MAGNETIC FIELD MODELING FOR MERCURY USING DYNAMO MODELS WITH STABLE LAYERS AND LATERALLY VARIABLE HEAT FLUX.

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Introduction: Mercury's magnetic field is dipole-dominated and characterized by its anomalously low intensity, large dipole offset and small dipole tilt [1]. Mercury's magnetic moment is ~190 nT*r_{planet}^3, less than 1/100 that of the Earth. The magnetic equator is offset by 480 km north of the geographic equator of Mercury, and the dipole axis is aligned with the rotation axis of the planet to within 0.8 degrees [2]. In this study we perform dynamo simulations to explain the observed characteristics of Mercury's magnetic field.

Background: Prior to the MESSENGER spacecraft's measurements of the dipole offset and tilt, many studies attempted to explain the low intensity of Mercury's magnetic field [3-12]. Some studies [10-12] applied a stable layer at the top of the outer core, which weakens the surface magnetic field through the skin effect and preferentially attenuates the higher multipole components of the magnetic field. The stable layer's stratification can result from subadiabatic heat flux [10] at the core-mantle boundary (CMB), or an enrichment of FeS in the outer region of the core. Other studies [3-9] have explained the weak magnetic field by introducing special geometries and setups of the dynamo. None of these efforts predicted a magnetic field with a large offset and a small tilt.

Saturn's magnetic field is also highly axisymmetic, with its axis aligned with the rotation axis to within 1 degree [13]. Stevenson [13] considered a variable heat flux at the outer boundary of Saturn's dynamo region, which produces differential rotation in the outer region of the dynamo that can axisymmetrize the magnetic field. Stanley [14] numerically investigated how variable heat flux applied to a dynamo with a thin stable layer can affect the magnetic field for Saturn, and found that heat flux of certain patterns and signs can axisymmetrize the magnetic field. Cao et al. [15] applied degree-2 and 4 variable heat flux at the CMB of Mercury together with volumetric buoyancy in the liquid core, and produced magnetic fields with large dipole offsets, an average dipole tilt of 3 degrees, and a magnitude weaker than that scaled from an Earth-like field, but still much larger than Mercury's observed field.

Methods: We simulate Mercury's magnetic field generation with the Kuang & Bloxham dynamo model [16], with two modifications: (a) we impose a stable layer at the top of the outer core; and (b) we implement a laterally-heterogenous, degree-1 thermal boundary condition at the CMB.

We set the core radius at 2030 km, and vary the inner/outer core radius ratio from 0.05 to 0.30, and the thickness of the stable layer in the range of 20% to 50% of the core radius.

The degree-1 laterally-variable thermal boundary condition, with a higher heat flux in the northern hemisphere, is consistent with extensive flood volcanism in the northern high latitudes 3.7 to 3.8 Ga ago, which is indicated by the northern lava plains [17]. The volcanism can be explained with more vigorous mantle convection and heat transport in the northern hemisphere. More rapid heat transport can result in lower temperatures at the CMB and thus a higher heat flux across the CMB. This heterogeneous heat flux can be roughly represented by a degree-1, order-0 spherical harmonic pattern. While Mercury's northern lava plains support the existence of a heterogeneous heat flux in the ancient times, it's not clear how this pattern can be maintained over history.

Results: With the stable layer and degree-1 heat flux, our simulations feature surface magnetic fields with magnitudes comparable to the observed value of 190 nT, large dipole offsets, and average dipole tilts as small as 0.5 to 0.6 degrees, which agree well with all three observational constraints of Mercury's magnetic field.

Implications: Our results show that a mechanically-stratified layer at the top of the liquid core plays an important role in producing the observed features of Mercury's magnetic field. The emergence of a stratified layer can be attributed to either the sub-adiabatic heat flux at the CMB, or chemical stratification of liquid FeS at the top of the outer core. The high abundance of S in the core needed for such an FeS enrichment is consistent with the observed high abundances of volatile S contents on Mercury's surface [18].

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