MERCURY MESSENGER

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MARINER 10: A RETROSPECTIVE

Greetings, Mercury fans! It has been awhile since our last issue (never mind how long!). We thought it would be inspiring, while we await the launch of another mission to Mercury, to tell the extraordinary story of the only previous mission to reach Mercury to date, *Mariner 10*. In a future issue, we will describe what is planned for the Mercury *MESSENGER* mission around the time of its launch.

Perhaps *Mariner 10* seems terribly limited in capability by today's standards. Yet its remarkable story illustrates how the combination of careful planning before launch and creative problem solving during the flight allowed mission objectives to be achieved despite unanticipated problems that could easily have ended the mission.

An Overview —

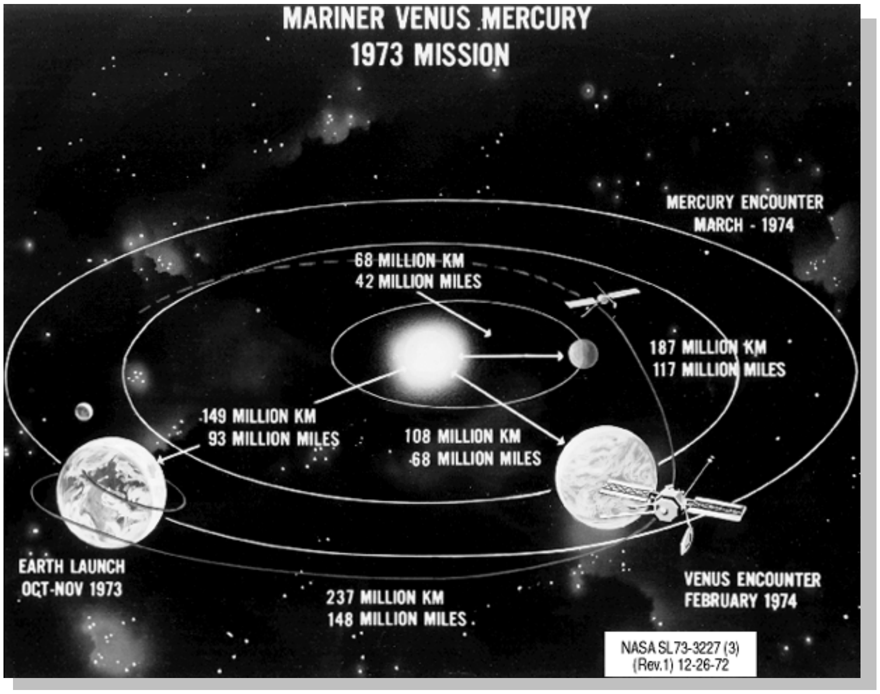
Mariner 10 was launched on November 3, 1973, on the first day of the scheduled launch period. The mission first encountered Venus in early 1974, providing the first close-range measurements of Venus and using that planet to provide a gravity-assist maneuver in order to reach Mercury. *Mariner 10* therefore became the first mission to use a gravitational-assist trajectory as well as the first to visit more than one planetary target at close range. The spacecraft was then transferred into a retrograde orbit around the Sun. In this orbit, the spacecraft encountered Mercury three times. Tables 1 and 2 list the mission firsts and details.

TABLE 1. *Mariner 10* firsts.

Gravitational assist trajectory
Mercury close encounter
Close encounter with more than one planet

TABLE 2. *Mariner 10* mission.

Mission Management:	JPL
Launch:	November 3, 1973, 5:45 UTC
Launch Site:	Cape Canaveral, USA
Launch Vehicle:	Atlas-Centaur 34
Spacecraft Mass:	502.9 kg
Arrivals —	
Venus:	February 2, 1974 (5768 km)
Mercury I:	March 29, 1974 (703 km)
Mercury II:	September 21, 1974 (48,069 km)
Mercury III:	March 16, 1975 (327 km)
End of Mission:	March 24, 1975



Mariner 10's first flyby (Mercury I), which had a darkside periapsis, occurred in March 1973, 146 days after launch. At closest approach, the spacecraft was 700 kilometers above the unilluminated hemisphere. A search was conducted for a tenuous neutral atmosphere by observing the extinction of extreme ultraviolet solar radiation and by observing thermal infrared emission from a favorable (dark) groundtrack. *Mariner 10* passed through a region in which the Earth is occulted by Mercury (as viewed from the spacecraft) to permit a dual-frequency (X- and S-band) radio occultation probe to search for an ionosphere and to measure the radius of the planet. A global magnetic field was discovered during this encounter, arguably the most unexpected finding of the mission.

Following a 176-day solar orbit, the second flyby, Mercury II, had a sunlit southern hemisphere passage with a periapsis of approximately 50,000 kilometers, which allowed the filling of the gap between the incoming and outgoing portions of Mercury photographed during the first encounter.

During the third and closest flyby, Mercury III, the spacecraft flew to within 330 kilometers of the surface, with the main objective of defining the source of the magnetic field that had been discovered during the first encounter. For that reason, the third encounter (like the first), was a darkside flyby. This encounter yielded the most accurate celestial mechanics data of the mission because of its close passage and the absence of an Earth occultation. Partial-frame pictures at the highest resolution obtained, as good as 90 meters, were acquired near the terminator in areas previously photographed at low resolution during the first encounter.

Data continued to be collected until March 24, 1975, when the supply of attitude-control gas was exhausted and the 506-day mission was terminated. *Mariner 10* is still orbiting the Sun, even though its electronic systems have probably been destroyed by solar radiation. Total research, development, launch, and support costs for the Mariner series of spacecraft (Mariners 1 through 10) was approximately $554 million, with an average cost of $55 million per mission.

Spacecraft and Subsystems —

The spacecraft bus structure was eight-sided and measured approximately 1.4 meters across and 0.5 meters in depth. The total weight of the spacecraft was 504 kilograms, including 80 kilograms of scientific payload and 20 kilograms of hydrazine fuel. With its two 2.7 × 1-meter solar panels deployed, the span of the spacecraft was 8.0 meters. Each panel supported 2.5 square meters of solar cell area and was attached to the top of the octagonal bus. The spacecraft measured 3.7 meters from the top of

its low-gain antenna to the bottom of the thrust vector control assembly of its propulsion subsystem. In addition, the high-gain antenna, magnetometer boom, and plasma science experiment boom were attached to the bus. The two-degrees-of-freedom scan platform supported the two television cameras and the ultraviolet airglow experiment. A two-channel radiometer was also onboard. The rocket engine was liquid-fueled, and two sets of reaction jets were used to provide three-axis stabilization. *Mariner 10* carried a low-gain omnidirectional antenna, composed of a 1.4-meter-wide honeycomb-disk parabolic reflector. The antenna was attached to a deployable support boom and was driven by two-degrees-of-freedom actuators to obtain optimum pointing toward Earth. The spacecraft could transmit at S- and X-band frequencies. A Canopus star tracker was located on the upper ring structure of the octagonal satellite, and acquisition Sun sensors were on the tips of the solar panels.

Simple thermal protection strategies consisted of (1) insulating the interior of the spacecraft top and bottom with multilayer thermal blankets, and (2) deploying a sunshade after launch to protect the spacecraft on the side oriented toward the Sun.

TABLE 3. *Mariner 10* payload.

Instrument	**P.I., Institute**
TV system	B. Murray, *California Institute of Technology*
IR radiometer	C. Chase, *Santa Barbara Research*
UV airglow and occultation spectrometers	A. Broadfoot, *Kitt Peak Observatory*
Radio science and celestial mechanics package	H. Howard, *Stanford University*
Magnetometer	N. Ness, *NASA Goddard Space Flight Center*
Charged particle telescope	J. Simpson, *University of Chicago*
Plasma analyzer	H. Bridge, *Massachusetts Institute of Technology*

Scientific payload. The television science and infrared radiometry experiments provided planetary surface data. The plasma science, charged particle, and magnetic field experiments supplied measurements of the environment around the planet and the interplanetary medium. The dual-frequency radio science and ultraviolet spectroscopy experiments were designed for the detection and measurement of Mercury's neutral atmosphere and ionosphere. The celestial mechanics experiment provided measurements of planetary mass characteristics as well as tests of the theory of general relativity. Table 3 lists the *Mariner 10* payload.

A study in scary problems and creative solutions. A mission to Mercury was a very challenging endeavor early in the space program, for the same reasons such a mission is challenging today: Dealing with the high thermal radiation environment and the large gravity well of the Sun. Thus, it was the last spacecraft in the Mariner series that was sent to Mercury to complete the survey of the inner solar system. Problems occurred throughout the mission, and were largely due to thermal stresses. Most were resolved soon after they occurred, others were dealt with by very creative use of the "work around" approach.

During cruise, a series of minor problems developed and were either corrected or disappeared on their own. Failure of a vidicon optics heater initially threatened to truncate the life of the TV camera. Unexpectedly, the heater began operating again before Venus encounter, and remained operational for the remainder of the mission. Part of the scanning electrostatic analyzer, designed for the solar wind experiment, failed before Venus encounter, possibly due to thermal stresses. The high-gain antenna suffered periodic loss of signal. The mission operations team, surmising that the problem resulted from low ambient temperature, developed and implemented a strategy to increase the temperature of the high-gain antenna. No further problems were experienced with it.

More serious problems occurred for which coping strategies had to be developed. The occasional loss of signal from the Canopus Star Tracker, caused by sunlight reflecting off stray particles that originated from and accompanied the spacecraft, was considered normal. This behavior was exacerbated as the spacecraft approached the Sun and the reflections off the stray particles became brighter. Canopus used a roll maneuver (which required firing of the gyros) to reestablish contact. This would have been a satisfactory, albeit distracting, solution, except for problems with the gyros. Prior to Venus encounter, an electrical short was thought to have caused a power glitch when the gyros were turned on, thereby resulting in loss of the nitrogen gas used to activate the gyros. The Canopus reacquisition roll maneuver, occurring at increasing frequency, aggravated this loss. The creative strategy developed to cope with this situation involved monitoring the star tracker and, as soon as this maneuver commenced, using the solar panels as “sails” to control the roll. When being used as “sails,” panels were differentially oriented toward the Sun so that a photonic force on the panels counteracted the spacecraft’s gyro-induced tendency to oscillate. The optimal tilts were discovered through a combination of calculations and trial and error until a workable solution was achieved. In addition, commands were uploaded to the onboard computer to allow automatic updating of reference pointing angles for the star tracker and high-gain antenna to eliminate the roll maneuver.

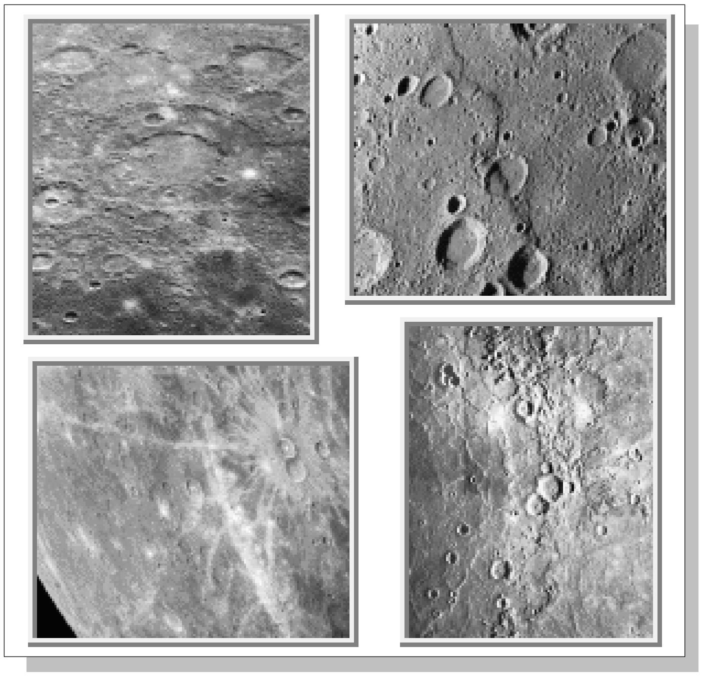
In the end, *Mariner 10*, limping along prior to the final Mercury encounter using “solar sailing” to preserve gas in the gyros, had great difficulty in performing the final maneuver of establishing its position, because the star tracker had to operate without being able to perform the normal roll. The operations team developed the clever strategy of tracking high-gain antenna patterns to determine position. The use of solar panels as sails is considered today to have been a major innovation in spacecraft technology.

In fact, the difficulty in performing this final position determination maneuver resulted in large errors in knowledge of the spacecraft’s position during the final encounter. As a result, the infrared radiometer, which had fixed body pointing near the orbit plane, did not acquire data during the last pass.

A final problem occurred just prior to the second encounter. The loss of functionality of the onboard tape recorder required extensive revision of the television sequencing, meaning that all data would have to be acquired on the ground in realtime. This effectively resulted in lower data rates, which translated to cutbacks in resolution and/or coverage, particularly with respect to imaging. Remarkable planning allowed the impact of this problem to be substantially mitigated, particularly during the relatively long second encounter.

The Imaging of Mercury —

Mariner 10 on television. During the first flyby, *Mariner 10*’s closest approach to the planet occurred when the cameras could not photograph the sunlit portion of Mercury. The cameras were equipped with 1500-millimeter focal length lenses so that high-resolution pictures could be taken during approach as well as postencounter phases. The imaging sequence was initiated 7 days before the encounter with Mercury, when about half the illuminated disk was visible and the resolution was better than that achievable with Earth-based telescopes. Photography of the planet continued until some 30 minutes before closest approach, thereby providing a smoothly varying sequence of pictures of increasing resolution. Pictures with resolutions



on the order of 2–4 kilometers were obtained for both quadratures during the first encounter. Resolution varied greatly, ranging from several hundred kilometers to approximately 100 meters. Large-scale features observed at high resolution were used to extrapolate coverage over broad areas photographed at lower resolution. The highest-resolution photographs were obtained approximately 30 minutes prior to and following the darkside periapsis during the first and third encounters. Pictures were taken in a number of spectral bands, enabling the determination of regional color differences.

The second Mercury encounter provided more favorable viewing geometry than the first. In order to permit a third encounter, it was necessary to target the second brightside encounter along a south polar trajectory. This trajectory allowed unforeshortened views of the south polar region, an area that had not previously been accessible for study. Images from this region provided a geologic and cartographic link between the two sides of Mercury photographed on the first encounter. Stereoscopic coverage of the southern hemisphere was also achieved. Because of the small field of view resulting from the long focal length optics, it was necessary to increase the periapsis altitude to about 48,000 kilometers to ensure sufficient overlapping coverage between consecutive images. The resolution of the photographs taken during closest approach ranged from 1 to 3 kilometers.

The third Mercury encounter was targeted to optimize the acquisition of magnetic and solar wind data. Therefore the viewing geometry, and hemispheric coverage, during the third encounter was very similar to that employed during the first encounter. However, the third encounter also presented the opportunity to provide high-resolution coverage for areas of interest seen previously at lower resolution. Because of ground communication problems, these pictures were acquired as quarter frames.

What was Actually Accomplished by *Mariner 10*?

The stated objectives of the mission were first and foremost (1) to measure the surface, atmospheric, and physical characteristics of Mercury, and (2) to measure the atmospheric, surface, and physical characteristics of Venus. Additional objectives were to (3) complete the survey of the inner planets, (4) validate the gravity assist trajectory technique, (5) test the experimental X-band transmitter, and (6) perform tests of general relativity theory. What were the actual scientific results of the mission?

Venus first. First of all, before reaching Mercury, *Mariner 10* provided some very interesting coverage of Venus, flying by the planet at a distance of 4200 kilometers, and revealing the planet to be nearly spherical and enveloped in extensive cloud layers. With its slow rotational period of 243 days, Venus was found to be nearly tidally locked to the Sun, and to have a miniscule magnetic field.

Mercury's interior. *Mariner 10* confirmed that Mercury has the highest observed mean uncompressed density of any planet: $5.3\ \mathrm{g/cm^3}$ at 10 kilobars, implying the existence of a huge iron-rich core and high bulk iron abundance. The moment-of-inertia measurements made during the mission (C_{20} to 30%, C_{22} to 50%; *Anderson et al.,* 1987) were not sufficiently accurate to distinguish between a differentiated and a homogeneous body. Composition was not directly measured, thus the mission provided little guidance for compositional or thermal models of the interior. However, *Mariner 10* made a critical discovery that supports the existence of an inner, partially molten, iron-rich core and extensive geochemical differentiation. The spacecraft passed nearly directly above the rotational north pole of Mercury at an altitude of 327 kilometers and measured a magnetic field of ~400 nanotons (*Ness et al.,* 1974, 1975). The variation and magnitude of this field along the spacecraft trajectory implied a planetary field of internal origin, closely approximated by a rotationally aligned dipole within the core. The magnetic dipole moment of ~300 nT/Rm^3 (5×10^{-4} that of Earth) indicates that Mercury has a global intrinsic magnetic field. Although fundamentally weak, the field appears to be too strong to be explained by remnant magnetism (*Schubert et al.,* 1988), although this as well as some more exotic possibilities cannot be ruled out completely. Several attempts to model the magnetic field configuration using *Mariner 10* measurements have led to nonunique models (*Connerney and Ness,* 1988).

TABLE 4. Past and planned mission measurements.

Measurement	***Mariner 10* (1974)**	***MESSENGER* (2010)**
Bulk composition/inner structure	0	2
Geological survey	1	2
Mineralogical survey	0	2
Atmosphere survey	1	2
Atmosphere/magnetosphere interaction	0	1
Core/mantle/surface interaction	1	1
3D magnetic field modeling	0	1
Second-order gravitational modeling	0	1
3D magnetosphere structure	1	1
Magnetosphere composition	0	1
Energetic particle acceleration	1	2

0 = none; 1 = partial; 2 = complete primary.

Mercury's surface. Mariner 10 provided imaging for just less than half the planet, which included limited stereo imaging, at resolutions up to 90 meters during the third-closest flyby. At first glance, Mercury was seen to be quite similar to the Earth's Moon, with a surface dominated by craters and lunarlike (some rugged and some smoother) terranes. The limited coverage and limited nature of many onboard measurements resulted in the rather slow development of theories of the planet's history and origin. Further study indicated that Mercury is distinctively different from the Moon. Except for impact basins and basin interiors, the most widespread features are without lunar analog. The earliest orthogonal network of lineaments formed during tidal spindown (*Melosh and McKinnon,* 1988). During the crustal expansion that followed, lineaments became strike-slip ridge and trough terrane (*Clark et al.,* 1988), while intercrater plains covered the surface as a result of volcanic or impact processes or both (*Spudis and Guest,* 1988). A later episode of crustal contraction resulted in the formation of an extensive network of north-south thrust fault scarps (*Strom et al.,* 1975). Finally, volcanic smooth plains, the most lunarlike of Mercury features, filled impact basins that formed during the late heavy bombardment (*Spudis and Guest,* 1988). Further assessment of Mercury's coordinate system (*Robinson et al.,* 1999) and interpretation of *Mariner 10* images (*Cook and Robinson,* 2000) continues, but the nature of the interior differentiation process and its surface expression remain largely unconstrained.

Mercury's atmosphere. Mariner 10 provided minimal "snapshots" of certain atmospheric constituents during the two dayside passes. The ultraviolet spectrometer was designed to detect species thought to be ubiquitous in terrestrial planetary atmospheres: CO_2, NH_3, Ar, and Ne. As a result, *Mariner 10* detected only three species with lines in the same spectral region: H, He, and O. In recent years, groundbased measurements have provided some additional insight about atmospheric constituents (*Morgan and Killen,* 1997), including their temperatures, distribution, and suspected sources. For example, H, believed to be derived from the solar wind along with He, has a colder (nightside) and hotter (dayside) component. Other components, believed to be derived from rock substrate, are hotter than (Na), much hotter than (Ca), or accommodated to (O) the surface. It is thought that temperature differences are related to source processes, but much about atmospheric components awaits *in situ* measurement by the next mission to Mercury.

Mercury's magnetosphere. During *Mariner 10*'s encounters, many structures and phenomena reminiscent of the Earth's magnetosphere were observed. The magnetic field was found to be aligned closely with Mercury's rotation axis, and to be two orders of magnitude weaker than the Earth's (*Ness et al.,* 1974, 1975). However, the magnetic field was strong enough to stand off the solar wind plasma at an altitude of 1 Rm above the subsolar point, creating a bow shock (in the supersonic solar wind flow) and thus diverting the incoming plasma around this small magnetosphere (*Ogilvie et al.,* 1974; *Hartle et al.,* 1975). Within the magnetosphere, several very intense energetic particles events were observed by *Mariner 10*'s cosmic-ray telescopes (*Simpson et al.,* 1974)! Measurements from these instruments, obviously not designed to study magnetospheric phenomena, along with detection of large magnetic field perturbations provided very strong evidence for Earth-like magnetospheric substorms (*Siscoe et al.,* 1975; *Ogilvie et al.,* 1977; *Christon et al.,* 1987; *Slavin et al.,* 1997). A magnetopause, magnetotail, and plasma sheet with familiar electron energy spectra were identified. Magnetic field depolarization occurred during multiple substorm-like plasma injections, as well as quasiperiodic alternating plasma sheet and boundary layer variations. Much of the solar wind appeared to be "stopped" by the magnetic field, except in the case of regional impacts during substorms. The magnetopause ranged from 1.5 to 2.4 planetocentric Mercury radii toward the Sun (*Russell et al.,* 1977; *Slavin and Holzer,* 1979). The presence of modest radiation belts was suspected. Extremely short substorm timescales (1–2 minutes vs. 1–2 hours) (*Siscoe et al.,* 1975; *Christon,* 1987) are implied by the extreme brevity of the magnetospheric phenomena observed, such as the 1–2-minute-duration substorms recorded by many workers (*Ness et al.,* 1974; *Ogilvie et al.,* 1974). Data from *Mariner 10* also indicated that the magnetopause had a significant aberration from the ecliptic plane (*Ness et al.,* 1975).

Mariner 10: Questions Left Unanswered —

Mariner 10 yielded some intriguing results (Table 4, in the context of measurements planned for the Mercury *MESSENGER* mission) and generated new questions (Table 5), which remain unanswered until we return to complete the exploration of the planet that has variously been called the "boring planet" (R. Strom, personal communication, 1980), the "elusive planet" (*Strom,* 1987), and the "iron planet" (*Strom,* 2003).

TABLE 5. Questions raised and left unanswered by *Mariner 10*.

Interior	What is the nature and origin of Mercury's interior structure, particularly in regard to its core? What is the nature of its magnetic field? Why is Mercury's internal density so great?
Surface	What is the nature and extent of volcanic activity on Mercury? What is the history of formation of Mercury's major terranes, and the nature of its core/surface interaction?
Atmosphere	What is the origin, nature, and distribution of Mercury's atmospheric constituents? What is the nature of its atmosphere/ magnetosphere/surface interaction?
Magnetosphere	What is the structure of its magnetosphere? What is the nature of its magnetosphere/solar wind interaction?

The Last Word —

In a telegram to Dr. Jim Dunne, Mariner 10 Project Scientist at JPL, Dr. Norm Ness, NASA Goddard leader of the Magnetometer Team, wrote " . . . To everyone . . . at JPL who has . . . helped to nurse the mission through to its brilliant conclusion, we offer our heartiest congratulations for a job well done and our thanks for helping us obtain these exciting and scientifically important measurements."

Editor's Note: Historical sources listed below, including Web sites, were freely used in constructing this newsletter. The bibliography includes material of historical significance not used in this newsletter. (Sources actually used are marked with an asterisk.) The *Mariner 10 Bulletins*, now available on line thanks to the efforts of Dr. Mark Robinson, provided much of the detail for the section on "Scary Problems and Creative Solutions." Fortunately, there is no book on Mercury that refers to it as "The Boring Planet."

Web Sites —

*NASA History, the SP-423 Atlas of Mercury On Line
http://history.nasa.gov/SP-423/mariner.htm

*NSSDC Site on Mariner 10
http://nssdc.gsfc.nasa.gov/database/MasterCatalog?sc=1973-085A

*Planetary Photojournal for Mariner 10
http://photojournal.jpl.nasa.gov/targetFamily/Mercury

*Mark Robinson's Mariner 10 Archive Project
http://www.earth.nwu.edu/research/robinson/image_archive.html
http://www.earth.nwu.edu/people/robinson/BULLETINS/bul-10.pdf

*Mercury and Mariner 10 Photoarchive
http://www.seds.org/billa/tnp/mercury.html

LANL History of Mercury Study (excellent images)
http://www.solarviews.com/eng/mercury.htm

National Air and Space Museum Archive
http://www.nasm.edu/ceps/rpif/mercury/rpifmerc.html

Educational materials from Spacelink, including Mariner 10 material
http://spacelink.nasa.gov/Instructional.Materials/Curriculum.Support/Space.Science/Our.Solar.System/Mercury/.index.html

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See also chapters on Mariner 10 in these books on Mercury:

Mercury: The Elusive Planet, By R. G. Strom, 1987, Smithsonian Institution Press, Washington, DC. 197 pp.

Exploring Mercury: The Iron Planet, By R. G. Strom and A. L. Sprague, 2003, Praxis-Springer Publishing Ltd., UK. 256 pp.