DETECTING CRUSTAL MAGNETIC FIELDS ON MERCURY WITH MESSENGER.

Reka Moldovan[1], Catherine L. Johnson[1,2], J. Andreas Ritzer[1], Michael E. Purucker[3], Sean C. Solomon[4], Brian J. Anderson[5], Brett W. Denevi[5], and Haje Korth[5]. [1]Department of Earth and Ocean Sciences, The University of British Columbia, 6339 Stores Road, Vancouver, V6T 1Z4, Canada (rmoldova@eos.ubc.ca; cjohnson@eos.ubc.ca; aritzer@eos.ubc.ca); [2]Planetary Science Institute, 1700 East Fort Lowell, Suite 106, Tucson, AZ 85719-2395; [3]Goddard Space Flight Center, 8800 Greenbelt Road, Greenbelt, MD 20771 (michael.e.purucker@nasa.gov); [4]Department of Terrestrial Magnetism, Carnegie Institution of Washington, 5241 Broad Branch Road, N.W., Washington, DC 20015-1305 (scs@dtm.ciw.edu); [5]Johns Hopkins University Applied Physics Laboratory, Laurel, MD 20723 (brian.anderson@jhuapl.edu; Brett.Denevi@jhuapl.edu, Haje.Korth@jhuapl.edu).

Summary: We investigate conditions under which crustal remanent magnetization can produce magnetic fields detectable by the MESSENGER spacecraft from orbit around Mercury. We find that detection of crustal magnetic fields at the shortest wavelengths resolvable by MESSENGER would imply either that Mercury's magnetic field was substantially stronger in the past than at present, or that the crust has a high bulk magnetic susceptibility. We superpose simulated crustal magnetic fields that are correlated with basin-scale geology on a core-dynamo dipolar field, and we test the recovery of both the crustal and dynamo fields with a variety of techniques. Future work will also test recovery of a weak global-scale signature of crustal magnetization [1], superposed on a dipole field.

Background: Mercury has a weak, but global, internal magnetic field that has been measured during two Mariner 10 and three MESSENGER flybys [2, 3]. On the basis of the Mariner 10 observations, the internal field was attributed to either a core dynamo [2] or long-wavelength crustal magnetization [1]. The MESSENGER and Mariner 10 observations are collectively best described by a dipole with a moment of 180 to 290 nT-R_M^3, where R_M, is Mercury's radius, and an axial tilt of less than 5° [3], favoring a core-dynamo origin. In particular, the magnetic field geometry predicted by geographical variations in the depth to a single Curie temperature [1] does not provide a better fit to the observations than a simple dipole field [4, 5]. Furthermore, the flybys show no evidence for small-scale features clearly attributable to crustal magnetization [4].

Detecting the presence of any crustal magnetization remains an important goal for MESSENGER because geographical variations in the strength and direction of such magnetization provide constraints on the onset and history of a core dynamo. During MESSENGER's orbital mission phase, magnetic field measurements at low altitudes ($200-500$ km) will be made over mid-to-high northern latitudes. Here we investigate conditions under which small-scale, basin-scale, and global-scale crustal remanence can be detected in the presence of a dipolar core-dynamo field.

Short-Wavelength Crustal Fields: We first calculate the maximum magnetic field intensity resulting from short-wavelength crustal magnetization, i.e., from a magnetized volume, V, of the smallest resolvable spatial extent. We assume that the maximum such magnetic field will occur where the depth to the Curie temperature is largest (at the pole), and for an idealized magnetization **M** whose direction is aligned with the spin axis. The magnetic field produced by such a volume can be expressed as the field intensity due to an equivalent dipole moment **m** = **M** V. The magnetic field intensity of the magnetized volume is given by

$$B_{\text{ml}} = \frac{V}{2\pi h_r^3}\chi_{\text{ml}} B_{\text{app}}, \tag{1}$$

where χ_{ml} is the bulk magnetic susceptibility of the layer, B_{app} is the magnetic field strength in which the magnetization was acquired, and h_r is the distance between the source (middle of the magnetized layer) and the observation point. The volume, V, is given by the smallest resolvable area ($\approx h_s^2$, where h_s is the spacecraft altitude at periapsis) multiplied by the maximum depth of magnetization, which is the depth to the Curie temperature for a given magnetic carrier. We calculate the depth to the Curie temperature for different minerals, for a given present-day heat flow [6] and a temperature boundary condition at the base of the regolith [7]. For single-domain pyrrhotite (a possible magnetic carrier on Mercury), the maximum depth is 120 km. This depth is broadly consistent with current bounds on the average crustal thickness on Mercury [8, 9]. We calculate the maximum crustal field intensity for a range of values of χ_{ml} and B_{app} (Figure 1).

We conservatively take a field strength of 10 nT as a detection limit for crustal fields, motivated by observations of field variations of ∼10 nT unrelated to internal fields but detected inside the magnetosphere during the first two MESSENGER flybys [3]. We note that it may be possible to reduce this limit if consistent small-scale signatures are seen from adjacent and/or repeated orbits. Our results show that unless Mercury's magnetic field was much stronger in the past or the crust has a very high bulk magnetic susceptibility, magnetic fields of crustal origin will be ∼4 nT or lower and are unlikely

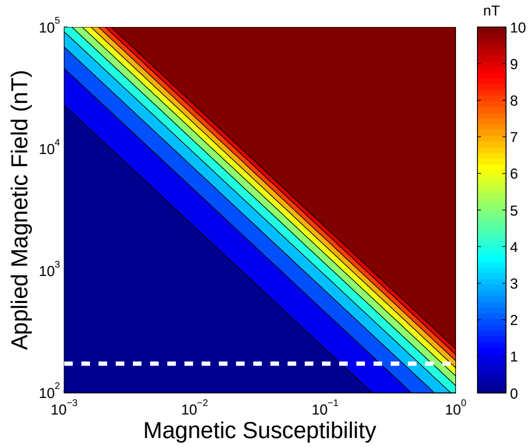

Figure 1: Magnetic field intensity at an altitude of 200 km, $B_{\rm ml}$, as a function of applied magnetic field strength and bulk magnetic susceptibility. The white dashed horizontal line shows the magnetic field strength of Mercury today at ~200 km. The dark red region indicates field strengths of 10 nT or higher, our detection limit for internal fields.

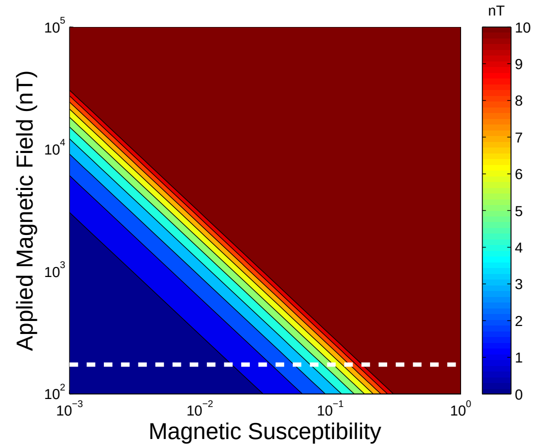

Figure 2: Magnetic field intensity as in Figure 1, calculated with equation (2).

to be detected.

We also recast the formulation of equation (13) of Parker [10] to establish a minimum bound on either $B_{\rm app}$ or $\chi_{\rm ml}$ for a single observation of magnetic field intensity. In this approach the magnetic layer is laterally extensive, extends from vertical distances h_1 to h_2 beneath the spacecraft, and has a magnetization that is constant in magnitude but varies in direction. The magnetic field intensity is given by

$$B_{\rm ml} = \frac{[6+\sqrt{3}\ln(2+\sqrt{3})]}{12} \ln\left(\frac{h_2}{h_1}\right) \chi_{\rm ml} B_{\rm app}. \quad (2)$$

As expected, for a given observed magnetic field intensity due to the crustal layer, this lower bound formulation permits a lower $B_{\rm app}$ or $\chi_{\rm ml}$ for a given $B_{\rm ml}$ (Figure 2) than the analyses shown in Figure 1. This outcome is due to the difference in the nature of the two solutions: our solution is for a single dipole placed at the center of the magnetized layer, whereas the solution of Parker [10] is for a distribution of dipoles that gives the minimum magnetization. Even this result, however, requires a bulk magnetic susceptibility higher than average values for crustal rocks on Earth [11].

Basin-Scale Crustal Fields: We test the recovery of crustal fields correlated with large-scale surface features such as impact basins and smooth plains. We model the crustal magnetic field of a large basin (e.g., Caloris) with an equivalent dipole source method [12]. The localized crustal magnetic field is simulated with an icosahedron grid of dipoles restricted to the basin region. The magnetization intensity was set to 1.6 A m^{-1} over the basin. We added a spherical harmonic degree-1 axisymmetric core field to simulate Mercury's global dipole field, and we predicted the global and crustal field together along MESSENGER orbital tracks at altitudes of less than 1000 km. Inversions for spherical harmonic fields with no regularization show that even for northern hemisphere basins, such as Caloris, the geometry of orbital observations prohibits accurate crustal field recovery. Regularization allows detection of basin-scale crustal fields, but the amplitudes of such fields may be underestimated because of the damping imposed.

Future Work: Additional simulations will investigate inversions that combine global (spherical harmonic) and local (e.g., equivalent dipole source) basis functions. Our analyses to date ignore the issue of external field removal: this step will be most important at the global scale, and in particular will affect our ability to determine whether global-scale crustal magnetization of the form predicted by Aharonson et al. [1] is present. Once MESSENGER is in orbit, repeatability of observations will ensure that the signatures detected are of crustal and not external origin.

References: [1] Aharonson, O. et al. (2003), *EPSL*, 218, 261. [2] Connerney, J.E.P. & N.F. Ness (1988), in Vilas, F. et al. (Eds.), Mercury, pp. 494-513, Univ. Arizona Press, Tucson. [3] Anderson, B.J. et al. (2010), *Space Sci. Rev.*, 152, 307. [4] Purucker, M.E. et al. (2009), *EPSL*, 285, 340. [5] Uno, H. et al. (2009), *EPSL*, 285, 328. [6] Hauck II, S.A. et al. (2004), *EPSL*, 222, 713. [7] Vasavada, A.R. et al. (1999), *Icarus*, 141, 179. [8] Nimmo, F. & Watters, T.R. (2004), *Geophys. Res. Lett.*, 31, L02701, 10.1029/2003GL018847. [9] Smith, D.E. et al. (2010), *Icarus*, 209, 88. [10] Parker, R.L. (2003), *JGR*, 108, 5006. [11] Dunlop, D.J. & Özdemir, Ö. (1997), Rock Magnetism: Fundamentals and Frontiers, 573 pp., Cambridge Univ. Press, New York. [12] Langlais, B. et al. (2004), *JGR*, 109, E02008, 10.1029/2003JE002048.