IAC-09-A3.6.2

THE MESSENGER MISSION: RESULTS FROM THE FIRST TWO MERCURY FLYBYS

Ralph L. McNutt, Jr.[1], Sean C. Solomon[2], Peter D. Bedini[3], Eric J. Finnegan[4], David G. Grant[5], and the MESSENGER Team

[1]*The Johns Hopkins University Applied Physics Laboratory, 11100 Johns Hopkins Road, M/S MP3-E128, Laurel, MD 20723 U.S.A. ralph.mcnutt@jhuapl.edu 443-778-5435, Fax: 443-778-0386*

[2]*Department of Terrestrial Magnetism, Carnegie Institution of Washington, 5241 Broad Branch Road, N.W., Washington, DC 20015 U.S.A. scs@dtm.ciw.edu 202-478-8850, Fax: 202-478-8821*

[3]*The Johns Hopkins University Applied Physics Laboratory, 11100 Johns Hopkins Road, M/S 23-282, Laurel, MD 20723 U.S.A. peter.bedini@jhuapl.edu 443-778-4642, Fax: 443-778-5295*

[4]*The Johns Hopkins University Applied Physics Laboratory, 11100 Johns Hopkins Road, M/S 23-282, Laurel, MD 20723 U.S.A. eric.finnegan@jhuapl.edu 443-778-1712, Fax: 443-778-6635*

[5]*The Johns Hopkins University Applied Physics Laboratory, 11100 Johns Hopkins Road, M/S 4-283, Laurel, MD 20723 U.S.A. david.grant@jhuapl.edu 443-778-5297, Fax: 443-778-5295*

ABSTRACT

NASA's MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) spacecraft is well into its voyage to initiate a new era in our understanding of the innermost planet. During 2008 MESSENGER flew by Mercury twice and completed the initial spacecraft reconnaissance of the planet begun 34 years earlier by Mariner 10. MESSENGER observations have illuminated how the 1500-km-diameter Caloris basin was a focus for magmatic and deformational activity. High-resolution images show evidence for volcanic vents, pyroclastic deposits, and volcanic flooding of its interior. Lobate scarps, discovered by Mariner 10, are the dominant tectonic landform across the planet and collectively record greater contraction of the surface than inferred from Mariner 10 images. On portions of the surface not seen by Mariner 10 are young craters with prominent ray systems that span most of a hemisphere. Variations in visible and infrared spectral reflectance correlate with geologic units. The lack of an infrared absorption band near 1 μm indicates a low ferrous oxide content in surface silicates, but absorption of thermal neutrons by surface material suggests the presence of surface iron in concentrations similar to low- to intermediate-Fe lunar soils. The most unanticipated result to date is the dynamic and complex nature of Mercury's exosphere-magnetosphere system. While Magnetometer measurements point to a dynamo origin for Mercury's main magnetic field, that field is significantly modified by the planet's small, dynamic magnetosphere. Emission-line measurements have revealed the distribution of neutral sodium, calcium, and magnesium in the exosphere and tail; plasma spectrometer observations indicate that these and other species become ionized to populate the planet's magnetosphere. MESSENGER's third Mercury flyby on 29 September 2009, the last prior to orbit insertion in 2011, largely duplicated the geometry of the second but added significant new observations of the planet's surface and a new perspective on the in situ environment as solar activity continues to change. A Participating Scientist Program has brought the Science Team to its current strength of 48 scientists and their associates. The spacecraft continues to perform as designed in its challenging thermal environment. Use of solar radiation pressure for maintaining momentum balance and supplementing maneuver capability is helping to maintain significant propellant reserves that could enable an extended mission. The MESSENGER team is continuing its informal interaction with members of the BepiColombo project to maximize the overall scientific return from both missions.

INTRODUCTION

The MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) mission to Mercury is now in its fifth year of flight as the first robotic spacecraft to launch to Mercury since the Mariner 10 mission of over 30 years ago. An overview of the mission in [*Solomon et al.*, 2007] and accompanying papers provide details on our scientific knowledge of Mercury based upon observations from the ground and Mariner 10 [*Boynton et al.*, 2007; *Domingue et al.*, 2007; *Head et al.*, 2007; *Slavin et al.*, 2007; *Zuber et al.*, 2007], the spacecraft [*Leary et al.*, 2007], mission design and navigation [*McAdams et al.*, 2007], the scientific instruments comprising the payload [*Anderson et al.*, 2007; *Andrews et al.*, 2007; *Cavanaugh et al.*, 2007; *Goldsten et al.*, 2007; *Hawkins et al.*, 2007; *McClintock and Lankton*, 2007; *Schlemm et al.*, 2007; *Srinivasan et al.*, 2007], early operations [*Holdridge and Calloway*, 2007], and the Science Operations Center [*Winters et al.*, 2007]. Background on mission formulation and a brief history through the second of two Venus flybys has also been detailed [*McNutt et al.*, 2008].

MESSENGER TRAJECTORY

The six planned "reversed gravity assists" of the MESSENGER mission are key to the eventual injection into orbit about the planet Mercury [*McAdams et al.*, 2007]. The flybys of Earth and Venus (twice) changed the heliocentric speed of the spacecraft by 6.0, 5.5, and 6.9 km/s, respectively, bringing the spacecraft's orbital plane into alignment with that of Mercury, while also lowering MESSENGER's orbital apoapsis.

Three Mercury flybys thereafter were required to decrease the apoapsis further, finally bringing the spacecraft into an orbit sufficiently close to that of the planet that the onboard propulsion system can manage to break the spacecraft motion into a captured orbit about the planet.

Following the second Venus flyby on 5 June 2007, Universal Time, Coordinated (UTC), two almost flawless flybys of Mercury, the first since the third and final flyby of the planet by Mariner 10 in 1975, occurred in 2008. On 14 January 2008, at 19:04:39.4 UTC, the MESSENGER spacecraft executed its first Mercury flyby, passing over the uncharted portions of the planet surface at an altitude of 201.4 km, an even more accurate aim than for the second Venus flyby. This activity shrank the orbital period of the spacecraft around the Sun by 11 days, bringing MESSENGER's orbit closer to that of Mercury.

On 6 October 2008, at 08:40:22.2 UTC, the MESSENGER spacecraft executed its second Mercury flyby, passing the surface at an altitude of 199.24 km. The first flyby provided a change in spacecraft speed of 2.3 km/s and the second a change of almost 2.5 km/s.

The flybys have been interspersed with deep-space maneuvers (DSMs) that make use of the large-velocity adjust (LVA) thruster using bipropellant mode to increase propellant savings [*Leary, et al.*, 2007]. The second DSM was carried out on 17 October 2007, changing the spacecraft speed by 226 m/s to enable the first Mercury flyby. The third DSM was executed on 19 March 2008 and changed the speed by 72 m/s to enable the second flyby. The fourth and fifth DSMs were designed to fine-tune the trajectory for the third flyby and Mercury orbit insertion (MOI), respectively.

The third flyby was successfully executed on 29 September 2009 at 21:54:55.8 UTC at an altitude of 228 km, about 300 m below the target altitude and less than 2 km from the targeted aim point. This flyby and the subsequent (and final) large deep-space maneuver will provide the final trajectory for MOI in March 2011. That trajectory will be subject to final correction maneuvers made via a combination of the onboard propulsion system and solar-radiation pressure on the spacecraft ("solar sailing"). The latter technique has been used to eliminate all scheduled trajectory-correction maneuvers (TCMs) since late 2007.

Now over five years past launch, and with several perihelion passes as close to the Sun as the spacecraft will ever reach (a record for a three-axis-stabilized spacecraft), the probe remains healthy with only minor anomalies encountered to date. Even prior to the initial Mercury flyby, plans began for orbital operation, and those activities continue to intensify.

THE MERCURY FLYBYS

Mariner 10 mapped only some 45% of Mercury's surface during its three flybys of the

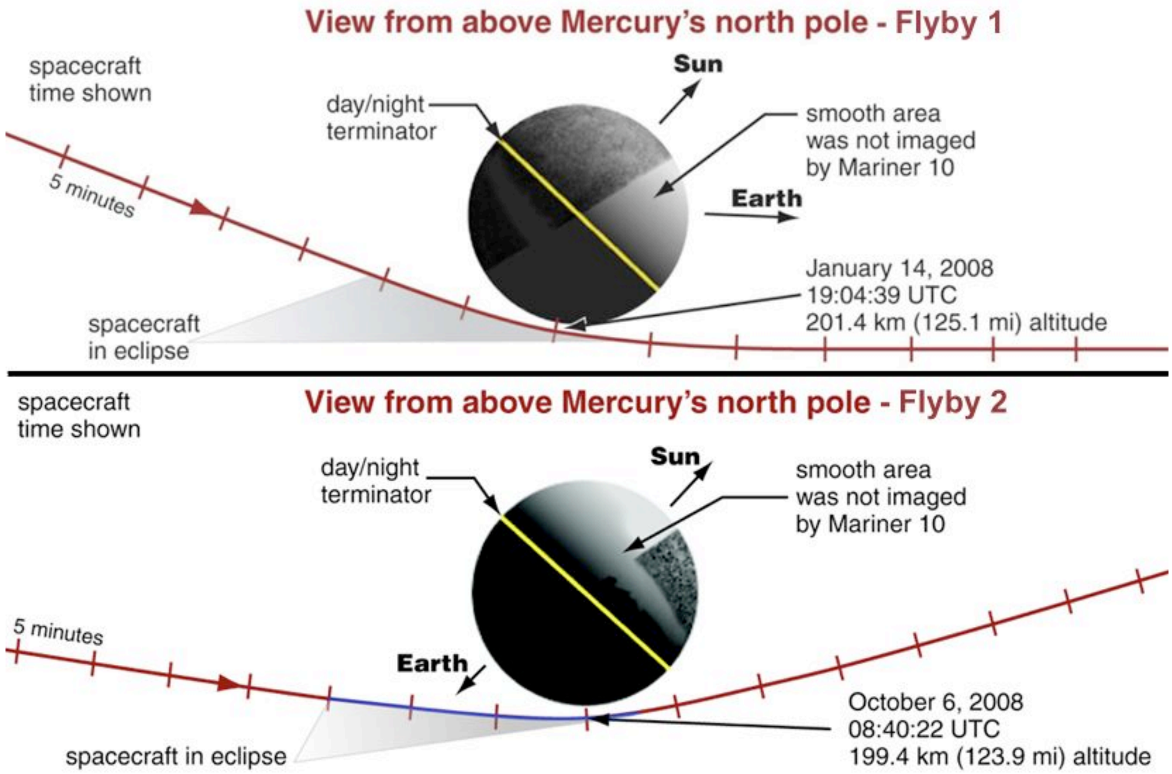

Fig. I. Geometries for the first and second flybys of Mercury by the MESSENGER spacecraft. Orbital constraints dictate that the flybys occur near Mercury perihelion.

planet, a consequence of the periodicity of its encounters with Mercury near the planet's aphelion. MESSENGER's use of Mercury to slow the relative spacecraft speed leads to the optimized timing of encounters near Mercury perihelion. In addition, the trajectory resonance requirement, coupled with Mercury's 3:2 spin-orbit resonance, meant that while the first flyby would see much of the same territory as did Mariner 10, the second MESSENGER flyby would see predominantly the opposite hemisphere (Fig. I). Hence, the use of the payload during the flybys would be instrumental not only for a "dress rehearsal" for orbital operations as well as measurements not possible with the Mariner-10 payload, but also for the mapping of almost the entire surface of the planet for the first time in history.

SCIENTIFIC RESULTS

MESSENGER executed Mercury flyby 1 on 14 January 2008 and flyby 2 on 6 October 2008. Together these flybys provided crucial gravity assists necessary to allow eventual injection of MESSENGER into Mercury orbit. The close proximity to the planet, even for the limited durations of the flybys, enabled full scientific investigations using the entire MESSENGER payload during both planetary encounters.

The flybys produced many new scientific results [*Solomon et al.*., 2008]. In particular, MESSENGER imaged about 50% of the planet never seen before by a spacecraft, bringing the total to nearly 90% of the planet seen at better than 2-km resolution, including the Mariner 10 observations (Fig. II). Neutral-atom "tails" of both sodium and calcium were mapped and a similar tail structure of exospheric magnesium was discovered. Simultaneous imaging and laser ranging to the territory viewed were possible for the first time on Mercury. The internal magnetic field of Mercury was observed under very different solar-wind conditions with different polarities of the interplanetary magnetic field (IMF). Significant magnetic reconnection was detected during the second flyby, but no energetic particles were seen above ~30 keV during either flyby.

Flyby 1 returned nearly 470 MB of data including 1213 images, and flyby 2 returned

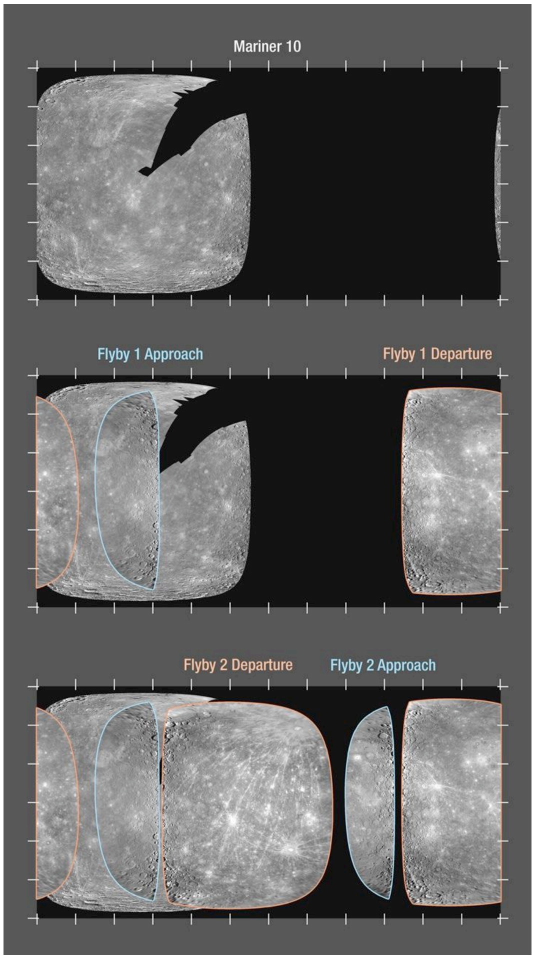

Fig. II. Spacecraft imaging coverage of Mercury, showing Mariner 10 coverage at top and coverage added by the first (center) and second (bottom) MESSENGER flybys.

650 MB of data including 1287 images. MESSENGER's was the closest spacecraft approach to the planet, and the observations included many "firsts" at Mercury, including the first spacecraft observations of the neutral tail [*McClintock et al.*, 2008a], the first plasma-ion measurements [*Zurbuchen et al.*, 2008], the first laser altimetry [*Zuber et al.*, 2008], the first 11-color imaging, the first high-resolution surface spectroscopy by spacecraft, and the first ultraviolet (UV) spectroscopy of the surface [*McClintock et al.*, 2008b].

Color imaging shows only subtle variations due mainly to changes in the slope of the reflectance continuum from visible to near-infrared wavelengths. The average reflectance of ~0.1 is intermediate between those of the lunar mare and lunar highlands [*Robinson, et al.*, 2008]. Principal-component analysis of color images

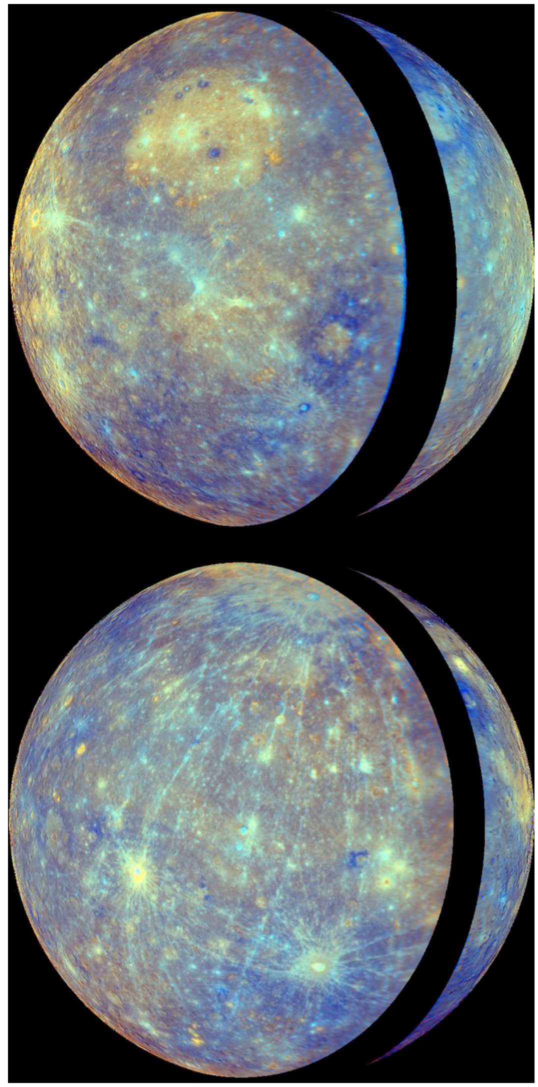

Fig. III. Enhanced-color images of Mercury imaged by MESSENGER during the two flybys of 2008.

reveals a variety of terrain types with high-reflectance plains (red) and low-reflectance material (blue) as spectral end members [*Denevi et al.*, 2009] (Fig. III). Imaging of regions seen at different lighting conditions than by Mariner 10 also revealed features not previously recognized as well as additional details of those seen earlier.

MESSENGER imaging confirmed the presence of widespread volcanism in Mercury's past [*Head et al.*, 2008] as well as the extensive presence of lobate scarps from global contraction as the planet cooled early in its history [*Solomon et al.*, 2008]. Caloris and Rembrandt basins display a variety of tectonic features [*Murchie et al.*, 2008; *Watters et al.*, 2009] as does the newly discovered Raditladi basin, a 260-km, double-

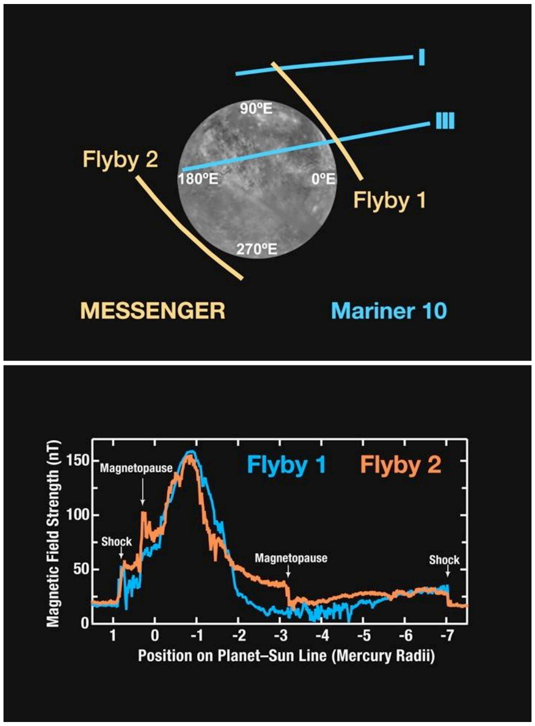

Fig. IV. (Top) Trajectories of Mariner 10 flybys I and III and MESSENGER flybys 1 and 2 projected onto Mercury's equatorial plane. The trajectory segments show the regions of measurements from which internal magnetic field models have been derived. (Bottom) Measured magnetic field strength as a function of distance from the Mercury-Sun line for MESSENGER flybys 1 and 2.

ring impact features with impact melt or volcanic deposits occupying its interior smooth plains.

The flybys provided a first look at crater-floor roughness and global trends in the equatorial surface shape of Mercury [*Zuber et al.*., 2008] as well as an initial cut at more accurate values for the lowest-order gravitational moments.

MESSENGER provided significant new constraints on the global properties of Mercury's internal magnetic field [*Anderson et al.*, 2008], although the observations also showed that magnetospheric currents provide a more substantial, and time-varying, contribution to the internal magnetic field than had previously been thought. Differing IMF conditions during the two flybys resulted in markedly different levels of magnetospheric activity during the two flybys [*Slavin et al.*, 2008, 2009] (Fig. IV).

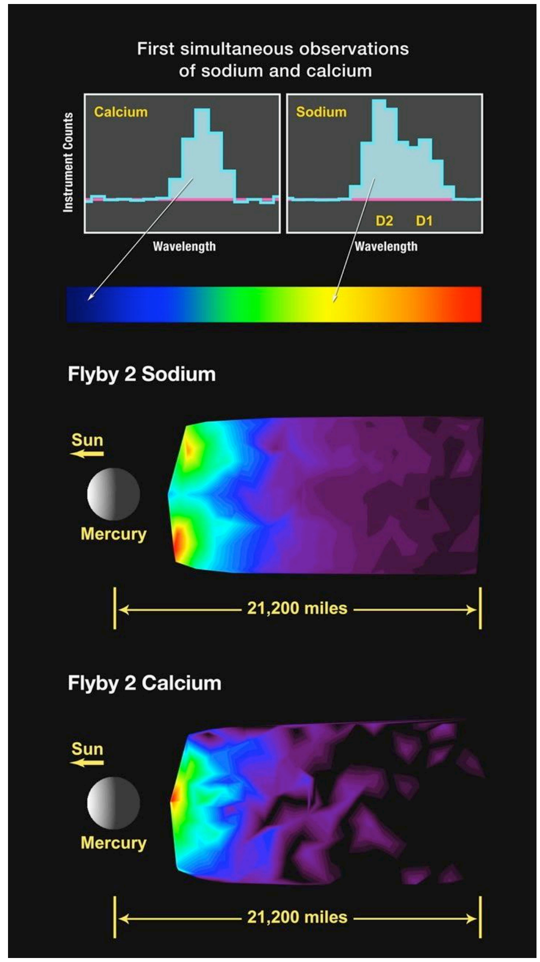

Fig. V. Simultaneous observations of sodium and calcium in Mercury's exospheric tail. (Top) Wavelengths of the spectral lines. (Center and Bottom) Emission intensities of sodium and calcium contoured on north-south planes through the planet center.

Thermal neutrons were observed near Mercury on both flybys. Their modulation with the angle of attack of the thermal neutron sensor with respect to spacecraft motion can be used to provide information on the weight abundance of neutron-absorbing materials, such as iron and titanium [*Solomon et al.*, 2008]. By modeling the spacecraft's neutron absorption in the vicinity of the Neutron Spectrometer and comparing with expected signatures of lunar analogue soils (for which assays of returned samples are available) upper limits for iron and titanium can be deduced (given the assumption that minimal amounts of the rare-Earth elements gadolinium and samarium, with their extremely high neutron-absorption cross sections, are present).

Exospheric observations, made by scanning for emission lines in the ultraviolet and visible portions of the spectrum, revealed the spatial structure of sodium and calcium emissions in the exospheric tail and led to the discovery of magnesium (visible only in the ultraviolet) [*McClintock et al.*, 2009] (Fig. V).

CRUISE OBSERVATIONS

The flybys of Mercury, along with those of Earth and Venus [*McNutt et al.*, 2008] provided invaluable experience with operating the payload instrumentation. From the time of the launch of MESSENGER (3 August 2004) through the third Mercury flyby (29 September 2009), there have been 387 events involving instrument operations, where "event" can refer to anything as simple as a power-down prior to a spacecraft maneuver to a more complex sequence of "canned" commands being used during a flyby. Phase E of the mission did not formally began until 13 September 2004, and 15 of these instrument-related events occurred during the early operations phase of the mission (these were early operations turn-on and check-out exercises for the instruments and Data Processing Units; operations also included successful power-off commands for the instruments).

A variety of activities were also associated with the several planetary flybys, required for trajectory gravity assists, and were used to check functionality, provide calibration data, and gather new scientific results. Activities have moved from calibration to acquisition of new scientific observations as the mission moved from the Earth flyby of 2005 through the second Venus flyby of 2007 and the three Mercury flybys of 2008-2009 (no data were taken at the first flyby of Venus because of the high altitude and solar conjunction constraints). During the mission cruise phase, a variety of calibration and instrument maintenance activities (for instrument health and safety) are carried out routinely. Other long-term operations of instruments for measuring the interplanetary magnetic field, energetic particles, and thermal neutrons, while useful for "cruise science," also provide important baselines on instrument operations, which feed into final calibrations and validation of operating parameters.

Flyby operations include a "core load" of spacecraft and instrument activities; however, flyby-associated activities also can, and do, occur in the preceding and following sequence loads.

A detailed accounting of all of these activities will be reported in forthcoming calibration papers for the payload instruments. Table I provides a summary of the operations by mission phase that is indicative of the extent of payload operations leading up to, encompassing, and following the three flybys of Mercury.

TABLE I: MESSENGER Instrument Activities

Mission phase	Number of activities
Early operations	15
Earth flyby	33
Venus flyby 2	26
Mercury flyby 1	17
Mercury flyby 2	25
Mercury flyby 3	29
Cruise	242
Total	387

LOOKING AHEAD

The use of solar radiation pressure to provide continuous course corrections, as well as momentum dumping, continues to be a successful strategy in the inner part of the solar system. This approach has led to minimization of propellant usage while also allowing for the cancellation of many previously scheduled trajectory-correction maneuvers.

With a full Science Team strength of 48 enabled by NASA's Participating Scientist Program for MESSENGER, the scientific output from the Mercury flybys has been maximized. Informal interactions continue with members of the BepiColombo Science Working Team at professional meetings, meetings of each individual team, and workshops on Mercury science, such as that held in Parma, Italy, in June 2009. With these interactions, MESSENGER has become a fully international mission of exploration.

MESSENGER remains on course for orbit injection at its next encounter with Mercury on 18 March 2011.

ACKNOWLEDGMENTS

The MESSENGER Team includes hundreds of scientists, engineers, designers, technicians, support personnel, subcontractors, and managers who helped MESSENGER reach all milestones achieved to date. We acknowledge as well the assistance of NASA personnel and others who gave of their time to oversee and review the program to assure mission success. Details on the mission, flybys, and Mercury orbit insertion are maintained and updated at the MESSENGER web site: http://messenger.jhuapl.edu/. The MESSENGER mission is supported by the NASA Discovery Program under contracts NAS5-97271 to the Johns Hopkins University Applied Physics Laboratory and NASW-00002 to the Carnegie Institution of Washington.

REFERENCES

Anderson, B. J., M. H. Acuña, D. A. Lohr, J. Scheifele, A. Raval, H. Korth, and J. A. Slavin (2007), The Magnetometer Instrument on MESSENGER, *Space Science Reviews*, *131*, 417-450.

Anderson, B. J., M. H. Acuña, H. Korth, M. E. Purucker, C. L. Johnson, J. A. Slavin, S. C. Solomon, and R. L. McNutt (2008), The Structure of Mercury's Magnetic Field from MESSENGER's First Flyby, *Science*, *321*, 82-85.

Andrews, G. B., T. H. Zurbuchen, B. H. Mauk, H. Malcom, L. A. Fisk, G. Gloeckler, G. C. Ho, J. S. Kelley, P. L. Koehn, T. W. Lefevere, S. S. Livi, R. A. Lundgren, and J. M. Raines (2007), The Energetic Particle and Plasma Spectrometer Instrument on the MESSENGER Spacecraft, *Space Science Reviews*, *131*, 523-556.

Boynton, W. V., A. L. Sprague, S. C. Solomon, R. D. Starr, L. G. Evans, W. C. Feldman, J. I. Trombka, and E. A. Rhodes (2007), MESSENGER and the Chemistry of Mercury's Surface, *Space Science Reviews*, *131*, 85-104.

Cavanaugh, J. F., J. C. Smith, X. Sun, A. E. Bartels, L. Ramos-Izquierdo, D. J. Krebs, J. F. McGarry, R. Trunzo, A. M. Novo-Gradac, J. L. Britt, J. Karsh, R. B. Katz, A. T. Lukemire, R. Szymkiewicz, D. L. Berry, J. P. Swinski, G. A. Neumann, M. T. Zuber, and D. E. Smith (2007), The Mercury Laser Altimeter Instrument for the MESSENGER Mission, *Space Science Reviews*, *131*, 451-479.

Denevi, B. W., M. S. Robinson, S. C. Solomon, S. L. Murchie, D. T. Blewett, D. L. Domingue, T. J. McCoy, C. M. Ernst, J. W. Head, T. R. Watters, and N. L. Chabot (2009), The Evolution of Mercury's Crust: A Global Perspective from MESSENGER, *Science*, *324*, 613-618.

Domingue, D. L., P. L. Koehn, R. M. Killen, A. L. Sprague, M. Sarantos, A. F. Cheng, E. T. Bradley, and W. E. McClintock (2007), Mercury's Atmosphere: A Surface-Bounded Exosphere, *Space Science Reviews*, *131*, 161-186.

Goldsten, J. O., E. A. Rhodes, W. V. Boynton, W. C. Feldman, D. J. Lawrence, J. I. Trombka, D. M. Smith, L. G. Evans, J. White, N. W. Madden, P. C. Berg, G. A. Murphy, R. S. Gurnee, K. Strohbehn, B. D. Williams, E. D. Schaefer, C. A. Monaco, C. P. Cork, J. D. Eckels, W. O. Miller, M. T. Burks, L. B. Hagler, S. J. Deteresa, and M. C. Witte (2007), The MESSENGER Gamma-Ray and Neutron Spectrometer, *Space Science Reviews*, *131*, 339-391.

Hawkins, S. E., III, J. D. Boldt, E. H. Darlington, R. Espiritu, R. E. Gold, B. Gotwols, M. P. Grey, C. D. Hash, J. R. Hayes, S. E. Jaskulek, C. J. Kardian, M. R. Keller, E. R. Malaret, S. L. Murchie, P. K. Murphy, K. Peacock, L. M. Prockter, R. A. Reiter, M. S. Robinson, E. D. Schaefer, R. G. Shelton, R. E. Sterner, II, H. W. Taylor, T. R. Watters, and B. D. Williams (2007), The Mercury Dual Imaging System on the MESSENGER Spacecraft, *Space Science Reviews*, *131*, 247-338.

Head, J. W., C. R. Chapman, D. L. Domingue, S. E. Hawkins, III, W. E. McClintock, S. L. Murchie, L. M. Prockter, M. S. Robinson, R. G. Strom, and T. R. Watters (2007), The Geology of Mercury: The View Prior to the MESSENGER Mission, *Space Science Reviews*, *131*, 41-84.

Head, J. W., S. L. Murchie, L. M. Prockter, M. S. Robinson, S. C. Solomon, R. G. Strom, C. R. Chapman, T. R. Watters, W. E. McClintock, D. T. Blewett, and J. J. Gillis-Davis (2008), Volcanism on Mercury: Evidence from the First MESSENGER Flyby, *Science*, *321*, 69-72.

Holdridge, M. E., and A. B. Calloway (2007), Launch and Early Operation of the MESSENGER Mission, *Space Science Reviews*, *131*, 573-600.

Leary, J. C., R. F. Conde, G. Dakermanji, C. S. Engelbrecht, C. J. Ercol, K. B. Fielhauer, D. G. Grant, T. J. Hartka, T. A. Hill, S. E. Jaskulek, M. A. Mirantes, L. E. Mosher, M. V. Paul, D. F. Persons, E. H. Rodberg, D. K. Srinivasan, R. M. Vaughan, and S. R. Wiley (2007), The MESSENGER Spacecraft, *Space Science Reviews*, *131*, 187-217.

McAdams, J. V., R. W. Farquhar, A. H. Taylor, and B. G. Williams (2007), MESSENGER mission design and navigation, *Space Science Reviews*, *131*, 219-246.

McClintock, W. E., and M. R. Lankton (2007), The Mercury Atmospheric and Surface Composition Spectrometer for the MESSENGER Mission, *Space Science Reviews*, *131*, 481-521.

McClintock, W. E., E. T. Bradley, R. J. Vervack, R. M. Killen, A. L. Sprague, N. R. Izenberg, and S. C. Solomon (2008a), Mercury's Exosphere: Observations During MESSENGER's First Mercury Flyby, *Science*, *321*, 92-94.

McClintock, W. E., N. R. Izenberg, G. M. Holsclaw, D. T. Blewett, D. L. Domingue, J. W. Head, J. Helbert, T. J. McCoy, S. L. Murchie, M. S. Robinson, S. C. Solomon, A. L. Sprague, and F. Vilas (2008b), Spectroscopic Observations of Mercury's Surface Reflectance During MESSENGER's First Mercury Flyby, *Science*, *321*, 62-65.

McClintock, W. E., R. J. Vervack, Jr., E. T. Bradley, R. M. Killen, N. Mouawad, A. L. Sprague, M. M. Burger, S. C. Solomon, and N. R. Izenberg (2009), MESSENGER Observations of Mercury's Exosphere: Detection of Magnesium and Distribution of Constituents, *Science*, *324*, 610-613.

McNutt, R. L., Jr., S. C. Solomon, D. G. Grant, E. J. Finnegan, and P. D. Bedini (2008), The MESSENGER mission to Mercury: Status after the Venus flybys, *Acta Astronautica*, *63*, 68-73.

Murchie, S. L., T. R. Watters, M. S. Robinson, J. W. Head, R. G. Strom, C. R. Chapman, S. C. Solomon, W. E. McClintock, L. M. Prockter, D. L. Domingue, and D. T. Blewett (2008), Geology of the Caloris Basin, Mercury: A View from MESSENGER, *Science*, *321*, 73-76.

Robinson, M. S., S. L. Murchie, D. T. Blewett, D. L. Domingue, S. E. I. Hawkins, J. W. Head, G. M. Holsclaw, W. E. McClintock, T. J. McCoy, R. L. McNutt, Jr., L. M. Prockter, S. C. Solomon, and T. R. Watters (2008), Reflectance and Color Variations on Mercury: Regolith Processes and Compositional Heterogeneity, *Science*, *321*, 66-69.

Schlemm, C. E., R. D. Starr, G. C. Ho, K. E. Bechtold, S. A. Hamilton, J. D. Boldt, W. V. Boynton, W. Bradley, M. E. Fraeman, R. E. Gold, J. O. Goldsten, J. R. Hayes, S. E. Jaskulek, E. Rossano, R. A. Rumpf, E. D. Schaefer, K. Strohbehn, R. G. Shelton, R. E. Thompson, J. I. Trombka, and B. D. Williams (2007), The X-Ray Spectrometer on the MESSENGER Spacecraft, *Space Science Reviews*, *131*, 393-415.

Slavin, J. A., S. M. Krimigis, M. H. Acuña, B. J. Anderson, D. N. Baker, P. L. Koehn, H. Korth, S. Livi, B. H. Mauk, S. C. Solomon, and T. H. Zurbuchen (2007), MESSENGER: Exploring Mercury's Magnetosphere, *Space Science Reviews*, *131*, 133-160.

Slavin, J. A., M. H. Acuña, B. J. Anderson, D. N. Baker, M. Benna, G. Gloeckler, R. E. Gold, G. C. Ho, R. M. Killen, H. Korth, S. M. Krimigis, R. L. McNutt, L. R. Nittler, J. M. Raines, D. Schriver, S. C. Solomon, R. D. Starr, P. Trávníček, and T. H. Zurbuchen (2008), Mercury's Magnetosphere After MESSENGER's First Flyby, *Science*, *321*, 85-89.

Slavin, J. A., M. H. Acuña, B. J. Anderson, D. N. Baker, M. Benna, S. A. Boardsen, G. Gloeckler, R. E. Gold, G. C. Ho, H. Korth, S. M. Krimigis, R. L. McNutt, J. M. Raines, M. Sarantos, D. Schriver, S. C. Solomon, P. Trávníček, and T. H. Zurbuchen (2009), MESSENGER Observations of Magnetic Reconnection in Mercury's Magnetosphere, *Science*, *324*, 606-610.

Solomon, S. C., R. L. McNutt, Jr., R. E. Gold, and D. L. Domingue (2007), MESSENGER mission overview, *Space Science Reviews*, *131*, 3-39.

Solomon, S. C., R. L. McNutt, T. R. Watters, D. J. Lawrence, W. C. Feldman, J. W. Head, S. M. Krimigis, S. L. Murchie, R. J. Phillips, J. A. Slavin, and M. T. Zuber (2008), Return to Mercury: A Global Perspective on MESSENGER's First Mercury Flyby, *Science*, *321*, 59-62.

Srinivasan, D. K., M. E. Perry, K. B. Fielhauer, D. E. Smith, and M. T. Zuber (2007), The Radio Frequency Subsystem and Radio Science on the MESSENGER Mission, *Space Science Reviews*, *131*, 557-571.

Watters, T. R., J. W. Head, S. C. Solomon, M. S. Robinson, C. R. Chapman, B. W. Denevi, C. I. Fassett, S. L. Murchie, and R. G. Strom (2009), Evolution of the Rembrandt Impact Basin on Mercury, *Science*, *324*, 618-621.

Winters, H. L., D. L. Domingue, T. H. Choo, R. Espiritu, C. Hash, E. Malaret, A. A. Mick, J. P. Skura, and J. Steele (2007), The MESSENGER Science Operations Center, *Space Science Reviews*, *131*, 601-623.

Zuber, M. T., O. Aharonson, J. M. Aurnou, A. F. Cheng, S. A. Hauck II, M. H. Heimpel, G. A. Neumann, S. J. Peale, R. J. Phillips, D. E. Smith, S. C. Solomon, and S. Stanley (2007), The Geophysics of Mercury: Current Status and Anticipated Insights from the MESSENGER Mission, *Space Science Reviews*, *131*, 105-132.

Zuber, M. T., D. E. Smith, S. C. Solomon, R. J. Phillips, S. J. Peale, J. W. Head, S. A. Hauck, R. L. McNutt, J. Oberst, G. A. Neumann, F. G. Lemoine, X. Sun, O. Barnouin-Jha, and J. K. Harmon (2008), Laser Altimeter Observations from MESSENGER's First Mercury Flyby, *Science*, *321*, 77-79.

Zurbuchen, T. H., J. M. Raines, G. Gloeckler, S. M. Krimigis, J. A. Slavin, P. L. Koehn, R. M. Killen, A. L. Sprague, R. L. McNutt, and S. C. Solomon (2008), MESSENGER Observations of the Composition of Mercury's Ionized Exosphere and Plasma Environment, *Science*, *321*, 90-92.