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Missions to Mercury

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Abstract Mercury is a very difficult planet to observe from the Earth, and space missions that target Mercury are essential for a comprehensive understanding of the planet. At the same time, it is also difficult to orbit because it is deep inside the Sun's gravitational well. Only one mission has visited Mercury; that was Mariner 10 in the 1970s. This paper provides a brief history of Mariner 10 and the numerous imaginative but unsuccessful mission proposals since the 1970s for another Mercury mission. In the late 1990s, two missions—MESSENGER and BepiColombo—received the go-ahead; MESSENGER is on its way to its first encounter with Mercury in January 2008. The history, scientific objectives, mission designs, and payloads of both these missions are described in detail.

Keywords Mercury · Mariner 10 · MESSENGER · BepiColombo

1 Introduction

Mercury is the innermost planet, the terrestrial planet closest to the Sun. It is very difficult to observe from the Earth because it can be viewed in visible light only just before sunrise

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or just before sunset, low above the horizon. The elongation of Mercury is always less than 30° from the Sun. Despite this handicap, it was already well known in the world of classical Greece and was named Hermes, the winged messenger of the gods; its Roman name was Mercury. (Of course, seeing with the naked eye was considerably better then, without the atmospheric and light pollution that we have to contend with today.)

The precise orbital period of Mercury around the Sun has been known for a long time. However, the difficulties of seeing features on Mercury to help with determining its rotation period (the Mercury day) delayed the recognition of the 3 : 2 resonance between Mercury's spin rate and orbital mean motion until the mid-1960s (Colombo 1965). The reason for this difficulty was another near-resonance: the synodic period of Mercury (the orbital period when seen from the Earth) is in an almost 4 : 3 resonance with Mercury's orbital period (e.g., Balogh and Giampieri 2002), so that the same face of Mercury is seen repeatedly from the Earth. This led to the earlier, erroneous conclusion that Mercury was in a 1 : 1 spin–orbit resonance state, as is the Moon with respect to the Earth.

Because of the proximity of Mercury to the Sun, there have been several difficulties in gaining better information about the planet. The first of these difficulties is to observe it from Earth, although significant progress has been made in radar, visual, and infrared (IR) observations (see articles in this volume: Harmon 2007; Ksanfomality et al. 2007; ...). The second challenge is to orbit Mercury by spacecraft, as the planet is deep inside the gravitational potential well of the Sun. The third obstacle is the very hostile thermal environment that awaits any spacecraft in Mercury orbit; this environment consists of increased solar irradiance (up to a factor 10) as well as the thermal radiation from the sunlit side of the planet. As a result, to date only one spacecraft, Mariner 10, reached Mercury more than 30 years ago. Another spacecraft, MESSENGER, is on its way at present to a first flyby in 2008 and insertion into Mercury orbit in 2011. Both spacecraft have been flown by the U.S. National Aeronautics and Space Administration (NASA). A third, more ambitious two-spacecraft mission, BepiColombo, is a joint undertaking by the European Space Agency (ESA) and the Japan Aerospace Exploration Agency (JAXA). Its construction will start in 2007 for a launch in 2013 and insertion into Mercury orbit in 2019.

This paper traces the history of the space missions and mission plans to Mercury, from Mariner 10 through the many proposals to space agencies that were never realised, to the present when, at last, two missions, MESSENGER and BepiColombo, will be targeting Mercury. These missions, their objectives, and their scientific payloads are described in some detail. Much is expected from these missions (Grard and Balogh 2001; Solomon 2003; McNutt et al. 2004; Solomon et al. 2007). It is clear that such a concentrated effort is required to resolve the many outstanding questions regarding this important planet, the end member of the terrestrial planets.

2 Mariner 10: Brief History and Achievements

The difficulties in observing Mercury from the ground, and even with space-based telescopes in Earth-orbit, have meant that little could be known of the planet without a close-up look with a space probe that actually travelled to it. Remarkably, it was only about 11 years after the launch of Sputnik 1 inaugurated the space era that NASA first considered launching a spacecraft to Mercury. The Space Science Board of the National Academy of Sciences, as part of a planetary exploration program developed in 1968, proposed a mission to Mercury via Venus for a 1973 launch opportunity. This was to be Mariner 10, a remarkable and still-unique mission that provided much of what we know, even now, about Mercury.

This was an era of unequalled activity in space, led by the United States, when not only the Apollo missions to the Moon became almost commonplace, but there were also numerous unmanned programs. Many scientific satellites, with a wide range of objectives, were orbiting the Earth, and several spacecraft, both American and Soviet, were sent to explore the two nearest planets, Venus and Mars. The main elements of NASA's planetary exploration program were the Mariner space probes. The objective of six of the 10 Mariner spacecraft built and launched between 1962 and 1973 was Mars; four of these reached their objective and successfully returned data from the red planet. Three were targeted to Venus; two of these successfully returned data from Venus and one of these, Mariner 2, also confirmed the existence of the solar wind during its interplanetary cruise in 1962. The tenth and last in the series, originally called the Mariner Earth–Venus–Mercury mission, acquired the Mariner 10 name after launch.

The mission to Venus and Mercury was made possible by the technique of gravity-assist flybys. Although some orbital calculations provided a likely basis for such a mission, the specific Venus gravity-assist opportunity that enabled it was worked out only in the late 1960s at the Jet Propulsion Laboratory (JPL) in Pasadena, CA. In the simple scenario first adopted for the Mariner Earth–Venus–Mercury mission, a single gravity-assist flyby of Venus was to modify both the velocity of the spacecraft and its orbital plane around the Sun to bring it to the orbital inclination of Mercury. As both Venus and Mercury had to be in specific points in their orbit for the two encounters, opportunities for the launch were identified in 1970 and 1973. The latter was in fact the launch date recommended by the Space Science Board.

Instruments for the scientific payload for what became known as Mariner 10 were selected in mid-1970, and a Project Management Team was formed at JPL. A contract to build the spacecraft was placed in mid-1971. It was a remarkable achievement that the spacecraft was ready and tested for launch on November 3, 1973, from Cape Kennedy onboard an Atlas-Centaur launcher. A number of "firsts" was achieved by Mariner 10. It performed the first gravity-assist flyby of a planet (Venus) on the way to another (Mercury), and it was the first to reach so close to the Sun, with all the challenges that represented for the thermal design of the payload and spacecraft.

It is interesting to note the scientific objectives as represented by the instruments selected for the payload: imaging (using dual television cameras and telescopes), IR radiometry, extreme ultraviolet (EUV) spectroscopy, magnetometry, plasma and charged particle characteristics, and radio wave propagation. The Mariner 10 spacecraft and its payload are illustrated in Fig. 1. The objective was to learn as much as possible about Mercury. This involved primarily the television (TV) cameras, as no reliable images of the planet existed. An interesting aspect of the payload was the inclusion of a magnetometer, as Mercury was thought not to possess a planetary magnetic field; it is fortunate that this instrument was included, as it led to the discovery of perhaps the most puzzling aspect of Mercury.

The Mariner 10 spacecraft weighed 503 kg; it was 140 cm diagonally and 46 cm high. It was three-axis stabilised using cold-gas thrusters. The two solar panels measured 2.7 × 1.0 m each, which represented in total an area of 5.1 m^2 of solar cells. The maximum power delivered by the solar arrays was 540 W. The parabolic antenna, for communication with the Earth through NASA's Deep Space Network, had a diameter of 137 cm.

From a technical point of view, there were a number of serious challenges during the construction and testing of the spacecraft, but these were overcome prior to the launch. One of these problems related to the tape recorder that was to be used during mission, in particular during the flybys, to buffer the data acquired by the instruments prior to transmission to the ground. This was clearly a critical subsystem; extensive testing led to the identification of

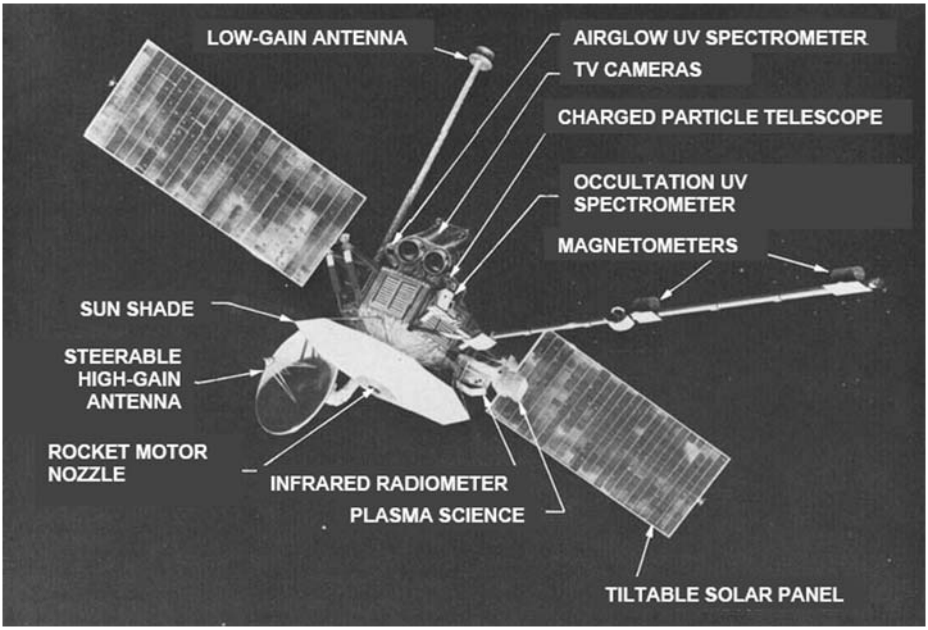
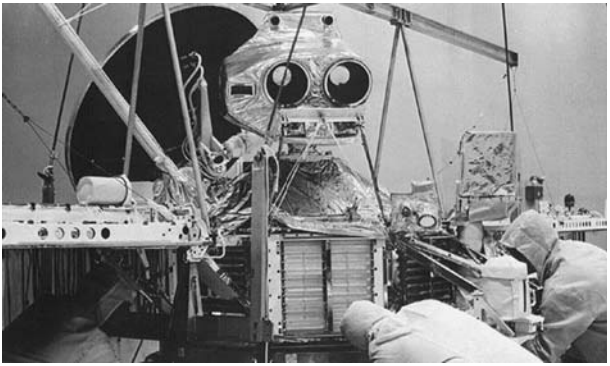


Fig. 1 The Mariner 10 spacecraft and its scientific payload

Fig. 2 The final assembly stage of the Mariner 10 spacecraft. Its most prominent feature is the dual vidicon stereo camera sent back images from the planet



the problem (the relative humidity levels of the tape and the internal atmosphere of the tape transport system) and its solution. In the end, the tape recorder worked very well throughout the mission, ensuring that all the flyby data were transmitted to the ground. A photo of the spacecraft during its final assembly stage is shown in Fig. 2.

There were also a number of difficulties and near-failures that occurred during the mission, such as the problem with the heaters which kept the telescopes and the TV cameras (vidicon tubes) warm. In fact, the heaters failed, but by changing the operation modes (keeping the vidicon tubes switched on) and by optimising the attitude of the spacecraft to prevent the cameras from cooling too much, the mission objectives were fully achieved. Other problems affected the gyros that controlled the attitude of the spacecraft; these problems, also potentially fatal to the mission, were overcome by using the star tracker, a risky strategy that paid off throughout the mission. There were several other moments of concern during the

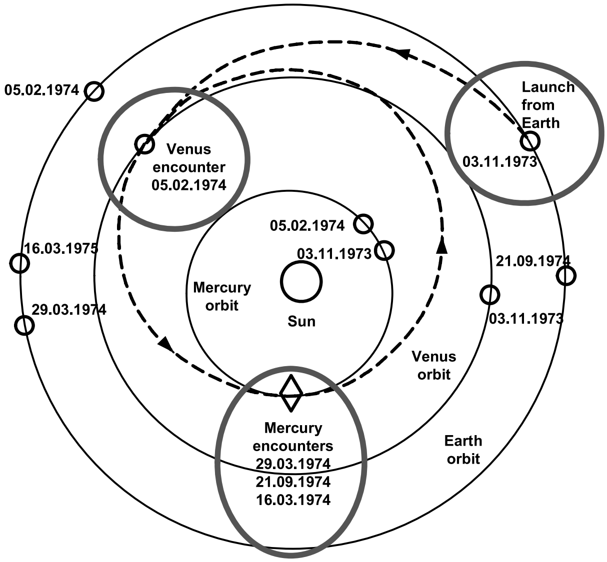


Fig. 3 The ecliptic projection of the trajectory of Mariner 10 and the orbits of Earth, Venus and Mercury, indicating the launch, the Venus flyby and the three Mercury flybys

mission, but thanks to the resilience of the spacecraft and the ingenuity of the mission team all these were overcome to ensure the success of the mission.

Following its launch in November 1973, Mariner 10 flew by Venus three months later on February 5, 1974, with a closest approach at an altitude of 5,768 km. Other than the gravitational kick that was necessary to place the spacecraft on its flyby trajectory towards Mercury, the scientific instruments on Mariner 10 targeted Venus and its atmosphere, returning some previously unknown data about the cloud cover of the planet. Following the Venus flyby, Mariner 10 followed a direct trajectory to Mercury for the first flyby. Originally only a single flyby had been foreseen, but Giuseppe (Bepi) Colombo—a professor from Padua, Italy, visiting JPL in the early 1970s—pointed out to NASA the possibility of a transfer, after the first flyby, to a resonant, multiple flyby orbit. This meant that Mariner 10 orbited the Sun in an eccentric orbit in a time (0.48 years) exactly twice the period of Mercury's orbit around the Sun. The mission trajectory is shown in Fig. 3.

The first encounter with Mercury, on March 29, 1973 (less than 5 months after the launch!), was targeted behind the planet. The spacecraft was able to take a remarkable set of pictures both before and after closest approach (at a height of 705 km). A bare, cratered surface, not unlike that of the Moon, was seen by the TV cameras. A typical illustration of the imaging of Mercury achieved by Mariner 10 is shown in Fig. 4. It shows the very large Caloris impact basin, about half of which was documented by Mariner 10. The major surprise was the detection of a magnetosphere around Mercury, implying the existence of an internal magnetic field that could form a protective shield preventing the solar wind from directly impacting the surface. The implied magnetic field was much weaker than the Earth's, so the magnetosphere was much smaller in relative terms than at the Earth. The existence of an internal magnetic field led to a fundamental revision of ideas regarding the internal evolution of the planet since its formation; the debate about the origin of this magnetic field continues to this day.

The second encounter, on September 21, 1974, had a trajectory on the sunlit side of the planet, with a more distant "closest" approach distance of 48,069 km. This flyby was

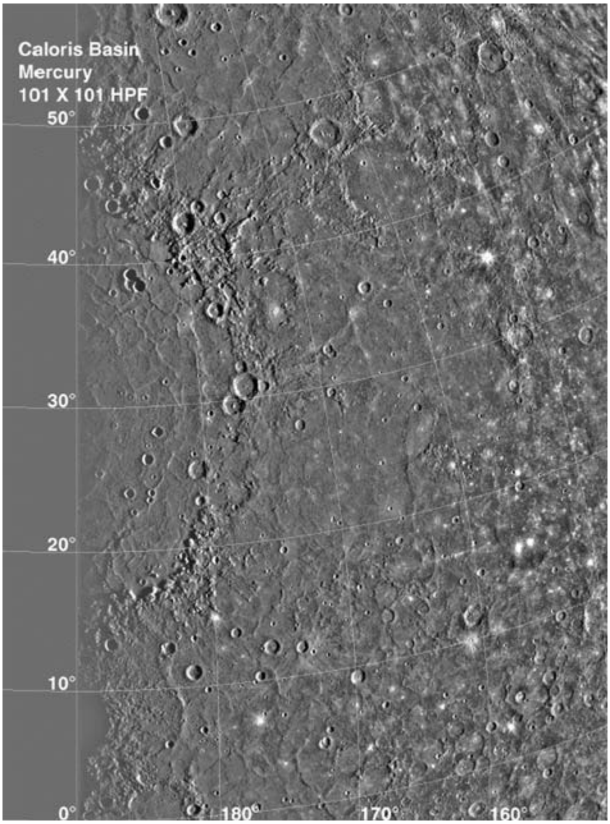


Fig. 4 The Caloris basin, shown here in a 1-km-per-pixel mosaic, is one of the largest basins in the solar system. Its diameter exceeds 1,300 km, and in many ways it is similar to the great Imbrium basin on the Moon (diameter >1,100 km). To enhance landforms a high-pass filter was used in processing. (Photo courtesy NASA)

dedicated to taking further images of Mercury, to ensure as much coverage of the planet as possible; in total, more than 750 images were taken during this encounter.

The dramatic nature of this first mission to Mercury is illustrated by the way the third encounter was achieved (Dunne and Burgess 1978). After the second flyby, the spacecraft was placed in a cruise mode in which the high-gain antenna and solar panels were oriented to use solar radiation pressure to maintain the orientation of the spacecraft to save attitude control gas for a third encounter. However, the Canopus star tracker lost its lock on the reference star, and the spacecraft went into an uncontrolled roll. Attempts to reacquire Canopus, however, depleted the gas supply below that required to achieve a third encounter. It was decided to abandon roll-axis stabilisation, and the spacecraft was allowed to roll slowly, the rate being controlled by differentially tilting the solar panels. The roll rates had to be maintained quite low to prevent excessive use of the pitch and yaw jets, and also to allow gyro turn-on for trajectory correction manoeuvres and pre-encounter reacquisition without inducing an oscillation. However, due to failures in the star tracker and its electronics, it was very difficult to reconstruct the roll position. Modulation in the intensity of the signal from the low-gain antenna dependent on roll position and roll rate was used for this. This emergency procedure was successful, and just enough fuel remained on board to implement the third flyby.

An additional, related problem was that the modulation of the signal from the spacecraft due to the roll introduced a modulation in the Doppler signal and therefore made the reconstruction of Mariner 10's orbit considerably more difficult. However, the three trajectory-correction manoeuvres needed for the third flyby could still be achieved, thanks to an ad hoc modification of the orbit-determination software. Another problem that arose in the approach to the third flyby was that the spacecraft rolled into a position that was a null in the low-gain antenna pattern, so that the spacecraft could no longer be tracked. Through some extraordinary effort and the use of the then-largest ground-tracking stations of NASA, reacquisition was achieved only hours before the encounter.

The objective of the third encounter was to investigate Mercury's magnetic field, one of the major discoveries made during the first flyby. For this, the encounter trajectory aimed at a closest approach point at an altitude of 327 km, the closest of all three flybys, and at higher latitude to see a stronger magnetic field. This tactic was completely successful; the resulting observations eliminated any doubt about the existence of the relatively weak, but still significant, magnetic field of planetary origin. In addition, many more images were returned from the vantage point along this orbit.

Until the new generation of spacecraft arrive at Mercury, Mariner 10 remains the most abundant source of our knowledge about that planet. For a summary, see Murray (1975); for a comprehensive description of our understanding of Mercury after Mariner 10, see the Mariner 10 special issues: *Science*, 185, No. 4146, July 12, 1974; *J. Geophys. Res.*, 80, 2341–2514, 1975; and the chapters in *Mercury*, edited by Villas et al. (1988). For more recent assessments, see Strom and Sprague (2003); and Shirley (2003). Although other planets (Mars, Venus, Jupiter, and now Saturn) have been quite thoroughly explored in comparison since the pioneering era of the 1960s and 1970s, Mercury waits for another space mission, more than 30 years after Mariner 10's achievements. Much is expected even from the first flyby of Mercury by MESSENGER in January 2008.

3 Plans to Follow up Mariner 10

The results of Mariner 10 justified the expectation of planetary scientists that another mission would soon follow the initial success. Further missions were sought to complete the imaging of Mercury, to map its internal magnetic field in order to determine its origin, and to provide the necessary data for better understanding this key terrestrial planet. The Space Science Board (later the Space Studies Board) of the U.S. National Academy of Sciences carried out in-depth studies of the priorities and objectives for exploring the inner planets, first in 1978, then in 1990. These reports, while noting the significance of Mercury, placed much greater emphasis on the detailed exploration of Mars and Venus. For Mercury itself, it was recognised that the difficulty of getting to Mercury probably implied the use of low-thrust propulsion systems. In the context of development studies for both solar sail and solar electric propulsion (SEP) missions, Mercury served as a potential target. However, such propulsion systems had not been developed at that time. In any case, the scientific arguments called for ambitious objectives for an eventual mission to Mercury, to complete the imaging began by Mariner 10 at higher resolution and to investigate the internal evolution and state of the planet. To meet this objective, clearly the full magnetic mapping of the planet was essential.

Even then, in fact, there was no shortage of mission proposals to Mercury in the 1980s and early 1990s, to both NASA and ESA. One of the first was called Messenger, submitted to ESA in 1983 by A.K. Richter and A. Balogh; this mission was to be a multiple flyby, somewhat similar to Mariner 10, but with space physics objectives. Other than flying by Mercury, the mission was also aimed at the further exploration of the inner heliosphere, following up on the successful German/American Helios probes. However, it was clear from the start that an orbiter was needed rather than just another flyby mission. The first such fully worked out proposal for a Mercury polar orbiter was made to ESA in 1985 by a consortium of scientists led by G. Neukum (1985). This proposal took into account the necessary propulsion requirements by including a gravity assist at Venus and the use of SEP. It was to be a large spacecraft, with a mass of 2,900 kg, carrying the SEP module as well as the spacecraft bus and a comprehensive payload for both planetary and space physics objectives. At that time, NASA was developing SEP for such missions (although these were not followed up at the time), but there was no prospect for a similar development in Europe, so Neukum's proposal was not considered further by ESA.

A major development for improving the prospect of a mission to Mercury was the discovery of a new class of gravity-assist missions by Chen-Wan Yen of JPL (Yen 1985, 1989) who identified ballistic trajectories using multiple-braking gravity-assist flybys denoted E-VVMM-M or E-VV-MMM-M that had, after a ballistic transfer from Earth (E) to Venus (V), repeated encounters with Venus and Mercury (M) before finally being placed in orbit around Mercury. In the first case, E-VVMM-M, there are two Venus flybys and two Mercury flybys before the arrival velocity at Mercury on the third approach is sufficiently low for the orbit insertion manoeuvre. The E-VV-MMM-M trajectory has an additional Mercury flyby before the final, orbit-insertion encounter. The braking gravity assists would decrease the final arrival velocity at Mercury down to 2 to 3 km/s that could be handled with an onboard chemical propulsion module for orbit insertion.

Taking advantage of Yen's mission concept, J. Belcher and J. Slavin led a very detailed study of a dual Mercury orbiter mission for NASA in 1988–1990 (Belcher et al. 1991; Rideourne et al. 1990). Using a Titan IV (with a solid booster added and the Centaur upper stage) the mission design, with the multiple Venus and Mercury flybys, was due to take between 3 and 7 years, depending on the selected launch date. Only rare launch opportunities provide an optimal alignment of the Earth, Venus, and Mercury to minimise the trip time to Mercury orbit insertion. Under conditions of optimal alignment, an E-VVMM-M trip takes 3 years, while a more realistic launch (for which there are more frequent opportunities) takes 4.9 years. Such a mission design was considered as the baseline for this mission, scheduled for launch in 1997. For comparison, an E-VVMMM-M trip, with a launch in 1999, was calculated to take almost 7 years.

Given the budgetary limits set for the mission ($500 million in 1988), the science team involved in the study put a higher priority on the space physics (magnetospheric) objectives, while accommodating as best they could some planetary objectives. Even then, the best way to implement the mission was through a dual spacecraft design (designated SC-1 and SC-2). In order to accommodate the space physics payloads, the two spacecraft were designed to be identical (including the payload) and spin-stabilised; this choice was also to help in the thermal design of the spacecraft in Mercury orbit. With the envisaged launcher, each spacecraft could have a dry mass of about 800 kg with a fuel load of 1,600 kg.

The two-spacecraft approach recognised that the short timescales and small spatial scales of Mercury's magnetosphere required at least two measurement points simultaneously for the interpretation of the observations. In particular, for determining the internal magnetic field of Mercury, the magnetic fields due to the magnetosphere need to be subtracted from the measurements along the orbit. This is possible only if the magnetosphere is well understood and well modelled, and if the state of the variable magnetosphere is monitored simultaneously.

The design of the Mercury orbiting phase of the mission was to be complex but ingenious, in order to reconcile the different mission objectives. Spacecraft 1 was to have an eccentric polar orbit of 12-hour period, with a periapsis of 200 km over Mercury's north pole and an

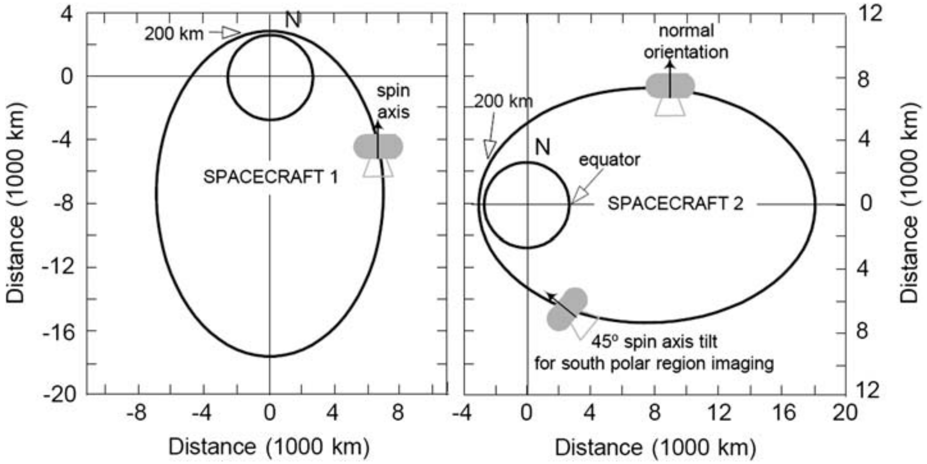


Fig. 5 NASA's proposed dual Mercury orbiter mission. *On the left*, the polar orbit of spacecraft 1 is shown, with the spin axis pointing north. *On the right*, the orbit of spacecraft 2, showing the 45° orientation of the spin axis optimised for imaging the south pole region. (From NASA Technical Memorandum 4255)

apoapsis at a height of 6.2 R_{M}. Spacecraft 2 was to have three different orbit phases. It was to have first a highly eccentric equatorial orbit, reaching out to over 80 R_{M} in the anti-Sun direction from the planet, deep into its magnetotail. This was to be a single orbit, almost a month in duration; following the completion of this orbit, the apoapsis of the elliptical, equatorial orbit was to be reduced to 32 R_{M}, with a periapsis altitude of 200 km. Spacecraft 2 was to remain in this orbit for more than a Mercury year (thus precessing around Mercury by over 360°). The final phase was to follow a change in the orbit plane to polar inclination and a 12-hour period, to engage in the closer observation of the planet, in particular to achieve imaging of the surface with a best resolution of about 100 m. This phase of the proposed mission is shown in Fig. 5.

This was an ambitious mission study, seriously addressing the complexities and challenges of a Mercury orbiter mission. In particular, the dual spacecraft approach, taken up later by the BepiColombo mission, pioneered the concept of simultaneous observations to reduce the uncertainties that arise from the complex and rapidly changing Mercury environment. However, the dual Mercury orbiter concept was not selected by NASA for implementation, so other proposals continued to be submitted.

The new proposals were submitted to NASA's Discovery Program, the framework for a range of medium-scale missions that was initiated in 1992. (For a brief history of the mission proposals to NASA at this time, see McNutt et al. 2006.) One such proposal, submitted in 1993 by JPL for selection as a Discovery-class mission, was a considerably more modest one than the dual orbiter. This mission, called Hermes (Nelson et al. 1994; Cruz and Bell 1995), was to carry only three scientific instruments: an imaging system that also included a dual wavelength laser altimeter, an ultraviolet (UV) spectrometer, and a boom-mounted magnetometer. The spacecraft was to be three-axis stabilised, but quite light, with a mass of only 320 kg. The mission was to follow a Yen design of the E-VVMM-M type with a flight time to orbit insertion of about 3 years. Launch opportunities were identified in 1999, 2000, 2004, and 2005. Another proposal was based on the successful Clementine mission to the Moon (Ely et al. 1995). The payload was to comprise UV/visible/IR imagers and a laser altimeter, but no magnetometer. It was an ambitious concept, with the spacecraft in a

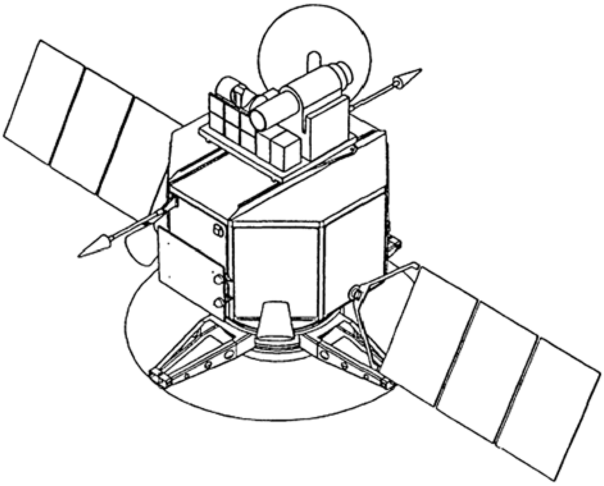


Fig. 6 Conceptual design of the spacecraft proposed to NASA as the Discovery Mercury Polar Flyby mission. (From Spudis et al. 1994)

300-km-altitude circular polar orbit around Mercury. All but one of the proposed missions were to use a Yen-type transfer to Mercury.

The only flyby mission proposed in this framework was the Mercury Polar Flyby mission (Spudis et al. 1994). The conceptual design of this spacecraft is shown in Fig. 6. It was to be launched into a similar transfer trajectory to that of Mariner 10, with a transfer to Venus and gravity-assist flyby, then targeted to Mercury in a solar resonant orbit for nominally three Mercury flybys, the first of which was to be over Mercury's north pole, the second one equatorial, and the third one over the south pole. The imaging was to be multi-spectral from 200 to 1,000 nm, with a coverage complementary to that of Mariner 10. Great emphasis was placed on investigating the polar regions with a neutron spectrometer, a radar scatterometer, and a thermal emission spectrometer. In particular, the nature and origin of polar deposits in the permanently shadowed craters discovered by Earth-based radar were to be studied. On the equatorial flyby, an X-ray fluorescence spectrometer was to study the rock-forming elements; use would also be made of data obtained by the thermal emission spectrometer.

Another proposal was made to both NASA (as a Pathfinder mission) and ESA (as a Flexi mission) quite late, effectively after the MESSENGER selection; this was LUGH (Low-cost Unified Geophysics at Hermes). It was to consist of three elements, a main spacecraft that would perform an equatorial flyby, with two polar nanoprobes released from the main spacecraft (Clark et al. 2003). While imaginative, given that MESSENGER had been approved, the LUGH proposal could not cover the detailed objectives made possible by an orbiter.

None of these proposals, or other, similar Mercury missions proposed at this time, was selected by NASA. However, it was in this framework that, after the second attempt a few years later, MESSENGER was selected. It was also at about this time, in 1993, that a mission proposal was made to ESA for a Mercury orbiter that eventually became the BepiColombo mission.

4 The MESSENGER Mission

4.1 Mission Origin and Design

In 1999, while ESA was studying what was to become the BepiColombo mission, NASA selected MESSENGER (MErcury Surface, Space ENvironment, GEochemistry, and Rang-

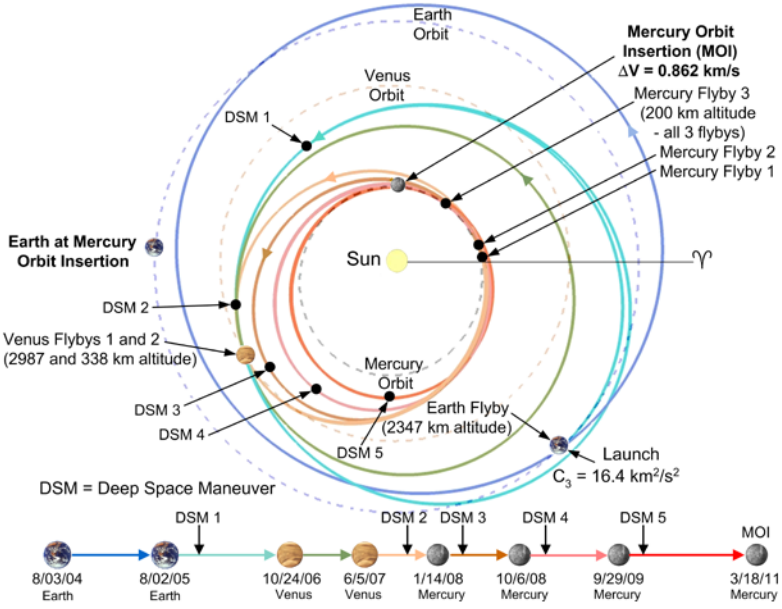


Fig. 7 The trajectory of MESSENGER with the mission timeline

ing) as a Discovery-class mission for launch in 2004. MESSENGER had originally been proposed in 1996 but was not successful until its second proposal in 1998 (McNutt et al. 2006). Three launch opportunities were considered, one in March, one in May and one in August 2004. The three launch opportunities were not equivalent: if launch were in March or May 2004, Mercury orbit would be reached in 2009; if launch were in August 2004, orbit insertion would not occur until 2011. In the end, it was the third launch date that was used (see the timeline of the MESSENGER mission in Fig. 7 and Table 1). MESSENGER had been proposed to NASA by a team led by S.C. Solomon and is described in detail by Solomon et al. (2001), Santo et al. (2001) and Gold et al. (2001, 2003). A single spacecraft will be placed in orbit around Mercury. The spacecraft is three-axis stabilised and carries a range of instruments that combines planetary and magnetospheric objectives.

The mission design is based on the multiple gravity-assist principles of Chen-Wan Yen (McAdams et al. 1998, 2006). Following the launch on August 3, 2004, MESSENGER spent a year in an orbit close to that of the Earth prior to a gravity-assist flyby on August 2, 2005, that placed it on a trajectory to Venus for two gravity-assist flybys in 2006 and 2007. The first Mercury flyby will be take place January 14, 2008. The geometry of this flyby is shown in Fig. 8. All three scheduled gravity-assist flybys of Mercury (used for slowing down the spacecraft relative to Mercury) have a similar geometry. However, contrary to the Mariner 10 flybys, successive flybys by MESSENGER will have their closest approaches at different longitudes of the planet, thereby extending the coverage of the imaging initiated by Mariner 10 (so that most of the planet will be imaged during the flybys) and providing a more global coverage of the magnetic field. Aspects of the first two flybys are illustrated in Figs. 8 and 9. In this way, these first two flybys will bring a very early harvest of important scientific data, some three years before orbit insertion and the more comprehensive coverage that will then be undertaken.

Table 1 The milestones of the MESSENGER mission

Events	Date
Selection as a Discovery mission	July 1999
Phase B (detailed design)	January 2000–June 2001
Phase C/D (fabrication, assembly and test)	July 2001–July 2004
Launch	3 August 2004
Earth flyby	2 August 2005
Venus flybys	24 October 2006, 5 June 2007
Mercury flybys	14 January 2008, 6 October 2008, 29 September 2009
Mercury orbit insertion	18 March 2011
Mercury orbit	March 2011–March 2012

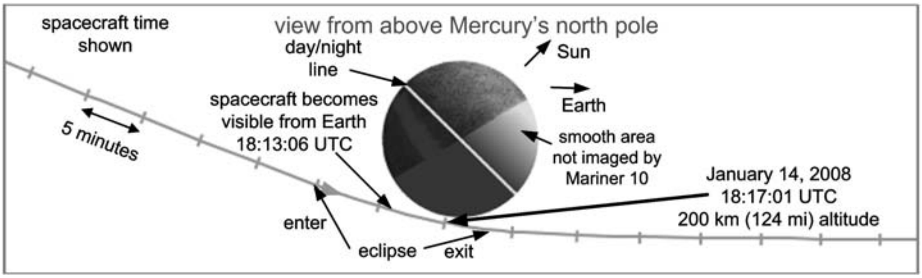


Fig. 8 The trajectory of MESSENGER around Mercury, seen from above the north pole during the first flyby on January 14, 2008. During flyby 1, approximately half of the hemisphere unseen by Mariner 10 will be imaged. It is also expected that the close flyby will give an early indication of the nature of the magnetic field of Mercury

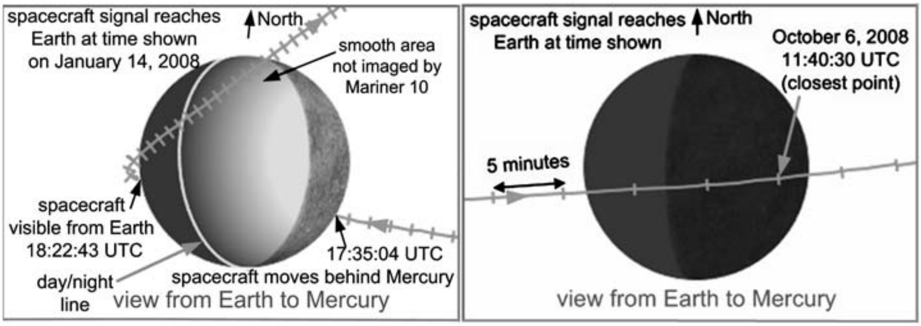
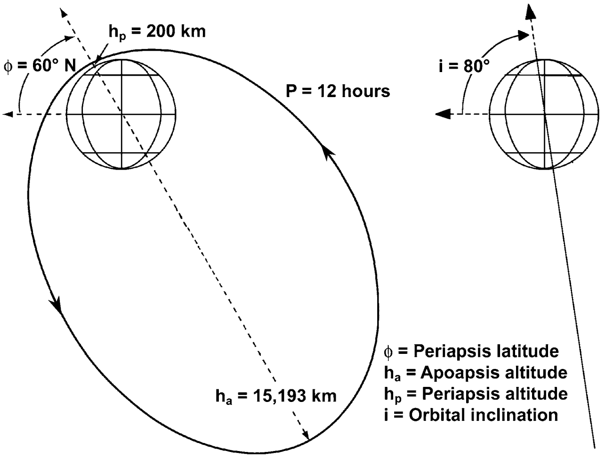


Fig. 9 The trajectory of MESSENGER around Mercury, seen from the Earth, during the first and second flybys of the planet on January 14, 2008, and October 6, 2008. The second flyby will almost complete the coverage of the imaging of the planet's surface not seen by Mariner 10. The two flybys are also complementary for mapping the planetary field of Mercury, with the first one covering a higher range in latitudes than the second, which is nearly equatorial

The planetary flybys make the mission possible by reducing the cumulative change in spacecraft velocity (ΔV) required for the mission, but MESSENGER was launched with a total ΔV capability of more than 2.2 $\mathrm{km\,s^{-1}}$; the fuel necessary for this corresponds to

Fig. 10 The operational orbit of MESSENGER



about 54% of the launch mass of MESSENGER. About a third of this fuel is required for Mercury orbit insertion; the rest is used for trajectory manoeuvres and orbit maintenance around Mercury.

MESSENGER's operational orbit, shown in Fig. 10, has an altitude of 200 km at periapsis and 15,193 km at apoapsis and a period of 12 hours. The plane of the orbit is nearly polar, with an initial inclination of 80°; periapsis is initially at 60°N and increases to 72°N by the end of one Earth year. This geometry allows a very close survey of the northern hemisphere. Part of the fuel carried is used to correct the perturbations that tend to raise the periapsis altitude. There is sufficient fuel to carry out these maintenance manoeuvres during the operational phase of the mission.

4.2 The MESSENGER Scientific Objectives and Payload

The questions that MESSENGER has set out to answer all relate to the unique properties of the planet. Although a member of the family of terrestrial planets, Mercury—just like Venus, the Earth, and Mars—has its own specific characteristic features that, in the case of Mercury, are poorly understood because of the lack of detailed observational evidence. The questions relate to Mercury's unusually large density, its geologic history (and the specific surface features discovered by Mariner 10), the structure of the planet's core (solid or partly liquid), the origin of its magnetic field, the nature of the radar-bright deposits in craters close to the poles, and the characteristics of Mercury's dynamic exosphere. The payload of MESSENGER was selected in the light of these objectives, which require a specific range of observations.

There are seven scientific instruments on board MESSENGER, as shown in Table 2. An artist's sketch of the spacecraft with the payload instruments is shown in Fig. 11. These instruments have been described in considerable detail by Gold et al. (2001), including their scientific objectives, placed in the general context of the scientific exploration of Mercury by Solomon et al. (2001). After the earlier papers, some of the instruments were redesigned prior to launch; an up-to-date, if brief, account is given by Gold et al. (2003). In the following is a summary of the instruments and their capabilities; more detailed descriptions of the individual instruments can be found in the set of recent papers referenced.

Mercury Dual Imaging System (MDIS) contains a reflective narrow-angle (NA) camera and a refractive wide-angle (WA) camera (Hawkins et al. 2007). MDIS will map the entire

Table 2 The scientific payload of MESSENGER

Instrument		Mass (kg)	Power* (W)
MDIS	Dual imagers, narrow and wide angle FOV	8	7.6
GRNS	Gamma-Ray and Neutron Spectrometer	13.1	22.5
XRS	X-ray spectrometer, 1–10 keV	3.4	6.9
MAG	Fluxgate magnetometer + 3.6 m boom	4.4	4.2
MLA	Laser altimeter, 1,200 km range	7.4	16.4
MASCS	UV/Visible spectrometer, visible/IR spectrograph	3.1	6.7
EPPS	Energetic particle spectrometer, fast imaging plasma spectrometer	3.1	7.8
DPU	Integrated electronics, power processing for all instruments, MDIS electronics	3.1	12.3
	Payload harness, purge system, magnetic shielding etc.	1.7	
Payload totals:		47.2	84.4

*Orbit average

planet in monochrome to an average resolution of 250 m per pixel or better, global colour images will be obtained at an average resolution of 2 km or better, and high-resolution images will be obtained of selected features at a resolution of 20–50 m per pixel. Because of the highly elliptical orbit at Mercury, MDIS has been constructed using on-board pixel summing to provide images of uniform resolution throughout the orbit. There is a common scan platform on which the two imagers are mounted to allow pointing the instruments with some independence from the attitude of the spacecraft, to optimise the coverage and to assist with navigation. The NA and WA imagers have fields of view, respectively, of 1.5° and 10.5°. The CCD detector is 1,024 × 1,024 pixels in size, with 14 μm/pixel. Spectral coverage is provided by the WA imager using 11 colour filters from 415 to 1,020 nm; there is also a clear filter (centred on 700 nm) for navigation.

The Gamma-Ray and Neutron Spectrometer (GRNS) consists of two sensors (Goldsten et al. 2007), the Gamma-Ray Spectrometer (GRS) and the Neutron Spectrometer (NS). The GRS is based on a cryogenically cooled, high purity germanium detector which is actively shielded by a surrounding plastic scintillator. The combination, using a Stirling-cycle active cooler that keeps the germanium sensor at 90 K, optimises, for the mass and power available, the signal-to-background ratio. This is needed for measuring the surface elemental abundances of O, Si, S, Fe, H, K, Th, and U. This instrument was developed late in the programme, to replace a scintillator-based instrument that had been originally proposed but could not meet the scientific requirements. The separate NS sensor consists of a slab of plastic scintillator (to measure fast neutrons) sandwiched between lithium glass scintillators to measure the thermal neutrons, taking advantage of the orbital velocity from the ratio of the fluxes in the ram and the wake directions.

The X-Ray Spectrometer (XRS) measures the surface abundances of the elements Mg, Al, Si, Ca, Ti, and Fe from the fluorescence induced by solar X-rays (Schlemm et al. 2007). The instrument uses an assembly of three copper honeycomb collimators with three proportional counters that have been developed from previously used components. The field of view is 12°. The instrument also includes a silicon PIN detector that looks at the Sun through an opening of 0.03 mm^2 in the spacecraft's sunshade to monitor the solar X-ray flux. This detector is protected by two foils from the heat of the solar radiation, ensuring its operation at a temperature at −45°C.

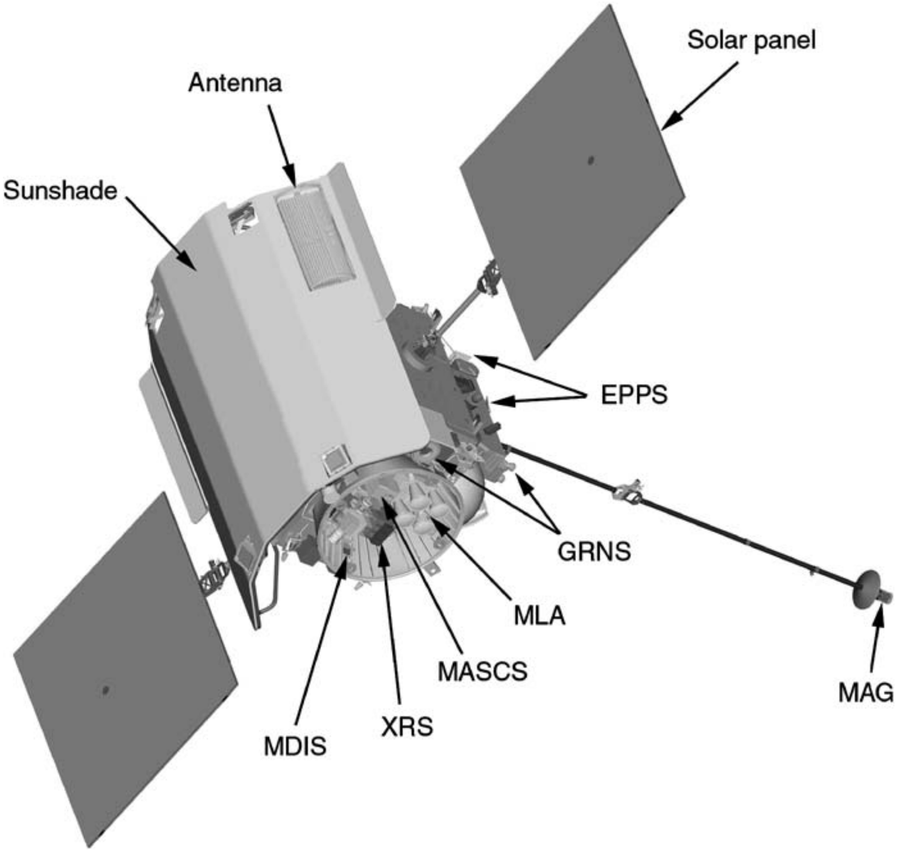


Fig. 11 The MESSENGER spacecraft showing the location of the scientific instruments (see text for explanation of the acronyms), as well as the sunshade, the solar panels, and one of the two phased-array antennas

The Mercury Laser Altimeter (MLA) uses a diode-pumped, Q-switched, Nd:Cr:YAG laser transmitter operating at 1,064 nm and four receiver telescopes with sapphire lenses (Cavanaugh et al. 2007). In orbit around Mercury, the MLA will measure at altitudes up to 1,200 km with 30-cm precision. Together with the exact positioning of the spacecraft using the tracking information from NASA's Deep Space Network and the imaging from MDIS, the MLA will deliver topographical information of very high accuracy. The elliptical orbit of MESSENGER means that the MLA will operate for about 30 minutes around the periapsis of each orbit. The performance of the MLA was tested in space in 2005 by exchanging laser pulses between MESSENGER, at the time at a distance of about 25 million km, and a ground station on Earth (Smith et al. 2006).

The Mercury Atmospheric and Surface Composition Spectrometer (MASCS) consists of two sensors, one covering the ultraviolet and visible wavelengths from 115 to 600 nm, the other the visible and infrared wavelengths in two bands, from 300 to 1,050 nm and 0.85 to 1.45 μm (McClintock and Lankton 2007). The two instruments share a common front-end Cassegrain telescope but have separate detection and signal-processing units. The UV/visible sensor will be used to study Mercury's very tenuous exosphere by scanning over the limb of the planet to determine its composition, while the visible/IR sensor will observe Mercury's surface composition.

Plasma and high-energy particles in the Mercury environment will be measured by two complementary sensors in the Energetic Particle and Plasma Spectrometer (EPPS) instrument (Andrews et al. 2007). For high-energy particles, an Energetic Particle Spectrometer (EPS) sensor measures the fluxes of ions from 10 keV/nuc to ~3 MeV and electrons up to about 400 keV, using time-of-flight and residual energy techniques. The directional measurements are performed over a field of view of 160° by 12° by a 24-pixel silicon detector array that is divided into six segments of 25° each. The Fast Imaging Plasma Spectrometer (FIPS) is a new design, using a complex electrostatic deflection geometry followed by a position-sensing time-of-flight measurement element for determining ion species in the plasma up to 20 keV per electronic charge. This instrument has a solid angle viewing coverage of almost 2π.

The Magnetometer (MAG) will map the magnetic field along the orbit, to study the magnetosphere and the origin of the planetary field (Anderson et al. 2007). MAG is a three-axis fluxgate instrument, following a very long line of similar instruments in space. In order to minimise the effect of the spacecraft-generated magnetic field on the measurements, the MAG sensor is mounted on a 3.6-m boom. The measurement rate will be 20 vector samples/s, but the transmitted rate will vary according to the telemetry capability; at lower transmission rates, the measurements will be averaged onboard prior to transmission. The normal range is ±1,530 nT, with a 16-bit or a 0.05-nT resolution.

5 BepiColombo

5.1 Origins of The BepiColombo Mission

5.1.1 Concepts of a Mercury Orbiter Mission in Europe

In the 1980s, the ESA received two proposals for a Mercury orbiter mission. Neither were selected by the European Space Agency (ESA), but European scientists interested in Mercury were optimistic because the science case for such a mission remained strong. Once a first study established the technical feasibility, it was expected that the scientific arguments would convince ESA and the planetary science community to undertake a mission to Mercury. In response to ESA's call for mission proposals in 1992, a Mercury Orbiter proposal was submitted in May 1993 by a team of European scientists led by A. Balogh (1993). The proposed mission, using a Chen-Wan Yen design of multiple Venus and Mercury flybys prior to insertion into orbit around Mercury, combined space plasma (magnetospheric) and planetary objectives. The prime motivation for the proposal was the study of the very intimate interdependence of the planetary interior and its magnetic field with the magnetosphere formed around Mercury by the interaction with the solar wind. The link provided by the magnetic field observations that needed interpretation in terms of the comparable external and internal contributions appealed to both planetary and magnetospheric scientists in ESA's science advisory committees.

A study was duly carried out within ESA in 1993–1994; the conceptual spacecraft design is shown in Fig. 12. However, at the conclusion of the study, the mission design was regretfully deemed to be beyond the budgetary limit of the "medium" scale missions in ESA's Horizon 2000 framework. However, by 1996, another round of strategic planning was carried out to define the Horizon 2000+ follow-up programme; in the context of this

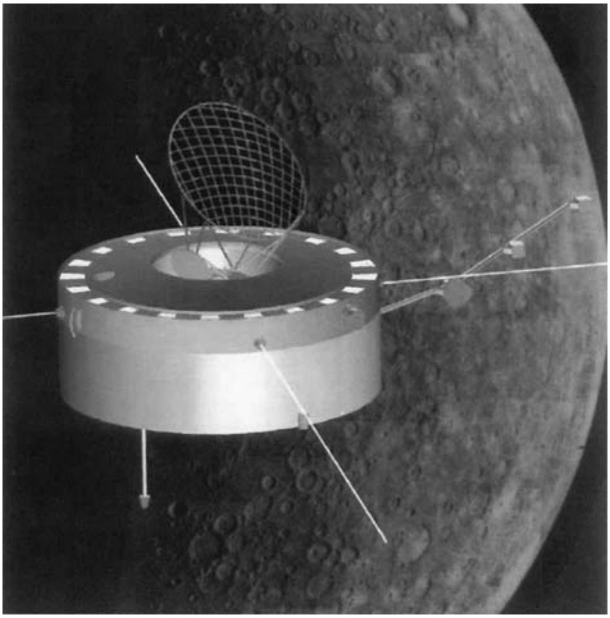


Fig. 12 Concept of the Mercury Orbiter spacecraft from the first study by ESA in 1993–1994. It was to be a spinning spacecraft, with a despun antenna to ensure a high data rate to Earth. Several of the instruments considered for the model payload were similar to those now selected for JAXA's Mercury Magnetospheric Orbiter

programme, a Mercury mission was to be the planetary "cornerstone" of the new programme phase, enabling the likely costs of the mission to be included in ESA's future budget.

One of the foundations of the new Mercury Orbiter cornerstone programme was the new mission design, based on solar electric propulsion (SEP, Racca 1997). This technology was to be tested by ESA through the first Small Mission for Advanced Research in Technology (SMART-1) to the Moon. This mission, launched in 2003 and very successfully implemented, used SEP for transfer to lunar orbit and concluded in 2006 when the spacecraft was crashed into the Moon, following a successful technological and scientific programme (Foing et al. 2006).

An industrial study of the new design for BepiColombo was undertaken under ESA direction in 1997. The design consisted of two orbiters, one a large, three-axis stabilized platform with large planetary instruments, the other a small spinning subsatellite with a modest space plasma payload. However, this study ran into considerable problems when the Mercury approach, orbit insertion, and operational phases were studied. The mission design was very reminiscent of the earlier proposal by Neukum (1985). Reconciling the conflicting requirements of instrument pointing, propulsion, and thermal design proved to be very difficult and could not be satisfactorily resolved within the mass budget.

At that point a new mission design was proposed by Y. Langevin, a member of ESA's scientific advisory team for the Mercury cornerstone mission (Langevin 2000, 2005). This scheme involved a single Ariane 5 launch with the composite spacecraft shown in Fig. 13. The mission plan consisted of a ballistic orbit to Venus followed by a gravity assist at Venus, solar electric propulsion for transfer to Mercury, followed by the jettisoning of the SEP module and orbit insertion using chemical propulsion. This plan provided a realistic basis for a new study that involved a two-spacecraft approach, one for planetary and one for magnetospheric objectives. At that point a lander, or surface element, was also included. The problem for a lander at Mercury is that due to the absence of an atmosphere, landing involves active retrorockets and flight control as on the Moon, but with the added difficulty of a very challenging thermal environment. During the study, even a "hard" lander was investigated,

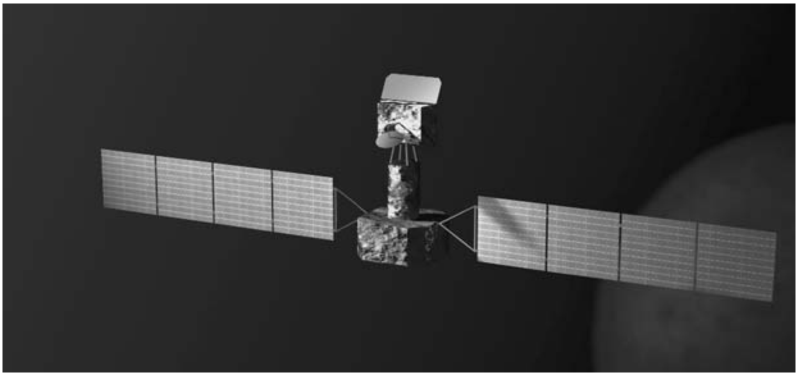


Fig. 13 The configuration of the Colombo (as it was then called) composite on its way to Mercury, comprising the planetary and magnetospheric orbiters, together with the large solar panels of the SEP subsystem. This concept was the outcome of the second industrial study in 1999

one that once released from the orbiter would free-fall onto Mercury's surface. Through the use of some exotic technologies, this option was found to be marginally feasible, but in the final version of the study the "soft" landing approach was adopted (Novara 2001). Although the lander was a popular element of the planned mission, it became a cost driver and was later dropped. At about the same time, in 2000, an agreement was reached with the Japanese Institute of Space and Astronautical Science (ISAS, now JAXA/ISAS) for the construction of the Mercury Magnetospheric Orbiter with ESA providing the other elements (Mercury Planetary Orbiter, SEP, and chemical propulsion modules and the launch of the composite). In the late 1990s, ISAS had in fact undertaken a study for a Mercury Orbiter mission (Yamakawa et al. 1999), so a cooperative mission with ESA could increase the scope of the science objectives beyond what could be achieved independently by the two agencies.

5.1.2 Japan's Plans for a Mercury Mission

In Japan, as a result of the successful technical developments that had been required for the first planetary mission, 'Planet-B' (Nozomi, the spacecraft intended to orbit Mars and launched in 1998), ISAS initiated consultations with the scientific community for missions to other planetary targets in the mid-1990s. Venus (Planet-C, to be launched in 2010) and Mercury were the strongest candidates. The latter target was supported by two groups, magnetospheric scientists motivated by the great success of Akebono (1989–) and Geotail (1992–), and the lunar science community as a follow-up to the Lunar-A (postponed) and Selene (to be launched in 2007) missions. The Mercury Exploration Working Group (MEWG) was formed in July 1997 to carry out detailed feasibility studies and an official proposal was submitted in November 1998 to the Steering Committee for Space Science (SCSS) of ISAS in November 1998 (Yamakawa et al. 1996, 1999).

ISAS M-V and NASDA H-IIA were considered as possible launch vehicles. The former was derived from the M-III-S2, which launched the first Japanese interplanetary missions Sakigake and Suisei to P/Comet Halley in 1985. However, its capability was deemed not sufficient for a realistic payload mass for a Mercury mission, so the larger H-IIA was assumed for system design. Two mission profiles were studied. The classical one was a spacecraft

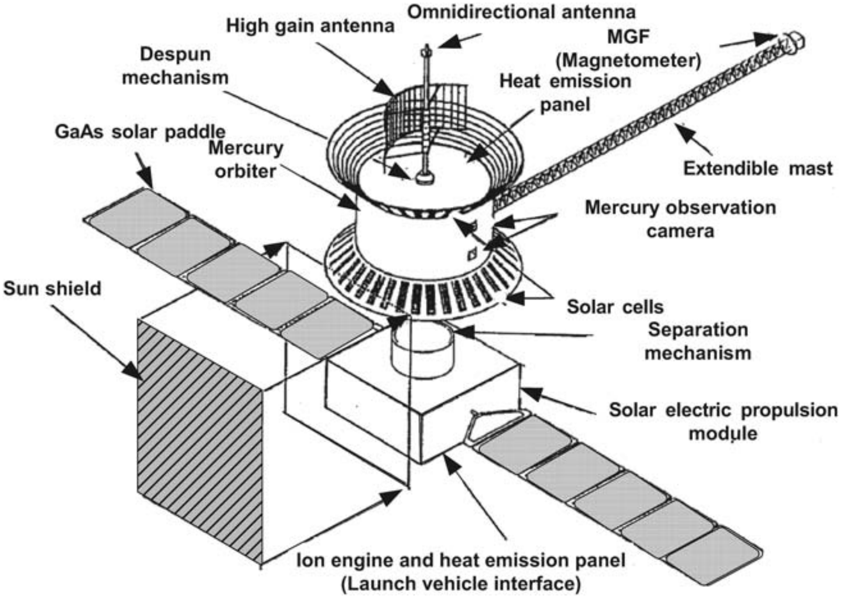


Fig. 14 The ISAS Mercury Orbiter design with SEP module in 1998 (Yamakawa et al. 1999)

with chemical propulsion that used a Chen-Wan Yen trajectory. For launch in 2005 with two Venus and two Mercury flybys, the overall transit time was 4.2 years. The launch mass was 1,650 kg including 950 kg fuel. A more ambitious proposal used SEP, based on the Hayabusa mission to asteroid Itokawa (2003–). For a launch window in 2005 with a single Venus flyby, the total flight time was to be 2.3 years. Wet mass at launch was to be 1,500 kg with an SEP module of 1,100 kg. To address simultaneously magnetospheric, exospheric, and planetological investigations, a 0.5-day-period polar orbit (300 km × 6 Mercury radii altitude, inclination = 90°) was selected. The argument of periapsis was proposed to be 30° with respect to the ecliptic plane to avoid long shadow periods.

The proposed orbiter was to be a Helios-type spinning spacecraft (6–10 rpm). A schematic view with the SEP module is shown in Fig. 14. The chemical propulsion was identical to the Mercury Orbiter in Fig. 12. The main objectives of the payload were the interior, surface, atmosphere, and magnetosphere of Mercury. The model payload (total mass 70 kg) consisted of multiband cameras, X- and gamma-ray spectrometers, magnetometers, plasma and energetic particle analyzers, plasma wave analyzer with radar sounder, dust detector, laser altimeter, and radio science instrument. The feasibility and required capabilities for a lander (300 kg), a penetrator (90 kg), and a small orbiter (20–30 kg) were also investigated. At the end of 1998, the remaining problems were cost, thermal design, and kick-motor development. The SCSS encouraged the MEWG to study those issues in more detail before a decision on the proposal could be made. This was to come to fruition in the context of the collaboration between ESA and (then) ISAS.

5.1.3 The BepiColombo Mission

In the meantime, ESA's Mercury Cornerstone mission was renamed BepiColombo, in memory of Giuseppe Colombo (see Fig. 15), who had played a crucial role in the design of

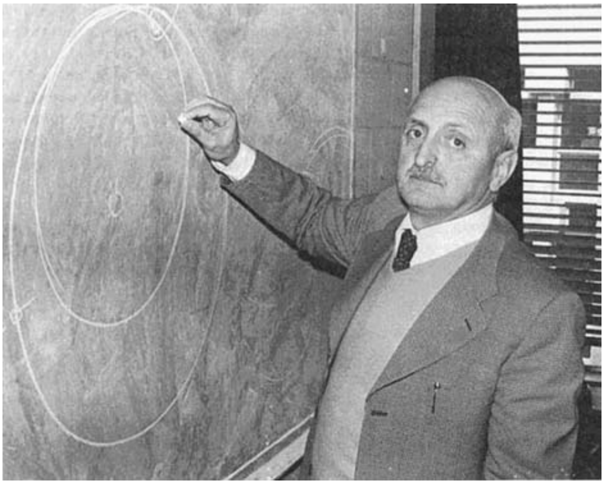


Fig. 15 Giuseppe Colombo (1920–1984), who discovered the orbital resonance of Mercury and who advised NASA to achieve three flybys of Mercury by Mariner 10. ESA and JAXA's joint, two-spacecraft mission is named in his memory

the Mariner 10 mission and in the determination of Mercury's orbital resonance (Colombo 1965). The discussion about the possibility of a collaboration with ESA was initiated in ISAS following the Inter-Agency Consultative Group (IACG) meeting of November 1999. The official request was sent in a letter from the Director-General of ISAS to the Directorate of Scientific Programme of ESA, dated July 31, 2000. Following the approval of BepiColombo as the fifth Cornerstone of ESA, the MEWG was re-convened to evaluate the role of the Japanese orbiter as one element of the BepiColombo mission. On the basis of this study, 'the international Mercury exploration mission BepiColombo' was approved by the SCSS of ISAS in January 2002, and by the Space Activities Commission of Japan in June 2003. In October 2003 JAXA was formed through the merger of ISAS, the National Space Development Agency (NASDA) and the National Aerospace Laboratory (NAL). ISAS is now part of JAXA.

The status of the BepiColombo project studies at the conclusion of these preliminary, but in-depth, technical and scientific studies is described by Grard and Balogh (2001), Anselmi and Scoon (2001), and Novara (2001, 2002).

The two-spacecraft approach, together with a possible a lander (called the Mercury Surface Element, or MSE), and both an SEP and a chemical propulsion subsystems, was quite a complex assemblage of elements for launch and delivery to Mercury. Two launch possibilities were envisaged: a launch of the whole assembly on a single Ariane 5, or two launches with Soyuz-Fregat, one for the Magnetospheric Orbiter and the Surface Element, the other for the Planetary Orbiter. A serious disadvantage of this second scenario was that two propulsion elements (SEP and chemical) were needed, as well as two service modules to support the two composites during the launch and the cruise to Mercury.

A more comprehensive study indicated that the Surface Element was too heavy and would need a separate (third) launcher, which finally led to the abandonment of the lander.

Although ESA approved BepiColombo as a cornerstone-class mission in late 2000, it became necessary to reassess the mission in 2002, due to budget restrictions within ESA. The approval was made subject to a satisfactory outcome of the reassessment studies that were initiated to refine the definition of the mission and its cost. The study was carried out from 2002 to 2003, with the help of both internal ESA support and further industrial contracts. A number of technical solutions were proposed at this stage, particularly for optimising the accommodation of the payload. In addition, the prospect of a more powerful Soyuz-Fregat launch vehicle (an upgraded Soyuz-2B with Fregat M upper stage, to be launched from Kourou) led to a single launch for the MPO, MMO, and propulsion modules assembly.

In February 2004, ESA's Science Programme Committee approved the Science Management Plan; this was followed by an Announcement of Opportunity to the scientific community for proposals for the payload of the European orbiter, and signalled the start of the industrial-definition Phase 2 studies. The instrument proposals were reviewed by ESA through 2004 and a payload was selected for the Planetary Orbiter in November 2004. At the same time, ISAS/JAXA successfully carried out a similar approval and payload selection procedure.

For ESA, it remained to determine that the payload instruments would be adequately supported by the national agencies; this was completed in the course of 2005, but not without some difficulties in some of ESA's member states. This ended the approval procedure of the MPO payload. The stage was thus set for ESA to issue an invitation to tender for the mission elements and the evaluation of the tenders and selection of the industrial Prime Contractor for the European elements of BepiColombo.

5.2 Mission Objectives and Mission Design

The objectives of BepiColombo have been formulated as a comprehensive set of questions that relate to all aspects of the planet Mercury and its environment (Grard et al. 2000). The objectives and the requirements on the mission take into account the capabilities and expectations of MESSENGER, which will bring answers to some of the key questions. The emphasis for BepiColombo is not so much the discovery of new features of Mercury (although this cannot be excluded), but rather the collection of a comprehensive set of observations that will bring knowledge of the planet on a par with the other terrestrial planets and describe satisfactorily its origin and evolution. The following summary of the mission objectives takes into account the two BepiColombo spacecraft, the MPO and MMO, each with its specific emphasis. It is anticipated, however, that for most objectives, the joint analysis of the observations will bring more substantial results than if the data collected by each spacecraft are analysed separately.

The questions follow the structure of the planet and its environment as a system of interacting parts. Starting with Mercury's internal structure (targeted more specifically for the MPO), the objective is to determine precisely the sizes and masses of the major chemical reservoirs, the crust, mantle, and core. The state of the core and the existence of an outer liquid layer need to be determined to account for the origin of the planetary magnetic field. Is a classic dynamo possible within Mercury's core? Observations are also required to detect radial and lateral heterogeneities in the crust and mantle structure and, in addition, topographic variations in the core–mantle boundary. The observations will be used to constrain models of the rheology and of the tectonic, volcanic, chemical, and thermal evolution of Mercury. Such modelling will also constrain hypotheses for the formation of the planet and even of the terrestrial planets as a family.

The requirement is to obtain accurate measurements of the gravity field, the topography, the amplitude of forced libration, and the obliquity. The observations will be solved for the long wavelength gravity field with a high relative accuracy (10^{-4}). Local gravity anomalies down to a resolution of 400 km will be determined. The Love number k_2 needs to be determined and the dissipation factor Q sufficiently constrained. In addition, the mean planetary moment of inertia and the ratio between the moments of inertia of the solid upper layer and of the entire planet need to be determined.

The measurement of the planetary magnetic field, up to high-order terms, will help constrain the interior structure. The existence of magnetic anomalies and/or short-spatial-wavelength magnetic structures needs to be investigated. This will be a difficult task, as the measurements will give the sum of internal and external contributions, possibly of comparable magnitude. This objective is intimately related to the magnetospheric objectives described in the following, and observations by both the MPO and MMO will contribute to meeting these, in particular by the joint analysis of both data sets.

The resolution with which Mariner 10 imaged somewhat less than half Mercury's surface will be considerably improved by MESSENGER, which will cover the entire surface, with a considerably improved resolution especially on features of interest. The objectives include (1) the global characterisation of tectonic and volcanic features (lineaments, scarps, and, possibly, domes); (2) the assessment of the roles of global cooling, major basin-formation events (e.g., Caloris), viscous relaxation and tidal stresses for the endogenic modification of the surface; and (3) the study of the crustal rheology from the relaxation of surface features (e.g., multi-ring basins). Similarly, the altimetry of surface features and crustal structure from geodesy at a lateral scale of 500 km or less are important related objectives.

The elemental and mineralogical compositions of the surface need to be determined on large, regional, and small scales. Of particular importance is the determination of key element ratios, such as potassium to thorium, iron to silicon, again on a range of scales. An important objective is the determination of the nature of volatiles in the permanently shadowed craters revealed by Earth-based radar imaging. There will still be a need to confirm and complement MESSENGER's mapping of craters and crater sizes, in particular over the southern hemisphere where BepiColombo will have a more uniform coverage.

The exosphere of Mercury is both tenuous and highly variable. Composition and height distributions of the constituent species of the exosphere will be determined, as will the dependence of the density vs. height profiles of the constituent species on local time (especially the differences between the nightside, terminator and dayside differences) and latitude. A particularly important topic is exospheric dynamics in response to solar wind variations and magnetospheric processes. There are intimate links between the surface and the exosphere on the one hand, and the exosphere and the magnetosphere on the other. Important to unravelling these links is a determination of the sources, production mechanisms, and loss processes of the different constituents of Mercury's exosphere. With observations from both the MPO and MMO of the exosphere and its dynamics, spatial ambiguities can be resolved and the data can be used to refine three-dimensional exospheric models.

Mercury's magnetosphere has significant differences from that of the Earth: it is considerably smaller, it is variable on very short timescales, there is no ionosphere, and the planetary surface is acting as an absorber. Furthermore, solar wind in the inner heliosphere has a higher density and stronger magnetic fields that strongly affect the structure, dynamics, and physical processes in the Hermean magnetosphere. The objectives therefore include the determination of the structure and temporal variability of the magnetosphere in response to the strongly variable solar wind and interplanetary magnetic field. In terms of structures, the dayside cusp, the location of the bow shock and the magnetopause will be studied, as well as the dynamics of the magnetotail (for instance, are there substorms on Mercury?). Magnetospheric current systems pose a particularly important question; although their existence cannot be in doubt, their topology is fundamentally unknown. Given the very different parameter regime, the observation of Mercury's magnetosphere will help to assess the importance of key parameters that control the structure, dynamics, and physical processes of other planetary magnetospheres. The MMO is optimised to make the necessary comprehensive observations, but the MPO will also contribute significantly to meeting these objectives.

Table 3 The milestones of the BepiColombo mission

Events	Date
Agreement ESA–ISAS (later JAXA)	2000
Confirmation as a Cornerstone mission	September 2000
Reassessment	2002 to 2003
Payload selection, detailed approval	2004 to 2005
Phase C/D (fabrication, assembly and test)	January 2007 to mid 2013
Launch	August–October 1013
Moon flyby	31 October 201 3
Earth flyby	1 February 2015
Venus flybys	February and September 2016
Mercury flybys	August and October 2018
Capture into Mercury orbit	March 2019
Mercury Magnetospheric Orbiter in place	June 2019
Mercury Planetary Orbiter in place	July 2019
Mercury Orbit	July 2019–July 2020

In addition to the objectives described above, the MPO and MMO each have additional objectives that go beyond planetology. The MPO, as part of its capabilities for mapping the gravitational potential of Mercury, can also address general relativity, testing it to a level better than 10^{-5} by measuring the time delay and Doppler shift of radio waves and the precession of Mercury's perihelion. Furthermore, the MPO can test the very strong equivalence principle to a level better of 4×10^{-5}, determine the oblateness (J_2) of the Sun to better than 10^{-8}, and set upper limits to the time variation of the gravitational "constant" G.

The MMO also provides an opportunity to revisit the inner heliosphere, which was only once explored previously 30 years ago by Helios 1 and 2. The MMO equipped with modern instrumentation will provide measurements of the solar electromagnetic radiation, solar wind and interplanetary dust at 0.3–0.5 AU. Given its orbit, the MMO will spend a significant fraction of time well in front of the magnetosphere, in the undisturbed solar wind, when its apoapsis is on the sunward side of Mercury. This will occur, due to the thermal design of the mission, around the perihelion of Mercury. Depending on the scheduling of the missions, collaboration with the planned ESA Solar Orbiter mission can also be envisaged.

The mission design of BepiColombo has been thoroughly analysed during the successive studies. The milestones of the mission are listed in Table 3. Essentially, once the cornerstone mission was selected as a dual spacecraft mission launched by a single Soyuz-Fregat, a ballistic-chemical propellant mission design was no longer possible and SEP became a requirement. The mission, as indicated above, combines chemical propulsion, repeated planetary flybys, and SEP.

The launch configuration consists of four main elements in the BepiColombo stack. There are two propulsion modules, the Chemical and the Solar Electric Propulsion Modules that constitute the Mercury Transfer Module, and the two spacecraft, the planetary and the magnetospheric orbiters. This configuration is shown in Fig. 16 after launch with the solar panels used for powering the SEP module deployed (Förstner et al. 2006).

Launch will take place from Kourou on board a Soyuz 2-1B/Fregat M in August 2013. Following injection into a Geostationary Transfer Orbit (GTO), chemical propulsion is used to raise the apogee to the Moon's orbit. A Moon flyby is foreseen to place the BepiColombo

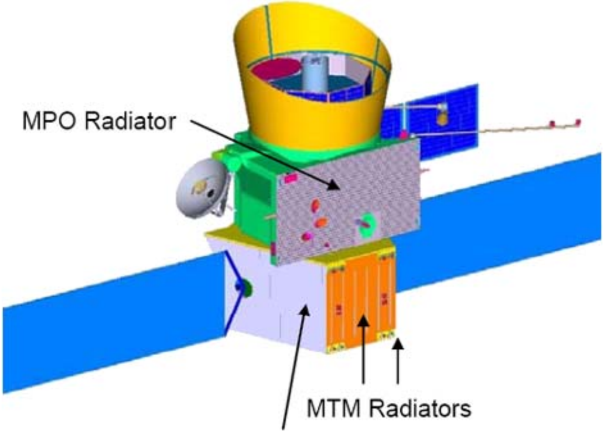


Fig. 16 The BepiColombo Mercury Composite Spacecraft (MCO) in the cruise configuration, with the Mercury Transfer Module (MTM) *at the bottom*, the Mercury Planetary Orbiter (MPO) *in the middle*, and the Mercury Magnetospheric Orbiter (MMO) *at the top* of the stack protected by a heat shield (Förstner et al. 2006)

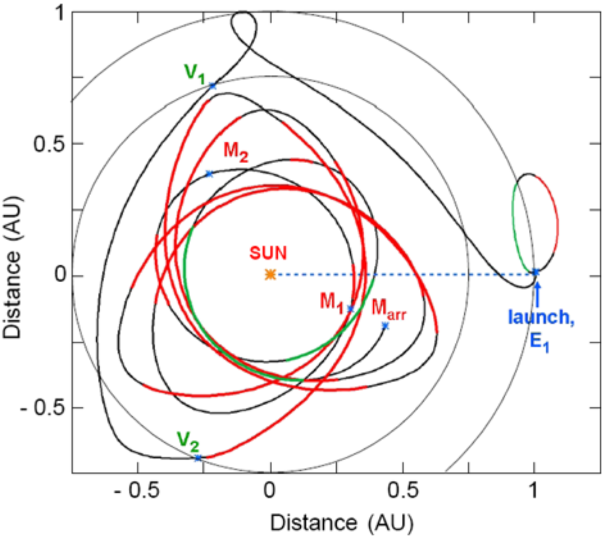


Fig. 17 The cruise trajectory of BepiColombo in an ecliptic projection, in a *coordinate system* with the *Sun–Earth line* fixed. The gravity-assist flyby encounters with the Earth (E_1), Venus (V_1 and V_2), and Mercury (M_1 and M_2) are indicated as is the final arrival to Mercury (M_{arr}). SEP thrust arcs are shown in red and green; coasting arcs are shown in black

composite into an interplanetary escape trajectory. The planned transfer to Mercury is shown in Fig. 17 (Förstner et al. 2006). There are gravity-assist flybys at Earth, at Venus (twice), and at Mercury (also twice) before a gravity-capture manoeuvre at Mercury. The strategy for planetary capture makes use of the weak stability boundary technique (see, e.g., Belbruno and Carrico 2000; Circi and Teofilatto 2001) to eliminate the risk of a critical injection burn. By approaching the planet slowly enough in the vicinity of one of the two libration points, L1 and L2, it is possible to weakly capture the spacecraft around Mercury without any propulsive manoeuvres (except for small trajectory corrections). The initial orbit (400 × 180,000 km) is stable for about one Mercury year (88 days) and can be readily stabilised with a very small manoeuvre. The apoapsis is then lowered to reach the operational orbit (400 × 11,824 km) of the MMO (Förstner et al. 2006).

Here the MMO as well as the Sun shield, which had been protecting the MMO during the cruise phase, will be separated from the MPO. Subsequently, the apoapsis of the MPO

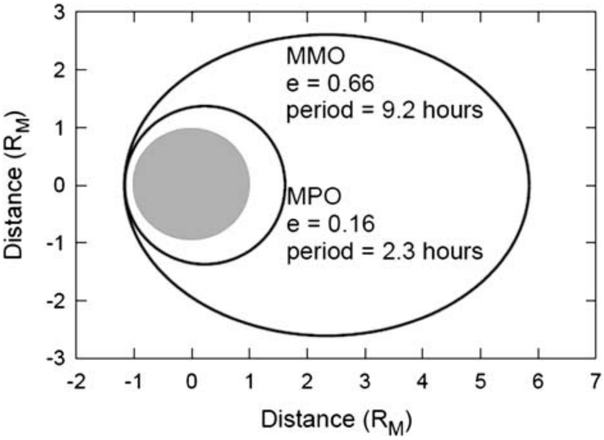


Fig. 18 The operational orbits of the Mercury Planetary and Magnetospheric Orbiters

Table 4 The scientific investigations of the BepiColombo Mercury Planetary Orbiter

Instrument		Mass (kg)	Power (W)
BELA	Laser Altimeter	12.5	52
ISA	Radio Science: Accelerometer	5.9	7
MERMAG	Magnetometer	2.0	3
MERTIS	IR Spectrometer	2.9	8.5
MGNS	Gamma Ray and Neutron Spectrometer	5.2	4
MIXS / SIXS	X-ray Spectrometer and Solar Monitor	5.5	15
		1.5	4
MORE	Radio Science: Ka-band Transponder	3.3	16
PHEBUS	UV Spectrometer	4.6	6
SERENA	Neutral Particle Analyser / Ion Spectrometers	5.0	21
SIMBIO-SYS	High Res.+ Stereo Cameras / Visual and NIR Spectrometer	7.2	23
Totals:		55.6	159.5

is further lowered until it reaches its operational orbit of 400 × 1,508 km in July 2019. The mission, in its operational orbit, is expected to last one Earth year.

5.3 The BepiColombo Mercury Planetary Orbiter (MPO)

The Mercury Planetary Orbiter is a three-axis-stabilised and nadir-pointing spacecraft. Its prime objective is to carry out remote sensing of the planet. It will be placed into a low-eccentricity polar orbit (400 × 1,500 km) that will provide an excellent spatial resolution over the entire surface of the planet. The MPO payload as selected and confirmed by ESA is listed in Table 4. The instruments on the MPO will concentrate on the investigation of Mercury's interior, surface, and exosphere (Schulz and Benkhoff 2006).

The imaging instruments of MPO will map the complete surface of Mercury with a resolution better than ~100 m globally in the stereo mode and ~5 m for selected areas. For meeting these measurement objectives, the composite instrument, SIMBIO-SYS consists of two imagers, one a stereo channel (STC) with a field of view of 4° and 50 m/pixel resolution, the other is the High Spatial Resolution Imaging Channel (HRIC) with a field of view of 1.47° and a resolution of 5 m/pixel. In both cases, the resolution is given from an altitude of 400 km. Both imagers have a spectral range of 400 to 900 nm and four spectral channels. Another instrument in this package is the Visible Infrared Hyperspectral Imager Channel (VIHI) targeting the mineral composition of the surface in the spectral range 400 to 2000 nm. The objective is to cross-correlate the mineralogical maps with the morphological maps produced by the visible/near infrared imagers.

The Mercury Radiometer and Thermal Infrared Spectrometer (MERTIS) is an IR-imaging spectrometer that will also provide information on the mineralogical composition of Mercury's surface by mapping its spectral emittance in the wavelength range of 7 to 14 μm.

The global abundance of rock-forming elements on Mercury's surface (in the uppermost one or two microns) will be measured by the X-ray spectrometer (MIXS). This instrument uses the activation of elements on the surface by solar X-rays; it will measure fluorescence line emission in the 0.5 to 7.5 keV energy range that corresponds to the emission energy of some important elements such as magnesium, aluminium, silicon, sulphur, calcium, titanium, and iron. Because the excitation of fluorescence emission lines depends on the variable solar X-ray and energetic particle flux, the latter will also be measured directly by another instrument, the Solar Intensity X-ray and particle Spectrometer (SIXS), to allow the absolute calibration of the MIXS measurements.

The composition of the surface layers deeper than those accessible to the X-ray measurements will be measured by the Mercury Gamma and Neutron Spectrometer (MGNS). The gamma-ray line spectra activated by the cosmic-ray flux are characteristic of elements that are within about 1 to 2 m from the surface. The instrument uses newly developed scintillation detectors which provide adequate energy resolution for the identification of elements. The same instrument also contains a detector for measuring the neutron flux (proportional counters).

The collective objective of these instruments is to characterise—morphologically and compositionally—Mercury's surface features to identify compositional variations. This will help determine whether specific landmarks have been produced by endogenic processes (e.g., volcanism) or exogenic processes (e.g., impacting objects). Knowledge of Mercury's surface composition will provide a key test of competing models for the formation and evolution of Mercury and the other terrestrial planets. The neutron spectrometer will additionally take measurements of the radar-bright spots observed from ground in the polar regions to identify their composition. If these spots, initially thought to reflect the presence of water ice, are covered with sulphur, this finding would support the idea that the planet's core is composed of Fe–FeS alloys which, compared with pure iron, remain liquid at lower temperatures.

The interior structure of Mercury will be investigated by measuring the planet's gravitational potential using the radio science experiment in combination with a laser altimeter, the high-resolution camera, an accelerometer, and (indirectly) by measuring the planet's magnetic field.

The radio science experiment (MORE) is a very sophisticated combination of data generated, gathered, and collectively analysed to determine with extreme precision the range and range rate of the spacecraft. These will be determined with an accuracy of 15 cm for range and 1.5 μm/s for the range rate at 1,000-s integration time. The key component of the "instrument" is an advanced Ka-band transponder carried on board for the very precise determination, in combination with the ground tracking and telemetry station, of the Doppler signal in the up-down (coherent two-way mode) radio link. The non-gravitational acceleration will be determined using an accelerometer (ISA). The data will be used to generate orbital solutions from which the gravitational terms can be derived. The surface gravitational potential will be linked to landmarks with high precision using the high-resolution

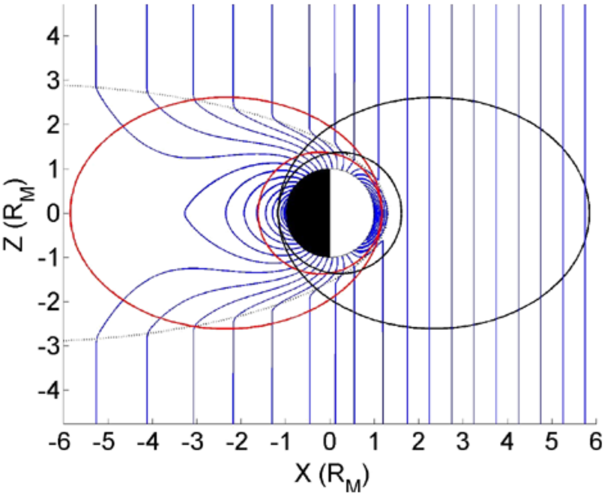


Fig. 19 The orbits of the BepiColombo Planetary and Magnetospheric Orbiters in the context of a model Mercury magnetosphere. Two sets of orbits are shown: at perihelion (with apoapsis in the solar wind, *black lines*) and at aphelion (with apoapsis in the tail of the magnetosphere, *red lines*)

camera and the topographic information from the laser altimeter. Thus, the joint analysis of observations from these three instruments will provide unprecedented quality of data on the geodesic properties of the surface of Mercury and the planet's gravitational potential.

The laser altimeter (BELA) provides absolute topographic height and position with respect to a Mercury-centred coordinate system. It uses a passive Q-switched Nd:YAG (neodymium-doped yttrium aluminium garnet; Nd:$Y_3Al_5O_{12}$) laser at 1,064 nm, generating high-energy pulses (50 mJ) at a rate of 10 Hz. The beam width is 50 microrads and results in a spot size on Mercury of 20 to 50 m. The time resolution of processing the return pulse is 2 ns, corresponding to a range resolution of 30 cm (comparable to the expected knowledge of the position of the spacecraft). This performance will be maintained up to an altitude of 1,000 km, above which it is expected that the laser will not be operated. Other than contributing to the joint analysis of the data, the laser altimeter will also provide information on the tidal deformation of the surface, surface roughness and local slopes, and albedo variations.

The determination of the planet's internal magnetic field will also contribute to the determination of its internal structure. The questions concerning the core, and the likely existence of an outer liquid layer that decouples the core from the mantle, will be answered from a combination of gravitational, orbital, and magnetic field measurements. The magnetometer (MERMAG) is due to map the magnetic field along the orbit of the MPO that is due in part to the internally generated field and in part to fields generated by the interaction of the internal field with the solar wind in Mercury's magnetosphere. In fact, estimates indicate that even along the low-altitude orbit of the MPO the contribution of externally generated magnetic field to the total field measured can be 20% to 50%. As described in more detail in Sect 5.4, Mercury's magnetosphere is not only small but is also very variable, so the external contributions (together with induction effects in the core due to the externally variable currents) make the separation of internal and external terms very difficult. It is expected that MESSENGER's magnetic survey of Mercury will determine the origin (dynamo, crustal magnetism, or other) of the internal field (Korth et al. 2004). But the detailed data that are relevant for better understanding the dynamo (such as the higher-order terms in the scalar potential of the magnetic field) will be more securely obtained by combining the data from the two BepiColombo orbiters, so that by modelling the variable external field its contribution to the MPO data can be removed. The possibility that Mercury's internal field displays secular variations can also be assessed from a comparison of MESSENGER and BepiColombo observations. The orbits of the MPO and MMO are shown in Fig. 17, in the context of Mercury's magnetosphere, for two epochs, at perihelion and aphelion. The overlap of the orbits with the magnetosphere (when the planetary magnetic field can be measured, i.e. when the spacecraft is not in the solar wind) shows how much the measurements will be affected by the magnetosphere. The synchronism of the orbits will be used for correlating the measurements.

In the absence of a stable atmosphere, Mercury has a tenuous and highly variable exosphere. Mariner 10 and ground-based observations have established the presence of Ca, Na, K, H, He, and O in the exosphere, and other elements are also likely to be present. The key questions relate to the sources and sinks of the variable exospheric populations and to their dynamics as a function of external forcing (solar and solar wind effects). The global state of the exosphere will be observed by a UV spectrometer (PHEBUS) and by the visible spectrometer component of SIMBIO-SYS. The UV spectrometer has two spectrographs, one covering the wavelength range 55 to 155 nm, the other from 145 to 315 nm. A scanning mirror is aimed at the planet's limb (one degree of freedom), and the instrument operates in the push-broom mode (viewing a swath of the limb in the direction of travel). The objectives include the discovery of new species in the exosphere and the temporal variations due to external conditions and dynamical effects.

A complex package of instruments (SERENA) will carry out in situ observations of the exosphere, and its objective is the investigation of the surface-exosphere-magnetosphere coupling. There are four spectrometers in the SERENA group of instruments. One is a neutral particle camera (ELENA) that will study the escape of, and dynamic processes in populations of neutral gases from the planet's surface. A neutral particle spectrometer (STROFIO) will measure the composition of exospheric gases directly with high sensitivity. Precipitating plasma will be measured by an ion monitor (MIPA) using an electrostatic deflector, followed by an electrostatic analyser and a time-of-flight section for determining the velocity, energy, electrical charge, and mass of the incident ions. An all-sky camera for charged particles (PICAM), acting as an ion mass spectrometer, will make observations of the generation of neutral particles from the planet's surface, their subsequent ionisation and their transport through the exosphere and magnetosphere.

The objective of the remote and in situ observations of the exosphere and its interactions with the surface and the magnetosphere is to understand the surface release processes and the source–sink balance of the exosphere. Together these measurements will help to explain the cycling of volatile elements between Mercury's interior, surface, and exosphere, and the contribution of meteoritic–cometary material and solar wind plasma to Mercury's near-surface volatile budget.

5.4 The BepiColombo Mercury Magnetospheric Orbiter (MMO)

The MMO's goal is to study Mercury's magnetic field, exosphere, and magnetosphere as well as the inner heliosphere. The spacecraft will accommodate instruments mostly dedicated to the study of the magnetic field, waves, and particles in the Mercury's environment. Four main scientific targets have been set for the MMO spacecraft on the basis of BepiColombo mission objectives. Achieving these objectives will significantly advance comparative studies of the magnetic fields and magnetospheres of the terrestrial planets (Hayakawa et al. 2004a, 2004b).

To achieve those objectives, the MMO spacecraft ($\sim$250 kg, octagonal shape with 180-cm diameter and 90-cm height, Fig. 20) is spin stabilized at 15 rpm, which facilitates the

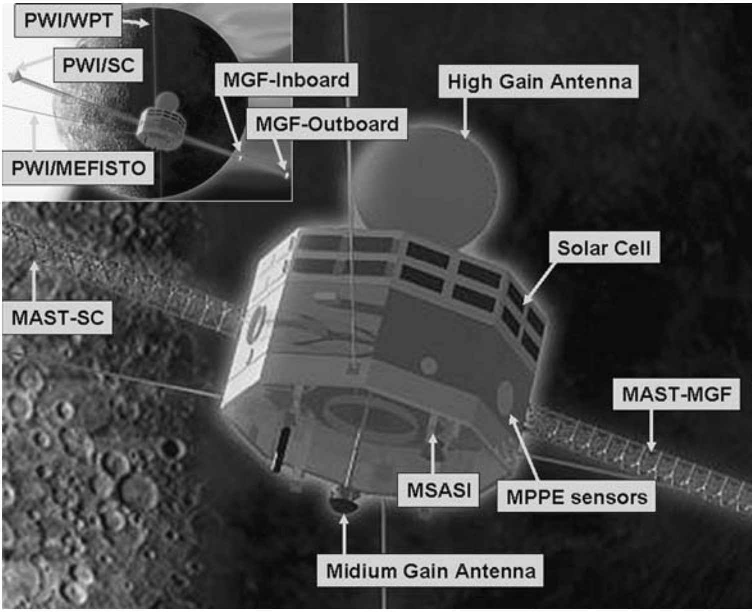


Fig. 20 The Mercury Magnetospheric Orbiter (MMO) in Mercury orbit. (Figure courtesy of JAXA and Kyoto University)

azimuthal scan of the particle detectors and the deployment of four wire antennas and two masts. Its spin axis is nearly perpendicular to the Mercury equator. The orbit is polar and highly elliptic, and its major axis lies in the equatorial plane to permit a global exploration of the exosphere, magnetic field, and magnetosphere up to an altitude of nearly six planetary radii, as well as the inner heliosphere. Details have been given by Yamakawa et al. (2002, 2004).

The MMO payload selected by JAXA in 2005 consists of five instruments or instrument packages (see Fig. 21): (1) wide range of capabilities for observing charged particles and energetic neutral atoms, (2) magnetic field, (3) electric field/plasma waves/radio waves, (4) dust, and (5) exospheric constituents (Mukai et al. 2006; Kasaba et al. 2007). Table 5 shows the list of MMO instruments. The Magnetic Field Investigation (MGF) consists of two sub-instruments, and the Mercury Plasma Particle Experiment (MPPE) for plasma and neutral particle observations consists of seven sub-instruments. The Plasma Wave Investigation (PWI) for electric field, plasma wave, and radio wave measurements with seven sub-instruments will be provided by large consortia from Japan, Europe, and elsewhere. Those payload packages will perform in-situ measurements of particles and fields in the magnetosphere of Mercury and its solar wind environment. The Mercury Sodium Atmosphere Spectral Imager (MSASI) is an imaging system included to map the sodium exosphere. The Mercury Dust Monitor (MDM) will characterise dust information around Mercury and the inner heliosphere. These scientific payload groups are coordinated by the Mission Data Processor (MDP) provided by JAXA which will ensure that the scientific objectives of the mission are fulfilled.

The MGF is designed to measure the magnetic field with an accuracy of about 10 pT, a dynamic range of $\pm 2,048$ nT and a time resolution of up to 128 Hz. Magnetic field measurements are essential to the fulfilment of the MMO scientific objectives; hence, two sets

Table 5 The scientific investigations on the BepiColombo Mercury Magnetospheric Orbiter

Instrument		Mass[*] (kg)	Power[*] (W)
MGF	Magnetic Field Investigation [2 sensors: MGF-Outboard, MGF-Inboard]	1.4	17.2
MPPE	Mercury Plasma Particle Investigation [7 sensors: MEA1, MEA2, MIA, MSA, HEP-ion, HEP-ele, ENA]	13.4	2.6
PWI	Plasma Wave Investigation [4 sensors: WPT, MEFISTO, SC-LF, SC-DB] [3 receivers: EWO, SORBET, AM2P]	5.4	8.5
MSASI	Mercury Sodium Atmosphere Spectral Imager	3.6	18.6
MDM	Mercury Dust Monitor	0.5	2.4
Totals[**]:		24.2	48.5

[*] Assigned values in Apr. 2005

[**] Mission Data Processor (MDP: for all) and mast (for MGF arid PWI) are not included

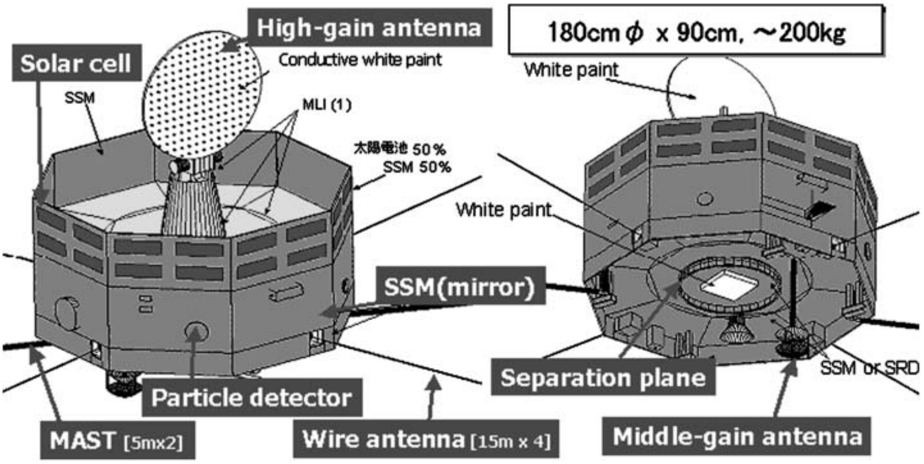


Fig. 21 The Mercury Magnetospheric Orbiter. Two views are shown to illustrate key features of the spacecraft. (Figure courtesy of JAXA)

of three-axis fluxgate sensors are installed in the middle and at the tip of a 5-m extendable mast (MAST-MGF) for redundancy, as well as for estimation of the residual field of the spacecraft. The outboard and inboard sensors are of different designs. The outboard sensor is a digital type developed in Europe, while the inboard one is an analogue type developed in Japan.

The MPPE is a composite of particle instruments: two Mercury Electron Analyzer (MEA) instruments, a Mercury Ion Analyzer (MIA), a Mercury Mass Spectrum Analyzer (MSA) for ions, High Energy Particle detectors for electrons and ions (HEP-ele and HEP-ion), and an Energetic Neutral Analyzer (ENA). These instruments are mounted on the side panels. Most of the plasma sensors have a 180° field of view (FOV) to yield full three-dimensional (3D) distribution within half a spin. Two electron sensors are looking in orthogonal direction and the full 3D distribution of electrons is measured with 1/4 spin, i.e. 1 s. MEA (3 eV ∼ 0 keV) employs two separate sensors, with variable geometrical factors, in order to cover the wide dynamic range ($\sim 10^6$) required for accurate measurements in the low-density plasma of Mercury's magnetotail on the one hand, and the dense plasma in the solar wind and the magnetosheath, cusp and boundary layers on the other hand. The two sensors point 90° apart in order to cover a 4π steradian solid angle in a quarter of the spin period when both sensors are working. The MIA (5 eV ∼ 30 keV) and MSA (5 eV ∼ 40 keV) also point 90° apart and have variable geometrical factors, but information about the ion species can be obtained only with the MSA. Measurements of low-energy electrons and ions, below 30 keV/q, have functional redundancies. Both the HEP-ele (30 keV ∼ 700 keV) and HEP-ion (30 keV ∼ 1.5 MeV) sensors use solid-state detectors (SSDs), and the HEP-ion sensor employs a time-of-flight (TOF) technique as well. The velocity analysis using the TOF technique is promising for high-energy ion measurements, even in the severe thermal Mercury environment. The combination of the SSD energy analysis and the TOF velocity analysis also provides information about ion species and a redundant estimation of electron fluxes. The ENA (25 eV ∼ 3.3 keV) is designed to measure neutral atoms produced by charge exchange between magnetospheric ions and exospheric particles, as well as neutrals sputtered from the planetary surface by impinging magnetospheric and solar wind ions. Hence the ENA provides imaging complementary to the MSASI observation of the exosphere.

The PWI is another composite instrument to study various plasma processes associated with radio and plasma waves (electric and magnetic components) and DC electric fields in the magnetosphere of Mercury and the solar wind environment. The instrument consists of three receivers. The first is the Electric Field Detector, Waveform Capture and Onboard Frequency Analyser (EWO) for frequencies from DC to 120 kHz for electric fields and from a few Hz to 20 kHz for magnetic fields. The second, the Spectroscopie Ondes Radio et Bruit Electrostatique Thermique (SORBET) covers the frequency range from 2.5 kHz to 10 MHz for electric fields and from 2.5 kHz to 640 kHz for magnetic fields. The third is the Active Measurement of Mercury's Plasma (AM2P) with a signal output in the range 0.7 to 120 kHz. These receivers are connected to two electric field sensors, the Wire Probe Antenna (WPT) and the Mercury Electric Field In-Situ Tool (MEFISTO) and also to two magnetic field sensors, the Low-Frequency Search Coil (LF-SC) and the Dual-Band Search Coil (DB-SC) magnetometers. Observations of solar radio activity will also be useful as background information on the solar activity level at the heliocentric longitude of Mercury. Each of the WPT and MEFISTO antennas are extended orthogonally to measure electric fields and consists of a pair of wire sensors, with an overall length of 32 m, tip-to-tip, but their configurations and frequency characteristics are different. LF-SC and DB-SC constitute a complementary set of three-axis search coil sensors.

The MSASI is located on the lower deck. It is a high-dispersion spectrometer working in the visible spectral range, around the sodium D2 emission line (589 nm), and is devoted to the study of Mercury's exosphere. A tandem Fabry–Perot etalon is used to achieve a compact design, and a one degree-of-freedom scanning mirror is employed to obtain full-disk images of the planet and selected regions of interest, such as the polar regions, Caloris basin, and the magnetosphere. The MSASI will provide information on the regolith-exosphere-magnetosphere interaction as well as of the dynamics governing the surface-bounded exosphere. The MSASI data are complementary to those obtained in situ by ENA, plasma and dust measurements, as well as surface composition investigations by the X-ray and gamma-ray instruments aboard the MPO.

The MDM is located on the side panel. The purpose of the MDM is to study the near-Mercury dust environment in terms of its interaction with the planetary surface and to improve our knowledge of the interplanetary meteoroid population obtained with the Helios spacecraft in the inner heliosphere (0.31–0.47 AU). The MDM employs four 5 cm × 5 cm light-weight, heat-resistant (up to about 300°C) piezoelectric ceramic (PZT) sensors, a combined area of 100 cm^2. Those sensors will have the capabilities for counting the number and determining (roughly) the direction and momentum of dust particles. The mass and velocity, if possible, might also be separated based on recent experiments carried out by the MDM team.

The two orbiters, MPO and MMO, have different orbits and attitudes around Mercury, optimized for each orbiter's set of main observational objectives directed at the planet and the magnetosphere, respectively. The MMO and MPO instrument teams are working in close collaboration. Simultaneous measurements of the magnetic field on the MMO and MPO will enable the separation of internal and external sources, thus resolving ambiguities in the higher orders of the internal magnetic field. This investigation is linked with the planetary interior studies and the gravitational field and composition observations of the MPO. Both the exospheric and magnetospheric objectives will benefit from simultaneous measurements on the MPO and MMO. Combining in-situ particles, fields and remote sensing measurements at different altitudes will resolve spatial and temporal ambiguities that would arise from single point observations. Simultaneous MMO and MPO measurements will elucidate the physical processes and interactions that take place in the magnetosphere–exosphere–surface system of Mercury.

6 Summary and Prospects

The exploration of the planets of the solar system has progressed, if occasionally slowly, from its early beginnings in the first decade of the space age to the sophistication of the current generation of missions to Venus (Venus Express), Mars (Mars Global Surveyor, Mars Odyssey, Mars Express, the Spirit and Opportunity rovers, Mars Reconnaissance Orbiter, with others to follow), and Saturn (Cassini-Huygens). The Galileo Jupiter Orbiter explored extensively that giant planet in the 1990s. Mercury is the only reasonably accessible planet for which the only completed mission remains Mariner 10, carried out in the first phase of planetary exploration.

Looking back at the remarkable achievements of Mariner 10, its rapid development is striking: the mission was undertaken in 1970, launched in late 1973, and by early 1975 had performed its three flybys and gathered all the vital data that have been the basis of much of what we know, even now, of the planet. In addition, like many other space missions from that early phase of space exploration, Mariner 10 remains, from the vantage point of the early twenty-first century, a source of wonder at the technological and scientific achievements of a bygone age.

The reasons for not undertaking another mission before the present have been described earlier and relate both to the technical difficulties (and therefore costs) of placing and operating an orbiter around Mercury and to the attraction of other planets, in particular Mars, to the planetary community. While clear priorities can be drawn up in planetary exploration that take into account costs and technical difficulties, as well as questions which have wider than scientific implications (e.g., the origin of life), Mercury nevertheless remains a key to understanding the formation and evolution of the family of terrestrial planets, to the same extent as the other three.

MESSENGER and BepiColombo are complementary missions (Grard and Balogh 2001; McNutt et al. 2004). Clearly, MESSENGER will be able to provide answers to many of the questions left unanswered by Mariner 10 and ground-based observations, by completing the imaging of the entire surface and determining its composition, mapping the magnetic field, and resolving the nature of the radar-bright spots in the permanently shaded craters. BepiColombo will arrive at Mercury eight years after MESSENGER; as a two-spacecraft mission, it can carry a more diverse payload, more specific to planetary and magnetospheric objectives. The two orbiters can be more specifically targeted, with the Planetary Orbiter in a low-altitude polar orbit, and the Magnetospheric Orbiter in a more eccentric, but synchronised orbit. The questions that will be addressed by BepiColombo will be evidently refined by the study of the earlier MESSENGER observations. At the same time, the two-spacecraft approach will provide coordinated measurements to investigate in detail the intimate relationship between the planet and its environment. The sophisticated gravitational field investigation in the low-altitude, low-eccentricity orbit of the BepiColombo MPO can provide more detailed answers related to the planet's interior, and the combination of measurements on the MPO and MMO will discriminate between external and internal magnetic fields to a greater extent than is possible by a single orbiter. Again, the orbit of the MPO will allow a more uniform, generally higher resolution coverage for imaging Mercury's surface that will be guided by, and complement, the MESSENGER observations.

The current opportunity with the two missions, MESSENGER and BepiColombo, represents a once-in-a-generation opportunity not only to carry out a detailed survey of Mercury and its environment, but also, as a result, to integrate our knowledge of the terrestrial planets as we face the prospect of having to study and explain similar, Earth-like planets around other stars.

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