The Mercury MESSENGER

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MeO Mission Overview

The Mariner 10 flybys of Mercury in 1974 and 1975 resulted in the unexpected discoveries of a planetary magnetic field and an active magnetosphere similar to that of Earth. Intense particle bursts and magnetic field disturbances were observed, indicating that magnetic substorms occur at Mercury much like those at the Earth. The surprising presence of an intrinsic magnetic field also implied an internal dynamo in a fluid core, posing fundamental, unresolved issues concerning the origin, composition, and thermal history of Mercury. The Mariner 10 images also revealed a number of surface features unique to Mercury, including large-scale thrust faults apparently associated with crustal compression as the planet cooled and contracted. Follow-on missions to Mercury were studied in the late 1970s, but were deferred because of perceived difficulties meeting propulsion and spacecraft thermal engineering requirements.

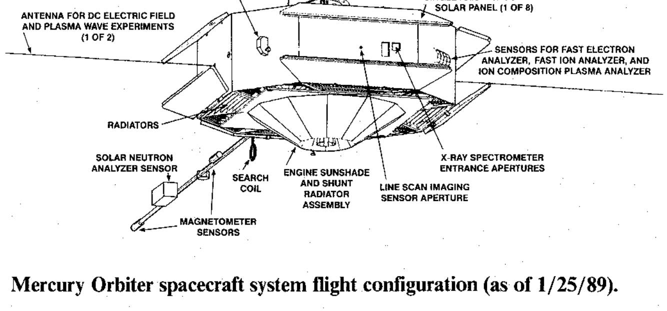
It is now apparent that a moderate-cost mission to Mercury—the Mercury Orbiter (MeO) mission—can in fact provide the particle and field measurements and planetological observations necessary to yield major advances in our understanding of Mercury and its magnetosphere. The mission involves two spin-stabilized spacecraft launched by a single Titan IV Centaur vehicle, a 4–5 year gravity-assist trajectory, and a nominal one Earth year duration mission at Mercury.

In 1988/1989 the Mercury Orbiter Science Working Team (SWT), under the auspices of the Space Physics and Planetary Exploration Divisions of NASA Headquarters, held three workshops to explore the feasibility of this mission. Spacecraft engineering and mission design studies at the Jet Propulsion Laboratory were conducted in parallel with this effort. The findings of the engineering study indicate that spin-stabilized spacecraft carrying comprehensive particle and field experiments and some planetology instruments in highly elliptical orbits can survive and function in Mercury orbit without costly sun shields and active cooling systems.

The magnetospheric and planetary physics rationale for a Mercury orbiter mission has been reported upon previously in JPL and NAS studies and, most recently, *Space Science in the Twenty-First Century* (NAS, 1988). The MeO/SWT has refined the science objectives and developed a strawman payload and mission plan that is responsive to the technical constraints placed on the spacecraft by Mercury's thermal environment and MeO's propulsion requirements. The primary space physics science objectives for MeO are to (1) map in three dimensions the magnetic structure and plasma environment of this "miniature" magnetosphere, (2) determine the principal processes taking place during magnetospheric substorms with an emphasis on differences from Earth due to Mercury's lack of a highly conducting ionosphere, (3) assess the role of interplanetary conditions in determining the rate at which this magnetosphere draws energy from the solar wind and the manner in which it is later dissipated, (4) investigate heliospheric structure and dynamics inside of 0.5 AU, and (5) utilize the closeness of Mercury to the sun to achieve fundamental solar physics goals by measuring neutrons emanating from the sun. The primary planetology science objectives for MeO are to (1) complete the global surface mapping initiated by Mariner 10, (2) obtain global geochemical terrain maps of the occurrence of such elements as Fe, Th, K, Ti, Al, Mg, and Si, (3) measure the intrinsic magnetic field in sufficient detail to allow for the detection of magnetic anomalies, and (4) measure the gravitational field of Mercury and associated anomalies.

To meet these science objectives, the MeO/SWT has identified a strawman payload consisting of 10 instruments: magnetometer, electric field analyzer, plasma wave analyzer, energetic particle detector, fast plasma analyzer, ion composition analyzer, solar-wind plasma analyzer, solar neutron detector, line-scan imager, and gamma/X-ray spectrometer. All of these instruments are based upon mature technologies and should require few modifications to meet the requirements of the MeO mission.

The MeO/SWT strongly endorses the mission plan developed by the JPL study team. The single-launch vehicle, dual-spacecraft baseline meets the fundamental magnetospheric science requirements for simultaneous multipoint measurements and provides critical redundancy in the event of a spacecraft failure. The coordinated orbit scenarios for the two spacecraft will provide unique particle and field measurements that are unobtainable elsewhere because of the large dimensions of other magnetospheres relative to their planetary bodies. In conjunction with the Earth-orbiting ISTP and CLUSTER missions to be flown in the 1990s, the Mercury Orbiter mission will provide the essential data necessary to formulate the next-generation theories and models of terrestrial-type magnetospheric structure and substorm dynamics. This mission will also return critical measurements necessary for the understanding of not just the surface history and internal structure of Mercury, but the



Mercury Orbiter spacecraft system flight configuration (as of 1/25/89).

formation and chemical differentiation of the solar system as a whole. The science objectives for this mission are expanded upon in the accompanying articles.

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Mercury Planetology

Mercury is an endmember planet because it formed nearest to the sun in the hottest part of the solar nebula. Although it superficially resembles the Moon, there are significant differences in both the internal constitution and surface geology. Mercury has an uncompressed mean density of 5.3 g/cm^3, larger than any other planet or satellite in the solar system. This indicates that it has an enormous iron core that constitutes about 75% of the planet's radius. The presence of a dipole magnetic field further suggests that the outer portion of the core is currently in a molten state. This requires a light alloying element in the core to lower the melting point and retain a partially molten core to the present time. Although oxygen is such an element, it is not sufficiently soluble in iron at Mercury's low internal pressures, and therefore sulfur is the most reasonable candidate. The present extent of the outer molten core and the onset of solid inner core formation are highly dependent on the abundance of sulfur in the core. For a sulfur abundance less than 0.2% the entire core should be solidified at the present time, while an abundance of 7% results in an entirely fluid core at present. Inner core formation begins about 3.9 g.y. ago for 0.2% sulfur and results in an outer fluid core about 100 km thick at present. For 5% sulfur the inner core begins to form about 2 g.y. ago, and results in an outer fluid core about 1150 km thick at present (*Schubert et al.,* 1988).

How Mercury acquired such a large percentage of iron is a major unsolved problem. Initial chemical equilibrium condensation models for Mercury's position in the solar nebula predicted an uncompressed density of only 4 g/cm^3 rather than the observed 5.3 g/cm^3 and the complete absence of sulfur (*Lewis,* 1972). Modified models (*Lewis,* 1988) where 60–90% of the material accreted at Mercury's present distance and 10–40% accreted from planetesimals perturbed into Mercury's position from the feeding zones of other terrestrial planets still fail to provide enough iron to account for Mercury's uncompressed density (4.2 vs. 5.3 g/cm^3). They do, however, predict from 0.1% to 3% FeS (*Lewis,* 1988).

Three very different hypotheses have been proposed to account for the large discrepancy between the iron abundance indicated by Mercury's high density and that predicted by equilibrium condensation models. One hypothesis (selective accretion) proposes a mechanical accretion process for concentrating the required iron at Mercury's position in the solar nebula while the other two (postaccretion vaporization and giant impact) account for Mercury's high density by removing a large fraction of Mercury's silicate mantle early in its history. In the selective accretion model, a differential response of iron and silicates to impact fragmentation and aerodynamic sorting leads to iron enrichment owing to higher gas densities and shorter dynamical time scales in the innermost part of the solar nebula (*Weidenschilling,* 1978). The postaccretion vaporization model proposes that intense bombardment by solar electromagnetic and corpuscular radiation in the earliest phases of the sun's evolution (T-Tauri phase) vaporized and drove off much of the silicate mantle (*Cameron et al.,* 1988). In the giant impact hypothesis, a collision of a planet-sized object with Mercury ejected much of the planet's silicate mantle, which is subsequently swept up principally by Venus and Earth (*Cameron et al.,* 1988; *Wetherill,* 1988). Each of these hypotheses has major consequences for the formation of the other terrestrial planets. Fortunately, each model predicates a significantly different chemical composition for Mercury's silicate mantle and therefore compositional information from a Mercury orbiter can help decide between these competing hypotheses. Until we understand how Mercury formed, we will not clearly understand the formational history of the other terrestrial planets.

Mariner 10 imaged only about 45% of Mercury's surface at resolutions comparable to Earth-based telescopic resolution of the Moon. As a consequence, our understanding of its geologic history and the origin of some of its surface features is incomplete. The surface viewed by Mariner 10 shows an ancient, heavily cratered terrain, as well as younger smooth plains that primarily fill and surround the 1300-km-diameter Caloris impact basin and occupy a large area of the north polar region. These surfaces are similar to the lunar highlands and maria of the Moon. Unlike the Moon, however, Mercury contains large areas of old intercrater plains interspersed among the heavily cratered terrain and a system of presumably global thrust faults (lobate scarps) that resulted from a period of global compression caused by planetary contraction. A peculiar hilly and lineated terrain occurs antipodal to the Caloris basin and probably resulted from large vertical surface movements caused by focused seismic waves from the Caloris impact.

Mercury's intercrater plains are the major terrain on Mercury and formed at various times during the period of late heavy bombardment. These plains are thought to be volcanic deposits erupted through fractures caused by planetary expansion during heating and core formation. The younger, smooth plains are also interpreted as volcanic deposits primarily erupted through fractures caused by the large basin-forming impacts with which they are associated. The global system of thrust faults appears to postdate intercrater plains formation, suggesting that the onset of planetary contraction began relatively late in mercurian history. The decrease of Mercury's radius estimated from the number and dimensions of thrust faults is about 2 km. However, these results are based on the examination of only about 25% of the surface and extrapolated globally. Both the time of onset of global contraction and the amount of radius decrease based on the geologic relationships are at variance with current thermal history models that predict that contraction began immediately following accretion and resulted in a radius decrease of about 6 to 8 km (*Schubert et al.,* 1988). The proposed Mercury orbiter mission could provide the information required to resolve the problem.

Almost nothing is known about Mercury's surface composition. The major terrain units (smooth plains, intercrater plains, and crater rays) have systematically higher albedos than comparable terrains on the Moon. The photometry and colorimetry suggests that Mercury's surface material may be depleted in iron and titanium relative to lunar rocks.

The proposed Mercury orbiter mission optimized for field and particle investigations has the potential of providing important new information about Mercury with only an imaging device, instruments to measure the surface composition, and Doppler radio tracking. The current mission design allows global imaging at a resolution of 1 km/lp or better, about 75% coverage at 400 m/lp or better, and about 20% coverage at 100 m/lp, a considerable improvement over Mariner 10 coverage and resolution. Also, it is possible that extensive stereo coverage may be obtained from images taken at different viewing angles. The surface elemental abundances of Si, Mg, Fe, Al, Ti, K, Na, Th, and Ca can be determined with the gamma-ray spectrometer and X-ray fluorescence experiment, but the accuracy and surface resolution depend on the spin rate. In addition, Doppler radio tracking should allow the determination of the local gravity field. If these data are obtained, then important new insights can be obtained about the origin of Mercury and its composition, crustal dynamics, internal constitution, magmatic processes and history, impact processes, and geologic and geophysical history.

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Mercury's Magnetospheric Laboratory

NASA's dual Mercury Orbiter mission (MeO) will conduct intensive and extensive measurements of the planet's magnetosphere. Since Earth's magnetosphere is easier to reach, what is the interest in Mercury's magnetosphere? The question demands a response when a proposed mission will cost a half billion dollars.

The answer lies in putting the knowledge to be gained in context. A question that has been asked many times before is why go to any planet? There are three compelling reasons. First, planets can be sorted into groups much as animals are. Genus Homo is a primate, like monkeys and apes; to learn more about humans, we often study the other primates. Analogously, Mars, Earth, Venus, and Mercury are "terrestrial" planets. We learn about Earth not only by finding out what it is, but also by finding out what it isn't, through detailed comparisons between it and the other planets, especially those of the same class. Second, planetological processes that operate at Earth occur elsewhere in the solar system, where they may be easier to study by virtue of being expressed more purely or intensely. Biologists use fruit flies, not humans, to study genetics, because fruit flies reproduce quickly. On the planetary side, the biggest geysers in the solar system erupt on Jupiter's satellite Io, and the greenhouse effect heats far more powerfully on Venus than on Earth. Third, theories advanced to explain terrestrial examples of planetary processes receive their severest test when applied to extraterrestrial examples that lie outside the parameter regimes for which they were devised. For example, the spacecraft Magellan now coasts toward Earth's sister planet Venus on a mission to quantify the nature and extent of venusian volcanism and plate tectonics. It seeks a second datum to test theories of volcanism and plate tectonics on Earth-like planets. In summary, we must go to the planets to (1) document their structures and processes to establish detailed taxonomic relations between them, (2) find places where planetary structures and processes are optimally expressed, and (3) obtain data to guide and test theories of planetary structures and processes.

Corresponding to these general imperatives, there are three prime reasons for going to Mercury to learn about magnetospheres: (1) Of all known magnetospheres, Mercury's is most Earthlike; (2) Mercury's magnetosphere is small; and (3) the solar wind and planetary boundaries to Mercury's magnetosphere are significantly different than Earth's.

Because its magnetosphere is the most Earthlike, Mercury is the best place to test our understanding of these planetary exosystems—an understanding that we have acquired chiefly by studying the terrestrial example. In effect, MeO will administer a certifying examination to the field of magnetospheric science. In exporting magnetospheric applications to other scientific disciplines and enterprises, such as astrophysics and space weather predictions, MeO will provide the data to test the product and confer a validation or a warning. Conversely, because of the similarity, new knowledge of magnetospheres gained at Mercury has ready application to Earth.

It takes 20 Mercury magnetospheres in a line, touching side by side, to span the breadth of 1 Earth magnetosphere. For an MeO mission, smallness brings several advantages. Measurements at Mercury would solve a space-time ambiguity problem that confounds synoptic studies at Earth. Roughly once per hour the solar wind changes significantly, and magnetospheres respond. An Earth-orbiting spacecraft needs many hours to traverse a magnetospheric structural unit, which meanwhile adjusts its shape and behavior to fit the solar wind. Inevitably a spacecraft rarely samples a complete structural unit before it alters. By contrast, at Mercury, a spacecraft crosses the entire magnetosphere in 20 minutes or less, completing a measurement sequence usually before the solar wind shifts. Thus the changes a spacecraft records in a magnetospheric structure at Mercury characterize that structure and its behavior for a fixed magnetospheric state.

Smallness also confers an important practical benefit. Since the orbits required at Mercury are small, and the orbital periods correspondingly short, complete magnetospheric measurement sequences accumulate about 25 times faster than at Earth. Combining this with the fact that most measurement sequences will be synoptic (obviating the many sequences needed for statistics), and the fact that the "metabolic rate" of Mercury's magnetosphere, as measured by the circulation timescale, is an order of magnitude greater than Earth's, one sees that the structure and processes of Mercury's magnetosphere can be surveyed and documented during a relatively short, magnetosphere-dedicated phase of a multidisciplinary mission.

Being the innermost planet and virtually airless, Mercury (compared to Earth) experiences markedly different conditions at the outer and inner boundaries of its magnetosphere. Outside, a denser solar wind pushes harder, while a stiffer interplanetary magnetic field pulls more powerfully. Inside, the ionosphere-thermosphere base, which marshals dynamics at Earth, is only nominally there. The situation creates opportunities to test solar-wind/magnetosphere/ionosphere coupling theories stringently, by applying them to an Earthlike magnetosphere shaped and driven by quantitatively different forces.

The boundaries can differ qualitatively as well. In 20 years the solar wind at Earth blew subsonic only once while detectors watched. At Mercury, subsonic flow must recur sufficiently to make the possibility of MeO observing a subsonic interaction likely. With no bow shock to overwhelm them, the effects of energy-transferring, tangential forces on the boundary dominate in shaping the magnetosphere's fore-aft asymmetry, affording a ready measure of their distribution and strength. At the other extreme, the wind occasionally blows hard enough to ram the bow shock into the planet, creating a headless magnetosphere.

Not only is Mercury highly valuable as a proving ground for testing our magnetospheric understanding, and as a new (and in some ways better) source of information on the structure and dynamics of Earthlike magnetospheres, it hosts the Proteus of magnetospheres, creating configurations unique in the solar system. For these reasons, Mercury is the ideal laboratory for magnetospheric science.

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Views on a Mercury Dual Orbiter Mission

As the preceding discussions have described, a technically feasible, scientifically important, and logically sequenced mission to Mercury has emerged from studies conducted up to this time. As a Space Physics Division follow-on to magnetospheric studies conducted at Earth, Jupiter, Saturn, Uranus, and, at the time of this writing, possibly Neptune, a return to Mercury in the latter 1990s or early 2000s has solid programmatic arguments in its favor. In fact, the systematic and quantitative development of comparative magnetospheric physics would be strongly advanced by the inclusion of Mercury among the magnetospheres that will have been studied in close detail.

The Mercury Orbiter (MeO) mission appears to be emerging as a strong candidate for a 1995 or later moderate mission new start. It will compete, of course, with other missions and its success is not assured. At the present time it is not included in OSSA 1990–1994 Strategic Plan. In order to gain consideration of MeO for inclusion in the next update of the Strategic Plan, the Space Physics Division will seek to present the study results to the scientific community and the Space Sciences Board as well as NASA advisory committees for evaluation and recommendation. If these evaluations are favorable as to scientific value and technical feasibility, then the arguments will be made within NASA management as to how and when MeO may fit into OSSA and Agency program plans. The result of these evaluation and planning steps will lead to a new start in the mid to late 1990s.

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About This Newsletter

This issue contains a description of the archetype MeO endorsed by the Mercury Science Working Group and short presentations of what we could learn about Mercury's crust and magnetosphere. Tom Armstrong discusses the prospects of the proposed payload. One issue of this newsletter provides inadequate space, so we hope to have an article on the heliospheric studies possible from the MeO in the next issue.

I hope that as you read these articles you come to feel, as I have, that Mercury represents a unique opportunity for solar system studies. Because of the small scale of the planet and the magnetosphere (relative to the Earth), the interrelations among the regolith, exosphere, magnetosphere, and solar wind on Mercury may be so important that interdisciplinary studies are required at the onset. We hope that future issues will have contributions that present these interrelationships and explain how their exploration will contribute to several fields at once.

Anyone wishing to contribute to the Mercury Messenger or to suggest topics of interest may contact me after September 1, 1989 at Code EL, NASA Headquarters, Washington, DC 20418.

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