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Comment

Magnetic field modeling for Mercury using dynamo models with a stable layer and laterally variable heat flux

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ABSTRACT

Mercury's surface magnetic field is unique among planetary magnetic fields for its weak intensity, spin-aligned axisymmetry, and large dipole offset. An Earth-like dynamo setup applied to Mercury does not reproduce these features. Here we explain the magnetic field observations by a combination of two effects: (1) a stably stratified layer at the top of the outer core, and (2) a degree-1 north–south asymmetric spherical harmonic heat flux variation at the core–mantle boundary (CMB). We vary the stable layer thickness and size of the inner core, and find models that can produce surface magnetic fields possessing the observed features of Mercury.

1. Introduction

Mercury's magnetic field is a weak, offset dipole-dominated, spin-aligned axisymmetric field (Anderson et al., 2011, 2012; Winslow et al., 2014). It is unique among all active dynamo-generated magnetic fields in the Solar System because of the following combination of properties:

(A) its magnetic moment is as weak as $\sim$190 nT $* r_{planet}{}^3$, less than 1/100 that of the Earth (Anderson et al., 2012);
(B) its dipole axis is aligned with Mercury's rotation axis to within 0.8° (Anderson et al., 2012). In a Gauss expansion of the magnetic field, this fact corresponds to small g_{11}/g_{10} and h_{11}/g_{10} ratios, where g_{lm} and h_{lm} correspond to the degree-*l*, order-*m* Gauss coefficients;
(C) its dipole offset, which is the distance between the magnetic dipole equator and Mercury's geographic equator, is $\sim$480 km (0.2 $* r_{planet}$). This offset corresponds to $g_{20}/g_{10} = 0.40$ at the planetary surface.

According to magnetostrophic balance and energetics arguments, and assuming an Earth-like partitioning of the core magnetic field between poloidal and toroidal components, Mercury's dipole moment is expected to be in the range 4×10^5–4×10^6 nT $* r_{planet}{}^3$ (Stanley and Glatzmaier, 2010). The observed weak field intensity alone poses a challenge to conventional Earth-like dynamo models.

Mercury's magnetic field is also anomalous for its morphology. Among axial dipole-dominated planetary magnetic fields, which include the magnetic fields of Mercury, Earth, Jupiter, Saturn and Ganymede, only Mercury and Saturn have confirmed dipole tilts less than 1° from the rotation axis (present data for Ganymede only provides an upper limit of 4° on the dipole tilt) (Smith et al., 1980; Kivelson et al., 2002; Anderson et al., 2012). Saturn, however, has a dipole offset of 0.04 $* r_{Saturn}$ (Smith et al., 1980), which is much smaller than Mercury in the ratio to the planetary radius.

Prior to the MESSENGER spacecraft's measurements of the dipole tilt and offset of Mercury's magnetic field, several analytic and numerical studies tried to explain the weak intensity of the magnetic field.

A thermoelectric dynamo was proposed (Stevenson, 1987; Giampieri and Balogh, 2002) in which thermoelectric currents are driven by temperature differences on an irregular CMB. These currents would produce a toroidal magnetic field, and the helical motions in the fluid outer core would interact with the toroidal field to produce a weak poloidal field observable at Mercury's surface (10^2–10^3 nT).

Stanley et al. (2005) used a thin shell dynamo model, in which fluid convection mainly operates outside the cylinder tangent to a very large inner core, to generate a non-Earth-like field partitioning between toroidal and poloidal components in the core. The core magnetic field is strong, but is dominated by toroidal components that do not penetrate outside the core, thus producing a weak surface field (10^3 nT).

Takahashi and Matsushima (2006) also used a thin shell geometry of outer core, and produced core magnetic fields that are dominated by high degree, multipole components which decrease to much lower intensities than the dipole on Mercury's surface. The surface magnetic field can be as small as 10^3 nT. However, their model requires the inner core to be electrically insulating.

Heimpel et al. (2005) investigated a very thick shell dynamo, which results in single-plume convection in the shell and produced relatively weak poloidal magnetic fields (10^4 nT at Mercury's surface).

The Vilim et al. (2010) model involves dissolution of Fe from S at some depth in the outer core, which results in two dynamo regions (the region above that depth, and the region below it) that can produce magnetic fields with opposite signs, thus weakening the observable surface magnetic field (160–1500 nT).

Several studies (Glassmeier et al., 2007; Gomez-Perez and Solomon, 2010; Heyner et al., 2010, 2011) investigated the feedback dynamo, in which there is a negative feedback between the dynamo-generated magnetic field and the magnetic field generated by the magnetospheric currents, where the magnetospheric currents result from the interaction between the internal planetary magnetic field and the solar wind. Mercury's magnetopause is close to the planet's surface as the weak dipole field is unable to push it farther away from the surface. This closeness of the magnetopause to the surface facilitates the magnetospheric field's substantial contribution to the overall field in Mercury's interior. The magnetospheric

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field is intrinsically anti-parallel to the internal dynamo field at the CMB, and lowers the saturation level of dynamo action in the core, therefore weakening the overall field in the core as well as on Mercury's surface (60 nT in Heyner et al., 2011, for example).

These dynamo models usually evoke some special geometry of the core dynamo region, and produce surface magnetic fields comparable in intensity to the observed magnetic field of Mercury. However, none of these models predict a surface magnetic field that is dominated by a highly axisymmetric and offset dipole.

It is difficult to generate a magnetic field that displays simultaneously a very small dipole tilt and a large dipole offset, *i.e.*, a field with both a large g_{20} and small g_{11} and h_{11}. This is because the g_{20} (axial quadrupole) and g_{11} and h_{11} (equatorial dipole) components belong to the same dynamo symmetry family (degree + order = even number). When fluid flows strongly excite one mode in the family, they typically excite other modes of similar wavelength in the same family (Bullard and Gellman, 1954). To numerically generate a magnetic field with these features, modifications to conventional dynamo models are needed.

To explain the weak intensity and axisymmetry of Saturn's magnetic field, Stevenson (1980, 1982) proposed a structure that featured a stably stratified layer with differential rotation at the top of the dynamo source region. The presence of the stable layer weakens the surface magnetic field by: (1) limiting the dynamo generation region to the deeper parts of the metallic H and He layer; and (2) attenuating the magnetic field, especially the rapidly varying, high multipole components, by the skin effect when the dynamo field passes through the stable layer. This stable layer, with differential rotation within it, can also act to "axisymmetrize" the surface magnetic field. Stevenson (1982) analytically determined that axisymmetrization should occur if the magnetic Reynolds number of dynamo action is sufficiently large. For Saturn, whose magnetic field is produced by the dynamo operating in the metallic hydrogen region, the stratified layer can be produced as helium rains out of the metallic hydrogen region of Saturn due to helium's immiscibility in metallic hydrogen in the molecular-metallic hydrogen transition region.

Later kinematic dynamo studies (Love, 2000; Schubert et al., 2004) examined the effect of a stable layer surrounding the dynamo generation region in axisymmetrizing the magnetic field. These models prescribe the fluid flow in the stable layer, neglect the effects of the Lorentz force on the fluid flow and the interactions between the stable and unstable layers, and track the evolution of the magnetic field. Results showed that the stable layer can affect the symmetry of the surface magnetic field, but the magnetic field need not attain axisymmetry. The symmetry of the resulting magnetic field depends on the prescribed flows in the stable layer and the geometry of the magnetic field within the region of dynamo generation.

Recent dynamic dynamo studies (Christensen, 2006; Christensen and Wicht, 2008; Stanley and Mohammadi, 2008) investigated the role of a stable layer, without latitudinally variable thermal boundary conditions, in determining the geometry of the surface magnetic field. Christensen and Wicht (2008) incorporated a very thick, stably stratified layer surrounding the dynamo region, and found that a weak, axisymmetric field can be achieved for certain parameter regimes. However, they did not typically produce the combination of a small dipole tilt and a large dipole offset. Stanley and Mohammadi (2008) instead looked at the effects of thin stable layers. They found that a thin, stably stratified layer surrounding the dynamo region, by itself, does not act to axisymmetrize the surface magnetic field. Some patterns of zonal flows in the stable layer may disrupt the dynamo action through interaction between the stable and unstable layers.

For the case of Saturn, Stanley (2010) further investigated how a thin, stably stratified layer can affect the magnetic field with latitudinal heat flux variations (spherical harmonic degrees 2 and 3) imposed at its outer boundary. She discovered that only a stable layer with heat flux variations of certain patterns and signs can axisymmetrize the magnetic field. With a standard dynamo model, which has no stable layer or laterally variable thermal boundary conditions, thermal winds in the dynamo region can arise as a natural result of fluid convection. For the case of Saturn, when the thermal boundary condition (spherical harmonic degree-2) is applied at the top of the stable layer, the resultant thermal winds in the stable layer are in the same direction as those that would naturally arise from convection in the unstable layer. In this situation, the differential rotation in the stable layer shears out the non-axisymmetric components of the magnetic field in the dynamo region and produces an axisymmetric surface magnetic field. However, when the applied thermal boundary condition is of the opposite sign, or an octupole mode (spherical harmonic degree-3), the thermal winds produced in the stable layer would act to destabilize the flows in the dynamo region through interactions between stable and unstable layers, therefore producing more non-axisymmetric magnetic fields at the planetary surface. This study demonstrates the importance of the direction and equatorial symmetry of differential rotation in the stable layer in axisymmetrizing the surface field.

For Mercury, a stably stratified layer can also form at the top of the outer core, and a latitudinally heterogeneous heat flux is likely to be present at the top of this stable layer. The stable layer can form as a result of thermal and chemical stratification. According to thermal evolution models (for example, Hauck et al., 2004), the heat flux at the CMB of Mercury is subadiabatic, which contributes to thermal stratification near the CMB. In addition, the high sulfur abundance and relatively low Fe content on the surface of Mercury (Nittler et al., 2011) indicate a chemically reducing environment during Mercury's formation, which favors an enrichment of sulfur and silicon in the core. Earth-based (Margot et al., 2007) and MESSENGER-derived (Smith et al., 2012) geophysical measurements initially required the presence of a solid FeS-rich layer at the top of the outer core (Smith et al., 2012) to explain the planet's radial density distribution. Subsequent refinement of the obliquity measurement (Margot et al., 2012) dictates that this layer is still consistent with the observations but is no longer required (Hauck et al., 2013). The presence of a solid FeS layer naturally requires an FeS-rich liquid layer to exist below it, which forms a stably stratified layer in the liquid core region.

Lateral variations in temperature within the mantle above the CMB are likely to occur in planets due to the pattern of mantle convection, the heterogeneous distribution of heat producing elements in the mantle, or the effect of giant impacts. Stanley et al. (2008) applied a degree-1 spherical harmonic heat flux distribution at Mars' CMB to produce a single-hemisphere dynamo for ancient Mars that could account for the concentration of the planet's remnant crustal magnetic field in the southern hemisphere. For Mars, the heterogeneous heat flux distribution at the CMB can be produced as the result of the giant impact creating the Borealis basin (Andrews-Hanna et al., 2008), or as the result of a hemispheric-scale pattern of mantle convection. Lateral variations in temperature at the Earth's CMB are evidenced by seismic tomography (van der Hilst et al., 2007). Unfortunately Mercury lacks seismic observations needed for tomographic mapping, however, geological features, such as large volcanic plains (Head et al., 2011), can be used to infer potential patterns of temperature variations at least in the era of formation of those features.

In a dynamo model for Mercury's magnetic field, Cao et al. (2014) applied spherical harmonic degree-2 and degree-4 heat flux variations at the CMB with the highest heat flow at the equator. They did not provide a justification for these conditions, though the surface boundary condition does have degree-2 structure due to latitude-dependent insolation (cf. Aharonson et al., 2004). Along with volumetric buoyancy applied in the core, they produced magnetic fields with large dipole offsets, an average dipole tilt of 3° (personal correspondence), and a magnitude somewhat weaker than that scaled from an Earth-like dynamo field, but still much larger than Mercury's observed field.

In this study, we assume a degree-1 heat flux distribution at the CMB. A degree-1, laterally variable mantle heat flux distribution is plausible in ancient Mercury. A laterally variable thermal structure in the mantle is consistent with geological observations (Head et al., 2011) of extensive volcanic flooding at the surface in Mercury's northern high latitudes between the late stages of the late heavy bombardment ~3.7–3.8 Ga ago. The widespread volcanism indicates more vigorous mantle convection and heat transport in the northern hemisphere. More rapid mantle heat transport can result in cooler temperatures near the CMB, and thus a higher heat flux across the CMB. Even though the northern volcanic plains only occupy 6% of Mercury's surface area, it is quasi-centered on the pole and the inferred spherical heterogeneity in heat flux can be roughly represented by a degree-1, order-0 spherical harmonic pattern. This assumes the area of volcanic flooding corresponds to the regions of higher rates of mantle convection, instead of an entire hemisphere of positive variable heat flux of the degree-1 spherical harmonic pattern.

The heterogeneous distribution of mantle convection rates can be attributed to either variations in concentration of heat-producing elements in the mantle or heterogeneous distribution of mantle viscosity. Mapping of the surface distribution of radioactive elements (Peplowski et al., 2012) reveals higher concentration of K in the surface tens of centimeters in the northern high latitudes compared to the equatorial regions. This was initially explained by a thermal redistribution mechanism, where K is transported from hotter equatorial regions to the cooler pole regions. But later findings of correlation of K and Mg/Si ratio distributions suggest that the surface K variations result from the compositions of the intrinsic crustal material (Weider et al., 2015). Currently a global map of surface concentration of radioactive elements is unavailable due to the high eccentricity of the MESSENGER spacecraft's orbit around Mercury, so we are not sure whether the southern high latitude regions also have higher than average concentrations of heat producing radioactive elements.

If more abundant heat producing elements are present in surface rocks, and thus the mantle source regions in the northern high latitudes but not in the southern regions, the resultant higher mantle temperature in the north would favor a higher heat flux at the CMB in the north. Even though a somewhat hotter mantle in the northern high latitudes lowers the rate of thermal conduction, the higher temperature makes the material less viscous and therefore increases the likelihood or vigor of mantle convection.

Thermal evolution studies (for example, Michel et al., 2013) suggest that at a mantle thickness of about 400 km, the mantle is just unstable enough to be in the convective state, and in some cases the convection does not persist to the present. Therefore, even moderately stronger internal heating in the mantle in the northern high latitudes would substantially promote convection there, resulting in either increased vigor of convection than other regions, or the persistence of convection to the present when convection in the southern regions has already ceased. In either case, since heat transport via convection tends to be more efficient than by the diffusive process in conduction, the overall rate of heat transport from the core to the planetary surface would be higher in the northern high latitudes than in the southern regions, thus creating a north–south asymmetric heat flux across the CMB, with the strong values the north.