Progress Report

Period 8/1/2003 to 7/31/2004

Internal Dynamics and Crustal Evolution of Mars

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PROPOSAL SUMMARY

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PROPOSAL TITLE: Internal Dynamics and Crustal Evolution of Mars

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.)

The objective of this work is to improve understanding of the internal structure, crustal evolution, and thermal history of Mars by combining geophysical data analysis of topography, gravity and magnetics with results from analytical and computational modeling.

Accomplishments thus far in this investigation include: (1) development of a new crustal thickness model that incorporates constraints from Mars meteorites, corrections for polar cap masses and other surface loads, Pratt isostasy, and core flattening; (2) determination of a refined estimate of crustal thickness of Mars from geoid/topography ratios (GTRs); (3) derivation of a preliminary estimate of the k_2 gravitational Love number and a preliminary estimate of possible dissipation within Mars consistent with this value; and (4) an integrative analysis of the sequence of evolution of early Mars.

During the remainder of this investigation we will: (1) extend models of degree-1 mantle convection from 2-D to 3-D; (2) investigate potential causal relationships and effects of major impacts on mantle plume formation, with primary application to Mars; (3) develop exploratory models to assess the convective stability of various Martian core states as relevant to the history of dynamo action; and (4) develop models of long-wavelength relaxation of crustal thickness anomalies to potentially explain the degree-1 structure of the Martian crust.

Papers of relevance to the investigation:

Zhong, S., and M.T. Zuber, Degree-1 mantle convection and the crustal dichotomy on Mars, *Earth Planet. Sci. Lett., 189,* 75-84, 2001.

Zuber, M.T., The crust and mantle of Mars, *Nature, 412,* 237-244, 2001.

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.

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

LIST OF PEER-REVIEWED PUBLICATIONS SUPPORTED ALL OR IN PART BY MDAP GRANT NAG5-13588 DURING FY04

Bills, B.G., G.A. Neumann, D.E. Smith and M.T. Zuber, Improved estimate of tidal dissipation within Mars from MOLA observations of the shadow of Phobos, submitted to *J. Geophys. Res.,* 2005.

Solomon, S.C., O. Aharonson, J.M. Aurnou, W.B. Banerdt, M.H. Carr, A.J. Dombard, H.V. Frey, M.P. Golombek, S.A. Hauck II, J.W. Head III, B.M. Jakosky, C.L. Johnson, P.J. McGovern, G.A. Neumann, R.J. Phillips, D.E. Smith, and M.T. Zuber, New perspectives on ancient Mars, *Science, 307,* 1214-1220, 2005.

Neumann, G.A., M.T. Zuber, M.A. Wieczorek,, P.J. McGovern, F.G. Lemoine, and D.E. Smith, The crustal structure of Mars from gravity and topography, *J. Geophys. Res., 109,* doi: 10.1029/2004JE002262, 2004.

Wieczorek, M.A., and M.T. Zuber, The thickness of the Martian crust: Improved constraints from geoid-topography ratios, *J. Geophys, Res., 109,* doi:10.1029/2003JE002153, 2004.

I. INTRODUCTION

This report summarizes progress made during FY04 in our approved research effort in Mars Data Analysis investigation: Internal Structure and Thermal Evolution of Mars. In the past year our research group has addressed several of the proposed questions. We have analyzed crustal structure, performed recovery of the tidal Love Number k_2 and analyzed this result in terms of Mars' dissipation, and performed preliminary thin shell dynamo modeling to gain insight into Mars thermal evolution.

During the past year we published or submitted, published, or contributed to four manuscripts under the auspices this grant. Below we briefly list results, and mention activities for the coming year

II. FY03-04 PROGRESS

Mars Crustal Structure: Neumann et al., *JGR,* 2004.

Using topography from the Mars Orbiter Laser Altimeter and gravity models resulting from five years of X-band tracking of the MGS spacecraft, we developed a new crustal thickness model of Mars. This model is intended to supercede the original model we produced from MGS data on a rapid basis to provide the community with a simple but viable model with which to work. We intended all along that a more carefully-produced model with more corrections and higher-resolution data sets would ultimately be constructed.

To develop the new model, we used the archived MGS gravity and topography data sets [*Lemoine et al.,* 2001; *Smith et al.,* 2001] and computed a Bouguer potential anomaly by applying finite-amplitude terrain corrections assuming a uniform crustal density. We then applied additional corrections for the anomalous density of the polar caps and the hydrostatic flattening of the core, and interpreted the resulting anomaly via nonlinear inversion for a Moho relief that satisfies topographic and gravitational potential constraints. Based on petrological and geophysical constraints, we invoked a mantle density contrast of 600 kg m^{-3}; with this assumption, the Isidis and Hellas gravity anomalies constrain the global mean crustal thickness to be > 45 km.

We showed that for Mars, as for the Moon, giant impacts remove most of the crust beneath the basin cavities, replacing it by uplifted mantle, so it is expected that our minimum constraint is close to the actual thickness. Adopting a value of 45 km, the model thickness of the crust varies from approximately 5-100 km, with the thinnest crust at the center of the Isidis basin.

We confirmed the result of our previous models [*Zuber et al.,* 2000; *Zuber,* 2001] that the crust is, to first order, characterized by a degree-1 zonal structure that is several times larger than any higher degree harmonic component. Also like previous models the new model contains considerable complexity at shorter wavelengths.

The degree-1 harmonic component of the crustal thickness model represents the geophysical manifestation of Mars' hemispheric dichotomy, and corresponds to a distinction between modal crustal thicknesses of 32 km and 58 km in the northern and southern hemispheres, respectively.

We also quantified that the Tharsis rise and Hellas annulus represent the strongest components in the degree 2 crustal thickness structure. The presence of a well-defined crustal thickness peak suggests a single mechanism for highland crustal formation, with modification by the Hellas impact, followed by additional construction of Tharsis. The largest surviving lowland impact, Utopia, appears to have postdated the formation of the crustal dichotomy. Its variations of crustal thickness are preserved, making it unlikely that the northern crust was originally thick, and subsequently thinned by internal processes following the Utopia impact.

Mars Geoid/Topography Ratios: Wieczoerk and Zuber, *JGR,* 2004.

Because we do not have a seismic "anchor" for the crustal thickness of Mars we desire to do as much as we can to constrain the average thickness of Mars' crust through available information. This desire led us to use geoid/topography ratios (GTRs) to study Mars' crustal structure. We investigated the average crustal thickness of the southern highlands by calculating GTRs and interpreting them in terms of an Airy compensation model appropriate for a spherical planet. Our analysis showed that: (1) if GTRs were interpreted in terms of a Cartesian model, that the recovered crustal thickness would be underestimated by a few tens of kilometers, and (2) the global geoid and topography signals associated with the loading and flexure of the Tharsis province must be removed before undertaking such a spatial analysis.

Assuming a conservative range of crustal densities (2700–3100 kg m^{-3}), we constrained the average thickness of the Martian crust to lie between 33 and 81 km (or 57±24 km). When combined with complementary estimates based upon crustal thickness modeling, gravity/topography admittance modeling, viscous relaxation considerations, and geochemical mass balance modeling, we found that a crustal thickness between 38 and 62 km (or 50±12 km) is consistent with all studies.

Isotopic investigations based upon Hf-W and Sm-Nd systematics suggest that Mars underwent a major silicate differentiation event early (within the first ~30 Ma) in its evolutio that gave rise to an "enriched" crust that has since remained isotopically isolated from the "depleted" mantle. In comparing estimates of the thickness of this primordial crust with those obtained in our study, we found that at least one-third of the Martian crust has an origin dating from the time of accretion and primary differentiation. Subsequent partial-melting of the depleted mantle would have given rise to the remaining portion of the crust. Interestingly, while we predict that a large portion of the crust should be composed of ancient "enriched" materials, a representative sample of this primordial crust does not currently exist among the known Martian meteorites.

Dissipation in Mars: Bills et al., *JGR*, 2005.

We used 10654-nm measurements of radiometry of the surface of Mars [*Sun et al.*, 2005] from the Mars Orbiter Laser Altimeter (MOLA) [Smiith et al., 2001] to improve knowledge of the orbit, and tidal acceleration, of Phobos. We then used these observations provide to estimate the rate of tidal dissipation within Mars under the assumption that all dissipation was occurring in the Martian interior.

The observations were made with the MOLA instrument on the Mars Global Surveyor spacecraft [*Zuber et al.*, 1992; *Smith et al.*, 2001]. We showed the rate of secular acceleration in along-track motion to be $(1.367\pm 0.006)^{\circ}y^{-2}$, and the corresponding fractional rate of change in orbital angular velocity to be $(6.631\pm 0.029)\times10^{-9}y^{-1}$, the highest measured of any natural satellite in the solar system. We also calculated the energy dissipation rate: (3.34±0.01) MW. Conversion of this orbital decay rate into estimates of tidal lag angle, or effective viscosity, of Mars was found to be limited by uncertainty in the elastic response of Mars to tides at harmonic degrees 2, 3 and 4.

New Perspectives on Early Mars: Solomon et al., 2005.

We engaged in an exciting group effort that was initiated with the hope of adding clarity to the sequence of evolution, both surface and internal, of early Mars. This study was ultimately published as a review in *Science* [*Solomon et al.*, 2005]. We scoped the study as we did, of course, because Mars was most active during its first billion years, and we sought to reconstruct its earliest, complex history. This study required some new analysis, particular in crustal structure and magnetics, but it drew significantly from synthesizing and critiquing existing literature.

We developed the following scenario for early Martian evolution: A magnetic dynamo in a convecting fluid core magnetized the Martian crust, and the Tharsis province became a focus for volcanism, deformation, and outgassing of water and carbon dioxide, possibly in quantities sufficient to induce episodes of climate warming. Surficial and near-surface water contributed to regionally extensive erosion, sediment transport, and chemical alteration. A more massive early atmosphere was shielded against solar wind stripping by a global magnetic field. Deep hydrothermal circulation may have accelerated crustal cooling, preserved variations in crustal thickness, and modified patterns of crustal magnetization.

In time to come we will have considerably more to say about many aspects of this fascinating topic.

III. WORK YET TO BE PERFORMED

Improving Crustal Structure-Crustal Magnetization Correlations

In the coming year, we intend to publish an error model of the crustal thickness of Mars, motivated by the considerable interest showed in a 2002 LPSC presentation on this topic [*Smith and Zuber*, 2002]. A key aspect of our crustal thickness analysis will be to quantitatively assess the "believability" of the models, particularly at short wavelengths. The resolution of current crustal models is a consequence of limitations in the gravity field [*Smith and Zuber*, 2002]. One of the goals of producing a very high-integrity crustal thickness model will be to search for magmatic intrusions that have been proposed to account for late-stage magnetization of the Martian crust [*Schubert et al.*, 2000]. While we do not expect a thermal anomaly, material intruded into the crust at a different time would plausibly be compositionally distinctive.

Fig. 1 summarizes one of numerous approaches that we will employ to evaluate the crustal thickness model. The figure plots the spectrum of crustal thickness [*Zuber*, 2001] along with a "Kaula-like" power law [*Kaula*, 1966] that describes the likely decrease of crustal thickness power with increasing spherical harmonic degree. At degrees above 40 the power inexplicably begins to increase in a manner that is almost certainly due to high frequency noise in the gravity field. Also plotted on the chart are the values of all individual crustal thickness coefficients as well as those for the zonal coefficients alone.

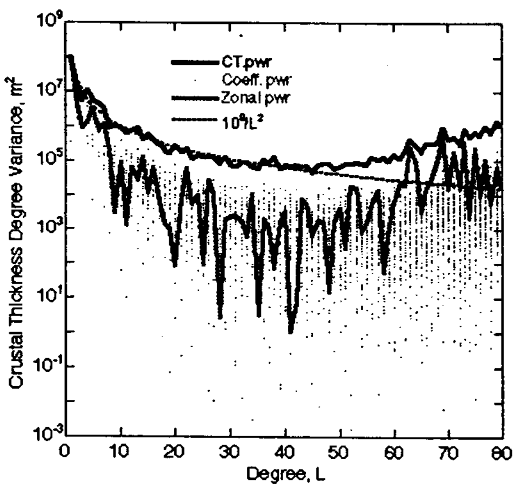

Fig. 1. Power spectrum of Mars crustal thickness (heavy black line) compared to expected power (dotted line). Excess power above degree 40 is spurious. Dots show power in individual crustal thickness coefficients and grey line shows zonals, illustrating that the excessive power is due to zonal gravity coefficients that are poorly determined at high degree and order due to the MGS orbit configuration. From [*Smith and Zuber*, 2002].

Fig. 1 shows clearly that the excess power at high degrees in the crustal thickness model lies in the recovery of the zonal gravity coefficients. This power is at the approximate spatial scale of magnetic anomalies, so conceivably could be misinterpreted as representing evidence for intrusions. (We have used lower resolution crustal thickness models in our crust/magnetics correlations [*Hutchison and Zuber*, 2002] so our interpretation is not influenced by this problem.) The spurious power is due to the near-polar orbit of MGS that makes it difficult to decorrelate certain coefficients.

Adding tracking data from the Odyssey, Mars Express, and Mars Reconaissance Orbiter spacecraft will mitigate this problem at least somewhat, but the bottom line is that we are able to assess the wavelength cutoff where we can interpret gravity anomalies or crustal thickness in terms of the magnitudes of recovered terms. (Note that the topography is essentially "perfect" at wavelengths of interest [*Smith et al.*, 2001].) In addition to spectral analysis we will also analyze the formal errors from the crustal thickness covariance, as well as "omission errors" in the coefficent recovery. The goal is to provide to the Mars community a clear indication of the interpretability of models for Mars' shallow interior structure. This work will be done in collaboration with Dave Smith of NASA/GSFC and Greg Neumann of MIT/GSFC.

Impacts and Mantle Convection

We seek to address the question of whether large impacts on Mars can perturb the lower mantle sufficiently to form plumes. To address the problem we will develop thermal convection models of a "Mars-like" interior in which we introduce one or more thermal perturbations representing large impacts, and we will explore the effect on the mantle circulation pattern. We will begin with simple conditions of a free-slip surface and core-mantle boundary (CMB), as well as a constant temperature at the surface and a constant heat flux at the CMB. We will impose an initial thermal perturbation corresponding to a major impact or impacts based on scaling relationships derived from numerical models of the cratering process [*Melosh*, 1989].

Our numerical experiments will combine 2-D and 3-D models. As part of an initial broad inquiry we will utilize the code NEWSCAM [*Elkins Tanton et al.*, 2002], which is a 2-D spherical axisymmetric version of the finite element code ConMan [*King et al.*, 1990] that has been modified to treat non-Newtonian viscosity effects. While to first order mantle flow occurs by diffusion creep, which is a Newtonian effect, large-scale melting is more appropriately treated with a non-Newtonian formulation. NEWSCAM has most recently been utilized in a study to assess the feasibility of impact-related heating on the Moon as a source of volcanism, due to induced convection and associated adiabatic melting [*Elkins Tanton et al.*, 2002].

For 3-D runs we will utilize the code CITCOM3 [*Zhong et al.*, 2000], which solves thermal convection with variable viscosity in a 3-D spherical geometry, developed by the PI's former post doc Shijie Zhong. The program utilizes the two-level Uzawa algorithm for the momentum and continuity equations, with a multi-grid solver for the inner level of velocity iterations and a SUPG method for the energy equation [*Moresi and Gurnis*, 1996]. CITCOM3 also has a full multi-grid solver combined with a consistent projection scheme that significantly improves the convergence for both variable and constant viscosity models. CITCOM3 will enable us to include a realistic temperature- and pressure-dependent viscosity and a lithosphere with dynamically evolving thickness. Temperature-dependent viscosity will also have important influences on heat transfer within the mantle [*Christensen*, 1984; *Ratcliff et al.*, 1996]. We will also need to examine the possible role of a deep phase transition in affecting the number of upwellings that can develop [*Breuer et al.*, 1998; *Weinstein*, 1995].

There are many variables in the problem and we do not think it will be possible to prove unequivocally a genetic linkage between Hellas and/or Utopia and Tharsis. Instead our goal is to identify a potential suite of plausible models (if they exist) that would demonstrate the feasibility of the hypothesis that a major plume or plumes can be generated at the antipode of a major impact or impacts. The plan is to perform 2-D axisymmetric runs for the case of a single impact, and then make 3-D runs that treat both a single impact and dual impacts. If the results turn out favorable we will need to consider why other impacts (Argyre, Isidis) did not produce antipodal volcanic provinces.

This study will include the involvement of Brad Hager of MIT, who oversaw the development of NEWSCAM. The modeling will be done by Wes Watters, an MIT graduate student in geophysics.

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Zuber, M.T., S.C. Solomon, R.J. Phillips, D.E. Smith, G.L. Tyler, O. Aharonson, G. Balmino, W.B. Banerdt, J.W. Head, F.G. Lemoine, P.J. McGovern, G.A. Neumann, D.D. Rowlands, and S. Zhong, Internal structure and early thermal evolution of Mars from Mars Global Surveyor topography and gravity, *Science*, *287*, 1788-1793, 2000

DATA REQUIREMENTS

We require gravity and topography from the Mars Global Surveyor mission. We are associated with both mission teams and so have this data, which in any case is freely available from the Geophysics Node of the NASA Planetary Data System at Washington University in St. Louis.

FACILITIES & EQUIPMENT

The MIT EAPS Geophysics group shares a computer laboratory that includes of order two dozen linux machines and G4/G5 macs, as well as scanners and various black-and-white and color printers.

In addition, the EAPS Program in Geophysics is a key participant in MIT's Alliance for Computational Earth Science (ACES), a collaboration between members of 5 MIT Departments and Laboratories. The ACES collaboration is developing advanced computational technologies to address the most challenging Earth/Planetary science problems, and applications run from planetary internal dynamics to global climate models The ACES cluster will be used in the dynamo and mantle convection modeling.

ACES consists of a distributed grid of four parallel compute systems for research in Computational Earth science, linked using a high-speed (10Gb/sec) network that allows parallel computations to span the entire system. The grid also includes 64-bit nodes with 128 GB core memory. The 155 compute nodes are at four cluster locations and utilize PowerEdge 1750 Servers with a 533MHz Front side bus. The nodes contain dual 2.4GHz Xeon processors with 512KB L2 cache. The ACES Geophysics node, which is now being installed, includes 66 compute nodes each containing 4Gb of DDR RAM.

The ACES hardware and networking was made possible by a generous arrangement with Dell Computers.

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.
List of 50 Most Important Women in Science, *Discover Magazine,* November, 2002.
Scientific Achievement Award, American Institute of Aeronautics and Astronautics, New England Section, 2002.
NASA Group Achievement Award for the Near Earth Asteroid Rendezvous Shoemaker 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
Co-chair, NASA Science Instruments and Sensor Capability Roadmap Team, 2004-Present.
President's Commission on Implementation of United States Space Exploration Policy, 2004.
Cassini Orbit Insertion Review Board, 2004.
Mars Exploration Rover Independent Status Review Board, 2003-2004.
Visiting Committee, Radcliffe Institute for Advanced Study, Harvard University, 2003-Present.
Review Board, NASA Mars Exploration Rover, Landing Site Selection Review, 2003.
NASA Jupiter Icy Moons Orbiter Science Definition Team, 2003-2004.
Review Board, Mars Gravity Biosatellite Mission Concept Preliminary Design Review, 2003.
Chair, Planetary Sciences Section Nominating Committee, American Geophysical Union, 2003.
Chair, AGU Honors and Recognition Committee, 2002-2004.
Visiting Committee and Advisory Council, Jet Propulsion Laboratory, 2000-Present.
Co-Investigator, NASA Dawn Mission to Vesta and Ceres, 2001-Present.
Prize Committee, Division of Planetary Sciences of the American Astronomical Society, 2001-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.
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Chair, Mars Observer Geodesy and Geophysics Working Group, 1993.
NASA Planetary Geology and Geophysics Program Review Panel, 1993-1995.
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