Chandrayaan-1: India's first planetary science mission to the moon

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Chandrayaan-1, the first Indian planetary exploration mission, will carry out high resolution remote sensing studies of the moon to further our understanding about its origin and evolution. Hyper-spectral imaging in the UV-VIS-NIR region using three imaging spectrometers, along with a low energy X-ray spectrometer will provide mineralogical and chemical composition of the lunar surface at high spatial resolution. A terrain mapping camera will provide high resolution three-dimensional images of the lunar surface and will be complemented by a laser ranging instrument that will provide lunar altimetry. Three payloads – a high energy X-γ ray spectrometer, a sub-keV atom reflecting analyser, and miniature imaging radar – will be used for the first time for remote sensing exploration of a planetary body. They will investigate transport of volatiles on the lunar surface, presence of localized lunar mini-magnetosphere and possible presence of water ice in the permanently shadowed lunar polar region respectively. A radiation dose monitor will provide information on energetic particle flux en route to the moon and in lunar orbit. An impact probe carrying an imaging system, a radar altimeter and a mass spectrometer will be released from the spacecraft to land at a predestinated lunar site. The design of the one tonne-class spacecraft is primarily adapted from flight proven Indian Remote Sensing satellite bus with several modifications that are specific to the lunar mission. The spacecraft was launched by using a variant of the indigenous Polar Satellite Launch Vehicle (PSLV-XL) and placed in a 100 km circular polar orbit around the moon with a planned mission life of two years. An Indian Deep Space Network and an Indian Space Science Data Center have been established as a part of Chandrayaan-1 mission and will cater to the need of future Indian space science and planetary missions.

Keywords: Chandrayaan-1, evolution, ISRO, moon, origin, planetary exploration.

Introduction

THE current decade has seen a revival in the field of planetary exploration, and in particular in lunar exploration, with several new initiatives by various national space agencies including the Indian Space Research Organization (ISRO). Even though the need for further exploration of the moon has been discussed in the late nineties, a renewed effort in this direction has formally begun in 2003 with the Smart-1 mission of ESA that was followed by the Changé-1 mission of China, the Japanese mission Kaguya (SELENE), both in late 2007, the Indian Chandrayaan-1 mission in late 2008 and the US mission LRO (Lunar Reconnaissance Orbiter) scheduled for launch in early 2009. The possibility of an Indian mission to the moon was mooted in the late nineties and was discussed extensively in different academic forums during 1999 and 2000. On the basis of recommendations from these forums, ISRO constituted a National Task team to look into both the technological feasibility and scientific return from such a mission. The recommendations of the task team were deliberated at length and ISRO formally proposed Chandrayaan-1 Mission to the Government of India in early 2003 and it was approved in November, 2003. The mission is international in character with the National Aeronautics and Space Administration (NASA), USA, European Space Agency (ESA) and the Bulgaraian Academy of Sciences (BAS) providing support for payloads selected for the mission following ISRO's announcement of opportunity (AO) to the global scientific community in early 2004. The AO payloads complement and supplement the Indian payloads and enhanced the scientific content of the mission. This paper describes the scientific objectives, the various payloads, mission details, observational plans and other related aspects of the Chandrayaan-1 mission. The accompanying papers in this special section describe in detail the scientific objectives and significant characteristics of each individual payload.

Science objectives

Astronomical observations of the moon to understand the brightness variation over its surface led to identification of distinctly different regions of the moon. However, relating these differences to different types of lunar material became possible only through laboratory studies of reflection properties of various minerals and analysis of lunar samples returned by Apollo and Luna missions dur-

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*For correspondence. (e-mail: goswami@prl.res.in) ing the late sixties and early seventies. These studies led to a broad understanding of the evolution of the moon and led to the suggestion that an impact of a mars-sized object on the early earth resulted in the formation of the moon. The concept of a magma ocean resulting from a global scale melting of the moon, soon after its formation, was also proposed. A calendar of events for the first one and half billion years of lunar evolution was drawn up based on the nature, chemical composition and ages of the returned lunar samples. However, both the remote sensing and surface exploration of the moon by the Apollo and Luna missions were restricted to the equatorial region of the moon. The next major advance came with the launch of the Clementine and Prospector remote sensing missions to the moon in 1994 and 1998 respectively, which provided the first set of data on lunar mineralogy and chemistry at a global scale. While these data provided new insight on lunar evolution, they also raised many new questions. Further, the mineralogical and chemical mappings of the lunar surface were done with either low spectral resolution (mineralogy) or with low spatial resolution (chemical composition). The need for studies with high spectral and spatial resolutions was obvious for furthering our understanding of the origin and evolution of the moon. The Chandrayaan-1 mission aimed to achieve this goal by carrying out remote sensing observations over a wide range of the electromagnetic spectrum for simultaneous mineralogical, chemical and photo-geological mapping of the lunar surface at resolutions better than previous and contemporary lunar missions.

Global interest in long duration mission to the moon and the possibility of using moon as a base for further exploration of the solar system also brought into focus the possible indigenous lunar resources that may be utilized during such missions. Expected excess of volatiles, including water ice, mixed with the near surface material in permanently shadowed lunar polar region, is a prime candidate in this regard. The Chandrayaan-1 mission will explore the nature of volatile transport on the moon using radioactive radon and its decay products as tracers, and also probe permanently shadowed base of deep craters in the lunar polar region using radio waves to look for possible presence of water ice in such areas. Devoid of an atmosphere and global magnetic field, the moon also provides free access to energetic particles of both solar and galactic in origin. The Chandrayaan-1 mission will conduct studies of interactions of low energy solar wind ions with the lunar surface to identify lunar mini-magnetospheres created by localized magnetic field. These studies are based on novel approaches that will be adopted for planetary exploration for the first time.

The payloads

A suite of baseline payloads, identified initially to meet the scientific objectives, include a Terrain Mapping Camera (TMC), a Hyper-Spectral Imager (HySI), a Low **e**nergy **x**-ray **s**pectrometer, a High Energy X-γ ray Spectrometer (HEX) and a Lunar Laser Ranging Instrument (LLRI). These payloads will provide simultaneous mineralogical, chemical and photo-geological data that will allow (i) three-dimensional mapping of the lunar surface and lunar altimetry at 5 m resolution, (ii) mineralogical mapping of the lunar surface at a resolution of ~100 m, (iii) direct estimation of lunar surface concentration of the elements Mg, Al, Si, Ca, Ti and Fe with spatial resolution of ~25 km, and (iv) probing the nature of volatile transport on the moon, particularly to the colder lunar polar region. An impact probe carrying a mass spectrometer, an imaging system and a radar altimeter will complement these baseline payloads and will be a technological forerunner for future proposed lunar landing missions.

ISRO also offered possibility for the international scientific community to participate in the Chandrayaan-1 mission through an AO in early 2004. The response was overwhelming and several payloads that complement and supplement the basic objectives of the Chandrayaan-1 mission have been selected based on peer reviews. These are: a miniature imaging radar instrument (Mini-SAR) to explore the polar regions of the moon to look for possible presence of water ice, two infrared spectrometers (SIR-2 and Moon Mineralogy Mapper: MMM) for extending the wavelength coverage beyond that of the HySI, a low-energy X-ray Spectrometer (C1XS) for high resolution chemical mapping, a Sub-keV Atom Reflecting Analyser (SARA) for studying solar wind–lunar surface interactions and lunar surface magnetic anomalies and a RAdiation DOse Monitor (RADOM) for monitoring energetic particle flux en route to the moon and in the lunar environment. Three of the payloads, SIR-2, C1XS and SARA, developed at the Max-Planck Institute, Lindau, Germany, Rutherford Appleton Laboratory, UK, and Swedish Institute of Space Physics respectively were provided by the ESA. NASA provided Mini-SAR, developed by Applied Physics Laboratory at John Hopkins University and NAWC, and the Moon Mineralogy Mapper, developed by Brown University and the Jet Propulsion Laboratory. RADOM was provided by the Bulgarian Academy of Sciences. Two of the AO payloads, C1XS and SARA, have Indian collaborations and realized with significant technical and scientific contributions from the ISRO Satellite Center, Bangalore, and the Vikram Sarabhai Space Center (VSSC), Thiruvananthapuram respectively. A schematic of the Chandrayaan-1 spacecraft with the location of the ten payloads and the Moon Impact Probe is shown in Figure 1. In the following, the basic characteristics of the payloads are described; more extensive description of each payload is presented in the accompanying papers in this special section. The Chandrayaan-1 spacecraft integrated with all the flight payloads prior to various pre-flight tests is shown in Figure 2.

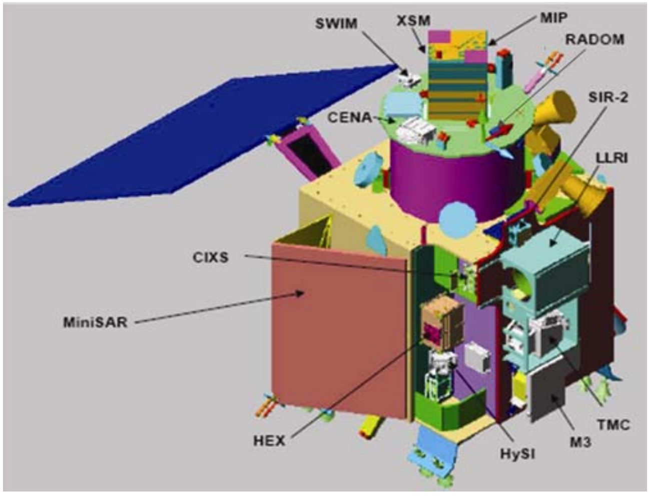

Figure 1. A schematic depiction of the Chandrayaan-1 spacecraft. The eleven payloads on board are also marked. The blue panel is the canted solar array.

Figure 2. The Chandrayaan-1 spacecraft.

HySI, SIR-2, MMM

Three payloads [Hyper-Spectral Imager (HySI), Near Infrared Spectrometer (SIR-2) and Moon Mineralogy Mapper (MMM)], will study solar reflected energy from the lunar surface covering the wavelength range of 0.4 to 3 micron and will provide high resolution mineralogical map of the entire lunar surface. HySI operates in the 400–950 nm range employing a wedge filter and will have spectral resolution of ~15 nm and a spatial (pixel) resolution of 80 m. SIR-2, a compact, monolithic grating near infrared point spectrometer covers the wavelength region 0.9–2.4 micron with a spectral resolution of 6 nm and spatial (pixel) resolution of ~80 m. MMM is a high throughput push broom imaging spectrometer operating in 0.7–3.0 micron range with high spatial (70 m per pixel) and spectral (10 nm) resolution. Intracalibration of the three instruments will be carried out in the overlap wavelength region from 700 to 950 nm. The flight models of these three payloads and the other eight payloads are shown in Figure 3.

C1XS

The Chandrayaan-1 X-ray Spectrometer (C1XS; Figure 3) is a collimated low energy (1–10 keV) X-ray spectrometer that employs a swept-charge X-ray detector (SCD) and has a field of view of ~25 km. It will detect fluorescence X-rays, characteristic of elements (magnesium to iron) on the lunar surface, produced by incident X-rays from the Sun during solar flares and allow direct determination of lunar surface abundances of the elements, Mg, Al and Si and also of Ca, Ti and Fe during major solar flares. An X-ray solar monitor (XSM) will provide data on the incident solar X-ray flux necessary for estimation of the elemental abundances.

HEX

The High-Energy X-γ ray Spectrometer (HEX; Figure 3) will use solid-state pixilated cadmium–zinc–telluride (CZT) arrays for detecting energetic photons in the energy range 30–270 keV from the lunar surface. An anti-coincidence system consisting of CsI(Tl) scintillator coupled with two PMTs is positioned below the CZT detector arrays to minimize the background events. A stainless steel collimator is mounted above the CZT arrays to limit the FOV to a 33 km × 33 km area on the lunar surface from the 100 km orbit of Chandrayaan-1. HEX is primarily intended for the study of volatile transport on Moon using the 46.5 keV γ ray line from ^{210}Pb (a decay product of volatile ^{222}Rn) as tracer. HEX will make the first attempt to detect low energy (<300 keV) γ rays from a planetary surface.

TMC, LLRI

The Terrain Mapping Camera (TMC; Figure 3) in the 500–850 nm band hosts three linear array detectors for nadir, fore and aft viewing and will have a swath of 20 km. TMC will provide 3D images of the lunar surface

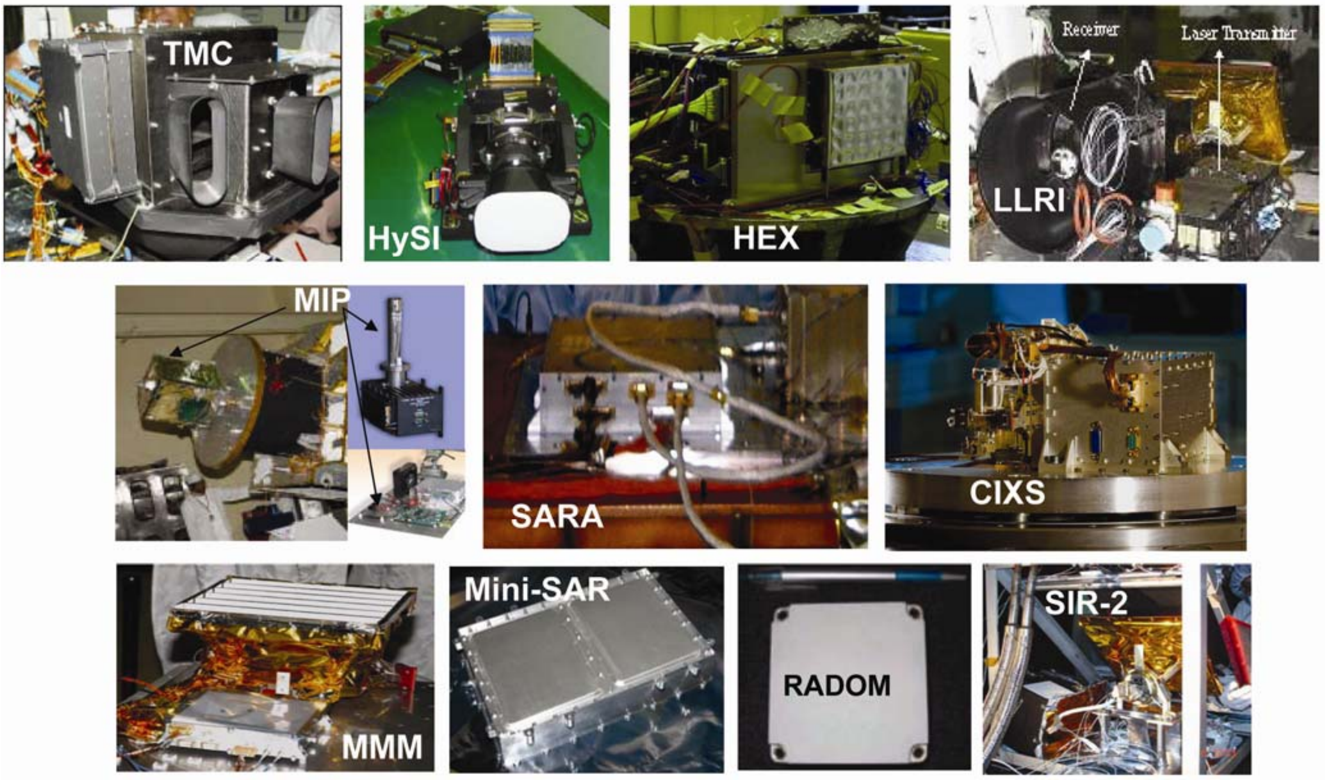

Figure 3. Flight model of the eleven payloads on board Chandrayaan-1. Four of the Indian payloads (TMC, HySI, HEX and LLRI) are displayed on the top panel; the middle panel displays the Moon Impact Probe and two of the instruments on it along with two AO payloads (C1XS and SARA from ESA) that have significant Indian collaborations. The four payloads shown in the lower panel are AO payloads provided by NASA (Mini-SAR, MMM), ESA (SIR-2) and BSA (RADOM).

with a ground resolution of 5 m with base to height ratio of one that will be used to generate topographic map of the Moon. The Lunar Laser Ranging Instrument (LLRI) employs an Nd–Yag laser with energy 10 mJ and has a 20 cm optics receiver. It will be operating at 10 Hz (5 ns pulse) and will provide a height resolution better than 5 m. Data from LLRI will provide accurate lunar altimetry with focus on the polar region, and the data will be used to generate a quantitative lunar gravity model.

Mini-SAR

The multi-function Mini-SAR (Figure 3), consisting of synthetic aperture radar, altimeter, scatterometer and radiometer, will be operating at 2.5 GHz. This instrument will probe the permanently shadowed areas near lunar poles to look for signature of water ice mixed within the top meter of the lunar surface material. Mini-SAR will transmit Right Circular Polarization (RCP) and receive both Left Circular Polarization (LCP) and RCP, and utilizes a unique hybrid polarization architecture, which allows determination of the Stokes parameters of the reflected signal to infer possible presence of water ice. The SAR system has a pixel resolution of 150 m and 8 km swath. This will be the first systematic approach to look for water ice in the lunar polar region.

SARA

The SARA payload (Figure 3) consists of two packages, the Chandrayaan-1 Low Energy Neutral Atom (CENA), and the Solar Wind Monitor (SWIM). CENA detects solar wind sputtered low energy (10 eV–2 keV) neutral atoms from the lunar surface and can broadly resolve H, O, Na–Mg, K–Ca groups and Fe atoms, and represents first such study in planetary context. SWIM is an ion mass analyser for determining energy and mass of the incident solar wind ions. SARA will study the solar wind–planetary surface interaction via measurements of the sputtered atoms and neutralized back-scattered solar wind hydrogen. SARA will image the lunar surface magnetic anomalies and also provide elemental surface composition including that of permanently shadowed areas.

RADOM

The miniature (98 g 100 mW) Radiation Dose Monitor (RADOM; Figure 3) uses a single 0.3 mm thick small area (2 cm^2) silicon detector and measure the deposited energy from primary and secondary particles of solar and galactic in origin using a 256 channel pulse analyser. The deposited energy spectrum can then be converted to deposited dose and flux of charged particles incident on the silicon detector.

MIP

The Moon Impact Probe (MIP; Figure 3) will be released at the beginning of the mission, after the spacecraft reach the designated 100 km lunar polar orbit. Its planned path will fly over the Malapert Mountain and the impact point will be close to the lunar South Pole. MIP will carry a moon imaging system for surface photography along its path in addition to a radar altimeter and an extremely sensitive mass spectrometer to detect possible presence of trace gases in the lunar exosphere.

The Spacecraft

The Chandrayaan-1 spacecraft design is adapted from flight proven Indian Remote Sensing (IRS) Satellite bus. Apart from the solar array, TTC and data transmission, that are specific to the lunar mission, other aspects of system design have flight heritage. Some changes specific to the mission such as extending the thrust cylinder and having an upper payload deck to accommodate MIP and other payloads have been implemented. Chandrayaan-1 will have a canted solar array since the orbit around the moon is inertially fixed, resulting in large variation in solar incidence angle. A gimbaled high gain antenna system will be employed for downloading the payload data to the Indian Deep Space Network (IDSN) established near Bangalore. The spacecraft is cuboid in shape of approximately 1.5 m side (Figures 1 and 2), with a liftoff mass of ~1300 kg with the bus elements accounting for ~400 kg, payload ~90 kg and propellant ~800 kg; the mass after reaching lunar orbit will be ~600 kg. It is a three-axis stabilized spacecraft generating about 750 W of peak power using the solar array and will be supported by a Li–ion battery for eclipse operations. The spacecraft adopted bipropellant system to carry it from the elliptical transfer orbits through lunar transfer orbit and finally in the designated 100 km lunar polar orbit, and for orbit and attitude maintenance in lunar orbit. The TTC communication would be in the S-band. The scientific payload data will be stored in two solid state recorders (SSR#1 & #2) and subsequently played back and down-linked in X-band through 20 MHz bandwidth by a steerable antenna pointing at IDSN.

Lunar observation plans

The varying solar illumination of the lunar surface dictates the operation of the imaging instruments (TMC, HySI, MMM, SIR-2) to within ±60° latitude during two prime imaging seasons, each of 60 days, in a given year. During intervening non-prime imaging seasons, 60° to 90° of North/South polar region will be covered to complete the coverage of the entire moon during the two-year mission. Mini-SAR polar imaging is planned during non-imaging seasons. Data from the imaging instruments and the mini-SAR will be stored in SSR#1 for subsequent transmission to ground. RADOM, LLRI, SARA and the two X-ray payloads will be kept 'ON' continuously and a second SSR (#2) will record data from these instruments. Two ground terminals (18 m and 32 m antenna), established at the IDSN provide communication link for the Chandrayaan-1 mission. The 18 m terminal was tested during SMART-1 EOL mission and other ongoing planetary missions and the newly built indigenous 32 m antenna (Figure 4) has undergone extensive tests and will support not only the Chandrayaan-1 mission but also proposed future Indian planetary missions to other inner solar system objects. The raw data along with auxiliary data will be stored at the newly commissioned Indian Space Science Data Centre (ISSDC), also set up at the ISDN site, for processing and archiving. It will be the focal point for Chandrayaan-1 science team. ISSDC will house and archive data from all future Indian space science missions.

Mission sequence

The Chandrayaan-1 spacecraft was launched on 22 October 2008 using a variant of the flight proven indigenous Polar Satellite Launch Vehicle (PSLV-XL) and injected into a 255 km × 22,860 km orbit. After separation from the launcher, the solar panel was deployed and the spacecraft raised to moon rendezvous orbit by five consecutive in-plane perigee manoeuvres to achieve the required 386,000 km apogee that placed it in a lunar transfer

Figure 4. The 32 m Indian Deep Space Network antenna with the Moon in the background.

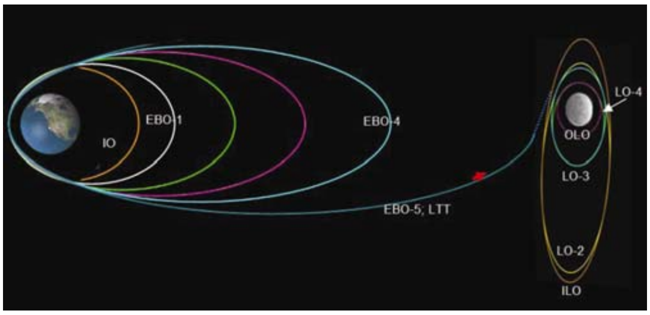

Figure 5. A schematic view (not to scale) of the Chandrayaan-1 mission profile. The spacecraft placed in the initial orbit (IO) by PSLV-XL was followed by five consecutive in-plane perigee manoeuvres in earth bound orbits (EBO) to place it in the lunar transfer trajectory (LTT). The next major manoeuvre, lunar orbit insertion, led to lunar capture in an elliptical initial lunar orbit (ILO). Four further orbit manoeuvres in lunar space placed the spacecraft in the operational lunar orbit (OLO) around the pole at 100 km altitude.

trajectory. The major manoeuvre, lunar orbit insertion leading to lunar capture, was executed to place the spacecraft in an elliptical (500 km × 7500 km) polar orbit. After checks of various spacecraft sub-systems, three further orbit manoeuvres were conducted to place the spacecraft at the designated 100 km circular polar orbit. The mission profile and the various orbit manoeuvres are schematically shown in Figure 5.

Commissioning of the payloads

The RADOM was switched on soon after launch of the Chandrayaan-1 to monitor the energetic particle fluence during the multiple passages of the spacecraft through the earth's radiation belts. The TMC was commissioned while the spacecraft was in earth bound orbit for tests and capture images of the Earth and the Moon. The MIP was released once the spacecraft was placed in its designated lunar polar orbit. All the other instruments are sequentially commissioned within a couple of weeks following MIP release.

Project management

Chandrayaan-1 is carrying eleven scientific instruments from an equal number of institutions. Accommodation of these instruments and meeting their stringent technical requirements in a small satellite bus was a challenging task. The difficulty and complexity of the task was further accentuated by the varying approaches in the design and development of the instruments at various Indian and foreign laboratories. Nevertheless, Chandrayaan-1 provided ISRO with a unique opportunity to demonstrate true international cooperation in the field of planetary exploration in general, and of lunar exploration, in particular.