BepiColombo mission

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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 Earth's 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 planet's 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.
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 Magnetospheric 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 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. Programmatic
- 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
- 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
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 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.

Table 1. Mission calendar

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

(*) Depending on the actual SEPS performance
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).

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 Sun’s flux of up to about 10 Solar constants. For example, the MESSENGER orbit design limits the distance to the planet’s hottest equatorial region by placing the perihelion at 60° northern latitude and selecting a highly eccentric orbit of 200 x 15193 km. Only a small fraction (less than 5% 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
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
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.

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. 5).

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-
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 m², 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,
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. 7). 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.

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

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