Progress Report

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

Planetary Geophysics and Tectonics

Grant #NAG5-11650

April 19, 2005

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PROPOSAL SUMMARY

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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:

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. Lett., 6945,* doi: 10.1016/j.epsl.2003.11.020, 2004.

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 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.

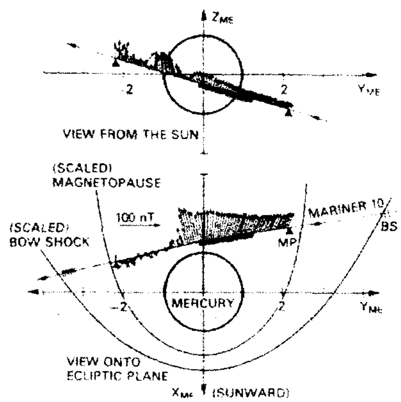
II. PROGRESS TOWARDS UNDERSTANDING THE MAGNETIC SIGNATURE OF MERCURY

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_{core} ~0.75 R_{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 has led to considerable debate about internal structure, particularly core state. The possibility that Mercury's magnetic field is a consequence of a core dynamo would require that the planet's metallic core is at present at least partially molten. For thermal evolution models in which core-mantle differentiation occurred early and the core is either pure iron or an iron-nickel solid solution, an initially molten core should have frozen out by now [*Cassen et al.*, 1976; *Fricker et al.*, 1976; *Siegfried and Solomon*, 1974]. However, a present-day fluid core is possible if a lighter element such as sulfur is present [*Schubert et al.*, 1988]. Alternatively, perhaps the magnetic signature detected by Mariner 10 indicates a frozen-in crustal field associated with thermal remanence, which could be consistent with a solid or non-convecting core. The evolution of core state with time has implications for orbital evolution: the presence of a fluid core at the time that Mercury entered its 3:2 spin orbit resonance would have enhanced its capture probability [*Peale*, 1988].

Mariner 10 Observations

Mariner 10 observed Mercury's magnetic field during 2 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_M^3 (1 R_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 theorm 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].



Mercury Encounter (29 March 1974) observations. Projection of the observed magnetic ... onto the Mercury ecliptic Y-Z (top) and X-Y planes.

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 librations 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.

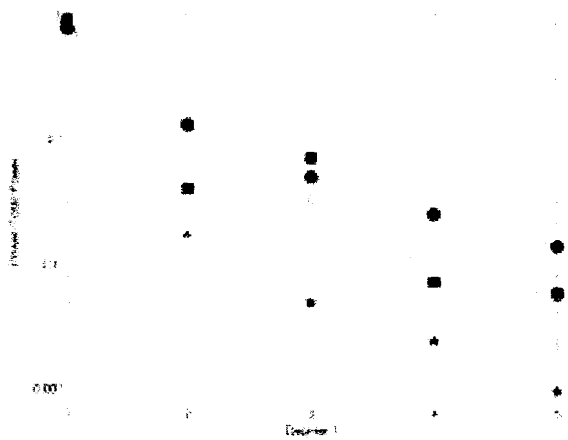
We considered the magnetic field of a shell uniformly magnetized by an internal dipole that is subsequently removed. The Gauss coefficients of the resulting field were given in terms of the spherical harmonic coefficients of the shell thickness. This general solution can easily be reduced to common special 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 fhe poloidal field is produced through upwellings interacting with the toroisal field. The poloidal field is also dominarted 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.

a)



(b)

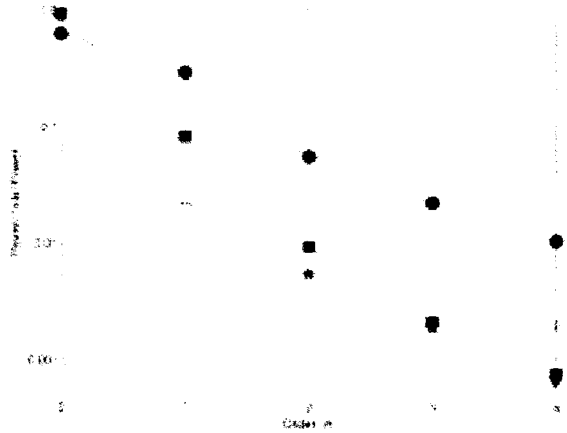


Fig. 3. Magnetic power spectra at the surface of Mercury for different numerical dynamo models. Average power over a magnetic diffusion time vs. spherical harmonic degree is shown in *(a)* and vs. spherical harmonic order is shown in *(b).* Models with different inner to outer core radius ratios (r_{io}) and modified Rayleigh numbers (Ra_m) are shown: r_{io} =0.35, Ra_m=18000 (red stars), r_{io} =0.8, Ra_m=25000 (black circles), r_{io} =0.8, Ra_m=40000 (blue squares) *and* r_{io} =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

Aharonson, O., M.T. Zuber, and S.C. Solomon, Crustal remanence in an internally magnetized non-uniform shell as a possible source for Mercury's magnetic field?, *Earth Planet. Sci. Lett.*, *218*, 261-268, 2004.

Anderson, J.D., G. Colombo, P.B. Esposito, E.L. Lau, and G.B. Trager, The mass, gravity field and ephemeris of Mercury, *Icarus*, *71*, 337-349, 1987.

Anderson, J.D., R.F. Jurgens, E.L. Lau, M.A.I. Slade, and G. Schubert, Shape and orientation of Mercury from radar ranging data, *Icarus*, *124*, 690-697, 1996.

Cassen, P., R.E. Young, G. Schubert, and R.T. Reynolds, Implications of an internal dynamo for the thermal history of Mercury, *Icarus*, *28*, 501-508, 1976.

Connerney, J.E.P., and N.F. Ness, Mercury's Magnetic Field and Interior, in *Mercury*, edited by F. Vilas, C.R. Chapman, and M.S. Matthews, pp. 494-513, Univ. Ariz. Press, Tucson, 1988.

Fricker, P.E., R.T. Reynolds, A.L. Summers, and P.M. Cassen, Does Mercury have a molten core?, *Nature*, *259*, 293-294, 1976.

Giampieri, G., and A. Balogh, Mercury's thermoelectric dynamo model revisited, *Planet. Space Sci.*, *50*, 757-762, 2002.

Kuang, W., and J. Bloxham, An Earth-like numerical dynamo model, *Nature*, *389*, 371-374, 1997.

Kuang, W., and J. Bloxham, Numerical modeling of magnetohydrodynamic convection in a rapidly rotating spherical shell: Weak and strong field dynamo action, *J. Comp. Phys.*, *153*, 51-81, 1999.

Margot, J.-L., S.J. Peale, R.F. Jurgens, M.A. Slade, and I.V. Holin, Earth-based measurements of planetary rotational states, *EOS Trans. Am. Geophys. Un.*, *85*, GP33A-02, 2004.

Ness, N.F., The magnetic fields of Mercury, Mars, and Moon, *Ann. Rev. Earth Planet. Sci.*, *7*, 249-288, 1979.

Ness, N.F., K.W. Behannon, R.P. Lepping, and Y.C. Whang, The magnetic field of Mercury, *J. Geophys. Res.*, *80*, 2708-2716, 1975.

Ness, N.F., K.W. Behannon, R.P. Lepping, and Y.C. Whang, Observations of Mercury's magnetic field, *Icarus*, *28*, 479-488, 1976.

Peale, S.J., The Rotational Dynamics of Mercury and the State of its Core, in *Mercury*, edited by F. Vilas, C.R. Chapman, and M.S. Matthews, pp. 461-493, Univ. Ariz. Press, Tucson, 1988.

Runcorn, S.K., An ancient lunar magnetic dipole field, *Nature*, *253*, 701-703, 1975a.

Runcorn, S.K., On the interpretation of lunar magnetism, *Phys. Earth Planet. Int.*, *10*, 327-335, 1975b.

Schubert, G., M.N. Ross, D.J. Stevenson, and T. Spohn, Mercury's thermal history and the generation of its magnetic field, in *Mercury*, edited by F. Vilas, C.R. Chapman, and M.S. Matthews, pp. 429-460, Univ. Ariz. Press, Tucson, 1988.

Siegfried, R.W., and S.C. Solomon, Mercury: Internal structure and thermal evolution, *Icarus*, *23*, 192-205, 1974.

Solomon, S.C., R.L. McNutt, R.E. Gold, M.H. Acuna, D.N. Baker, W.V. Boynton, C.R. Chapman, A.F. Cheng, G. Gloeckler, J.W.I. Head, S.M. Krimigis, W.E. McClintock, S.L. Murchie, S.J. Peale, R.J. Phillips, M.S. Robinson, J.A. Slavin, D.E. Smith, R.G. Strom, J.I. Trombka, and M.T. Zuber, The MESSENGER mission to Mercury: Scientific objectives and implementation, *Planet. Space Sci.*, *49*, 1445-1465, 2001.

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

Stephenson, A., Crustal remanence and the magnetic moment of Mercury, *Earth Planet. Sci. Lett.*, *28*, 454-458, 1976.

Stevenson, D.J., Mercury's magnetic field: a thermoelectric dynamo?, *Earth Planet. Sci. Lett.*, *82*, 114-120, 1987.

Stevenson, D.J., T. Spohn, and G. Schubert, Magnetism and thermal evolution of the terrestrial planets, *Icarus*, *54*, 466-489, 1983.

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. Lett., 6945,* doi: 10.1016/j.epsl.2003.11.020, 2004.

Montesi, L.G.J. and M.T. Zuber, Clues to the lithospheric structure of Mars from wrinkle ridge sets and localization instability, *J. Geophys. Res., 108,* 10.1029/2002JE001974, 2003.

Simons, F.J., R.D. van der Hilst, and M.T. Zuber, On the measurement of non-stationary anisotropic coherence functions: Application to the isostatic response of Australia, *J. Geophys. Res., 108,* doi:10.1029/2001JB000704, 2003.

Binzel, R.P., M. A'Hearn, E. Asphaug, M.A. Barucci, M. Belton, W. Benz, A. Cellino, M. Festou, M. Fulchignoni, A.W. Harris, and M.T. Zuber, Interiors of small bodies: Foundations and perspectives, *Planet. Space Sci., 51,* 443-454, 2003.

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
Ph.D. Geophysics, Brown University, 1986.
Ph.D. Thesis: Unstable Deformation in Layered Media: Application to Planetary Lithospheres. Thesis Advisor: E.M. Parmentier
Sc.M. Geophysics, Brown University, 1983.
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.
E.A. Griswold Professor of Geophysics and Planetary Science, Massachusetts Institute of Technology, 1998-Present.
Professor of Geophysics and Planetary Science, Massachusetts Institute of Technology, 1995-1998.
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.
Associate Research Professor of Geophysics, Johns Hopkins University, 1991-1992.
Geophysicist, Geodynamics Branch, NASA/Goddard Space Flight Center, 1986-1992.
National Research Council Research Associate, Geodynamics Branch, NASA/GSFC, 1985-1986.
Research Assistant, Department of Geological Sciences, Brown University, 1980-1985.

Honors and Awards
NASA Distinguished Public Service Medal, 2004.
Member, National Academy of Sciences, 2004.
Fellow, American Academy of Arts and Sciences, 2004.
NASA Group Achievement Award for the Mercury Laser Altimeter, 2004.
NASA Group Achievement Award for the Mars Global Surveyor Project Science Team, 2003.
Scientific Achievement Award, American Institute of Aeronautics and Astronautics, New England Section, 2002.
NASA Group Achievement Award for the Near Earth Asteroid Rendezvous Mission Team, 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.
NASA Group Achievement Award for the Mars Global Surveyor Science Team, 2000.
Distinguished Leaders in Science Lecturer, National Academy of Sciences, 1999.
Asteroid 6635 Zuber discovered and designated by Carolyn and Eugene Shoemaker at Palomar Observatory, 1987; approved by the IAU, 1998.
NASA Group Achievement Award for the Near Earth Asteroid Rendezvous spacecraft encounter of Asteroid 253 Mathilde, 1998.
Planetary Society Thomas O. Paine Memorial Award for the Advancement of the Human Exploration of Mars, 1998 (awarded to Mars Global Surveyor and Pathfinder Teams).
NASA Exceptional Scientific Achievement Medal, 1995.
Johns Hopkins University David S. Olton Award for Outstanding Contributions to Undergraduate Student Research, 1995.
NASA Group Achievement Award for the Deep Space Program Science Experiment Lunar Orbit Mission Operations Support Team, 1994.

JHU Oraculum Award for Excellence in Undergraduate Teaching, 1994.
JHU Second Decade Society Faculty Development Chair, 1993-1995.
NASA Group Achievement Award for Mars Observer Payload Development Team, 1993.
Harold S. Masursky Lecturer, 24th Lunar and Planetary Science Conference, 1993.
NASA Group Achievement Award for the Mars Observer Laser Altimeter Project, 1991.
NASA Outstanding Performance Award, 1988, 1989, 1990, 1991, 1992.
NASA Peer Award, 1988.
Sigma Xi, 1983, 1985.

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 Directors, The Planetary Society, 2000-Present.
Mars Program Independent Assessment Team, 2000.
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.
President, Planetary Sciences Section, American Geophysical Union, 1998-2000; President-elect,1996-1998.
Co-investigator, NASA MESSENGER Mission to Mercury, 1999-Present.
NASA Europa Orbiter Science Definition Team, 1997-1999.
Local Organizing Committee, AAS Division for Planetary Sciences Mtg., Cambridge, 1997.
Chair, AGU Best Student Paper Award in Planetary Sciences Selection Committee, Fall Meeting, 1996; Spring Meeting, 1997.
Co-author, National Academy of Sciences/NASA "Nature of Origins" Report, 1996.
Chair, AGU, Eos Editor Search Committee, 1997-Present; Member, 1996-1997.
NASA Mars Exploration Working Group, 1996-1997.
National Academy of Sciences Committee on Earth Gravity from Space, 1996-1997.
American Geophysical Union Edward A. Flinn Award Committee, 1996-Present.
Chair, NASA/Mars Surveyor 1998 Lander Science Payload Selection Panel, 1995.
NASA/NEAR Mission Science Data Center Review Board, 1995.
Team Leader, Laser Ranging Investigation, NASA Near Earth Asteroid Rendezvous Mission, 1994-2001.
Space Studies Board Review Committee, NASA Space Science R&A Program, 1994.
Deputy Principal Investigator, Mars Orbiter Laser Altimeter, Mars Global Surveyor Mission, 1994-Present.
National Academy of Sciences Comm. on Planetary and Lunar Exploration, 1994-1996.
Chair, Mars Observer Geodesy and Geophysics Working Group, 1993.
NASA Planetary Geology and Geophysics Program Review Panel, 1993-1995.
Ballistic Missile Defense Organization/NASA Clementine Mission Gravity and Altimetry Team, 1993-1995.
NASA Mars Science Working Group, 1993-1996.
NASA Planetary Geology and Geophysics Management & Operation Working Group, 1993-1995.
American Geophysical Union Bucher Medal Selection Committee, 1992-1995.
Co-investigator, Mars Observer Laser Altimeter, 1990-1993.

Selected Refereed Publications (out of more than 90 in peer-reviewed journals)
Wieczorek, M.A., and M.T. Zuber, The composition of the lunar crust as inferred from central peaks and geophysical crustal thickness modeling, submitted to *Geophys. Res. Lett.*, 2001.
McGovern, P.J., S.C. Solomon, D.E. Smith, M.T. Zuber, M. Simons, M.A. Wieczorek, R.J. Phillips, G.A. Neumann, O. Aharonson, and J.W. Head, Localized gravity/shape

admittance and correlation spectra on Mars: Implications for regional and global evolution, submitted to *J. Geophys. Res.*, 2001.

Montesi, L.G.J., and M.T. Zuber, Quantitative description of localization for application to large-scale tectonics, submitted to *J. Geophys. Res.*, 2001.

Zuber, M.T., The crust and mantle of Mars, *Nature,* in press, 2001.

Solomon, S.C., R.L. McNutt, R.E. Gold, M.H. Acuna, D.N. Baker, W.V. Boynton, C.R. Chapman, A.F. Cheng, G. Gloeckler, J.W. Head III, S.M. Krimigis, W.E. McClintock, S.L. Murchie, S.J. Peale, R.J. Phillips, M.S. Robinson, J.A. Slavin, D.E. Smith, R.G. Strom, J.I. Trombka, and M.T. Zuber, The MESSENGER mission to Mercury: Scientific objectives and implementation, *Planet. Space Sci.,* in press, 2001.

Lemoine, F.G., D.E. Smith, D.D. Rowlands, M.T. Zuber, G.A. Neumann, D.S. Chinn, and D.E. Pavlis, An improved solution of the gravity field of Mars (GMM-2B) from Mars Global Surveyor, *J. Geophys. Res.*, in press, 2001.

Wieczorek, M.A., and M.T. Zuber, A Serenitatis origin for the Imbrium grooves and South Pole-Aitken thorium anomaly, *J. Geophys. Res.,* in press, 2001.

Neumann, G.A., D.D. Rowlands, F.G. Lemoine, D.E. Smith and M.T. Zuber, The crossover analysis of MOLA altimetric data, *J. Geophys. Res.,* in press, 2001.

Smith, D.E., Zuber, M.T., and 21 others, Mars Orbiter Laser Altimeter (MOLA): Experiment summary after the first year of global mapping of Mars, *J. Geophys. Res.,* in press, 2001.

Wieczorek, M.A., M.T. Zuber and R.J. Phillips, The control of magma buoyancy on the eruption of lunar basalts, *Earth Planet. Sci. Lett., 185,* 71-83, 2001.

McGovern, P.J., S.C. Solomon, J.W. Head, D.E. Smith, M.T. Zuber, Extension and uplift at Alba Patera, Mars: MOLA observations and loading models, *J. Geophys. Res.*, in press, 2001.

Phillips, R.J., M.T. Zuber, S.C. Solomon, M.P. Golombek, B.M. Jakosky, W.B. Banerdt, R.M.E. Williams, B.M. Hynek, O. Aharonson, S.A. Hauck, II, Ancient geodynamics and global-scale hydrology on Mars, *Science, 291,* 2587-2591, 2001.

Cheng, A.F., O. Barnouin-Jha, M.T. Zuber, G. Neumann, J. Veverka, D.E. Smith G.A. Neumann, M. Robinson, P. Thomas, J.B. Garvin, C. Chapman, and L. Prockter, Laser altimetry of small-scale features on 433 Eros from NEAR Shoemaker, *Science, 292,* 488-491, 2001.

Tracadas, P.W., M.T. Zuber, D.E. Smith, and F.G. Lemoine, Density structure of the upper thermosphere of Mars from measurements of air drag on the Mars Global Surveyor spacecraft, submitted to *J. Geophys. Res.,* 2000.

Zuber, M.T., D.E. Smith, A.F. Cheng, J.B. Garvin, O. Aharonson, T.D. Cole, P.J. Dunn, Y. Guo, F.G. Lemoine, G.A. Neumann, D.D. Rowlands, and M.H. Torrence, The Shape of 433 Eros from the NEAR Laser Rangefinder, *Science, 289,* 2097-2101, 2000.

Hood, L., and M.T. Zuber, Recent refinements in geophysical constraints on lunar origin and evolution,*Origin of the Earth and Moon,* ed. R. Canup and K. Righter, Univ. of Ariz. Press, Tucson, 397-409, 2000.

Zhong, S. and M.T. Zuber, Crustal compensation during mountain building, *Geophys. Res. Lett., 27,* 3009-1012, 2000.

Simons, F.J., M.T. Zuber, and J. Korenaga, Isostatic response of the Australian lithosphere: Estimation of effective elastic thickness and anisotropy using multitaper spectral analysis, *J. Geophys. Res., 105,* 19,163-19,184, 2000.

Zhong, S., M.T. Zuber, L. Moresi, and M. Gurnis, The role of temperature-dependent viscosity and surface plates in spherical shell models of mantle convection, *J. Geophys. Res., 105,* 11,063-11,082, 2000.

Zhong, S., M.T. Zuber, and E.M. Parmentier, A dynamic origin for the global asymmetry of mare basalts, *Earth Planet. Sci. Lett., 177,* 131-140, 2000.

Zuber, M.T., and 13 others, Internal structure and early thermal evolution of Mars from Mars Global Surveyor topography and gravity, *Science, 287,* 1788-1793, 2000.

Zhong, S., and M.T. Zuber, Long wavelength topographic relaxation for self-gravitating planets with multilayer viscoelastic rheology, *J. Geophys. Res., 105,* 4153-4164, 2000

BUDGET SUMMARY for year 3

For period from 4/1/2004 to 03/31/2005

- Provide a complete Budget Summary for year one and separate estimated for each subsequent year.
- Enter the proposed estimated costs in Column A (Columns B & C for NASA use only).
- Provide as attachments detailed computations of all estimates in each cost category with narratives as required to fully explain each proposed cost. See *Instructions For Budget Summary* on following page for details.

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