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Planetary Magnetic Fields: Achievements and Prospects

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Abstract The past decade has seen a wealth of new data, mainly from the Galilean satellites and Mars, but also new information on Mercury, the Moon and asteroids (meteorites). In parallel, there have been advances in our understanding of dynamo theory, new ideas on the scaling laws for field amplitudes, and a deeper appreciation on the diversity and complexity of planetary interior properties and evolutions. Most planetary magnetic fields arise from dynamos, past or present, and planetary dynamos generally 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 one percent or less that of a typical metal, appropriate to ionic fluids and semiconductors. In all planetary liquid cores, the Coriolis force is dynamically important. 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 an iron-rich core guarantees a high thermal conductivity (through the Wiedemann-Franz law), which allows for a large core heat flow by conduction alone. This has led to an emphasis on the possible role of ongoing differentiation (growth of an inner core or "snow"). Although planetary dynamos mostly appear to operate with an internal field that is not very different from $(2\rho\Omega/\sigma)^{1/2}$ in SI units where ρ is the fluid density, Ω is the planetary rotation rate and σ is the conductivity, theoretical arguments and stellar observations suggest that there may be better justification for a scaling law that emphasizes the buoyancy flux. Earth, Ganymede, Jupiter, Saturn, Uranus, Neptune, and probably 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. Even small, differentiated planetesimals (asteroids) may have been capable of dynamo action early in the solar system history. Induced fields observed in Europa and Callisto indicate the strong likelihood of water oceans in these bodies. 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. As a consequence, the understanding of planetary

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magnetic fields depends as much on our understanding of the history and material properties of planets as it does on our understanding of the dynamo process. Future developments can be expected in our understanding of the criterion for a dynamo and on planetary properties, through a combination of theoretical work, numerical simulations, planetary missions (MESSENGER, Juno, etc.) and laboratory experiments.

Keywords Planets · Magnetism · Dynamos

1 Overview

Magnetic fields are everywhere in the universe. In particular, they are often a characteristic of planets and most of the planets in our solar system have substantial fields. In many planets, the cause of this field is electrical currents deep within the body and its presence and behavior tells us something about the physical state and dynamics of the material deep within the planet. Indeed, the magnetic field is one the few ways of probing the interior structure. Moreover, the field can usually be determined remotely (i.e., by an orbiting or flyby spacecraft). Many conventional geophysical techniques for determining interior structure (e.g., seismology) are not readily accessible from orbit or flyby. In some cases, the field is only present as remanent magnetism (the "permanent" magnetism of minerals in the outer part of a solid body) but even then it may be telling us about past dynamics of the deep interior. In a few cases (notably the Galilean satellites Europa and Callisto) there are induced fields arising from the time variation of an external field. These are also telling us something important about the body. My focus here is on the information magnetic fields provide us about history and structure of bodies in our solar system, not just the planets as conventionally defined but also satellites and even small bodies (e.g., asteroids). The absence of a present-day large field (e.g Venus, Mars) is just as interesting as its presence and the nature of the field when present (i.e., its harmonic spectrum, possible time variability) is also of great interest.

In many respects, this chapter is an update of a recent review (Stevenson 2003). However, a remarkable amount of relevant new work and some new observations have occurred since then and this necessitates not merely an update but also some new perspectives. Additionally, this chapter offers some views on the future of the field, part of which is linked to future spacecraft missions or extrasolar planet observations and part of which is linked to future directions in theory and in understanding the material properties and dynamics of planets. The chapter ends with a commentary on each planetary body (including hypothetical planets in other planetary systems.)

2 Observed Fields

Details of planetary observations are well covered elsewhere. Here, the intent is to make a summary of the current observational situation, with comments on the particular distinctive features of these observations. See Table 1.

3 The Nature of Dynamos

The central idea for understanding large, planetary scale magnetic fields is the hydromagnetic dynamo. The essence of a dynamo lies in electromagnetic induction: The creation of

Table 1 Observed magnetic fields (*based on* Stevenson 2003)

Planet or satellite	Observed surface field (in Tesla, approximate)	Comments and interpretation
Mercury	2×10^{-7}	Not well characterized or understood yet, but MESSENGER data suggest a dynamo
Venus	$<10^{-8}$ (global); no useful constraint on local fields	No dynamo at present. Small remanence is possible
Earth	5×10^{-5}	Core dynamo
Moon	Patchy; (10^{-9}–10^{-7} T) No global field	Ancient dynamo? Remanent magnetism is related to impact. More data needed
Mars	Patchy but locally strong (10^{-9}–10^{-4} T); may field	Ancient dynamo, Strong remanent magnetism
Jupiter	4.2×10^{-4}	Dynamo (extends to near surface). Earthlike dipole tilt.
Io	$<10^{-6}$?	Complex (deeply imbedded in Jovian field. Data do not require a dynamo
Europa	10^{-7}	Induction response (Salty Water Ocean)
Ganymede	2×10^{-6}	Dynamo likely. May also exhibit an induction response (like Europa and Callisto)
Callisto	4×10^{-9}	Induction response (Salty Water Ocean)
Saturn	2×10^{-5}	Dynamo (deep down?). Field appears to be spin-axisymmetric
Titan	$<10^{-7}$	No evidence for a dynamo or internal induction response.
Uranus	2×10^{-5}	Dynamo with large dipole tilt and quadrupole
Neptune	2×10^{-5}	Dynamo with large dipole tilt and quadrupole

emf and associated currents and field through the motion of conducting fluid across magnetic field lines (Moffatt 1978; Parker 1979). This can expressed mathematically through the combination of Ohm's law, Ampere's law and Faraday's law of induction (often called 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 rigidly rotating frame of reference, the normal choice for planetary fluid dynamical problems) and $\lambda \equiv 1/\mu_0\sigma$ is known as the *magnetic diffusivity* (μ_0 is the permeability of free space, $4\pi \times 10^{-7}$ in SI units and σ is the electrical conductivity in S/m, and assumed constant). If there is no fluid motion ($\mathbf{v} = \mathbf{0}$) then the field will undergo free ("diffusive") decay on a timescale $\tau \sim L^2/\pi^2\lambda \sim (3000\ \text{yr}) \cdot (L/1000\ \text{km})^2 \cdot (1\ \text{m}^2\ \text{sec}^{-1}/\lambda)$ 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 liquid metallic iron, modified by alloying with other elements (e.g., sulfur). This corresponds to $\sigma \sim 5 \times 10^5$ S/m and $\lambda \sim 2\ \text{m}^2/\text{sec}$ (cf. Merrill et al. 1996) but the uncertainties on this value remain large (roughly a factor of two, sometimes more) depending on pressure and assumed composition. 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, $\lambda \sim 5$ to $50\ \text{m}^2/\text{sec}$) at pressure $P \sim 1.5$ Megabar and $T \sim a$ few thousand degrees (Nellis 2000). This corresponds to the conditions at 0.8 of Jupiter's radius or 0.5 of Saturn's radius. The dynamo in Jupiter may operate at radii beyond the peak conductivity reached in these experiments (this is discussed further in the sections on Jupiter and Saturn). Shock wave experiments (Nellis et al. 1997) 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/sec), 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 timescale 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.

Dimensional analysis of the induction equation above immediately suggests that the importance of a flow 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). The existence of solutions in which the field does not decay to zero after a long time depends on R_m and a value exceeding ~10 or 100 is thought sufficient, but this is a vague criterion: Which velocity and how is it determined? We return to this below.

4 The Nature of Planets and Their Evolution

Planets are conveniently categorized according to their primary constituents (De Pater and Lissauer 2001; Stevenson 2002; Guillot 1999). 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. This persistence of a liquid layer arises from the eutectic nature of the phase diagram and, more generally, the fact that one must go to a temperature lower than that needed to get heat out through the mantle in order to produce *complete* freezing. It is for this reason that the presence or absence of a dynamo should not be thought of as related to the presence or absence of an outer liquid core but rather to the vigor of motions in that layer. This argument only fails for very small bodies (even smaller than Earth's moon). *Gas giants* (Jupiter and Saturn) have hydrogen as their major constituent. They may possess "Earthlike" central cores but this may have little bearing on understanding their magnetic fields. Freezing is a non-issue. *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 ~80% of their radii. Freezing in these bodies seems unlikely given that their interiors are mixtures, but would perhaps be marginally possible if one thought that the freezing curve of *pure* water were relevant (cf. French et al. 2009). *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 Earthlike 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, however, because the heat carried by conduction alone is typically within a factor of two of the expected core heat flow.

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, a major 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; Guillot 1999). In this approximation, and assuming that the core cools everywhere at the about the same rate, we have

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

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:

$$F_{\text{total}} > F_{\text{cond,ad}} \equiv k\alpha \text{Tg}(r)/C_p \quad \Leftrightarrow \quad \text{thermal convection} \tag{3}$$

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 Earthlike) 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/m^2.

From condensed matter physics, we also have the Wiedemann-Franz "law" (e.g., Poirier 1991);

$$k/\sigma T \equiv L \approx 2 \times 10^{-8}\ \text{W Ohm/K}^2 \tag{4}$$

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 (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.)

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 (Poirier 1994; Gessmann et al. 2001). As the inner core freezes, it is likely that some or all of these light elements are partially 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 (Gubbins 1977; Loper 1978; Labrosse et al. 2001; Buffett and Bloxham 2002). 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 or absent). 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 (Buffett et al. 2000) and has been advocated by this author at recent conferences. There may also be more complicated phase diagrams that allow freeze-out away from either the top or bottom of the core; this is mentioned in the summaries offered below for specific planets; especially Mercury and Mars.

5 Dynamo Theory and Dynamo Scaling

Numerical and analytical work suggest 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 (Roberts and Glatzmaier 2000; Jones 2000; Busse 2000; Gubbins 2001; Christensen et al. 2001, 2009). 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., Rossby number $Ro \equiv v/2\Omega L < 1$ 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 the recent dramatic advances in numerical simulation referenced above. In particular, we do not know the quantitatively precise sufficient conditions for the existence of a planetary dynamo. How can we assess the value for the velocity v that enters into the "typical" estimate of magnetic Reynolds number? One possible estimate comes from mixing length theory (Clayton 1968; Stevenson 1979, 1987a):

$$v_{ml} \sim 0.3(lF_{\mathrm{conv}}/\rho H_T)^{1/3} \tag{5}$$

where v_{ml} is the predicted velocity, l is the "mixing length" (plausibly the size of the core), $F_{\mathrm{conv}} = F_{\mathrm{total}} - F_{\mathrm{cond.ad}}$, and $H_T \equiv C_p/\alpha g$ 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 (Jones 2000). In this magnetostrophic regime,

$$v_{\mathrm{mac}} \sim (F_{\mathrm{conv}}/\rho\Omega H_T)^{1/2} \tag{6}$$

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). We can also envisage estimates intermediate between (5) and (6) in which the dependence on rotation is intermediate between inverse square-root and no dependence. As discussed in Stevenson (2003) both parameterizations (but especially the simple mixing length theory choice) have the property that the convective velocity rises rapidly once F is positive, because of the cube root and square-root behaviors, respectively. As a consequence, it follows that except for small bodies or bodies of low electrical conductivity (the ice giants, perhaps), the issue of sufficiently vigorous convection for a dynamo is almost identical to the issue of whether convection is possible at all. There is only a narrow range of conditions for which the convection is present but insufficiently vigorous for dynamo action. Of course, these arguments remain plausible rather than rigorous and one awaits a more quantitative assessment of this important question.

The expected value of the field has long fascinated people. There are two kinds of arguments that can be made on this question (with intermediates of these two extremes also possible). One extreme is to view the field amplitude as being a strictly dynamical issue, involving force balances but not (directly) involving the vigor of the convection (the buoyancy flux). In this picture, it has been argued that 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, which implies $B \sim (2\rho\Omega/\sigma)^{1/2}$ where ρ is the fluid density. This is approximately satisfied by the values listed in Table 1 of observed fields (and see Stevenson 2003, for more details), 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 fields is difficult because they are not predominantly dipolar. The testing of this expectation is made difficult by quite large uncertainties in some parameters.

Recently, Christensen et al. (2009) made a persuasive case for a very different kind of scaling; in effect one in which there is a proportionality between the energy in the field and the "nominal" kinetic energy estimate provide by mixing length theory (5). A remarkable feature of this scaling (field proportional to the cube root of buoyancy flux, or $B^2/2\mu_0 \sim f\rho v_{ml}^2$ where f is a nearly universal dimensionless number) is that it does not give any dependence of field strength on either the rotation rate or the magnetic diffusivity. The evidence in favor of this scaling is partly theoretical but also from some stars, where there is a much larger buoyancy flux and a much larger observed field. This assumes that these stars operate in the same dynamo regime as planets. The new proposal is actually the same as the "scaling" suggested based on energy considerations by Stevenson et al. (1983) in their discussion of how Earth's field might change through geologic time depending on the presence or absence of an inner core. It must be stressed, however, that this old suggestion was not based on deeply considered arguments of how dynamos actually operate. The Elsasser number criterion can also be made consistent with the energy budget (at least in principle) by assigning most of the dissipation to higher harmonics of the field. The new scaling proposal should be regarded as a major development, given the arguments advanced in its support. Depending on one's point of view, this very different scaling law does as well, or as poorly, as the one based on Elsasser number. But certainly the theoretical evidence (numerical dynamo models) argues against a strict constancy of Elsasser number, so it seems likely that the Elsasser number "rule" is not well-justified.

6 Field Geometries

External to the planet and the large currents responsible for most of the field, the magnetic field **B** can be written as the gradient of a scalar potential that satisfies Laplace's equation. In the standard way, 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, $l = 2$ 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 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 degrees 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 40–60 degrees. Evidently, Uranus and Neptune represent a different class of dynamos. The peculiarities of these planets are described below and attributed to distinctive features of their internal structure.

7 Induction Fields

The requirement for a significant induction field is much less restrictive than for a dynamo (Zimmer et al. 2000). The conductivity can be much smaller and the fluid does not have to be in motion (it can be even 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 $\lambda \sim 10^6$ m^2/sec) 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, Callisto are consistent with an externally induced induction field, and the most likely conductor is salty water (Stevenson 2000).

8 A Survey of the Planets

Mercury has been determined to have a liquid outer core (Margot et al. 2007) and some models predict that this core could continue to convect and perhaps sustain a dynamo (Stevenson et al. 1983; Schubert et al. 1988). Some models suggest that an additional energy source may be needed (e.g., Williams et al. 2007) but there are additional complications that may arise from new evidence of a more complicated Fe–S phase diagram than previously assumed; one that allows for the formation of "snow" (Chen et al. 2008). Mercury is nonetheless an enigma because the observed field is over an order of magnitude smaller than the field strength predicted for either scaling law described above. There are at least four possibilities: permanent magnetism (e.g., Aharonson et al. 2004), an exotic non-dynamo explanation such as thermoelectric currents (Stevenson 1987b; Giampieri and Balogh 2002), a dynamo that produces much larger internal (e.g., toroidal) fields than the observed external fields (Stanley et al. 2005), or a dynamo that for some reason fails to reach the expected field amplitude, for example by operating at greater depths in a core that is layered or partially stratified (e.g. Christensen 2006; Christensen and Wicht 2008). The conventional dynamo explanation is most likely, and is compatible with the earliest results from MESSENGER (Anderson et al. 2008), suggesting a relatively simple field geometry.

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. Equation (6) suggests that slow rotation may be 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 (Stevenson et al. 1983) 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 (Schubert et al. 1998). In this scenario, Venus had a dynamo in the past. Since the surface rocks are at a temperature below the blocking temperature of likely carriers of remanent magnetism, a small paleofield is marginally possible.

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 (see references cited earlier for the need for compositional convection). 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 order a couple of billion years. An additional energy source may be needed; potassium-40 has been suggested. See Labrosse et al. (2001) for a discussion of this. 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 (Stevenson 1983; Williams et al. 2001). It has patches of strong crustal magnetization that may have been acquired following impacts and compression of conducting plasma at the antipode (Hood et al. 2001). 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 (Williams et al. 2001). Rapid cooling of a boundary layer immediately above the core mantle boundary might also conceivably maintain a dynamo for some time. The latest paleomagnetic results (Garrick-Bethell et al. 2009) make the demands on a dynamo less stringent than previously thought, but clearly more data are needed: This new work also casts doubt on much of the previous paleomagnetic work.

Mars had an ancient dynamo, probably in the period prior to 4.0 Ga (Acuna et al. 2001; Stevenson 2001). 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); Stevenson et al. (1983).
(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 (Nimmo and Stevenson 2000). 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. However, Mars may also be more complicated than these simple models; e.g. Stewart et al. (2007); and more needs to be known about paleointensities (cf. Weiss et al. 2008b). Unorthodox alternatives exist to conventional dynamos, e.g. Arkani-Hamed (2009).

Some *asteroids* underwent differentiation early in solar system history and had liquid cores that may have convected vigorously for a short period of time (of order a million years). These bodies may have had dynamos that were then responsible for the observed meteoritic paleomagnetism (Weiss et al. 2008a; Nimmo 2009). This exciting possibility deserves more study since it may give us some information on the lower limit of size needed for a dynamo.

Jupiter may have dynamo generation out to levels where hydrogen is only a semiconductor, perhaps 80 to 85% of the planet radius. However, coupling of the flows with the field may persist out to larger radii (Liu et al. 2008). There is a hint of complex field structure in the observations of the aurora (Grodent et al. 2008). Despite the central importance of Jupiter in our solar system there is not yet a successful numerical simulation that looks like Jupiter's observed field and contains the essential physics (e.g. very large variation in electrical conductivity and density).

Io exhibits no convincing evidence of a dynamo and no simple inductive response (Kivelson et al. 2001). Although Io has a metallic core, it might not be undergoing much long-term cooling if the mantle is heated steadily by tides. Recent astrometric data (Lainey et al. 2009) suggest that Io is spiraling in towards Jupiter but is in thermal equilibrium (i.e., as much heat is escaping as is being tidally generated). This suggests a non-steady–state regime for the thermal history but does not offer an immediate explanation for the absence of a dynamo.

Europa has a clear signature of an induction field (Zimmer et al. 2000) 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 $\sim$10 km. No other plausible source of the required conductivity has been suggested.

Ganymede has a clear signature of a permanent dipole (Kivelson et al. 1998). A permanent magnetism explanation is conceivable but unlikely, and the most reasonable 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 large ^{40}K mantle heating may help. There may also be a much smaller induction signal from a water ocean.

Callisto has a clear induction signal (Zimmer et al. 2000); explained by a salty water ocean that underlies the low pressure (phase I) of water ice layer, around 150 to 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 (Stevenson 1982; Christensen and Wicht 2008).

Titan has an observed upper bound to the field that is less than the field expected for a Ganymede-like dynamo. 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 ionic (not metallic) water can provide the desired conductivity for a dynamo, it is marginal and the observed field strength seems smaller than expected . This raises the question of whether these planets are actually generating their fields deeper down. Quadrupolar dynamos are permitted by dynamo theory, and the dynamo activity might be limited to a thin shell (Hubbard et al. 1995). Models of this kind have been developed (Stanley and Bloxham 2004, 2006).

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. It is possible that "hot Jupiters" have field lines that connect the planet to the neighboring star; this could have observational consequences.

9 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, a determination of whether Venus has any (small spatial scale) field, lunar paleomagnetism, a detailed correlation of Mars magnetism and geology and ages of surface units, and better spatial and time resolution of the Jovian field. We can expect the MESSENGER mission and the follow-on European effort (Bepi Colombo) to do an excellent characterization of Mercury's field environment, though the relatively large magnetospheric effects may limit precise determination of the purely internal part. We also expect Juno (launch in 2011, arrival at Jupiter in 2016) to do a spectacular job on Jupiter; indeed the field will be better characterized than Earth's dynamo (because there is no confusion from a crustal field). As described above, we may be making progress on lunar and meteoritic paleomagnetism, and this can also help our understanding of dynamos.

Dynamo simulations continue to benefit from Moore's law and creep ever upwards in spatial and temporal resolution (e.g., Kageyama et al. 2008). However, dynamo theory requires clever ideas as well as merely brute force improvement of the parameter regime. In particular, we need a useful criterion for planetary dynamos. The definition of useful is this: Given perfect knowledge of all the planetary physical parameters, what is the minimal convective heat flow or buoyancy flux needed for sustaining a dynamo? What field amplitude is then expected?

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. Significant new developments (described above) suggest that we need a better understanding of the phase diagram in particular. We still do not know for sure whether Earth's core contains significant radioactive heating. Laboratory simulations of dynamos also play a role by testing our understanding of the relevant fluid dynamics.

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 mixing deep within giant gas and ice planets. Ultimately, these issues cannot be separated from the big questions of how planets form, differentiate and evolve. The spectacular explosion in work on extrasolar planets can be expected to affect our thinking on these issues in the coming decade.

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