2

The *Mariner 10* mission

2.1 THE ONLY ONE

Mariner 10 is the only spacecraft to have visited Mercury. In the early 1960s a number of planetary missions were being considered, particularly to Mars. However, it was discovered in 1962 that the positions of the Earth, Venus, and Mercury would be configured in such a way in 1970 and 1973 that a spacecraft launched to Venus could be nudged by its gravity field to send it on a new trajectory to Mercury. Thus, with a single spacecraft it would be possible to visit two planets with a minimum expenditure of on-board fuel. The launch had to take place in 1970 or 1973 because the next economical opportunity would not occur until the mid-1980s. Therefore, there was a sense of urgency to devise a mission to Venus and Mercury as soon as possible. In 1968 the Space Science Board of the National Academy of Sciences endorsed a mission to fly by Venus and Mercury in 1973. Late in 1969 Congress approved the mission to begin development in 1970.

2.2 MISSION CONCEPT

It was never intended for this mission to orbit Mercury because it would be traveling so fast past Mercury (~50 km/sec) that it would require a huge amount of fuel to slow down the spacecraft enough to put it into orbit. The size of the retrorocket would have to be equivalent to a medium-sized launch vehicle of that era, and require a launch vehicle comparable in size to the *Saturn V* moon rocket. At that time we did not know about multiple encounters with Venus and Mercury that could slow the spacecraft to low enough speeds to put it in orbit with a relatively small retrorocket. Furthermore, this mission was conceived as a first reconnaissance of Mercury that would be followed in several years by a more sophisticated orbiter. Of course, this is still not the case, and it will have been over 35 years before the next spacecraft explores Mercury.

2.2.1 NASA chose the Jet Propulsion Laboratory

The National Aeronautics and Space Administration (NASA) designated the Jet Propulsion Laboratory (JPL) of the California Institute of Technology to develop and operate the mission. A *Mariner*-type spacecraft was chosen for the mission, and the project was named the Mariner Venus/Mercury Mission. The spacecraft was called *Mariner 10* because it was the 10th *Mariner* to be launched.

Although this spacecraft had to penetrate and operate in a more hostile environment than any previous spacecraft, NASA insisted that it initiate a new breed of low-cost missions. This may sound familiar to the concept of "faster, cheaper, better" that NASA espoused in the 1990s. As with the failures of the two Mars missions in 1998 and 1999, this concept of "cheaper and better" in 1970 almost resulted in the loss of the Mercury mission. One of the most severe restrictions was the use of only one spacecraft to explore two planets. Previous lunar and planetary missions had used two or more spacecraft to gather more data and provide a backup in case one failed. The *Mariner 8* spacecraft to Mars, for instance, experienced a launch failure, leaving only *Mariner 9* to carry out the first orbital mission to that planet. Fears of a similar failure prompted the Mariner Venus/Mercury Mission to request a backup spacecraft when it became evident that one could be prepared within the total project cost of $98 million. Basically, a backup involved only a small increase in the number of spare components. However, this backup spacecraft was to be used only if a failure of the prime spacecraft or launch vehicle occurred during the 16 October to 21 November launch window. If the primary spacecraft failed on or after 21 November, the second spacecraft could not be launched and the mission would be lost. Understandably, the project scientists and engineers were very concerned. Naturally the scientists and engineers wanted to launch both spacecraft so that more data could be obtained, and also in case one spacecraft failed after 21 November. However, to save money they only launched one. As it turned out, this spacecraft was successful, but it almost failed just before it encountered Mercury, as you will see later in this chapter. Today the backup spacecraft is on display at the Smithsonian Air and Space Museum in Washington, D.C.

2.2.2 A necessary gravity-assist

The *gravity-assist* trajectory technique was needed to obtain an economically acceptable mission. This technique allows a spacecraft to change both its direction and speed without using valuable fuel, thereby saving time and leaving more weight for the scientific instruments. Thus, the *Mariner* spacecraft could be launched with an acceptable payload by a relatively cheap *Atlas/Centaur* rocket. If a direct flight to

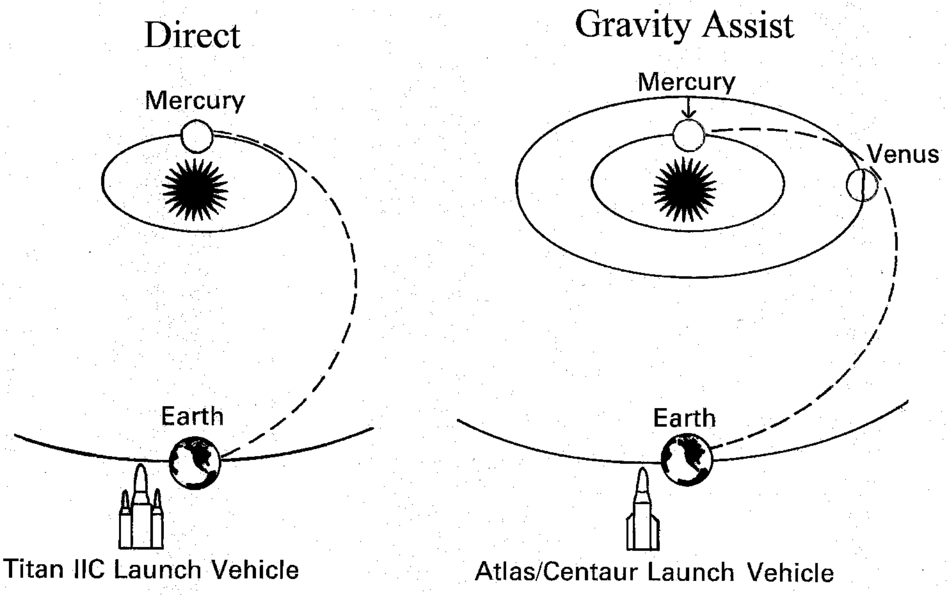

Figure 2.1. The gravity-assist trajectory to Mercury used the gravity and orbital motion of Venus to send the spacecraft into the innermost part of the solar system without the need to expend precious fuel except for minor trajectory corrections. A direct flight without a Venus assist would require a much larger launch vehicle to deliver the same payload. *Mariner 10* was the first planetary mission to use the gravity assist trajectory, which has since been used by other missions such as *Voyager* and *Cassini* for the exploration of the outer solar system (modified from Dunne and Burgess 1978).

Mercury were used, a much larger and more costly *Titan IIIC/Centaur* would be required, and its high speed past Mercury would permit only a short time to acquire data. Not only did this gravity-assist trajectory enable one spacecraft to explore two planets, it also provided a bonus return visit to Mercury (Figure 2.1).

At a conference in February, 1970, on Mercury and the Venus/Mercury Mission at Cal Tech in Pasadena, California, the late celestial mechanician Giuseppe Colombo of the Institute of Applied Mechanics in Padua, Italy, noted that after *Mariner 10* flew by Mercury, its orbital period around the sun would be quite close to twice Mercury's orbital period. He suggested that a second Mercury encounter could therefore be accomplished. A detailed study of the trajectory by JPL confirmed Colombo's suggestion and showed that by carefully selecting the Mercury flyby point, a gravity correction could be made that would return the spacecraft to Mercury about six months later. In fact, it would be possible to achieve multiple encounters with Mercury; the number depending on the fuel available for midcourse corrections and attitude control. *Mariner 10* would eventually achieve three encounters with Mercury before it ran out of fuel.

2.3 THE FLIGHT PLAN

2.3.1 A narrow launch window

The mission plan for *Mariner 10* was the most complex for any planetary mission up to that time. It called for a launch sometime between 16 October and 21 November, 1973. NASA chose 3 November so that the spacecraft would encounter Mercury at a time when it could view the planet about half lit (quadrature). Viewing Mercury at this phase would make it easier to distinguish surface features by their shadows. The trajectory relied on Venus' gravitational field to alter the spacecraft's flight path and speed relative to the Sun. Properly aimed, the spacecraft's speed would be reduced, causing it to fall closer to the Sun and cross Mercury's orbit at the precise time needed to encounter the planet.

New levels of navigational accuracy were required to intercept Venus with high precision. The flyby point at Venus had to be controlled within 400 km, or a Mercury encounter would not occur. At least two spacecraft maneuvers would be needed between Earth and Venus, and probably a further two between Venus and Mercury. *Mariner 10* would be the first planetary mission to use this gravity-assist technique.

The flight plan called for the upper-stage *Centaur* rocket to be turned off for 25 minutes shortly after launch from the Kennedy Space Center. This would place it in a parking orbit that would carry it partway around the Earth. Then a second ignition would thrust the *Mariner* spacecraft in a direction opposite to the Earth's orbital motion, providing the spacecraft with a lower velocity relative to the Sun than the Earth's orbital velocity. This would allow it to be drawn inward by the Sun's gravitational field to achieve an encounter with Venus. After a few months *Mariner 10* would approach Venus from its night side, pass over the sunlit side, and, slowed by Venus' gravitational field, fall inward toward the Sun to rendezvous with Mercury.

2.3.2 Spacecraft design

The *Mariner 10* spacecraft evolved from more than a decade of *Mariner* technology, beginning with the Venus mission in 1962 and culminating with the Mars orbiter in 1971. *Mariner 10* would be the last of the *Mariner* spacecraft to fly. Like the other *Mariners*, it consisted of an octagonal main structure, solar cell panels, a battery for electrical power, nitrogen gas jets for three-axis attitude stabilization and control, star and Sun sensors for celestial reference, S-band radio (12.6 cm wavelength) for command and telemetry, a *high-* and *low-gain antenna*, and a *hydrazine* rocket propulsion system for trajectory corrections (Figure 2.2, see colour plate section).

Mariner 10 flew much closer to the Sun than any previous spacecraft. It was subjected to solar intensities up to 4.5 times greater than at Earth, requiring thermal control to maintain temperatures at a level that would not damage the spacecraft systems. To meet this requirement, a large sunshade, louvers and protective thermal blankets, and the ability to rotate the solar panels were added to the design. Because

Mariner 10 would be so close to the Sun, only two solar panels were needed to generate enough electricity to power the spacecraft. As the spacecraft approached the Sun, the panels could be rotated to change the angle at which light fell on them, and thus maintain a suitable temperature of about 115°C.

Another major design change from past *Mariners* was the addition of a capability to handle up to 118,000 bits per second of imaging data. If this high data rate had not been implemented, all television pictures of Mercury would necessarily have been recorded on the tape recorder and played back at a later time, as occurred on previous planetary missions. Since the tape recorder was capable of holding only 36 images, the amount of high-resolution coverage of Mercury taken during the short interval near closest approach would have been severely limited. The high data rate permitted the spacecraft to transmit high-quality pictures in "real time", or as fast as they were taken, thereby allowing hundreds of images to be obtained during the missions critical encounter phases. This capability provided 5 times as many images and much greater high-resolution coverage than would otherwise have been possible. The high data rate capability turned out to be crucial to the success of the second and third encounters, because the tape recorder failed after the first flyby. Today we fly reliable solid-state storage devices with large capacities rather than tape recorders.

2.3.3 Scientific payload

Since so little was known of Mercury, the scientific instruments to be flown by *Mariner 10* had to be chosen carefully in order to explore the planet as thoroughly as possible. To this end, seven experiments were selected: television imaging: *infrared radiometry*; *ultraviolet spectroscopy*; magnetic fields; *plasma science*; charged particles; and radio science. Radio science did not require a special instrument because it uses the onboard radio system. These experiments would provide data to explore the interior, surface, and near-planet environment of Mercury, and also to obtain data on the atmosphere and space environment of Venus.

2.3.3.1 The television experiment

The imaging system consisted of two *vidicon cameras*, each with an eight-position filter wheel. The vidicons were attached to long focal-length *Cassegrain telescopes*, which were mounted on a scan platform for accurate pointing. These telescopes provided narrow-angle, high-resolution images, and were powerful enough to read fine newsprint from a distance of a quarter of a mile. They were absolutely essential for the study of Mercury's surface.

A principal concern of the atmospheric scientists on the Imaging Science Team was the inability of the narrow-angle cameras to image large portions of Venus with one image around the time of encounter. To study atmospheric circulation it is desirable to take pictures of large portions of the atmosphere over a relatively long period, even if the images are at relatively low resolutions. Since this flight would be the first time a spacecraft imaged the atmosphere of Venus, atmospheric scientists desperately wanted such pictures. The budget for this project, however, was extremely tight, and any system to obtain such pictures had to be inexpensive and not interfere with the narrow-angle optics. One evening after an Imaging Science Meeting in Pasadena, California, several team members were discussing this problem over cocktails at a local restaurant. During this discussion, Bruce Hapke suggested an optical design (which Verner Suoumi and Michael Belton sketched on the back of a cocktail napkin) that could provide the equivalent of wide-angle cameras within the budget. The design consisted of auxiliary optics attached to each camera and could be operated by moving a mirror on the filter wheel to a position in the system's optical path. The next morning this design was presented at the team meeting at JPL, and eventually it was incorporated into the camera system.

The primary objective of the imaging experiment was to study the physiography and geology of Mercury's surface, determine accurately its size, shape, and rotation period, evaluate its photometric properties (the manner in which light is reflected from its surface), and search for possible satellites and color differences on its surface. The cameras also took pictures of Venus to determine its cloud structure and atmospheric circulation. Five filters on the two different cameras were used at Mercury. The effective central wavelengths of the filter band passes were: clear (CLR, 487 nm); ultraviolet (UV, 355 nm), blue (BL, 475 nm); minus ultraviolet (MUV, 511 nm); and orange (OR, 575 nm). In addition to wide-angle capability, the filter wheels included a UV polarizer for Venus observations and a calibration lens.

2.3.3.2 Infrared radiometer

The infrared radiometer measured the thermal emission from Mercury and the clouds of Venus using two broad wavelength bands centered at 11 and 45 μm. Brightness temperatures provided information on the thermal properties of Mercury's surface material and were used to infer surface roughness, size of the particles that make up the surface, and whether or not there were rock outcrops and if so, their size. The thermophysical properties of the top few centimeters of the surface were inferred from the rate of cooling on the evening side of the planet. The spatial resolution of the observations was as small as 45 km.

2.3.3.3 Extreme ultraviolet (EUV) experiments

Theoretical predictions indicated that the most likely constituents of an atmosphere on Mercury would be hydrogen, helium, carbon, oxygen, argon, and neon. Even carbon dioxide was a possibility. Consequently, extreme ultraviolet spectrometers were designed to detect these elements. Two instruments sensitive in the extreme ultraviolet (300–1657 Å) were designed and flown on the spacecraft. The airglow spectrometer (polychromator) was placed on the scan platform and the occultation grating spectrometer was mounted on the spacecraft body.

The instrument called the occultation spectrometer was designed to make measurements of the Sun as it passed behind the *limb* of the planet. Any extinctions of sunlight above the limb of Mercury could be attributed to gases in the atmosphere. Channel electron multipliers measured the solar flux at four wavelength positions chosen to cover the first ionization bands of Ne, He, Ar, and Kr.

The second instrument was a spectrometer designed to search for airglow at wavelengths specifically chosen as possible sources: H, He, He^+, Ar, Ne, O, Xe, and C. There were 10 airglow channels and 2 control channels. This instrument was on the scan platform so that measurements could be made across the disk of the planet.

Observations of the bright side of the Moon and Mercury were made with the airglow spectrometer and obtained the first and only measurements of Mercury in the EUV. In addition, Venus, and hydrogen and helium radiation emanating from outside the Solar System were observed with the spectrometer.

2.3.3.4 Magnetic field experiment

The purpose of this investigation was to study any possible magnetic field environment around Mercury and the nature of the *solar wind* interaction with the planet. The magnetic field experiment consisted of two triaxial fluxgate magnetometers located at different positions along a 6-m (20 ft) boom extending from the spacecraft. The spacecraft itself generated a magnetic field, so it was necessary to place the sensors at different distances from the spacecraft to measure this field and then to subtract it from the interplanetary field and any magnetic field associated with Venus or Mercury. There was onboard verification of the assumption that the magnetic field of the spacecraft solar array panels was negligible. The spacecraft itself had a variable magnetic field, although this was small compared to the fields found to be associated with Mercury. More about the particles and fields instruments will be found in Chapter 5.

2.3.3.5 Plasma science experiment

To understand the interaction of the solar wind with Mercury, it was necessary to observe the velocity and directional distribution of positive ions and electrons in the solar wind. Two plasma detectors were therefore located on a motor-driven platform attached to the spacecraft body. This experiment showed whether the solar wind interacted with Mercury in a manner analogous to the Earth rather than to the Moon or Venus, thus indicating an intrinsic magnetic field. Thus, the plasma detectors strongly complemented the measurements of the magnetic field discovered by the magnetometer.

The charged particle experiment was designed to observe high-energy charged particles (atomic nuclei and electrons) over a wide range of atomic numbers and energies. The objectives of this experiment included the determination of the effects of the Sun's extended atmosphere (heliosphere) on cosmic rays entering the Solar System from elsewhere in the galaxy, and the search for charged particles in the vicinity of Mercury.

2.3.3.6 Radio and telemetry system

Finally, the radio waves emitted by the spacecraft telemetry system were mathematically analyzed to determine the gravitational effects of Mercury on the predicted trajectory of the spacecraft. In this way, it was possible to accurately measure Mercury's mass and radius. These data provided a means of accurately determining Mercury's density and, hence, estimates of its internal constitution and structure. Gases in an atmosphere refract and scatter a radio signal, and by measuring these effects it is possible to calculate atmospheric pressures and temperatures. An occultation experiment sought to observe changes in the radio waves as they moved through the atmospheres of Venus and Mercury when *Mariner 10* passed behind the planets as viewed from Earth.

2.4 *MARINER 10* GOES TO MERCURY

Finally, all was ready and the launch day approached. The finalized configuration was tested and mounted on the top of the *Atlas/Centaur 34* launch vehicle on Complex 36's Pad B of Cape Canaveral about 10 days before the 3 November, 1973 launch date.

2.4.1 Launch

After numerous tests of the spacecraft and science instruments under the simulated hostile conditions expected on the Venus/Mercury mission, all was ready for this epic journey of exploration. The spacecraft had to be launched on 3 November, 1973, during a short 1.5 hour period. At 12:45 a.m. Eastern Standard Time, *Mariner 10* was sent aloft (Figure 2.3, see colour plate section).

For the first time on any planetary mission, the science instruments were turned on soon after launch. The purpose was to calibrate them in the well-known environment of the Earth–Moon system. Images of Earth were taken for comparison with Venus, and pictures of the Moon were taken for comparison with Mercury. At this time the first of many problems to plague this historic mission occurred. Heaters designed to hold the television optics at temperatures of 4° to 15°C failed to operate. It was feared that the temperatures would drop to a level low enough to affect the sensitive optics and distort the images. Fortunately, the temperature stabilized at an acceptable level and the cameras maintained their sharp focus. Pictures of Earth showed complex cloud patterns in about the same detail expected at Venus (Figure 2.4). They could provide valuable comparisons with the Venus clouds. The spacecraft's trajectory took it over the Moon's north pole, where pictures provided the basis for subsequently improving the lunar cartographic network and extending it more accurately to the far side – a prelude to a similar application for constructing maps of Mercury (Figure 2.5). Plasma, ultraviolet, and magnetic measurements were also made within the Earth–Moon system.

On 13 November the first midcourse correction was successfully executed, and

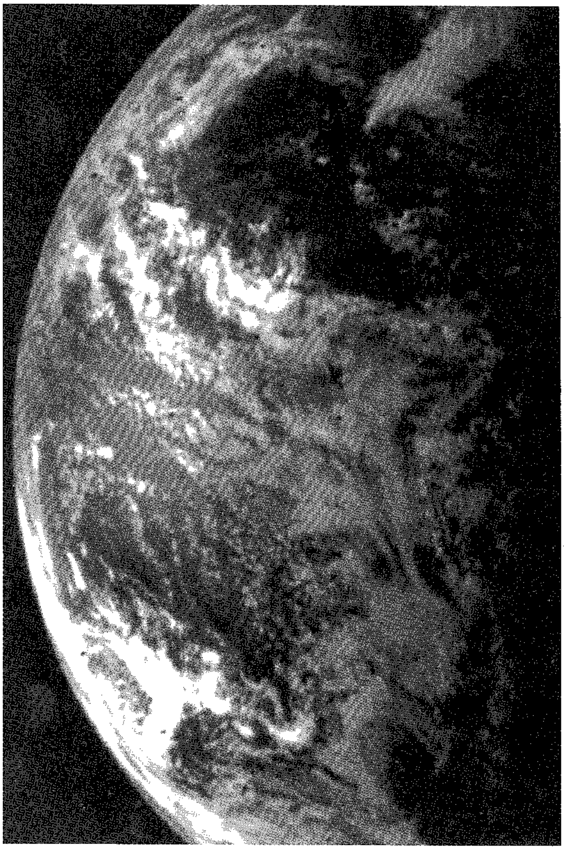

Figure 2.4. This picture of Earth was taken by *Mariner 10* 6 November, 1973 from a distance of 1.6 million kilometers. Most of the image shows the eastern Pacific Ocean. This was the first time our planet was imaged from farther away than the Moon.

by 28 November it was known that a second correction would be necessary to achieve the required trajectory past Venus. However, the mission plan had always included two maneuvers before reaching Venus. By this time, the launch window had closed and the backup spacecraft, waiting in case *Mariner 10* failed, could not be launched. *Mariner 10* was now completely alone. If it experienced a catastrophic failure after this time, the exploration of Mercury could not take place again for a decade.

2.4.2 Trouble begins

To the shock of scientists, engineers, and operations personnel, *Mariner 10* began experiencing serious problems just after the launch window closed. When the gyros were turned on to roll the spacecraft through a calibration maneuver, the flight data

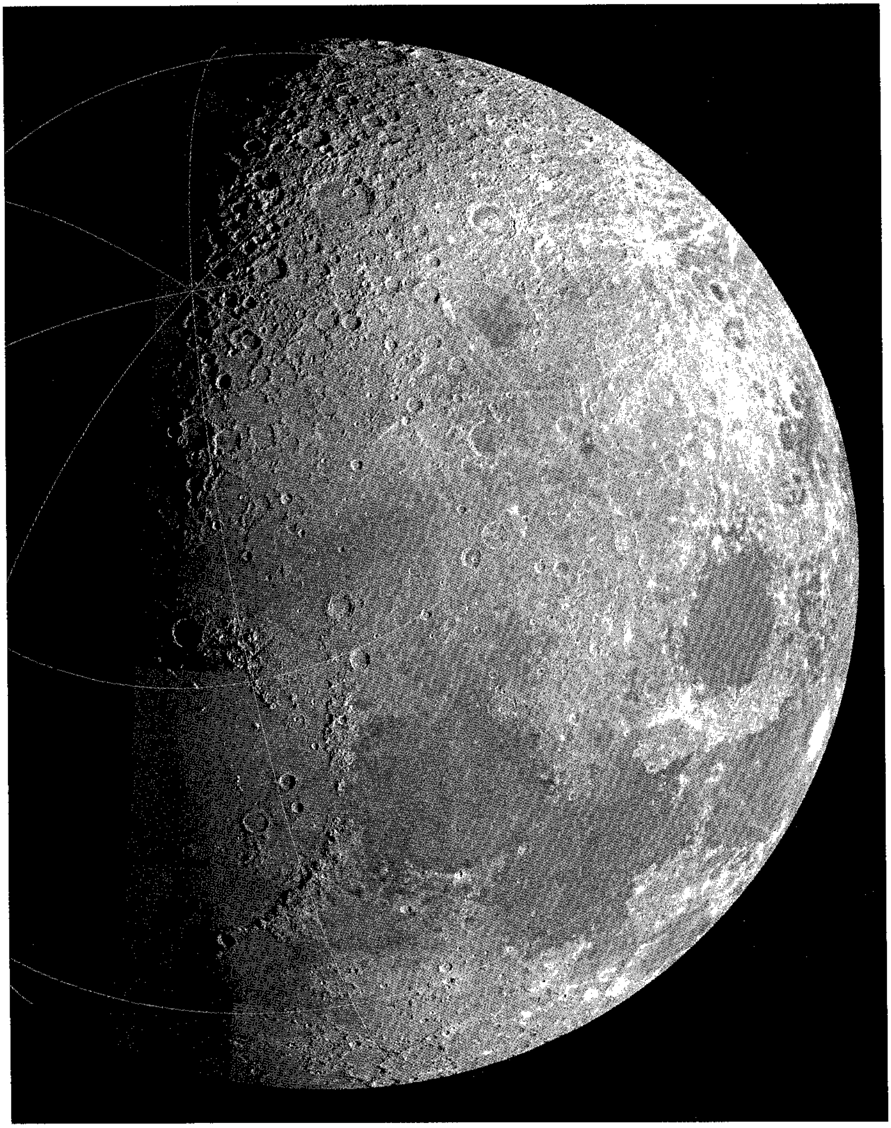

Figure 2.5. On route to Venus and Mercury *Mariner 10* took this photomosaic of the Moon on 3 November, 1973 to test the performance of the television cameras. It shows a portion of the front and farside (courtesy Mark Robinson, Northwestern University).

system, which kept track of spacecraft events, automatically reset itself to zero. Although this was not a serious problem, it suggested something might be wrong with the power system. Then on Christmas Day, part of the high-gain antenna's feed system failed and caused a significant dip in the signal power emitted by the antenna. Testing indicated that a joint in the feed system may have cracked due to temperature changes. If this problem persisted, no real-time images could be transmitted, and most of the best pictures planned for the Mercury exploration would be lost. The antenna healed itself, and then failed and healed itself again two more times between 25 December, 1973, and 6 January, 1974.

When the gyros were turned on for another roll calibration maneuver, the flight data system did not reset itself as it had done before. The spacecraft appeared to be behaving neurotically. Then on 8 January, the spacecraft automatically and irreversibly switched from its main power system to its backup system. If the backup failed, the mission would be over. From this point on, extreme care was taken in changing the power status of the spacecraft.

2.4.3 Systems restored

Finally, some good news for a change. On 21 January the second midcourse correction was successfully completed. This maneuver was required to make *Mariner 10* fly through a 400 km diameter area about 16,000 km to the right and in front of Venus, as seen from the approaching spacecraft. Failure to achieve this manouver would mean *Mariner 10* would not continue on to its rendezvous with Mercury. Analysis of the trajectory showed that *Mariner 10* would fly within 27 km of the aim point – a magnificent achievement comparable to hitting a dime with a bullet fired from a distance of about 12 km. At this point, all the science equipment was working well, and even the heaters for the cameras came back on by themselves.

On 28 January another near-calamity struck. During a series of spacecraft roll calibration maneuvers, a gyro-induced instability caused the expulsion of attitude control gas at a dangerously high rate. Without this gas it would not be possible to keep the antennas pointed at Earth, and contact with the spacecraft would be lost forever. Before the problem could be corrected, about 16% of the gas was lost. This would prove costly when time came to do subsequent Mercury encounters.

2.4.4 Venus flyby

Despite these problems, *Mariner 10* made its closest approach to Venus at about 10 a.m. Pacific Standard Time on 5 February, 1974. It took more than 4,000 pictures of Venus' atmospheric structure and circulation patterns between 5 February and 13 February, and acquired a wealth of new information about its atmosphere and environment (Figure 2.6). The ailing spacecraft now headed for its primary target, Mercury, which it would encounter 43 days later. But before it could reach Mercury another midcourse correction was necessary.

Mariner 10's troubles were still not over. On 18 February the spacecraft lost celestial reference on the star Canopus. Apparently its star tracker had locked onto a small particle that had drifted off the spacecraft. By the time *Mariner 10* reacquired Canopus, the gyros had been on for 1 hour and 48 minutes, causing more precious attitude control gas to be lost. As the spacecraft neared the Sun it became hotter and hotter, and more particles drifted from the spacecraft, causing the star tracker to lose Canopus lock frequently. More gas was lost. In response, the operations team on earth devised an ingenious method of conserving attitude control gas, called "solar

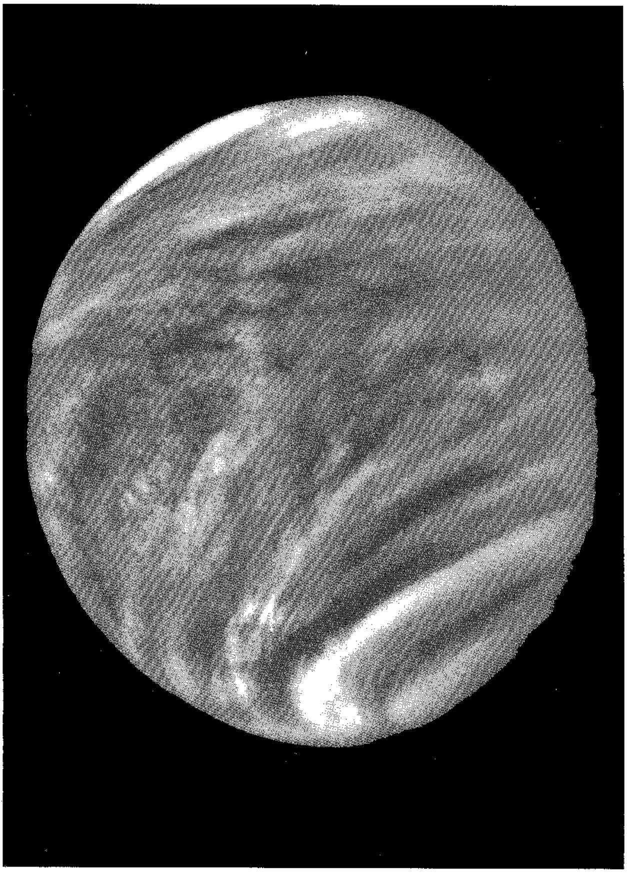

Figure 2.6. This photomosaic of Venus, taken through the *Mariner 10* ultraviolet filter, shows the structure of sulfuric acid clouds in the upper atmosphere.

sailing”. By differentially tilting the solar panels to use solar photon pressure on the panels in a controlled fashion, it proved possible to significantly reduce the amount of gas needed for a celestially controlled cruise mode. This and other techniques conserved enough gas to accomplish two subsequent Mercury encounters. Without this technique there would have been only one encounter.

The trajectory past Mercury had been carefully chosen to ensure that the best possible science data could be gathered, and also to allow the spacecraft to return to the planet six months later. This plan required a flyby on the night side at an altitude of about 900 km above the surface. Due to the precise aiming at Venus, only one more midcourse correction was needed to change the flyby from the planet's sunlit side to its night side. Because the planned trajectory correction maneuver would have caused the loss of too much precious gas in gyro oscillations, it was decided to execute a Sun-line maneuver that would not require the gyros. In mid-March *Mariner 10*'s position and orientation were such that its rocket engine could be fired toward the Sun without having to roll or pitch the spacecraft. By applying the proper amount and direction of thrust at the right time, the spacecraft was pushed slightly away from the Sun to fly by the night side of Mercury (Figure 2.7, see colour plate section). On 16 March the maneuver was successfully completed, but the flyby was 200 km closer to Mercury than planned. Since this still satisfied the requirements for science and a Mercury return, no additional maneuvers were planned.

The day after the maneuver, the non-imaging science experiments were turned on in preparation for the encounter. Now some truly good news cheered project personnel, particularly the Television Science Team. The high-gain antenna had miraculously recovered and was able to transmit its signal at full strength. Apparently the crack in the antenna feed closed when the temperature rose as the spacecraft approached the Sun. Now most pictures could be taken in real time. The high-resolution coverage originally planned could now be accomplished.

2.5 THE FIRST MERCURY ENCOUNTER – MERCURY I

2.5.1 The first images of the unknown planet

The first pictures of Mercury were taken on 24 March from a distance of 5.3 million kilometers. They were initially about the same quality as pictures taken from Earth, but as *Mariner 10* neared Mercury the images showed a heavily cratered surface superficially resembling the Moon's. The picture-taking sequence called for a series of photographic mosaics to be taken of the half-lit hemisphere as the spacecraft approached the planet. Near closest approach a series of individual high-resolution pictures was taken near the terminator (the line that separates day and night) (Figure 2.8).

Mariner 10 reached closest approach to Mercury at 1:47 p.m. Pacific Daylight Time on 29 March, 1974. For a short time around closest approach, the Earth was occulted by Mercury, cutting off the spacecraft radio signal. All science data, including the highest-resolution television images, were placed on the tape recorder for later playback. As the spacecraft receded from Mercury, a series of image mosaics similar to those obtained on approach were taken of the other side of the half-lit planet.

The pictures revealed a heavily cratered surface similar to the lunar highlands. An enormous impact basin about 1,300 km in diameter was revealed half illuminated at the terminator. There were also large expanses of smooth, lightly cratered plains that resembled the Moon's maria. All these surface characteristics were similar to the now-familiar features seen on the Moon. There were, however, several aspects of Mercury's surface that differed significantly from the Moon's. Long, sinuous cliffs or scarps traversed the surface for hundreds of kilometers and appeared to be almost everywhere. The heavily cratered regions contained large areas of moderately cratered plains interspersed among clusters of craters. A large region of hilly and lineated ground – nicknamed the "weird terrain" – was discovered on the incoming side viewed by *Mariner 10*. These features would enable scientists to reconstruct a

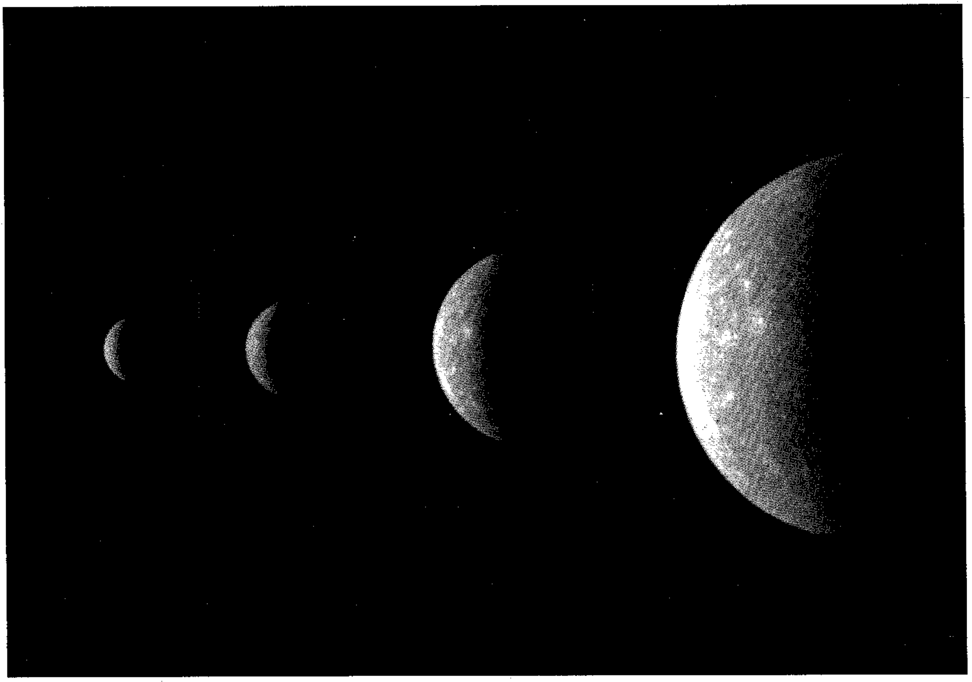

Figure 2.8. As *Mariner 10* approached Mercury, more details could be observed. The image at far left, taken 24 March, 1973, from a distance of 5.4 million kilometers, shows about the same amount of detail as the best Earth-based images obtained at that time. The right-hand image taken 5 days later from a distance of about 1 million kilometers, shows Mercury has a cratered surface.

geologic history of Mercury that was similar to the Moon's in some respects, but significantly different in others (Figure 2.9).

2.5.2 The first real surprise

Because Mercury was not thought to possess a significant magnetic field, it was generally believed that its interaction with the solar wind would be quite similar to that of the Moon, where the wind impinges directly on the surface and the satellite causes a cavity in the wind behind it. At the Earth, Jupiter, Saturn, Uranus, and Neptune, the solar wind is held away from the surface by their magnetic fields. *Mariner 10*'s trajectory would carry it through the anticipated plasma cavity behind Mercury. To the astonishment of scientists monitoring the plasma data telemetered from the spacecraft, 19 minutes before closest approach the plasma flux suddenly increased and peaked in a manner indicating that *Mariner 10* had crossed a *bow shock wave*. At about the same time, the charged particle experiment detected a violent increase in energetic charged particles, confirming that the spacecraft had crossed a shock wave. Several other unusual peaks in the intensity of

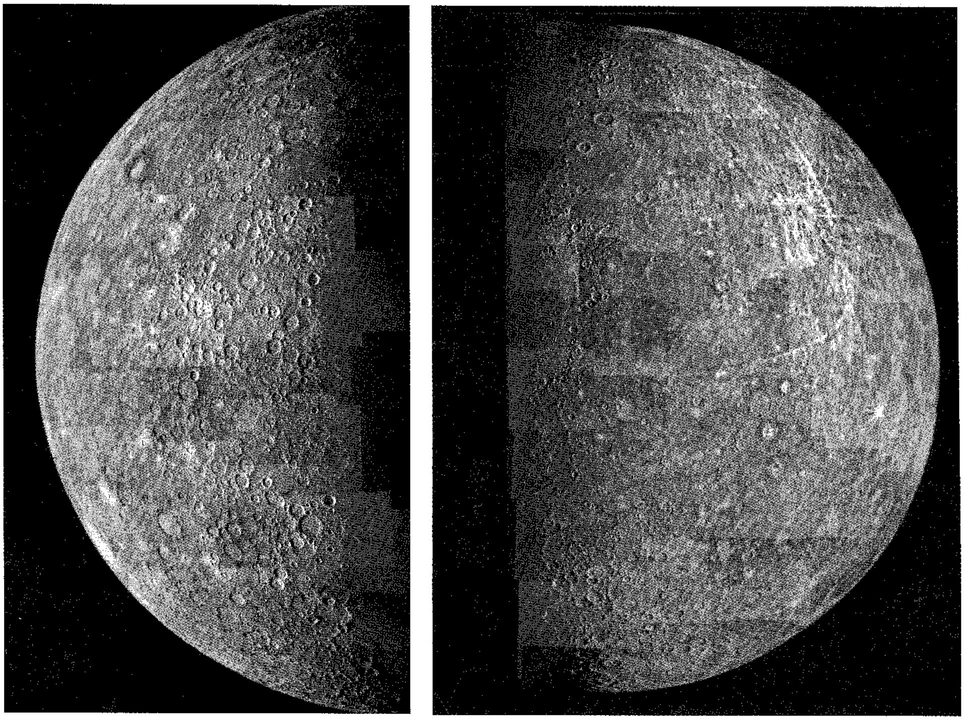

Figure 2.9. These hand-made photomosaics of Mercury were made from medium-resolution images taken on the first encounter. The one on the left shows the incoming side as viewed by *Mariner 10* and the other shows the outgoing side.

charged particles subsequently occurred. They were similar to phenomena observed in the Earth's geomagnetic tail, where oppositely directed field lines meet.

Scientists were both elated and perplexed over this completely unexpected discovery. What could be the source of this magnetic field? Was it internally generated or was it due to electric currents induced in the surface by the solar wind? Another Mercury encounter would be required to answer these questions (see Chapter 5).

2.5.3 A very thin atmosphere, no molecular species found

The ultraviolet experiments put upper limits on molecular and atomic gaseous species at Mercury and determined that the planet possessed a very thin atmosphere of H, He, and perhaps O. More atomic species have since been discovered and will be discussed in Chapter 6. Also, the light emitted in the inner solar system by H atoms (Lyman-α at 1216 Å), much of it coming from H in the solar wind, was measured and mapped.

2.5.4 Hot, hotter, hottest

The infrared radiometer measured a low temperature of −183°C (−297°F) on the night side just before dawn, and a high temperature of 186°C (368°F) in the late afternoon. When Mercury makes its closest approach to the Sun, however, the temperature range can reach 610°C (1,130°F). This enormous temperature difference between night and day is greater than on any other planet or satellite in the Solar System. The temperature gradient between Mercury's day and night side showed that its surface consists of a light, porous insulating layer of dust similar to that on the Moon. Slight temperature variations on the night side indicated the presence of small rock outcrops, probably due to boulder fields around impact craters.

Radio tracking of *Mariner 10* provided an accurate radius of the planet and showed that it is much closer to a sphere than either Earth or Mars. Its mass was measured to an accuracy 100 times greater than previous Earth-based determinations. These values could now provide an accurate density of Mercury, which, in turn, would yield information on its bulk composition and internal structure.

Mariner 10's first encounter with Mercury was an outstanding success that exceeded all expectations. The achievement was particularly noteworthy because of the numerous spacecraft problems that had to be overcome and that had threatened to end the mission before it accomplished its objective. *Mariner 10* provided us with our first close-up glimpse of Mercury and returned thousands of pictures and tens of thousands of non-imaging measurements of its surface and environment. A few hours of spacecraft observations had obtained more data about this poorly known planet than centuries of Earth-based observations. They revealed a planet with a combination of Earth-like and Moon-like characteristics that provided important new information on the evolution of the Solar System.

But this was no time to bask in the glories of the success. A second and possibly a third encounter with Mercury were possible, to add to and complement the knowledge acquired during the first. It was now up to the engineers and operations personnel at JPL to guide the ailing spacecraft to further Mercury flybys.

2.6 THE SECOND ENCOUNTER – MERCURY II

2.6.1 Troubles are overcome

Several additional trajectory corrections were required to return the spacecraft to Mercury. But *Mariner 10* continued to experience serious problems that threatened to terminate the extended mission. Only two days after the first encounter, while the cameras were still taking far encounter pictures, the temperature in the power electronics compartment rapidly rose and was accompanied by an additional 90-watt drain on the power system. The spacecraft remained on its backup power system, and if it failed the mission would be over. The operations team therefore turned off the cameras and other power-consuming instruments, and implemented additional techniques to accommodate the stress on the power system. This response seemed to stabilize the system, but other problems followed.

Without command, the tape recorder turned on and off several times and then failed completely. Without it, all science data would have to be sent back in real time during subsequent Mercury encounters. The high-gain antenna, which had experienced previous problems, would need to transmit at full strength or most of the subsequent pictures would be lost. To make things worse, the flight data subsystem experienced a failure that terminated many of the engineering data channels. This failure greatly increased the difficulty of nursing the ailing spacecraft around the Sun before encountering Mercury for the second time. Finally, the amount of attitude control gas was now quite low because of the oscillation problems, and, therefore, its use would have to be drastically reduced below the normal cruise rate if two more encounters were to be achieved. At this point it looked as if subsequent encounters with Mercury would have only a slim chance to succeed.

Despite these seemingly insurmountable problems, the exhausted personnel at JPL Mission Operations managed to keep *Mariner 10* operating and to preserve enough attitude control gas to accomplish two more Mercury encounters. Because Mariner 10's orbital period around the Sun was almost exactly twice Mercury's period, and since Mercury's rotation period is in $\frac{2}{3}$ resonance with its orbital period, the spacecraft would view exactly the same side of the planet on the second and third encounters as it did on the first.

2.6.2 Conflicts over experiments and spacecraft control

A serious conflict emerged between the magnetic fields and charged particles experiments and the imaging experiment over the trajectory past Mercury for the second encounter. The fields and particles experiments required a night-side trajectory close to the planet, to obtain information needed to determine whether the magnetic field was internally or externally produced. The imaging experiment needed data on the south polar region, to link the two sides of Mercury seen on the first encounter and to determine the polar distribution of the *lobate scarps* in order to decide whether they were produced primarily by *planetary despinning* or by cooling of the interior. This objective required a day-side trajectory at a relatively large distance from the planet. The imaging trajectory would provide little useful information on the magnetic field and interacting particles, while the fields and particles trajectory would yield no new information on Mercury's surface. This was an extremely difficult conflict to resolve. After an agonizing evaluation of both cases by the Science Steering Group, it was decided that the second encounter would take an imaging trajectory, and that the third would be planned primarily for fields and particles. This decision was largely based on the improbability of achieving an adequate imaging trajectory on the third encounter if the second encounter followed a fields and particles trajectory.

2.6.3 Decisions were made

Mariner 10's second encounter with Mercury (known as Mercury II) was chosen to take place on the sunlit side at an altitude of 50,000 km over the southern hemisphere, 40° below the equatorial plane. This trajectory permitted pictures to be taken of a previously unimaged region and provided a photographic tie over the southern hemisphere between the sides of the planet viewed during the first encounter. A rather large miss distance was required to completely cover the southern hemisphere with narrow-angle pictures at resolutions of 1–3 km. Furthermore, the trajectory would enable a third and final encounter with Mercury. The second encounter was designed primarily as an imaging flyby to photograph new areas and to provide important geologic and cartographic links between the two sides seen previously, thereby facilitating further geologic interpretation. An added bonus would be the acquisition of stereoscopic coverage by combining the first and second encounter pictures of the same regions taken at different viewing angles.

2.6.4 Arrival at Mercury

After two more successful midcourse corrections, *Mariner 10* encountered Mercury for the second time at 1:59 p.m. Pacific Daylight Time on 21 September, 1974. The scientists and engineers were jubilant.

About 360 images were returned during the 3-day encounter sequence. They showed details of the south polar regions never seen before and extended the coverage of Mercury from about 50 to 75% of the illuminated hemisphere (see Figure 2.12). The south polar regions revealed a cratered surface similar to that seen on the first encounter (Figure 2.11). An important observation was the presence of numerous sinuous scarps, first seen on the previous encounter, which indicated that these structures have an extremely widespread distribution, possibly on a global scale. This fact has important implications for interpreting the planet's tectonic history and internal dynamics. This similarity of the terrain in the south polar regions with the terrain on other parts of Mercury increased the suspicion that the unseen side was similar to the explored side.

The ultraviolet experiment was able to obtain excellent data. It set accurate upper limits on the density of several molecular species that had been predicted, and detected atomic species of H and He. Two modes of observations were made: (1) an *occultation experiment* searched for molecular absorptions in the solar spectrum; and (2) UV emission lines were searched for in especially chosen wavelength intervals. More about these issues will be found in Chapter 6.

2.6.5 Some historical precedents set

The second encounter was historic because it was the first time any spacecraft had returned to its target planet. Furthermore, engineers at the Goldstone Tracking Station in the Mojave Desert of California were successful in developing a new technique to obtain relatively low noise pictures, required because *Mariner 10* was

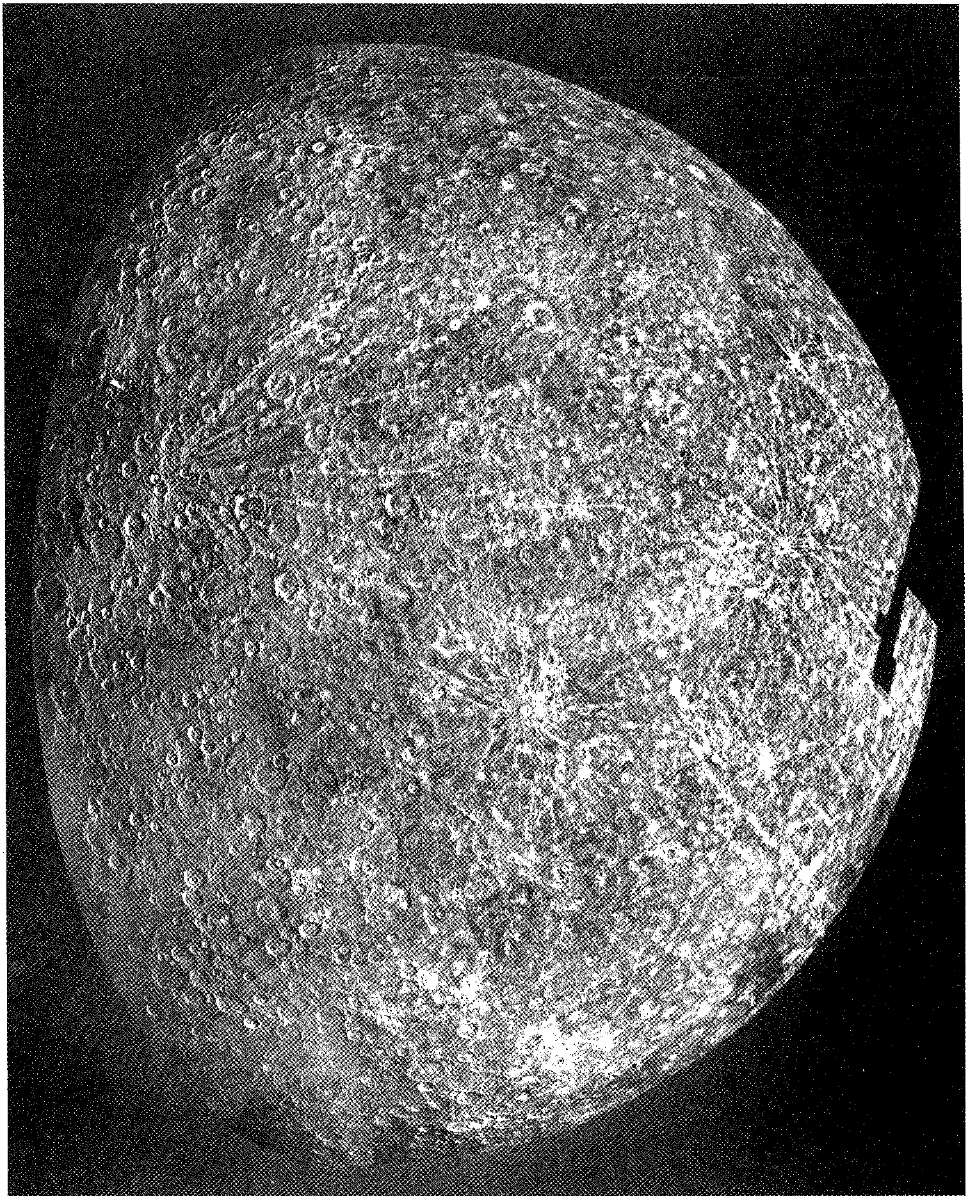

Figure 2.11. This hand-made photomosaic of Mercury's southern hemisphere was made from images taken during the second flyby.

at a much greater distance from the Earth than during the first encounter, and, therefore, its signal was much weaker. They connected three large antennas by microwave links and operated them as a single large antenna. Without this technique, the quality of the full-frame images would have been so degraded that

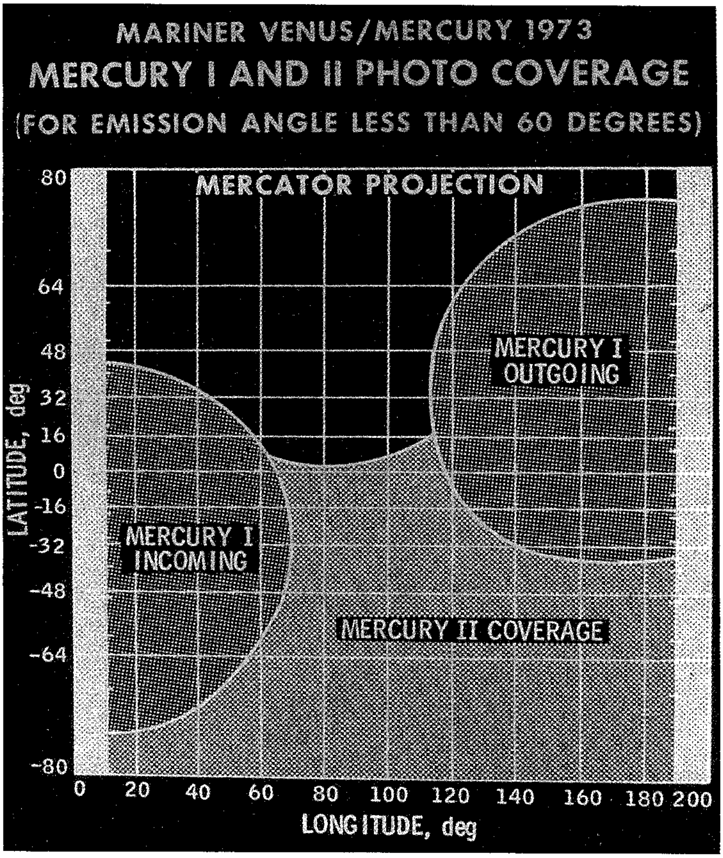

Figure 2.12. The additional coverage of Mercury obtained on the second encounter joined the two sides seen on the first encounter.

they would have been of little scientific value, or it would have been necessary to transmit only $\frac{1}{4}$ of each image at a lower telemetry rate. In either case, most of the objectives of the second encounter would have been lost. Thanks to the ingenuity of the Goldstone engineers, a full complement of excellent images was obtained in real-time. Although these, like the real-time first encounter images, have some noise, it could be removed by image processing techniques.

Up until this time all interplanetary flights had relied solely on Earth-based radio measurements for navigation. In the second *Mariner 10* encounter, a new navigational technique was tested that used the stars as celestial reference points. This navigation method was not unlike that used by ancient mariners to guide them over the vast seas in their explorations of Earth. More than 100 pictures of star fields were taken to obtain angular measurements between Mercury, the spacecraft, and the stars. The experiment was successful, and it demonstrated that long missions to the outer planets could use this method to navigate a spacecraft through the intricate orbits of the outer planets' satellites. *Voyagers I* and *II* would later use this technique on their historic explorations of the outer Solar System.

2.7 THE THIRD ENCOUNTER – MERCURY III

As *Mariner 10* began its second orbit around the Sun in preparation for the third encounter (Mercury III), the spacecraft was returned to cruise mode. The high-gain antenna and solar panels were again used to gather light pressure from solar photons in order to conserve attitude control gas, which was now dangerously low.

2.7.1 Loss of the star tracker

On 6 October the Canopus star tracker again lost its lock on the star when a bright particle passed through its field of view. The spacecraft went into an uncontrolled roll that could not be corrected before the attitude control gas was thought to be depleted below that required to achieve the third encounter.

The situation was now desperate. What could be done to save the remaining attitude control gas for the crucial third encounter? The operations team decided to abandon roll axis stabilizations and permit the spacecraft to slowly roll, the rate controlled by differentially tilting the solar panels. The rates had to be very accurately controlled to prevent excessive use of the pitch and yaw jets, and this was made extremely difficult by the earlier loss of many of the engineering channels. The continuous rolling of the spacecraft also made navigation much more complicated. Despite these problems, however, three more trajectory correction maneuvers were successfully completed that placed the spacecraft on a path that would take it closer to Mercury (327 km) than any previous planetary flyby.

The measures taken to preserve the attitude control gas seemed to be working, and it looked as if there would be enough to achieve the third encounter. Then, a few days before encounter another problem occurred that nearly ended the mission there and then. While trying to reacquire the reference star Canopus, the spacecraft rolled into a position where the signal strength from the low-gain antenna plummeted to a level that essentially broke communications with Earth. If communications with the spacecraft were not reestablished soon, *Mariner 10* would fly by Mercury in utter silence. Only the large 64-m antennas of the Deep Space Tracking Network were capable of emitting a signal strong enough to command the spacecraft to reacquire Canopus. But these antennas were currently being used to communicate with the *Pioneer* and *Helios* spacecraft.

Time was running out, so a spacecraft emergency was called. To save *Mariner 10*, the big antenna at Madrid, Spain, was directed to send a command to the spacecraft that, it was hoped, would result in the reacquisition of Canopus and the positioning of the spacecraft to resume normal communications. Even though this was the period of maximum scientific interest for the *Helios* Mission, the Madrid station sent the command, and shortly thereafter *Mariner 10* achieved its correct orientation for the third flyby – just 36 hours before its closest approach to Mercury.

2.7.2 Magnetic field measurements

The primary goal of the third encounter was to obtain measurements of the magnetic field that would determine whether it was internally generated or produced externally by electric currents induced by the solar wind. If the field was internally produced representing a scaled-down version of Earth's magnetic field, then the time expected for events to be observed by *Mariner 10* at encounter could be accurately predicted. The actual time that *Mariner 10* passed through the bow shock, the magnetopause, and the maximum field strength proved to be almost exactly those predicted. Thus, Mercury's magnetic field was thought to be internally generated and similar in form to the Earth's field.

2.7.3 Final imaging sequence, diminished but important

Although the non-imaging science instruments were returning important new results, the imaging science experiment was experiencing serious difficulties. Only the Canberra station of the Deep Space Network was within receiving view of the spacecraft during the third encounter. Earlier, an experimental ultra-low-noise feed was installed so that high-quality, real-time images could be received at the high data rate. Near encounter, however, the feed developed a leak in its cooling system, and the imaging data had to be returned at a much lower data rate. As a result, only $\frac{1}{4}$ of each picture could be returned in real time. Of course, *Mariner 10*'s tape recorder had failed much earlier, and hence there was no way to store the pictures for later playback to recover the full-frame images. The imaging sequence had been planned to return high-resolution images of geologically interesting areas seen during the first encounter. Although much of the image data was lost, even the strips of high-resolution pictures proved to be important (Figure 2.13).

2.8 MISSION'S END – A JOB WELL DONE, BUT INCOMPLETE

On 24 March, 1975, just one week after the third encounter, *Mariner 10* ran out of attitude control gas. It began tumbling uncontrollably, and communications were lost forever. The mission was over. On its epic journey of discovery, *Mariner 10* had traveled more than 1.5 billion kilometers since it had been launched 506 days earlier. It used for the first time the gravity assist technique to send a spacecraft on a new trajectory, and pioneered many other new engineering techniques. It had transmitted important new information on the atmosphere and space environment of Venus, and provided detailed information about a planet that had baffled scientists for centuries. None of this would have been possible without the Herculean efforts and ingenious devices employed by the project personnel to keep the ailing spacecraft alive. Today *Mariner 10* continues its endless journey around the Sun, returning every 6 months to the vicinity of its prime target, Mercury.

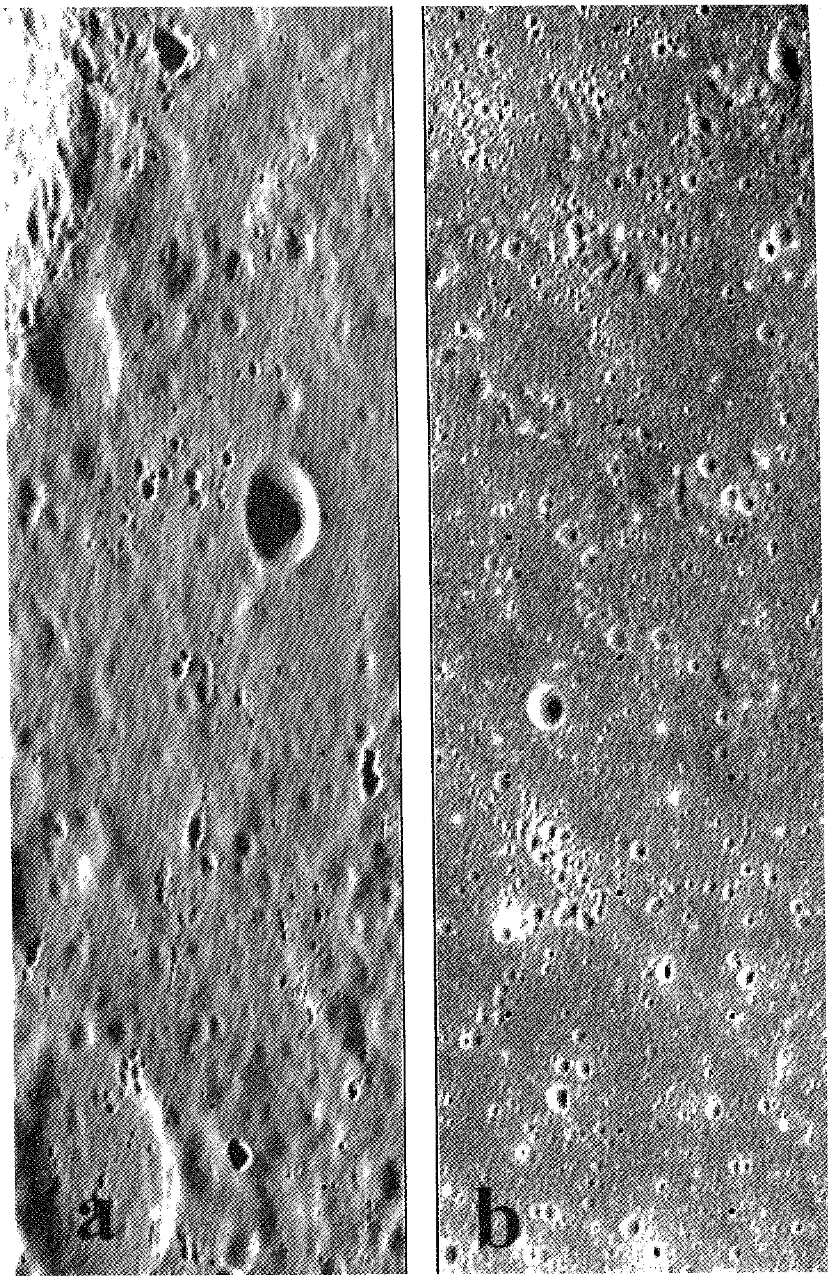

Figure 2.13. The images taken on the third encounter were limited to quarter frames because of ground-based antenna problems. These pictures included high-resolution images of a cluster of sharp secondary craters on the incoming side (a) and a portion of the smooth plains on the outgoing side (b).