Mercury redux

In January 2008, 33 years after Mariner 10 flew past the solar system's innermost planet, MESSENGER crossed Mercury's magnetosphere. Ancient volcanoes, contractional faults, and a rich soup of exospheric ions give clues to Mercury's structure and dynamical evolution.

The Mercury flyby of the MESSENGER (Mercury surface, space environment, geochemistry and ranging) probe was the first of three braking manoeuvres for the spacecraft, in preparation for its insertion into a polar orbit in 2011. The probe achieved the closest approach (201 km) of Mercury's surface yet, and took a variety of measurements in the magnetosphere, exosphere and on Mercury's surface. Some of the first results of the MESSENGER mission[1–6] reveal Mercury as a planet with richly interconnected dynamics, from the dynamo in its molten outer core, a crust and surface with great lobate faults and relatively young volcanoes, to a magnetosphere that interacts with the core dynamo and the interplanetary solar wind.

Until the mid-1970s, it was thought that Earth was the only planet inside the asteroid belt with an internally generated global magnetosphere. Scientists were astonished when the Mariner 10 spacecraft sent evidence of a global magnetic field enveloping Mercury. Space missions to the outer planets have revealed global magnetism on Jupiter, Saturn, Uranus and Neptune, and even a few planetary satellites. Of the terrestrial bodies, only Mercury and Earth have significant internally generated magnetic fields. It is not known whether Venus and the Moon had intrinsic fields in the past. The Moon has patches of magnetized crust, and evidence of a past venusian dynamo may have been wiped out because its surface temperature of 730 Kelvin is near the Curie point, above which remanent magnetism cannot persist. Strong magnetic anomalies indicate an ancient global field on Mars, but it is thought that the martian dynamo ceased to operate early in the planet's evolution, perhaps over 4 billion years ago.

MAGNETIC FIELD AND CORE DYNAMICS

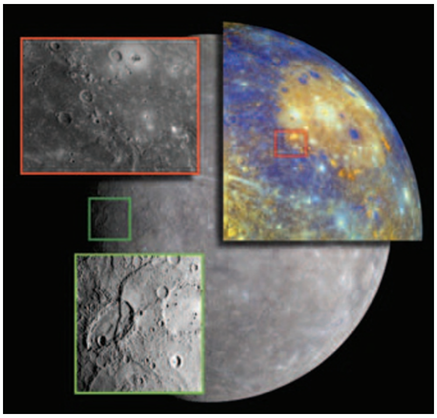

Figure 1 Four images of Mercury. The more colourful image in the northeast shows the Caloris basin, a large impact crater. Bright gold-coloured features near the Caloris basin's rim are interpreted to be volcanos[6]. Red boxes: One volcano with a central vent is surrounded by a smooth dome. Green boxes: A major lobate contractional fault about 650 km long called Beagle Rupes, in a region of Mercury imaged for the first time by MESSENGER's Mercury Dual Imaging System, is shown in the equatorial West near the terminator. Images courtesy of NASA/Johns Hopkins University Applied Physics Laboratory/Carnegie Institution of Washington.

Mercury's magnetic field, as observed by the two flybys of the Mariner 10 spacecraft that penetrated the magnetosphere (one of which was a polar pass), had a magnitude of roughly 300 nT at the surface[7]. The flyby of MESSENGER in January 2008 was equatorial, and new information about the high latitudes must therefore wait until orbital insertion in 2011. Nevertheless, MESSENGER largely confirmed the Mariner 10 observations and provided additional constraints on the field morphology. The modelled observations yield a surface field of 230–290 nT that is primarily dipolar. However, additional higher multipolar contributions could account for up to half the magnetic field strength[1]. This magnetic field, although sufficient to form a global magnetosphere, has a surface strength only roughly 1/100 that of the Earth.

Three types of mechanisms are currently considered plausible candidates for the generation of Mercury's intrinsic magnetic field: coherently distributed remanent magnetization of the crust[8], a thermoelectric dynamo[9] or a convective dynamo[10]. The first two have not been ruled out, but for those mechanisms shorter-wavelength magnetic features would be expected, which were not observed during the MESSENGER flyby[1]. Recent libration observations that require a partially molten core[11], and the limited contraction of Mercury, which implies a largely molten core, favour a convective dynamo origin for Mercury's magnetic field.

Although Mercury's magnetosphere looks like a miniature version of Earth's, Mercury's relatively weak magnetic field implies that its dynamo must work differently from that of the Earth. The geodynamo, which gives the Earth its strong magnetic field, is thought to operate in a magnetostrophic regime in which the Coriolis force, due to the Earth's rotation, roughly balances the magnetic Lorentz force. Such a balance may also operate in Mercury's core. Indeed, several recent modelling efforts have shown that there are many ways for dynamos, even ones with strong internal fields, to produce relatively weak external (that is, measurable) magnetic fields[12–16].

One way to produce a weak external magnetic field is with a slow planetary rotation rate. Numerical simulations have shown that when rotational forces are too weak to maintain large scale convection vortices, the magnetic field structure, which tends to follow the flow field, becomes small-scale. This effect leads to a multipolar dynamo with a sharply reduced dipolar component. Assuming that the dynamos of Earth and Mercury have driving forces that scale similarly, Mercury's slow rotation (its sidereal day is 58.6 Earth days) means that its dynamo is expected to operate in the multipolar regime[12]. Given the uncertainty in the relative contributions of dipolar and multipolar components, and that the higher multipolar components decay more rapidly outward from the outer core source region, the MESSENGER observations indicating a dipolar external field could still be consistent with a multipolar core dynamo.

For a different class of models, Mercury's weak global field can be produced by a dipolar or multipolar dynamo that is constrained to a small volume of its large core. This can be accomplished in several ways, including flow in a thick liquid shell, in which strong convection is regionalized near a small inner core[13], or alternatively through convection in a thin shell, which tends to generate magnetic flux more efficiently at low latitudes[14]. Further reductions in magnetic field strength occur if the upper part of the liquid outer core is stably stratified. In that case the magnetic field, produced by compositional convection and confined near the inner-core boundary, is strongly attenuated by the stratified layer above[15]. Finally, if solidification occurs away from the inner-core boundary, convection could be restricted to a thin layer above the horizon of iron precipitation, which 'snows' down to the deeper core[16]. From the available data it is not yet possible to distinguish between these various possibilities.

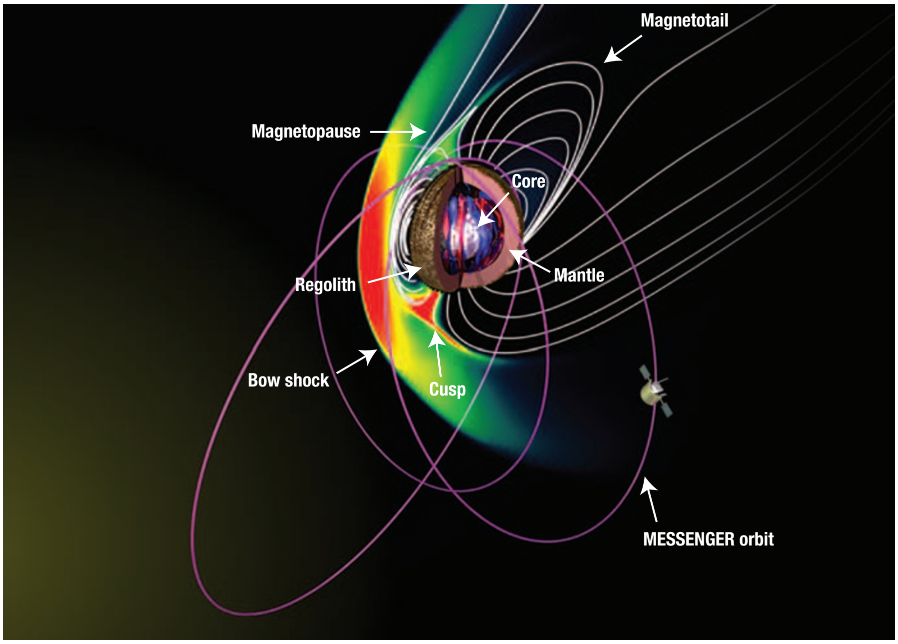

Figure 2 Modelling perspective of dynamical processes of Mercury's magnetosphere and core. Purple lines are orbit trajectories planned for MESSENGER when it arrives in 2011. Magnetosphere dynamics taken from a magnetohydrodynamical simulation of the interaction of the solar wind magnetic field with a dipolar intrinsic magnetic field[19] are visualized. Magnetic field lines are shown in white. Plasma pressure is shown in meridional plane through the magnetosphere: red and blue indicate high and low pressure respectively. Core dynamics are taken from a numerical dynamo simulation that produces a dipolar magnetic field[12]. Isosurfaces of the fluid vorticity component parallel to the planetary rotation axis are shown in the outer core. Red and blue vortices indicate prograde and retrograde convective flow. The inner core is shown as a silver sphere. Artistic visualization and model rendering by Chris Want.

CONTRACTION AND INNER-CORE GROWTH

Because Mercury's contraction places constraints on the fraction of melt in its core, the planet's surface tectonics, cratering and history of volcanism are intimately related to inferences about the growth of the inner core, the operation of the dynamo and the planet's thermal evolution. In its January 2008 flyby, MESSENGER imaged 21% of Mercury's surface that had never before been observed by a spacecraft. Moreover, in areas previously imaged by Mariner 10, different lighting conditions allowed MESSENGER to reveal new relationships between contractional faults and volcanic plains. The discovery of additional contractional faults, such as the contractional lobate fault called Beagle Rupes (Fig. 1), results in estimates of global surface contraction that are about a third higher than those based on the Mariner 10 observations[2]. At present the total radial contraction estimated from lobate faults is less than 3 km. However, the increased contraction inferred from MESSENGER's observations must be considered a lower bound. Future observations during the remaining two flybys and the orbital phase of MESSENGER's mission will no doubt reveal more observations of contractional faults, even in areas previously imaged, owing to increased coverage and resolution as well as changes in lighting and perspective.

Chronological relationships between lobate thrust faults, cratering and volcanic plains reveal an extended period of global contraction. Many instances of lobate faults cutting across and deforming older craters and relatively young smooth plains, which are interpreted as volcanic flows, have been observed in the Mariner 10 and MESSENGER images. Some images also show younger craters overprinting contractional scarps. The new MESSENGER images now reveal more detailed features, including the embayment of lobate faults by volcanic flows[2]. These observations show that contractional faulting commenced before many of the volcanic plains were emplaced and continued after the eruption of the younger volcanics.

The observations of contractional faults help infer Mercury's thermal evolution, interior composition and the growth of the planet's inner core. In standard thermal evolution models, global contraction is preceded by a phase of early planetary expansion, fuelled primarily by the mass distribution and gravitational energy release during differentiation into core and mantle. The timing of the onset of core solidification and global contraction is not known. Any evidence of contraction that occurred before 3.8 Gyr ago would have been erased by impact flux during the period of heavy impact bombardment[2].

Given the large uncertainties in core formation, and additional uncertainties in how much observed contraction was due to mantle and lithosphere cooling, it is difficult to estimate the total amount of core solidification precisely. Nevertheless, the observationally inferred contraction of less than 3 km is small compared to the 17 km of contraction estimated to result if the entire core were solidified[17]. This is consistent with a dynamo origin for Mercury's magnetic field. Furthermore, the small amount of contraction, which scales with the volume of solidification, implies that the modern-day solid inner core is relatively small, perhaps Earth-like in relative scale. (The fraction of Earth's inner core radius to the total core radius is 0.35.) The inference of a largely molten outer core also puts constraints on the dynamics of Mercury's relatively thin rocky mantle, and on the composition of the core. The operation of a convective dynamo in the core requires thermal or compositional buoyancy (and probably both) generated by outward heat flux and solidification of the inner core. It is likely that the mantle, through solid-state convection, has efficiently transferred heat from the interior over much of Mercury's history. If that is the case then a light element like sulphur, which lowers the melting temperature of iron alloy, must be present at a relatively large concentration in the core[17,18].

MAGNETOSPHERE AND EXOSPHERE

The space environment of Mercury is determined by the interaction of the planet's internal magnetic field with the magnetized solar wind, in the same process that defines the magnetospheres of Earth, Jupiter, Saturn, Uranus and Neptune. Mariner 10 and MESSENGER observed similar properties to other planetary magnetospheres — the bow shock, magnetopause, magnetotail and plasma sheet, cusp regions, pick-up ions, and Alfvenic and other plasma waves[3,4]. Particularly intriguing is new evidence from MESSENGER of Kelvin–Helmholtz instabilities, which may provide an important entry mechanism for solar wind into the hermean magnetosphere[19], and a driver for various types of magnetospheric waves.

Despite similarities with the different planetary magnetospheres, the details of physical processes in Mercury's magnetosphere are unique in the solar system, and several features have not been found elsewhere to date. One example is the structure of the magnetopause, the thin interface between the solar wind and the magnetosphere. As MESSENGER exited the hermean magnetosphere during the first flyby it detected two current layers, instead of the usual single magnetopause current sheet[3]. This double layer structure of the magnetopause may be associated with effects of heavy ions gyrating in the magnetic field, but a complete theoretical explanation is still lacking. Ultra-low frequency waves observed by both Mariner 10 and MESSENGER[3] have unique properties at Mercury because of the small spatial and temporal scales that characterize the planet's magnetosphere. Interaction of the intense solar wind with Mercury's small magnetosphere causes heavy ions, such as sodium, oxygen and potassium, to be sputtered from the surface of the planet. The dynamics of this process are very different from those for planets with atmospheres and/or stronger magnetic fields (such as Earth), where ions do not interact appreciably with the surface[4].

The lower Alfven–Mach number (the ratio of the solar wind speed to the Alfven wave speed, which controls the relative importance of gas dynamic and electrodynamic effects) of the impinging solar wind also has important consequences for the global magnetospheric picture. In addition to causing bow shock and magnetosheath asymmetries, this also leads to a higher efficiency of the magnetic reconnection process. For example, during the flyby, MESSENGER recorded several flux transfer events[3]. Combined with the smaller spatial scale of Mercury's magnetosphere this efficiency leads to a more direct control of the magnetosphere by the solar wind and the interplanetary magnetic field than any other planetary magnetosphere[1,20]. In fact, the dynamic magnetospheric magnetic field can be so large, relative to the internal field, that the dynamo action in Mercury's core may be significantly affected by the interaction with the solar wind[21]. The possibility of such an interaction of the solar wind with core dynamics is further facilitated by Mercury's thin mantle, which places the planet's small magnetosphere in close proximity to its relatively large core. Figure 2 illustrates some of the dynamical aspects of this remarkably proportioned planet.

> The dynamo action in Mercury's core may be affected by the interaction with the solar wind on this remarkably proportioned planet.

Apart from Mercury, all other planets in the solar system have gravitationally bound atmospheres which give rise to ionospheres, providing a natural barrier between the space environment of the planet and its surface. Mercury has no atmosphere and only a tenuous and constantly recycled exosphere[4,5]. This leads to the heavy space weathering of Mercury's surface, which is one of the processes supplying new atoms to the exosphere[22]. The lack of a highly conducting ionosphere leads to a yet another mystery of the hermean magnetosphere: how do the electric currents close? This lack of a conducting layer close to the surface of Mercury may produce a truly unique magnetospheric current system, which still remains to be discovered.

FUTURE EXPLORATION

The findings from the first flyby of Mercury by MESSENGER[1–6] are just the beginning of an extended period of observations of the solar system's innermost planet. The next flyby is coming up in October 2008 and comprehensive mapping of the planet will begin in earnest when MESSENGER is placed in orbit in 2011. The planet is also targeted by the European–Japanese mission BepiColombo, scheduled to be launched in 2013. That mission will have two orbiters, allowing the simultaneous monitoring of the solar wind and the magnetosphere interior.

Observations from the combination of the two missions will be over a sufficiently long period to allow the detection of changes in Mercury's magnetosphere and exosphere.

A lack of changes in the global magnetic field would suggest a dynamo that is deeply buried near the inner-core boundary[15]. On the other hand a multipolar dynamo that operates near the core–mantle boundary would likely result in secular variation of Mercury's intrinsic field that would be measurable over the time span covered by the MESSENGER and BepiColombo missions. We can hope that at least some of Mercury's secrets will be revealed in the not-to-distant future.

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