SEARCH FOR VULCANOIDS AND MERCURY SATELLITES FROM MESSENGER. William J. Merline[1], Clark R. Chapman[1], Peter M. Tamblyn[1,2], Hari Nair[3], Nancy L. Chabot[3], Brian L. Enke[1], and Sean C. Solomon[4,5], [1]Southwest Research Institute, Boulder, CO 80302 USA (merline@boulder.swri.edu), [2]Binary Astronomy, LLC, Dillon, CO 80435, USA, [3]Johns Hopkins University Applied Physics Laboratory, Laurel, MD 20723, USA, [4]Lamont-Doherty Earth Observatory, Columbia University, Palisades, NY 10964, USA, [5]Department of Terrestrial Magnetism, Carnegie Institution of Washington, Washington, DC 20015, USA.

Introduction: The delivery of a telescope to the environs of Mercury by the MErcury Surface, Space ENvironment, GEochemsity, and Ranging (MESSENGER) mission provided an ideal opportunity to search for small bodies near the Sun that are difficult to detect from Earth. Specifically, we discuss here searches for two classes of objects that could have influenced Mercury's impact history: vulcanoids and satellites. We chose to make these searches because (1) there have long been suspicions that these objects may exist, yet despite numerous surveys, no definitive evidence has been found, (2) their presence may have affected the cratering history on Mercury [1], (3) the close proximity to the Sun and Mercury, coupled with the relative difficulty of observations from Earth, improves chances of detection, (4) such objects may be highly refractory and thus have implications for close-in extrasolar planets, and (5) this effort assists in completing the inventory of objects in our solar system.

Theoretical work has shown that there may be a stable population of small objects, called "vulcanoids," orbiting the Sun inside Mercury's orbit [1,2]. The dynamically stable region is predicted to be approximately 0.08–0.21 AU from the Sun (Mercury, in its eccentric orbit, ranges from 0.31 to 0.47 AU from the Sun). If such objects ever existed, they could have cratered Mercury's surface after the Late Heavy Bombardment (while not affecting the cratering record of the other terrestrial planets), and thus may have made its surface appear older than it is. Satellites, if found, would have implications for Mercury's formation and, in addition, could point to the existence of prior satellites with orbits that may have decayed, impacting Mercury and potentially forming some of its basins. Because these searches were not included in the original science goals for MESSENGER, the observations were planned and executed in a manner that avoided conflict with other science objectives and minimized impact on mission resources. Observations from near Mercury (versus Earth-based) have an advantage in the apparent brightness of the targets (5 times closer for vulcanoids, equivalent to a 3.5-magnitude boost, and even better for satellites), but the Mercury Dual Imaging System (MDIS) wide-angle camera (WAC) had only an 8 mm aperture, so the resulting limiting magnitude for stars in a single exposure was only about V=8. To achieve the greatest sensitivity, the maximum exposure time of 10 s was used for all observations, along with the clear (broad-band) visible filter. The WAC was used because of its 10.5° × 10.5° field of view. For all observations, multiple images were acquired at each time step, primarily for rejection of artifacts (e.g., cosmic-ray hits), but also for co-adding frames to improve sensitivity. Groups of observations were made in specific time sequences, so that any motion could be distinguished from stars.

Vulcanoids: Many previous attempts have been made to detect objects in orbits interior to that of Mercury, but all have failed. Among the techniques used were observations during solar eclipses, use of thermal infrared to increase sensitivity, high-altitude jet flights at dusk, and space-based observations. The main difficulty in trying to detect vulcanoids from Earth is that the angular separation from the Sun is very small. Thus, observations must be conducted in competition with sunlight or the bright sky at dusk. The expected inner edge of the vulcanoid zone is determined by the lifetime against solar radiation. Even a large (100-km diameter) pure iron body at 0.06 AU would evaporate within the age of the solar system [3,4]. The outer edge is set by dynamical instability, because the perturbing effects of Mercury, in its elongated orbit, can clear objects on short timescales. Prior to our survey, the upper limit on the diameter of these objects at the outer edge of the zone was about 60 km (limit of V=8 from Earth) set by a search with the SOHO spacecraft [5]. The smallest diameter that can survive the Yarkovsky effect or Poynting-Robertson drag is about 1 km.

Our original goal was to reduce the size limit to 15 km diameter or less. One drawback of the instrumentation was that we could not point closer to the Sun than 30°. This limit restricted our observations to the outer portion of the vulcanoid zone, namely 0.18–0.21 AU. This outer region represents 46% of the volume of the zone and is where vulcanoids are expected to be more likely [6]. To probe to this minimum solar distance of 0.18 AU, however, required that our observations be made when the spacecraft was close to Mercury perihelion. Such circumstances were met 12 times during approach of the spacecraft to Mercury prior to orbit insertion. We were able to search for vulcanoids at six of those opportunities, collectively covering 46% of the volume of the vulcanoid zone. At each search, we observed one field width north and south of the ecliptic and on both sides of the Sun. We repeated fields over three time scales: (1) immediate, to reject artifacts, (2) over a few hours to distinguish motion from stars, and (3) over a few days to attempt to recover an object and estimate an orbit.

The results of these searches in cruise phase were that we could ultimately achieve a completeness of about 95% at V=9 (10 km diameter) and about 50% at V=10 (6.5 km diameter), better than our original goal of 15 km. We found no definitive evidence of vulcanoids. Simultaneous with the MESSENGER effort, a search was made with the STEREO spacecraft pair [7], with sensitivity increased by occulting disks that blocked the Sun, yielding a 3-standard-deviation confidence that no vulcanoids exist larger than 5.7 km.

To push our limits farther, we altered our strategy for the final searches, at the expense of coverage. We achieved deeper searches by co-adding more images or making longer strings of sequential observations, thus making any motion much more prominent. We made two such searches from Mercury orbit, where additional complications (coordination with other instruments observing Mercury itself and added noise from heat load) made the observations more challenging. Each of these searches covered 5% of the vulcanoid volume, but we were able to push the limits to nearly 100% completeness at 6.5 km diameter and 90% completeness at 4 km. Again, no vulcanoids were found.

Mercury Satellites: There have been few previous searches for satellites of Mercury. The Mariner 10 flybys of Mercury in 1974–1975 put size limits at 5 km diameter for ranges inside 30 R_M, where R_M is Mercury's radius. Probably the most definitive search was a ground-based study from La Palma [8], claiming to be complete over 19–73 R_M at 1.6 km diameter and partially complete at 0.5 km for some ranges. The range of stability for a satellite around a planet (Hill radius) is proportional to the planet's perihelion distance. Mercury's close perihelion distance of ~0.3 AU means that its Hill radius extends only to about 75 R_M.

The goal of our original observing plan was to detect satellites larger than ~1 km diameter over the full Hill sphere. That search, planned to be performed on departure from Mercury during MESSENGER's third and final flyby, was lost because of a spacecraft anomaly. From a planned observation range well away from Mercury, we could have scanned the entire system, using a small mosaic and relatively few images. We did not seek to re-schedule the experiment, because the fourth Mercury encounter was dedicated to orbit insertion.

Our alternative plan involved making satellite observations from Mercury orbit. Doing so had the advantages that we would be closer to any satellites and so could detect smaller ones. We could make better observations than any Earth-based system, because we could observe regions very close to Mercury, which would be lost in the glare from Earth. We could also observe over several hours, prohibitive from Earth. But this scheme also had disadvantages: from orbit, we were "inside looking out." To cover the entire "sky" for all possible satellites would take many images and much more time than could be accommodated. We also were in a much more challenging thermal environment than during cruise. We had to change many of the techniques used for the vulcanoid searches.

Imaging had to be done at the apoapsis of MESSENGER's eccentric orbit about Mercury, when other activities were somewhat diminished. We also wanted to observe any satellites close to opposition, when they would be at the largest solar elongation to improve brightness and detectability. In addition, we required that the searches be made near Mercury perihelion, to enhance the brightness of the satellites. Despite these restrictions on our observing strategy, we were able to make four separate searches. Each search looked northward ("upward" from the orbital apoapsis below Mercury's south pole) toward the expected equatorial orbital plane. Several pointing steps were made, spanning a range from Mercury of (2–75) R_M. Each step overlapped with the previous step in radial distance. The sequence began at the greatest distance, stepped to the smallest, and then stepped back to the largest. This pattern allowed faster motion of an inner satellite to be detected (before an object left the field) while still allowing the slower motion of an outer satellite to be detected (because enough time had passed). We again used multiple images at a single step to reject artifacts. Motion expected was due primarily to parallax from the spacecraft motion. Each step could cover only a limited span of orbital longitudes, and those spans depended on radial distance. We repeated the entire sequence after a fixed time. At some ranges, the same orbital longitudes of possible satellites were sampled multiple times, whereas at other ranges, different orbital longitudes were sampled at each sequence.

We estimate that the combined searches covered ~20% of the (near-equatorial) orbital phase space. No satellites were found at the 90% completeness level at diameters of about 10 m at 2 R_M and 100 m at 75 R_M.

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