EPSC Abstracts
Vol. 5, EPSC2010-384, 2010
European Planetary Science Congress 2010

Mercury after MESSENGER's Three Flybys

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Introduction: NASA's MESSENGER spacecraft, launched in August 2004, will be the first probe to orbit the planet Mercury. MESSENGER's three flybys of Mercury in 2008-2009 marked the first spacecraft visits to the innermost planet since those of Mariner 10 in 1974-1975 [1]. Here we give a summary of the observations made during MESSENGER's three flybys and the view of Mercury that is emerging as the spacecraft heads toward Mercury orbit insertion in March 2011.

Magnetic Field and Magnetosphere: MESSENGER's first flyby (M1) confirmed that Mercury's internal magnetic field is primarily dipolar [2,3], and the second flyby (M2) showed that the dipole is closely aligned with the spin axis [4]. These characteristics, together with the absence to date of detected crustal magnetic anomalies [5], suggest that the field is the product of a dynamo in Mercury's fluid outer core [6]. The weak dipole strength remains a challenge to explain, with core geometry [7,8], outer core stratification [9], and induction by magnetospheric currents [10] possible contributors.

Mercury's magnetosphere was markedly different during each of the MESSENGER flybys. At the time of M1, the interplanetary magnetic field (IMF) had a northward component, the magnetosphere was comparatively steady, and there was little energy input from the solar wind [11]. During M2, the IMF was southward and solar wind energy input was much higher, with magnetic reconnection rates ~10 times greater than typical at Earth [12]. At the third flyby (M3), the IMF direction was variable, and MESSENGER found evidence for "loading" and "unloading" of magnetic energy in the tail at timescales (1-3 min) much shorter than at Earth (1-3 hr) [13]. The tail energy is so intense during loading events that the ability of Mercury's dayside magnetosphere to shield the surface from solar wind ions is substantially curtailed.

Exosphere and Neutral Tail: The constituents in Mercury's exosphere and anti-sunward neutral tail that are heavier than He are derived from Mercury surface materials by ion sputtering, micrometeoroid bombardment, and other processes, so detailed observations promise to elucidate source and loss mechanisms as well as surface composition information. During M1, MESSENGER mapped a north-south asymmetry in the planet's Na tail and determined the Na/Ca ratio near the tail and near the dawn terminator [14]. During M2, MESSENGER revealed the presence of neutral Mg in Mercury's anti-sunward tail and documented strongly differing distributions of Mg, Ca, and Na in the tail and the near-planet nightside exosphere, the result of different combinations of time-variable source, transfer, and loss processes [15]. During M3, MESSENGER detected Ca^+ in the exosphere and tail [16], important for an understanding of the exospheric Ca cycle because of the short timescale for ionization of neutral Ca by solar ultraviolet radiation. The Na emission level in Mercury's tail during M3 was less by a factor of 10-20 than during M2, at least in part due to variations in radiation pressure with position in Mercury's orbit [16].

Surface Composition: Reflectance spectra of Mercury's surface obtained during M1 showed no evidence for FeO in surface silicates and a slope from visible to near-infrared wavelengths consistent with space weathering by some combination of micrometeoroid bombardment and sputtering by solar wind ions [17]. The reflectance and color imaging observations provide fresh support for earlier inferences that Mercury's surface material consists dominantly of iron-poor, calcium-magnesium silicates with a spatially varying admixture of spectrally neutral opaque minerals [18,19] such as iron-titanium oxides [20]. Analysis of the thermal neutron flux measured during the three flybys combined with calculations of the effects of the spacecraft on the spectrometer response indicate that Mercury's surface material matches the neutron absorption characteristics of Luna 24 soil from Mare Crisium [21]. Given that little of this Fe+Ti is in silicate phases, the measured neutron absorption is consistent with 7-19% ilmenite by weight [21], a range broadly consistent with that inferred from color and reflectance observations [20].

Volcanism: Images from MESSENGER's first flyby provided evidence for widespread volcanism [22]. The ~1500-km-diameter Caloris basin was the focus for concentrations of volcanic centers [23], some displaying evidence for pyroclastic deposits [22,24], and smooth plains interior and exterior to the basin that postdate the basin-forming event [25,26]. Color images from M1 and M2 showed that the largely volcanic smooth plains constitute ~40% of the surface area and span nearly the full range of visible–near-infrared spectral types seen on Mercury [20]. Excavation of spectrally similar material by large craters and basins suggests that much of the upper crust of Mercury was emplaced by a succession of plains volcanic flows [20,27].

Images from M3 added to our understanding of Mercury's magmatic history. The comparatively young, 290-km-diameter Rachmaninoff peak-ring basin is floored by inner smooth plains deposits that differ in color from and are lower in crater density than the peak ring, outer plains, and basin rim, indicating that the central plains are one of the youngest expanses of volcanic deposits on Mercury [28]. An irregular rimless depression ~30 km across surrounded by a high-reflectance halo of distinctive color ~200 km in diameter is a candidate for a volcanic vent amid what may be the largest expanse of pyroclastic deposits yet seen on Mercury [28]. The former feature extends the known history of magmatism, and the latter provides another indication that Mercury's interior may at least locally contain larger concentrations of volatiles than predicted by most models for Mercury's formation [24].

Deformation: Images from M1 showed widespread lobate scarps and other tectonic landforms supportive of the view that Mercury contracted globally in response to interior cooling [29,30], pervasive contractional and extensional deformation across the Caloris basin floor [31,32], and concentric extensional faults within the peak ring of the comparatively young [25], ~250-km-diameter Raditladi basin [33]. Both the areal density [29,30] and the typical relief [34] on lobate scarps are greater than appreciated from Mariner 10 observations, an important constraint on thermal history and power available for a core dynamo. M2 revealed the ~700-km-diameter Rembrandt basin, less volcanically infilled than Caloris, but similarly a focus for concentrated magmatic and deformational activity [34]. The Rachmaninoff basin provides a second example of concentric graben inside a basin peak ring [28]. Images from M3 also revealed the first known example of extensional faulting unrelated to an impact basin, a family of narrow graben that crosscut an elevated block and may be the result of relaxation of topographic relief on a crustal plateau. These examples of extensional deformation constrain the relief of global compressional stress that accompanied impacts and large-scale faulting.

Generalizations and Prospects: Mercury's environment is extremely dynamic, with interactions among the solar wind, magnetosphere, internal field, and surface that are stronger and operate on shorter timescales than for any other Solar System body. In the geological past, the planet is now known to have experienced a volcanic and tectonic history that was more protracted and characterized by more diverse processes than previously appreciated. The views from the three flybys, snapshots obtained under restricted viewing geometries, have set the stage for the sustained orbital observations to come.

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