6

Planetary dynamos: updates and new frontiers

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In the study of heliophysics, planetary dynamos are important in understanding how various planetary bodies produce their magnetospheres which then so intricately interact with the solar wind. The dynamo mechanisms in planets are also very similar to those in the Sun, as well as in stars and other astrophysical bodies. Investigating planetary magnetic fields, therefore, provides data points in understanding magnetohydrodynamic processes in a broad range of astrophysical settings.

The investigation of planetary dynamos was predominantly focused on Earth's magnetic field until the mid-to-late twentieth century when planetary missions began to provide data on magnetic fields of other planets. Through our exploration of the solar system, we have discovered the diversity of planetary magnetic fields and realized the importance of magnetic fields in acting as probes of planetary interior structure, composition, and thermal evolution. As examples, magnetic field data were fundamental in discovering the global oceans of Europa, Ganymede, and Callisto, they demonstrated that Mercury and Ganymede each have a liquid iron outer core, and provided a main line of support for a helium-insolubility layer in Saturn.

Several aspects of planetary dynamos have been covered in previous chapters in the Heliophysics series. For a review of theoretical magnetohydrodynamics, applicable to planets as well as other astrophysical bodies, see Ch. 3 in Vol. I (Rempel, 2009a). In addition, an overview of planetary magnetic field properties can be found in Ch. 13 of that volume (Bagenal, 2009) and further details on the geomagnetic field and planetary dynamos can be found in Ch. 7 of Vol. III (Christensen, 2010).

This chapter serves two purposes. First, it provides an update on our understanding of planetary magnetic fields and dynamos from new mission data and dynamo models since the previous volumes of this series were written. Wherever possible, we refer the reader to specific chapters in previous volumes (see Table 1.2) rather than repeat too much information. However, we review the most important concepts and findings needed here so that this chapter is also self-contained. Second, this chapter delves into the frontier (or fringe, depending on your perspective) of planetary dynamo studies by reviewing our understanding of dynamos in small bodies and extrasolar planets.

6.1 Dynamo fundamentals

Dynamo action refers to the conversion of mechanical energy into electromagnetic energy through induction. In planets, the mechanical energy is supplied by fluid motions in electrically conducting regions inside the planets and the electromagnetic energy produces the observed planetary magnetic fields. A dynamo is referred to as *self-sustaining* if it does not require any external magnetic field contributions for regeneration (except initially for a starting seed field).

6.1.1 The magnetic induction equation

The fundamental equation governing this induction process is known as the *Magnetic Induction Equation*:

$$\frac{\partial \vec{B}}{\partial t} = \nabla \times (\vec{u} \times \vec{B}) + \lambda \nabla^2 \vec{B}, \tag{6.1}$$

where $\vec{B}$ is the magnetic field, t is time, $\vec{u}$ is the fluid velocity, and λ is the magnetic diffusivity, defined as:

$$\lambda = \frac{1}{\mu\sigma}, \tag{6.2}$$

where μ is the magnetic permeability and σ is the electrical conductivity.

The Magnetic Induction Equation can be derived from Maxwell's equations and Ohm's law in the magnetohydrodynamic limit (i.e., with fluid velocities much slower than the speed of light). The derivation is given in Sect. 3.3 of Vol. I (Rempel, 2009a).

6.1.2 Requirements for planetary dynamo action

At present, a complete minimal set of necessary and sufficient conditions for planetary dynamo action is not known. The definition of a planetary dynamo hints at some necessary conditions for this process. The planet must contain an electrically conducting fluid region. There must also be motions in this fluid region and hence a power source for the mechanical energy associated with these motions. Below we discuss other necessary conditions that are required for dynamo action.

6.1.2.1 The Magnetic Reynolds Number criterion

By inspecting the two terms on the right-hand side of Eq. (6.1) we see that magnetic field can grow or decay in time through two processes. The first term involves interactions of the velocity and magnetic fields through electromagnetic induction and acts as a source/sink term for field generation. The second term represents diffusion due to Ohmic dissipation. To ensure magnetic field does not decay away in time, field must be generated as fast or faster than its diffusion. A necessary condition for self-sustained dynamo action is therefore that the induction term be larger than the diffusion term in Eq. (6.1). By using characteristic scales for the variables in the Magnetic Induction Equation (i.e., B for the magnetic field scale, U for the velocity scale and L for a length scale) we derive a common measure of the ratio of field generation to field diffusion known as the *Magnetic Reynolds Number*:

$$Re_M = \frac{|\nabla \times (\vec{u} \times \vec{B})|}{|\lambda \nabla^2 \vec{B}|} \approx \frac{UB/L}{\lambda B/L^2} = \frac{UL}{\lambda}. \tag{6.3}$$

Upon first glance, it seems reasonable that the Magnetic Reynolds Number must be larger than unity in order for dynamo action to be possible. However, more rigorous theoretical analyses suggest that the lower bound for Re_M is instead closer to π^2 (Jones, 2008) and planetary numerical dynamo simulations typically find Re_M must be larger than $\sim 20-50$ for self-sustained dynamo action to occur. These higher values are due to the complexities in the velocity field morphologies that cannot be captured in the simple estimate given in Eq. (6.3).

6.1.2.2 Power source for fluid motions

In most planetary dynamo source regions, the fluid motions required for dynamo action result from convection. Thermal convection results if the heat output from the dynamo source region is higher than what can be transported down the conductive adiabatic gradient. This can be represented with the criterion:

$$q > q_{\mathrm{ad}} \Rightarrow k|\nabla T| > k|(\nabla T)|_{\mathrm{ad}} = \frac{k\alpha T g}{C_{\mathrm{P}}}, \tag{6.4}$$

where q is the heat flux, subscript "ad" refers to the adiabatic value, k is the thermal conductivity, T is temperature, g is gravitational acceleration, α is the thermal expansion coefficient, and C_{P} is the heat capacity at constant pressure. The propensity for dynamo action is therefore strongly linked to the thermal evolution and heat-transport properties of the planetary interior.

Compositional convection may also be important for driving motions. These motions result when there are density differences in a multi-component fluid. For example, in the Earth's core, the solidification of the inner core releases a fluid enriched in light elements compared to the bulk core and hence, is buoyant and will rise, thereby driving motions.

In the absence of convection, the most feasible mechanism to generate flows in dynamo regions is fluid instabilities resulting from mechanical boundary forcings such as those due to precession, tides, or impacts.

6.1.2.3 Morphology of fluid motions

The intensity of fluid motions is also not a sufficient criterion for dynamo action. The morphology of the flow is also crucial. For example, in the spherical geometry of dynamo regions, basic flows such as solid body rotation or flows without radial components cannot sustain dynamo action. Motions must be fairly complex and three-dimensional (Jones, 2008).

Another concern is how to ensure generation of a large-scale magnetic field (i.e., with wavelengths much larger than the turbulent motions generating the field). To do so, the flow must contain a net helicity. Turbulent motions alone do not guarantee this as some symmetry-breaking mechanism is required. In planetary cores, the flow constraint due to rapid rotation acts as an excellent mechanism for generating this net helicity and large-scale field. Further information on dynamo generation mechanisms and constraints can be found in Ch. 3 in Vol. I (Rempel, 2009a).

6.1.3 Dynamo scaling laws

A major goal of dynamo studies is to develop predictions of dynamo characteristics based on the physical parameters (e.g., size, rotation rate, available energy) of the system. Researchers have been working to refine such scaling laws for planetary dynamos; see Sect. 7.6.5 of Vol. III (Christensen, 2010) for details. Aside from (hopefully) minor tunings, scaling laws seem to be effective in numerical dynamo simulations for predicting magnetic field strength, the degree of dipolarity of the magnetic field, and heat transport. Some of these scalings also seem to work well for actual planets (but not all!).

6.2 Planetary dynamos: updates

Since the previous volume in this series, advances have been made on several fronts which have improved our knowledge of planetary dynamos.

- New mission data have been gathered on planetary magnetic fields and interior properties.
- Computational resources and numerical methods have improved, allowing new regions of parameter space to be explored with numerical dynamo simulations.

- Significant theoretical and experimental work has been carried out on the properties of materials at high pressure and temperature, most notable for dynamo studies is the work on iron alloys and water.
- Paleomagnetic instrumentation advances have resulted in exciting new data on meteorite magnetism.

In the sections below we briefly review the main results discussed in Ch. 11 of Vol. III (Christensen, 2010) on planetary dynamos and discuss subsequent findings in these areas.

6.2.1 Terrestrial planets

6.2.1.1 Earth

Earth's dynamo is generated in the liquid Fe-rich core. The resulting surface field is predominantly axially dipolar (see Fig. 6.1) and experiences variability on a range of time scales. Paleomagnetic studies suggest that the geomagnetic field has maintained a similar field strength as today for at least the past three billion years.

The source of motions in the core is convection, both thermal and compositional in origin. It is believed that compositional convection is the dominant source in recent times. Seismic data demonstrate that, in addition to iron and nickel, the core must contain roughly 10% lighter elements such as Si, S, O, or H. Compositional convection results from the release of light-element-rich fluid at the inner core boundary upon solidification of the inner core as the planet cools. Thermodynamic estimates suggest that the inner core began solidifying as late as a billion years ago which implies that thermal convection must have been the dominant source of convection before then.

Chapter 11 in Vol. III (Christensen, 2010) provides more detailed information on the geodynamo. Below, I highlight two fundamental discoveries that have occurred since that chapter was written with profound implications for the geodynamo.

(1) New estimates for Fe conductivities Recent ab-initio density functional theory computations by Pozzo *et al.* (2012) have revised the thermal and electrical conductivity of Fe alloys to be 2–3 times higher than previously thought at core pressures and temperatures. This has two implications for the geodynamo. First, the higher electrical conductivity means that the diffusive time scales of the dynamo are longer than previously thought. Second, the higher thermal conductivity means that more heat can be transported down the core adiabat than previously thought.

With this revised adiabatic core heat flux, estimates for how much of Earth's surface heat flow comes from the core imply that the outer portion of the outer

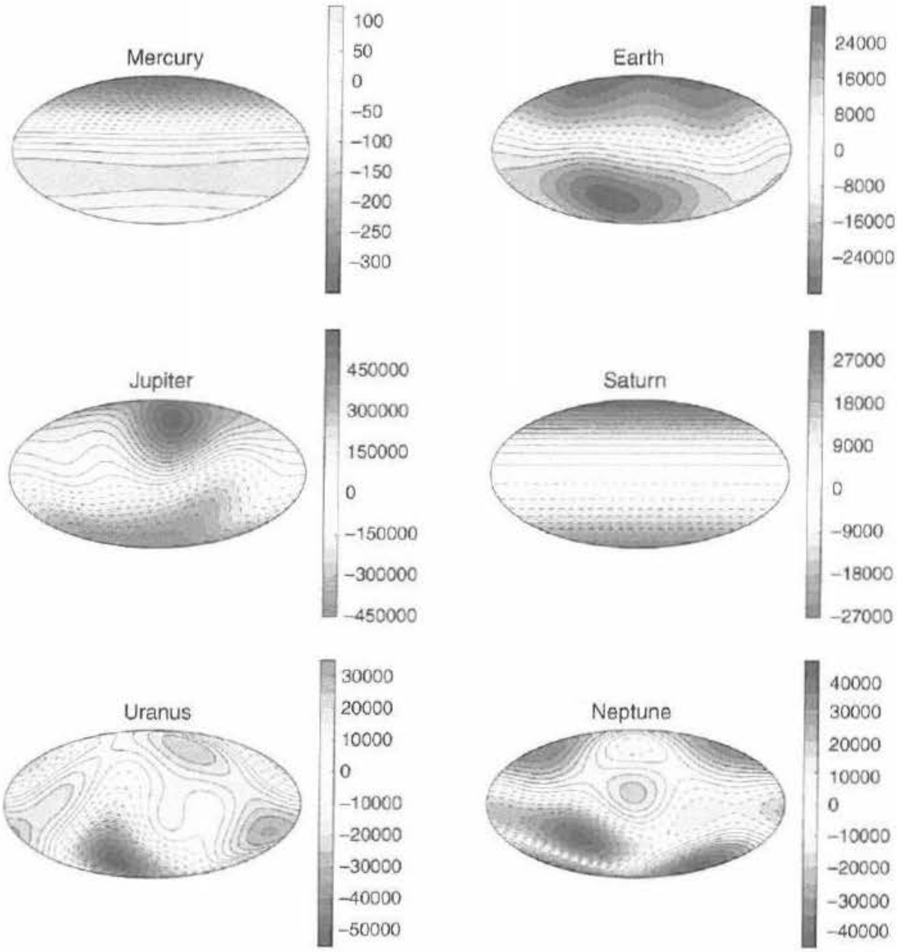

Fig. 6.1 Filled contours of the radial component of the surface magnetic field for planets in our solar system with active dynamos. Dashed contours represent negative values. Units are nT.

core is most likely thermally stably stratified. This would imply that convection is concentrated in the deeper portion of the core, that the smaller and faster scales of magnetic-field variability may be somewhat screened from observation by the stable layer, and that waves in the stable layer may contribute to the observed geomagnetic secular variation (Buffett, 2014).

(2) The translating inner core In the simplest prescription, the inner core is a spherical phase boundary where an iron-rich fluid is crystallizing as the planet cools. However, seismologists have known for some time that there are anomalies within the inner core. First, seismic waves travel faster in certain directions through the inner core. This is known as *seismic anisotropy*. Recent

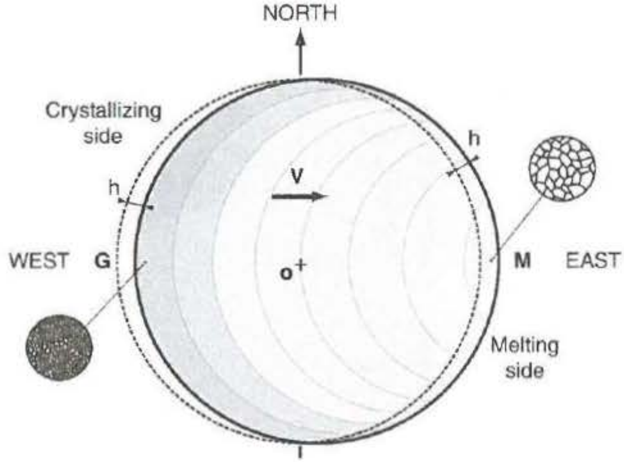

Fig. 6.2 Schematic of a translating inner planetary core due to inner-core convection. The dashed circle is the equilibrium position of the inner core. Thermal perturbations from degree-one inner-core convection cause the inner core to shift to the right inducing melting on the warm side and crystallization on the cold side. (From Monnereau *et al.*, 2010.)

work has also demonstrated that this anisotropy is different in the western and eastern hemispheres of the inner core. What could be responsible for such a lateral difference? Studies suggest that the inner core might evolve in a very interesting manner. If the inner core experiences large-scale solid-state convection (Buffett, 2009), then the thermal perturbations (resulting in density perturbations) in the inner core could shift it from the center of the planet due to gravitational forces. This would displace the inner core boundary from the geocentric freezing boundary (see Fig. 6.2). Ultimately, this process leads to crystallization at the inner core boundary predominantly occurring in one hemisphere and melting occurring in the other hemisphere (Monnereau *et al.*, 2010; Alboussiere *et al.*, 2010). This would make the age of the material in the inner core younger on the crystallizing side and older on the melting side explaining the hemispheric seismic differences. What this means for the dynamo is that the buoyancy sources driving the dynamo (the release of light elements and latent heat at the solidifying boundary) may not be homogeneous at the inner core boundary. Dynamo simulations by Aubert *et al.* (2013) have demonstrated that such variations may explain the inhomogeneity in secular variation rates in the Pacific and Atlantic hemispheres.

6.2.1.2 Mercury

The fact that Mercury possesses an intrinsic magnetic field has been known since the Mariner 10 mission in the mid 1970s. From Mariner 10 it was determined that Mercury's observed magnetic field is predominantly dipolar but much weaker than expected from standard scaling studies. Previous dynamo studies and simulations have worked to explain this weakness in the field strength (see Stanley and Glatzmaier, 2010, for a review).

The more recent MESSENGER mission has provided exciting new data on Mercury, including its magnetic field. In addition to the weakness of Mercury's field, the dipolar field is offset by approximately 480 km northward from the equator (equivalent to having a magnetic field with a $\sim 40\%$ magnetic quadrupole component relative to the dipole). In addition, present data suggest the field is fairly axisymmetric (see Fig. 6.1) with a dipole tilt smaller than $0.8°$ (Anderson *et al.*, 2012).

New dynamo simulations are working towards producing all three of Mercury's field characteristics: (1) weak intensity, (2) predominantly dipolar but with a large quadrupole component, and (3) large-scale axisymmetry. To achieve (2) and (3) simultaneously is challenging due to dynamo selection rules (Bullard and Gellman, 1954). Models suggest that lateral thermal heterogeneities at the core-mantle boundary may be able to explain the strong quadrupole component (Cao *et al.*, 2014).

6.2.1.3 Mars

Mars does not have an active dynamo today, although it does have a crustal magnetic field indicating Mars did possess a dynamo in its early history that subsequently died. There may be a connection between the death of the Martian dynamo and the loss of its early thick atmosphere due to solar wind erosion in the absence of a global magnetosphere, although this is contentious (see Ch. 7). At first glance the Martian dynamo may be easily explained as a brief-lived version of the geodynamo with the explanation for the brevity lying in the smaller size (and hence faster cooling) of Mars' core. However, the Martian crustal field is extremely intense and concentrated in the southern hemisphere. If the Martian dynamo had produced an Earth-like axially dipolar dominated magnetic field, and the Martian crust is similar in age and composition in both hemispheres, then one would not expect this asymmetry in the crustal magnetic field.

To explain this feature, researchers have suggested that either crustal reworking after magnetic-field emplacement removed the magnetization in the northern hemisphere (Nimmo and Gilmore, 2001; Solomon *et al.*, 2005), or that the dynamo on Mars produced a very asymmetric surface magnetic field, where surface fields were strongest in the southern hemisphere (Stanley *et al.*, 2008; Amit *et al.*, 2011; Dietrich and Wicht, 2011). The reason for this single-hemisphere dynamo relies on hemispheric thermal variations on Mars' core–mantle boundary due to the same mechanism that generated the Martian crustal dichotomy during crust formation.

This may have been a spherical harmonic degree-one mantle circulation pattern or a giant impact in the northern hemisphere of Mars.

Researchers are also investigating the potential for giant impacts to kill the Martian dynamo. If an impact can transfer enough heat to the core, the core can stratify and hence convection and the dynamo will shut down (Arkani-Hamed and Olson, 2010).

6.2.1.4 Ganymede

Ganymede is the only moon in our solar system with evidence of a present-day dynamo. The Galileo mission to the Jupiter system detected magnetic field signatures at the other Galilean satellites, but they are due to influences from Jupiter's magnetic field interacting with electrically conducting layers in these bodies, rather than due to an internal dynamo. The Cassini mission at Saturn detected no intrinsic magnetic fields in Titan (Saturn's largest moon) or any of the smaller moons that it has visited. As discussed in the next section, Earth's Moon most likely had a dynamo in its past, but it has since decayed.

The challenge with Ganymede is to explain the longevity of the dynamo because, as a smaller body, it should have cooled fairly quickly and convection should have ceased by now. Present thinking is therefore that novel convection sources may exist in Ganymede. If sulfur is the main light element in Ganymede's core, then at the modest planetary pressures in Ganymede the core may actually begin solidification at its outer boundary resulting in Fe snow, or solid FeS may precipitate deeper in the core (Hauck *et al.*, 2006; Zhan and Schubert, 2012). These methods of convection are not well studied and it is likely that Ganymede's ability to maintain a dynamo is rooted in the details.

6.2.1.5 Moon

Evidence for crustal magnetism on Earth's Moon comes from Lunar Prospector's electron-reflectometry and fluxgate magnetometer instruments (Mitchell *et al.*, 2008; Purucker and Nicholas, 2010) as well as from paleomagnetic analyses of Apollo samples (Wieczorek *et al.*, 2006). This remanent crustal magnetic field is most likely due to dynamo action. Recent advances in seismology and paleomagnetic techniques have led to new insights regarding the past lunar dynamo:

(1) **Lunar seismology** The Apollo Passive Seismic Experiment recorded seismic activity from lunar quakes in the 1970s. Since then, seismologists have made significant advances in processing of seismic data for Earth-based studies and recently Weber *et al.* (2011) applied such methods to the old lunar seismic data. This unraveled much information on the lunar interior structure including the size of the lunar core (~400 km) and the fact that there is likely

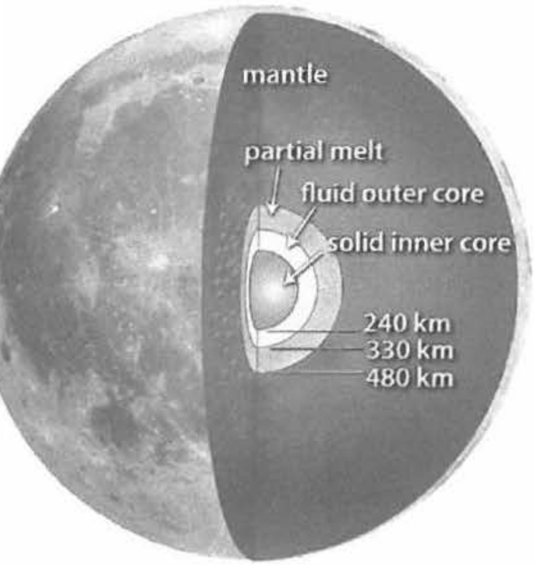

Fig. 6.3 Schematic of the lunar interior from lunar seismic data. (From Weber *et al.*, 2011.)

a solid inner core and a partially molten layer above the lunar core–mantle boundary (Fig. 6.3). This has allowed for more accurate modeling of lunar thermal evolution and dynamo simulations.

(2) **Lunar paleomagnetism** Advances in paleomagnetic techniques have resulted in re-analyses of the magnetic fields in lunar samples from the Apollo missions (Garrick-Bethell *et al.*, 2009; Shea *et al.*, 2012; Suavet *et al.*, 2013). This has allowed for estimates of the intensity of the magnetizing field present on the lunar surface as a function of time. These studies suggest that a lunar dynamo produced a fairly intense surface field (10–100 microtesla) from 4.25 to 3.56 billion years ago. This implies that the lunar dynamo was long-lived which is challenging to explain if it is driven by convective motions.

To explain the longevity of the lunar dynamo, alternative driving mechanisms have been proposed. Repetitive torques on the lunar mantle by large impacts have been shown to produce core–mantle boundary forcings that are energetic enough to sustain a dynamo and produce flows that are dynamo-capable (Le Bars *et al.*, 2011), but due to the interim nature of impacts, it is difficult to understand how the longevity of the field can be explained. Alternatively, precessionally forced flows in the core early in lunar history may provide the answer (Dwyer *et al.*, 2011). Numerical simulations have demonstrated that this mechanism can explain both the necessary intensity and longevity of the lunar surface field (Tian *et al.*, 2014). It is also possible that a relatively wet and compositionally stratified lunar mantle can keep convection going in the core for long enough to explain the paleomagnetic data (Evans *et al.*, 2014).

6.2.2 Giant planets

All four giant planets in our solar system have dynamo-generated magnetic fields. Sections 7.3 and 7.7 of Vol. III (Christensen, 2010) provide a nice discussion of the morphology of the giant-planet magnetic fields as well as their interior dynamo-region structure. Below, we highlight some recent results from numerical simulations and mission data on these bodies.

6.2.2.1 Jupiter

Jupiter's magnetic field is very similar in morphology to Earth's field in that it is dominated by an axial dipole component (Fig. 6.1) and has a similar dipole tilt ($\sim 10^{\circ}$). Jupiter's surface field is about ten times stronger than Earth's, which is expected based on simple scaling laws using Jupiter's size and rotation rate.

The jovian dynamo is generated in the metallized hydrogen region of the planet which extends from deep in the planet out to a radius of about $0.85 R_{\mathrm{Jup}}$. Dynamo scaling studies for Jupiter are capable of predicting the similarity of their field morphologies if you take into account that the dynamo region in Jupiter is very thick, like in Earth, and the planet is a rapid rotator.

However, there is one major difference between Jupiter and Earth that might be important for dynamo action. As a gas giant planet, there is no sharp boundary in physical properties between the dynamo region and the surrounding layers. Instead, Jupiter's physical parameters can depend strongly on pressure and temperature (and hence depth) in the planet. For example, density, as well as the electrical and thermal conductivities vary by orders of magnitude from the atmosphere of the planet to its deep interior. Recent Jupiter dynamo simulations have attempted to recreate the interior dynamics in a body with these varying properties (Stanley and Glatzmaier, 2010; Duarte *et al.*, 2013). The key goal is to produce a simulation that simultaneously generates the famous observed surface zonal jets on Jupiter while also generating a dynamo that produces a surface magnetic field similar to Jupiter observations.

6.2.2.2 Saturn

Saturn's magnetic field is of similar intensity to Earth's, but is unique in its level of axisymmetry (Fig. 6.1). No non-axisymmetric spectral components are required to explain present Saturn data, even with re-analysis of Cassini data providing field models resolved to spherical harmonic degree $L_{max} = 5$ (Cao *et al.*, 2012).

The lack of non-axisymmetry in the observed data has been discussed as problematic since Voyager observations. This is due to Cowling's theorem (Cowling, 1933) which states that a dynamo cannot generate a perfectly axisymmetric magnetic field. The most likely explanation for Saturn's field is therefore that the helium insolubility layer which surrounds the dynamo region in Saturn is responsible for attenuating non-axisymmetric field components so they are not visible at the planetary surface (Stevenson, 1980).

Numerical dynamo simulations by Christensen and Wicht (2008) and Stanley (2010) have implemented stably stratified layers surrounding dynamo regions in an effort to demonstrate the feasibility of this mechanism. Although the studies use substantially different thicknesses for the helium insolubility layer, both are able to produce more axisymmetrized fields.

A data analysis by Cao *et al.* (2012) suggest another unique feature of Saturn's field geometry. There appears to be a preference for odd harmonics (i.e., modes with equatorial anti-symmetry) in the surface magnetic field spectrum. The signs of the largest odd modes (dipole and octupole) result in concentrations of field in the polar regions. This is opposite to what is observed on Earth where the dynamo-generated magnetic fields are weaker near the poles. Recent dynamo models attempt to explain this feature in addition to the field's axisymmetry (e.g., Cao *et al.*, 2012).

6.2.2.3 Uranus and Neptune

Data from the Voyager 2 mission demonstrated that the ice giants have multipolar magnetic fields rather than the axial-dipolar magnetic fields of other solar-system bodies (Fig. 6.1). Previous numerical models involving stably stratified layers interior to the dynamo-generating water-rich layers were used to explain this field morphology (Stanley and Bloxham, 2004, 2006). Recent models involving 3D-turbulence dynamos (Soderlund *et al.*, 2013) or the lower electrical conductivity of ionic water (Gómez-Pérez and Heimpel, 2007) have also been proposed as solutions.

The most significant insight into the ice giant dynamos has, arguably, resulted from new ab-initio studies of the properties of water at high pressure and temperature. Redmer *et al.* (2011) demonstrate that a new phase of water, known as *superionic water* may occur in the deeper regions of Uranus and Neptune (see Fig. 6.4). The physical properties of this new phase, such as its electrical conductivity, thermal conductivity, and viscosity may strongly impact the dynamo processes in these bodies. As Redmer *et al.* (2011) demonstrate, it may not be a coincidence that the radius of the stably stratified layers required in the models by Stanley and Bloxham (2004, 2006) occur at approximately the same depth as this new water

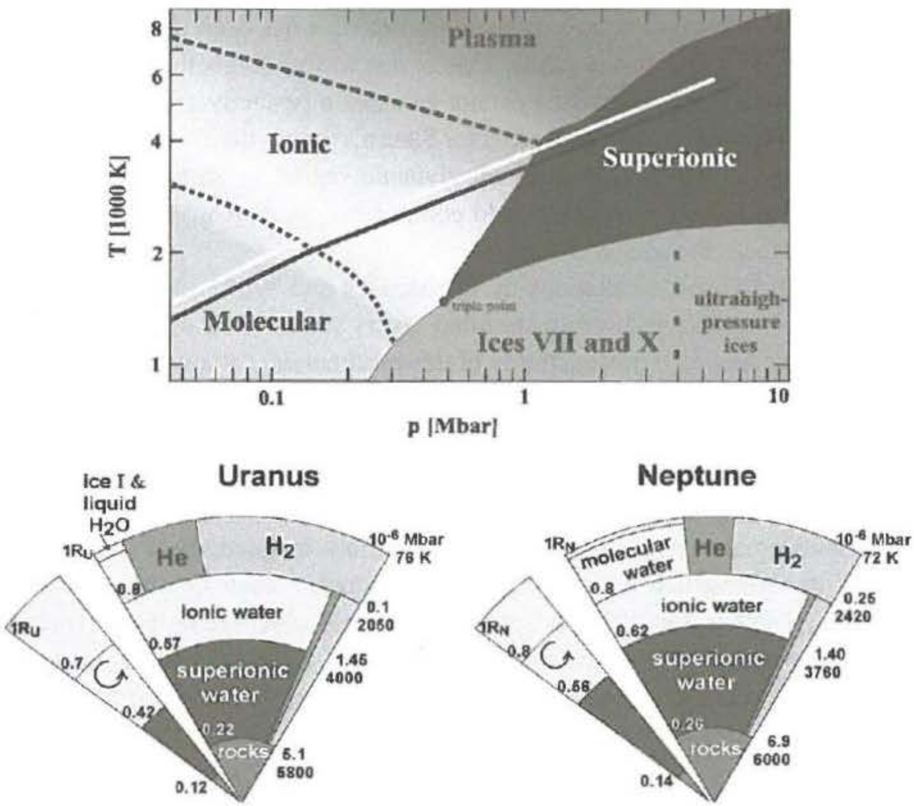

Fig. 6.4 Top: phase diagram of water for temperatures and pressures relevant to the ice giant planet interiors. Isentropes for Uranus (white) and Neptune (black) are also shown. Bottom: three-layer interior composition models for Uranus and Neptune that reproduce the gravity field data. The thin slice on the left of each figure is the structure of the dynamo source region used in Stanley and Bloxham (2006) for dynamo models. Figures from Redmer *et al.* (2011).

phase. Further work on the properties of superionic water will likely produce the biggest advances in understanding the ice giant dynamos.

6.3 Planetary dynamos: new frontiers

6.3.1 Small body dynamos

The Magnetic Reynolds Number criterion in Eq. (6.3) makes dynamo action in smaller bodies problematic due to the inherent smaller length scales. Exacerbating this problem is that thermal conduction is relatively more efficient at cooling small bodies and therefore driving fluid motions through convection for long times in smaller bodies is also problematic. This means that the lifetimes of small-body dynamos are typically much shorter than in larger bodies, all other things being equal.

Here, we consider two groups of small bodies for which some evidence of past or present dynamo action exists: planetesimals and asteroids.

6.3.1.1 Planetesimals

Planetesimals were the large (tens to hundreds of km) building blocks of planets that were present in the early solar system during planet formation. Although no planetesimals currently exist (unless you count asteroids and comets), there are remnants of planetesimals in the form of meteorites that have been found on Earth. Some very old meteorites, such as a group of basaltic achondrites called the Angrites (Weiss *et al.*, 2008) and the CV chondrite, Allende (Carporzen *et al.*, 2011), demonstrate strong magnetization for which the best explanation is that they formed on parent bodies which had differentiated to form cores early in solar system history and sustained an active dynamo for millions of years.

Planetesimals can differentiate fairly early in solar system history due to the formation of magma oceans on these bodies which result from radiogenic heating by ^{26}Al in the early solar system. These magma oceans also aid in cooling the planetesimal cores rapidly enough to generate core convection (i.e., the core heat flows are super-adiabatic). Thermal modeling by Weiss *et al.* (2008) demonstrates that super-adiabatic heat flows can be maintained until the magma ocean solidifies and this process can last for tens of millions of years (Fig. 6.5a).

Using scaling laws to estimate Magnetic Reynolds Numbers (Fig. 6.5b) and surface magnetic field strengths, Weiss *et al.* (2008, 2010) show that these super-adiabatic core heat fluxes can result in dynamos with appropriate duration and field intensities to explain the Angrite magnetism (Fig. 6.5c).

The magnetism of the Allende meteorite is a bit of a puzzle because, along with other CV chondrites, its texture suggests it has not experienced significant melting, which one would expect if it formed on a differentiated planetesimal with a core. However, the magnetism in Allende can be explained if the magma ocean on the CV chondrites' parent body was not global, but instead, only occurred at depth (Fig. 6.5d). This would leave an unmelted shell surrounding the magma ocean and core which would be producing the dynamo (Elkins-Tanton *et al.*, 2011; Weiss and Elkins-Tanton, 2013).

6.3.1.2 Asteroids

No presently active dynamos have been found on asteroids. This is not surprising because, although these bodies are of similar sizes to planetesimals, they are now far too old to presently have convecting cores. However, it is possible that some differentiated asteroids possessed dynamos in their pasts. For example, paleomagnetic

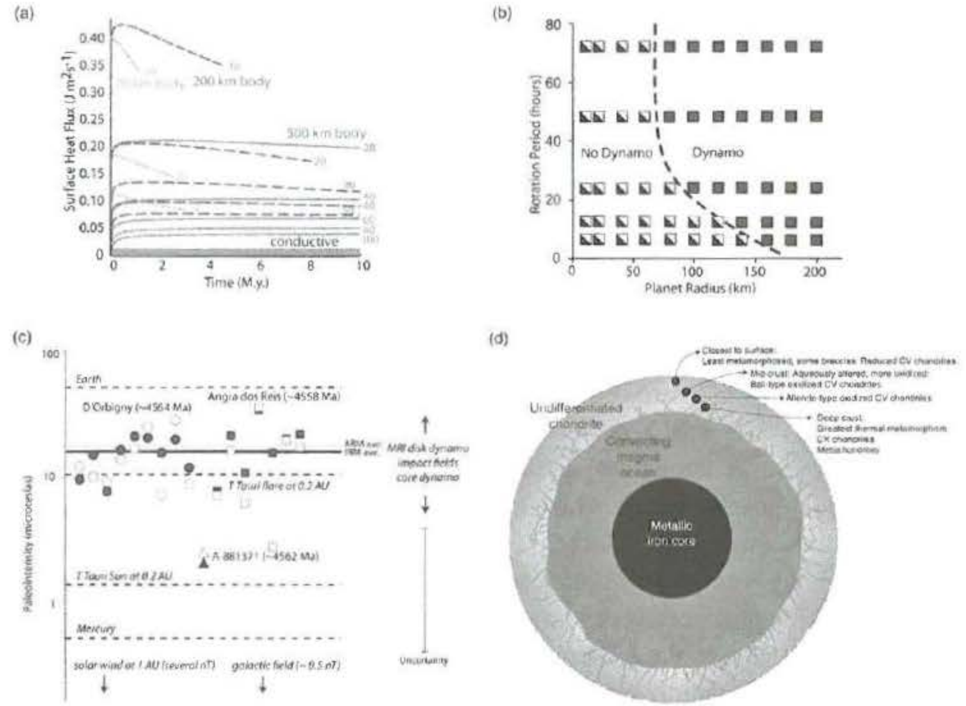

Fig. 6.5 Planetesimal dynamos. (a) Estimates of lifetimes of convection from thermal modeling. (b) Regions of phase space where dynamos have supercritical Magnetic Reynolds Numbers. (c) Paleointensity measurements for various Angrite meteorites as well as thresholds for magnetizing field strengths from different sources. (d) Interior structure of a chondrite parent body. Panels (a), (b), and (c) from Weiss *et al.* (2008). Panel (d) from Elkins-Tanton *et al.* (2011).

studies of the eucrite meteorite Allan Hills A81001, believed to have formed on the differentiated asteroid Vesta (with a core radius of ≈ 110 km); Russell *et al.*, (2012) suggest that Vesta possessed a surface field strength of at least 2 microteslas 3.69 billion years ago (Fu *et al.*, 2012). It is therefore possible that Vesta currently has a crustal magnetic field that could be measured from spacecraft magnetometers.

6.3.2 Extrasolar planets

The study of exoplanet dynamos is interesting for several reasons. First, the existence of a dynamo-generated magnetic field that can produce a large magnetosphere may have implications for habitability. Second, radio emissions from stellar wind–magnetosphere interactions provide a potential new detection mechanism for extrasolar planets.

Possible mechanisms to detect magnetic fields from extrasolar planets include detection of stellar spectral features indicative of magnetic interactions between close-in planets and their parent stars (Shkolnik *et al.*, 2003; Cohen *et al.*, 2009), and the observation of synchrotron emission from stellar wind interactions with planetary magnetospheres (Griessmeier *et al.*, 2011). At present, no radio emissions have been detected from extrasolar planets, although campaigns are searching. This is most likely due to the fact that the emissions need to be extremely strong and in an appropriate bandwidth to be detected from the Earth's surface. I shall make a bold prediction that it is only a matter of time for such emissions to be detected.

Observational campaigns have demonstrated that both a large range of masses and compositions are possible in planets (cf., Ch. 5). These necessarily have implications for the structure, composition, and evolution of the dynamo source regions in these bodies. In addition, planets can form in quite different environments than seen in our solar system. For example, many planets have been found that are extremely close to parent stars. This means they exist in a much hotter environment, that tidal effects can influence their orbits, that the stellar wind can be much stronger near the planets and that magnetic fields may even connect planets and parent stars. Below, we consider several classes of exoplanets that exhibit properties not seen in our solar system and discuss what this might mean for their dynamo-generated magnetic fields.

6.3.2.1 Rocky planets

The rocky (terrestrial) planets in our solar system all have similar structure and composition. Namely, an iron-rich core is surrounded by a rocky mantle made up predominantly of magnesium silicates. For example, Earth's mantle is approximately 80% $(Mg,Fe)SiO_3$ and 20% $(Mg,Fe)O$. The terrestrial planets differ slightly in the bulk Fe/Si ratio (higher for Mercury, possible lower for Mars) and the amount of Fe in the mantle, but to a large extent are quite similar to Earth. The rocky planets in our solar system are also relatively small, with Earth being the largest. Because the internal pressures in the planets depend on the planet size, this means that the highest mantle pressures seen in our solar system are in Earth, and are about 135 GPa near the core–mantle boundary. At these pressures, magnesium silicates are good electrical insulators and do not affect the magnetic field generation process in the core.

Exoplanet studies have demonstrated that terrestrial planets can form that are much larger than Earth. Dubbed *super-Earths*, these exoplanets naturally experience much higher pressures in their mantles. Pressures in deep mantles of super-Earths can reach the TPa ($= 10^{12}$ Pa) level. It is also possible that rocky exoplanets have mantles with significantly different composition than solar system planets. For example, they may have larger fractions of iron oxides like FeO or more exotic compositions.

There have been a few studies that use existing dynamo scaling laws to estimate surface field strengths in rocky exoplanets. For example, Driscoll and Olson (2011) consider optimal scenarios for super-Earth core evolution to derive magnetic dipole moments as a function of planetary mass and Zuluaga and Cuartas (2012) consider the influence of rotation on super-Earth magnetic fields. However, different exoplanet compositions and environments may result in other factors that need to be considered when predicting dynamo properties.

Theoretical and experimental work on different rocky compositions have found the regions of pressure–temperature phase space where these compositions become metallic (Ohta *et al.*, 2012; Nellis, 2010; Tsuchiya and Tsuchiya, 2011). Interesting results include that FeO metallizes at about 60 GPa (notice these pressures exist at quite shallow depth even in Earth's mantle), Al_2O_3 metallizes at 300 GPa (pressures not seen in solar system terrestrial mantles), and $CaSiO_3$ metallizes at 600 GPa (a pressure which would occur near the core–mantle boundary in a super-Earth with mass 5 times that of Earth).

If a rocky exoplanet contains a significant fraction of a mantle composition that is metallic at some depth (Fig. 6.6c), then there are implications for the dynamos in these bodies.

- Thermal and mechanical effects.
  - The metallic phase should decrease the mantle viscosity compared to the insulating phase. This may either make mantle convection easier resulting in faster core cooling or result in layered mantle convection making core cooling slower.
  - The metallic phase would also have a larger thermal conductivity than its insulating counterpart implying that heat could be removed faster from the core.
- Electromagnetic effects.
  - An electromagnetic screening effect would attenuate the rapidly time-varying magnetic fields in the dynamo source region from reaching the planetary surface.
  - The electromagnetic boundary condition at the core–mantle boundary (CMB) would be different if the mantle-side of the CMB were a good conductor.
  - Magnetic fields that penetrate (and effectively anchor in) the metallic mantle layer could experience significant stretching due to shearing motions on the core-side of the CMB resulting in new field generation mechanisms.
  - If the temperatures are high enough in the planet such that the metallic mantle layer is liquid, then it is also possible that a dynamo may operate in this mantle layer.

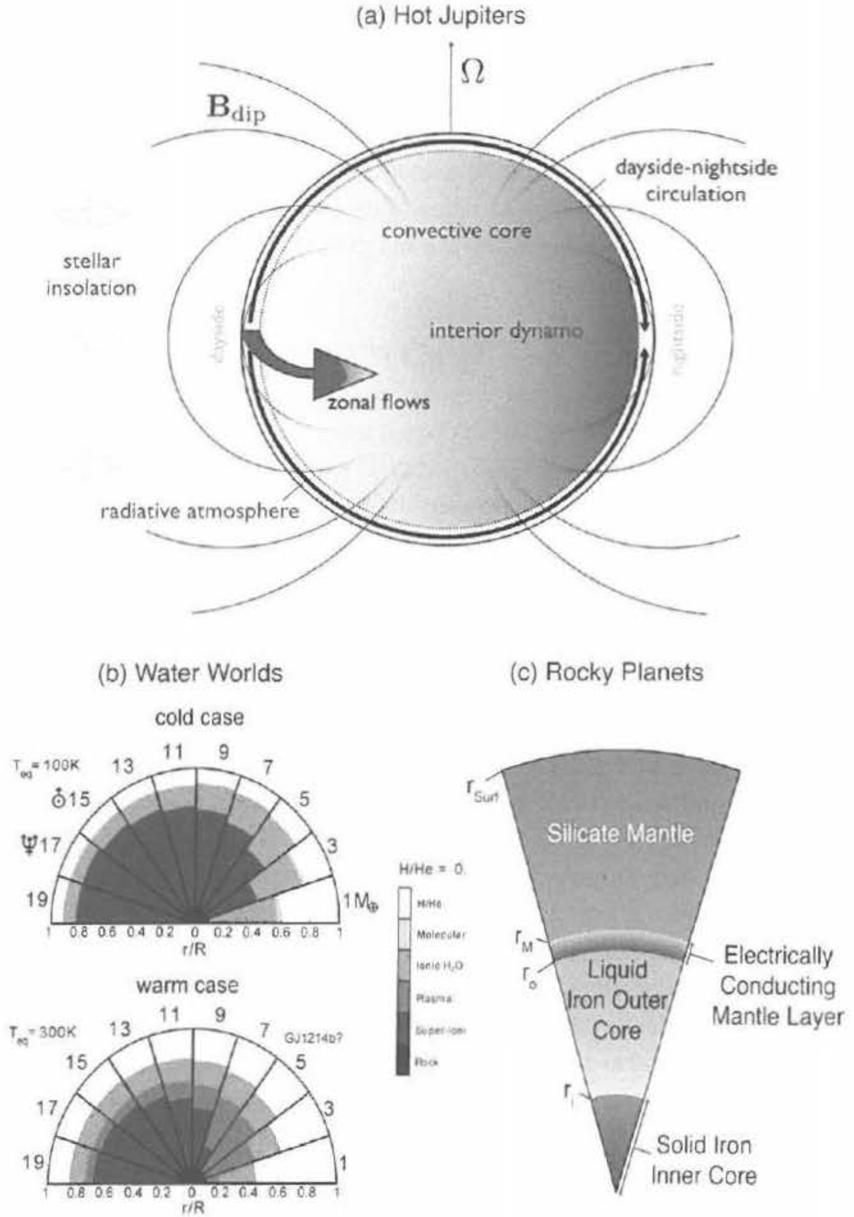

Fig. 6.6 Interior structure diagrams for various categories of exoplanets. (a) Schematic of a Hot Jupiter indicating dayside–nightside atmospheric flows which can interact with a dynamo-generated magnetic field (from Batygin *et al.*, 2013), (b) Potential interior structures for water-rich planets of varying mass and equilibrium temperature (from Tian and Stanley, 2013). Possible interior structures corresponding to Uranus (♅), Neptune (♆) and GJ1214b are marked. (c) Interior structure schematic for a rocky exoplanet with an electrically conducting mantle layer (from Vilim *et al.*, 2013).

Vilim *et al.* (2013) investigated the electromagnetic effects of an electrically conducting mantle on the dynamo and the observable surface magnetic field. They demonstrated that metallized mantle layers result in stronger magnetic fields inside the dynamo source region, but that the field can be somewhat weaker at the surface, especially for planets with thinner convective fluid cores. This implies that for rocky exoplanets, those with smaller masses (i.e., less likely to have metallic mantles) may exhibit stronger surface magnetic fields than planets with larger masses.

6.3.2.2 *Water-rich planets*

The water-rich bodies in our solar system include comets (~1–10 km radii), the solid, icy-surfaced moons (~10–1000 km radii), and the fluid ice giant planets, Uranus and Neptune (~25 000 km radii). Here, we concentrate on ice giant exoplanets as these objects may actually have dynamo action occurring in their water-rich layers (as opposed to an iron-rich core). They may differ in size from our ice giants as well as be located at different orbital distances resulting in hotter or colder surface temperatures. In addition, the amount of hydrogen and helium atmosphere surrounding the water-rich layer may vary. All three of these aspects can affect the dynamo source region in these bodies.

As discussed in Sect. 6.2.2.3, the phase diagram of water has been recently revised to include a transition to the superionic water phase at high pressures and moderate temperatures. This phase may exist in exoplanets and if so, is likely to have implications for the dynamos in these bodies. Tian and Stanley (2013) created 1D interior structure models for water-rich bodies with a range of masses, H/He envelope mass fraction, and equilibrium temperatures. By calculating the temperature–pressure profiles for these bodies and comparing them to the phase diagram of water by Redmer *et al.* (2011), they found that small changes in planetary mass and moderate changes in H/He content can significantly affect which water phases are present in the planet (Fig. 6.6b). This may result in large differences for the dynamo source regions if, for example, the viscosity, electrical conductivity, or stability of the superionic water layers differ from ionic and plasma phases. One prediction from these models is that GJ1214b (a possible water-rich exoplanet), does not have a significant superionic water layer, and instead, may have a thick plasma phase of water in its deep interior where the dynamo is generated.

6.3.2.3 *Hot Jupiters*

Hot Jupiters are gas giant planets with close-in orbits (i.e., within ~0.1 AU of their host star). Owing to this proximity to the parent star, these planets are highly irradiated and are most likely tidally locked such that they have permanent daysides and nightsides. The locations of the dynamo regions in these bodies are, at first glance, expected to be similar to that in Jupiter, namely at depths such that hydrogen sufficiently metallizes to produce a supercritical Magnetic Reynolds Number. However at least a couple of complications need to be considered.

- Because of the highly irradiating environment, the radiative-convective boundary in the atmospheres may be quite deep ($\sim$100−1000 bar, compared to a depth of $\sim 0.01-1$ bars in Jupiter).
- Owing to the permanent dayside/nightside divide, there may be significant lateral thermal variations deep in these bodies. This means that the physical properties that depend on temperature (such as the thermal and electrical conductivity) may vary significantly with longitude.

Both of these speculations depend on how efficiently the outer atmospheric layers in these bodies can redistribute heat laterally (i.e., from the dayside to the nightside as shown in Fig. 6.6a). Several global circulation models (GCMs) of the atmospheric dynamics in Hot Jupiters attempt to answer this question (Showman *et al.*, 2011).

Another scenario that arises in Hot Jupiters is the partial ionization of certain alkali metal species, such as Na and K, in atmospheric layers due to the high temperatures. This can result in atmospheric layers with significant electrical conductivity. Batygin and Stevenson (2010) demonstrate that electrical currents in these atmospheric layers driven by the dayside–nightside flows may generate enough ohmic dissipation to explain the inflated radii of these planets. Therefore, there is a coupling between the internal dynamo-generated field and the flows in these ionized atmospheric layers. Several groups have worked on producing more sophisticated models of the magnetic interactions between the dynamo and these atmospheric layers (Perna *et al.*, 2010; Menou and Rauscher, 2010; Rauscher and Menou, 2013; Batygin *et al.*, 2013; Rogers and Showman, 2014). These studies demonstrate that zonal jets in the atmospheric layers are likely damped by Lorentz forces.

6.4 Outlook

For studies of planetary dynamos, there is much to look forward to. Advanced numerics and experiments will bring new insights from numerical dynamo simulations, paleomagnetism, and high-pressure material physics. Complementary information about planets (e.g., gravity fields, compositional studies, thermal evolution) will also aid in answering the fundamental questions in this area. There will also be new mission data on planetary magnetic fields. Upcoming or active magnetic missions that will provide new data include the following.

- **Juno** En route to Jupiter, Juno will provide the best magnetic field data for Jupiter to date. This year-long polar orbiter is predicted to resolve the surface magnetic field up to spherical harmonic degree $L_{max} \approx 20$ and there is a possibility of detecting secular variation in the field. This will be the first time such time variability has been observed from a dynamo-generated field in a planet other than Earth.
- **Cassini** Cassini's final orbits will be at higher latitudes and closer to Saturn than has been possible to date. This will provide new magnetic field data in polar regions that may help to answer outstanding questions about Saturn's magnetic field.
- **Swarm** The Swarm constellation of satellites was launched in 2013 and will provide new global geomagnetic data to answer outstanding questions regarding the geodynamo.
- **BepiColombo** Expected to reach Mercury in 2024, the BepiColombo mission will provide new magnetic data for Mercury. With the time between MESSENGER and BepiColombo, it will be interesting to investigate possible changes in the magnetic field.
- **Juice** The Jupiter Icy moons Explorer (slated for possible arrival at the Jupiter system in the 2030s) will provide the first new data on Ganymede's magnetic field as well as explore the magnetic environment and internal oceans of the Galilean satellites.

Looking beyond our solar system will also be crucial, both by providing further data points from exoplanet magnetic field studies and by refining our understanding of MHD processes in other astrophysical bodies.