Scientific challenges of CHANDRAYAAN-1: The Indian lunar polar orbiter mission

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The Indian Space Research Organisation is planning to send a polar orbiting satellite called CHANDRAYAAN-1 to the Moon, for remote sensing of the lunar surface. The scientific objectives of the proposed mission are simultaneous geochemical, mineralogical and photogeological studies of the whole lunar surface. The payloads include hyperspectral imager for mineralogical mapping, X-ray fluorescence spectrometer for elemental mapping, low energy gamma-ray spectrometer for mapping some radioactive elements, a terrain mapping camera and a laser altimeter, leaving a provision for some additional instruments, which may enhance the capability of this mission in achieving its objectives. A plausible launch scenario using the Polar Satellite Launch Vehicle (PSLV) suggests that a lunarcraft (dry weight 440 kg), carrying about 60 kg of payloads can be inserted in a 100 km altitude polar orbit around the Moon with adequate fuel (about 80 kg) for orbit maintenance to sustain it for two years of observations for complete coverage of the lunar surface. Here we describe the scientific reasons for undertaking such a mission and some of the major scientific challenges. The purpose of this article is to involve the scientific community of the country in formulating the best possible objectives and participating in the mission.

LABORATORY study of lunar samples brought back by APOLLO and LUNA missions and direct exploration of the Moon, particularly by CLEMENTINE and LUNAR PROSPECTOR missions carried out during the past century have provided a considerable amount of data which gave us an insight into the processes responsible for its formation and subsequent chemical and geological evolution. Based on the radiometric dating of a variety of lunar rocks and their chemical composition, some important stages in the chemical, physical and geological history of the Moon have been constructed. A synthesis of these results shows that impact of a giant (0.1 M_E), differentiated planetesimal on the Earth, followed by accumulation of impactor's crustal material and the impact generated terrestrial ejecta, thrown in a low circumterrestrial orbit led to the formation of the Moon[1]. The giant impact probably occurred early (4.56 to >4.46 b.y. ago) while the earth was still accreting but had already differentiated into core and mantle. This event occurred soon (within ~10^7–10^8 years) after the first solid grains started condensing from the cooling solar nebula, which are dated at 4.566 b.y. ago, considered to be the age of the solar system. Simulation of the giant impact and the processes that followed indicate that the ejected debris in the circumterrestrial orbit started accreting in a disk within a period of a day and the protomoon accreted from this disk within a period of weeks[2] after the impact. Major stages in early evolution of the Moon, after its accretion was complete, include formation of magma ocean (~ 4.53 b.y.), crustal differentiation and solidification (~ 4.4 b.y.), a delayed surge in large impacts leading to mare excavation (called the Late Heavy Bombardment, LHB, 4.26–3.86 b.y. ago, with a peak at 3.8–3.9 b.y.) and their subsequent filling due to volcanism during the first 1.5 billion years of the lunar history[3]. Some of these stages have been discussed in a previous article[4] and based on the information available, the major stages are summarized in Table 1 in a chronological sequence although there are some uncertainties in their absolute ages and time spans.

Although this general picture has emerged, several aspects of these events and processes responsible for them, remain uncertain. Size and composition of the lunar core, if it exists, and internal and bulk composition of the Moon, essential for modelling the formation of the Moon, are not accurately known[4,5]. Some isotopic data are not consistent with the values expected in high temperature fractionation expected due to the giant impact. Since the Earth formed by accreting planetesimals, it is reasonable to assume that a small fraction of them, depending on their orbital geometry, will be captured in geocentric orbits. The role of these ‘moonlets’, which might have been existing in circumterrestrial orbits when the giant impact took place, in accretion of the proto-Moon and subsequently in formation of large basins on the Moon is not fully understood. Furthermore, several aspects of

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Table 1. Geochronological history of major events on the Moon

Event	Time since present	Time since formation of the solar system
Formation of solar system	4.566 b.y.	0
Giant impact event resulting in formation of proto-Moon	~4.52 b.y.	15–50 m.y.
Formation of magma ocean on the Moon	4.53–4.4 b.y.	40–160 m.y.
Solidification of lunar crust	~4.4 b.y.	~160 m.y.
Impact craters on crust based on breccia ages	4.4–4.2 b.y.	150–350 m.y.
Late heavy bombardment resulting in young large basins	4.2–3.8 b.y.	350–750 m.y.
	(Peak 3.8–3.9 b.y.)	650–750 m.y.
Mare volcanism based on melt rock ages	3.8–3.1 b.y.	750–1500 m.y.
Comet and meteoritic impacts	Till present	

crustal inhomogeneity, particularly the mechanisms that gave rise to hemispheric asymmetry between the Earth-facing and the far side of the Moon are still a matter of debate. The depth to which the Moon melted during magma ocean formation, the rates of cooling and the mechanism of late heavy bombardment remain open questions. Existence of ice in the permanently shadowed lunar polar regions[6,7] has been a subject of intense interest and needs to be confirmed. Some areas on the Moon, such as the South Pole Aitken (SPA) basin[8], north and south polar regions appear to be of special interest requiring a more detailed study. These questions have been extensively debated recently[1,4,9]. Bhandari[4] has summarized the current knowledge of the Moon based on astronomical, physical, chemical, isotopic, geological and geochronological data and, to understand some of the outstanding questions, made a case for further exploration. Presently, therefore, there is a renewed interest in new missions for exploration of the Moon. SMART-I mission by the European Space Agency is already on its way to the Moon and several other missions, e.g. SELENE and LUNAR-A by Japan, and missions by USA and China, which might answer some of these questions are planned during this decade.

In view of these problems of considerable scientific interest, the Indian Space Research Organisation (ISRO) has examined the possibility of a series of missions which may orbit, land and return samples of the moon from some selected areas. The first mission, CHANDRAYAAN-1 is proposed to be a long duration (~2 years), low altitude (100 km), polar orbiter mission. It can complement, to some extent, the information which can be obtained from lunar landing and sample return missions, by providing a synoptic view of the Moon. Recent advances in sensor technology and planetary remote sensing techniques should enable us to obtain better spatial resolution and quality of data compared to the past missions. The proposed launch scenario, scientific objectives and payloads of this mission are briefly described here.

However, before describing the salient features of the CHANDRAYAAN-1 mission, it may be useful to focus on some key issues in lunar science which can be addressed by chemical, mineralogical and topographic mapping.

Key questions in lunar science

As has been mentioned above, the most enigmatic question about the Moon is its origin. After several decades of intense study of the Moon and its samples in the laboratory, it is now clear that the Earth acquired such a large satellite neither directly by condensation of the solar nebula in a binary planetary (Earth–Moon) system nor by fission of a fast rotating Earth, but by a rare chance coincidence of an impact of a large differentiated asteroid called ‘Theia’ on the infant Earth. Bulk composition of the Moon has been modelled with the experimental data available on various lunar rocks, but large uncertainty remains because its interior composition is not known. Precise bulk composition should enable us to determine the composition of the impactor(s) and probably their source regions in the solar system. The purpose of chemical mapping with high spatial resolution is to identify terrains having different chemical compositions and also to get stratigraphic variations based on study of deep material which may lie exposed on the surface. It is known that the central upland areas of large craters represent deep material. In addition, there are large basins, e.g. the South Pole Aitken basin which probably has deep crustal material or even upper mantle material excavated during the basin formation event, now lying at the surface. One way to identify the chemical stratigraphy of the crust is by measuring magnesium number (Mg/Mg + Fe), which can be easily accomplished by chemical mapping.

An important problem in crustal formation is the size of the magma ocean and its cooling rate. The crust is made of Ca–Al rich plagioclase and is poor in iron and other siderophile elements. The end member (highest Al and lowest Fe) composition can be used to infer the time taken by the crust to crystallize. This can also be determined by chemical mapping. The enrichment of refractories, relative to the Earth’s crust, is one of the important characteristics of lunar samples which may have clues about the processes responsible for formation of the Moon. Several other problems can be enumerated where high precision chemical mapping with good spatial resolution can provide useful insight, but one which is important from the point of mare formation is the composition of the basin-forming impactors, whose signatures can be found in brecciated rocks and ejecta around the large basins. The minerals formed on the Moon are largely products of primary differentiation or subsequent volcanic events. A simultaneous chemical and mineral mapping can constrain some of these early lunar processes. The main payloads for CHANDRAYAAN-1, i.e. Hyperspectral imager, X-ray fluorescence spectrometer and low energy gamma-ray spectrometer have been designed keeping these problems in view as will be discussed later.

Launch scenario

ISRO has two rockets available for launching satellites and spacecrafts: the Polar Satellite Launch Vehicle (PSLV) and the Geosynchronous Satellite Launch Vehicle (GSLV). PSLV is a well-tested rocket and has been used for several successful launches in the past five years. Recently, on 12 September 2002, PSLV-C4 successfully launched the METSAT spacecraft weighing 1050 kg in Geosynchronous Transfer Orbit (GTO) in a polar trajectory with an inclination of 18°, which is similar to the initial orbit proposed for CHANDRAYAAN-1. In view of its successful track record, PSLV is favoured as the carrier vehicle for the first Indian mission to the Moon. It is proposed to use a GTO–ETO (Earth Transfer Orbit), LTT (Lunar Transfer Trajectory) and LOI (Lunar Orbit Insertion) sequence to insert the lunarcraft in a 1000 km lunar capture orbit which will be subsequently brought down to 100 km altitude for prolonged observation of the lunar surface features. PSLV is capable of injecting 1050 kg satellite in ETO with perigee of 240 km and apogee of 36000 km. The lunar craft propulsion system, equipped with adequate quantity (610 kg) of propellant and a liquid engine of 440 N thrust capability, is used to carry out a series of critical orbit maneuvers like injecting from ETO into LTT, LOI maneuvers to capture the lunar craft in polar orbit around the moon, orbit acquisition maneuvers to attain 100 km altitude, circular orbit and further maintain the orbit altitude, nominally within 15 km over the mission life of two years. The mission profile[10,11] is shown in Figure 1.

Recently the GSLV had two successful test flights. It has significantly larger capability and can insert about 1560 kg into a geosynchronous transfer orbit (with perigee about 180 km and apogee of 36,000 km) and can place a heavier lunarcraft in the lunar orbit. For example, it can insert about 800 kg weight in a 100 km orbit around the Moon and therefore it may be better suited for a lunar sample return mission. Furthermore, it is also capable of launching space missions to Venus, Mars, asteroids and comets.

Science objectives and payloads

CHANDRAYAAN-1 is a remote sensing satellite for high resolution photogeological, chemical and mineralogical mapping of the Moon. It will contain several instruments which have been selected to meet these objectives considering the radiation environment of the Moon. The radia-

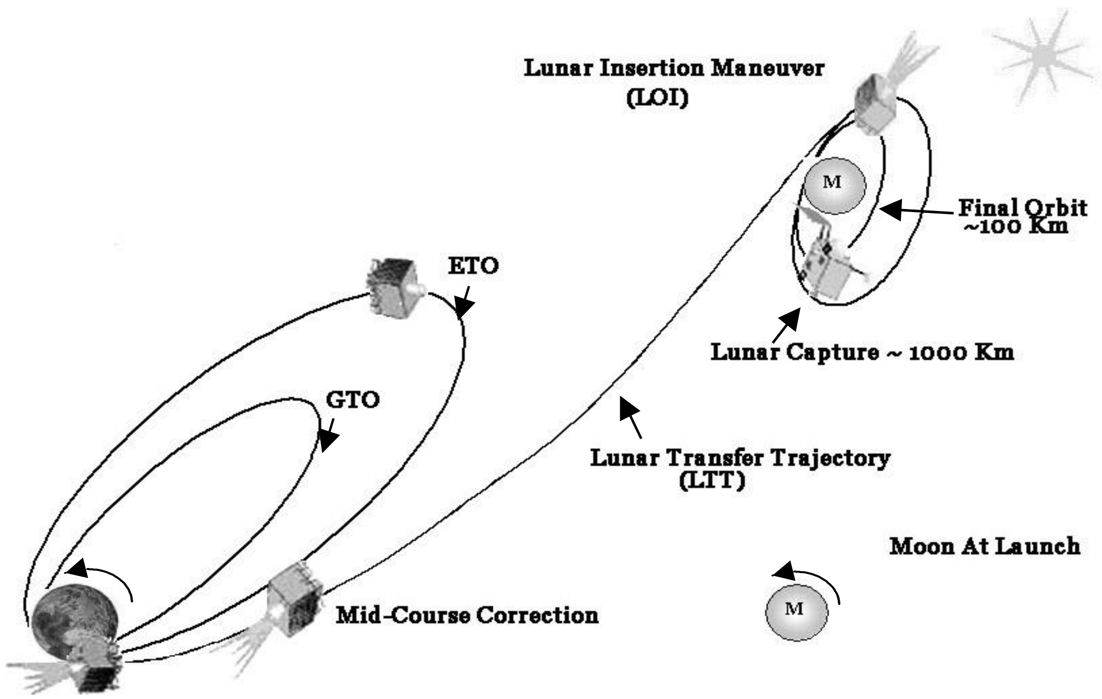

Figure 1. CHANDRAYAAN-1 mission profile[11] using Polar Satellite Launch Vehicle (after Adimurthy, priv. commun.).

tion and particles around the Moon arise either by processes inherently occurring in the Moon such as radioactive decay of naturally occurring or cosmic-ray produced radioisotopes (alpha particles, gamma rays, X-rays, etc.) or are induced by radiations from the Sun (visible, UV and X-rays) and solar and galactic cosmic rays. These solar and galactic particles, mainly protons and alpha particles, interact with the lunar surface materials and produce radiations (X-rays, gamma rays, neutrons for example) which have signatures of lunar surface chemistry. On the macroscopic scale, impacts of micrometeorites, asteroids and comet, covering a large range of sizes from microns to hundreds of kilometers sculpture the lunar surface and are responsible for the lunar surface topography and morphology. Taking advantage of these processes and considering the launch vehicle capabilities, various payloads of CHANDRAYAAN-1 have been proposed[10]. These instruments are briefly described below.

Geochemical mapping

Major element composition using X-ray fluorescence spectrometer. X-ray fluorescence is ideally suited for determining the major element composition of the lunar surface materials and therefore the geochemical mapping of elements like Mg, Al, Si, Ca, Ti, Fe, etc. is accomplished using Low Energy X-ray fluorescence spectrometer (LEX). These elements have characteristic K_a X-rays in the energy range of 1.25 keV to 6.4 keV and therefore the device has to be sensitive between < 1 and 10 keV. Adler *et al.*[12] first used this technique on Apollo missions for study of the lunar surface composition employing proportional counters and obtained some elemental ratios, e.g. of Si/Al around the lunar equatorial region. Detectors giving much superior spectral resolution have since been developed. Two options are currently available for detectors which can be used for measurement of concentration of elements mentioned above. A swept charge X-ray device, like the one developed for SMART-1 mission[13,14] is ideal for this purpose but a Charge Couple device (CCD) can also be used for this purpose. These devices are expected to have high spectral resolution (about 4% at 6 keV) that is sufficient to distinguish between nearby elements by resolving their K_a peaks. It has been est imated that a detector having an area of 50 cm^2 should enable us to obtain reasonable signal compared to the expected background. A collimator having a 5° field of view should provide a good spatial resolution of about 10 km.

The X-ray fluorescence flux from the Moon mainly depends on the X-ray fluxes incident on the Moon, their source being the Sun. X-ray and charged particle fluxes from the Sun show large time variability. The flare frequency and energy spectrum depend on the phase of the 11-year solar cycle and vary significantly between solar minima and solar maxima. During the quiet period, the energy may be adequate to produce fluorescence in only the low Z elements, e.g. Mg, Al and Si, whereas during active periods, when large energetic flares are produced, it may be possible, in addition, to measure concentrations of Ca, Ti, Fe, etc. It is therefore necessary to have a solar X-ray monitor on board to determine the energy spectrum of solar X-rays so that the composition of various elements can be computed from the fluorescence spectrum. For this purpose a Solar X-ray Monitor (SXM) consisting of two Si-pin diodes having a wide field of view (>90°), measuring X-rays of 2 to 10 keV has been included in the payloads. It is estimated that LEX will weigh between 5 and 8 kg consuming 15 to 25 watts of power and SXM (including the electronics and the cooling system) will weigh 3 kg consuming about 3 watts of power.

Measurement of some trace elements using a low energy gamma-ray spectrometer (HEX). Nuclear interactions of solar and galactic cosmic rays and their secondaries (including protons, alpha particles and neutrons) excite various elements present within about a metre of the lunar surface. De-excitation of these nuclides and decay of radioactive nuclides produced in their nuclear reactions result in characteristic gamma rays which can be used to infer the abundance of various nuclides. In addition, long-lived radioactive nuclides like K, U and Th (and their daughter products) which serve as the internal heat source of the moon, can be estimated by measuring the flux of their decay gamma rays. Some rare earth elements which occur at microgram levels but have high neutron capture cross-sections, like Gd and Sm can probably also be measured by their de-excitation radiation or decay gamma rays of their radioactive isotopes. Thus gamma-ray spectroscopy provides an important tool for determining abundances of certain elements, which cannot be determined by the X-ray fluorescence spectrometer described above. The two instruments are thus complementary to each other.

Gamma-ray spectroscopy was first used by Metzger *et al.*[15] on the APOLLO missions using NaI(Tl) scintillator, and maps of radioactive elements like K and Th around the equatorial belt of the Moon were thus obtained. More recently, Lawrence *et al.*[16] have measured the gamma-ray spectra above about 200 keV using a BGO (bismuth germanate) detector with suitable active anticoincidence system on the LUNAR PROSPECTOR mission. They have produced chemical maps of several elements with superior resolution for the whole lunar surface.

The low energy gamma rays (10 keV to 200 keV), however, have not yet been measured. The main difficulty in measurement of this low energy region is the high detector background in space, mainly due to Compton scattering. This region contains several interesting lines from radioactive elements like Th, ^{222}Rn, ^{210}Pb and some rare earth elements which are of interest from the point of

Table 2. Low energy (10–200 keV) gamma-ray fluxes from various lunar terrain types and expected detector background*

	Nuclides	Energy keV	Flux at lunar surface (photons/cm^2 min) KREEP	High Al basalt	Crust	Counts per sec (for 100 cm^2) KREEP	High Al basalt	Crust	Estimated background Cps/keV	CdZnTe interferences
U	^{210}Pb$^{\#}$	46.5	0.167	0.029	0.012	0.340	0.060	0.020	0.121	–
Th, U	^{228}Ra, ^{228}Th, ^{231}Th	84.2–84.4	0.290	0.060	0.025	0.551	0.114	0.048	0.106	–
Th, U	^{228}Ra, ^{234}Th, ^{228}Ac, ^{231}Th	89.9–93.4	0.610	0.110	0.045	1.122	0.202	0.083	0.104	^{67}Ga, ^{67}Cu
Th	^{228}Ac, ^{228}Ra, ^{232}Th	129.1	0.200	0.040	0.020	0.260	0.052	0.026	0.089	–
U	^{226}Ra, ^{235}U	185.7–186.0	0.810	0.140	0.060	0.292	0.050	0.022	0.066	^{67}Ga, ^{67}Cu, ^{114}In, ^{125}In
Gd	^{153}Gd	97.4	0.050	0.010	0.003	0.085	0.017	0.004	0.101	^{67}Ga, ^{67}Cu, ^{120}In
Gd	^{157}Gd (*n*, *ã*)	181.9	0.050	0.010	0.003	0.020	0.004	0.001	0.068	^{67}Ga, ^{67}Cu, ^{114}In, ^{125}In
Sm	^{153}Sm, ^{155}Sm	103.2–104.3	0.060	0.010	0.004	0.098	0.016	0.007	0.099	^{124}In

*From Bhandari and Banerjee[17].

$^{\#210}$Pb has three components as discussed in the text. Only the flux from *in situ* production due to decay of U series nuclides is given here.

view of lunar surface chemistry as well as for understanding processes responsible for transport of volatiles in the lunar atmosphere. Th and U daughters (^{228}Ra, ^{228}Th and ^{231}Th) will give a broad peak at 84.2–84.4 keV, whereas ^{228}Ra, ^{234}Th, ^{228}Ac and ^{231}Th should give a broad peak between 89.9 and 93.4 keV. A peak at 129.1 keV is produced by some Th daughter nuclides and at 185.7–186 keV by ^{226}Ra and ^{235}U. Some of these lines are listed in Table 2. With the recent development of several new solid state detectors, such as hyperpure germanium and cadmium zinc telluride (CZT), it seems possible now to make these measurements. The germanium detector, having reliable heritage and superiority in resolution and performance, requires cooling below 100 K. In view of the challenging design and development aspects of cooling of the germanium detector and considering the weight and power constraints, CZT has been preferred for the CHANDRAYAAN-1 mission. The instrument (HEX) will consist of a collimated 100 cm^2 array of CZT chips with a CsI scintillator as a veto device to reduce the cosmic-ray background. A field of view of 10° should be optimum for a good signal-to-background ratio with a desirable spatial resolution of about 20 km.

Bhandari *et al.*[11,17] have estimated the flux of some of the lines expected at 100 km for a detector with 100 cm^2 area, following the procedure of Reedy[18]. The calculations show that some of these lines will be comparable to the background, particularly in the radioactive surface materials like KREEP and high aluminum basalts. However, CZT detector itself produces certain lines due to cosmic-ray interactions. These are also listed in Table 2. They however do not fall in the region of our interest and therefore do not produce any serious interference.

Study of volatile transport on the lunar surface using radon as a tracer. Radon is a gaseous daughter of uranium (Figure 2) and escapes from the lunar interior by thermal diffusion or leaks through cracks, fractures and faults. Seismic activity and micrometeorite impacts may also help radon atoms to collect in small bubbles and escape from the lunar interior together with other gases like He, Ar, CO_2, N_2 which have significant inventories on the Moon[19]. The melting point of radon is –71°C and its boiling point is –61.8°C. Because of large temperature variation on the lunar surface and the interior which may range between –170°C and +130°C, radon can occur as solid, liquid or gas depending on phase of the day, depth and location. Although it has a short half life (3.8 days) and there is a competition between decay and escape, significant amounts of radon (and other gases) are expected to escape from the hot sunlit side and some special regions of the Moon which have been observed to exhibit Lunar Transient Phenomena (LTP). Radon decays by alpha emission (5.48 MeV) and many of its radioactive daughters also emit alpha particles. These nuclei produced in the lunar atmosphere follow a ballistic trajectory. Two nuclides are of interest here, ^{210}Pb and ^{210}Po. ^{210}Pb has a half life of 22.4 years and emits 46.5 keV gamma ray whereas 138-day ^{210}Po emits an alpha particle of 5.33 MeV. These nuclides can be used as tracers for understanding the transport of radon and hence other volatiles on the Moon. The relative amounts of ^{222}Rn : ^{210}Pb : ^{210}Po may enable us to understand the past history (for about 60 years) of degassing of local areas on the moon. Three cases may arise: (i) steady rate release of radon will result in a typical ^{222}Rn/^{210}Pb or ^{222}Rn/^{210}Po ratio, determined by the escape rate of radon. (ii) abrupt release of radon (followed by a steady state release) will result in excess radon to ^{210}Pb or ^{210}Po ratio for a few weeks compared to the value expected in case (i). (iii) Abrupt release of radon will result in low radon to ^{210}Pb or ^{210}Po ratio after a period of a few weeks to a few decades compared to the value expected in case (i).

Measurements of ^{222}Rn and ^{210}Po by alpha spectrometers on SURVEYOR landers and APOLLO orbiters and study of ^{222}Rn and ^{210}Pb in lunar rocks and soils[20,21] suggest that their concentrations are spatially and temporally variable. Turkevich *et al.*[21] found ^{210}Po in excess over

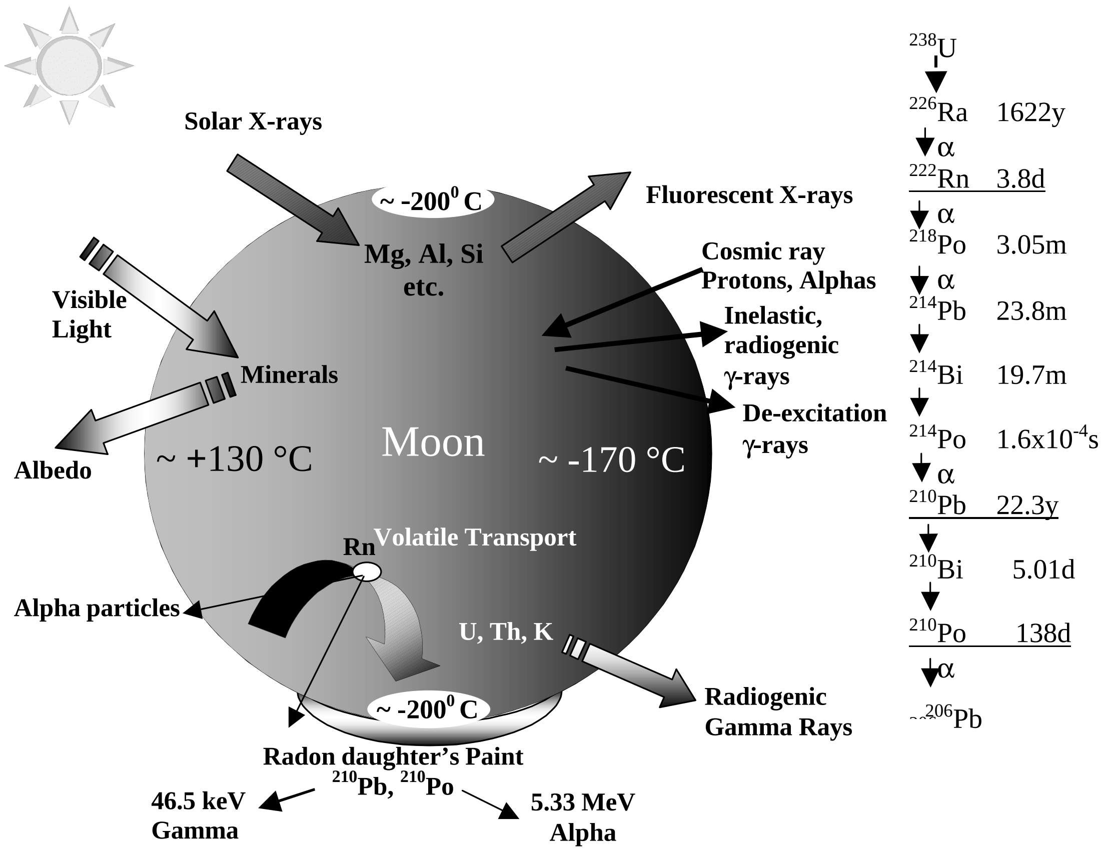

Figure 2. Radiation environment of the Moon produced by solar radiation and solar and galactic cosmic rays. The reflectance spectrum is useful for mineral identification, the fluorescent X-ray spectrum and solar and galactic cosmic-ray produced gamma radiation for chemical mapping, and radiogenic gamma and alpha particle spectrum for mapping of radioactive nuclides (U, Th, K, etc.) and in understanding the leakage of radon from the lunar interior and its transport on the lunar surface. The uranium decay chain which produces ^{222}Rn and its daughters, forming a thin 'paint' on the lunar surface are shown on the right. The temperature regimes on the sunlit and night side of the Moon and the permanently shadowed cold polar regions are shown schematically.

^{222}Rn at SURVEYOR 5 site and Gorenstein *et al.*[20] found that the edges of several lunar maria, as also the crater Aristarchus, showed higher concentration of radon over its surroundings. Its excess in maria edges, the most dramatic being Mare Fecunditatis, is attributed to radon emanation from dark haloed craters. On the other hand, Lindstrom *et al.*[22] did not find any excess of ^{210}Pb in the topmost lunar soil core layer and concluded that the diffusion coefficient of radon in lunar soil is $< 3 \times 10^{-8}$ cm^2/s.

In case of alpha spectrometer, the background is largely due to backscatter solar alpha particles which depends significantly on the solar alpha particle fluxes and, in turn, on the phase of the solar cycle and active periods when large particle flares are produced. Therefore, for CHANDRAYAAN-1 mission, we are considering a low energy gamma-ray detector, which should be able to measure the 46.5 keV gamma ray of ^{210}Pb. The advantage with the alpha spectrometer is that the concentration of the parent–daughter pair of ^{222}Rn and ^{210}Po can be simultaneously measured. Laboratory experiments are underway to assess the relative merits of alpha and gamma-ray spectrometer for determining relative amounts of radon and its daughters.

Mineral mapping

Minerals present on the lunar surface provide an insight into the melting, differentiation, crystallization and volcanic history of the lunar surface and also give us some idea of the time scales on which these processes occurred. It can, for example, give information on extent of magma ocean and crustal formation processes. The minerals also bear signatures of the material from which the Moon was formed and together with their chemical composition, enable us to model the differentiation sequence. In addition, these studies also throw light on various geological units, impact-derived stratigraphy and composition of the lower lunar crust, which may be exposed in certain areas. Major rock types on Moon are anorthosite, Kreep basalt, ferroanorthosite, norite, gabbronorite and troctolite on the highlands and high and low Ti basalts and high Al basalts in mares. The study of lunar minerals has been done in the past by earth-based observations, GALILEO fly-by, APOLLO landers, laboratory studies of lunar samples and CLEMENTINE orbiter. The highland areas are known to contain dominantly Ca-rich plagioclase and the mares primarily contain iron-bearing olivine, high Ca pyroxene and opaques (mainly ilmenite and spinels). Spectroscopy of the light reflected from the surface provides a clue to the minerals present.

Figure 3 shows typical spectra of some minerals in wavelength range of 400 to 2600 nm[8,23]. Olivine and pyroxene can be identified by iron absorption feature around 1000 nm. Olivine shows multiple absorption bands and pyroxene shows a simple absorption band whereas plagioclase shows a broad dip between 900 and 1600 nm, centered around 1200 nm (Figure 3). The reflectance spectrum obtained from the lunar surface depends upon grain size, viewing geometry, maturity, temperature, etc. Composite mixtures of minerals which occur everywhere on the Moon and shadow zones make the spectrum very complicated. CLEMENTINE has provided lunar mineral maps with a resolution of ~ 120 m using a multispectral camera having discrete spectral band at 415, 750, 900, 950 and 1000 nm. Hyperspectral observations in the VIS-NIR region are better-suited for mineral studies and for CHANDRAYAAN-1, it is proposed to obtain the spectra with a wedge filter camera. Wedge filter is an interference filter with varying thickness along one dimension which provides the reflectance spectrum covering the spectral range of 400 to 900 nm storing it in 32 programmable channels, covering the spectral range of interest with maximum resolution of 15 nm. The different pixels of this area array detector in a row receive irradiance from the same spectral region but different spatial regions whereas different rows of the detector will receive irradiance of different spectral and spatial regions. The full spectrum of the target area is obtained by acquiring image data in push-broom mode as the satellite moves along the column direction of the detector. The swath of the detector, located 100 km above the lunar surface, is 40 km. The instrument can be built within the weight limit of ~8 kg and its power requirement is 15 W. It is expected to provide a spatial resolution of 80 m. It may be useful to extend the spectral region to 1700 nm or beyond to 2600 nm, to cover important absorption bands. The abundance of various minerals, specially pyroxene and plagioclase, can thus be quantitatively estimated from the shape of the composite curve obtained by visible and NIR spectrometers.

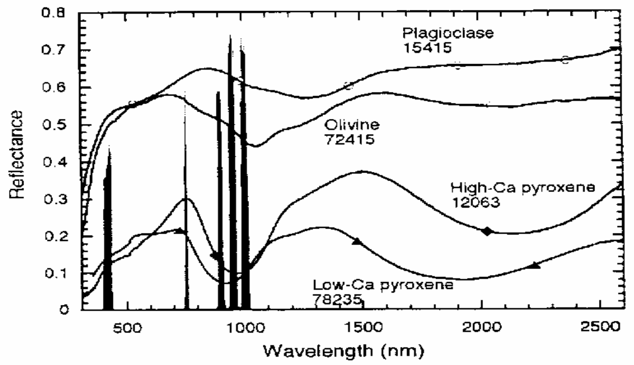

Figure 3. Reflectance spectra of some typical lunar minerals based on laboratory study of lunar rocks[8]. The band positions used for the CLEMENTINE mission are shaded[23].

To determine the abundances of different minerals from the reflectance spectra of a target area is a complicated problem and requires, not only determination of corrections due to variation of various physical parameters like grain size, maturity, temperature, etc., but also a library of spectra for comparison. However together with the chemical data obtained by fluorescence spectrometer (LEX), it should be possible to get an internally consistent chemical and mineralogical map of the lunar surface.

There are areas exposed on the lunar surface which have signatures of the lower crust, excavated by large and deep impacts early in the lunar history. Based on the CLEMENTINE data, Pieters *et al.*[8] have studied the South Pole Aitken basin, which is the largest impact basin (~2500 km diameter and ~12 km deep) known in the solar system. In this basin an 'Olivine Hill' has been identified which contains the lower crust or upper mantle material[8]. In addition, the Bhabha (diameter, 64 km) and Bose (91 km) craters probably also contain deep-seated material. The other areas of interest are the central uplands of large craters where the lunar interior is exposed. They are small in size and therefore we need instruments with high spatial resolution so that their mineral and chemical composition can be determined.

Topographic mapping

The information obtained from chemical, radioactive and mineral mapping has to be superimposed on a topographic map to identify the areas of interest. Therefore a Terrain mapping camera has been included in CHANDRAYAAN-1 mission as one of the payloads. Three-dimensional topographic mapping of the lunar surface will enable us to study the geomorphological features of the lunar surface and correlate them with chemical and mineralogical features. These primarily include physical components of the craters such as crater rim, central hill, secondary craters, ejecta blanket, etc. In addition to these, other features of interest include fault scarps, sinuous rilles, terminus of individual lava flows, the edges of mares and the regions that show the transient lunar phenomena (TLP).

The terrain-mapping camera is a stereo camera meant for systematic imaging to generate a high-resolution cartographic map of the lunar surface. The instrument is designed as a compact single optic push broom camera with the focal length of 14 cm. It has three linear array detectors (Active Pixel Sensors with 8000 linear elements) which are parallel to each other, placed at the focal plane of the lens for nadir, fore and aft viewing. The fore and aft camera look angle with respect to nadir is about ± 19.4°. Although in principle two images of the same area are required to find out the parallax and estimate the height, because of the oblique view, occlusion occurs and hence the parallax extraction becomes difficult. This is more serious for highly undulating terrain, as is the case for the Moon. The problem of occlusion can be overcome by obtaining three images of a given area namely fore, aft and nadir. Thus three cameras will ensure full coverage of the terrain and height to be determined with good precision.

A ground resolution of 5 m (from 100 km orbit) can be achieved by the camera. It should be possible to obtain the elevation to an accuracy of 5 to 10 m. The weight of the camera is expected to be 7 kg and power required is 20 W. Spatial resolution of about 5 m is sufficient to find out the size distribution of meter size impactors from crater counts on the freshly created surfaces. On the other hand, crater size distribution should enable us to identify freshly created surfaces by recent volcanism.

It is proposed to cover the whole lunar surface with TMC, HySI, LEX and HEX during the 2-year life of the lunarcraft. There are several difficulties in obtaining a good coverage all over the Moon because of poor lighting conditions in the polar regions and different ground coverage of various instruments. Some areas around the north and south poles are under permanent shadow and the sunlight does not reach these regions, they are also expected to contain most of the lunar volatiles and possibly water-ice. An imaging strategy, with suitable changes in ground resolution, has therefore to be followed to get maximum information from CHANDRAYAAN-1.

It may be recalled that the expected ground coverage are LEX (~10 km), HEX (~20 km), and HySI and TMC (40 km). The 100 km orbit chosen for surface mapping provides ground distance of 32 km between consecutive paths at the lunar equator. In order to cover the lunar surface with HySI and TMC, a year is divided into four imaging seasons, two primary seasons covering 60°N to 60°S, and two secondary seasons covering 30° latitude around the poles. If solar aspect angle of 30° at the lunar equator is acceptable, then the minimum time required to cover all the longitudes at the equator is estimated to be 20 months. However, since the ground coverage of LEX and HEX is smaller, it is proposed to displace the lunarcraft by 10 km after every prime imaging season to get a complete coverage of the Moon by these two instruments. In view of the repeated path of the lunarcraft over the lunar poles, they will have multiple coverage but because of poor lighting conditions, only coarse resolution imaging may be possible.

Laser ranging. The altitude of the lunarcraft will be continuously changing due to variation of the gravitational potential field of the Moon. Most mares are known to have MASCONS (high density mass concentrations), resulting in large changes in lunarcraft altitude as it orbits above these areas, requiring correction in its orbit to avoid crash on the lunar surface. Using the LUNAR PROSPECTOR gravity model (JGL165P1), it has been estimated that the altitude of CHANDRAYAAN-1 can be maintained between 85 and 115 km if an orbit correction is made every four weeks or so. Even with this restricted change in altitude, the ground resolution and ground coverage will change significantly, requiring significant corrections in the LEX, HEX, HySI and TMC data. To make appropriate corrections, the altitude information is required with high accuracy. For this purpose, a Lunar Laser Ranging Instrument (LLRI) has been included as a payload.

This laser altimeter consists of two principal components: the transmitter and receiver subsystems. The transmitter subsystem is composed of a diode pumped Nd : YAG laser source (1064 nm) which transmits a 10 ns wide pulse, with repetition rate of 1 Hz. The divergence of the laser beam and hence the size of the footprint on the ground is determined by a beam expander telescope.

The receiver subsystem includes a telescope (150 mm diameter, f/10) for collecting the returned photons. The photons after entering the telescope are allowed to fall on silicon avalanche photodiodes (Si APD) detector. Suitable electronics is provided for ranging and analysis of the wave form. The weight of the payload is expected to be ~3.5 to 5 kg and it requires about 8 W of power for its operation.

The laser as such can provide accurate height information but because of the change of lunarcraft altitude, due to gravity variations, elevation information of various lunar features cannot be accurately determined. The assembly is expected to provide a vertical resolution of better than 10 m with some limitations. It is expected that a digital elevation map of the lunar surface and better gravity model of the Moon can be constructed with these data.

Configuration of various instruments are listed in Table 3. In addition to these instruments, there is a provision of about 10 kg and 10 W of power for additional instruments, which may integrate with the objectives of CHANDRAYAAN-1. As mentioned above, it may be useful to include a UV imaging system or a near infrared sensor which will extend the wavelength range covered by HySI and may enable better identification of various minerals present on the lunar surface. A radar may also enable us to look below the surface for ice and other components and may be a suitable addition to the CHANDRAYAAN-1 payload.

Development of these payloads is a challenging problem of the CHANDRAYAAN-1 mission. It involves a comparative study of the available detectors suitable for the experiment and selection of the best detector based on its response function, heritage, degradation in space due to

Table 3. CHANDRAYAAN-1 Payload configuration

Payload	Configuration	Range	Resolution	Objective
Hyper Spectral Imager (HySI)	Wedge filter pixilated image	0.4–0.9 μm	Spatial – 80 m Spectral-15 nm 32 channels	Mineralogical mapping
Terrain Mapping Camera (TMC)	Three stereo cameras with pixilated imagers	Panchromatic (40 km swath)	Spatial – 8 m Vertical – 5 m	To prepare a high resolution atlas of the whole Moon
Laser Ranging (LLRI)	Pulsed Nd–Yag laser	1064 nm	Vertical – 10 m or better	Gravity model and topography
Low Energy X-ray spectrometer (LEX)	X-ray CCD or SCXD type detector 50 cm^2 area	0.5–10 keV	10–20 km	Elemental mapping Si, Al, Mg, Ca, Fe, Ti
High energy X-ray spectrometer (HEX)	CdZnTe detector 100 cm^2 area	10–200 keV	18 km	^{210}Pb, radon degassing, U, Th
Solar X-ray Monitor (SXM)	Si-Pin diode 2 or 3 detectors to provide complete sun coverage	2–10 keV	–	Solar X-ray flux monitoring

thermal variations, radiation, solar flares, solar wind effects, etc. For determining radiation effects, laboratory studies involving protons, neutrons and gamma rays have to be conducted in various particle accelerator facilities available in the country (e.g. Variable Energy Cyclotron, Pelletron, nuclear reactors, etc.). Their response function has to be determined in the laboratory, based on their efficiency, background level, interferences, etc. and their performance based on illumination angle, shadow effects, viewing and collimation geometry, topographic effects, etc. has to be understood. An imaging strategy and schedule for transmission of data have been worked out which will allow a complete coverage of the Moon. The effects of grain size variation of lunar surface materials, their maturity and space weathering effects have to be quantified. A library of database has to be built and suitable algorithms have to be developed. Once all these parameters are quantified, instrument testing and their data acquisition capabilities based on possible balloon flights for some of them in the Earth's atmosphere and space worthiness have to be established. Lonar impact crater in Maharashtra is a good target area for testing various instruments as described below. For each instrument, an in-flight strategy of operation has to be formulated. Once the mission becomes operational, there is the equally difficult aspect of data acquisition, conversion in a usable form, interfacing between various users and comparative study with data available from other missions which are necessary for a proper interpretation. A testing and calibration protocol for various lunar terrain types for each instrument described above will therefore be useful. This discussion is not meant to be exhaustive and its purpose is merely to point out that extensive laboratory studies are required for this mission.

Relevance of Lonar and Ramgarh impact craters

For field testing of various instruments, designed for CHANDRAYAAN-1, the most useful structures in India are the Lonar and Ramgarh craters. Lonar, located in Buldana district of Maharashtra is the only impact crater on Earth which is formed in a basaltic terrain, similar to lunar mare regions. It has a diameter of 1.8 km and depth of 130–150 m. The present crater rim stands 20 m above the surrounding area. It is dated to be about 50 ka old[24,25], although there is some uncertainty. Because of its young age and low erosion, the crater morphological features like crater rim and ejecta material are relatively well preserved. It is ideal for testing some payloads of CHANDRAYAAN-1 (e.g. TMC, LLRI and HySI) using an airborne platform.

The Ramgarh crater is 4 km in diameter and 250 m high, located in Baran district of Rajasthan[26]. In spite of some uncertainties, there are evidences that it is an impact crater. It is thus another good crater analogue for testing the CHANDRAYAAN-1 instruments. In order to compare the instrumental data, specially LLRI, a high resolution topographic mapping of these craters is required.

Areas of special interest

Apart from a general study of the whole lunar surface, it is recognized that some areas are of special interest particularly on the far side of the Moon and the polar regions which are under permanent shadow, where temperatures can be as low as –230°C. Specifically, the South Pole Aitken Basin (SPA), north and south poles, some aspects of which have been discussed above, deserve detailed study. The SPA is one of the oldest basins (> 4.2 b.y.) on Moon and the largest in the solar system. It has anomalous depth to diameter ratio and its origin is being intensely debated. It is possible that it was formed by impact of a moonlet in a geocentric orbit as the Moon was receding away from the Earth. Some areas within the basin, e.g. Olivine Hill and Bhabha and Bose craters probably have deep lunar material, i.e. from lower crust exposed on the surface[8]. Edges of large mare and the rings in multiple ring mares are of special interest here. In addition, it will be useful to identify the end members of the highland rocks if that can be done on the basis of major element chemistry (Ca, Al, etc.). The polar regions are of special interest because the volatiles are expected to be deposited there[6,16]. Shackleton crater close to the south pole is expected to have water-ice on its walls and the bottom and would be a prime target for study. Malapert mountain range, near the south pole, receives sunlight for a significant fraction of the year (~93%) and has been proposed as a possible site for a permanent lunar laboratory[27]. The areas showing TLP and the young lunar volcanic terrains also deserve special high resolution study. Although the major volcanic activity on the Moon terminated at about 3.1 b.y. ago, there are reports that later events of volcanism have occurred, some as recently as 800 m.y. ago, and it will be useful to identify them from the chemical point of view and date them on the basis of crater counts. The scope of this article is limited to pointing out only a few typical areas which require a comprehensive study and not to enter into an exhaustive discussion of all the features of interest on the Moon.

CHANDRAYAAN-1, together with SMART-1, SELENE, LUNAR A, CHANG'E-1 and some other missions which are being planned (e.g. by USA) will provide more than five years of continuous observation of the Moon. This may constitute the longest continuous and overlapping period of study of the Moon and should help us resolve some of the outstanding questions regarding chemical, mineralogic and geological evolution of the lunar surface, Earth–Moon interactions in the remote past and size-dependent evolution of the planetary bodies.

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