Why India Went to Mars

India went to Mars in 2013 because both Japan and China had tried and failed. If India could succeed where Japan and China had not, it would be next after the US, USSR/Russia and ESA to orbit Mars. India had published its intensions for the exploration of Mars, the solar system and human spaceflight but the decision to go to Mars in 2013 was in response to external events. While India's journey to the Moon in 2008 was planned and matured over time, the mission to Mars was more opportunistic and finalised in haste. India always had plans for a mission to Mars, the decision to go in 2013 was in response to the failure of China's mission to Mars in 2011. Publicly, ISRO had declared that there "is no race with anybody" but later conceded that the decision to go to Mars was taken following the failure of the Chinese mission.[1]

Orbital mechanics dictate that the opportunity for a journey to Mars comes around only once every two years. After 2011, the next opportunity would be the autumn of 2013. Neither Japan or China could attempt a Mars mission for 2013 but India could. Japan had unsuccessfully attempted to fly its spacecraft Naomi to Mars in 1999, and although eventually, it got to Mars in 2003, Nozomi failed to enter the Martian orbit and flew past instead. Exactly when ISRO began seriously contemplating a mission to Mars is unclear. Ajey Lele, a Senior Fellow at the Institute for Defence Studies and Analyses in New Delhi, considers that this could have been an outcome of the 2006 meeting of leading Indian scientists to discuss the future of India's space programme.[2] That was the time when India's first mission to the Moon was taking shape. Through this scientific collaboration, India wanted the US to start to ease its sanctions on high technology. In March 2006, India and the US signed a deal that paved the way for scientific instruments from the US to be installed on Chandrayaan-1. In media reports of that agreement, the NASA chief stated, "We are also looking at sharing of data for Earth sciences and Earth resources and broader scientific cooperation in exploring beyond the Earth."[3]

By November 2008, ISRO's first Moon mission Chandrayaan-1 had been in lunar orbit for two weeks and had successfully deployed its MIP to the surface. Riding high on this success, ISRO's then chairman Madhavan Nair publicly announced that "the study for Mars exploration has already started."[4] During the 2010 Indian Science Congress, Nair confirmed India's plans for a Mars mission to a visiting journalist from the UK.[5] During the same Congress, Abdul Kalam, who had been instrumental in incorporating the MIP on Chandrayaan-1, raised the idea of Mars as a mission objective.[6] By the time the Chandrayaan-1 mission came to a premature end in 2009, India may not have had a specific timeline, but it did have a firm conviction that Mars was the next destination.

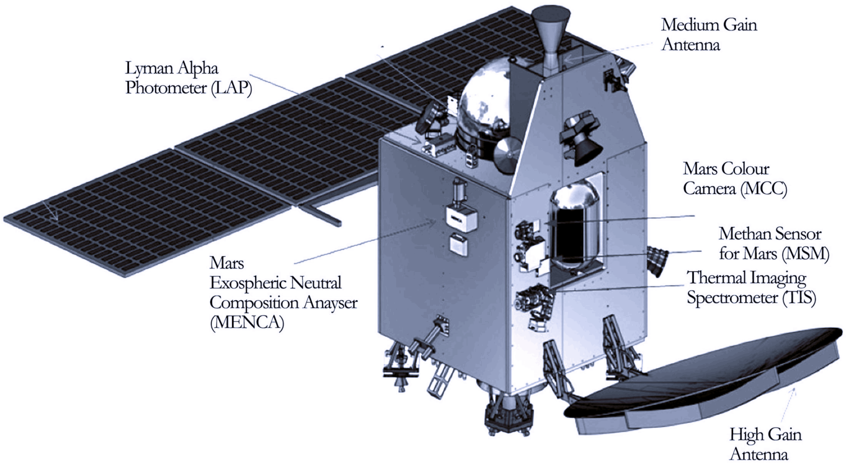
Prior to the failure of the Chinese space mission to Mars in November 2011, China had chalked up a series of successes in space. It successfully completed three human spaceflights, including one with three astronauts; delivered a module for its space station to orbit and placed its Chang'e 1 spacecraft in lunar orbit in October 2007, a year before Chandrayaan-1. Although its first Mars mission failed in 2011, China was not culpable for the failure. Its spacecraft, Yinghuo-1, was designed to enter Martian orbit after hitching a ride on an ambitious Russian space mission called Phobos-Grunt. This Russian spacecraft was to land on the Martian moon Phobos, collect a sample of material from the surface of Phobos and return it to Earth. Russia signed an agreement with China that Yinghuo-1 would be launched on the same rocket as Phobos-Grunt. However, neither Phobos-Grunt nor Yinghuo-1 left Earth orbit following a launch vehicle failure. The fourth stage of the launch vehicle, along with both spacecraft, disintegrated during Earth re-entry several weeks after launch.[7] Following this failure in 2011, China could not have readied another Mars mission for November 2013, but India could.

Further, while India's PSLV-XL launcher could just about get a spacecraft to Mars in 2013, for the next two opportunities in 2016 and 2018, an additional velocity of at least 380 m/s would be required compared to 2013. That was just outside the reach of the PSLV-XL.[8] So, India had to go in 2013 or wait until 2020. India saw 2013 as the best opportunity to get to Mars before China and took it.

From Sriharikota to Mars

India's first Mars mission called Mars Orbiter Mission (MOM) or Mangalyaan (in Sanskrit, Mangala = Mars and Yaan = vehicle) was launched at 14:38 IST on 5 November 2013, not towards Mars, but a 50-km cubic volume of space near where Mars would be at 07:27 IST on 24 September 2014.[9] Not only was Mars a target moving around the Sun at 24 km/s, but MOM would be launched from Earth moving at 30 km/s around the Sun. In addition, MOM's launch pad at Sriharikota) was moving at about 0.5 km/s (Earth's rotation). MOM would have to hit that small target after a journey of 667 million kilometres 300 days after launch. Timing was critical. If MOM arrived a little earlier or later, it would either crash into Mars or pass it by. Once it arrived at the precise time and place, there was one more critical step; MOM had to fire its engine to slow down to enter orbit around Mars, a key manoeuvre that ISRO had not conducted before.

On 24 September, everything went to plan. MOM arrived at precisely the right spot, its engine fired, and it entered the planned highly elliptical orbit of 421 by 77,000 km. With that, India became the fourth space agency to arrive at Mars, and it had done it on its first attempt. The Indian Prime Minister was present at Sriharikota watching MOM arrive and embraced the ISRO chairman on live TV in celebration. In some ways, India's arrival at Mars was tantamount to a rebirth of the Indian Space Programme. With the widespread national and international press coverage that followed, many within India, as well as outside, realised for the first time that India had an active and effective space programme.



Mars Orbiter Mission and Its Science Payload. Credit Adapted from ISRO

As part of the planning process for MOM, ISRO had studied historical Mars missions, particularly the 29 missions that had failed of the total 55 until then. Each of the 29 failures were "carefully addressed during the preparation for MOM."[10] ISRO had been designing, building, launching and operating satellites for over three decades. On the face of it, MOM was yet another mission to put a satellite in orbit, further away but conceptually the same. In practice, building and sending a satellite to Mars introduced a host of new engineering challenges.

Although launched on 5 November, MOM remained in Earth orbit until 1 December before embarking on a nine-month journey to Mars. During this extended period, MOM was exposed to potential harm from the intense radiation environment of space as it crossed the radiation fields around the Earth (Van Allen belt) 39 times. Japan's attempt to reach Mars in 1999 with its Nozomi spacecraft had failed in part because of radiation damage to some of the control systems.[11] MOM's radiation shielding was designed for protection against an accumulated dose of 9 krads for packages inside the cuboid and 15 krads for packages mounted on the outside.[12]

The vast Earth-Mars distance generated two additional challenges. While ISRO was familiar with operating satellites in Earth orbit at 36,000 km, Mars-Earth distance varied between about 50 million km and 400 million km. The round-trip communication interval between Earth and MOM could take up to 42 minutes (21 minutes each way at 400 million km or 5 minutes at 50 million km). ISRO not only had to develop the infrastructure to communicate over this vast distance, but it also had to build in additional level of autonomy, given the time lag, MOM needed to "think and do" by itself.[13]

The solar panel was MOM's only source of electrical power. Mars orbits the Sun at a distance that is about 1.5 times that of the Earth, where the intensity of the Sun is only 42% compared to that at the Earth-Sun distance.[14] The battery and efficiency of its solar panel had to be designed to operate in that context. While the battery used was the same as in Chandrayaan-1, a single 36 Ah lithium-ion battery, MOM was fitted with a three-panel solar array (each panel 1.8 m by 1.4 m) generating 840 W instead of a single panel solar array required for Chandrayaan-1 which had generated 750 W in Lunar orbit.

To catch the 2013 Earth-to-Mars launch window (21 October – 19 November), ISRO worked to a hectic schedule with no contingency. The launch window is the period when a journey from Earth to Mars can take place with minimum energy. This window appears once every 780 days when the orbits of Mars and Earth line up so that the angle between Earth, Mars and the Sun is 40°. This configuration is necessary for a Hohmann Transfer Orbit, and all spacecraft that have ever gone to Mars from Earth have used it. MOM's journey from Earth to Mars had three phases, Geocentric, Heliocentric and Martian, determined by which body is producing the dominant gravitational influence, the Earth, Sun or Mars. The Geocentric phase, where MOM was in the Earth's gravitational field, lasted until it had travelled 918,347 km from the Earth. It entered the Martian phase once it got closer than 573,473 km to Mars. In between, MOM was predominantly under the Sun's gravitational force, and thus in the heliocentric phase. The MOM spacecraft design was a modified version of that used for Chandrayaan-1 which in turn was based on the IRS/INSAT bus. ISRO chose a design with proven reliability given the tight timeline. On 21 September 2012, just a month after the formal announcement, ISAC in Bangalore took delivery of the structure of the MOM spacecraft built by Hindustan Aeronautics Limited (HAL). MOM's sub-systems, some of which were already being developed, were then transferred to the structure, and the spacecraft began to take shape. Installation of science instruments started in April 2013, testing from August onwards, and on 3

October 2013, the spacecraft was delivered to Sriharikota to begin preparation for launch.

The PSLV-C25 launch from the FLP was initially scheduled for 28 October but then pushed to 5 November 2013. This was the first time Sriharikota conducted a launch in the month of November is avoided as the rainy season typically spans October and November. MOM was launched by the most powerful variant of ISRO's reliable and in practice only operational launch vehicle, the PSLV-XL. Despite this, there was a velocity shortfall of around 1.5 km/s. This shortcoming in PSLV-XL's power dictated the overall mission profile, the smaller science payload of 15 kg, the six Earth orbits (known as Gravity Assist) and the highly elliptical Martian orbit of 418 by 76,872 km when it got there. ISRO turned this highly elliptical orbit into an opportunity by configuring experiments that exploited such an orbit.[15] During the same launch window, NASA launched its spacecraft called Maven to Mars. With a launch vehicle that can put seven tonnes into GTO compared to PSLV's 1.3 tonnes, Maven was launched two weeks after MOM and was on its way to Mars an hour after launch compared to MOM's three weeks and arrived at Mars three days before MOM.

Date	IST	Event	Engine Burn duration (s)	Apogee (km)
05/11/13	14:38	Launch	935	23,550
07/11/13	01:17	1st orbit increase	416	28,825
08/11/13	02:18	2 ND orbit increase	570.6	40,186
09/11/13	02:10	3rd orbit increase	707	71,636
11/11/13	02:06	4th orbit increase	incomplete	78,276
12/11/13	05:03	4th orbit increase (supplemental)	303.8	118,642
16/11/13	01:27	5th orbit increase	243.5	192,874
01/12/13	00:49	Trans Mars Injection	1328.89	

Series of Earth orbits prior to departure for Mars

PSLV's unusual destination called for a unique launch trajectory. Typically, a PSLV delivers its payload to Earth orbit in about twenty minutes, from where the payload proceeds under its own power to the final destination. The fourth stage ignition and payload separation is monitored from ground stations in Port Blair in Brunei, Biak in Indonesia and Canberra in Australia. For MOM's eventual trajectory to Mars, an interval of 24 minutes was required between the end of stage three and the ignition of stage four. By that time, the ground track of the fourth stage would have travelled beyond Australia. The nine-minute fourth stage burn would take place over the south Pacific, well beyond the reach of any of ISRO's or its international partners' ground stations.[16] To ensure that the telemetry of the fourth stage burn and MOM separation was recorded, ISRO commissioned two ships from the Shipping Corporation of India, Nalanda with a 4.6 m antenna and Yamuna with a 1.8 m antenna. Poor weather conditions at sea delayed these ships from getting to the operational sites as scheduled, resulting in the launch date moving from 28 October to 5 November. They arrived on location about three days before launch and positioned themselves approximately 2,000 km apart near Fiji.[17] One would monitor the fourth stage ignition and burn and the other the release of MOM from the spent fourth stage.

During the 300-day cruise from Earth to Mars, ISRO monitored MOM using its ground stations during the 12 hours a day that it was visible in the sky from India and with assistance from NASA's DSN at other times.[18] The first picture taken by the Mars Colour Camera was of the Earth two weeks after launch. The other four instruments, too, were switched on for short periods for testing and calibration. To ensure that MOM arrived at the right place at the right time with high precision, four Trajectory Control Manoeuvers (TCM) were scheduled, of which only three were carried out, TCM-1 on 11 December 2013, TCM-2 on 11 June 2014, TCM-3 scheduled for August 2014 was omitted as no correction was deemed required and TCM-4 on 22 September 2014. The TCMs were designed to cater for small course variations resulting from navigation errors and effects of external forces, such as gravity or solar radiation pressure.

The first two TCMs required engine burns for forty seconds and nine seconds, collectively changing MOM's velocity by 9.33 m/s.[19] The third TCM was skipped in favour of revised TCM-4. Two days before arrival, a joint LAM and eight-thruster burn lasting for four seconds reduced MOM's velocity by 2.1 m/s. Although a very short burn resulted a tiny change in velocity, this burn was significant as it verified that the LAM operated as expected. For additional assurance, ISRO had been mirroring on the ground the LAM burns using an identical LAM at the VSSC. Had this test on 22 September not gone according to plan, ISRO would have had time to engage plan B for Mars Orbit Insertion. Plan B involved using only the eight small thrusters to perform the breaking manoeuvre to enter Martian orbit. The lower capacity of the smaller thrusters would have required a longer burn of ninety minutes. The mid-point of the burn would have remained the same, but it had to start earlier. That is why a test was conducted on 22 September. Plan B would have resulted in an even more elliptical orbit (an apoapsis of 0.27 million km) and only about 3 kg of propellant would have remained making mission success a "touch and go."[20]

Navigation and guidance had brought MOM to within 1,847 km of the surface of Mars on 24 September 2014. Travelling at 6.5 km/s and accelerating by virtue of its approach to Mars, MOM had to slow down by 1099 m/s to enter orbit.[21] Had the braking manoeuvre failed, the mission would have become a flyby and not an orbiter. To decelerate, MOM had to point in the opposite direction of travel and fire its LAM and the eight small thrusters for 24 minutes. Two key events coincided with this breaking manoeuvre. Five minutes after firing the LAM and the eight small thrusters, MOM entered Mars' shadow and lost sight of the Sun for the first time since leaving Earth. A few minutes later, still during the engine burn, MOM disappeared behind Mars and lost contact with Earth. Both events were expected and planned for. The required commands for reorientation, start engine firing, stop engine firing and re-point to Earth had been uploaded to MOM a few days earlier. Given the 42-minute lag in round trip communication, real-time communication was not practical, and all spacecraft far from Earth are designed to operate autonomously.

Following the engine burn, which consumed 250 kg of propellant, MOM decelerated and entered Martian orbit. A few minutes after MOM came out of the eclipse, it reoriented its high gain antenna to point to Earth and then sent signals to Earth that the engine burn and orbit insertion went to plan. About 12.5 minutes after transmission, NASA's DSN station in Canberra, Australia, received the signals from MOM and forwarded them to ISRO, confirming that MOM had entered orbit around Mars and could finally live up to its name, Mars Orbiter Mission. MOM achieved an orbit of 421 x 76,993 km with a period of 73 hours and had 37 kg of usable propellant left. On 24 September 2014, MOM joined four other Mars orbiters, ESA's Mars Express and three NASA orbiters, Mars Reconnaissance Orbiter, Mars Odyssey and MAVEN (Mars Atmosphere and Volatile EvolutioN), which had arrived just three days earlier. In addition, NASA was operating two rovers, Opportunity and Curiosity, on the Martian surface.

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9. Interestingly, whereas Chandrayaan-1 was known as Chandrayaan-1 from the outset, Mangalyaan was not known as Mangalyaan-1. However, ISRO's next mission to Mars is known as Mangalayaan-2. Perhaps, this was also a consequence of the haste under which the Mars mission was executed.

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11. Initially, it was a faulty main engine valve that impeded its Trans Mars Injection burn, and later, a powerful solar flare in April 2002 damaged its attitude control heating system and communications. Despite these problems, the Japanese engineers succeeded in getting Nozomi to Mars in December 2003, but a planned final main engine burn failure prevented a Mars Orbit Insertion on arrival, and Nozomi is now out of contact in a solar orbit.

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13. Some very helpful graphics that illustrate the distances involved and the reasons why spacecraft autonomy is essential for deep space missions. Arya A. S. et al. 2015. Mars Colour Camera: The Payload Characterization/calibration and Data Analysis from Earth Imaging Phase. *Current Science* 109 (6): 1076–86.

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15. However, the highly elliptical orbit was not necessarily a disadvantage as was thought at the early planning stage "what initially appeared to be a limitation, can be turned into a unique opportunity by configuring experiments that exploit the highly elliptic orbit."

16. The 4th stage was beyond the view of ISRO's eastern-most ground station Biak in Indonesia. Had the altitude been higher than 100 km, the two large antennae (18 and 32 m) of IDSN could have been used.

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