

Frontiers

Planetary magnetic fields

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Abstract

The past several years have seen dramatic developments in the study of planetary magnetic fields, including a wealth of new data, mainly from the Galilean satellites and Mars, together with major improvements in our theoretical modeling effort of the dynamo process believed responsible for large planetary fields. These dynamos arise from thermal or compositional convection in fluid regions of large radial extent. The relevant electrical conductivities range from metallic values to values that may be only about 1% or less that of a typical metal, appropriate to ionic fluids and semiconductors. In all planets, the Coriolis force is dynamically important, but slow rotation may be more favorable for a dynamo than fast rotation. The maintenance and persistence of convection appears to be easy in gas giants and ice-rich giants, but is not assured in terrestrial planets because the quite high electrical conductivity of iron-rich cores guarantees a high thermal conductivity (through the Wiedemann–Franz law), which allows for a large core heat flow by conduction alone. In this sense, high electrical conductivity is unfavorable for a dynamo in a metallic core. Planetary dynamos mostly appear to operate with an internal field $\sim (2\rho\Omega/\sigma)^{1/2}$ where ρ is the fluid density, Ω is the planetary rotation rate and σ is the conductivity (SI units). Earth, Ganymede, Jupiter, Saturn, Uranus, Neptune, and maybe Mercury have dynamos, Mars has large remanent magnetism from an ancient dynamo, and the Moon might also require an ancient dynamo. Venus is devoid of a detectable global field but may have had a dynamo in the past. The presence or absence of a dynamo in a terrestrial body (including Ganymede) appears to depend mainly on the thermal histories and energy sources of these bodies, especially the convective state of the silicate mantle and the existence and history of a growing inner solid core. Induced fields observed in Europa and Callisto indicate the strong likelihood of water oceans in these bodies.

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1. Where do magnetic fields come from?

Magnetic fields, unlike electric fields, do not come from monopoles but from an electrical cur-

rent, or from the fundamental magnetic moments of elementary particles. In everyday experience, substantial fields arise either from permanent magnets where the magnetism arises at the microscopic level and is a thermodynamic property of the material, or through macroscopic currents in electrical conductors (e.g. as in a Helmholtz coil). Permanent magnetism is a satisfactory explanation for modest amounts of observed magnetism

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in solid bodies (e.g. Moon, Mars, and maybe even Mercury), but it requires low temperature (outer regions only of a planet) and it requires an adequate abundance of the minerals that exhibit permanent magnetization (e.g. magnetite, metallic iron). Typically, crustal magnetism has a coherence length that is small compared to the planet radius, so no large global field arises. On Earth, permanent magnetization accounts for typically 0.1% or less of the observed field. *Localized* fields of up to Earth's global field ($\sim 10^{-4}$ T) are possible from permanently magnetized materials; this happens rarely on Earth but may be common in the Southern Hemisphere of Mars. On Earth, we have a much stronger argument for something else: The field is dynamic (time varying on all time scales from years to billions of years.) This field is generated in Earth's conducting core by a process known as a dynamo and involves very large-scale electrical currents. A similar process operates in many large cosmic bodies including the Sun [1–3].

By Faraday's law, a planetary body can also have an 'internal' field that is induced by a time-variable external field. These eddy currents and associated fields can be identified by their distinctive time variability, phase and amplitude. On Earth, these are called magnetotelluric currents and fields. They are also observed for the Moon, Europa, and Callisto.

2. Why are planetary magnetic fields interesting?

There are four reasons:

1. When a planet has a large global field, this provides us with insight into the state of matter and the dynamics deep down. There is currently no other way to do this from orbit.
2. When a planet has remanent magnetism of near surface rocks, this may tell us about the past behavior of the global field (cf. geomagnetic reversals) and geological activity. Plate tectonics was deduced primarily from paleomagnetism. The history of the field may also affect climate (by modulating atmospheric escape) and the evolution of life.
3. When a body has an induced field, its magni-

tude and phase tell us about the body's conductivity structure.

4. Dynamo field generation is a non-linear chaotic process whose dynamics are of interest in their own right (as a fundamental and very difficult problem in complex systems).

3. What is the nature of planets?

Planets are conveniently categorized according to their primary constituents [4–6]. Planets and their satellites are not distinguished because satellites are subject to the same planetary processes if they are sufficiently large (> 1000 km radius, roughly). *Terrestrial planets* (Mercury, Venus, Earth, Moon, Mars, and Io) consist primarily of materials that condense at high temperatures: oxides and silicates of iron and magnesium, together with metallic iron. The high density and lower melting point of iron alloys relative to silicates generally lead us to expect that these bodies form metallic iron-rich cores. These cores are generally at least partially liquid, even after 4.5 billion years of cooling, because at least one of the core-forming constituents (sulfur) lowers the freezing point of the iron alloy below the operating (convecting) temperature of the overlying mantle. If the sulfur content is small then the fluid region of a core may be thin. *Gas giants* (Jupiter and Saturn) have hydrogen as their major constituent. They may possess 'Earth-like' central cores but this may have little bearing on understanding their magnetic fields. *Ice giants* (Uranus and Neptune) contain a hydrogen-rich envelope but their composition is rich in H_2O , CH_4 and NH_3 throughout much of the volume, extending out to perhaps $\sim 80\%$ of their radii. *Large icy satellites and solid icy planets* (Ganymede, Callisto, Titan, Triton, Pluto; also Europa as a special case) contain both ice (predominantly H_2O) and rock. They may be differentiated into an Earth-like structure (silicate rock and possibly an iron-rich core), overlain with varying amounts of primarily water ice, or (as in the case of Callisto) the ice and rock may be partly mixed. Europa is a special case because the water-rich layer is relatively small and may be mostly liquid.

Planets differ from small masses of the same material because of the action of gravity and the difficulty of eliminating heat on billion-year time scales. Gravity causes pressure, which can modify the thermodynamic and phase equilibrium behavior of the constituents. This is why bodies rich in materials that are poor conductors at low pressures (e.g. hydrogen, water) may nonetheless have high conductivity at depth. In giant gas and ice planets, the heat of formation is sufficient to guarantee fluidity and convection. In terrestrial planets, the difficulty of eliminating the heat of formation and subsequent radioactive heat generation leads to unavoidably large internal temperatures, usually sufficient to guarantee fluidity of a metallic core, and sustained mantle convection. Terrestrial core convection may not be easily sustained, as explained in Section 7.

4. What planetary fields are observed?

Except for the special case of Jupiter, which is a synchrotron source of radio waves, we learn about planetary magnetic fields by the direct detection of the field (the magnetosphere) from a flyby or orbiter spacecraft [7,8]. Orbital data are preferred (even for Earth), provided you can measure or get below the effects of an ionosphere. The observations, with likely interpretations, are given

in Table 1, based on [7–10]. For the large satellites imbedded in giant planet magnetospheres, the quoted values have the external field subtracted.

5. What is the geometry of large fields?

External to the planet and the large currents responsible for most of the field, the magnetic field \mathbf{B} can be written as the gradient of a scalar potential that satisfies Laplace's equation. In the standard way [3], we can identify general solutions to Laplace's equation in terms $\propto Y_{lm}r^{-(l+1)}$ for internal sources, where Y_{lm} is a spherical harmonic, r is the distance from the center of the planet $l=1$ is the dipole, $l=2$ and $m=0$ is the quadrupole and so on. Terms with $m=0$ represent spin-axisymmetric components (if we choose the pole of coordinates to be the geographically defined pole of planet rotation), so (for example) $l=1$ and $m=\pm 1$ represents the tilt of the dipole and the longitude of that tilted dipole. Planetary fields are sometimes described as 'tilted, offset dipoles' but this is misleading at best. There is no fundamental significance to a dipole: A current distribution of finite extent will typically produce many additional harmonics. It might be imagined that all harmonics are comparably important at the core radius. However, many bodies have fields that are predominantly dipolar, in the sense that

Table 1
Observed magnetic fields (based on [7–10])

Planet or satellite	Observed surface field (in T, approximate)	Comments and interpretation
Mercury	2×10^{-7}	Not well characterized or understood
Venus	$< 10^{-8}$ (global); no useful constraint on local fields.	No dynamo. Small remanence
Earth	5×10^{-5}	Core dynamo
Moon	Patchy (10^{-9} – 10^{-7}). Impact-generated? No global field	Ancient dynamo?
Mars	Patchy but locally strong (10^{-9} – 10^{-4}) field	Ancient dynamo, remanent magnetic lineations
Jupiter	4.2×10^{-4}	Dynamo (extends to near surface)
Io	$< 10^{-6}$?	Complex (deeply imbedded in Jovian field)
Europa	10^{-7}	Induction response (salty water ocean)
Ganymede	2×10^{-6}	Dynamo likely
Callisto	4×10^{-9}	Induction response (salty water ocean)
Saturn	2×10^{-5}	Dynamo (deep down)
Titan	$< 10^{-7}$	Need more data
Uranus	2×10^{-5}	Dynamo(uncertain depth)
Neptune	2×10^{-5}	Dynamo (uncertain depth)

the power in the higher harmonics is significantly smaller than that in the dipole component, when evaluated at the core radius. For Earth, Jupiter and Saturn (and probably Ganymede, maybe also Mercury), the field is predominantly dipolar. The tilt of the dipole relative to the rotation axis is of order 10° for Jupiter and Earth and near zero for Saturn. For Uranus and Neptune, the field is about equally dipole and quadrupole and the tilt of the dipole is $40\text{--}60^\circ$. Evidently, Uranus and Neptune represent a different class of dynamos.

6. Why do large magnetic fields require energy sources?

Ohm's law, Ampere's law and Faraday's law of induction lead to the *induction equation*:

$$\partial \mathbf{B} / \partial t = \lambda \nabla^2 \mathbf{B} + \nabla \mathbf{x} (\mathbf{v} \times \mathbf{B}) \quad (1)$$

where \mathbf{B} is the magnetic field, \mathbf{v} is the fluid motion (relative to a rotating frame of reference) and $\lambda \equiv 1/\mu_0\sigma$ is known as the *magnetic diffusivity* (μ_0 is the permeability of free space, $4\pi \times 10^{-7}$, and σ is the electrical conductivity in S/m and assumed constant). If there is no fluid motion then the field will undergo free ('diffusive') decay on a time scale $\tau \sim L^2/\pi^2\lambda \sim (3000 \text{ yr}) \cdot (L/1000 \text{ km})^2 \cdot (1 \text{ m}^2 \text{ s}^{-1}/\lambda)$ where L is some characteristic length scale of the field, no more than the radius of the electrically conducting region (the core). In terrestrial planets, the electrical conductivity corresponds to the liquid metallic iron, modified by alloying with other elements (e.g. sulfur). This corresponds to $\sigma \sim 5 \times 10^5$ S/m and $\lambda \sim 2 \text{ m}^2/\text{s}$ [3]. In gas giants, shock wave experiments suggest that hydrogen attains the lowest conductivities appropriate to metals ($\sigma \sim 2 \times 10^4$ to 2×10^5 S/m, $\lambda \sim 5\text{--}50 \text{ m}^2/\text{s}$) at pressure $P \sim 1.5$ Mbar and $T \sim$ a few thousand degrees [11]. (The dynamo in Jupiter may operate at radii beyond the peak conductivity reached in these experiments.) This corresponds to the conditions at 0.8 of Jupiter's radius or 0.5 of Saturn's radius. Shock wave experiments [12] suggest that an 'ice' mixture (dominated by water, but containing many ionic species) will reach conductivities of $\sigma \sim 1 \times 10^4$ S/m ($\lambda \sim 100$

m^2/s), conditions met in Uranus and Neptune at around 0.7 of their radii.

In each case, the free decay time is much less than the age of the solar system. For example, in Earth's core, this time scale is ten thousand years or so. The fact that free decay times are geologically short means that if a planet has a large field now then it must have a means of generating the field now; it cannot rely on some primordial field or pre-existing field.

7. How does a dynamo work?

The essence of a dynamo lies in electromagnetic induction: The creation of emf and associated currents and field through the motion of conducting fluid across magnetic field lines [1,2]. Dimensional analysis of the dynamo equation immediately suggests that the importance of this is characterized by the *magnetic Reynolds number* $R_m \equiv vL/\lambda$ where v is a characteristic fluid velocity and L is a characteristic length scale of the motions or field (e.g. the core radius). Numerical and analytical work suggests that a dynamo will exist if the fluid motions have certain desired features and the magnetic Reynolds number R_m exceeds about 10 or 100 [13–20]. It seems likely that fluid motions of the desired character arise naturally in a convecting fluid (irrespective of the source of fluid buoyancy), provided the Coriolis force has a large effect on the flow, i.e. $v/\Omega L < 1$ where Ω is the planetary rotation rate. This is easily satisfied for any plausible fluid motion of interest, even for slowly rotating planets such as Venus.

Although the dynamo mechanism is much studied, it is still imperfectly understood, despite recent dramatic advances in numerical simulation [13,16]. In particular, we do not know the quantitatively precise sufficient conditions for the existence of a planetary dynamo [15,17,19]. Some of the issues can be appreciated by considering the simple case of a generic planet in which the heat flow in the proposed dynamo region arises primarily from cooling, and no phase changes (e.g. freezing or gravitational differentiation) take place. (In terrestrial planets, the dominant source of *surface* heat flow is radioactive decay, but the

radioactive elements are thought not to reside in the core. In giant planets, cooling from a primordial hot state probably dominates at all levels, though gravitational differentiation may also contribute significantly [6]. In this approximation, and assuming that the core cools everywhere at the about the same rate, we have:

$$F_{\text{total}}(r) = -\rho_c C_p r (dT_c/dt)/3 \quad (2)$$

where $F_{\text{total}}(r)$ is the total heat flow at radius r , ρ_c is the mean core density, C_p is the specific heat, T_c is the mean core temperature and t is time. In fluid cores, the viscosity is so small that it plays a negligible role in the criterion for convection (totally unlike the case for convection in solid silicate mantles). To an excellent approximation, the condition for convection is that the heat flow must exceed that which can be carried by conduction along an adiabat:

$$F_{\text{total}} > F_{\text{cond,ad}} \equiv k\alpha Tg(r)/C_p \Leftrightarrow$$

thermal convection (3)

where k is the thermal conductivity, α is the coefficient of thermal expansion, and $g(r)$ is the gravitational acceleration at radius r . If the heat flow were less than this value then the core would be stably stratified (vertically displaced fluid elements would tend to oscillate). We can approximate $g(r)$ by $4\pi G\rho_c r$ where G is the gravitational constant. Notice that both F_{total} and $F_{\text{cond,ad}}$ are linear in r in this approximation, so the comparison of their magnitudes will be the same independent of planet size and location in the core. From this, we obtain a critical cooling rate that must be exceeded for convection. It is typically about 100 K/Ga for parameters appropriate to Earth's core and may be as large as 300 or 400 K/Ga for smaller (but Earth-like) cores, e.g. Ganymede. It is substantially lower for giant gas or ice planets, where the conductivity is lower. For Earth's core, a cooling rate like 100 K/Ga corresponds to a heat flow at the top of the core of around 20 mW/m².

From condensed matter physics, we also have the Wiedemann–Franz ‘law’ (e.g. [20]) that:

$$k/\sigma T \equiv L \approx 2 \times 10^{-8} \text{ W } \Omega/\text{K}^2 \quad (4)$$

where L is called the Lorenz number. This applies to a metal in which the electrons dominate both the heat and charge transport and is accurate to better than a few tens of percent. Combined with Eq. 3 this implies an *upper* bound to the electrical conductivity in order that thermal convection take place. For nominal parameter choices, this upper bound is roughly the actual value of the electrical conductivity in Earth's core. This makes the important point that high electrical conductivity may indirectly prevent a dynamo! (The use of Wiedemann–Franz is specifically for terrestrial planets: In gas and ice giants, we have independent estimates for thermal conductivity that show that the heat flow along the adiabat is much smaller than the actual heat flow.) See Fig. 1.

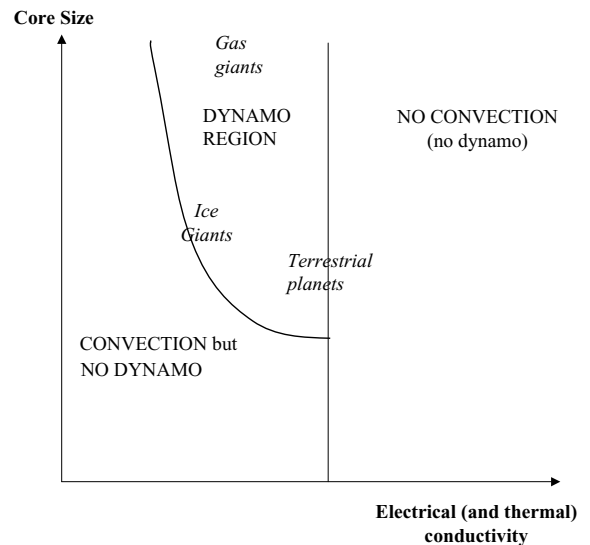


Fig. 1. Dependence of dynamo operating region on planet size and electrical conductivity. This schematic diagram focuses on two of the many parameters that determine whether a thermal convection dynamo exists in a planet. At sufficiently low conductivity, there is a size-dependent cut-off based on the need to exceed a critical magnetic Reynolds number. As explained in the text, there is also an approximately size-independent criterion for the existence of convection, since if the conductivity is too high then the heat can be carried by conduction. Specific values are omitted from the plot because they depend on many (often poorly known) parameters. However, it is likely that terrestrial planets lie near the right hand dynamo boundary, ice giants lie near the left hand boundary and gas giants are comfortably removed from either boundary. A more complicated but conceptually similar diagram will apply if there is compositional convection or latent heat release from an inner core.

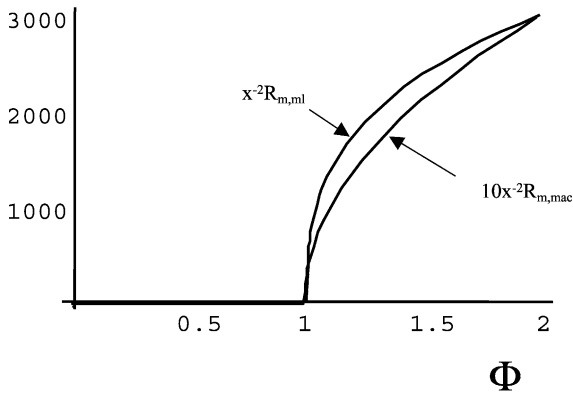


Fig. 2. Variation of magnetic Reynolds number with heat flow. The horizontal coordinate Φ is the total heat flux in units of $F_{\text{cond,ad}}$. Purely thermal convection is assumed and requires $\Phi > 1$. The vertical axis is the value of the functions labeling the curves. $R_{\text{m,ml}}$ is the magnetic Reynolds number for mixing length theory and $R_{\text{m,mac}}$ is the estimate for the magnetostrophic regime (see text). Note that $R_{\text{m,mac}}$ is typically smaller by an order of magnitude. x is the core radius in units of Earth's core. This plot shows that R_{m} may rise rapidly once the criterion for convection is satisfied, so that the criterion for a dynamo may not differ greatly from the criterion for convection, at least for $x \sim 1$. A similar diagram applies for compositional convection but Φ is then related to the buoyancy flux and the critical heat flow is different.

We turn now to the requirement that the convection must be sufficiently vigorous. Two possible estimates for convective velocity might be considered. One comes from mixing length theory [21–23]:

$$v_{\text{ml}} \sim 0.3(lF_{\text{conv}}/\rho H_{\text{T}})^{1/3} \quad (5)$$

where v_{ml} is the predicted velocity, l is the ‘mixing length’ (plausibly the size of the core), $F_{\text{conv}} = F_{\text{total}} - F_{\text{cond,ad}}$, and $H_{\text{T}} \equiv C_{\text{p}}/\alpha g$ is the temperature scale height, not enormously larger than the core radius except in the limit of small bodies. An alternative estimate, plausibly more relevant if a dynamo is operating, assumes that buoyancy, Coriolis and Lorentz forces are comparable [14, 22–23]. In this magnetostrophic regime,

$$v_{\text{mac}} \sim (F_{\text{conv}}/\rho \Omega H_{\text{T}})^{1/2} \quad (6)$$

and this is typically an order of magnitude or so smaller than v_{ml} . Note that slow rotation is favorable (i.e. increases convective velocity). If we define x as the radius of the core in units of Earth's core, then $l \propto x$, $F_{\text{cond,ad}} \propto x$ and $H_{\text{T}} \propto x^{-1}$, so $R_{\text{m,ml}} \equiv (v_{\text{ml}}/l) \propto x^2(\Phi - 1)^{1/3}$ and $R_{\text{m,mac}} \equiv (v_{\text{mac}}/l) \propto x^2(\Phi - 1)^{1/2}$ where $\Phi \equiv F_{\text{total}}/F_{\text{cond,ad}}$. This is illustrated in Fig. 2 using terrestrial parameters. We see that the value of F_{conv} required to get a large R_{m} is small compared to $F_{\text{cond,ad}}$, at least for Earth-sized terrestrial bodies. This may mean that the criterion for convection is almost coincident with the requirement for a dynamo.

In the dynamo regime, the expected field magnitude *inside the region of field generation* is given by Elsasser number $\Lambda \equiv \sigma B^2/2\rho\Omega$ of order unity [13–15], which implies $B \sim (2\rho\Omega/\sigma)^{1/2}$ where ρ is the fluid density. As Table 2 shows, this is approximately satisfied, especially if one allows that the field inside the dynamo region may be larger than at the top of the dynamo region by a factor of a few. The exception may be Uranus and Neptune, although downward extrapolation of their

Table 2
Operating conditions for representative dynamos

	Earth	Ganymede	Jupiter	Uranus
Ω , rotation rate (s^{-1})	7×10^{-5}	1×10^{-5}	2×10^{-4}	1.4×10^{-5}
Density (kg/m^3)	1.1×10^4	6×10^3	1×10^3	1×10^3
Size of dynamo region (m)	3×10^6	7×10^5	3×10^7	$\sim 1 \times 10^7$
H_{T} , temperature scale height (m)	1×10^7	4×10^7	1×10^8	1×10^7
Conductive heat flow along adiabat (W/m^2)	1.5×10^{-2}	1×10^{-3}	$< 10^{-1}$	$< 10^{-2}$
Nominal convective heat flow (W/m^2)	1×10^{-2}	1×10^{-3}	3	$\sim 10^{-1}$
Magnetic diffusivity (m^2/s)	2	4	30	~ 100
R_{m} based on v_{ml}	3×10^3	70	3×10^4	700
R_{m} based on v_{mac}	50	5	400	25
Λ , Elsasser number at top of dynamo	0.3	0.3	0.3	$\sim 0.01?$

fields is difficult because they are not predominantly dipolar.

The cooling rates of giant gas and ice planets can be estimated [6] and predict heat flows that are large compared to conductive transport, and close to the ‘nominal’ values tabulated. However, the situation is far from clear in terrestrial planets, where our understanding of cooling rates is dictated by our (imperfect) understanding of mantle rheologies and heat production [24]. It is possible that the actual heat flow does not exceed the conductive heat flow. This can happen in a convecting fluid provided that there is also compositional buoyancy.

8. Do terrestrial dynamos require compositional convection?

If the core is cooling and the central temperature drops below the liquidus for the core alloy, then an inner core will nucleate. In Earth, we know from seismic evidence that the core is $\sim 10\%$ less dense than pure iron and many suggestions have been offered for the identity of the light elements that are mixed with the iron [25,26]. As the inner core freezes, it is likely that some or all of these light elements are excluded from the crystal structure. The introduction of light elements into the lowermost core fluid will tend to promote convection and cause mixing throughout all or most of the outer core, provided the cooling is sufficiently fast [27–31]. Latent heat release at the inner core–outer core boundary will also contribute to the likelihood of convection. However, inner core growth permits outer core convection even when the heat flow through the core–mantle boundary is less (perhaps much less) than the heat carried by conduction along an adiabat. In this regime, the temperature gradient is very slightly less steep than adiabatic and the compositional convection carries heat *downwards*. The total heat flux is still outwards, of course, since the heat carried by conduction is large. This state is possible because the buoyancy release associated with the compositional change exceeds the work done against the unfavorable thermal stratification.

It is possible but not certain that terrestrial planets require inner core growth in order to sustain a dynamo at the present epoch. It does *not* follow that there is a one-to-one correspondence between presence of an inner core and presence of a dynamo. One can have an inner core without a dynamo (conceivably present Mars if the cooling of the core is insufficiently rapid). One can also imagine a dynamo without a growing inner core (conceivably early Earth or other bodies early in their history) if the core were then cooling much more rapidly than now. Partial freeze-out of light material from the core is also a possible dynamo driving mechanism [32].

9. What about induction fields?

The requirement for a significant induction field is much less restrictive than for a dynamo [33]. The conductivity can be much smaller and the material does not have to be in differential motion (e.g. it can be a solid). For an external field that varies as $\exp(i\omega t)$, and a thin, conducting shell of thickness d and radius R , there will be a large induction response if the electromagnetic skin depth $(\lambda/\omega)^{1/2} < (Rd)^{1/2}$. For example, a layer of low-pressure salty water (such as Earth’s oceans, with $\lambda \sim 10^6$ m²/s) will satisfy this for a thickness of order 10 km and $\omega \sim 2 \times 10^{-4}$ (corresponding to the frequency of Jupiter’s tilted dipole field as it sweeps by Europa). A plausible estimate for R_m in such an ocean is 10^{-3} so there is no significant *internal* induction effect. The observed fields of Europa and Callisto are consistent with an externally induced induction field, and the most likely conductor is salty water [34].

10. Summary for each planet

Mercury is likely to have a liquid outer core and some models predict that this core could continue to convect and perhaps sustain a dynamo [35,36]. Mercury is nonetheless an enigma because the observed field is over an order of magnitude smaller than the field strength predicted for $\Lambda \sim 1$. There are at least four possibilities: permanent

magnetism, an exotic non-dynamo explanation such as thermoelectric currents [37], a dynamo that produces much larger internal (e.g. toroidal) fields than the observed external fields, or a dynamo that for some reason fails to reach the expected field amplitude. The latter is still the most likely explanation, and acceptable given our current imperfect understanding of dynamo theory. Future missions may test the alternatives through assessment of the harmonic structure of the field [38].

Venus is likely to have a liquid outer core (with or without an inner core) but has no dynamo at present. The predicted dynamo field is over two orders of magnitude larger than the observational upper bound. Slow rotation is good for dynamos (provided the Coriolis force remains dynamically important, as it is for all planets), so if *Venus* were like *Earth* in all respects except for its rotation then it would have no difficulty exceeding this upper bound. The most probable interpretation is that the liquid core of *Venus* does not convect. This could arise because there is no inner core [35] or because the core is currently not cooling. The absence of an inner core is plausible if the inside of *Venus* is hotter than the corresponding pressure level of *Earth*. This can arise because *Earth* has plate tectonics, which eliminates heat more efficiently than a stagnant lid form of mantle convection. Alternatively (or in addition), *Venus*' core may not be cooling at present because it is undergoing a transition in convective style following a resurfacing event ~ 700 Ma ago [39].

Earth remains imperfectly understood, a humbling reminder of the dangers of claiming an understanding of other planets. Growth of the inner core is thought essential for sustaining convection and sufficient energy to run the dynamo field [27–31]. Doubts have been expressed about whether *Earth*'s field can be sustained for its known history (at least 3.5 Ga) if the inner core has existed for only of the order of a couple of billion years [29]. An additional energy source may be needed [31,32]. Another possibility is that cooling rates of the lower mantle have been underestimated for earlier epochs.

Moon probably has a core that is at least partially liquid [40,41]. It has patches of strong crus-

tal magnetization that may have been acquired following impacts and compression of conducting plasma at the antipode [42]. It is not known whether the pre-impact field was necessarily a global field of the kind that only a dynamo produces. Even if it is a dynamo, it may (uniquely among planets in our solar system) have arisen through mechanical stirring of the inner core [41]. Rapid cooling of a boundary layer immediately above the core–mantle boundary might also conceivably maintain a dynamo for some time [43].

Mars had an ancient dynamo, probably in the period prior to 4.0 Ga [10,44]. There are three possibilities for why this dynamo existed and then died: (1) Core cooling decreased to the point where conductive heat loss dominated (but no inner core formed). This is the most well developed hypothesis [35]. (2) *Mars* underwent a change in convective style, from an efficient mode (e.g. plate tectonics) to the currently observed stagnant lid mode. This would cause the mantle and core to stop cooling and turn off core convection and the dynamo [45,46]. This model would work irrespective of whether *Mars* has an inner core. (3) The core of *Mars* froze sufficiently so that the remaining fluid region was too thin to sustain a dynamo [44].

Jupiter may have dynamo generation out to levels where hydrogen is only a semiconductor, perhaps 80–85% of the planet radius [11]. This is compatible with the magnitude and harmonic structure of the field [47].

Io exhibits no convincing evidence of a dynamo and no simple inductive response [48]. Although *Io* has a metallic core, it might not be undergoing much long-term cooling if the mantle is heated steadily by tides.

Europa has a clear signature of an induction field [33] and no evidence of a permanent dipole. The induction field can be explained by a water ocean of similar conductivity to *Earth*'s oceans, provided this ocean has a thickness exceeding ~ 10 km. No other plausible source of the required conductivity has been suggested.

Ganymede has a clear signature of a permanent dipole [49]. A permanent magnetism explanation is conceivable [50] but unlikely, and the most rea-

sonable interpretation is a dynamo in the metallic core. A liquid Fe–S core is expected in Ganymede. Nonetheless, this dynamo is surprising, partly because of Ganymede’s size but mainly because of the difficulty in sustaining convection in such a small body. The presence of large amounts of sulfur and mantle heating by decay of a lot of ^{40}K may help. There may also be a much smaller induction signal from a water ocean.

Callisto has a clear induction signal [33], explained by a salty water ocean that underlies the low pressure (phase I) of water ice layer, around 150–200 km in depth. This ocean is expected because of radioactive heating alone.

Saturn may have a dynamo very similar to that of Jupiter, but more deep-seated (the reason for the smaller surface field). It may be overlain by a region that greatly reduces the non-spin axisymmetric components, perhaps explaining the small observed dipole tilt ([51]; but see [52]).

Titan has an observed upper bound to the field that exceeds the field expected for a Ganymede-like dynamo [53]. It may have a water ocean and thus produce an induction signal, potentially detectable by Cassini. However, this will be more difficult to detect because Saturn lacks a significant dipole tilt, so the time-variable part of Saturn’s field is much smaller than that for Jupiter.

Uranus and *Neptune* are very similar in structure and in field strength and geometries. Their very different obliquities are evidently irrelevant to understanding their fields. Although it seems likely that high-pressure water can provide the desired conductivity for a dynamo, it is marginal and the observed field strength seems smaller than expected (see Table 2). This raises the question of whether these planets are actually generating their fields deeper down. Quadrupolar dynamos are permitted by dynamo theory, e.g. [54], and the dynamo activity might be limited to a thin shell [55].

Triton and *Pluto* might possibly have water–ammonia oceans and might therefore be capable of induction signals, to the extent that they are subjected to small, time-varying external magnetic fields.

Extrasolar giant planets can be expected to be convective at depth, and to have the conductivities sufficient for dynamo action.

11. The future

Future developments in this field depend on four things: More observations, more dynamo simulations, more lab data and more synthesis. Observational priorities include: Mercury [56], a determination of whether Venus has any (small spatial scale) field, a detailed correlation of Mars magnetism and geology and ages of surface units, and better spatial and time resolution of the Jovian field. Dynamo simulations require clever ideas as well as merely brute force improvement of the parameter regime. In particular, we need a useful criterion for planetary dynamos. Lab data are essential to understand the transport properties of various cosmically important mixtures as well as the alloying properties relevant to Earth’s core. We still do not know for sure whether Earth’s core contains significant radioactive heating. Synthesis requires knowing the regimes and scaling behaviors of mantle convection, with and without plate tectonics and mantle layering (both for silicates and for ice). It also requires understanding the extent of deep mixing within giant gas and ice planets. Ultimately, these issues cannot be separated from the big questions of how planets form, differentiate and evolve.

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