Mercury: Inside the Iron Planet

Steven A. Hauck, II[1] and Catherine L. Johnson[2,3]

1811-5209/19/0015-0021$2.50 DOI: 10.2138/gselements.15.1.21

NASA's *MESSENGER* spacecraft orbited Mercury from 2011 to 2015 and has provided new insights into the interior of the innermost planet. Mercury has a large metallic core ~2,000 km in radius covered by a thin layer of rock only ~420 km thick. Furthermore, a surprisingly large fraction of this outer layer was produced by melting of deeper rocks, forming a light crust ~35 km thick. The core is now known to produce a magnetic field that has intriguing similarities and differences compared to Earth's field. Some rocks near the surface are magnetized, and the strongest magnetizations are likely to be >3.5 billion years old. This new understanding of Mercury's interior is helping reveal how rocky planets operate.

Keywords: Mercury, *MESSENGER* mission, internal structure, magnetic field, metallic core

INTRODUCTION

The planet Mercury has long held the fascination of scientists both because it eluded extended investigation and because of several enigmas about how the planet formed and evolved. Chief among these open questions was how the interior of the planet is organized, referred to by planetary scientists as its "internal structure". For the terrestrial (i.e., rocky) planets of the inner solar system and Earth's Moon, the basic structure is a series of concentric layers that are distinguished primarily by their density: the central core of the planet comprises metallic iron alloys and is overlain by less dense silicate rock layers.

Determining the internal structure of a planetary body is crucial for developing an understanding of how it formed and the processes that have shaped its history. For example, the ratio of rock-to-metal is an indicator of how the planet formed because it is the result of the chemical composition of the building blocks of the planet and also the processes that brought the planet together (see Charlier and Namur 2019 this issue). Knowledge of interior layering also provides necessary information to understand if and how a magnetic field is or was generated in a metallic core and the manner in which the solid rock of the interior delivers heat to the surface during planetary cooling.

Scientists can determine the internal structure of a planet using a variety of approaches. On Earth, the primary method uses seismometers to measure sound waves that pass through the planet as the result of earthquakes. Sadly, among the other bodies in our solar system, only the Moon has had a network of seismometers, installed by the Apollo astronauts, to study its interior. In the case of Mercury, the primary tools to peer inside the planet are measurements of its size, its mass, how it spins, and its magnetic field.

Two enigmas about Mercury and its deep interior have persisted for decades. First, the planet's high average density suggested a metallic core occupying 72%–90% of the planetary radius (see Schubert et al. 1988), compared with ~55% for Earth, Venus, and Mars. Hence, although Mercury is a rocky planet, it is, relatively, significantly more metal-rich than the other terrestrial planets. Second was the discovery that Mercury has a magnetic field perhaps similar to Earth's but about 100 times weaker (Ness et al. 1974). However, whether this field was generated in the planet's metal core, in the rocks nearer the surface, or by some other exotic mechanism was unknown (Schubert et al. 1988).

THE LAYERED IRON PLANET

Mariner 10 was the first spacecraft to visit Mercury in 1974–1975, and it provided a broad-brush understanding of how the planet is organized. Yet, the observations from that mission could not strongly constrain the nature of the layering. In the absence of seismic data, information about how a planet rotates and the spatial variation in the gravity field are needed for determining a planet's internal structure. In particular, the planet's moment of inertia—the resistance changes in rotation—can help inform how mass is distributed in the interior. Qualitatively, for planets, smaller moments of inertia mean more of the mass is near the center of the planet and larger values imply mass is more homogeneously distributed.

Mercury is unique in that it is the only planet or moon in the solar system that has been observed to be in a 3:2 spin–orbit resonance. That is, Mercury spins on its axis three times for every two orbits around the Sun. Mercury is also in a special orbital and rotational configuration called a Cassini state (e.g., Peale 1988). In this state, the precession of the planet's spin rate and the rate at which the orbit precesses are equal, and the rotation axis is close to, but not exactly, perpendicular to the orbital plane. This means that, unlike Earth, Mercury does not have

1 Department of Earth, Environmental, and Planetary Sciences
Case Western Reserve University
Cleveland, OH, USA
E-mail: hauck@case.edu

2 Department of Earth, Ocean, and Atmospheric Sciences
University of British Columbia
Vancouver, British Columbia, Canada
E-mail: cjohnson@eoas.ubc.ca

3 Planetary Science Institute
1700 East Fort Lowell, Suite 106
Tucson, AZ, USA

seasons. Peale (1988) used this set of rotational circumstances to outline an elegant methodology to determine (a) whether Mercury's core has a liquid portion, (b) the moment of inertia of the planet, and (c) the fraction of the moment of inertia that results from just the solid rock lying atop a liquid outer core. His calculation approach required measuring only four quantities: the small tilt of the rotation axis (known as the obliquity), the change in the rotation rate of the planet due to the Sun's tug on its rotational bulge (called the physical libration), and two measures of the largest-scale variation of the gravity field – the flattening of the gravity field along the rotation axis and, similarly, the flattening of the field at the equator.

Although *Mariner 10* made measurements of Mercury's gravity field during its three flybys, uncertainties in the parameters were large and the obliquity and physical libration could not be measured at all. Technological advances in radar, laser altimetry, and gravity analysis eventually led to multiple approaches to determining the obliquity and physical librations of Mercury. Using Earth-based radar measurements of Mercury's rotation over several years, Margot et al. (2007) determined the obliquity and physical libration and discovered that the planet has a liquid portion to its metallic core. These same data were crucial to the determination of the internal layering of Mercury after *MESSENGER* became the first spacecraft to orbit Mercury in 2011 and proceeded to precisely measure the gravity field (Hauck et al. 2013; Rivoldini and Van Hoolst 2013). Recent analyses of the *MESSENGER* laser altimetry and image-based digital terrain models have improved the accuracy and precision of the parameters needed to fill in the four key parameters for a Peale experiment (Margot et al. 2018).

A common way to describe a planet's internal layering is one focused on the primary mineralogical composition over a range of depths. For Earth (Fig. 1), the innermost layers are a solid and liquid metallic iron alloy. Above the metal are three layers with different dominant silicate and oxide minerals: the lower mantle, the upper mantle, and the crust. Whereas the crust is the result of accumulated partial melts of the mantle, the primary distinction between Earth's upper and lower mantle are the different mineral assemblages that are stable under different pressure regimes. Because Mercury is smaller than Earth, the pressures in its interior are lower, and pressure-induced mineralogical changes within the rocky portion do not induce pronounced additional layering. However, Mercury is similarly arranged in a configuration that has one or more metal phases overlain by two or more rock layers.

The measurement of the moment of inertia and the portion of the moment of inertia due solely to the solid layer above the liquid outer core has transformed our understanding of Mercury's interior. In order to determine the layering that produces those observations, scientists use computer simulations of layered planets and compare them with data for the average density of the planet, the moment of inertia, and the fraction of the moment of inertia from the outermost solid layer. These simulations may be as simple as two layers or contain several thousand layers (Margot et al. 2018). Each layer has a density assigned to it based on the kind of material and the pressure and temperature expected at the depth of the layer. The density for each layer is calculated from an equation-of-state that is based upon laboratory experiments and describes how the density of a material varies as a function of pressure and temperature.

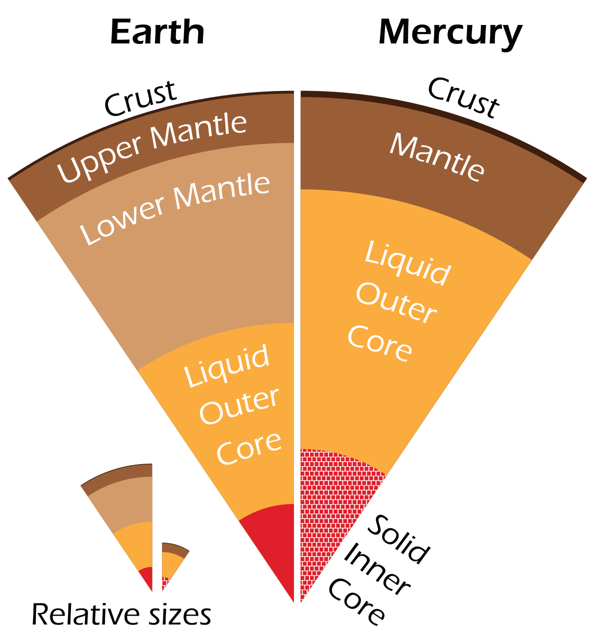

Figure 1 Internal layering of Mercury compared to Earth. Mercury has a proportionally larger metallic core and smaller silicate mantle than the Earth. The inset shows the relative sizes of the two planets. The patterned fill for the solid inner core of Mercury is to indicate that the existence and size of a solid inner core is uncertain.

MESSENGER's determination of Mercury's gravity field, and, hence, the moment of inertia, led to an early surprise: the metallic core is larger—and the outer rock shell is thinner—than once thought. The top of the liquid core was found to be only 420–435 km below the surface (Table 1), whereas previously it was commonly assumed to be at ~600 km, despite a large uncertainty in the estimate. Mercury's metallic core has a density of ~7,000 kg m^{-3} and the average density of the rock layer is about ~3,300 kg m^{-3}. The core density is much less than that expected for pure iron at the pressures in Mercury's core and indicates the presence of a substantial quantity of light elements, likely silicon and/or sulfur, alloyed with the iron. Such elements are important because they reduce the melting temperatures of iron alloys (by up to several hundred or even a thousand degrees Celsius) and, hence, are consistent with the determination of a liquid layer in the core. Interpreting the internal layering of a planet from a single measure

Table 1 ESTIMATES OF MERCURY'S INTERNAL LAYERING

Crust–mantle boundary depth	*Source*
35 ± 18 km	Padovan et al. (2015)
> 35 km	James et al. (2015)
Core–mantle boundary depth	
419 ± 30 km	Hauck et al. (2013)
435 ± 39 km	Rivoldini and Van Hoolst (2013)
Silicate shell (crust + mantle) density	
3,380 ± 200 kg m^{-3}	Hauck et al. (2013)
Core density	
6,980 ± 280 kg m^{-3}	Hauck et al. (2013)
7,233 ± 267 kg m^{-3}	Rivoldini and Van Hoolst (2013)

of the moment of inertia is nonunique because there are direct tradeoffs between the density and thicknesses of layers. However, additional information, such as composition, or additional measures of layering, such as the fraction of the moment of inertia due to the outermost solid layer, reduce, though do not eliminate, this nonuniqueness in interpretation. At present, the uncertainty in the moment of inertia values, due primarily to uncertainty in the very small tilt of the rotation axis, is a major factor in the difficulty of being able to discriminate additional layers, such as a solid inner core. Future improvements in rotation and gravity parameters for Mercury will lead to a better knowledge of the internal layering.

Measurement of geographical variations in gravity, as well as the shape of the planet, provides an independent way to estimate the thickness of the outermost layer of rock: the crust. Variations in the gravity field are the result of small differences in the mass below a point on the surface. Some of those differences are due to the topography—compared to an even surface, mountains have more mass and basins have less mass—but some result from spatial variations in the thickness or density of rock layers. By assuming that the topography of Mercury is essentially in hydrostatic equilibrium and that the observed gravity field is the result of that topography and variations in the thickness of the crust, it is possible to determine the average crustal thickness and its lateral variations (James et al. 2015; Padovan et al. 2015). Furthermore, those studies indicate Mercury's average crustal thickness is more than 35 km, which means that it accounts for more than 10% of the volume of the rocky material of the planet. Such a large volume of crust implies that crust formation has been quite efficient on Mercury compared to the other rocky planets (James et al. 2015).

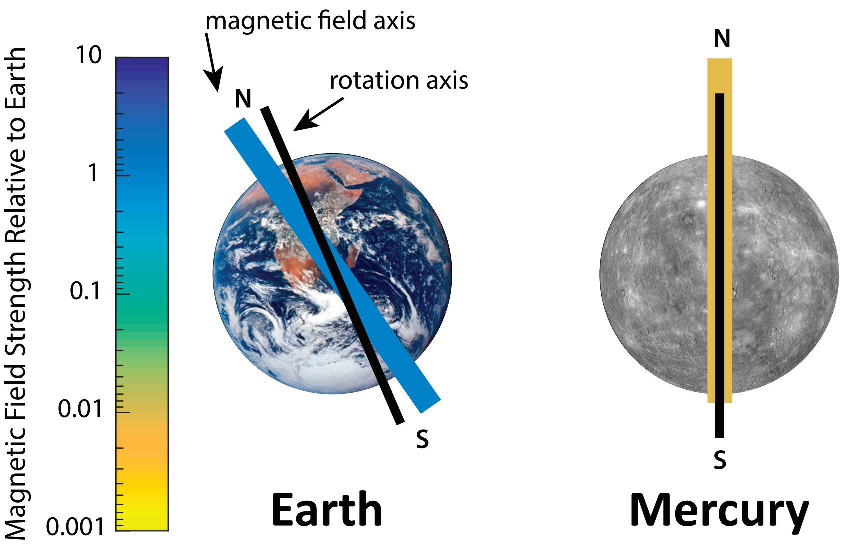

Figure 2 Schematic comparison of the relative magnetic field strengths and dipole orientations of the internally generated magnetic fields of Earth and Mercury. The solid line indicates the orientation of the spin axis relative to how the planet orbits the Sun. The thick colored bar shows the strength of the field relative to Earth's field. Mercury's field is 1% of the Earth's and the center of the dipole field is offset northward along the rotation axis. Earth image is from *Apollo 17*, Mercury image is from *MESSENGER*.

MAGNETIC MERCURY

Mercury's Core Dynamo

The detection of Mercury's magnetic field by *Mariner 10* raised a host of questions, the most important of which was the field's origin. During the 1970s, it was not known if Mercury's core was partly liquid. So, whether the magnetic field could even be generated in the core was debated, because some thermal evolution models predicted that the core would have solidified very early in Mercury's history (Schubert et al. 1988). Evidence supporting a liquid core was not yet known (Margot et al. 2007). Further, *Mariner 10* discovered that Mercury's magnetic field, relative to the size of the planet, was substantially weaker than other planetary magnetic fields, such as Earth's. Magnetic fields are stronger the closer one is to their source, so the fact that *Mariner 10* was close to Mercury's core (because the core is large) made the weakness of the field even more perplexing. Alternatively, the field might have been the result of rocks magnetized in an ancient, now extinct, core field, but this hypothesis suffered from two problems: the magnetized rock layers would need to be much stronger or thicker than on Earth, and the structure of the field appeared to be global rather than regional.

Results from *MESSENGER* firmly established that the magnetic field structure is similar to Earth's field in that it is dipolar (like the field of a bar magnet) with the same polarity as Earth's field. This field structure rules out a crustal origin for the field (Anderson et al. 2008). However, unlike Earth, Mercury's magnetic equator does not pass through the center of the planet (Fig. 2) but is offset ~480 km north along the rotation axis (Anderson et al. 2011). Also, unlike Earth, the magnetic dipole axis (i.e., the line joining magnetic north and south poles) is aligned with Mercury's rotation axis. Furthermore, reanalysis of *Mariner 10* data confirms that this offset dipole structure has likely been unchanged since the 1970s (Philpott et al. 2014). These magnetic-field characteristics place important constraints on the properties of the interior: specifically, the convecting liquid iron alloy that generates a dynamo in the core needs to be able to produce a field that is weak, unusually symmetric with respect to the planet's rotation axis, and that has a magnetic equator that is offset far north of the geographic equator.

Magnetized Rocks

Toward the end of its mission, *MESSENGER*'s orbit moved progressively closer to the planet. At its lowest altitudes (less than ~50 km above the planet's surface), magnetic field measurements yielded the discovery of weak, spatially localized, signals that resulted from magnetized rocks (Johnson et al. 2015). This unprecedented set of observations, taken so close to the planet, has allowed maps of the distribution of magnetization to be made (Hood 2016; Johnson et al. 2018). The maps (e.g., Fig. 3) show that much of the crust in the northern hemisphere of Mercury is weakly magnetized and that stronger magnetizations are associated with the region around Mercury's largest impact crater (Caloris, which is ~1,550 km wide) and also with some, but not all, other impact craters. As for Earth rocks, some of this magnetization is likely induced in iron-bearing minerals by Mercury's present field, but the strongest magnetizations point to at least some of the magnetization being a relic of an ancient dynamo field (Johnson et al. 2015, 2018). Understanding the depth extent of the magnetization and what minerals in the crust or mantle carry this signal are areas of current investigation.

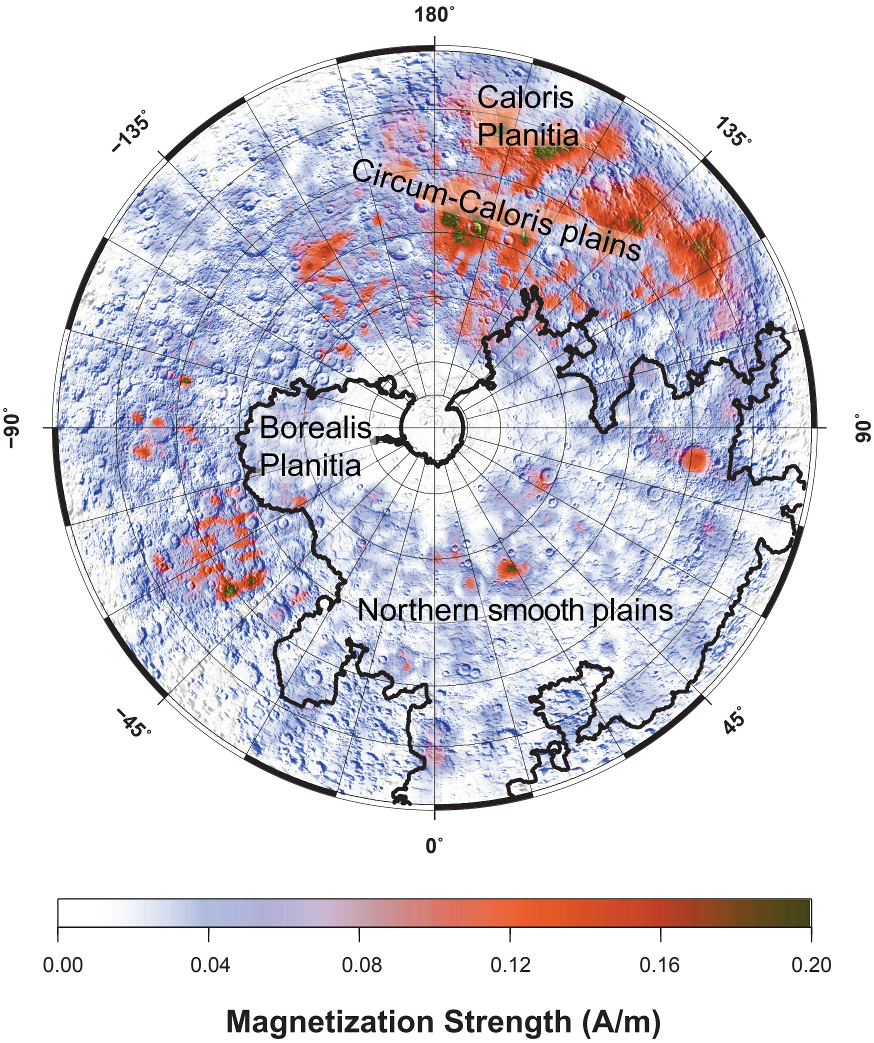

FIGURE 3 Map of magnetization strength overlain on shaded relief for Mercury's northern hemisphere, from 30°N to the pole. The magnetization strength assumes a 10 km thick magnetized layer, and scales inversely with the layer thickness. The black contour outlines the largest contiguous volcanic province on Mercury, the Northern smooth plains. Magnetizations denoted by the reddish/brown hues are too strong to be explained in terms of magnetization induced in the present field, and, thus, likely comprise an ancient (remanent) component. The Caloris basin, the surrounding plains, and another major basin that is filled by smooth volcanic material (Borealis Planitia) are labeled. Grid lines are every 10° of latitude and 15° of longitude; 10° of latitude on Mercury is ~430 km. Units of magnetization strength are in amperes per meter (A/m).

An Interior that "sees" the Surrounding Space Environment

Mercury's large iron core, eccentric orbit, and the absence of a significant atmosphere results in unique interactions between the planet's interior and the surrounding space environment. Similar to Earth, the region around Mercury that contains the planet's magnetic field, known as the magnetosphere, responds to the solar wind. Time variations in the solar wind pressure (e.g., resulting from a 50% change in the planet's distance from the Sun during a Mercurian year) drive compression and expansion of the wind-sock-shaped magnetosphere. Mercury's core attempts to resist these changes by generating electric currents (Faraday's law) at the very top of the core, which in turn results in annual variations in the dipole field (Ampere's law). These annual changes are small, but because Mercury's core is large, they are measurable and their magnitude has independently confirmed the depth to the top of the core (Johnson et al. 2016). Changing solar wind conditions can also induce much smaller currents in iron-bearing rocks in the mantle that could, in future, allow the electrical conductivity, and by inference the mineralogy, of Mercury's silicate shell to be probed.

IMPLICATIONS FOR MERCURY'S FORMATION AND EVOLUTION

Understanding the internal layering of a planet is a key first step toward unraveling how the planet ended up in the state we observe today. The amount of iron that Mercury contains can be compared with the types of meteorites that might have formed the planet's building blocks, and it could constrain the final outcome of computer simulations for how the planet was assembled. Precisely why Mercury has a much larger fraction of metal-to-rock than the other terrestrial planets remains an enduring enigma (Ebel and Stewart 2018).

Mantle Convection and Crustal Formation

The diverse records of geology on each of the four terrestrial planets and the Earth's Moon are a testament to the multitude of paths that a large rocky body may take through time. The principal process that leads a planet through its history is the loss of heat to space. Transporting heat from the deep interior of a planet to the surface, and the resultant cooling, drive crucial processes such as tectonic activity, volcanism, mantle convection, the generation of a magnetic field, and the production (or not) of an atmosphere. A major question prior to *MESSENGER* was whether Mercury's rock mantle was capable of convection, the slow flow of solid rock that also occurs within the Earth (Redmond and King 2007). Mantle convection is the most efficient way to cool a planet; however, whether it occurs depends very strongly on the thickness of the mantle. Thin layers do not convect easily, and, until *MESSENGER*, the mantle thickness was uncertain. Surprisingly, even though Mercury's mantle is now known to be substantially thinner than the often previously assumed 600 km, numerical models show that mantle convection has been likely for most of Mercury's history, possibly to the present day (Hauck et al. 2018).

Mantle convection is crucial for the production of crustal rocks. During convection, warmer rock rises from the deep interior and cooler rock sinks. The rising rock tends to cool very little during its upward trajectory, but the pressure it feels from the overlying rock lessens. The melting temperature of rock is quite sensitive to pressure, and, thus, the rising rock may partially melt. The melt, or magma, then rises quickly and is the source for the volcanic rocks observed at the surface. On Mercury, nearly all the volcanic rocks on the surface are older than 3.5 billion years old (Byrne et al. 2018b), and the volume of volcanism and the physical characteristics of the rocks suggest that the lavas were very hot when they erupted. Thus, the volcanic record provides observational evidence for early vigorous mantle convection.

The Tectonic Record of Global Contraction

There is another curious observation that is linked to Mercury's interior structure, convection, and melting of the mantle. Mercury is shrinking. *Mariner 10* discovered that the 45% of the planet's surface that it saw contained large contractional tectonic features called lobate scarps, but no complementary extensional features. The interpretation was that the planet must have shrunk over time, its radius decreasing by 0.5–2 km over the past 4 billion years (Watters et al. 1998). Global, higher resolution imagery from *MESSENGER* has led to a dramatic revision of that estimate: the planet has shrunk by 5–7 km in radius (Byrne et al. 2014; Byrne et al. 2018a). This global contraction is a powerful constraint that simulations of Mercury's history must explain (Hauck et al. 2018). Contraction is directly related to how much the interior has cooled and to the thickness and thermal expansion properties of the internal layers. When the entire planet is contracting and its surface is compressing, pathways for rising magma from the mantle are closed. As a result, the waning of surface volcanic activity more than 3.5 billion years ago is likely related to both the shrinking of the planet and to a reduction in the amount of melt created in its interior (Byrne et al. 2018b; Hauck et al. 2018).

Mercury's Enigmatic Dynamo

Cooling of a planet and layering within the core govern whether a magnetic field can be generated in the core and the resulting strength and structure of that field. The presence of elements such as silicon and sulfur in the core are critical to Mercury's ability to retain a partly liquid core today. The rapid convective motions that can generate a magnetic field require buoyancy sources. However, the precise combination of these sources, and how they might have varied through time, is unknown. In Mercury, as at Earth, there are two such buoyancy sources: (1) light elements that are concentrated into the liquid core (and then rise through it) as the core solidifies from the center outward; (2) the heat flowing from the core into the mantle as a consequence of the inevitable cooling of the planet. However, stably stratified layers at the top of Mercury's core may play an important role in explaining the weak strength and peculiar geometry of the magnetic field (Christensen and Wicht 2008). Indeed, such stratification may arise from crystallization of the core from the top down, rather than the bottom up (like the Earth), and from the core cooling so slowly that convective motions are restricted to deeper zones within the core. Furthermore, the discovery that Mercury likely also had a magnetic field in its ancient past (Johnson et al. 2015) places an important constraint on the evolution of Mercury's core structure and cooling over time.

OUTSTANDING QUESTIONS AND FUTURE PROSPECTS

Observations by *MESSENGER* have fundamentally changed how we view Mercury and have raised new questions about how planetary interiors are organized and evolve. One set of outstanding questions relates to the composition and state of the outer core, including the core–mantle boundary region. Understanding the properties of the core is fundamental for constraining the source(s) of buoyancy for driving the convection responsible for magnetic field generation, as well as Mercury's cooling and contraction history.

Early estimates of Mercury's internal layering from *MESSENGER* data suggested the possibility of a solid iron sulfide layer at the base of the rocky mantle and at the top of the liquid outer core (see review in Margot et al. 2018). Such an idea was consistent with, but not required by, chemical information about surface materials and the moment of inertia data. Chemical data from *MESSENGER* now indicates that surface materials formed in relatively oxygen-poor conditions (Nittler et al. 2011) and suggested a possible core composition of iron, sulfur, and silicon. The result would be two immiscible core liquids that could separate by density, with sulfur-rich liquids floating, and, perhaps, later freezing onto the core–mantle boundary. Later geochemical work has led to a debate as to whether Mercury's core composition permits formation of two liquids that are capable of separating (Chabot et al. 2014; Namur et al. 2016).

Related to the properties of the core–mantle boundary region are the mechanisms that could produce stratification of the outermost liquid core (Hauck et al. 2018) and how the core is undergoing solidification. The issue of the existence of a solid inner core and its size remains open. For Earth, recent work shows that standard ideas for how solids start solidifying in its core have traditionally neglected an important energy barrier for the spontaneous nucleation of crystals, a factor that also applies to Mercury (Huguet et al. 2018).

MESSENGER has enabled a new baseline of knowledge regarding Mercury's magnetic field. However, important questions such as the regional-scale (nondipole) structure in the magnetic field and its variability on timescales of years to decades remain. At Earth, this structure has provided key diagnostics of the role of the core–mantle boundary in determining the patterns of convective flow in the outer core (see summary in Johnson et al. 2018). *MESSENGER* has shown that such nondipole structure is certainly weak, but that it may also be masked by variations in the fields that are not of internal origin. These latter fields could, in the future, themselves be a tool to detect the electrical conductivity structure of Mercury's crust and mantle.

The discovery of Mercury's crustal field demonstrates the presence of magnetized rocks; however, two issues of fundamental importance remain unresolved. First, what minerals carry the magnetization? Second, are the magnetized rocks in the crust and/or in the upper mantle? Modeling of *MESSENGER* observations can address this question, yet fundamental trade-offs remain because the measured crustal fields can be matched by stronger magnetizations deep below the surface or weaker ones close to the surface. Third, how much of the planet's magnetization is induced in the present-day field, and how much magnetization is "permanent" and was locked in during the presence of an ancient field? For Earth rocks, laboratory measurements can investigate how much magnetization was induced by measuring the rock in a field-free environment versus the rock being in the Earth's magnetic field. Addressing this issue for Mercury is challenging because of the absence of samples from the surface, but it is of critical importance to understanding where on the planet, and when, any ancient magnetizations were acquired. Progress can be made on these issues by laboratory measurements of the magnetic properties of candidate iron-bearing minerals that are compatible with the geochemical constraints on Mercury's crustal composition (Strauss et al. 2016).

When it arrives at Mercury in the mid-2020s, the *BepiColombo* mission will provide many opportunities to improve our understanding of the planet's interior. In particular, *BepiColombo* comprises two spacecraft that will have different orbits around the planet. The *BepiColombo Mercury Planetary Orbiter* will be in a quite different orbit from that of *MESSENGER* and will obtain greatly improved gravity, magnetic field, and topography data. The second spacecraft, the *Mercury Magnetospheric Orbiter* (also called *Mio*) will have an orbit that will often provide simultaneous information on solar wind conditions, thereby allowing unprecedented studies of the interaction of the internal magnetic field and the surrounding space environment. Collectively, these new data, together with modeling efforts and laboratory measurements, will open a new era of discovery and understanding of Mercury from its surface to its interior.

ACKNOWLEDGMENTS

We gratefully acknowledge Dan O'Shaughnessy, Jim McAdams and Haje Korth for planning the low altitude observations that enabled the discovery of Mercury's crustal magnetic field. This work was supported by the Natural Sciences and Engineering Research Council of Canada (CLJ), NASA Solar System Workings Program grant NNX15AH31G (SAH). The research contributions of CLJ and SAH were supported during the *MESSENGER* mission by the *MESSENGER* Participating Scientist Program.

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