MERCURY: A WORLD OF FIRE AND ICE?

by

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Abstract

During this decade we will make a historic return to Mercury. The MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) mission is designed to answer many of the questions raised during the brief encounters of Mariner 10 with Mercury in 1974 and 1975, and by innovative ground-based telescopic observations and discoveries made over the past two decades. The planned launch date is March, 2004 and the first encounter with Mercury is scheduled for July, 2007. Of particular interest are detailed observations of planetary figure and librations, geologic history, volatiles stored in high latitude craters (polar ices?), evidence for volcanism, trace constituents in the thin atmosphere, Mercury's magnetosphere, and its interaction with the solar wind. The European Space Agency (ESA) is planning a mission to Mercury for the next decade: Bepi Colombo.

Introduction

Because of its proximity to the Sun, Mercury is a difficult object to observe from ground-based telescopes. For this reason practically nothing was known about Mercury's surface or thin exosphere until the three flybys of Mariner 10 in 1974 and 1975. As remote sensing technologies improved, so did our ability to reexamine the Mariner 10 color television images with new image processing techniques, and to make diagnostic measurements with a new generation of visible and infrared imaging spectrographs as well as rapid imaging VCR recorders. This paper discusses new accomplishments, discoveries, and questions raised since the Mariner 10 flybys. A discussion of the MESSENGER spacecraft, mission design, scientific goals, and scientific instruments carried to acquire the data to meet these goals, follows.

Reanalysis of Mariner 10 Images

Two outstanding geologic questions are whether the smooth plains on Mercury's surface are a result of volcanism or coverage by ejecta following cratering events, and whether clear differences in stratigraphy indicate compositional differences. A real advance toward answering these questions was made with the reanalysis of many of the Mariner 10 three color television images. After removing vidicon blemishes and radiometric residuals, new color maps were created using UV (355 nm) and orange images [1]. By using ratio techniques that have been successful analyzing lunar data at visible and near-infrared wavelengths, the image shown in Fig. 1 was created. Blue indicates the intensity of the ratio

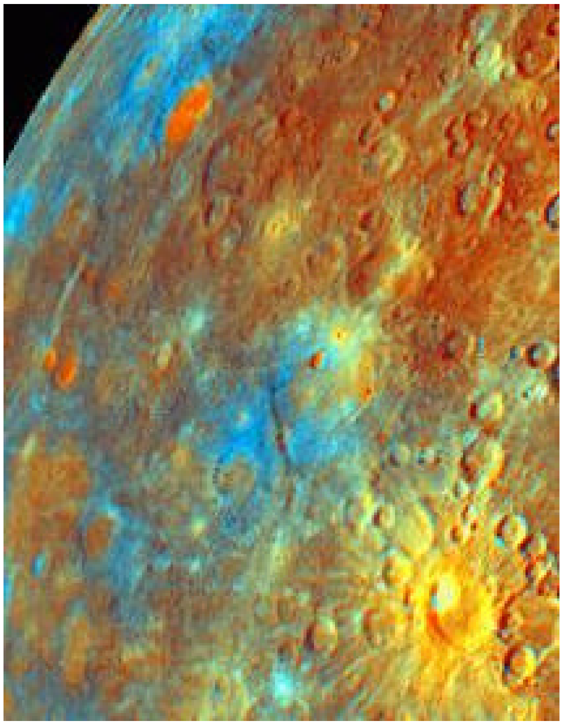

Fig. 1 Reanalysis of Mariner 10 UV and orange color television images, from Robinson and Lucey [1].

of ultra-violet to orange light. Using other ratios, the colors combine to make all the shades seen in the image.

By inference from color ratios of visible and near-infrared wavelength lunar images, Robinson and Lucey [1] deduce that blue regions are typical of pyroclastic deposits from fire fountains driven by volatiles. On Earth these volatiles would be gases such as CO_2, SO_2, and H_2O. On Io considerable Na and Cl are also expelled from gas rich volcanoes. Green regions are either low in FeO or have been protected from long term effects of space weathering (solar wind bombardment, micrometeoritic impact and comminution, etc.). Bright yellow regions, such as that in the lower right corner are recently exposed and indicate a low abundance of spectrally neutral, opaque minerals such as titanium. Orange and red are colors indicative of more "mature" surfaces reddened by space weathering. Based on the analysis [1], it appears that Mercury has compositionally distinct units at both small and large scales, is differentiated, and has had episodes of magmatic and pyroclastic volcanism.

Ground-based Telescopic Discoveries

Spectroscopy

Mariner 10 was unable to make mineralogic identifications. Thus, a serious effort by ground-based observers in the near- and mid-infrared spectral region has been made, with some success, finding that Mercury's surface is generally low in crystalline Fe^{2+} and is feldspar-rich. Using near-infrared spectroscopic measurements, McCord and Clark [2] put an upper limit of ~6% FeO at locations observed. This quantity was lowered to ~3% by Vilas et al. [3] in a series of measurements covering most longitudes. With the advent of new, high resolving power mid-infrared spectrographs it was possible to search for emission features indicative of specific mineral species and rock types. Sprague et al. [4, 5] find regions on Mercury's surface that exhibit spectral features similar to those of feldspar-rich basalt, Na-rich feldspars. In addition, one spectrum from ~34^{o} longitude exhibits similarity to spectra from particulate lunar breccias composed of 90% anorthosite and 10% pyroxene. No evidence for highly mafic mineralogies has been found so far. Fig. 2 shows some of these Mercury mid-infrared spectra along with laboratory spectra from a variety of feldspars

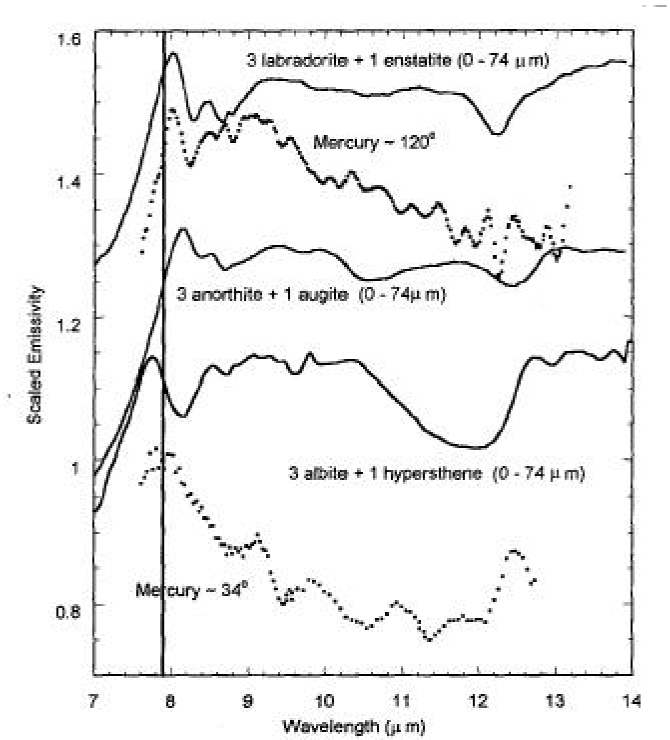

Fig. 2. Telescopic mid-infrared spectra from Mercury's surface along with some laboratory spectra of terrestrial rock and mineral soils, from Sprague and Roush [5].

and mixtures with pyroxenes for comparison. No match is perfect but comparisons are suggestive of labradorite and some (up to 25%) pyroxene, of unidentified composition. With the added constraint provided by near-ir spectroscopy, low-iron pyroxene is the most likely. These observations and interpretations are consistent with microwave imaging and modeling of Mercury's regolith up to a few meters deep that show it to be of lower conductivity (less mafic) than that of the Moon [6].

Radar Imaging of the Surface

Radar imaging has revealed several highly backscattering regions on the side of Mercury not imaged by Mariner 10 [7, 8, 9]. One view of these is shown in Fig. 3 where bright red regions are the most radar reflective. There is new and exciting science related to these radar-bright spots. At the very top of Fig. 3 is a bright region corresponding roughly to the north polar region. This has been interpreted as a region of stored icy volatiles, perhaps even water ice. The two larger bright regions, both of which are at about the same longitude (355 ^{o}) and at latitudes centered at about 55^{o} N and 25^{o} S are caused by some other physical property of the surface. The reflectivity of the northern feature shows some similarity to the large shield volcanoes on Mars while that from the southern feature has characteristics resembling those from large impact craters seen on Mars and the Moon [10]. A bright albedo feature has been imaged at the location of the southern feature and is discussed later.

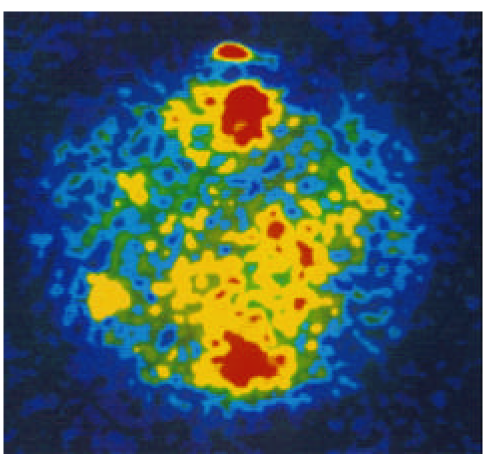

Fig. 3. Radar image of Mercury on side not imaged by Mariner 10, courtesy of Brian Butler [9].

As illustrated by the small northernmost bright red spot of Fig. 3, radar imaging of Mercury's north and south high-latitude regions made the startling discovery of deposits of a substance capable of generating a highly coherent backscatter signal [7, 8, 9]. A similar highly coherent backscatter signal is returned from the icy

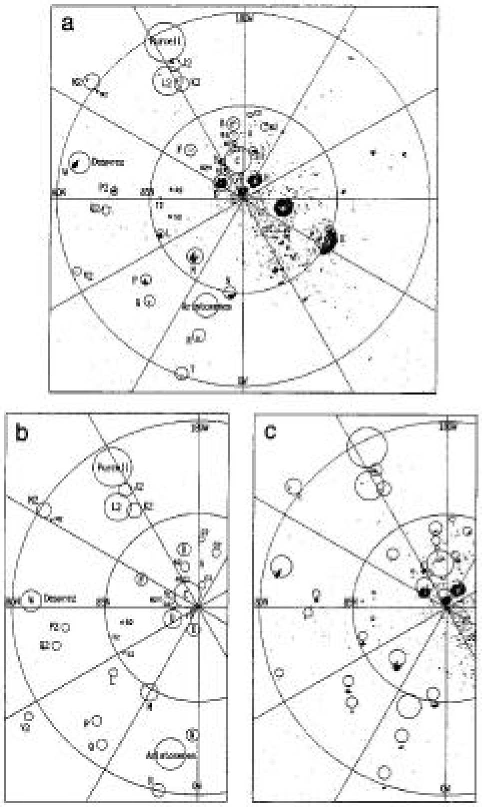

Fig. 4. High spatial resolution radar coherent-backscatter maps of stored volatiles on Mercury at very high north latitude, from Harmon et al. [11]

polar regions on Mars and the Galilean satellites. Thus, a good candidate for the material stored in the craters is water ice. Subsequent radar imaging found that deposits are limited to regions deep within walls of craters at high latitude, presumably where they are never exposed to sunlight.

A recent map of these regions at high northern latitudes is shown in Fig. 4, a reproduction from Harmon et al. [11]. While most of the deposits are located at latitudes greater than 85° (both north and south), some are located as low as 72° N. There are problems explaining how water ice could remain stable at all these locations. Perhaps a thin layer of regolith covers them from sunlight. Another possibility is that sulfur, which would be more stable at higher temperatures than water ice [12] is the stored material. Or, perhaps these shaded craters contain a mixture of these and other, as yet unsuspected compounds.

Imaging of the Na and K atmosphere

While studying scattering properties of Mercury's surface, the exciting discovery of a thin Na atmosphere was made [13]. A year later, K in the atmosphere was also discovered [14]. The atmosphere is very tenuous (a few thousand kg of Na and K combined). Because the ionization time of Na and K is short and the new ions are swept into the interplanetary medium by electric fields in the solar wind, the neutral atoms must be continuously supplied to the atmosphere. Sources are surface materials, meteoritic material, and minor amounts from the solar wind. Atoms do not collide with each other, they interact only with the surface. Thus the atmosphere is called a surface-bounded exosphere. It has been the object of ground-based high resolving power spectroscopic studies for over a decade [15, 16].

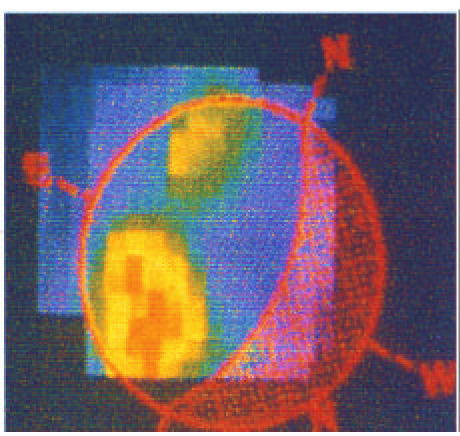

Fig. 5. Bright atmospheric Na emission patches over radar-bright regions on surface located at 355° longitude, from Potter and Morgan [17].

One interesting discovery is that the abundance and brightness of emission from Na and K are changeable on timescales from hours to years. Often the bright patches of emission are associated with surface features. Such an example [17] is illustrated by Fig. 5 which shows Na bright spots corresponding rather well with the radar bright regions along 355^o longitude shown in Fig. 3. This may indicate the surface at these locations is Na-rich. Bright emission spots of Na and K have also been observed in the region of Caloris Basin and an equatorial region of high radar reflectivity, southwest of Caloris, and over the Kuiper-Murasaki crater complex (shown as the bright yellow crater complex in the lower right of Fig. 1) [18]. Calcium has also been discovered in the exosphere extending to high altitudes off very high southern latitudes [19], along with H, He, and O, measured by instruments on Mariner 10, this brings the number of known species in Mercury's surface-bounded exosphere to 6. Helium is outgassed from the interior, H is from the solar wind. Na, K, Ca, and O are probably from meteorites and the regolith.

Visible Imaging of Mercury's Surface

Recent imaging of Mercury in visible and near-infrared wavelengths has resulted in some remarkable successes. By using sensitive equipment and short exposure times, moments of extremely good seeing permit the capture of relatively good views of Mercury's surface. All longitudes of Mercury have now been imaged with enough clarity to see distinct and unambiguous features on the surface. A composite of these images as cylindrical projection maps of Mercury is shown in Fig. 6. The top panel is from Warell and

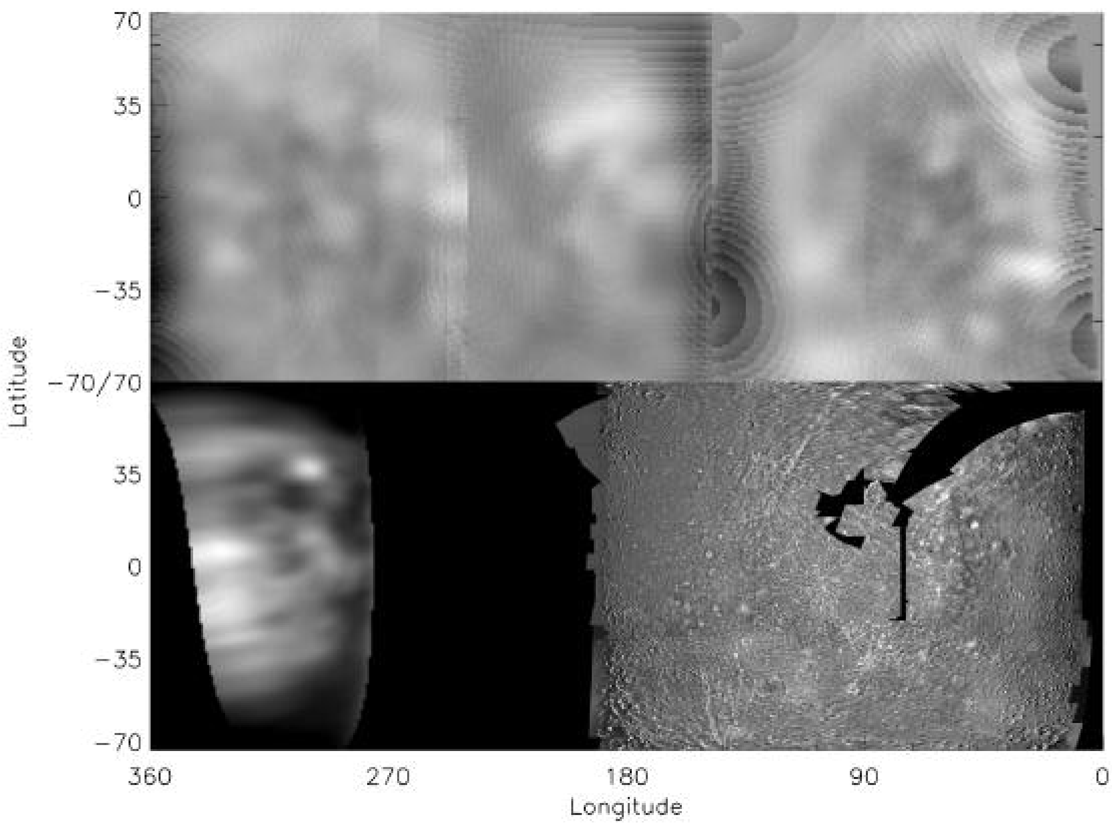

Fig. 6 Telescopic imaging of all longitudes of Mercury by Warell and Limaye [11] and Baumgardner et al. [20]. Lower right is a cylindrical coordinate map of images from Mariner 10 (courtesy of A. Tayfun Oner). Figure is from Mendillo et al. [21].

Limaye [11]. The bottom left panel shows an image of longitudes 270 - 320 never imaged by Mariner 10 from Baumgardner et al. [20] and Mendillo et al. [21] and bottom right of the same panel, a cylindrical projection of entire portion imaged by Mariner 10.

The Baumgardner *et al.* [20] observations were made at the Mount Wilson Observatory in California during a joint observing run with staff from the Boston Museum of Science. The Warell and Limaye [11] research program uses the Swedish Vacuum telescope operated on the island of La Palma by the Royal Swedish Academy of Sciences in the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofisica de Canarias. These images are the first set of optical wavelength images of Mercury for longitudes between 270 and 360^o. The best spatial resolution is a region ~240 km on a side. Overall the images give the appearances of regions of low albedo maria and higher albedo highlands with some fresh impact excavation regions, however, this may not be the correct interpretation. The brightest albedo feature seen in the bottom left is located at ~38^o N, 298^o longitude. Dark albedo features centered at ~15^o N, 285^o; 0^o, 305^o ; and 26^o N, 305^o latitude, longitude; respectively are located in regions showing low radar reflectivity, and thus relatively smooth terrain. This lends support to the interpretation of these regions as "lunar, maria-like" material. However, the albedo differences could be of surface maturity.

MESSENGER

More questions have been raised than answered by the innovative observations and important discoveries made by the ground-based Mercury observations described above. The answers to these questions are not just important for understanding Mercury's formation but will also help to understand the origin of all the terrestrial planets. These questions, along with lingering ones following discoveries made by the Mariner 10 flybys will be addressed by MESSENGER, the long-awaited Mercury orbiting spacecraft.

Major scientific questions to be addressed by MESSENGER

Solomon et al. [22] give a detailed account of the major scientific issues to be addressed by MESSENGER. The interpretation of measurements made by the suite of 7 instruments when combined are designed to answer the following questions.

1. What planetary formational processes led to the high metal/silicate ratio in Mercury?

note: Mercury has an uncompressed density of 5.3 g/cm^3 , higher than any other terrestrial planet. the core is 75% of the planetary radius and fractional core mass ~65%, more than twice that of Earth, Venus or Mars.

2. What is the geologic history of Mercury?

note: In the Mariner 10 images there are no evident volcanic landforms. Yet, as we have seen above, there is now new evidence for them. Are the huge thrust faults a global system?

3. What are the nature and origin of Mercury's magnetic field?

note: Based on only tens of minutes of measurements during three Mercury fly bys it is deduced that Mercury's intrinsic magnetic field has a dipole component ~orthogonal to Mercury's orbital plane and a moment ~ 1/100 that of the Earth's. The source of the field is unknown.

4. What are the structure and state of Mercury's core?

note: If Mercury's magnetic field arises from a core dynamo then there must be at least a partially molten metallic core. Measuring the physical libration of the mantle about the mean resonant angular velocity of the planet permits detecting a liquid outer core, if one exists.

5. What are the radar-reflective materials at Mercury's poles?

note: Coherent backscatter from circularly polarized radar is known to correspond to ice on Mars and the Galilean satellites. The same signature coming from Mercury may also indicate ice, or some other very radar-transparent material like sulfur.

6. What are the important volatile species and their sources and sinks on Mercury?

note: The discovery of new atomic and molecular species in Mercury's exosphere will help to identify the sources, recycling character, and sinks governing them. The discovery of S in abundance in the atmosphere would have direct bearing on the formation, thermal history, and composition of Mercury's surface, as well as the material stored in perpetual shadow at high latitudes.

Spacecraft, mission design, and scientific instrument payload

The spacecraft and mission design [23] are optimized to have the duration and proximity required to acquire data from a scientific instrument payload [24] especially built to meet the science objectives. The biggest challenges to an orbiting Mercury mission are thrust requirements required to acquire stable orbit and protection of instruments from extreme heating by the Sun and Mercury itself. Launch by Delta II vehicle, 475 kg of dry chemical propulsion and unpowered gravity assists from Venus (twice) and Mercury (twice) will put Mercury into orbit in April, 2009. Periapsis varies from 200 - 465 km in altitude and from 60 to 73.9^{o} N latitude during the following four mercurian years. A ceramic-cloth thermal shade will maintain spacecraft and instruments at room temperature. The 12 hour, near polar orbit, and long-duration orbital mission (1 Earth year/4.2 Mercury years) permits exploration of the most exciting -- and least understood -- scientific puzzles of Mercury's magnetosphere, exosphere, composition, a close up view of the northern high latitude stored volatiles, and perhaps the unusual radar feature centered at 55^{o} N, 355^{o} longitude (is it a shield volcano?!).

MESSENGER carries seven scientific instruments. These, along with the telecommunications system provide the measurements necessary to meet the scientific objectives [22]. The total mass of the payload, all electronics, thermal accommodations, booms, brackets, and cables, is about 40 kg [24]. The directional instruments are co-aligned on the bottom deck of the spacecraft. A shared data processing unit (DPU) and instrument power system is designed for data processing and compression [24]. Telemetry and the associated radio science also enable the spacecraft to meet the scientific objectives. These include the Mercury Dual Imaging System (MDIS), a Gamma-Ray and Neutron spectrometer (GRNS), an X-ray Spectrometer (XRS), a Magnetometer (MAG), the Mercury Laser Altimeter (MLA), the Mercury Atmospheric and Surface Composition Spectrometer (MASCS), an Energetic Particle and Plasma Spectrometer (EPPS), and Radio Science (RS). Table 1 gives details of the scientific payload and a brief statement of objectives.

Table 1

INSTRUMENT NAME	INSTRUMENT DETAILS	SCIENCE OBJECTIVE
Mercury Dual Imaging System (MDIS) Wide angle (WA) Narrow angle (NA)	WA: 10 filters centered at 415, 480, 560, 650, 750, 830, 900, 1000, 1020 nm two clear filters centered at 750 nm (200 and 100 nm width), 10.05^o FOV NA: 1.5^o FOV	mineral identification, geology, volatiles, calibration
Gamma-Ray and Neutron Spectrometer (GRNS)	active, shielded CsI scintillator can measure O, Si, S, Fe, H, K, Th, U lithium glass and neutral absorbing scintillators; primarily H	surface elemental abundances, volatile identification
X-ray Spectrometer (XRS)	measures from 1 - 10 keV covering emission lines from Mg, Al, Si, S, Ca, Ti, and Fe	surface elemental abundances
Magnetometer (MAG)	three-axis, ring-core fluxgate on 3.6 m boom in anti-sunward direction	map strength and configuration of magnetic field
Mercury Laser Altimeter (MLA)	pulsed laser with receiving telescope	planet figure, librations, interior; determine topography when surface is closer than 1000 km
Mercury Atmospheric and Surface Spectrometer (MASCS)	Ultra Violet Visible Spectrometer (UVVS) 10 - few kR from 0.19 - 0.45 μm in 100 s Visible-Infrared Spectrograph (VIRS) 0.3 - 1.025 and 0.95 - 1.45 μm	exospheric atomic and molecular emissions surface reflectance, rock type and mineral identification
Engineering Particle and Plasma Spectrometer (EPPS)	Energetic Particle Spectrometer (EPS) energetic ions and electrons Fast Imaging Plasma Spectrometer (FIPS) thermal plasmas mounted near top deck	pickup ions, ions and electrons in the magnetosphere and solar wind, ions from Mercury's surface and ionosphere
Radio Science (RS)	telecommunications subsystem and DSN	gravity field and laser altimetry support, physica librations, interior

If spacecraft and instrumentation function as planned, the MESSENGER mission should make all necessary measurements for a thorough understanding of the many outstanding scientific questions put forward above [22] and insights into the formation and early history of the terrestrial planets. The ESA, Bepi Colombo mission to Mercury is also ambitious and will greatly add to the information expected to be retrieved by MESSENGER. The opportunity is great and we await the exciting missions with pleasant anticipation.

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