SPACE

Space missions aimed at visiting Mercury and the Sun have been significantly redesigned in a bid to cut project costs, writes *Maria Kielmas*.

Playing interplanetary billiards

The ESA-JAXA BepiColombo mission to Mercury lifts off from Europe's Spaceport in Kourou

Photo: ESA–S Corvaja

The Parker Solar Probe and BepiColombo space missions, both of which launched this year, have undergone a series of ingenious project redesigns in response to growing budget constraints.

Based on an idea first raised in 1958 and named after Eugene Parker, an astrophysicist who postulated the existence of the solar wind, NASA's Parker Solar Probe was launched on 12 August 2018. The spacecraft is a robot the size of a small car that will fly into the Sun's corona, its outer atmosphere. It will investigate the solar wind and observe how it speeds up from subsonic to supersonic. This could lead to improved space weather forecasting.

The probe will be exposed to temperatures of up to 1,370°C while orbiting the Sun at a heliocentric speed of 246,960 kph in a total of 24 close encounters that will carry it within 6.1mn km of the Sun's surface. At its last solar flyby in 2025 it will reach a top speed of 690,000 kph. A thermal protection system (TPS) consisting of a 4.5-inch thick carbon composite shield and cooling system radiators will keep instruments within the shield safe at a temperature of 30°C.

The joint European Space Agency (ESA)/Japanese Aerospace Exploration Agency (JAXA) BepiColombo mission to Mercury was initially conceived in early 1993 and named after Italian astrophysicist Giuseppe (Bepi) Colombo, who first explained the nature of Mercury's orbit around the Sun. Launched on 19 October 2018, it consists of three spacecraft travelling initially as a unit towards Mercury. ESA's Mercury Planetary Orbiter (MPO) will have a circular orbit around the planet and map its surface, while JAXA's Mercury Magnetospheric Orbiter (MMO) will have a more elliptical orbit and probe Mercury's extensive magnetic field. These two craft will be carried by the Mercury Transport Module (MTM) that will be jettisoned in space when the other two go into orbit. The two modules will collect data on the planet's geology, tectonics, polar deposits and magnetosphere dynamics.

Since their conception both the Parker Solar Probe and BepiColombo missions have been redesigned, primarily because of budget constraints. Space missions are always a compromise between scientific ambitions and instruments, launch and propellant costs, and taxpayer-funded budgets. 'Generally speaking, the design and selection of the propulsion system is an outcome of a trade-off study of the overall spacecraft and the mission,' says Yang Gao, Professor of Space Autonomous Systems at the University of Surrey, Guildford. 'We need to look at the trajectories selected for operating the payload instruments and the constraints of the mass, volume and power of the spacecraft, as well as the overall costs and timeframe of the mission, such as launch.'

Getting to the Sun

Getting a spacecraft to Mercury and the Sun remains a serious challenge. It takes about 55 times more energy to reach the Sun in a spacecraft launched from Earth than to reach Pluto.

Mercury is located deep in the Sun's gravitational well. The Sun's gravity pulls in a space vehicle, interacts with its speed and locks it in an orbit. A spacecraft must decrease its velocity Sun-wards to penetrate the solar system's elliptical plane, meaning it has to reduce the enormous energy it possesses when moving out of its Earth orbit. This can be achieved with a gravity assist manoeuvre, a method for a spacecraft to change its speed and direction while saving fuel, and expense. This is a slingshot effect that NASA engineers have dubbed a version of 'interplanetary billiards', which uses the relative motion and gravity of astronomical bodies to accelerate and decelerate the space vehicle. The theory was first proposed in 1916 by Ukrainian mathematician Yuri Kondratyuk.

In December 1973, NASA's Pioneer 10 spacecraft performed a gravity assist around Jupiter to propel it into deep space and out of the solar system. According to data collected at the time, the manoeuvre changed the spacecraft's heliocentric speed from 9.8 km/s to 22.4 km/s and increased its kinetic energy by a factor of 5.2. At the time astrophysicists were convinced that the only way for a space mission to succeed reaching outer planets such as Pluto, or move inwards towards the Sun, would be via Jupiter gravity assists.

Nevertheless, NASA's Mariner 10 probe to Mercury flew past the planet three times between September 1975 and March 1975 using Venus gravity assists alone. It did not orbit Venus and now remains locked in a solar orbit. A later NASA proposal for a Mercury orbiter was discounted initially because of projected launch costs and the propellant needed to slow down the vehicle into an orbit round the planet. Matters changed in the mid-1980s when NASA engineer Chen-Wan Yen proposed a trajectory for the future Messenger mission to Mercury. This included Earth, Venus and Mercury flybys to accelerate the Messenger's speed relative to the Sun, but decrease it relative to Mercury because of that planet's high heliocentric velocity. Messenger was deflected into Mercury's path and orbited Mercury between 2011 and 2015, before impacting on the planet's surface.

Redesigning the solar probe

NASA's budget changed the trajectory of the Parker Solar Probe mission. The first idea was to launch the probe to Jupiter and use a gravity assist to redirect the probe towards the Sun, where it would make two near-Sun passes with the closest approach at 4 solar radii (2.78mn km) from the Sun's surface. Operations of the probe throughout the mission were to be supported by power supplied onboard from three radioisotope thermoelectric generators (RTGs). The total mission cost was an estimated $1.1bn in FY2007 dollars.

A tightening of NASA's funding budget called for the mission to cost no more than $750mn in FY2007 dollars and neither RTGs nor any other kind of nuclear power was to be used. The aim was to preserve scarce plutonium-238 for later deep space missions.

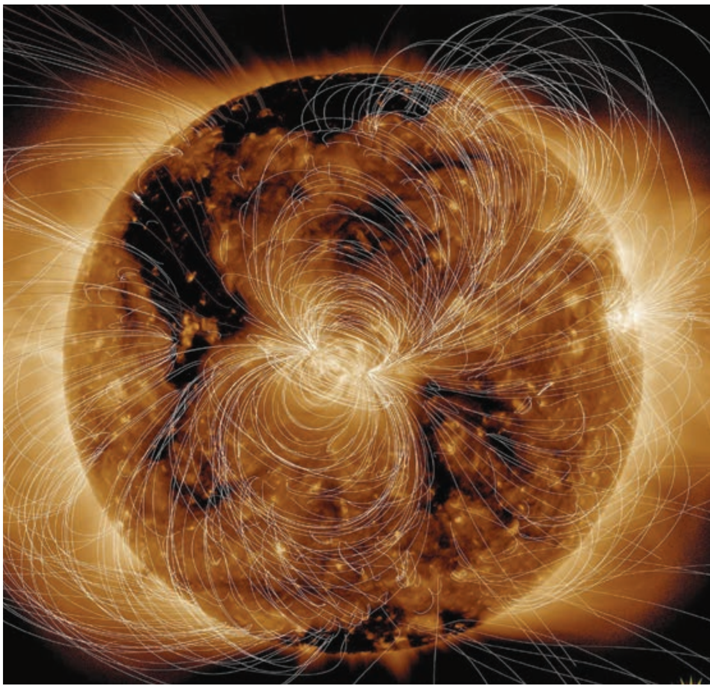
The constraints made a Jupiter gravity assist impractical. Such a trajectory would require oversized solar panels for power generation in weakening solar radiation outwards from the Sun to Jupiter. On returning Sun-wards, the panels would have to be ejected near perihelion – the closest approach to the Sun – because they would be too large to retract under the spacecraft's thermal protection shield.

Reducing delta-v

The Parker Solar Probe mission was redesigned in 2007 and included seven gravity assists around Venus, the first of which occurred on 3 October 2018. Avoiding a Jupiter flyby meant no deep space manoeuvres, and the spacecraft's power system could be simplified by using photovoltaic cells throughout the entire mission.

But a Venus gravity assist (VGA) is only a fraction, about 0.3%, of one Jupiter gravity assist. NASA engineer Yanping Guo, who pioneered the trajectory design, solved this problem with a course that sequentially reduces the spacecraft's delta-v – the impulse required for a velocity change during manoeuvres – and hence its fuel use. There will be multiple VGAs over a period of six years. These have to be tailored individually depending on Venus' orbital position. Sometimes the VGAs are resonant with Venus' orbit – when the probe's and planet's orbits have periods that amplify the gravitational pull – and sometimes non-resonant.

The aim is to minimise the craft's post-launch delta-v, and keep the propulsion system simple and the propellant mass as low as possible. It also exposes the probe to 900 hours in the solar area to collect data compared with just 100 hours in the original design.



Sun's magnetic field
Photo: NASA

Following a three-stage lift-off from Earth, escape from Earth's gravitational shield and separation of the probe from the remaining vehicle parts, the probe set on its course to the Sun. Its in-space propulsion system consists of three hydrazine thrusters providing attitude control – ie orientation relative to another entity – and trajectory corrections. Its two, 1.26 sq metre solar arrays provide just 388 watts of power, depending on their configuration, about sufficient to power a kitchen blender.

Mission to Mercury

The ESA/JAXA BepiColombo mission has also been redesigned, but not as significantly as the Parker Solar Probe. Originally, BepiColombo was to send a lander, the Mercury Surface Element (MSE), onto Mercury's surface. This was abandoned in November 2003 because of budget considerations. Such a lander would have required a significant amount of extra fuel on the spacecraft.

'When it comes to landing on Mercury you need something powerful to slow down, that means chemical propulsion,' explains Steven Hauck, Professor of Planetary Geodynamics at Case Western University, Cleveland, Ohio. 'Mercury has the same gravity as Mars – both about 38% of Earth gravity. However, Mars has a slight atmosphere that is enough to help slow down a landing spacecraft there while Mercury has no atmosphere. So any Mercury landing has to be accomplished completely with rockets.' But this means extra propellant, higher payload, and higher costs.

Enigmatic planet

Colombo first solved the mathematical enigma of getting to Mercury, the Solar System's most unusual body. It is closest to the Sun but not the hottest (that's Venus). It's the smallest planet but has the largest core relative to its size. Temperatures range from –173°C to +420°C. The planet completes three rotations on its axis for every two of its orbits around the Sun. But this 3:2 resonance is complicated by its rapid orbital velocity that combines with its slow sidereal motion – ie on its axis. The result is that a day on Mercury lasts for two of its years.

Colombo's calculations helped NASA's Mariner 10 trajectory to orbit round the Sun and to fly past Mercury. But it did so when the Sun was illuminating only one side of the planet. Mercury's overall surface structure was discovered with the Messenger mission that orbited the planet between 2011 and 2015 before crashing into it.

Electric propulsion

Nevertheless, the BepiColombo trajectory has been difficult to achieve. Mercury's orbital velocity of 47.6 km/s is 60% higher than Earth's 30 km/s. The spacecraft launched at 3.4 km/s faster than Earth's escape velocity of 11.2 km/s. However, achieving the necessary delta-v through chemical propulsion to get into an orbital trajectory on Mercury would require two tonnes more of propellant, increasing launch costs.

Solar electric propulsion (SEP) is eight times more efficient than chemical propulsion, according to ESA. So this spacecraft is using four xenon-ion engines, two large solar arrays providing electric power, and 24 chemical thrusters. BepiColombo is the first interplanetary mission using SEP for primary propulsion, although such technologies have been used on previous missions such as NASA's Dawn and JAXA's Hayabusa Explorer.

Solar electric thrusters provide a low thrust but operate for a long period and deliver a high specific impulse, a measure of propellant efficiency when compared with chemical rockets. According to Farnborough-based Qinetiq, the ion engine manufacturer, each thruster on BepiColombo is required to operate over a range of 75–145 millinewtons (mN), with a specific impulse of nearly 4,300 seconds at 145mN thrust. This will be the greatest total impulse ever achieved in a space mission. As a comparison, NASA's Space Shuttle solid rocket booster's specific impulse was 350 seconds while the Dawn spacecraft's impulse was 3,100 seconds at a thrust of 90mN.

After launch, BepiColombi is set to make 1.5 orbits of the Sun and return to Earth in 2020 to pick up a gravity assist, fly past Venus in 2020 and 2021, and later perform six gravity assists from Mercury between 2021 and 2025. ESA says that the ion engines will be used for only about 50% of the time. From 2025, the MTM module will be jettisoned and the MPO module will fire chemical thrusters to lower the orbit on Mercury. At this point, the MPO and MMO will start autonomous orbits and their scientific data gathering tasks.

These two missions, launched two months apart and both lasting around seven years, are set to unlock some of the Solar System's most intriguing questions. Redesigned with ingenuity over decades, now they need good luck. ●