Mem. S.A.It. Vol. 82, 394

Memorie della

BepiColombo mission

J. van Casteren and M. Novara

ESA/ESTEC, Keplerlaan 1, 2200AG Noordwijk, The Netherlands

Abstract. BepiColombo is a dual spacecraft mission to Mercury carried out jointly between ESA (European Space Agency) and JAXA (Japanese Aerospace Exploration Agency). The mission will address a comprehensive set of scientific questions in order to gain knowledge about the planet, its evolution and its surrounding environment. Both spacecraft will be launched together in July 2014. An extensive suite of state-of-the-art scientific instruments, flying on the two spacecraft, allow a wide range of scientific questions to be addressed that will provide important clues on the origin and formation of terrestrial planets. This paper will review the capabilities of the missions, its payload and operative scenario.

1. Introduction

Mercury is small compared to the Earth, with a diameter of only 4878 km. It orbits the Sun in an elliptic orbit between 0.3 and 0.47 AU from the Sun. Mercury is difficult to observe from the Earth, due to its close proximity to the very bright Sun. For an in-depth study of the planet and its environment, it is therefore necessary to operate a spacecraft equipped with scientific instrumentation around the planet. It is, however, difficult for a spacecraft to reach Mercury, as even more energy is needed than sending a mission to Pluto.

Departing from Earth, a spacecraft needs to decelerate to come closer to the Sun and as the solar gravitational force increases with the square of the distance, the required reverse thrust increases accordingly. Furthermore, the thermal environment close to the Sun and close to the hottest planet in the Solar System is extremely aggressive, as the direct solar radiation is 10 times higher than at Earths distance. Despite the advances in space flight and the growth in planetary research over the last few decades, enabling detailed investigations of the Earth, Mars, Venus, the outer planets and several moons and asteroids, scientists have not been able to observe much of Mercury.

For a very long time the data delivered by the NASA mission Mariner 10, which visited Mercury in 1974-1975, was among the best available. During these flybys Mariner 10 was able to image about 45 percent of the planets surface and to discover its unexpected magnetic field. Further discoveries by Mariner 10 are the existence of gaseous species forming an exosphere and the presence of a unique magnetosphere. However, little to nothing is known about Mercury's interior structure or its elemental and mineralogical composition.

With the launch of the NASA Discovery class mission MESSENGER (Mercury Surface, Space ENvironment, Geochemistry and Ranging) in 2004, a new spacecraft is under way to orbit Mercury. MESSENGER already collected data from two Venus flybys and three Mercury flybys in 2008 and 2009.

Send offprint requests to: M. Novara

The orbital phase of the MESSENGER mission will start in March 2011. MESSENGER will provide valuable discoveries of Mercury and its environment that can be used by the BepiColombo mission in tuning its observations to the most important investigations of planet Mercury.

BepiColombo is a dual spacecraft mission to Mercury carried out jointly between ESA and JAXA. The mission will address a comprehensive set of scientific questions in order to gain knowledge about the planet, its evolution and its surrounding environment. Both spacecraft will be launched together in July 2014. An extensive suite of state-of-the-art scientific instruments, flying on the two spacecraft, allow a wide range of scientific questions to be addressed that will provide important clues on the origin and formation of terrestrial planets and help to answer fundamental questions like: *How do Earth-like planets form and evolve in the Universe?*. One spacecraft, the Mercury Planetary Orbiter (MPO), is led by ESA and its payload comprises eleven experiments and instrument suites.

The MPO will focus on a global characterization of Mercury through the investigation of its interior, surface, exosphere and magnetosphere. In addition, it will test the Einstein theory of general relativity.

The second spacecraft, the Mercury Magnetosphere Orbiter (MMO), is led by JAXA and will carry five experiments or instrument suites to study the environment around the planet including the planet exosphere and magnetosphere, and their interaction processes with the solar wind and the planet itself. Upon arrival in the second half of 2020 after a cruise phase of about 6 years, the Mercury Transfer Module (MTM) will be jettisoned and chemical propulsion will be used to inject both spacecraft into their dedicated polar orbits. The MMO will be released first, after which an additional thrust phase will insert the MPO into its final orbit. Both orbits are polar elliptical with eccentricity optimized for the study of Mercury (MPO orbit: 400x1508 km) and its magnetosphere (MMO orbit: 400 x 11824 km). A summary of the BepiColombo mission is given hereafter.

2. BepiColombo mission summary

2.1. Scientific objectives

- Origin and evolution of a planet close to the parent star
- Mercury as a planet: form, interior, structure, geology, composition and craters
- Mercury's vestigial atmosphere (exosphere): composition and dynamics
- Mercury's magnetized envelope (magnetosphere): structure and dynamics
- Origin of Mercury's magnetic field
- Test of Einstein's theory of general relativity

2.2. Payload

- Mercury Planetary Orbiter (MPO): cameras, spectrometers (IR, UV, X-ray, gamma-ray, neutron), radiometer, laser altimeter, magnetometer, particle analysers, Ka-band transponder, accelerometer.
- Mercury Magnetospheric Orbiter (MMO): magnetometer, ion spectrometer, electron energy analyser, cold and energetic plasma detectors, plasma wave analyser, and imager.

2.3. Ground station

- Cebreros (Spain) Deep Space Station (primary for cruise and MPO)
- New Norcia (Australia) Deep Space Station (critical mission phases)
- Usuda (Japan) 64 m Antenna (back-up for MPO)
- NASA DSN Goldstone(for Radioscience)
- Usuda (Japan) 64 m Antenna (primary for MMO)

2.4. Programmatics

- CESA is responsible for MPO, MTM, launch and transfer to Mercury of composite spacecraft including MMO, spacecraft deployment at Mercury and MPO operations
- JAXA procures MMO and operates the MMO at Mercury

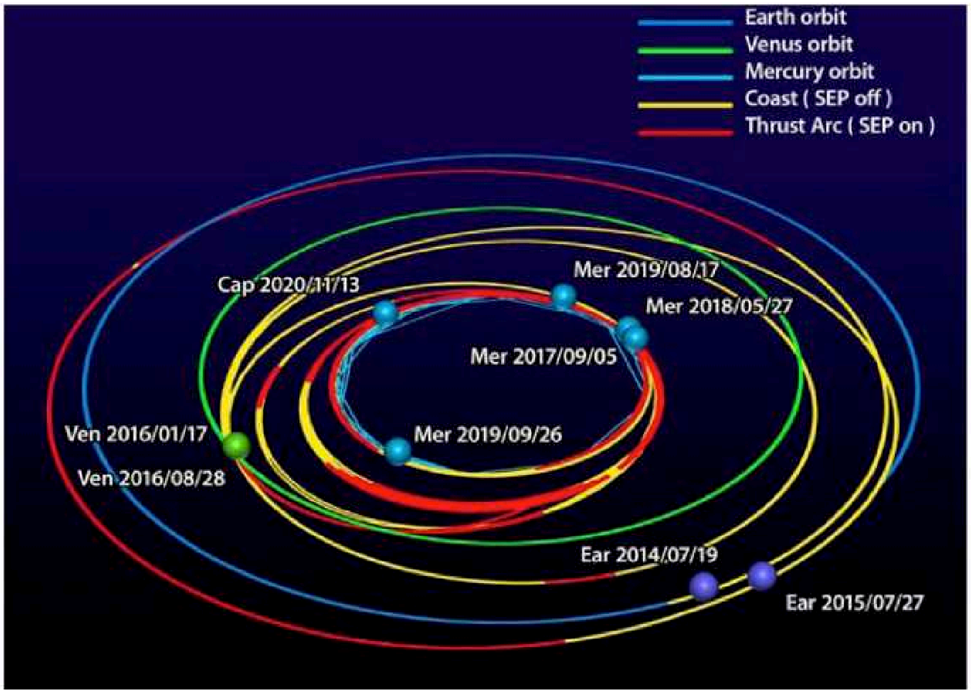

Fig. 1. Mission profile.

- BepiColombo is the first ESA mission in close cooperation with Japan

The mission has been named in honour of Giuseppe (Bepi) Colombo (1920-1984), who was a brilliant Italian mathematician, who made many contributions to planetary research, celestial mechanics, including the development of new spaceflight concepts. He is well-known for explaining that Mercury rotates three times about its axis while it completes two orbits around the Sun. He also proposed to NASA an interplanetary trajectory for Mariner 10 using gravity assist that allowed more Mercury flybys (1974-1975).

3. Mission scenario

The BepiColombo trajectory employs a solar electric propulsion system so that a combination of low-thrust arcs and flybys at Earth, Venus and Mercury are used to reach Mercury with low relative velocity. The advantage of such trajectories, thanks to electric propulsion, is that they offer large flexibility to design the trajectory within the boundaries of launcher capability, spacecraft mass and flight duration, at very low propellant cost. The mission requires the delivery of 2224 kg of mass for the MPO and MMO in the initial Mercury orbit. The baseline scenario foresees the launch by an Ariane 5 from Kourou of both spacecraft in a composite with a propulsion element, the Mercury Transfer Module (MTM). The lift-off mass will be 4200 kg (including a Launch Vehicle Adapter) of which approximately 32 percent is propellant. The nominal launch date is 19 July 2014. The launch window is driven by the interplanetary cruise to Mercury, which employs an Earth, two Venus and four Mercury gravity assists. Together with these flybys, the utilization of highly efficient solar electric propulsion (SEP) helps to reduce the required propellant mass. The duration of the cruise phase will be about 6 years for a planned arrival at Mercury in the second half

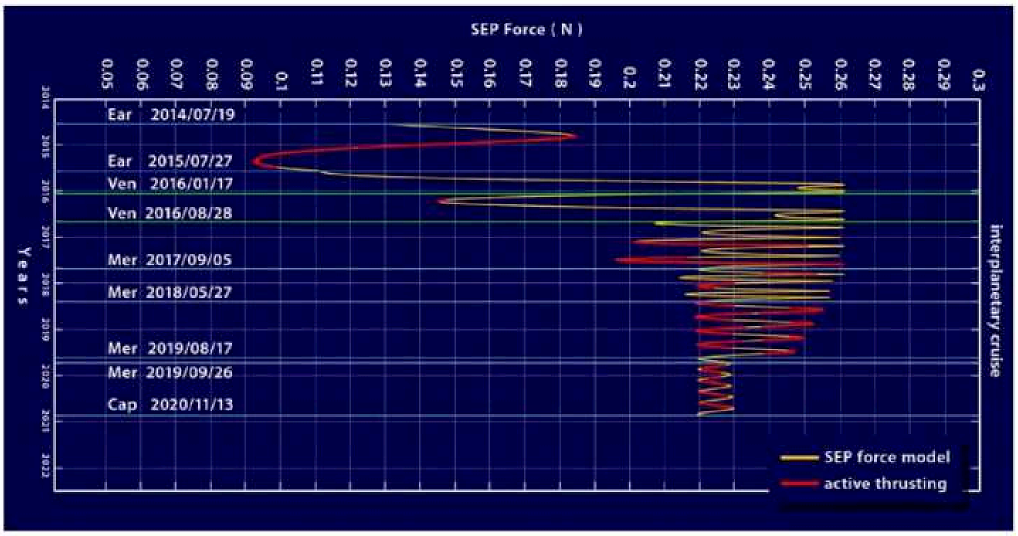

Fig. 2. Thrust profile over mission time.

of 2020. An added benefit of using the solar electric propulsion systems is that it gives flexibility in choosing the trajectory, thereby providing robustness to the mission operations. A backup launch opportunity will occur in August 2015. The mission profile is schematically depicted in Fig. 1 and the mission calendar is given in Table 1.

The composite spacecraft is launched on an escape trajectory that brings it into heliocentric orbit on its way to meet the Earth for a flyby approximately one year after launch. Two consecutive Venus flybys reduce the perihelion to Mercury distance with almost no need for thrust. A sequence of four Mercury flybys and a series of low thrust arcs reduce the relative velocity such that the spacecraft will be weakly captured by Mercury even before any insertion maneuver takes place. Power is available from solar arrays for only one electric thruster to be operated at a thrust level between 100 and

Table 1. Mission calendar

Date	Mission Event
19/7/2014	Launch
25/7/ 2015	Earth flyby
17/1/ 2016	First Venus flyby
29/8/ 2016	Second Venus flyby
4/9/2017	First Mercury flyby
27/5/2018	Second Mercury flyby
17/8/2019	Third Mercury flyby
25/9/2019	Fourth Mercury flyby
21/5/ 2020-13/11/ 2020 (*)	Arrival at Mercury
20/8/2021-10/2/2022 (*)	End of nominal mission
20/8/2022-10/2/2023 (*)	End of extended mission

(*)Depending on the actual SEPS performance

130 mN at about 1 AU from the Sun. Thrust arcs inside Venus orbit can be carried out with up to 290 mN (2 thrusters in simultaneous operation), because of the increased power from the solar arrays while coming closer to the

Sun. The thrust profile over the mission time is given in Fig. 2. The total velocity increment to be provided by electric propulsion is between 5 km/s (2014 launch) and 5.8 km/s (2015 launch).

Fig. 3 shows the interplanetary trajectory in ecliptic projection and the Earth to Mercury trajectory in a Sun-Earth fixed coordinate system. The spacecraft has the capability of continuing nominal thrusting operations, including the autonomous management of simple contingencies (e.g. switchover to redundant equipment) for up to 2 weeks, during which communications with Ground may be impeded in the case of e.g. a superior solar conjunction. The heliocentric low thrust arcs reduce the approach velocity at Mercury arrival to low values such that when the spacecraft passes the Sun-Mercury Lagrange points L1 and L2 it is weakly captured in a highly eccentric orbit around Mercury. After the approach through a weak stability boundary of the planet, the spacecraft needs only a small velocity change for a firm capture. Mission analysis has shown that this gravity capture strategy has significant advantages by a) reducing the fuel needed for injection, b) eliminating the necessity of an immediate orbit insertion burn which is a single-point failure in traditional hyperbolic approaches and providing several recovery opportunities in case of failed insertion and c) increasing the flexibility of choosing appropriate sets of arrival conditions (in particular: a Mercury true anomaly at arrival which is, indicatively, larger than 60° away from the thermally critical perihelion conditions). While this capture technique has been used by SMART-1 (ESA spacecraft mission to explore Earth moon), BepiColombo will be the first mission to employ gravity capture at a planet. The insertion manoeuvres are performed by the more effective chemical propulsion engines, which are embedded in the MPO. The MPO Chemical Propulsion System (CPS) will provide the required thrust for a firm Mercury capture and orbit injection, utilizing a set of four 22 N thrusters. After reaching the MMO orbit, the MMO is released, followed by the jettison of the MMO Sunshield and Interface Structure (MOSIF). An additional thrust phase will insert the MPO into its final orbit. Subsequent burns of the chemical propulsion lower the apocentre to 1,508 km and rotate the line of apsides. The velocity change needed to go into the MMO orbit is 325 m/s and a 620 m/s to go into the MPO orbit, respectively. The arrival conditions are constrained such that the MPO and MMO operational orbits have their line of apsides close to the Mercury equator and their periherm on the anti-solar side at Mercury perihelion, which creates a more benign thermal environment. The polar orbits, which have been selected, are optimal to obtain global coverage of the measurements.

The baseline lifetime of the MPO and MMO in Mercury orbit is 1 Earth year (about 4 Mercury years, or 2 Mercury solar days). A mission extension by another Earth year is optional. However, it is factored into the consumables and expected radiation damage, although without any design margins. Orbit maintenance is not required over the planned operational MPO and MMO lifetime.

4. Mercury orbit

The choice of the orbit is mainly a compromise between science objectives and thermal load onto the spacecraft. Science objectives prefer a global, high resolution coverage, implying a polar orbit at low altitude. However, the closer the spacecraft will be to the Mercury surface, the larger the received thermal flux from the planet infra-red and albedo, which will come on top of the Suns flux of up to about 10 Solar constants. For example, the MESSENGER orbit design limits the distance to the planets hottest equatorial region by placing the periherm at 60 northern latitude and selecting a highly eccentric orbit of 200 x 15193 km. Only a small fraction (less than 5 precent) of the orbit is spent at low altitude in the hottest thermal environment so that the spacecraft can take advantage of its thermal inertia to survive planetary heat load at 200 km. As a consequence, high resolution data can be obtained for only parts (about 25%) of the Mercury surface, concentrated in the northern hemisphere at the low altitudes. For BepiColombo a full high-resolution mapping coverage of the planet is

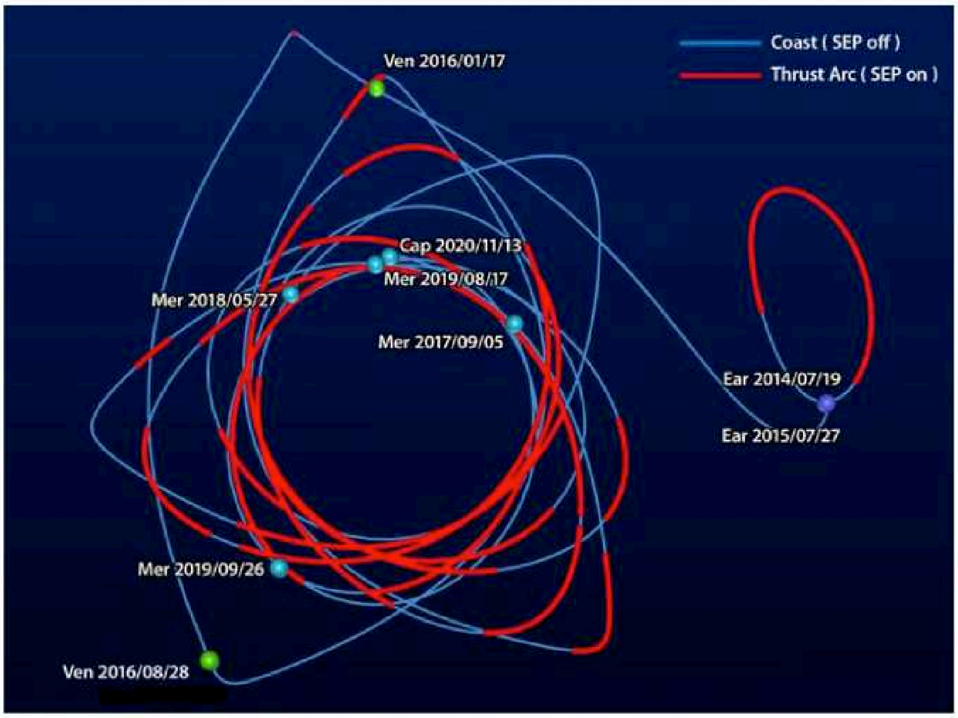

Fig. 3. Earth to Mercury trajectory in a Sun-Earth fixed coordinate system.

one of the main scientific objectives, which requires an MPO orbit much closer to the planet at all times. A polar orbit at 400x1508 km with a 2.3 hour period was selected with its apoherm on the equator on the Sun side when Mercury is at its perihelion. This is a subsolar point where the thermal load on the spacecraft is at its maximum. Half a Mercury year later, at aphelion, the subsolar point occurs when the spacecraft is at its minimum distance to the planet. A highly eccentric orbit at 400x11824 km was selected for the MMO, co-planar with the MPO orbit, in order to allow mapping of the magnetic field and study the magnetosphere, covering the bow- shock, the magneto-tail and the magnetopause (Fig. 4).

5. The BepiColombo system

The BepiColombo system consists of the following segments:

- Space segment
  - Mercury Planetary Orbiter (MPO), carrying remote sensing and in-situ particle, magnetometry and radio science instrumentation
  - Mercury Magnetospheric Orbiter (MMO), carrying electromagnetic field and wave and in-situ particle (neutral, charged and dust) instrumentation as well as one remote sensing instrument
  - MMO Sunshield and Interface Structure (MOSIF) for the thermal protection of the MMO during the interplanetary cruise phase
  - Mercury Transfer Module (MTM) for propulsion during the interplanetary cruise
- Launch Service Segment
- Ground segment
  - The Ground Stations that are provided by ESA, NASA/DSN and JAXA

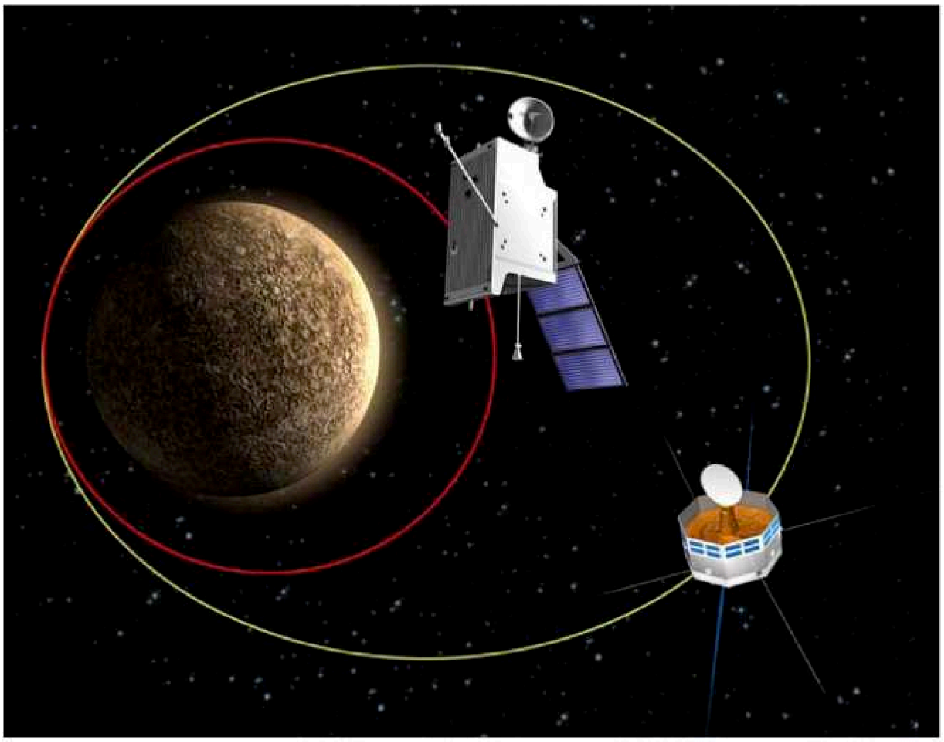

Fig. 4. The MPO and MMO in Mercury orbit.

- The Mission Operations Centres (MOC) that are located in ESOC, Darmstadt, for MPO and in JAXA, Sagamihara, Japan, for MMO
- The Science Ground Segment Centres (SGS) that are located in ESAC, Villafranca, Spain, for MPO and in JAXA, Sagamihara, Japan, for MMO
- The Communications Network that links the centres and stations together

The space segment design (Fig. 5) is driven essentially by the scientific payload requirements, the launch mass constraints and the harsh thermal and radiation environment at Mercury.

Key technologies required for the implementation of this challenging mission include the following:

- High-temperature thermal control materials (coatings, adhesives, resins, MLI, OSR)
- Radiator design for high-infrared environment
- High-temperature and high-intensity solar cells, diodes and substrates for the solar arrays
- High-temperature steerable high gain and medium gain antennas
- High specific impulse (Isp = 4300 s) and high total impulse (23.4 MNs), to be provided by gridded ion engines
- Payload technology, such as detectors, filters and laser technology

6. The Mercury Planetary Orbiter (MPO)

The BepiColombo MPO accommodates the 11 scientific instruments and has a box like shape with a size of 1.6 x 1.7 x 1.9 m. The entire MPO totals up to 1147 kg of nominal dry mass. A double-H primary structure allows mount-

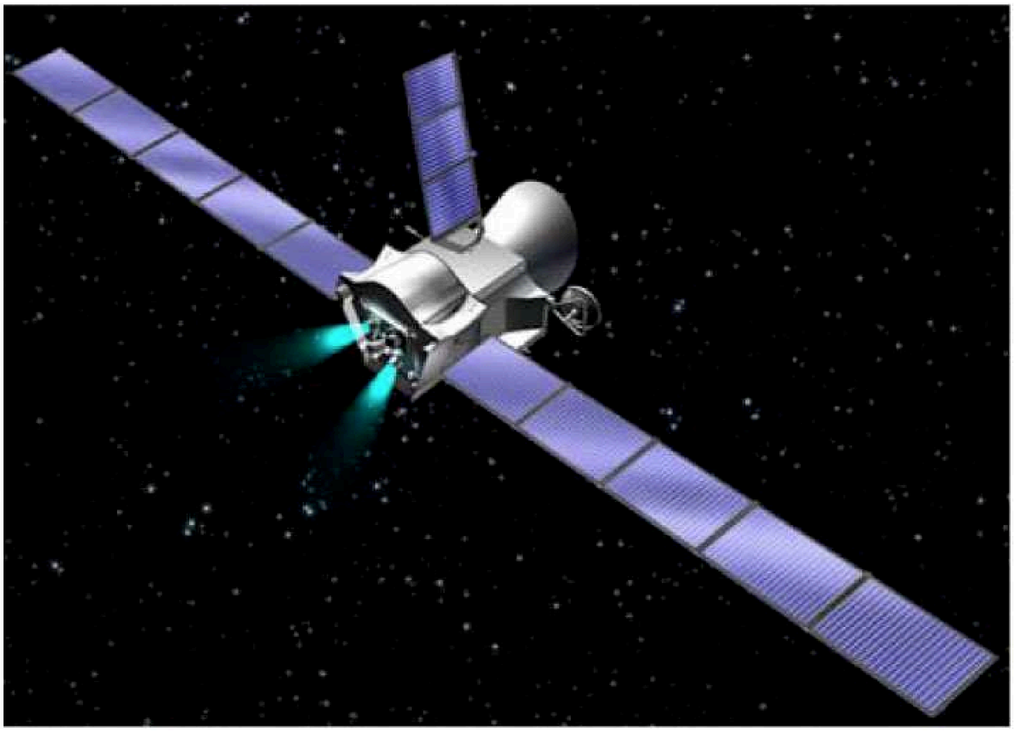

Fig. 5. Mercury Composite Spacecraft in cruise configuration.

ing most units and payloads on the outer face of it, ensuring a good accessibility during the integration process. The primary structure carries a thin cage structure to which the high-temperature Multi-Layer Insulation (MLI) is fixed. In the centre of the MPO two tanks are placed carrying the propellant for the propulsion system. The MPO is designed to take scientific measurements in all parts of the orbit throughout the Mercury year, implying that most of the instrument apertures are continuously nadir-pointing. As a consequence, 5 out of 6 spacecraft faces may be illuminated by the Sun at some point. This leaves only one spacecraft side for a radiator to dump excess heat into space and to avoid solar exposure of the radiator. A further consequence is a spacecraft flip-over manoeuvre, which is needed twice per Mercury year. The heat load is severe: at the perihelion sub-solar point it is 14 kW/m^2 from the Sun and nearly 6 kW/m^2 from Mercury. This environment poses strong requirements on the spacecraft design, particularly to all elements that are exposed to Sun and Mercury, such as the solar array, mechanisms, antennae, multi-layer insulation, thermal coatings and radiator. The development of these elements, together with the solar electric propulsion system are the main cost drivers for this mission and at the same time are responsible for a sizable share of the overall spacecraft mass (Fig. 6).

7. The Mercury Magnetospheric Orbiter (MMO)

The BepiColombo MMO (Fig. 7) is a spin-stabilized spacecraft after it is separated from the MPO following the Mercury orbit insertion. The MMO is optimized for in situ plasma and electromagnetic field measurements in Mercury orbit. The nominal spin rate is 15 rpm (spin period of 4 s) due to the scientific require-

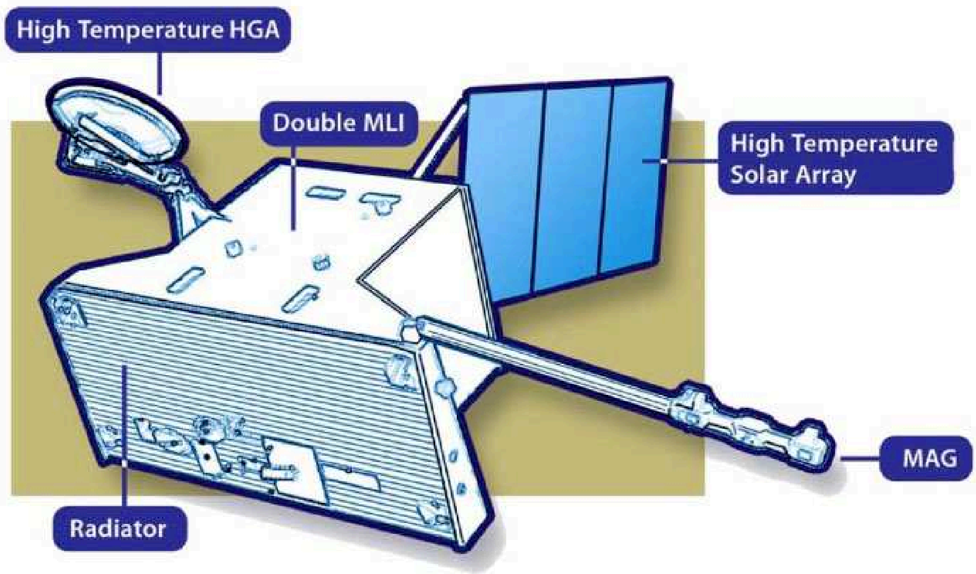

Fig. 6. MPO configuration.

ments. The spin axis is pointed nearly perpendicular to the Mercury orbital plane.

The MMO total mass is 275 kg including N2 gas for attitude control. The MMO main structure consists of two decks (upper and lower), a central cylinder (thrust tube) and four bulkheads. The external appearance has an octagonal shape, which can be surrounded by a 1.8 m diameter circle. The height of the side panel is 0.9 m, whose upper portion is covered to 50% by solar cells and to 50% by optical solar reflectors (OSR). The lower portion is covered by OSRs only. The instruments are located on the upper and lower decks whose interval is 40 cm. For the high gain antenna (HGA), a helical array antenna of 80 cm diameter is mounted on top of MMO. The HGA is pointed toward the Earth by the antenna de-spun motor (ADM) and an elevation control mechanism, the antenna pointing mechanism (APM). As for the medium gain antenna (MGA), a bi-reflector type antenna is mounted on the lower surface with deployment mechanism. Most of the scientific instruments are located on the upper side of the lower deck, while two pairs of probe antennas for PWI are installed on the lower side of the lower deck.

8. The Mercury Transfer Module (MTM)

The Mercury Transfer Module (MTM) provides the acceleration and braking required during Cruise to reach the eventual capture by Mercury and the large amount of power required by the Solar Electric Propulsion System (SEPS). The MTM also constitutes the bottom element in the overall spacecraft structure. Fig. 8 shows the MTM without its two solar array wings totalling over 40 m^2, which provide the power for the SEPS during the Cruise.

The MTM is equipped with a bi-propellant propulsion system of 10N thrusters that are used for the attitude control activities during Cruise. The bi-propellant system is also able to provide navigation V manoeuvres during Cruise. By far the major part of the Delta-V required during Cruise is delivered by the SEPS, using its four 145 mN ion thrusters that are initially operated singly and later in pairs. The MTM solar arrays use the same high-temperature technologies as developed for the MPO and are rotated away from the Sun for the purpose of temperature control. At their peak output the MTM solar arrays deliver 14 kW,

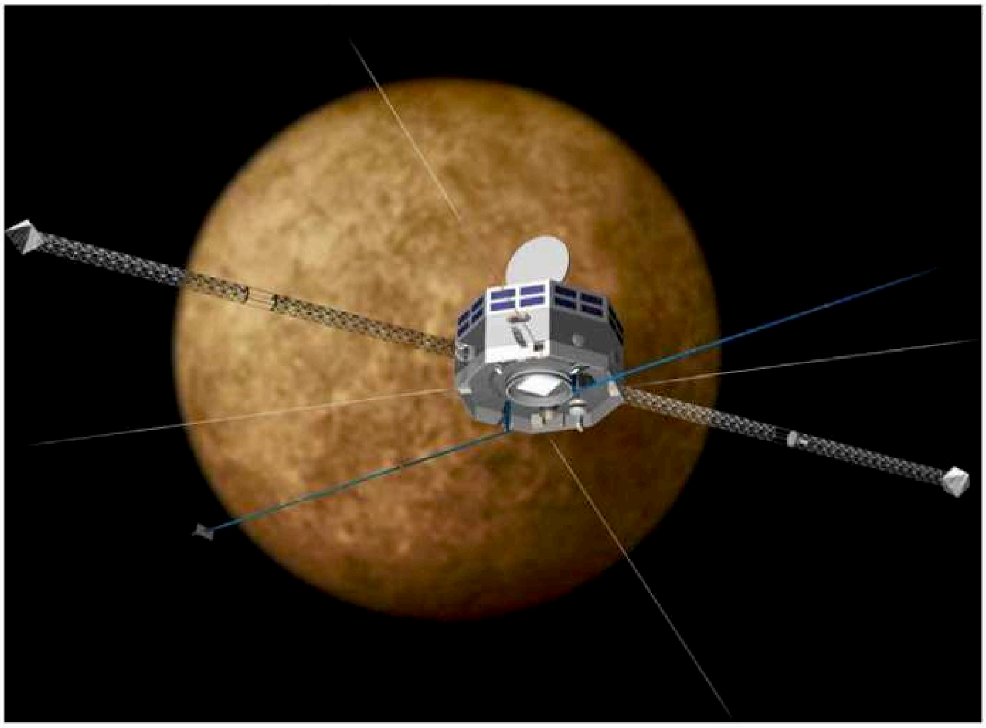

Fig. 7. MMO configuration at Mercury Orbit Phase.

of which 10.6 kW is required by the SEPS. The MTM structure is based on a Carbon Fibre Reinforced Plastic (CFRP) conical primary structure interfacing with the Launch Vehicle Adapter and the MPO. The mechanical interfaces to MPO are characterised by cup-cone separation systems for in-flight separation 6 years after launch whilst initially providing the primary load path through the Mercury Composite Spacecraft (MCS) structure at launch.

9. The MMO Sunshield and Interface Structure (MOSIF)

The MOSIF is the MMO Sunshield and Interface Structure (Fig. 9). It provides the interface structure between the MPO and the MMO and protects the MMO from the full intensity of the Sun until its separation having reached its operational orbit. The Sunshield is a metal truss structure covered with MLI with appropriate thermal finishes inside and out to ensure suitable temperatures for the MMO. The conical shape of the MOSIF with an opening angle of about 16 is needed to allow for the lateral velocity and wobble of the MMO generated during its spin-up at separation.

10. The BepiColombo instruments

To contribute and give answers to the main scientific topics presented in the previous section, a highly comprehensive set of instruments and instrument suites was selected and confirmed in early 2005 (Table 2). The science goals and instrument requirements are described in more detail in another paper presented at this event (*BepiColombo Instruments* by E. Flamini).

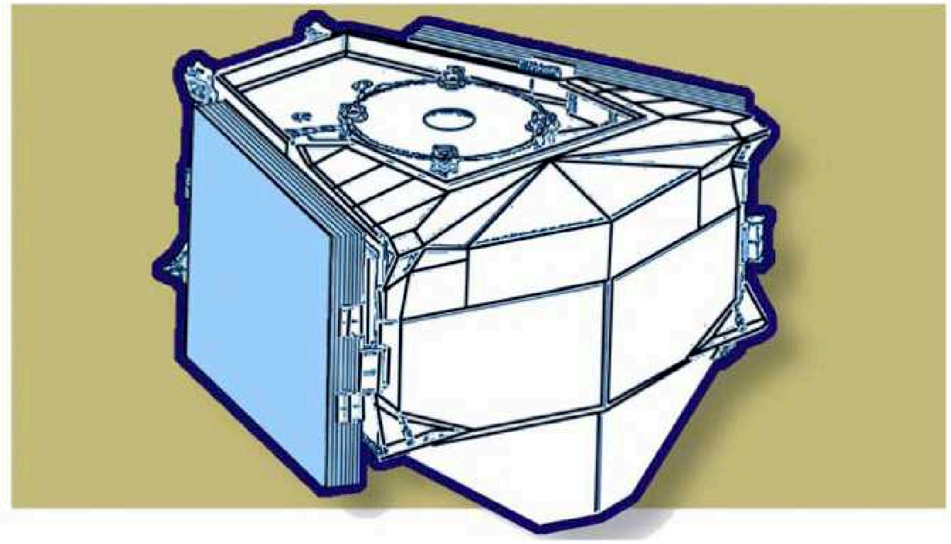

Fig. 8. MTM configuration with folded solar arrays.

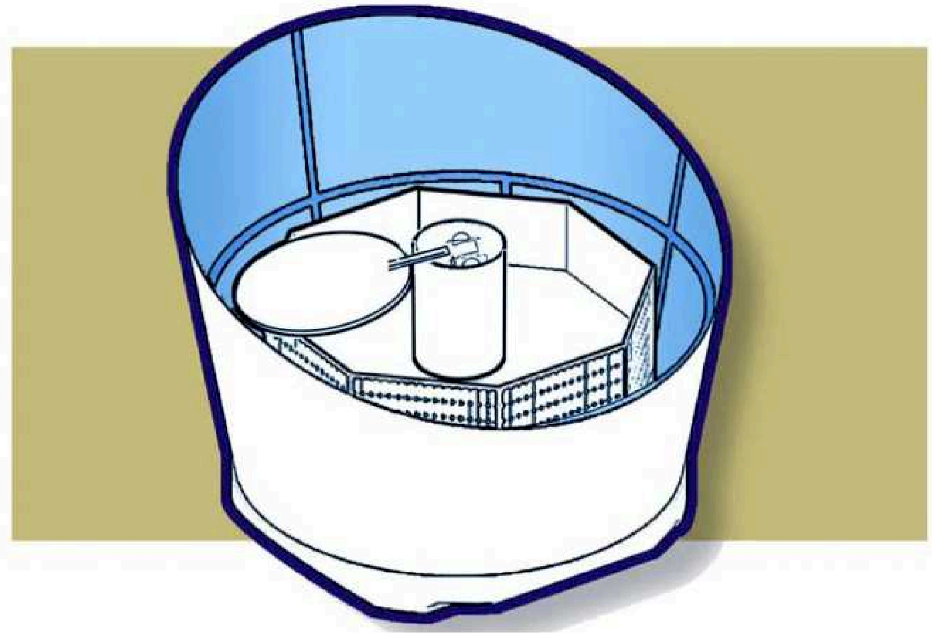

Fig. 9. MOSIF surrounding the MMO and with closure MLI to MPO.

Table 2. BepiColombo scientific instruments.

	MPO
Co-PIs: N. Thomas, CH; T. Spohn, D	BELA BepiColombo Laser Altimeter
PI: V. Iafolla, I	ISA - Italian Spring Accelerometer
PI: K.H. Glassmeier, D	MERMAG - Magnetic Field Investigation
PI: H.Hiesinger, D	MERTIS - Mercury Radiometer and Thermal Imaging Spectrometer
PI: I. Mitrofanov, RUS	MGNS, Mercury Gamma-Ray and Neutron Spectrometer
PI: G. Fraser, UK	MIXS, Mercury Imaging X-ray Spectrometer
PI: L. Iess, I	-2.37 MORE, Mercury Orbiter Radio Science Experiment
PI: E. Quèmerais, F	PHEBUS Probing of Hermean Exosphere by UV Spectroscopy
PI: S. Orsini, I	SERENA Search for Exospheric Refilling and Emitted Natural Abundances
PI: J. Huovelin, FIN	SIXS Solar Intensity X-ray and particle Spectrometer
PI: E. Flamini, I	SIMBIO-SYS Spectrometers and Imagers for MPO BepiColombo Integrated Observatory System
	MMO
PI: W. Baumjohann A	MERMAG Mercury Magnetometer
PI: Y. Saito, JPN	MPPE Mercury Plasma Particle Experiment
PI: Y. Kasaba, JPN	PWI Plasma Wave Instrument
PI: PI: I. Yoshikawa, JPN	MSASI Mercury Sodium Atmospheric Spectral Imager
PI: K. Nogami, JPN	MDM Mercury Dust Monitor

11. Conclusions

BepiColombo is the planetary Cornerstone of ESA's Cosmic Vision Programme, and is devoted to the thorough exploration of Mercury and its environment. It will be carried out as a joint project between ESA and JAXA. With its two-spacecraft, interdisciplinary approach, the BepiColombo mission will provide the detailed information necessary to understand the process of planetary formation and evolution in the hottest part of the proto-planetary nebula, as well as the similarities and differences between the magnetospheres of Mercury and Earth. In addition, the mission offers unique possibilities for testing Einstein's theory of general relativity.

Acknowledgements. This paper is extracted from "BepiColombo Comprehensive exploration of Mercury: Mission overview and science goal", by Johannes Benkhoff, Jan van Casteren, Hajime Hayakawa, Masaki Fujimoto, Harri Laakso, Mauro Novara, Paolo Ferri, Helen R. Middleton, Ruth Ziethe, published in Planetary and Space Science 58 (2010) 2-20. Reference sources are provided therein. The authors wish to thank the Project Teams in industry (EADS Astrium GmbH, EADS Astrium Ltd and Thales Alenia Space Italia), JAXA and ESA for their contributions to the system definition and for providing information for this article. Special thanks to Rudiger Jehn who provided the Mission Analysis information.