BepiColombo – A Multidisciplinary Mission to a Hot Planet

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Introduction

The planet Mercury has a radius of 2440 km and is slightly larger than our Moon. It revolves around the Sun in approximately 88 days and rotates around itself in two-thirds of that time, i.e. 58.6 days. Quite surprisingly, this resonance means that the same side of the planet faces the Sun every two hermean years. Its orbit is very eccentric and its distance to the Sun varies between 0.308 and 0.466 AU*.

Mercury was already known to the ancient Egyptians (Fig. 1), but is still largely unexplored. Its proximity to the Sun makes it a difficult target for ground-based observations and space missions (Fig. 2). Seen from Earth, Mercury's maximum elongation from the Sun is 28°. It is visible for just two hours before sunrise or after sunset, so that Earth-based observations have normally to be performed in front of a strong sky background. Earth-orbiting optical telescopes, such as the Hubble Space Telescope, usually cannot target Mercury either, because of the high potential risk to instruments when pointed so close to the Sun. On the other hand, putting a spacecraft into orbit around Mercury is not a trivial task, because of the

As the inner end-member of the planetary system, Mercury plays an important role in constraining and testing dynamical and compositional theories of planetary formation. With its companions Venus, Earth and Mars, it forms the family of terrestrial planets, a category of celestial object where each member holds information essential for retracing the history of the whole group. For example, knowledge about the origin and evolution of these planets is one of the keys to understanding how conditions to support life have been met in the Solar System and, possibly, elsewhere. This quest is all the more important as terrestrial-like objects orbiting other stars are not accessible; our own environment remains the only laboratory where we can test models that are also applicable to other planetary systems. The exploration of Mercury is therefore of fundamental importance for answering questions of astrophysical and philosophical significance, such as: 'Are terrestrial bodies a common feature of most planetary systems in the Galaxy?'.

* 1 Astronomical Unit is the average distance from the Earth to the Sun, which is about 150 million km.

Figure 1. Mercury was already known in ancient Egypt (after an engraving of Régnier Barbant in G. Flammarion, Astronomie Populaire, 1881)
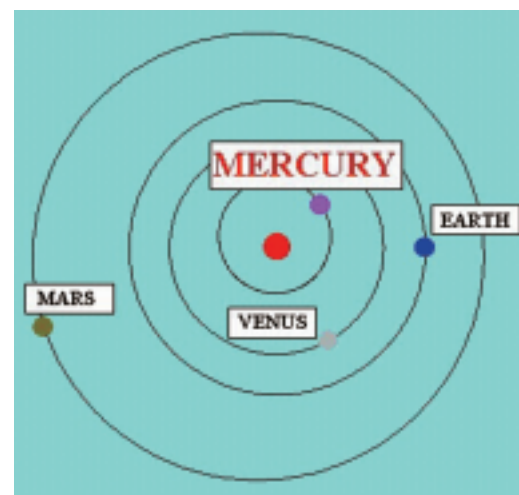

Figure 2. The terrestrial planets: the cradle of life

large difference in the gravitational potentials of the Sun at the orbits of Earth and Mercury. The solar irradiation is about 10 times larger at Mercury and the heat flux is further increased above the dayside because of reflected sunlight and infrared emission, which puts enormous thermal constraints on any orbiter.

Missions to the giant planets and to the small undifferentiated bodies, such as comets and asteroids, provide information on the cold regions of the Solar System. With the Rosetta mission to comet P/Wirtanen, to be launched in 2003 as Cornerstone-3, ESA is conducting a programme that will investigate some of the pristine material found in the outer regions of the heliosphere. Mercury represents the other challenge, since this small and important body will yield complementary data about planetary formation in the hottest part of the proto-solar nebula. Consequently, the Cornerstone mission to Mercury, BepiColombo, appears the logical next step for the Agency's planetary exploration programme.

Einstein explained the advance of Mercury's perihelion (43 arcsec per century) in terms of space-time curvature (Fig. 3). Owing to the proximity of the Sun, a mission to Mercury offers, in addition, unique possibilities for testing general relativity and exploring the limits of other metric theories of gravitation with unprecedented accuracy. The discovery of any violation of general relativity would have profound consequences in theoretical physics and cosmology.

Mercury is also an unrivalled vantage point from which to observe minor bodies with semi-major axes of less than 1 AU, the so-called Atens and Inner-Earth Objects which might possibly impact our planet.
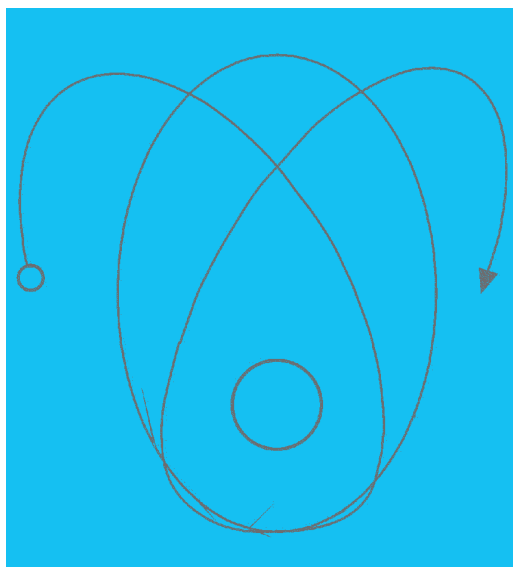

Figure 3. Advance of Mercury's perihelion (schematic only)

In summary, BepiColombo not only covers objectives related to the exploration of the planet and its environment, but also addresses fundamental science and minor-body issues. Some of the questions that form the rationale behind this mission are:
– What is on the unimaged hemisphere of Mercury?
– How did the planet evolve geologically?
– What is the chemical composition of the surface?
– Why is Mercury's density so high?
– What is Mercury's internal structure and is there a liquid outer core?
– What is the origin of the magnetic field?
– How does the planetary magnetic field interact with the solar wind in the absence of any ionosphere?
– Is there any water ice in the polar regions?
– Which volatiles compose the exosphere?
– What new constraints can we set on general relativity and gravitational theories?
– Is the Earth threatened by cosmic impactors?

The space segment of the BepiColombo mission consists of two orbiters and one lander, to fulfil the scientific goals in an optimum way:
– The Mercury Planetary Orbiter (MPO), a three-axis-stabilised and nadir-pointing module, revolves around the planet at a relatively low altitude and is dedicated to planet-wide remote sensing and radio science.
– The Mercury Magnetospheric Orbiter (MMO), a spinner in a relatively eccentric orbit, accommodates mostly the field, wave and particle instruments.
– The Mercury Surface Element (MSE), a lander module, performs in-situ ground-truth physical, optical, chemical and mineralogical observations, which serve as references for the remote-sensing measurements.

The method selected for transporting the spacecraft elements to their destinations is the result of a trade-off between mission cost and launch flexibility. It combines electrical propulsion, chemical propulsion and gravity assists. The interplanetary transfer is performed by a Solar Electric Propulsion Module (SEPM), which is jettisoned upon arrival. The orbit injection manoeuvres are then realised with a Chemical Propulsion Module (CPM), which is also jettisoned once deployment of the spacecraft elements is completed. The spacecraft concept is modular and lends itself to a large variety of schemes. Two specific scenarios have been studied:
– a single-launch scenario, in which the three spacecraft elements and the two propulsion modules are injected together into an inter-planetary orbit with a large rocket, such as an Ariane-5

– a dual-launch scenario, in which the spacecraft is divided into two composites with nearly identical propulsion elements, which are launched separately with smaller rockets, such as a Soyuz-Fregat.

The two approaches have been shown to be feasible and compatible with the given mission objectives and scientific instrumentation. They also provide flexibility and offer alternative routes with different schedules and funding scenarios.

Rationale

What is on the unimaged hemisphere of Mercury?

Mariner-10 returned images of less than half of the planet (Fig. 4). This first question is therefore pragmatic and reflects the curiosity of both the layman and the scientist. Our knowledge of the topography of Mercury, in terms of global coverage and spatial resolution, reminds us of that of the Moon in the Sixties, which was derived from Earth-based telescopic observations. The images of Mariner-10 show a cratered and lunar-like landscape, but with many different characteristics, indicating the different evolutions of the two bodies. As for the Moon, the unknown hemisphere might prove quite different from the known side; for example, ground-based radar observations suggest the presence of a gigantic dome on the unseen hemisphere.

How did the planet evolve geologically?

The surface of Mercury has been shaped by various exogenic (bombardment) and endogenic (volcanic) processes. The major impacts occurred before the end of the accretionary period and the age of the surface generally exceeds 3.5 Ga*. The collisional

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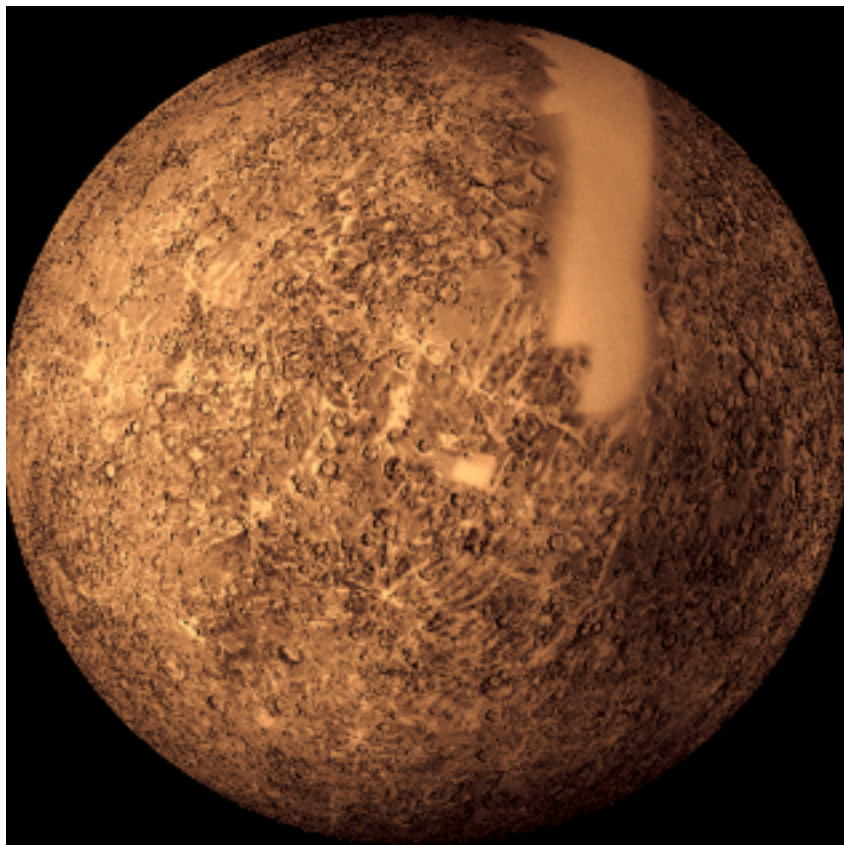* One giga-annum (Ga) is equivalent to one thousand million years

energies were relatively more important on Mercury than on any other terrestrial planet, because of the lack of an atmosphere and the larger relative velocities between impactor and target (Fig. 5). Inter-crater plains have been formed before the end of the heavy bombardment, 4 Ga ago, but it is not known whether these features are associated with volcanic activity or widespread basin ejecta. Mercury may still be tectonically active now; the relaxation of the equatorial bulge, the contraction due to the cooling of the mantle and the tidal stresses caused by a highly eccentric orbit, have induced scarps, faults and lineaments, which bear evidence of these processes. A systematic investigation of the

Figure 4. Hemisphere of Mercury imaged by Mariner-10 (courtesy of NASA: no data available in blank areas)
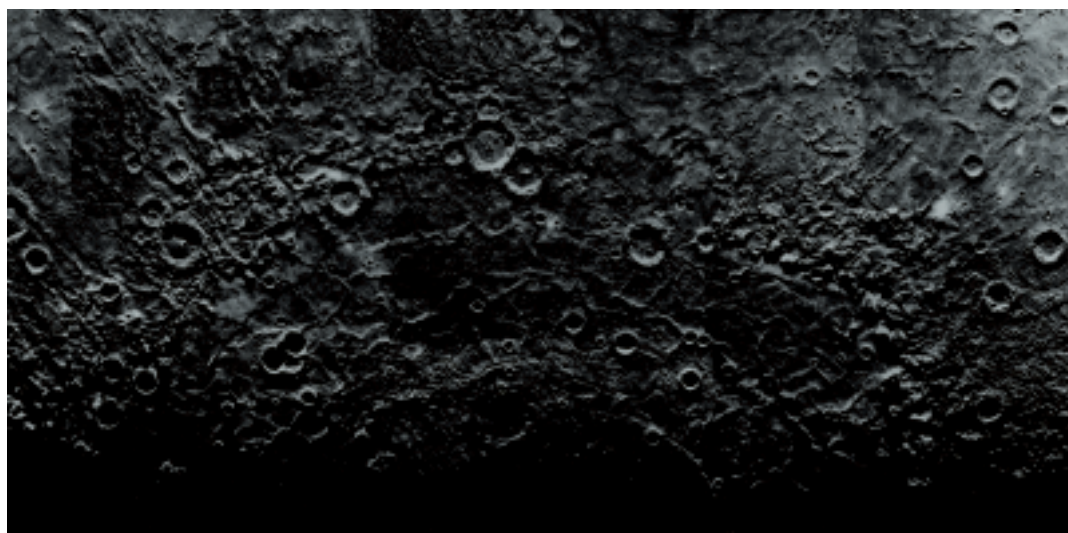

Figure 5. Caloris basin (1300 km in diameter), the curved features of which were formed when a giant projectile hit Mercury 3.9 Ga ago. Many small craters are superimposed on the sunlit part; the rest of the basin is in shadow. Strange lineaments extending outwards can be traced to the opposite side of the planet (courtesy of NASA)

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geologic evolution of Mercury will require the global imaging of the surface, as well as data on topography, core and crust densities, mascons and gravity anomalies.

What is the chemical composition of the surface?

The mineralogical and elemental composition mapping of the surface provides the means of distinguishing between various models of the origin and evolution of the planet. The iron-oxide content of silicates, for example, is one indicator of the condensation temperature of the solar nebula during the accretion of the planet. The concentration ratio of key elements such as potassium, uranium and thorium also reflects the temperature of the feeding zone where the body was accreted.

Why is Mercury's density so high?

The density of Mercury does not line up with those of the other terrestrial planets, including the Moon (Fig. 6); when corrected for compression due to size, it is the largest of all. Several scenarios have been proposed to explain this anomaly:

(a) The iron concentration was larger in the feeding zone where the planet accreted.

(b) Oxides were reduced to metallic form due to the proximity of the Sun.

(c) The temperature of the young Sun was sufficient to sublimate and blow off silicates, thereby leaving only materials with higher condensation temperatures.

(d) The initial composition of the planet has been significantly altered by gigantic impacts, which may have removed a substantial part of the mantle.

What is Mercury's internal structure and is there a liquid outer core?

The high density also suggests a relatively large iron core in which 70 to 80% of the planetary mass is concentrated, and implies a low

Figure 6. Absolute densities of the terrestrial planets and the Moon

moment of inertia factor. The very existence of a molten outer core is a challenge because such a small planet should have frozen out early in its history. A small concentration of sulphur (1 to 5%) could, however, account for the molten shell, because this element would depress the freezing point of the core alloy.

Knowledge of global shape, gravity field and rotational state are required to estimate the radius and the mass of the core. For example, the amplitude of the 88-day libration in longitude, which is influenced by the orbit eccentricity, is small for a rigid body and increases significantly when the surface layer (crust and mantle) is decoupled from the solid inner core by a molten shell.

What is the origin of the magnetic field?

The previous issue is all the more important as it is directly related to the existence of the magnetic field, one of the most remarkable discoveries of Mariner-10 (Fig. 7). The field is weak, a few 100 nT at the equator equivalent to about one hundredth of that of the Earth, and could be generated by an internal hydromagnetic dynamo driven by a liquid shell, perhaps 500 km thick, in the outer core. While it is possible to produce thermal and compositional models compatible with a planetary dynamo, we must also account for the absence of substantial magnetic fields at Venus and Mars.

A detailed mapping of the magnetic field will provide the necessary constraints on the structure and mechanism of the internal dynamo.

How does the planetary magnetic field interact with the solar wind in the absence of any ionosphere?

Much can be learned from a comparative study of the magnetospheres of Earth and Mercury, due to their vastly different volumes and boundary conditions. The size of the hermean magnetosphere is only 5% of that of the Earth, although the planetary radii differ by less than a factor of 3 (Fig. 8). The magnetosphere of Mercury is exposed to a solar-wind density and an interplanetary magnetic field (IMF) which are 4 to 9 times larger than at 1 AU. The absence of an ionosphere and the massive emission of photoelectrons on the dayside poses interesting problems regarding the closure of the magnetospheric currents, the topology of which might differ significantly from that observed at the Earth.

If magnetospheric substorms occur, are they triggered by IMF reversals or internal instabilities? Are they waves at the electron gyro frequency similar to the auroral kilometric radiation emitted from the Earth? Is the
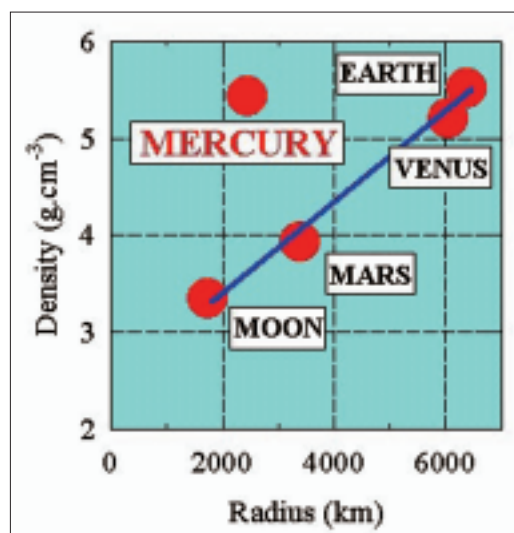
planetary magnetic field perturbed by a ring current associated with possible radiation belts? How are field-line resonances, if they occur, affected by the reflection properties of the surface? Magnetic-field, wave and particle observations will tell us whether phenomena reminiscent of the Earth's environment also take place in the magnetosphere of Mercury.

Is there any water ice in the polar regions?
Mercury is a world of extremes. The surface temperature at the sub-solar point reaches 700 K (427°C), 100°C above the melting point of lead, but it can be as low as 100 K (-173°C) in shadowed areas. New observations from the ground have added new questions to the long list left open by Mariner-10. A major discovery was made by radar observations in 1992. The possibility that water ice or, more prosaically, sulphur may be present in permanently shadowed craters near the poles, deposited there by meteorites or diffused and trapped from the planet's crust, is potentially important for the study of surface processes.

Which volatiles compose the exosphere of Mercury?
Mercury has no stable atmosphere; the gaseous environment of the planet is best described as an exosphere, i.e. a medium so rarefied that its neutral constituents never collide. The existence of five elements – O, H, Ne, Na and K – has been established by Mariner-10 and by ground-based observations. Other elements, contributed by the regolith, and possible ices near the poles may be detected using UV spectroscopic observations of the limb. Production mechanisms include solar photo-

and ion sputtering, and impact vaporisation by in-falling micrometeorites. Study of the exosphere will therefore provide another clue as to the chemical composition of the surface.

Can we take advantage of the proximity of the Sun to test general relativity with improved accuracy?
A Mercury orbiter offers a unique opportunity to test general relativity and alternative theories of gravity. Classical tests can be repeated with improved accuracy and new experiments based upon different observable quantities can be performed due to the proximity of the Sun, the high eccentricity of Mercury's orbit and frequent solar occultations. The classical tests rely upon the precession of the perihelion of Mercury, the deflection of radio waves by the Sun, and the time delay of radio signals. The accurate orbital determination required by
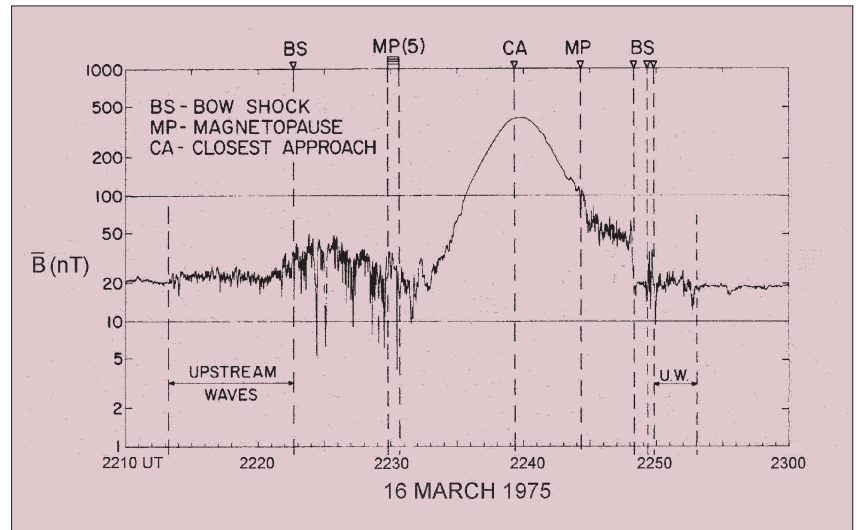
Figure 7. Modulus of Mercury's magnetic field (in nanotesla) measured during the third flyby of Mariner-10 (after Ness et al., J. Geophys. Res.. 80: 2708, 1975)
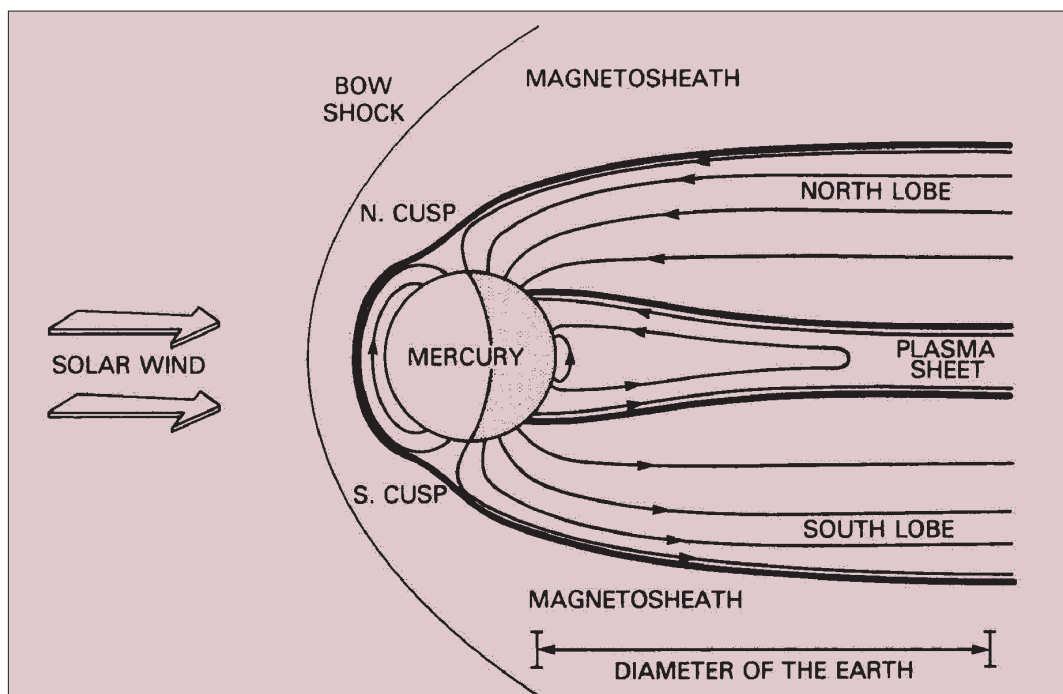

Figure 8. The magnetosphere of Mercury (from Slavin et al., Planet. Space Sci. 45: 133, 1997)

these measurements also yields the quadrupole moment of the Sun and the time derivative of the gravitational 'constant'. All of these experiments require precision spacecraft tracking, a good solution for the gravity field of Mercury, and accurate measurement of non-gravitational accelerations, in particular the radiation pressure.

The importance of the tests of general relativity could indeed justify a fully dedicated Mercury orbiter, but BepiColombo combines these objectives with others pertinent to planetary and magnetospheric physics in a truly multi-disciplinary mission.

Is the Earth threatened by cosmic impactors?
A mere 65 million years ago, an impact created the Chicxulub crater in Mexico and wiped out 70% of the Earth's living species, including the dinosaurs. It is believed that there are many Near-Earth Objects (NEOs) with small aphelia, or whose orbits lie entirely within that of the Earth (IEOs), which have never been detected. BepiColombo has the potential to observe such objects at distances from the Sun as small as 0.4 AU.

Launch configuration and mission design
The scientific payload is a combination of high-priority instruments and forms a representative model that addresses the scientific objectives of BepiColombo. These instruments do not necessarily constitute the final payload, but they provide a set of realistic requirements for the system design, mission analysis, data links and flight operations.

The planetary and magnetospheric instruments have very specific requirements in terms of orbit, attitude and electromagnetic cleanliness. They are therefore carried by two different spacecraft elements: MPO (Mercury Planetary Orbiter) and MMO (Mercury Magnetospheric Orbiter).

The main requirements of the orbiters and those of MSE (Mercury Surface Element) are compared in Table 1. The orbits are polar in order to ensure global coverage of the planet. The data volume of MPO is about 10 times that

of MMO because Ka-band rather than X-band telemetry is required to fulfil the imaging requirements. The MSE data are relayed by one of the two orbiters; the largest data volume is achieved with MPO, which has an orbital period four times smaller than that of MMO and therefore offers more opportunities for telemetry links with MSE.

A mass of 1000-1200 kg must be placed in orbit around Mercury to fulfil the mission objectives. The elements of the spacecraft composite can either be launched together on one large rocket (Ariane-5) from Kourou, or separately on several smaller rockets (Soyuz-Starsem) from Baikonur.

In the single-launch approach, the spacecraft composite consists of MPO, MMO and MSE; the wet mass of the total system (SEPM and CPM included) is 2500-2800 kg at launch. In the dual-mission scenario, MPO and the MMO-MSE composite are launched separately with their own electric and chemical propulsion modules, the overall system masses at launch both being close to 1500 kg.

An artist's impression of the single-launch cruise configuration (height 5.1 m; wing span up to 32.8 m) is shown in the frontispiece. The split configurations are illustrated in Figures 9a,b, which show MMO on top of MSE and MPO, respectively. The split-spacecraft elements are designed for a dual launch on a Starsem-Soyuz, but are also compatible with a single Ariane-5 launch, using the Speltra adapter.

Combining electrical propulsion with Venus, Mercury and even Moon gravity assists provides mission flexibility and short cruise times of 2.6 to 3.6 years, against 6 years or more for entirely ballistic flights, which constitute back-up options. Electrical propulsion is therefore considered as a baseline (Table 2); launch windows at intervals of 1.6 years, the synodic period of Venus, offer optimal conditions for the first gravity assist from this planet.

Depending upon the size of the spacecraft composite, SEPM is equipped with a solar array delivering 6 to 10 kW of power at 1 AU and 3 or 5 engines having individual nominal thrusts of 0.2 N, which provides for recovery strategies in the event of single, or even double, thruster failures. NASA has successfully tested electrical propulsion with the DS1 mission and ESA will launch SMART-1 in late 2002 to validate all aspects of a mission associating this technique with gravity assists.

The Mercury capture manoeuvres are executed

Table 1. Requirements summary

Spacecraft Element	MPO	MMO	MSE
Stabilisation	3-axis	Spin	NA
Altitude/latitude	400 km x 1500 km	400 km x 12000 km	± 85 °
Payload mass	> 50 kg	> 25 kg	~ 6 kg
Data volume	1550 Gb/yr	160 Gb/yr	75-138 Mb/week
Equivalent bit rate	50 kb/s	5 kb/s	128-228 b/s
Nominal lifetime	> 1 yr	> 1 yr	> 1 week

with CPM, which can also be used earlier during the transit for a partial recovery of the mission in the event of total SEPM failure. The chemical module is a bi-propellant system with a 400 N main engine and eight 20 N thrusters for attitude control during the cruise.

Figure 10 shows one of many possible interplanetary trajectories. In the single-launch scenario, MMO is first placed in its Mercury orbit with CPM; a second burn lowers the apoapsis to an altitude of 1500 km as required for MPO. In the split-launch scenario, a similar approach is used to insert MMO and MPO independently into their nominal orbits (Fig. 11). The pericentre of the two orbits is in the antisolar direction when Mercury is at perihelion to minimise thermal constraints; the ratio of the orbital periods is an integer (4:1), so that a back-up telemetry relay configuration can be implemented around periapsis if the two spacecraft are operated simultaneously. MSE is delivered from the MPO or MMO orbit to its destination on the surface of the planet, at a latitude of ± 85° near the terminator, where the environmental conditions are less severe.

Spacecraft composite
Planetary Orbiter
The Planetary Orbiter configuration is driven by scientific requirements as well as thermal constraints (Fig. 12). It has the shape of a truncated pyramid; the apertures of the remote-sensing instruments are located on the base and point constantly along the nadir direction; the antenna is mounted on an articulated arm attached to the opposite side and has a diameter of 1.5 m. The radiator is never illuminated by the Sun and is protected from the planet IR flux by a shield; the three other sides are covered with solar cells, which deliver 420 W. The mass of MPO is 360 kg.

An imager system performs a global mapping of the surface at better than 200 m resolution and explores selected areas (up to 5% of the total surface) at better than 20 m resolution; the orbital period of 2.3 h provides for a suitable shift in ground track between successive orbits. An IR spectrometer has a range that covers the absorption bands of most minerals, and its spatial resolution varies from 150 m to 1.25 km. A UV spectrometer observes the limb airglow by means of an articulated mirror and identifies the constituents of the exosphere through their emission lines. A geochemistry package yields the surface concentrations of various elements and searches for polar water deposits.

A radio-science experiment (RAD) investigates the rotation state (libration), global gravity field and gravity anomalies (mascons) of the planet
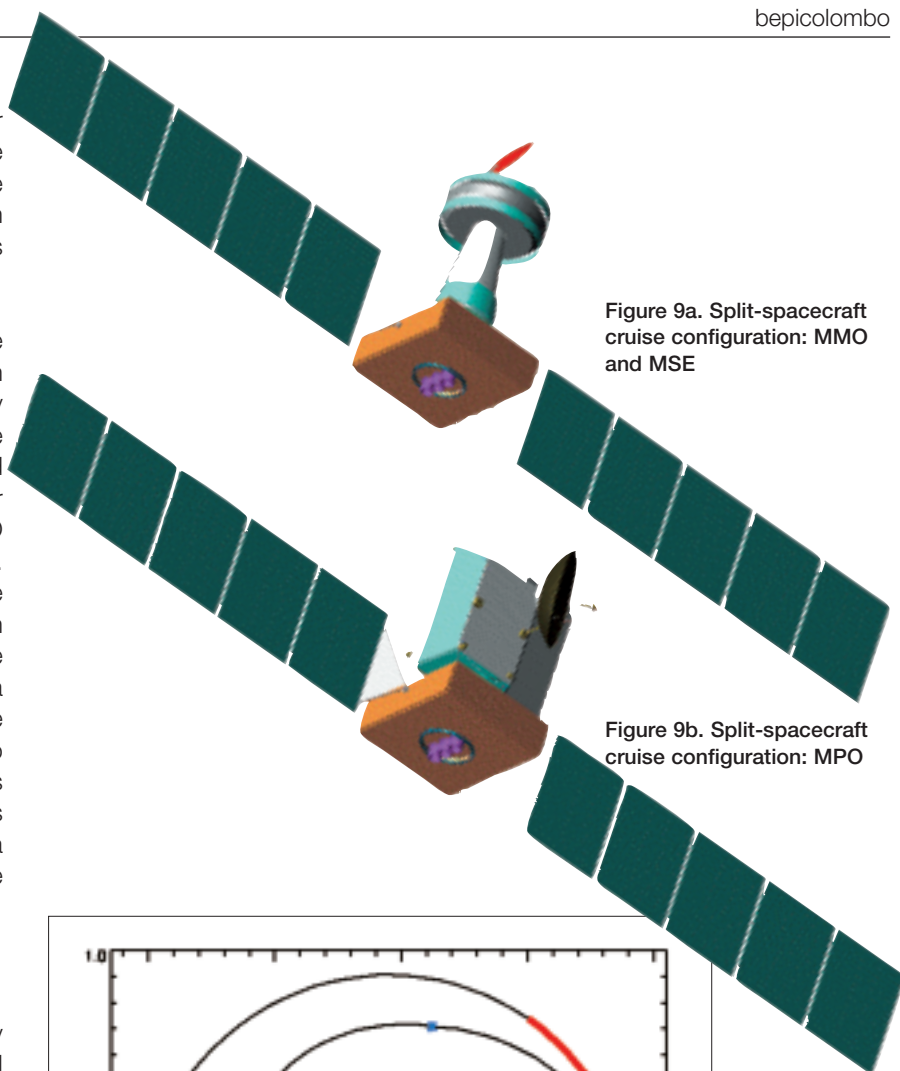

Figure 9a. Split-spacecraft cruise configuration: MMO and MSE

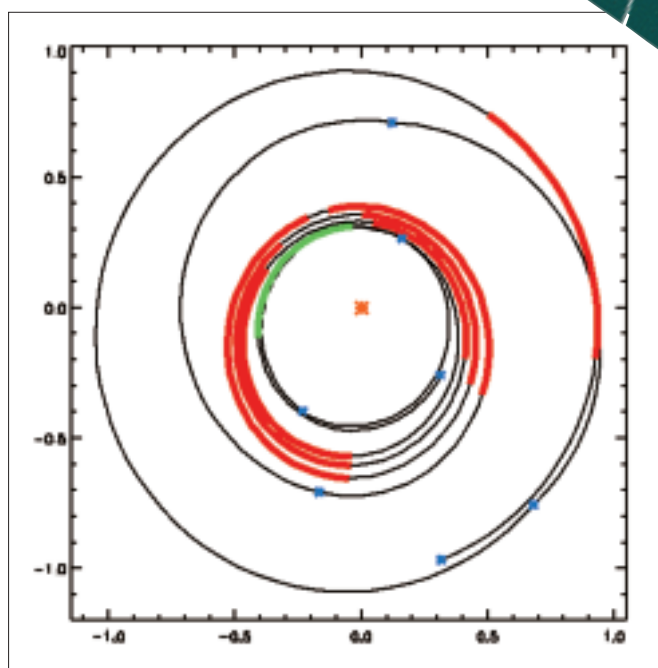**Figure 9b. Split-spacecraft cruise configuration: MPO**

Figure 10. Ecliptic projection of the trajectory from Earth to Mercury for a launch in 2009 (the SEPM thrust is parallel or antiparallel to the direction of motion along the green and red arcs, respectively; planetary flybys are indicated by stars)

Table 2. Mission opportunities with Ariane-5 and Starsem-Soyuz

Date	Launcher	Mass margin*	Cruise time (yr)
2009/01	Ariane-5	41 %	2.6
2008/01	Starsem-Soyuz**	24 %	3.6
2009/07	Starsem-Soyuz**	22 %	3.3

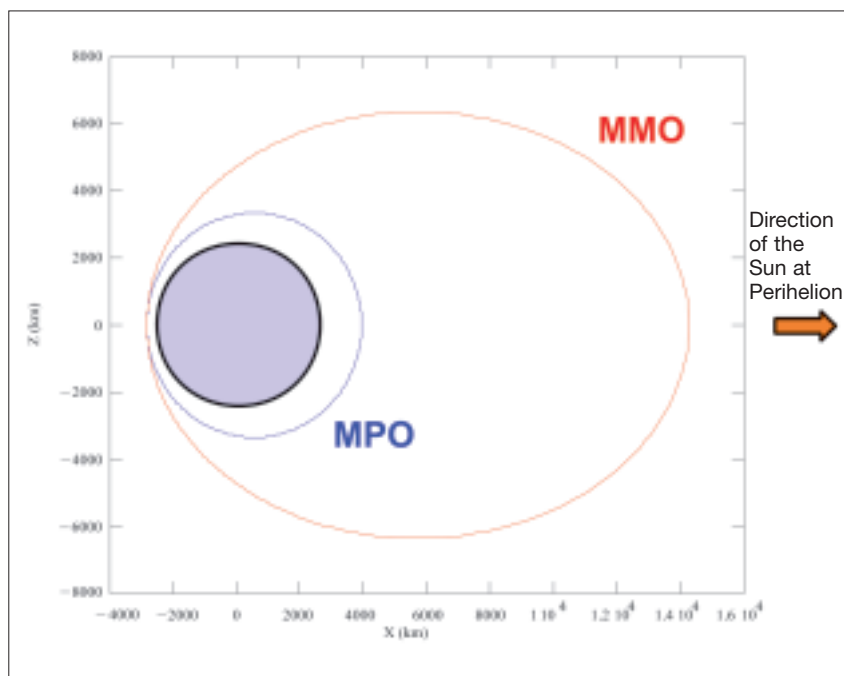* with ion thrusters

** with lunar flyby

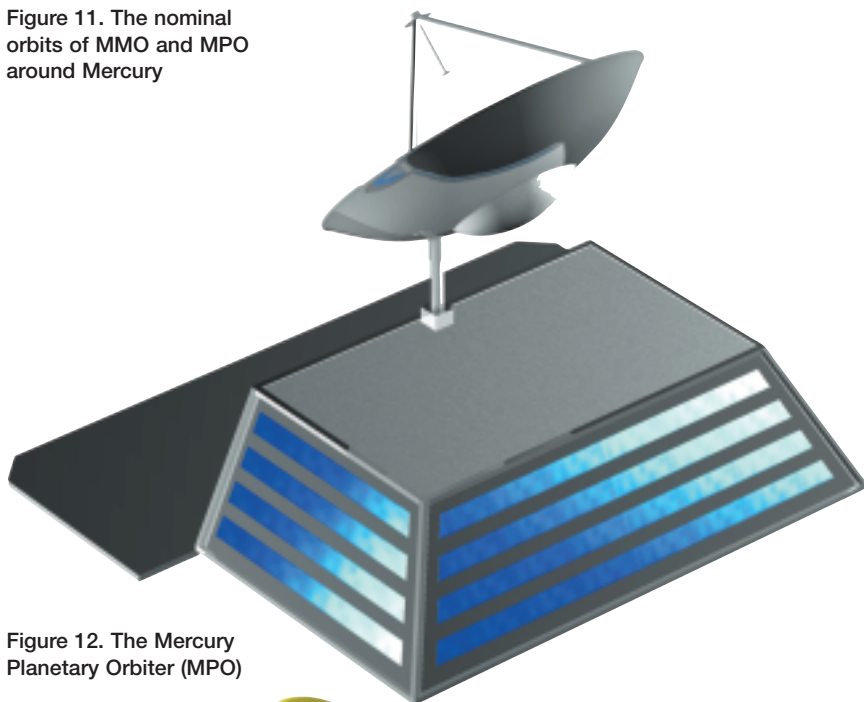**Figure 11. The nominal orbits of MMO and MPO around Mercury**

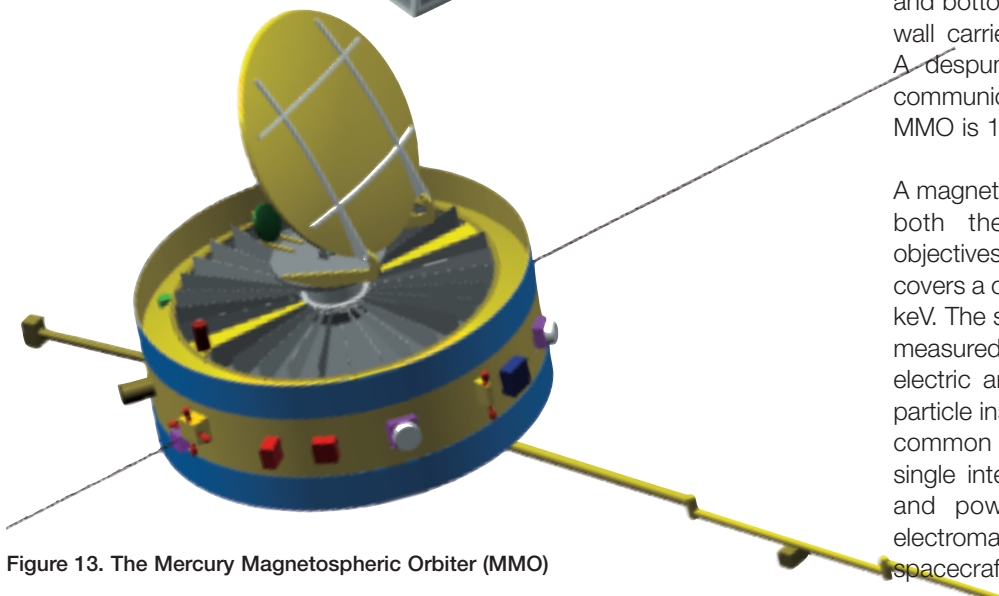**Figure 12. The Mercury Planetary Orbiter (MPO)**

Figure 13. The Mercury Magnetospheric Orbiter (MMO)

to constrain its internal structure and the physical state of its core; RAD observes the motion of Mercury around the Sun and studies the propagation of electromagnetic waves between Mercury and the Earth to solve for fundamental quantities such as the oblateness of the Sun, J_2, the general relativity parameters, β, γ and η, and the time derivative of the gravitational 'constant' G, with unprecedented accuracy. RAD is a complex experiment which combines the measurements performed with a dedicated radio transponder, an accelerometer, a high-resolution imager and a star tracker.

A laser altimeter is also considered as a desirable addition to the payload, because topographic measurements with a resolution of a few 10 m are required for the evaluation of the gravimetry data.

A small telescope with an aperture of 20 cm can be dedicated to the observation of NEOs with few additional constraints on spacecraft resources and operation. Owing to the unique location of Mercury, it is believed that, in order to fulfil similar objectives from an Earth orbit, one would require an instrument with the capability of detecting objects with magnitudes of the order of 20-21 and pointing at angles of less than 20 deg from the Sun.

Magnetospheric Orbiter
The Magnetospheric Orbiter is spin-stabilised at 15 rpm about an axis perpendicular to Mercury's equator, which facilitates the deployment of a wire antenna and the azimuthal scan of the particle detector fields of views. The line of apsides of the orbit lies in the equatorial plane, which makes it possible to explore the magnetotail up to planetocentric distances of almost 6 Mercury radii.

MMO is cylindrical in shape (Fig. 13); the top and bottom are used as radiators and the side wall carries solar cells, which deliver 185 W. A despun 1m-diameter antenna is used to communicate with Earth. The overall mass of MMO is 160 kg.

A magnetometer is essential since it addresses both the planetary and magnetospheric objectives. A set of charged-particle detectors covers a combined energy range of several 100 keV. The spectrum of electromagnetic waves is measured with a search coil and a 70m-long electric antenna. The mass of the wave and particle instruments is minimised by including a common central processor, which ensures single interfaces for telecommands, telemetry and power. MMO is electrostatically and electromagnetically clean. The surface of the spacecraft is conductive and an ion emitter is
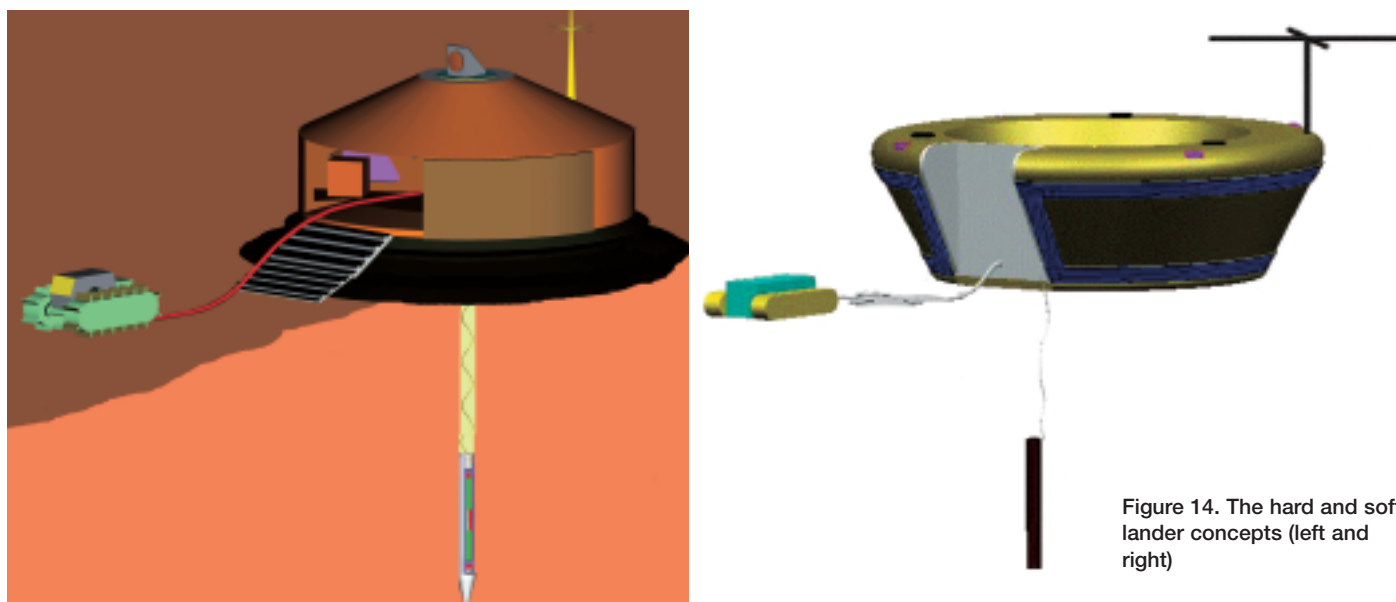
included to prevent its potential from reaching several 10 V and invalidating the low-energy particle measurements.

A multicolour camera is considered as a backup for the imagers carried by MPO; its resolution varies from a few 10 m to a few 100 m from periapsis to apoapsis. This payload complement is certainly not exhaustive and additional, or alternative, instruments such as an energetic neutral imager are also desirable.

Surface Element
Two versions of the Surface Element have been studied: a hard-lander consisting of a penetrator linked to a surface station by means of an umbilical, and a soft-lander equipped with a self-penetrating device (Fig. 14). The hard-lander relies on a solid-propellant descent motor and crushable material to limit the impact deceleration. The soft-lander makes use of a liquid propellant motor and airbags to further constrain the impact shock below 250 g (1 g = 9.81 ms^{-2}). The dry mass of MSE is of the order of 50-70 kg. The hard-lander version is assumed in the cruise configurations illustrated in the frontispiece and in Figure 9a.

A heat flow and physical properties instrument performs measurements which can only be achieved in-situ; it can be integrated in the fore-body, or penetrator, of a hard lander or in a self-penetrating device, or mole, in the case of a soft-lander. A alpha X-ray spectrometer is transported to selected surface areas by a micro-rover and provides measurements that serve as ground-truth for the MPO observations.

Two cameras record images before and after landing. A magnetometer characterises the magnetic properties of the surface and yields the electrical conductivity of the ground by recording simultaneously, both on MMO and MSE, the magnetic-field fluctuations induced by the solar wind. A seismometer enhances the scientific return provided that MSE's lifetime is significantly longer than one week.

Conclusion
The potential scientific return from the BepiColombo mission is both significant and novel; it addresses the planet's internal structure and magnetic field, the surface features and composition, the planetary environment, as well as important fundamental science issues and Near-Earth Object (NEO) observations.

The study has demonstrated that an attractive strategy exists for interplanetary transfer to Mercury, combining gravity assists and electric propulsion. The requirements of the electric-propulsion elements (thrusters, solar array) are compatible with current technologies. The proposed concept is modular, and lends itself to reconfiguration depending on the future evolution in terms of mission goals, funding scenarios and international cooperation.