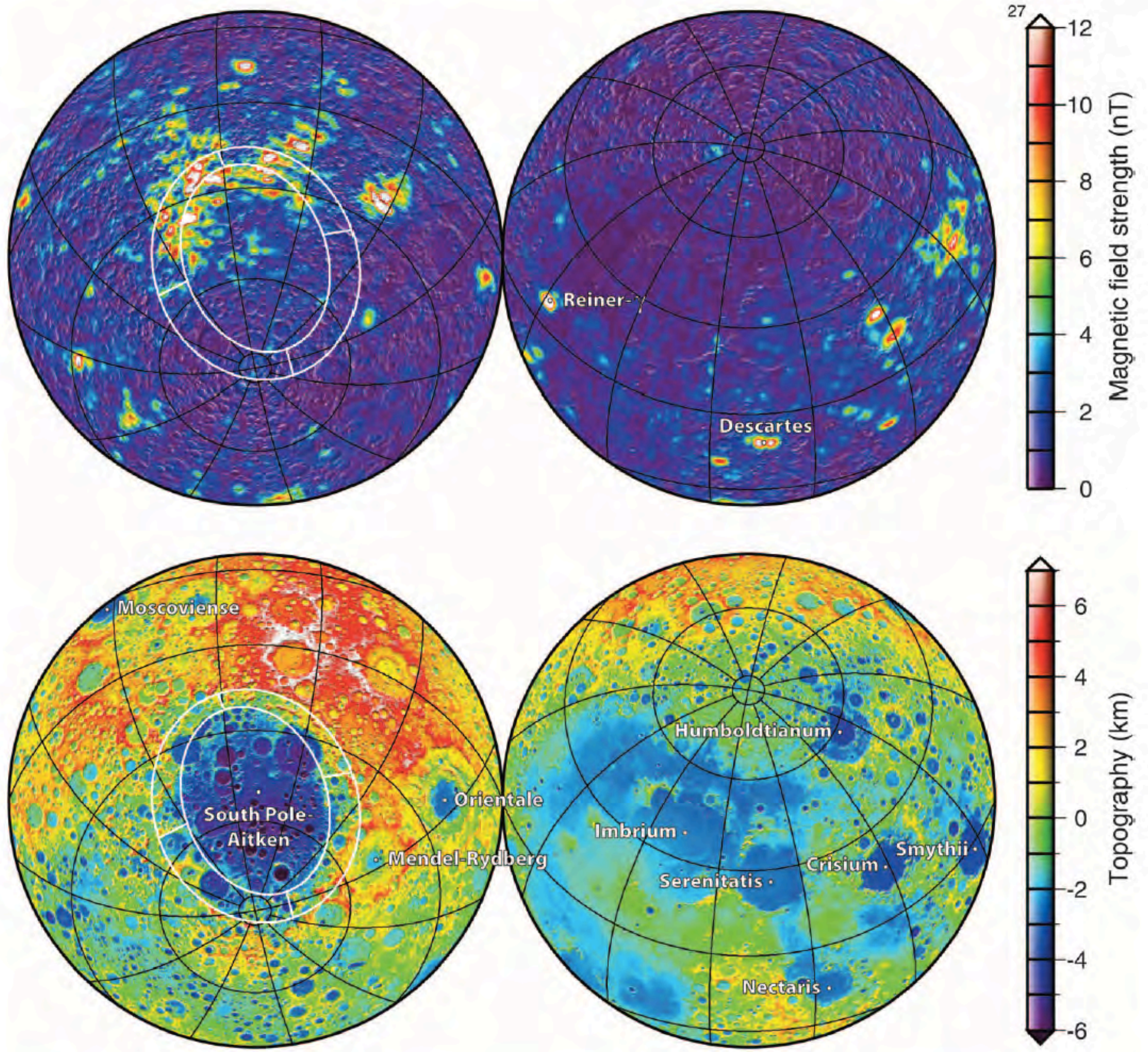


The finding by Suavet et al. (2013) of magnetization in 3.56 Ga mare basalts suggests that the lunar dynamo was continuously active until well after the final large basin-forming impact. This likely excludes impact-driven changes in rotation rate as the source of the dynamo at this time in lunar history (Suavet et al., 2013). Possible persistent power sources for the lunar dynamo are precession of the lunar mantle and compositional convection driven by inner core freezing.

Another Problem

Another difficulty in understanding lunar magnetic anomalies is that they are relatively strong despite the weak magnetism of lunar rocks. They are also localized and relatively few in number. If lunar crustal rocks were magnetized as the crust formed one would expect more widespread crustal magnetization on the Moon.

To deal with these issues Wieczorek et al. [2012] proposed that lunar magnetic anomalies were formed from the more magnetic materials of impacting bodies. They showed that the most prominent group of lunar anomalies could be explained by highly magnetic extra-lunar materials from the projectile that formed the South Pole Aitken basin, the largest and oldest impact crater on the Moon. It is still required in this scenario that a lunar dynamo be operating at the time of the impact when the extra-lunar material is cooling below the Curie temperature.

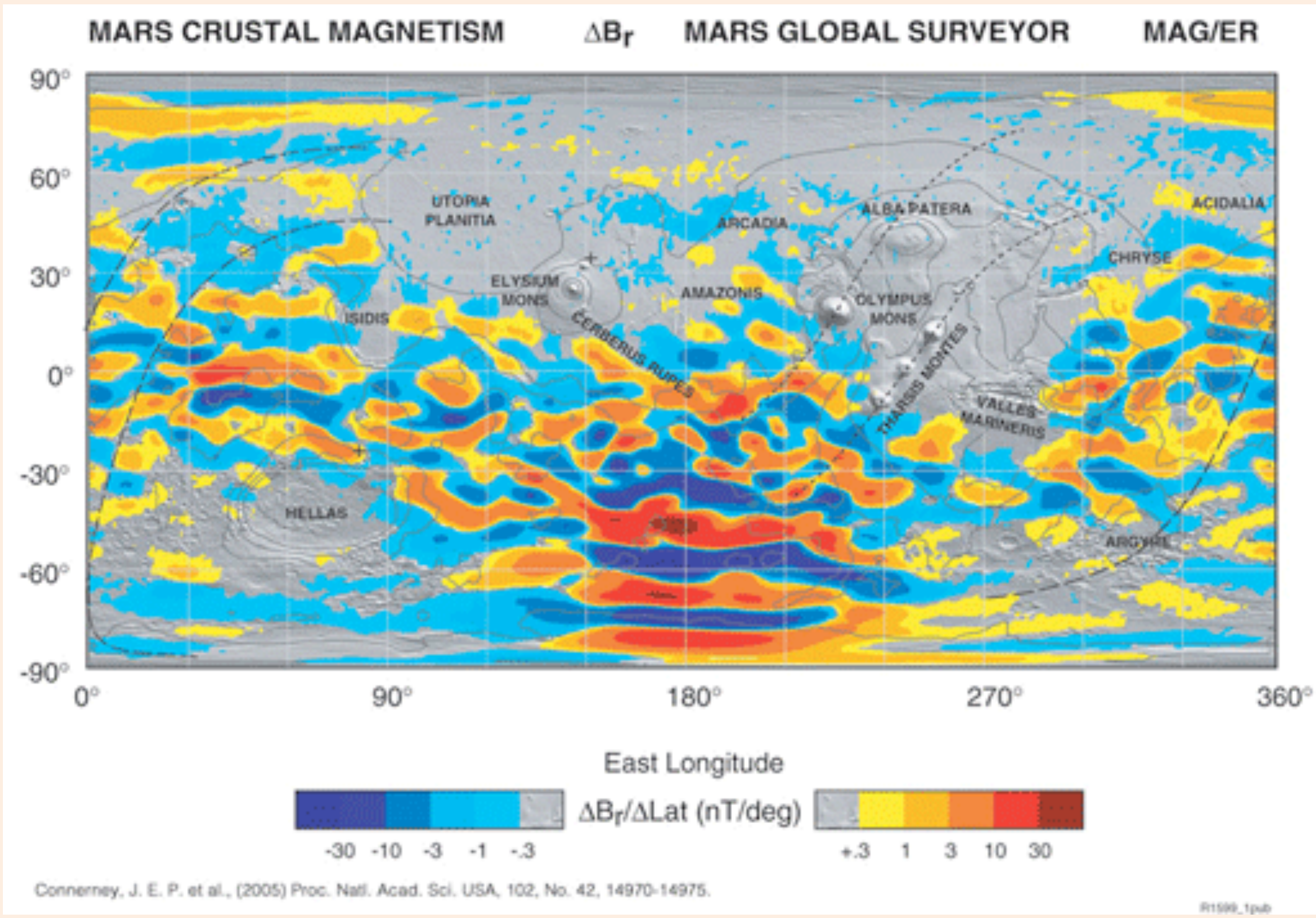


(Wieczorek et al., 2012)

Clearly, lunar magnetism raises a number of questions whose answers have profound connections with the thermal, orbital, and impact histories of the Moon.

Mars

Mars does not have a magnetic field at present but its crust is highly magnetized and it must have had an active dynamo early in its history.



When was the Martian Dynamo Active?

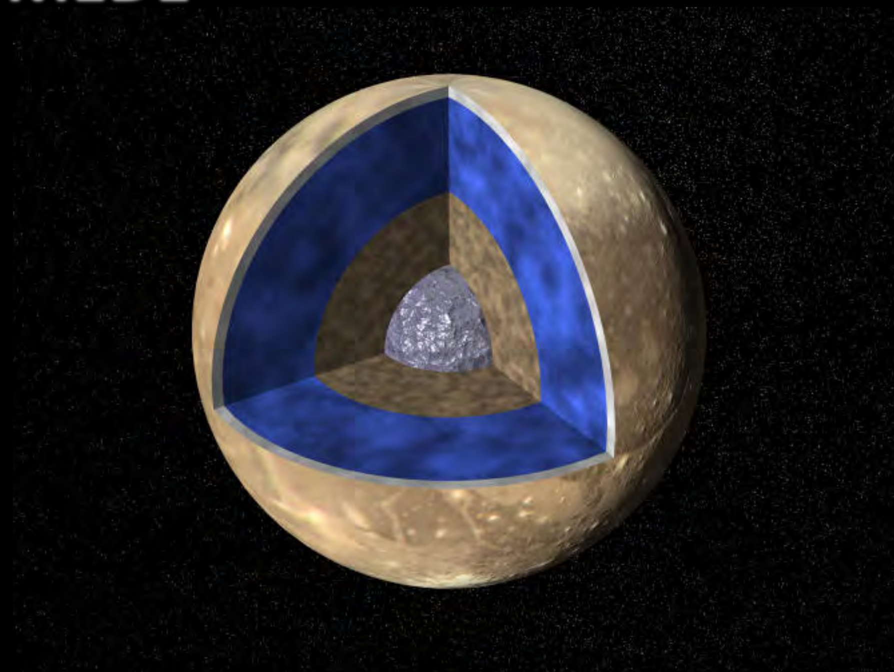
It has been argued that the dynamo was active in the early Noachian (first Martian geologic period) and ceased to operate prior to the formation of the Hellas impact basin about four billion years ago (Acuña et al., 1999; Acuña et al., 2001).

Schubert et al. (2000) proposed that the onset of dynamo activity could have postdated the formation of Hellas with continued operation into the Hesperian or Amazonian periods.

Another possibility is that the Martian dynamo was active for part of the Noachian prior to the Hellas impact and was re-activated after the Hellas event (Lillis et al., 2005).

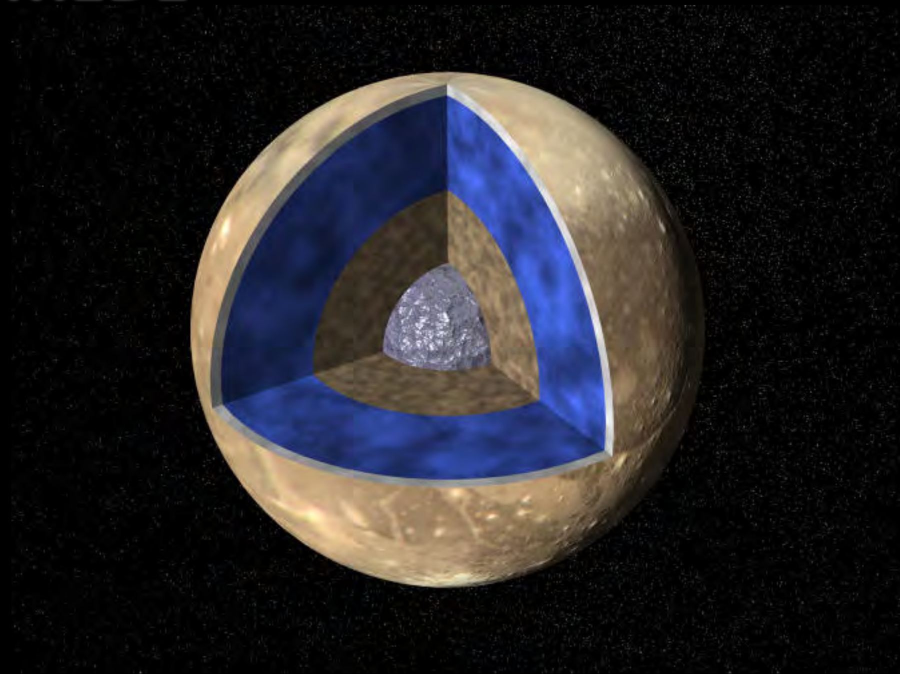
A recent study of the magnetic anomalies associated with the volcanic structures Tyrrhenus Mons and Syrtis Major, suggest that the Martian dynamo was active in the Hesperian and that polar wander has occurred (Milbury et al., 2012).

GANYMEDE

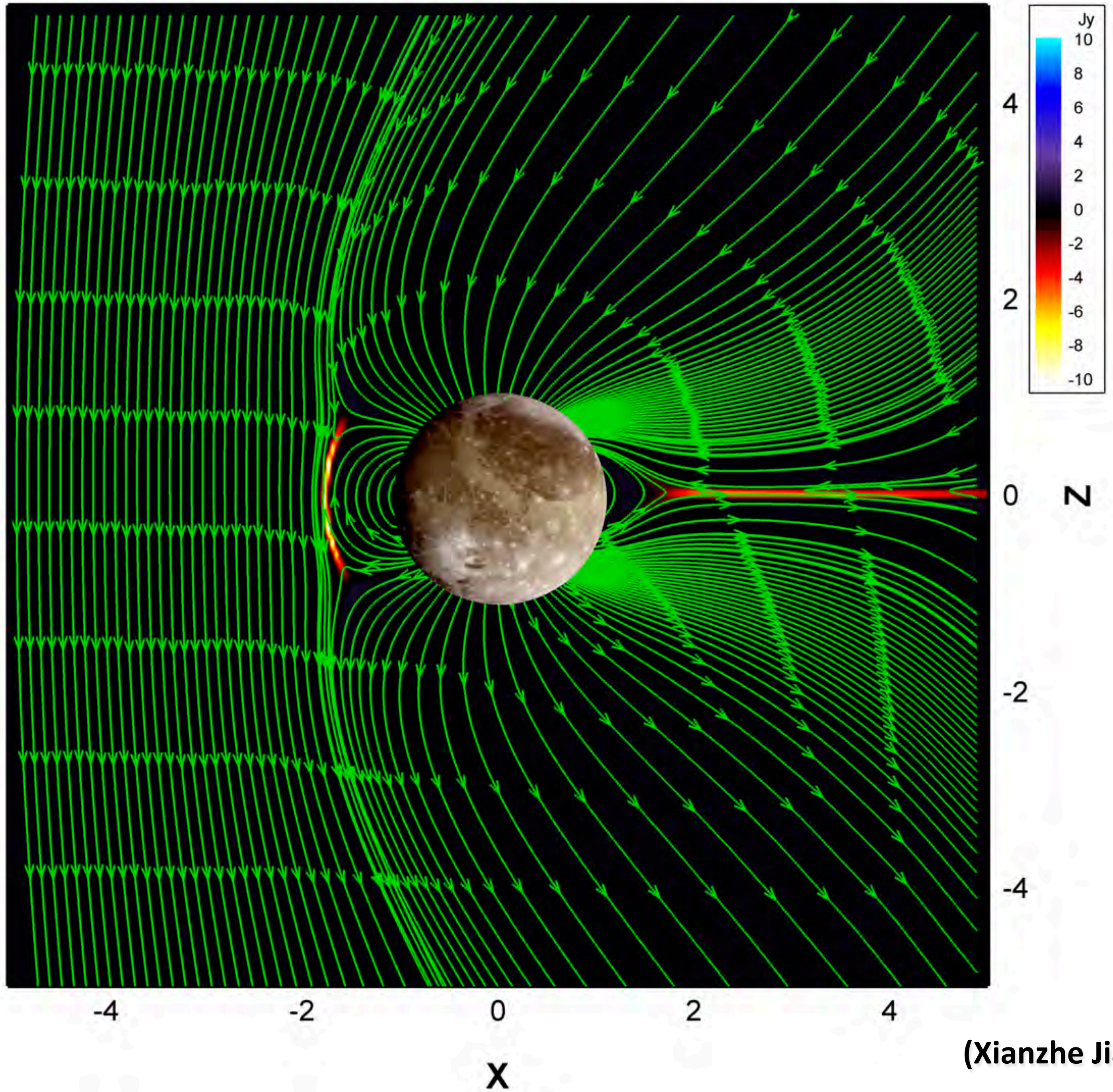


- Jupiter’s moon Ganymede, which is larger than the planet Mercury, is the only moon in the solar system known to have a magnetic field.
- Galileo measurements suggest that the field is nearly axially-aligned and dipole-dominated with a mean surface strength of about 1 µT.
- Ganymede’s magnetic field at the ice-rock boundary is 3 µT assuming an ice shell thickness of about 900 km, about an order of magnitude larger (smaller) than Mercury’s (Earth’s) surface field.
- Ganymede has its own magnetosphere inside Jupiter’s magnetosphere.
- Ganymede’s magnetic field is generated by dynamo action in a liquid iron core.

GANYMEDE



- Ganymede's magnetic moment is about 1.3×10^{13} T m^3 , about 3 times larger than the magnetic moment of Mercury.
- The dipole is tilted about 176° with respect to the rotational axis.
- The magnetic field at the equator is about 719 nT and is directed opposite to the Jovian field. The Jovian field at Ganymede is about 120 nT.



(Xianzhe Jia)

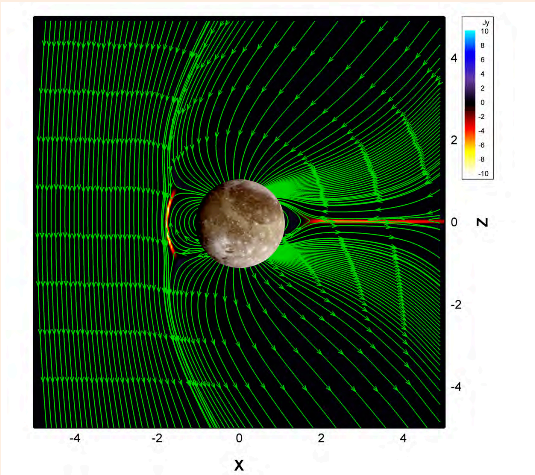
Generation of Ganymede's Magnetic Field

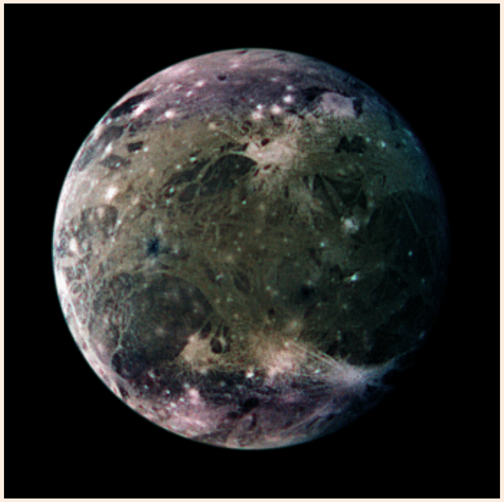
Similar to Mercury, Ganymede's dynamo acts in a relatively low pressure, low temperature environment compared with the Earth. Solidification of Ganymede's core and the associated compositional driving of its dynamo might then be completely different from the freezing out of Earth's core and the compositional buoyancy driving the geodynamo. According to Hauck et al. (2006), Ganymede's dynamo can be driven in part by compositional buoyancy released through the sinking of Fe snow formed below the core-mantle boundary or by the upward flotation of solid FeS formed in the deep core.

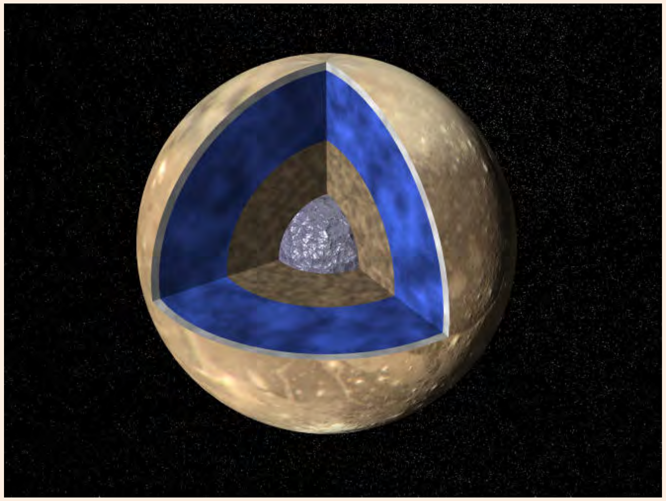
Though Ganymede is larger than Mercury, the silicate-metal part of the satellite is only about the size of Io and the Moon, and Ganymede's core is at most about half that large (Schubert et al., 2004). It is perhaps surprising that such a small core could support dynamo action over a geologically long time. What supplies the energy to drive the dynamo? Why is the core not almost completely solidified?

Powering Ganymede's Dynamo

At Ganymede's core pressures convection can be driven by growth of a solid inner core, Fe snow and FeS flotation. Dynamo calculations by Zhan and Schubert (2012) have shown that multipole-dominant magnetic fields are generated by Fe-snow, while dipole dominant dynamos are produced by FeS flotation and inner core growth. Ganymede's present dipole-dominant magnetic field suggests that the Fe-snow process does not play a primary role in driving Ganymede's core convection.



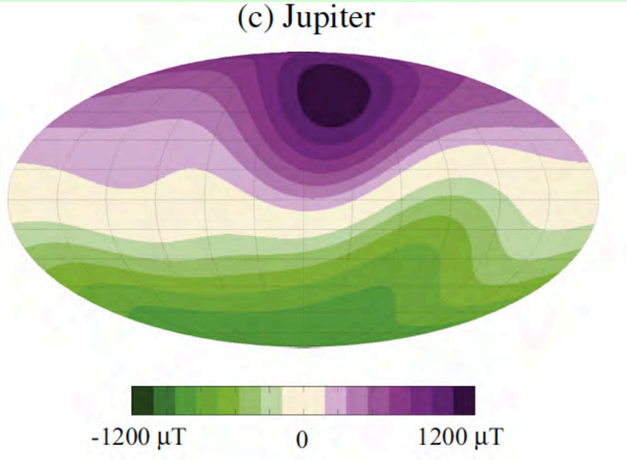




Jupiter's Magnetic Field

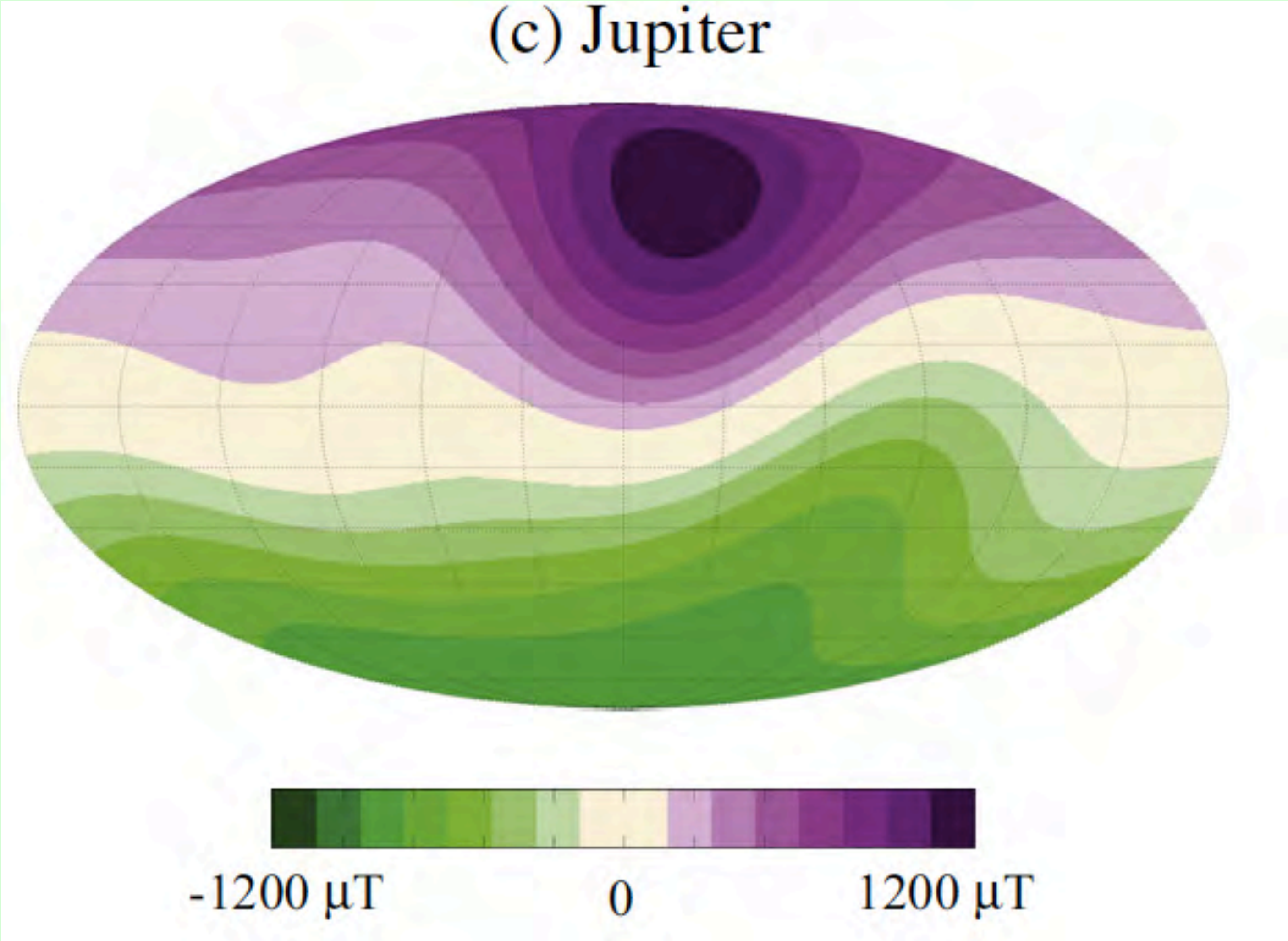
The magnetic field is dominated by the axial dipole component and is the strongest field in the solar system with a mean surface strength of 550 µT.

The magnetic field is produced by convectively-driven dynamo action in the highly electrically conducting metallic hydrogen layer and in the less electrically conducting region near the base of the molecular envelope. The upcoming Juno mission will critically improve our understanding of Jupiter by resolving the magnetic field up to spherical harmonic degree 14 and detecting short timescale secular variation.



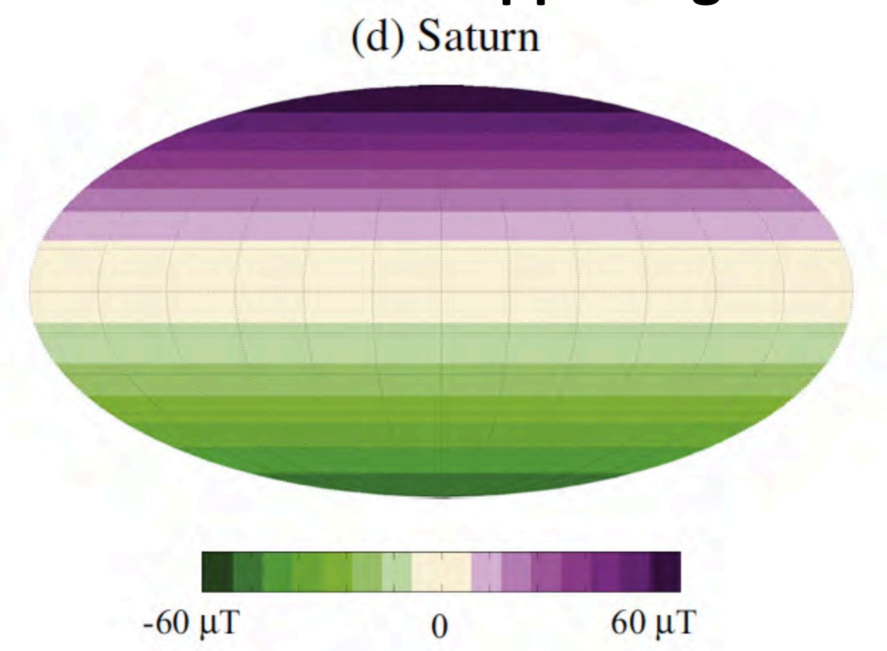
Jupiter's Magnetic Field

The tilt of Jupiter's dipole by almost 10° is especially important because it is responsible for electromagnetic induction in the Galilean satellites.



Saturn's Magnetic Field

The field is strongly dipole-dominated with a mean surface (1 bar) strength of about 30 μT and has a remarkably small offset of less than 1°. No other observed magnetic field has such a small dipole tilt. According to Cowling's theorem, no axisymmetric magnetic field can be generated by dynamo action, so the field must have unresolved nonaxisymmetric components. Alternatively, there could be a "filter" between the dynamo and the observation level that removes the nonaxisymmetric components. Such a filter might involve a sheared zonal flow in the upper region of Saturn.



Saturn’s Magnetic Field

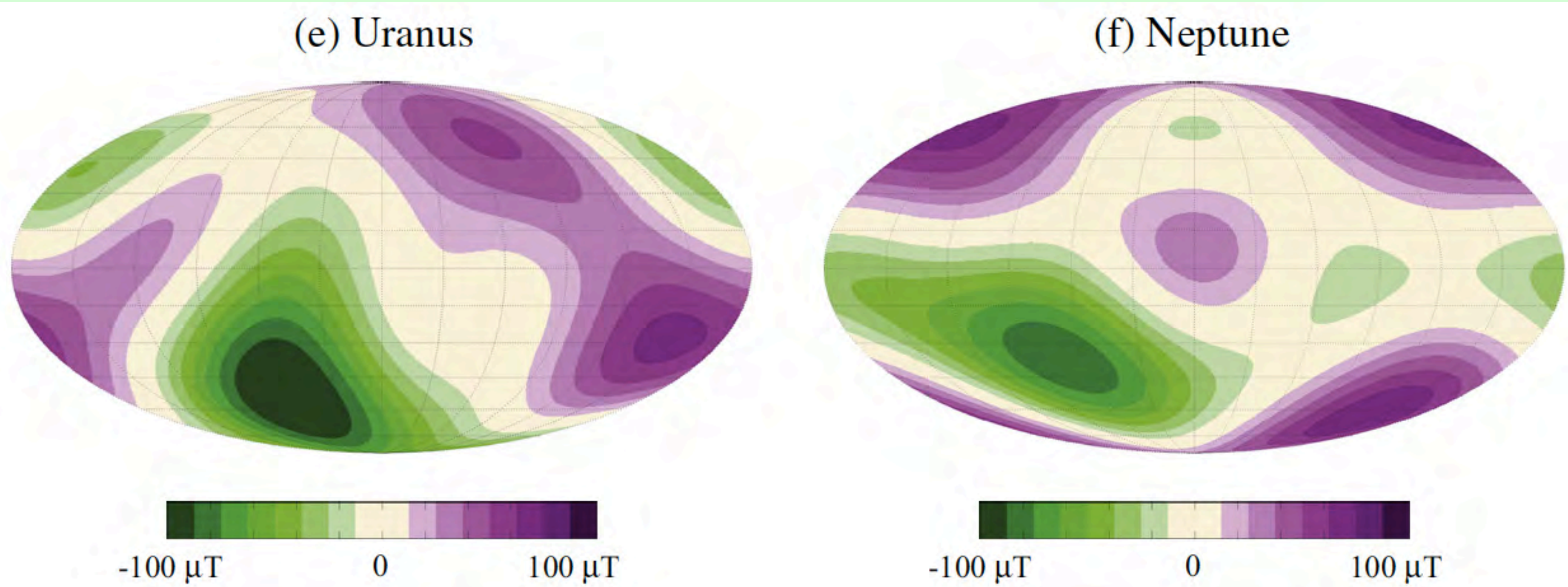
Saturn’s negligible dipole tilt and almost perfectly axisymmetric magnetic field have unfortunate consequences for probing the planet’s interior structure and that of its moons.

Negligible dipole tilt removes the Jovian mechanism for inducing electric currents in the moons. Accordingly, we cannot determine from magnetometer measurements whether Enceladus or Titan have internal salt water oceans.

The axisymmetry of the magnetic field eliminates the possibility of determining Saturn’s rotation rate by tracking the motions of nonaxisymmetric field structures. The SKR is variable with time and results in an uncertainty of about 10 minutes in Saturn’s rotation period.

Magnetic Fields of Uranus and Neptune

The ice giants' magnetic fields are fundamentally different from other known planetary fields since they are predominantly multipolar. The dipole component is tilted about 59° and 47° from the rotation axis for Uranus and Neptune, respectively. Both planets have mean surface field strengths near 30 μT, comparable to that of the Earth and Saturn. The fields are thought to be generated in the planets' ionic oceans



CONCLUDING THOUGHTS

The magnetic fields of planets and moons and small bodies provide unique windows into their origins and evolutions.

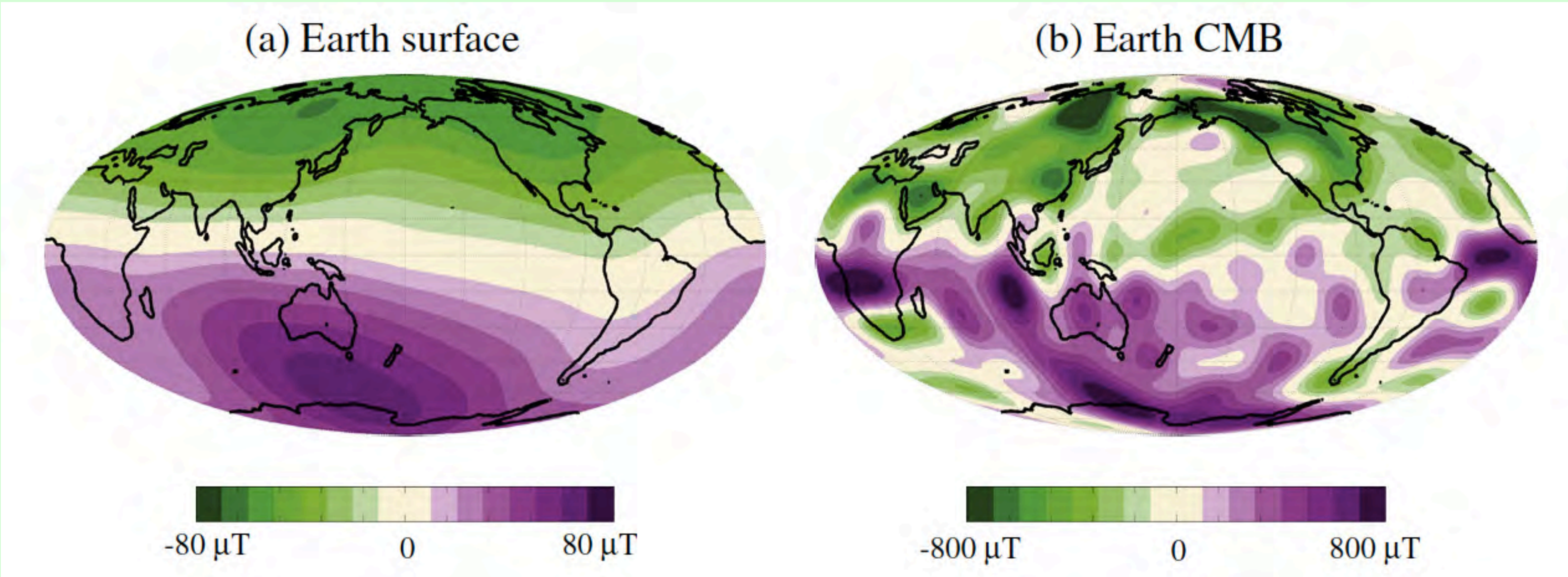
The most challenging problems today in planetary physics relate to the presence and absence of magnetic fields and the crustal magnetization signatures of extinct dynamos.

Planetary magnetism is a vigorous field of study offering challenges for discovery and breakthroughs in understanding.

Understanding planetary magnetic fields will help us better understand the magnetic field of the Earth.

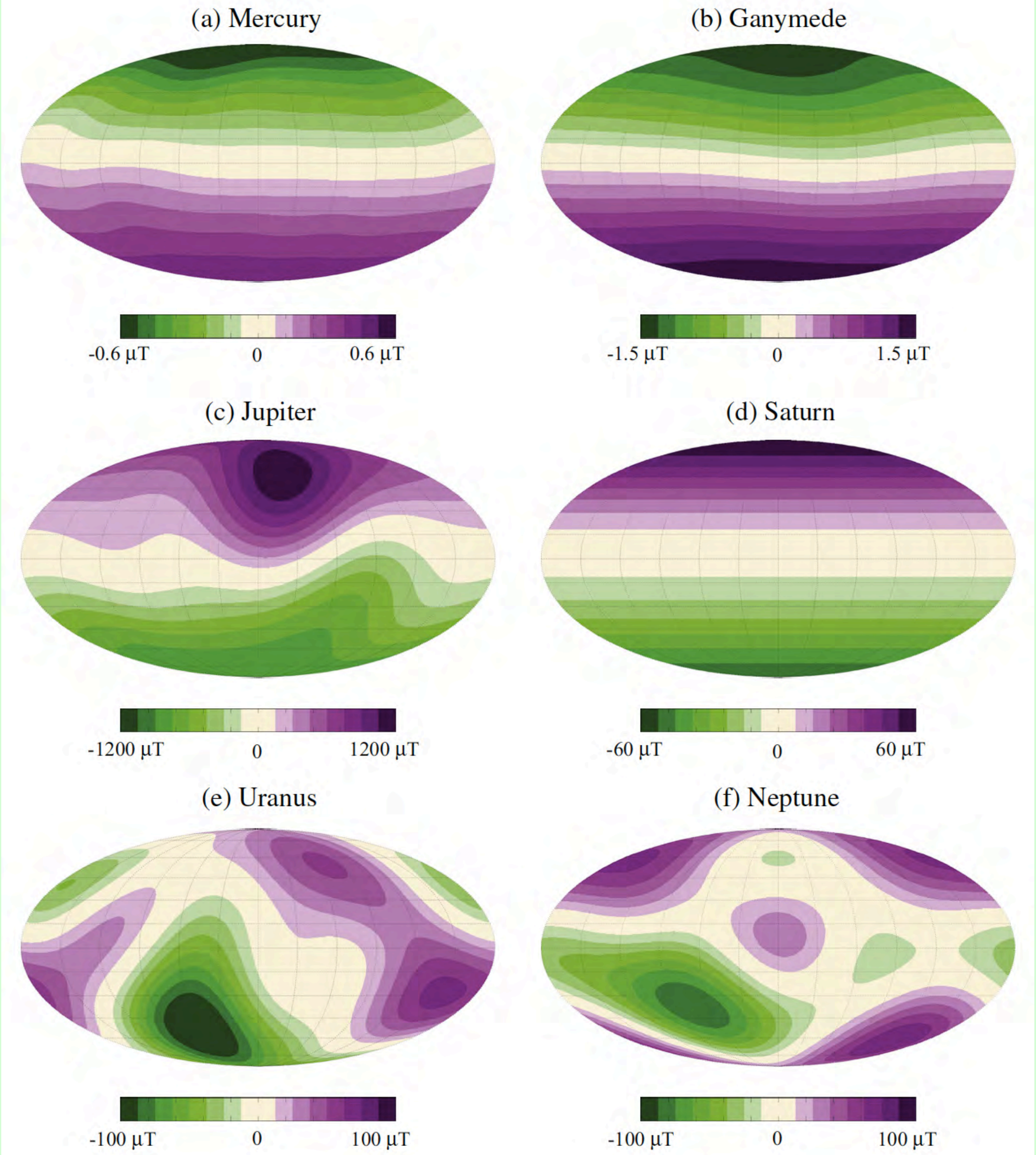
Additional Slides

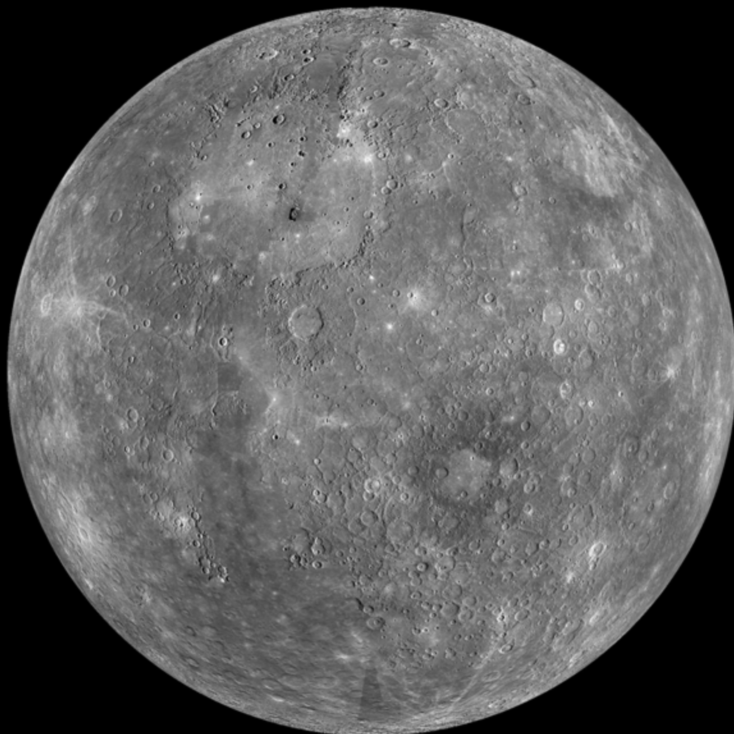
	Surface Radial Magnetic Field (μT)	Dipole Tilt (Degrees)
Mercury	0.30	<3
Earth	38	10
Jupiter	550	9
Ganymede	0.91	4
Saturn	28	<0.5
Uranus	32	59
Neptune	27	45



Radial magnetic field of Earth at (a) the surface and (b) the core-mantle boundary (CMB). The colors represent field intensity where purple (green) indicates outward (inward) directed field.

Note the enhanced small-scale structure at the CMB.


(a) Mercury
-0.6 µT
0
0.6 µT
(b) Ganymede
-1.5 µT
0
1.5 µT
(c) Jupiter
-1200 µT
0
1200 µT
(d) Saturn
-60 µT
0
60 µT
(e) Uranus
-100 µT
0
100 µT
(f) Neptune
-100 µT
0
100 µT



MERCURY

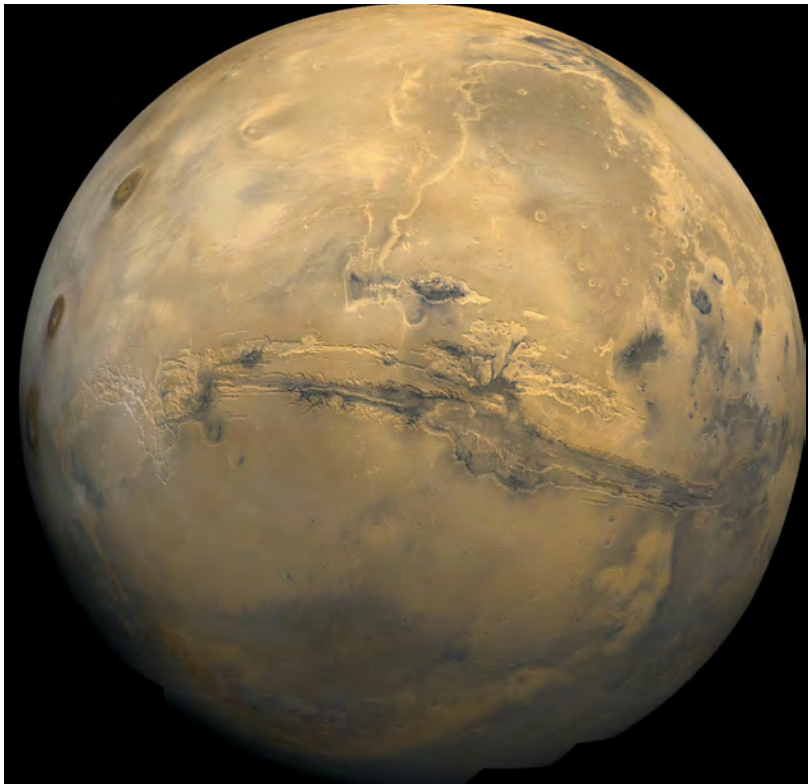
Large bulk density (5430 kg m^{-3}), large iron core.

Earth-based radar observations constrain Mercury's spin state and the amplitude of its forced libration in longitude [Margot, J. L., et al. (2007) Science, 316, 710-714.]. Mercury occupies a Cassini state in which the axis of rotation is nearly perpendicular to the orbital plane and the spin and orbital precession rates are equal. (The axis of rotation remains coplanar with the orbit normal and the normal to the Laplace plane as the spin vector and the orbit normal precess together about the latter with an ~300,000 yr period. The large amplitude of Mercury's forced libration indicates the core is partially molten.

Because Mercury occupies the Cassini state, the second-degree harmonics of its gravity field, C_{20} and C_{22} , together with the amplitude of Mercury's forced libration, its obliquity, precession rate and pole position determine its normalized polar moment of inertia C/MR^2 and the ratio of the polar moment of inertia of the outermost solid shell to that of the entire planet C_m/C. $C/MR^2 = 0.353 \pm 0.017$, $C_m/C = 0.452 \pm 0.035$.

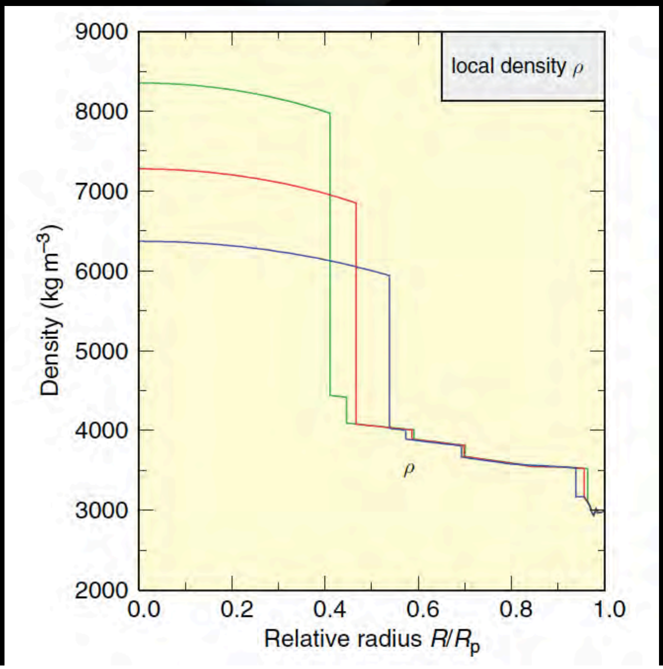
Iron core, partially molten, mantle, and crust.

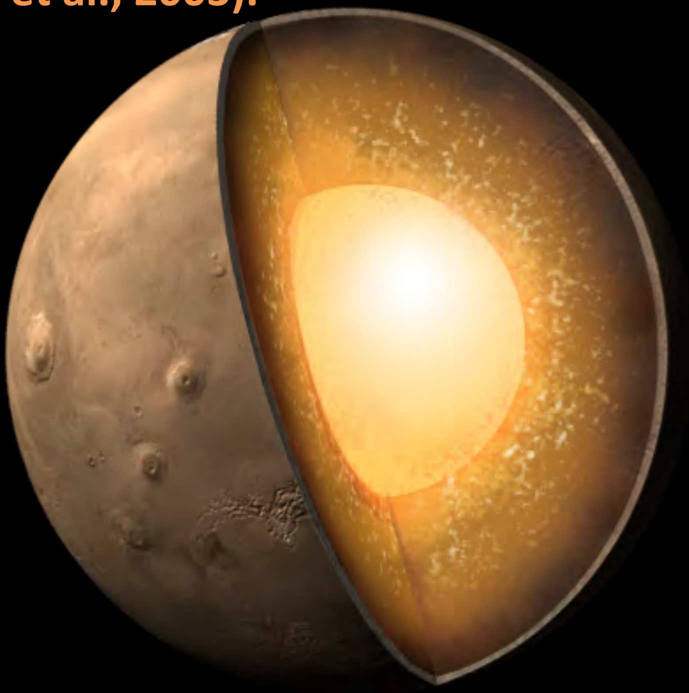
Mars



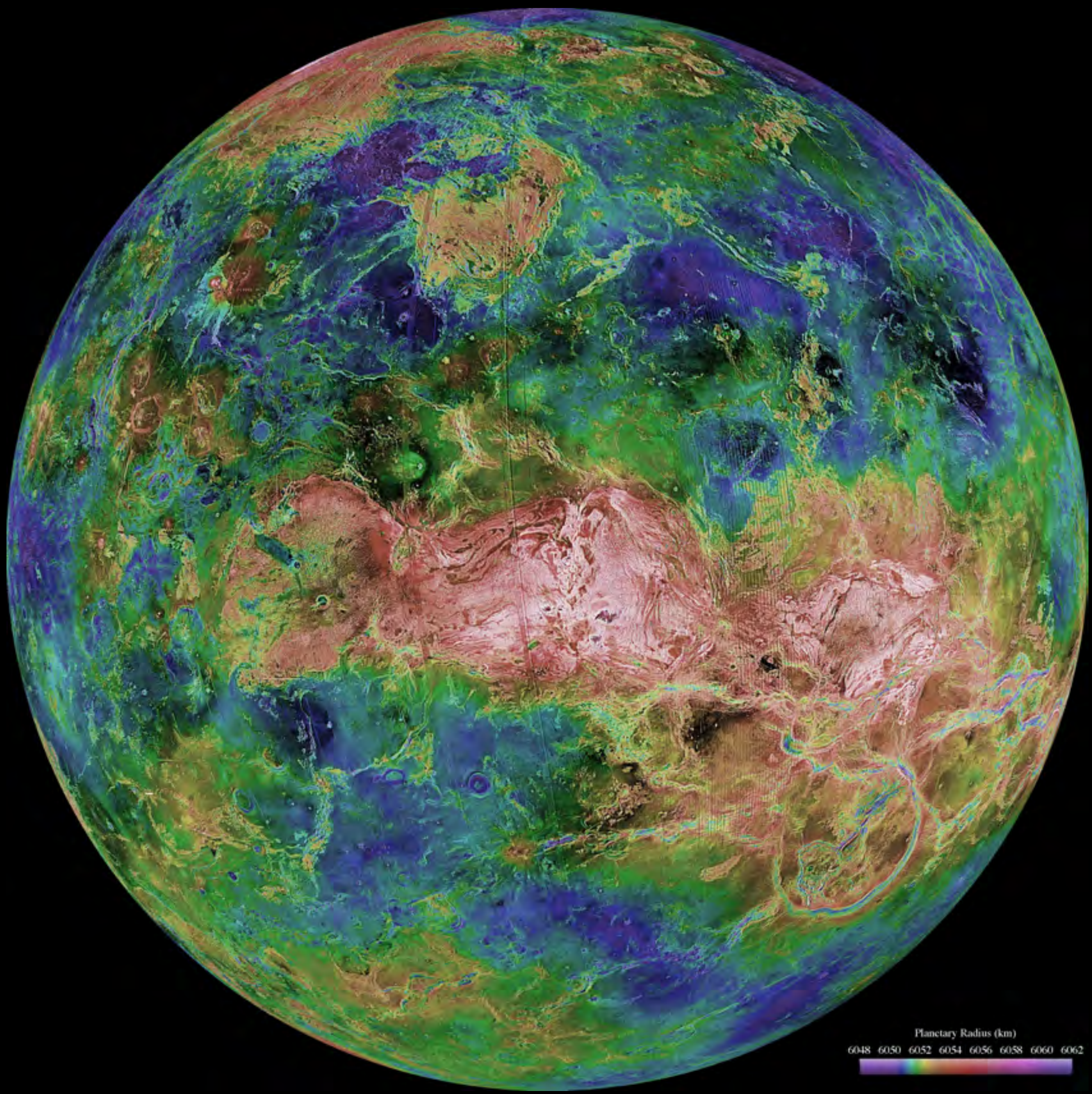
The polar moment of inertia of Mars has been derived from a combined analysis of Mars Global Surveyor tracking and Mars Pathfinder and Viking Lander range and Doppler data.
The MOI factor = 0.365.

The solar tidal deformation of Mars, measured by Mars Global Surveyor radio tracking indicates that at least the outer part of the core is liquid. The inferred core radius is between 1520 and 1840 km (Yoder et al., 2003).





VENUS



Mean Density = 5243 kg m^{-3}

$J_2 = 4.458 \times 10^{-6}$ (Much smaller
(than Earth. Venus
rotates slowly and is
hardly oblate.)

$k_2 = 0.295 \pm 0.066$ (Detection of
solar tide in Magellan
Doppler data).

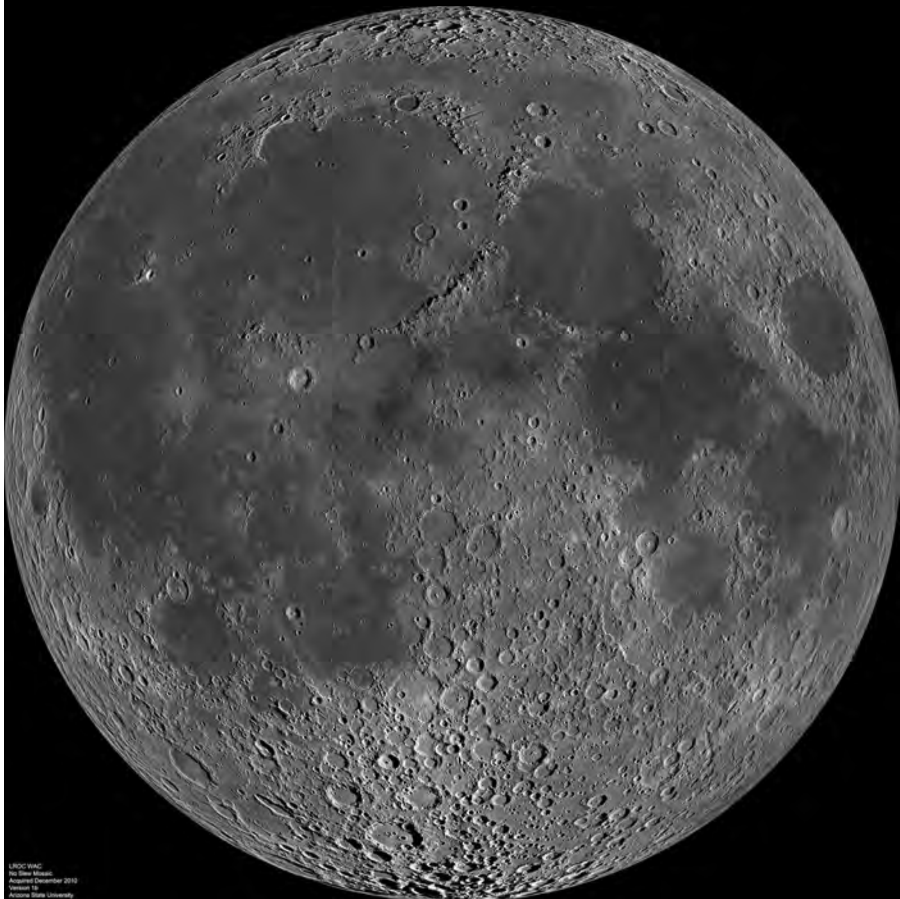
MOI: 0.33 – 0.34 ?

Likely has an iron core like Earth.

What is the physical state of the core? Likely at least partially liquid.

What does lack of a magnetic field tell us about the core?

Moon



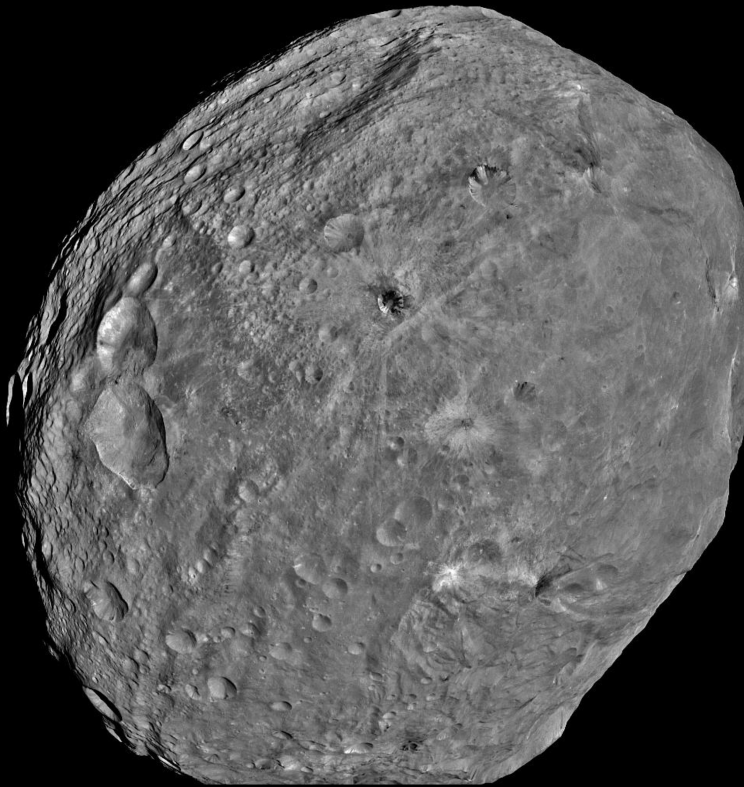
Mean Density = 3350 kg m^{-3}

MOI = 0.393 (LLR and Gravity)

Many lines of evidence suggest that the Moon has a small (~ 330 km diameter) partially molten core.

> **Reanalysis of Apollo era seismic data by Weber et al. (2011) (Science, 331, 309).**
>
> **Lunar Laser Ranging (LLR): Analysis of LLR data for lunar rotation determined approximate size of lunar core and its partially molten state (Williams et al., 2004).**
>
> **Lunar Induced Magnetic Dipole Moment: Analysis of Lunar Prospector magnetometer data (Hood et al., 1999).**

Vesta



Vesta is considered to be a differentiated protoplanet with an iron core that survived essentially intact from the earliest stages of Solar System formation. This view is based on the identification of Vesta as the source of the howardite-eucrite-diogenite (HED) meteorites. All the data acquired by Dawn are consistent with this paradigm.

The average density of Vesta is 3456 kg m^{-3}. When combined with its measured second degree gravitational moment and reasonable assumptions about iron core density in a 2-layer model, values of core radius and core mass fraction are about 110 km and 18 %, respectively [Russell et al., 2012].

Jupiter

Molecular hydrogen envelope, metallic hydrogen interior.

Distribution of He and other heavy elements?

Central core of rock and metal?

Depth of zonal winds?

J_2 = 14696.43 ± 0.21; J_4 = -587.14 ± 1.68; J_6 = 34.25 ± 5.22
all times 10^{-6}.

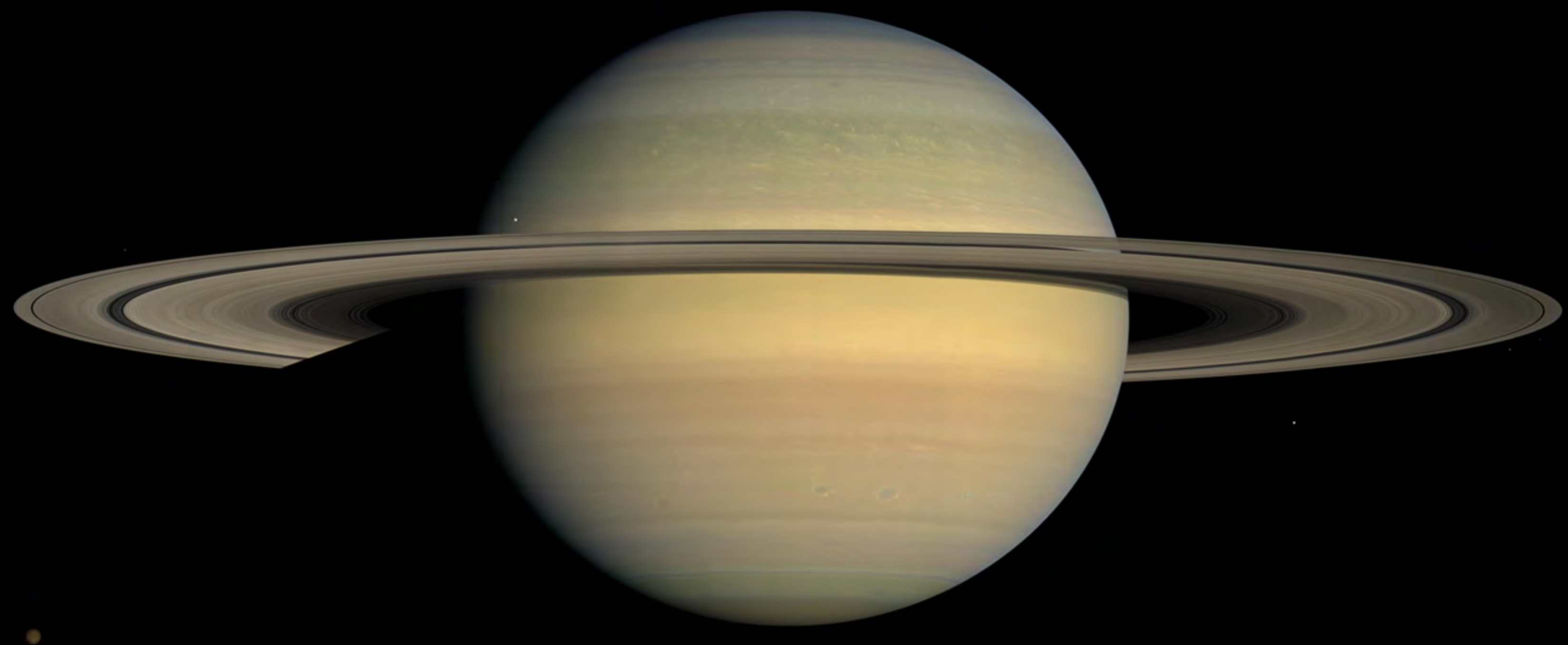
MOI factor = 0.2645 (From HE, J_2 and Radau-Darwin).

More accurate modeling gives MOI between 0.2629 and 0.2645.

The Juno mission could determine Jupiter's MoI directly by measuring Jupiter's pole precession and the Lense-Thirring acceleration of the spacecraft. Juno will determine the gravitational coefficients to higher accuracy and to high order.

If JUICE carries a Doppler Imager instrument (Echoes) it may be possible to get at Jupiter's internal structure using a Jovian seismological approach.

Saturn



Molecular hydrogen envelope, metallic hydrogen interior. Distribution of heavy elements? Central core of rock and metal? Depth of zonal winds? *Rotation Rate?*

J_2 = 16290.71 ± 0.27; J_4 = -935.8 ± 2.8; J_6 = 86.1 ± 9.6 all times 10^{-6} (Voyager rotation period).

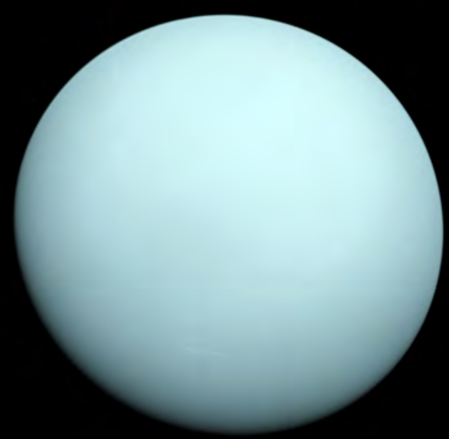
MOI factor = 0.213-0.220 (From HE and J_2).

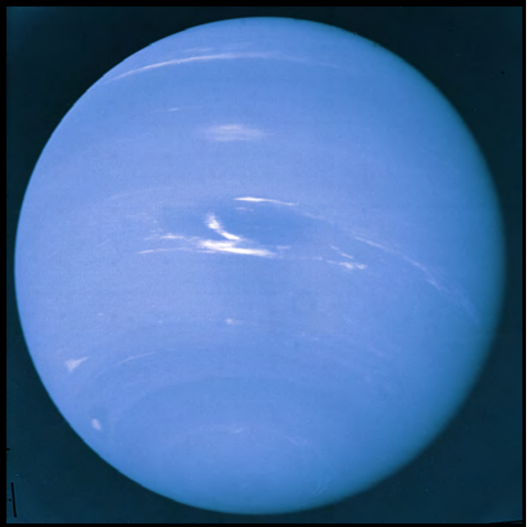
The Cassini Solstice mission (2016), a Juno-like mission, will measure the gravitational field more precisely and to higher order and may help determine Saturn's rotation rate.

Uranus and Neptune

Hydrogen/helium envelopes, interiors a mixture of rock and ices.

	Uranus	*Neptune*
J_2 ($\times 10^6$)	3341.29 ± 0.72	3408.43 ± 4.50
J_4 ($\times 10^6$)	-30.44 ± 1.02	-33.40 ± 2.90
MOI	*0.225?*	*0.225?*

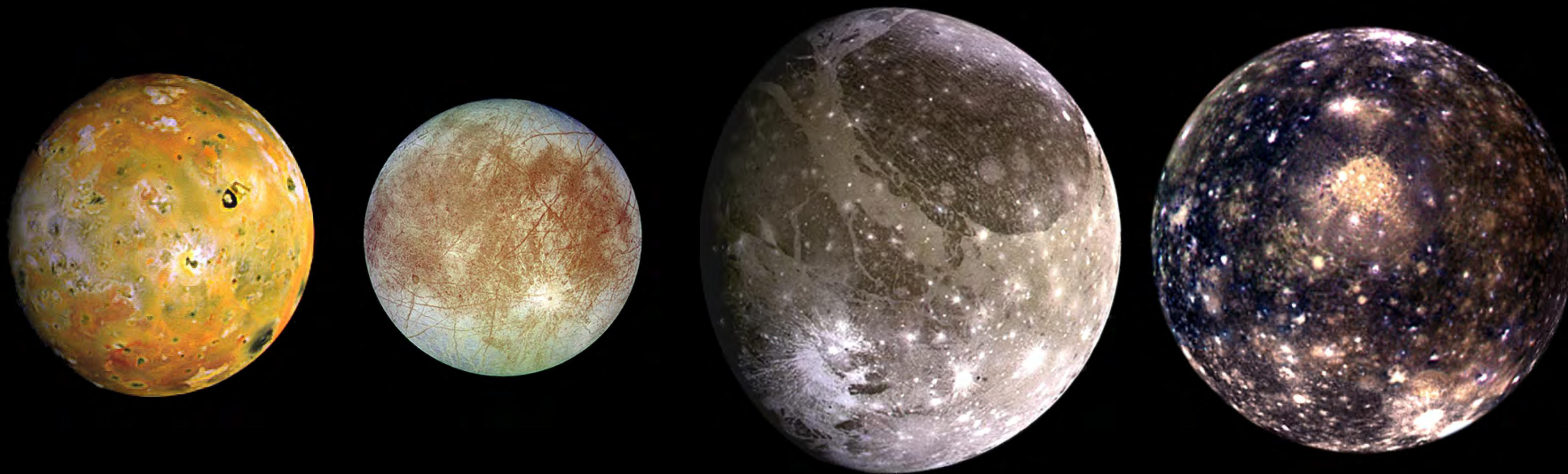




Cores? Heavy elements in both Uranus' and Neptune's interiors might increase gradually with depth. It is possible to fit the gravitational moments without sharp compositional transitions.

Neptune has a large thermal flux, so an adiabatic thermal gradient might be a good approximation to its interior. However, Uranus' thermal emission is close to zero and it is possible that Uranus' thermal gradient is non-adiabatic and its interior non-convective. The magnetic fields of Uranus and Neptune require highly electrically conducting fluid regions, probably dominated by water and situated at relatively shallow depths, to account for the multipolar nature of the fields.

Galilean Satellites



Galileo flyby determinations of gravitational coefficients together with assumption of HE yield values of mean density and the MOI factor.

Io: Fully differentiated with an iron core and rocky mantle. Partially molten asthenosphere known from EM induction measurements by the Galileo magnetometer.
MOI = 0.378

Europa: Fully differentiated. Iron core, rocky mantle, water ice outer shell. Liquid water ocean beneath the ice known from EM induction measured by Galileo.
MOI = 0.346

Ganymede: Fully differentiated. Iron core, rocky mantle, water ice outer shell. Magnetic field. Possible liquid water internal ocean.
MOI = 0.312

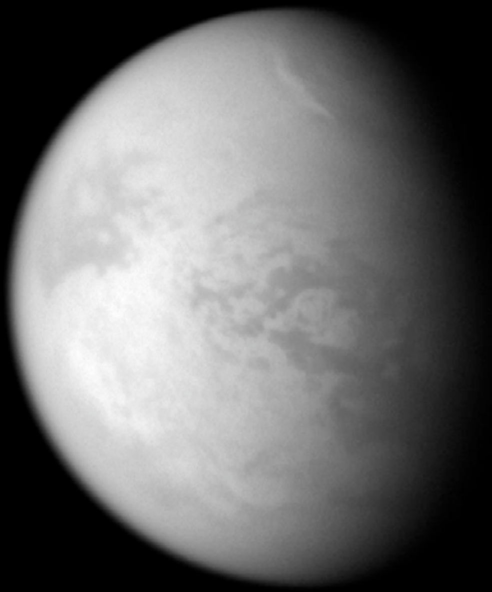
Callisto: Undifferentiated or slightly differentiated. Essentially a uniform mixture of ice and rock.Liquid water internal ocean.
MOI = 0.355

Titan

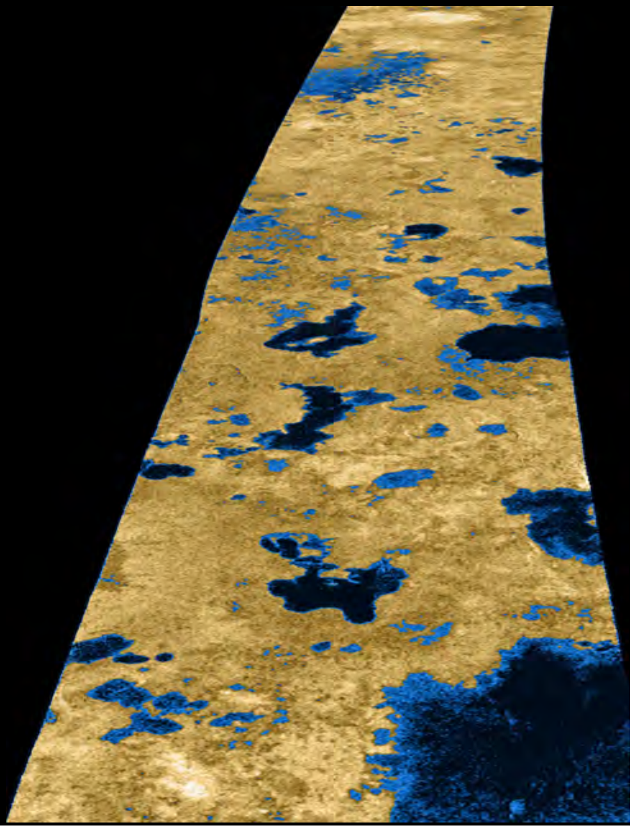
Titan is an icy satellite with mean density = 1882 kg m^{-3} and a rock mass fraction = 48%.

Radio Doppler from multiple Cassini flybys has been used to infer that Titan is in HE with $C_{22} = 10 \times 10^{-6}$ and k_2 about 0.6 (Iess et al., 2010; 2012).

The inferred C_{22} and the assumption of HE gives an MOI = 0.34. Titan is only partially differentiated. All the ice and rock are not separated. The inferred value of k_2 derives from Titan's inferred response to the Saturnian-induced tide and suggests that Titan might have an internal ocean.

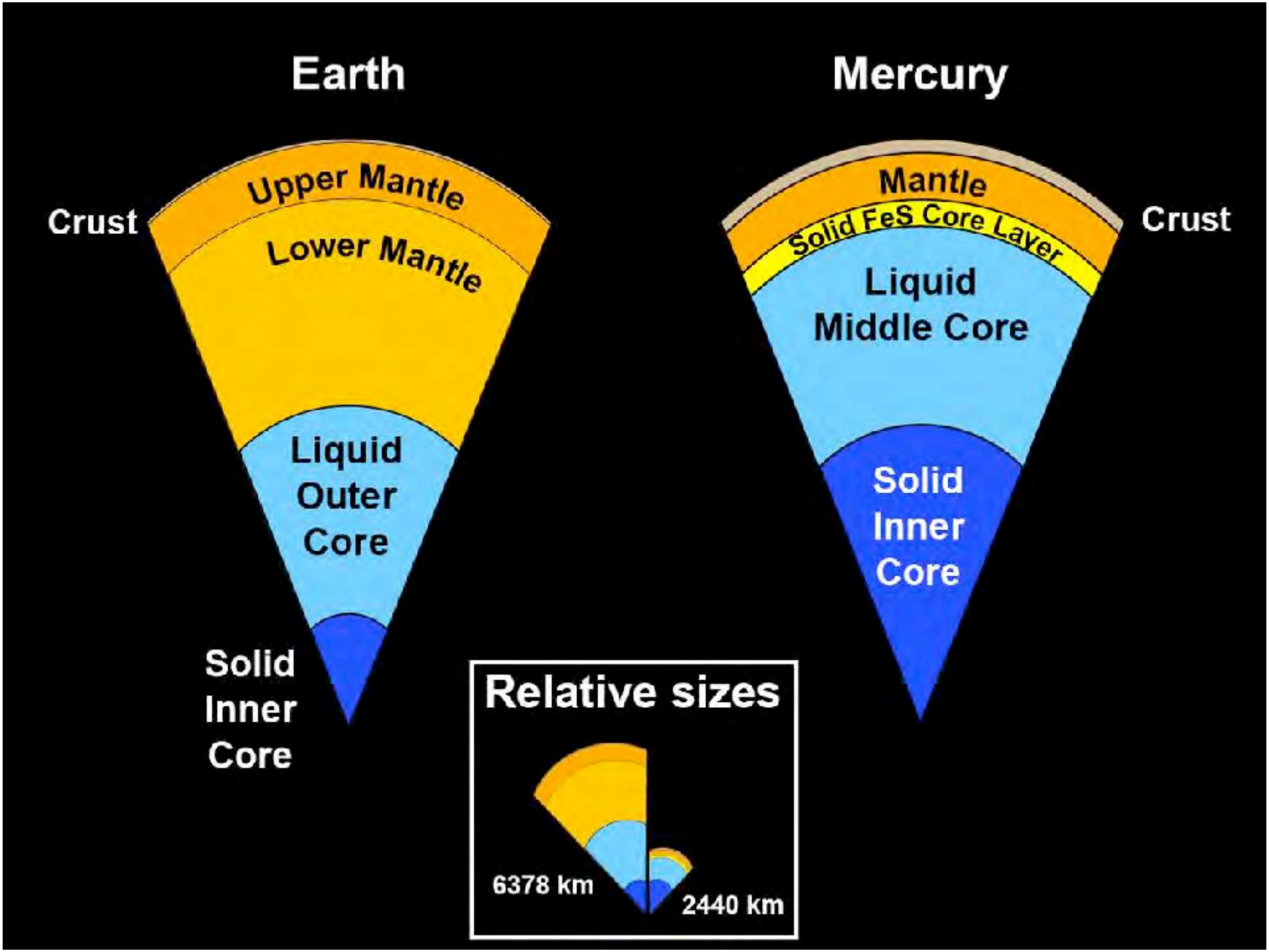


Our independent analysis, not yet complete, is indicating that Titan is even less differentiated than thought and its tidal response has not been detected.

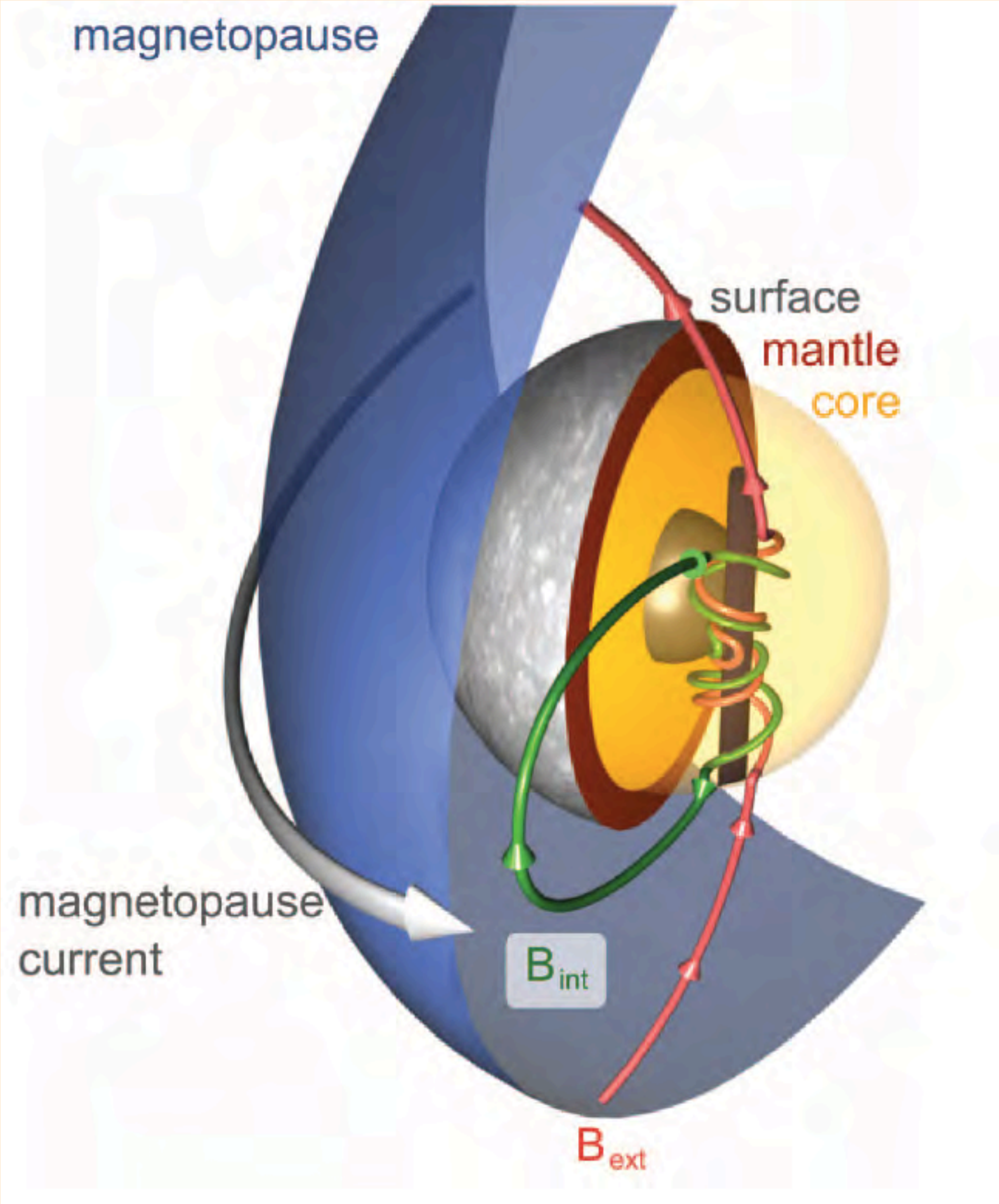


Why is Mercury's magnetic dipole offset toward the northern hemisphere?
Why is Mercury's magnetic field mainly the sum of a dipole and a quadrupole?

Hao Cao et al. have offered an explanation in terms of a dynamo driven by excess heat loss from the core at the equator compared with the poles. This is difficult to understand since such a boundary condition is equatorially symmetric. Also, the physical process involved in the mantle removing more heat from the core in the equatorial region needs to be explained.


Earth
Mercury
Crust
Upper Mantle
Lower Mantle
Liquid Outer Core
Solid Inner Core
Mantle
Solid FeS Core Layer
Crust
Liquid Middle Core
Solid Inner Core
Relative sizes
6378 km
2440 km

Feedback Dynamo Generating Mercury's Magnetic Field



(Heyner et al., 2011)

Remnant Magnetization on Mercury

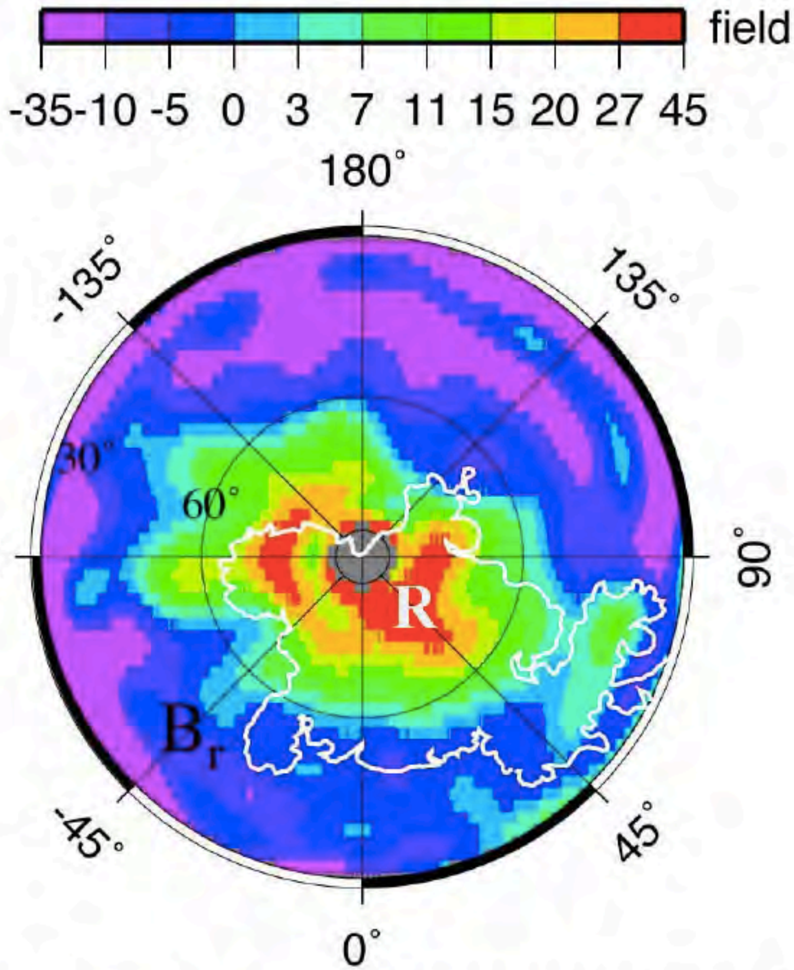
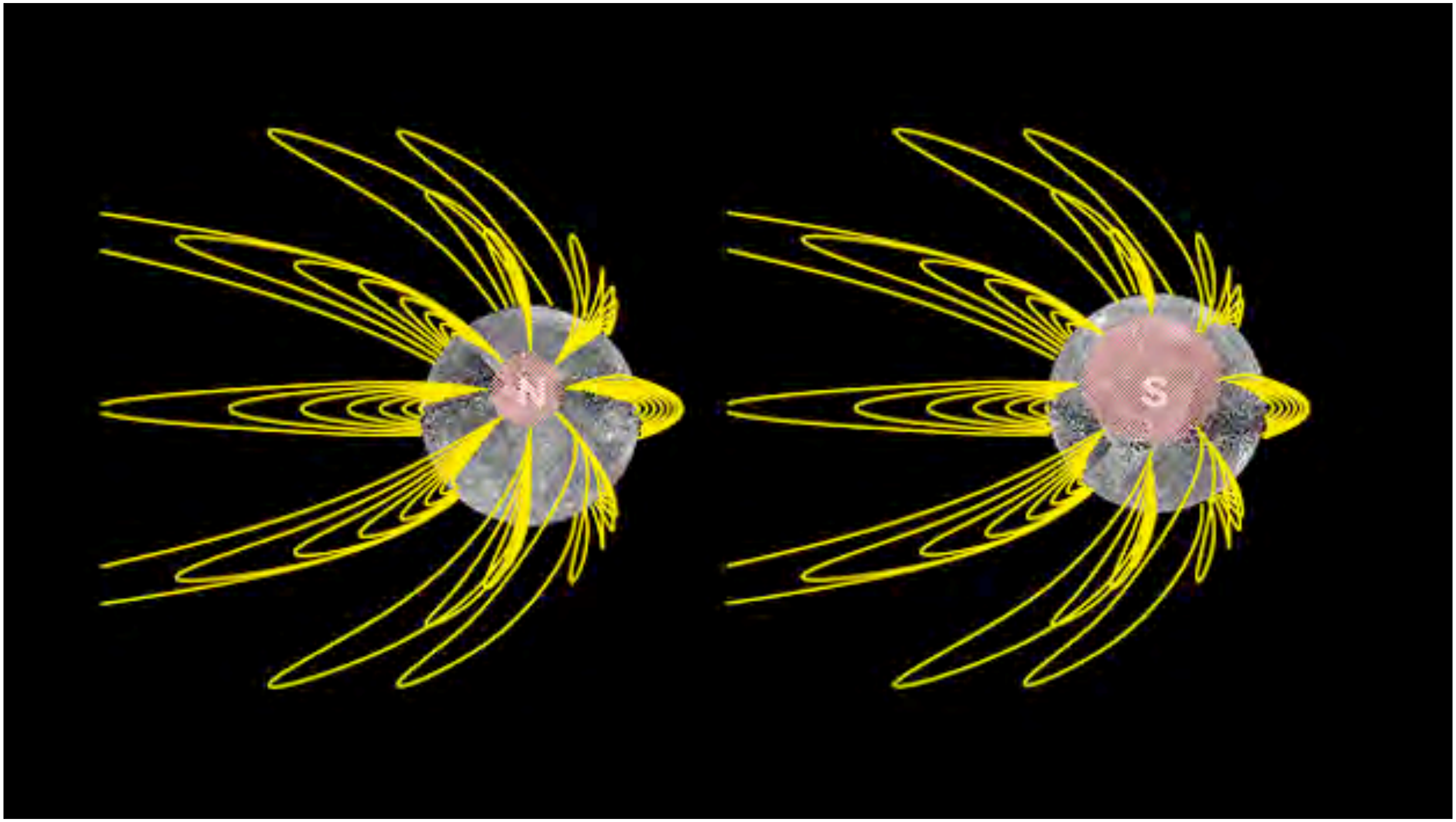
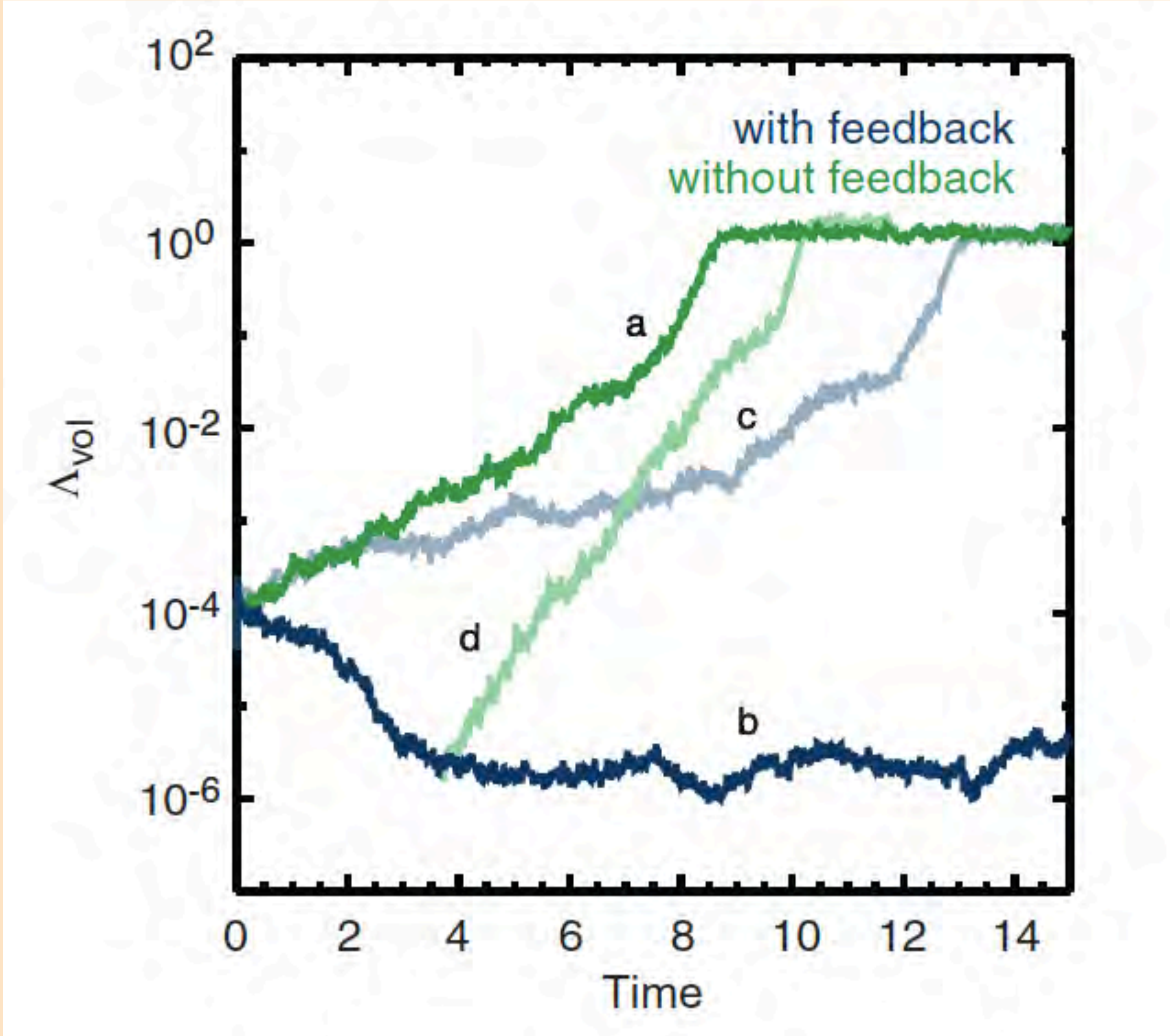


Figure 2. Residual radial magnetic field (nT) of internal origin normalized to 300 km altitude. Observations are from days 83-326 in 2011 at altitudes of 200-700 km. White line outlines the extent of the northern volcanic plains [8]. The white R locates the center of the topographic rise in the northern volcanic plains [10].

Purucker et al. (2012)



Magnetic lines of force (yellow lines) for two views of Mercury. The polar region (red shading) within which the local magnetic field opens to the solar wind, and is not connected to the opposite hemisphere of the planet, is four times larger in the south than in the north. The magnetic field offset strongly enhances the exposure of the surface at high southern latitudes to bombardment by charged particles in the solar wind.



Volume-averaged Elsasser number vs. time. Time is in units of a magnetic diffusion time. a, reference case without external field; b, feedback-stabilized dynamo; c, same dynamo as b but with a lower amplitude of the external field; d, control case (restart of b with external field turned off). Heyner et al. (2011)

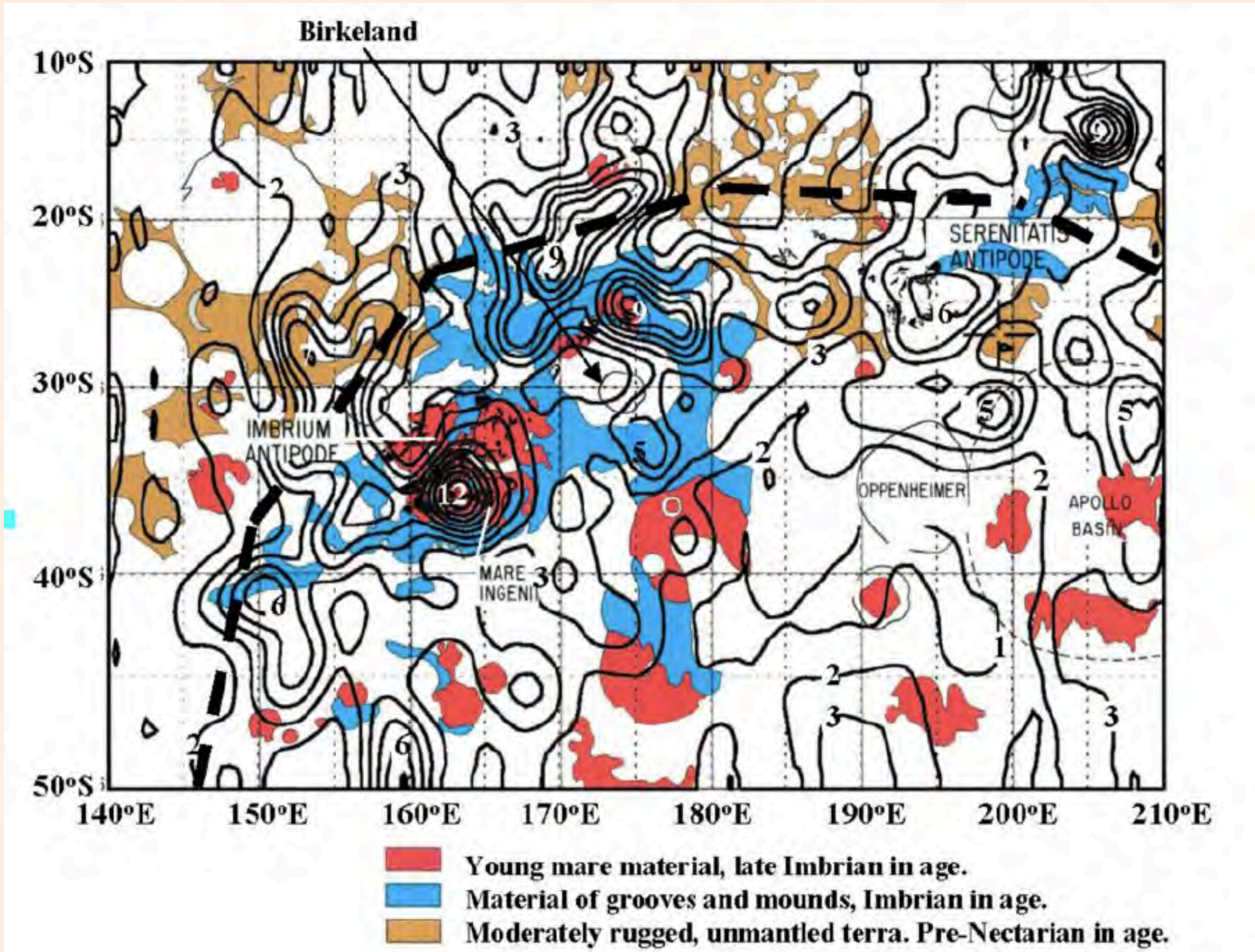
Mercury's Weak Magnetic Field

Yet another explanation for Mercury's weak magnetic field involves the self-interaction of its internal dynamo with the magnetosphere created around the planet by the dynamo itself, a type of feedback effect (Glassmeier et al., 2007; Gomez-Perez and Solomon, 2010; Gomez-Perez and Wicht, 2010). Mercury is effectively embedded in an external magnetic field generated by Chapman-Ferraro currents in its magnetopause. This self-generated ambient magnetic field influences the dynamics of the internal dynamo, similar to the way the Jovian magnetic field influences dynamo action in Jupiter's moon Ganymede (Sarson et al., 1997). Chapman-Ferraro currents generate a magnetic field that enhances the magnetospheric field and tends to cancel the field outside the magnetosphere. In the dynamo region, the Chapman-Ferraro field opposes the dynamo-generated field so that the dynamo is embedded in an ambient field of opposite polarity. Glassmeier et al. (2007) show that the feedback dynamo indeed has a Mercury-type solution with a weak magnetic field.

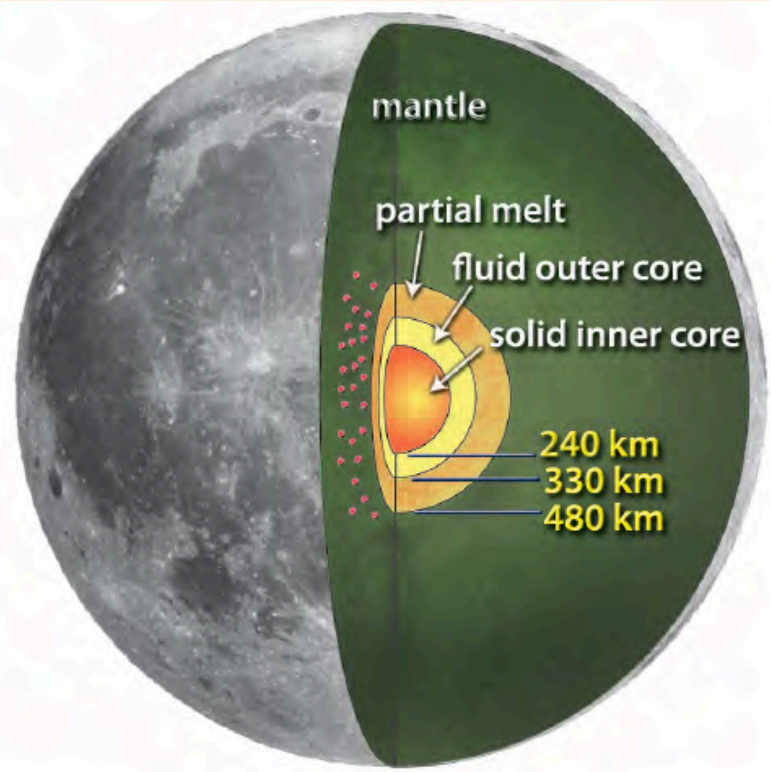
Why is Mercury’s magnetic dipole offset toward the northern hemisphere?
Why is Mercury’s magnetic field mainly the sum of a dipole and a quadrupole?

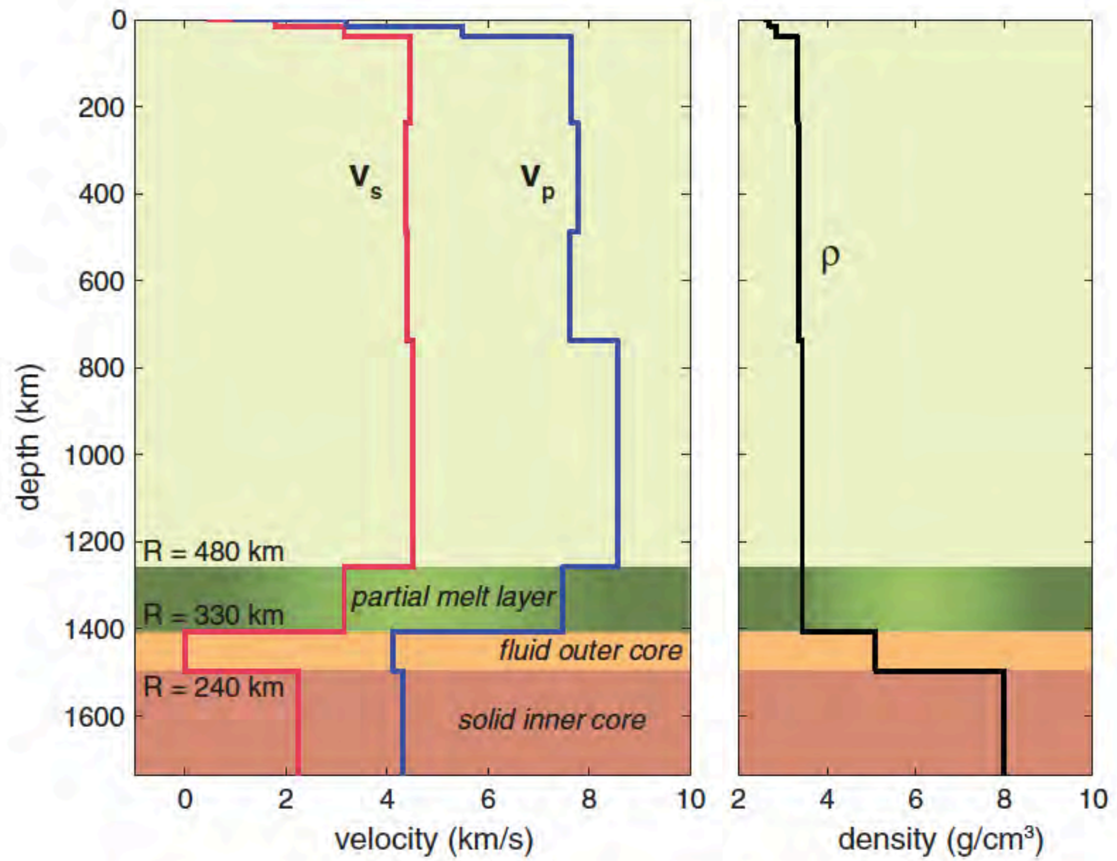
No explanation has yet appeared in the literature. An explanation must involve imposition of hemispherical asymmetry through boundary conditions or a way of exciting core modes that are equatorially asymmetric.

Significantly, the largest magnetic anomalies are antipodal to major impact basins, particularly Imbrium and Orientale. In contrast, magnetic fields within the impact basins themselves are rather weak. An expanding plasma cloud propagating away from the impact and converging at the antipode could have concentrated magnetic field lines there and shock magnetized the crust (Hood et al., 2013).



That the Moon could have had an early dynamo is consistent with the accumulating evidence for a present day metallic core that is liquid in its outer part. Four decades of Lunar Laser Ranging data for the rotation and orientation of the Moon substantiates this view. It is further supported by a recent reanalysis of seismic data from the Apollo program which claims to have detected an iron-rich core with a radius of about 330 km and a solid inner core with radius of about 240 km [Weber et al., 2011].



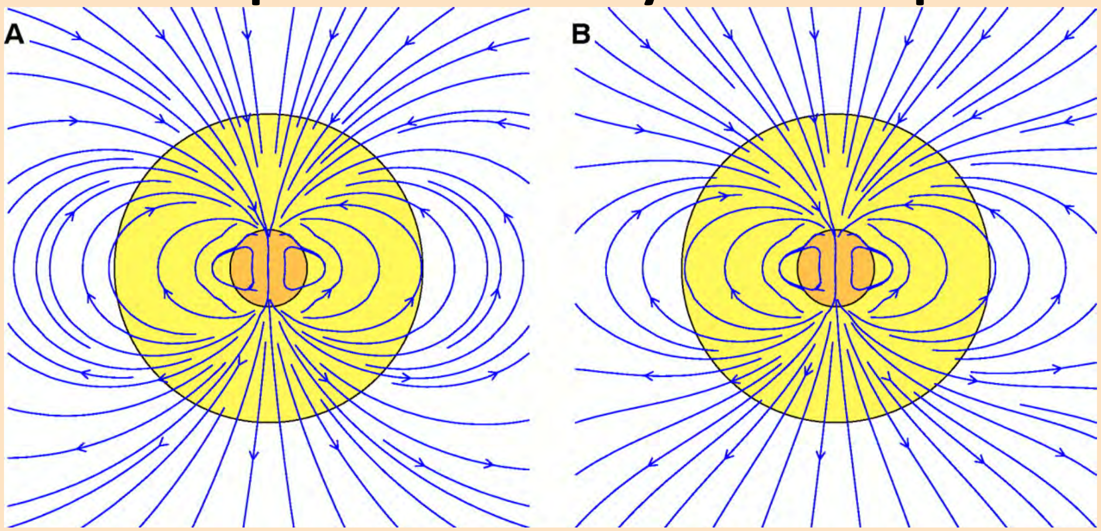


If we accept that there was a lunar dynamo early in the evolution of the Moon then the question arises as to when dynamo action began and how long it lasted. At the heart of this question is what provided the energy to drive the dynamo. It has been asserted that a convectively driven lunar dynamo would not last for more than a few hundred million years (Dwyer et al., 2010). If true, and if the onset of dynamo action occurred within a few hundred million years of lunar formation, then there is a problem reconciling this with evidence from magnetization in a mare basalt sample that the lunar dynamo survived till at least 3.7 Ga [Shea et al., 2012].

More recently, Suavet et al. (2013) have reported analyses of two 3.56 Ga mare basalts demonstrating that they were magnetized in a stable and intense dynamo magnetic field of at least~13 μT.

Generation of Ganymede's Magnetic Field

Dynamo action in Ganymede's core was first studied by Sarson et al. (1997) who investigated how Jupiter's magnetic field might influence magnetic field generation in the satellite. The Jovian magnetic field at Ganymede's orbit is much weaker than the satellite's intrinsic magnetic field and, therefore, is not expected to play a significant role in the operation of Ganymede's dynamo. The dynamo model of Sarson et al. (1997) confirmed this, but left open the possibility that in the initial stages of dynamo activity, the Jovian magnetic field could provide a seed field that would explain the anti-alignment of Jupiter's and Ganymede's dipole moments.



Mean Field Dynamo (Sarson et al., 1997)