Progress Report

Period 4/1/2003 to 3/31/2004

Planetary Geophysics and Tectonics

Grant #NAG5-11650

April 19, 2005

Maria Zuber
Principal Investigator
Massachusetts Institute of Technology
Department of Earth, Atmospheric and Planetary Sciences
Building 54, Room 518
77 Massachusetts Avenue
Cambridge, MA 02139
617-253-6397

MIT Institution contact:
Cheryl Magoveny
Office of Sponsored Programs
Building E19-750
77 Massachusetts Avenue
Cambridge, MA 02139
617-253-4170
PROPOSAL SUMMARY

PRINCIPAL INVESTIGATOR: Maria T. Zuber
Dep. of Earth, Atmospheric, and Planetary Sciences
Massachusetts Institute of Technology
Cambridge, MA 02139-4307
phone: (617) 253-6397    fax: (617) 258-9697

CO-INVESTIGATORS: None

PROPOSAL TITLE: Planetary Geophysics and Tectonics

ABSTRACT: (Type single-spaced below line. Lettered paragraphs (a) through (d) should include: a. brief statement of the overall objectives and justification of the work; b. brief statement of the accomplishments of the prior year, or "new proposal;" c. brief listing of what will be done this year, as well as how and why; and d. one or two of your recent publications relevant to the proposed work.)

(a) The broad objective of this work is to improve understanding of the internal structures and thermal and stress histories of the solid planets by combining results from analytical and computational modeling, and geophysical data analysis of gravity, topography and tectonic surface structures.

(b) During the past year we performed two quite independent studies in the attempt to explain the Mariner 10 magnetic observations of Mercury. In the first we revisited the possibility of crustal remanence by studying the conditions under which one could "break symmetry" inherent in Runcorn's model of a uniformly magnetized shell to produce a remanent signal with a dipolar form. In the second we applied a thin shell dynamo model to evaluate the range of intensity/structure for which such a planetary configuration can produce a dipole field consistent with Mariner 10 results.

(c) In the next full proposal cycle we will: (1) develop numerical and analytical and models of thin shell dynamos to address the possible nature of Mercury's present-day magnetic field and the demise of Mars' magnetic field; (2) study the effect of degree-1 mantle convection on a core dynamo as relevant to the early magnetic field of Mars; (3) develop models of how the deep mantles of terrestrial planets are perturbed by large impacts and address the consequences for mantle evolution; (4) study the structure, compensation, state of stress, and viscous relaxation of lunar basins, and address implications for the Moon's state of stress and thermal history by modeling and gravity/topography analysis; and (4) Use a three-dimensional viscous relaxation model for a planet with generalized vertical viscosity distribution to study the degree-two components of the Moon's topography and gravity fields to constrain the primordial stress state and spatial heterogeneity of the crust and mantle.

(d) Papers of particular relevance to the proposed investigation:
I. INTRODUCTION

This report summarizes progress in our research effort in planetary geophysics and tectonics. During the past year our research group has addressed a range of questions that involve aspects of these processes as applied to the terrestrial planets, with an emphasis on the Moon and Mercury.

During the past year we published or submitted or contributed to six manuscripts and one book chapter under the auspices of this grant. A list of these publications follows the technical report. A discussion of future work was presented in the full proposal to the PGG program.

II. PROGRESS TOWARDS UNDERSTANDING THE MAGNETIC SIGNATURE OF MERCURY

Some Background

Mercury represents a key towards understanding the evolution of the terrestrial planets. In striking contrast to the Moon's depletion in iron and small (if any) core, Mercury's size and mass [Anderson et al., 1987; Anderson et al., 1996] indicates a high metal/silica ratio and a metallic mass fraction of about twice that of the Earth, Venus and Mars. The uncompressed density (5500 kg m\(^{-3}\)) suggests that if the planet differentiated into a silicate mantle and iron core then \(R_{\text{core}} \sim 0.75 R_{\text{planet}}\) and the fractional core mass is about 0.65 [Siegfried and Solomon, 1974]. This unusual internal structure combined with the puzzling detection of a dipole magnetic signature [Connerney and Ness, 1988] during two Mariner 10 flybys of the planet in 1974-1975 (Figs. 1 and 2), revealing the presence of a magnetic field with dipole moment of about 300 nT\(R_{\text{M}}\)\(^2\) (1 \(R_{\text{M}} = 2440\) km) [Ness et al., 1975; Ness et al., 1976]. The magnetic observations can be consistent with a present-day dynamo [Connerney and Ness, 1988], but other interpretations of the data are possible. Crustal remanence is possible but was discounted for some time due to a well known theorem indicating that a uniformly magnetized shell in the presence of an internal source will have no external field subsequent to the removal of the source [Runcorn, 1975a; Runcorn, 1975b].

Determining unambiguously whether the observed field is due to crustal remanence, an active dynamo, or thermoelectric currents is difficult [Aharonson et al., 2004; Giampieri and Balogh, 2002; Schubert et al., 1988; Stanley et al., 2005; Stevenson, 1987] because of the field's magnitude and the limited spatial and temporal resolution of
the current data [Connerney and Ness, 1988; Ness, 1979]. For example in the last funding cycle we developed an analytical theory [Aharonson et al., 2004] (Appendix 2) that showed that a remanent signature on Mercury can have a significant dipole component due to the latitudinal influence of surficial heating on the depth to the Curie isotherm.

Recent ground-based observations of Mercury's forced vibrations in longitude provide compelling indirect evidence that Mercury's core is at least partially fluid [Margot et al., 2004]; hence a basic necessary condition for dynamo action appears to be fulfilled. However energetic and magnetostrophic balance arguments [Schubert et al., 1988; Stevenson, 1987] show that a dynamo source for Mercury's observed magnetic field is problematic if one expects an Earth-like partitioning of toroidal and poloidal components of the field.

The Future

Future observations from the NASA MESSENGER mission [Solomon et al., 2001] will provide a range of geophysical, geochemical and geological observations relevant to addressing the nature of Mercury's thermal evolution, with detection of the core state and the mechanism of magnetic field generation being high priority science objectives. In the mean time, we develop a suite of models to potentially explain Mercury's magnetic signature.

III. MODELS TO EXPLAIN THE MARINER 10 MAGNETIC SIGNATURE OF MERCURY

A Remanent Magnetization Model

Previous attempts to explain Mercury's magnetic field as a consequence of remanent magnetization were dismissed [Stephenson, 1976] because of an assertion of Runcorn [Runcorn, 1975a; Runcorn, 1975b], that lacking any lateral variations in shell thickness an external magnetic field vanishes. But if the symmetry of the shell can be broken, then remanent magnetization should be possible.

In the past year we investigated how variations in the thickness of a surficial layer that is available to be magnetized might be responsible for external magnetic fields. Our work [Aharonson et al., 2004] provides a general solution to the variable layer-thickness problem, demonstrates some special cases that are easily obtained from it, and applies the formulation to Mercury. Our aim was not to dispute that Mercury's magnetic field may indeed originate in the core, but rather to reexamine the often dismissed [Stephenson, 1976] that it originates in the crust.

We considered the magnetic field of a shell uniformly magnetized by an internal dipole that is subsequently removed. The Gauss coefficients of the resulting field were given in terms of the spherical harmonic coefficients of the shell thickness. This general solution can easily be reduced to common special cases by superposition. For a shell of constant thickness the External field vanishes (by Runcorn's theorem). But for a laterally varying temperature field, such as would be expected for Mercury due to latitudinal differences in illumination and longitudinal differences associated with Mercury's orbit, the resulting magnetic moments are appreciably greater than the previously published correction due to rotational flattening. We showed that if the crust of Mercury contains rocks capable of sustaining high specific magnetizations, then the Mariner 10 observations of Mercury's magnetic field are consistent in magnitude and geometry with the predictions of this model [Aharonson et al., 2004]. For such a scenario, the requirement of a fractionally large molten outer core would be relaxed.

A Thin Shell Dynamo Model

In a preliminary study, we [Stanley et al., 2005] used a formulation for a 3-D numerical dynamo model [Kuang and Bloxham, 1997; Kuang and Bloxham, 1999] to demonstrate that if Mercury's core consists of a thin fluid shell surrounding a solid core (the geometry suggested by some thermal evolution models for Mercury [Schubert et al., 1988; Stevenson, 1987; Stevenson et al., 1983]), then a thin shell dynamo is capable of producing fields with toroidal-poloidal field partitioning similar to Mercury (and different from Earth). The purpose of the study was to determine whether dynamo models capable of explaining Mercury's observed magnetic field plausibly could have existed.
As shown in Fig. 3, we examined the ratio of the dipole field at the core-mantle boundary to the toroidal field in the core for various shell thicknesses and Rayleigh numbers. We found that some thin shell dynamos can produce magnetic fields with Mercury-like dipolar field intensities. In such dynamos, the toroidal field is produced more efficiently through differential rotation than the poloidal field, and the poloidal field is produced through upwellings interacting with the toroidal field. The poloidal field is also dominated by smaller-scale structure that was not observable by the Mariner 10 mission, in comparison to the dipole field. We submitted a paper on this study, which is currently in press [Stanley et al., 2005]. The results predict the poloidal field power and structure, and these are observations that can be tested during the MESSENGER mission.

Fig. 3. Magnetic power spectra at the surface of Mercury for different numerical dynamo models. Average power over a magnetic diffusion time vs. spherical harmonic degree is shown in (a) and vs. spherical harmonic order is shown in (b). Models with different inner to outer core radius ratios ($r_0$) and modified Rayleigh numbers ($Ra_m$) are shown: $r_0 = 0.35, Ra_m = 18000$ (red stars), $r_0 = 0.8, Ra_m = 25000$ (black circles), $r_0 = 0.8, Ra_m = 40000$ (blue squares) and $r_0 = 0.9, Ra_m = 60000$ (green diamonds). Differences can be seen between the models: The thicker, Earth-like shell thickness model (red stars) contains less power in degrees 3 and higher than thinner models, the two thin shell models with convection occurring both inside and outside the tangent cylinder (blue squares, green diamonds) have higher degree 3 components than degree 2 components unlike the other models, and the thin shell model with convection occurring only outside the tangent cylinder (black circles) appears to have less power in axisymmetric modes (order 0) than non-axisymmetric modes. For more information on these models, see Stanley et al. [2005] (Appendix 1).

REFERENCES

Anderson, J.D., R.F. Jurgens, E.L. Lau, M.A.I. Slade, and G. Schubert, Shape
LIST OF PAPERS SUPPORTED
ALL OR IN PART FROM NASA
PGGP PROGRAM IN FY03-04

Stanley, S., J. Bloxham, W.E. Hutchison, and
M.T. Zuber, Thin shell dynamo models
consistent with Mercury's weak magnetic
field, *Earth Planet. Sci. Lett.*, in press,
2005.

Aharonson, O., M.T. Zuber and S.C. Solomon,
Crustal remanence as a source for
Mercury's magnetic field, *Earth Planet. Sci.
2004.

Montesi, L.G.J. and M.T. Zuber, Clues to the
lithospheric structure of Mars from wrinkle
ridge sets and localization instability, *J.
2003.

Barucci, M. Belton, W. Benz, A. Cellino, M.
Festou, M. Fulchignioni, A.W. Harris, and
M.T. Zuber, Interiors of small bodies:
MARIA T. ZUBER

Research Interests
Theoretical modeling of geophysical processes; analysis of altimetry, gravity and tectonics to determine the structure and dynamics of the Earth and solid planets; space-based laser ranging.

Education
B.A. Astrophysics (honors) and Geology, University of Pennsylvania, 1980.
   Senior Thesis: Velocity-Inclination Correlations in Galactic Clusters

Employment
Head of the Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology, 2003-Present.
Professor of Geophysics, Johns Hopkins University, 1995.
Senior Research Scientist, Laboratory for Terrestrial Physics, NASA/GSFC, 1994-Present.
Second Decade Society Associate Professor of Geophysics, JHU, 1993-1995.

Honors and Awards
Member, National Academy of Sciences, 2004.
Fellow, American Academy of Arts and Sciences, 2004.
Scientific Achievement Award, American Institute of Aeronautics and Astronautics, New England Section, 2002.
Fellow, American Geophysical Union, 2001.
NASA Group Achievement Award for the Mars Program Independent Assessment Team, 2000.
Inaugural Carl Sagan Lecturer, American Geophysical Union, December, 2000.
Asteroid 6635 Zuber discovered and designated by Carolyn and Eugene Shoemaker at Palomar Observatory, 1987; approved by the IAU, 1998.
Johns Hopkins University David S. Olton Award for Outstanding Contributions to Undergraduate Student Research, 1995.
JHU Oraculum Award for Excellence in Undergraduate Teaching, 1994.
JHU Second Decade Society Faculty Development Chair, 1993-1995.

Professional Societies
American Geophysical Union
American Association for the Advancement of Science
American Astronomical Society, Division for Planetary Sciences

Selected Professional Involvement
Visiting Committee, Jet Propulsion Laboratory, 2000-Present.
Board of Reviewing Editors, Science, 2000-Present.
American Geophysical Union Edward A. Flinn Medal Selection Committee, 2000-Present.
NASA Space Science Advisory Committee, 1999-Present.
Chair, AGU Audit and Legal Affairs Committee, 1998-2000; Member, 1996-2000.
Chair, AGU Best Student Paper Award in Planetary Sciences Selection Committee, Fall Meeting, 1996; Spring Meeting, 1997.
Chair, AGU Eos Editor Search Committee, 1997-Present; Member, 1996-1997.
American Geophysical Union Edward A. Flinn Award Committee, 1996-Present.
Deputy Principal Investigator, Mars Orbiter Laser Altimeter, Mars Global Surveyor Mission, 1994-Present.
Chair, Mars Observer Geodesy and Geophysics Working Group, 1993.

Selected Refereed Publications (out of more than 90 in peer-reviewed journals)


<table>
<thead>
<tr>
<th></th>
<th></th>
<th>NASA USE ONLY</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Direct Labor (salaries, wages, and fringe benefits)</td>
<td>63,281</td>
<td></td>
</tr>
<tr>
<td>2. Other Direct Costs:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>a. Subcontracts</td>
<td></td>
<td></td>
</tr>
<tr>
<td>b. Consultants</td>
<td></td>
<td></td>
</tr>
<tr>
<td>c. Equipment</td>
<td></td>
<td></td>
</tr>
<tr>
<td>d. Supplies</td>
<td>1,103</td>
<td></td>
</tr>
<tr>
<td>e. Travel</td>
<td>2,205</td>
<td></td>
</tr>
<tr>
<td>f. Other</td>
<td>22,628</td>
<td></td>
</tr>
<tr>
<td>3. Facilities and Administrative Costs</td>
<td>45,783</td>
<td></td>
</tr>
<tr>
<td>4. Other Applicable Costs:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5. SUBTOTAL--Estimated Costs</td>
<td>135,000</td>
<td></td>
</tr>
<tr>
<td>6. Less Proposed Cost Sharing (if any)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7. Carryover Funds (if any)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>a. Anticipated amount</td>
<td></td>
<td></td>
</tr>
<tr>
<td>b. Amount used to reduce budget</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8. Total Estimated Costs</td>
<td>135,000</td>
<td>XXXXXXX</td>
</tr>
<tr>
<td>9. APPROVED BUDGET</td>
<td>XXXXXX</td>
<td>XXXXXXX</td>
</tr>
</tbody>
</table>