Lunar Science from Chandrayaan-1 Data: An Indian Perspective

Introduction:
During the last four decades, India has achieved a successful space based Earth Observation (EO) program, and has achieved noteworthy progress in design, development and operation of satellite systems for EO missions as well as in applications of remote sensing data for meteorology, natural resource mapping and disaster management (Navalgund et al. 2007). With the successful launch of Chandrayaan-1 on October 22, 2008, country ushered into a new era of Planetary Exploration. The data provided by the instruments onboard Chandrayaan-1, have been extensively used to pursue questions related to lunar science and applications of remote sensing data to understand early history of lunar evolution, and assessment of lunar resources. Chandrayaan-1 spacecraft carried eleven sophisticated instruments to investigate mineral distribution, surface morphology, elemental distribution and to characterize radiation environment around the Moon (Bhandari, 2005; Goswami and Annadurai, 2009; Goswami, 2010). A large number of lunar science studies initiated by Indian researchers, in particular, morphology, surface age determination and composition of the lunar surface, have provided new insights into lunar evolutionary processes.

Out of eleven instruments, three instruments, Hyperspectral Imager (HySI) by Indian Space Research Organization (ISRO), Moon Mineralogy Mapper (M3) by NASA/JPL and SIR-2 by Max Planck Institute, Germany, have provided high spatial resolution data on lunar surface mineral composition by measuring lunar surface reflectance in an extended range of 0.4 to 3.0 µm of electromagnetic spectrum (Kiran Kumar et al. 2009a). A high-resolution camera called Terrain Mapping Camera (TMC) provided stereoscopic images of the lunar surface at 5m spatial resolution for photogeological mapping and three dimensional visualization of the lunar surface (Kiran Kumar et al. 2009b). The questions related to presence of ice in the polar region were addressed by Mini-SAR instrument. Results from Mini-SAR data indicated possible presence of ice and provided information on the spatial distribution of buried sub-surface ice on the Lunar poles (Spudis et al. 2009). This review attempts to provide a glimpse of achievements during 2008-2013 by Indian researchers in the broad area of lunar science.

Characterization of Mare Basalts:
The spectral reflectance data were used to study the litho units of near and far side lunar mare basalt basins. Bhattacharya et al. (2011a) used HySI data to map various lithological units of the Mare Moscoviense on the far side of the Moon. Five major compositional units of highland soils, ancient mature mare, highland contaminated mare unit, buried lava flows with low Ca-pyroxene and young mare units were identified.
Mare Serenitatis basin situated on the near side of the Moon has been studied for its mineralogy (Kaur et al. 2013). Detailed spectral analyses reveal uniformity in pyroxene composition across the basaltic units of Mare Serenitatis. Fig. 1 shows the spectral units delineated within Mare Serenitatis. This observation implies a stable basaltic source region filling the basin and has not experienced large-scale fractionation.

Dark halo craters on Moon excavate the cryptomare layer (hidden ancient mare units) and thus provide an opportunity to study the sub-surface composition. One such study of dark halo craters has been done for Mare Nectaris basin on the near side of the Moon. Chauhan et al. (2011a) used high spatial and spectral resolution data from TMC and M3 and concluded that the Crater Beaumont-L (~5km diameter) situated on the western edge of Mare Nectaris is an exogenic impact crater and has excavated the olivine rich mare basalt from beneath the ejecta blanket emplaced by nearby large craters like Theophillus and Madler (Fig. 2 (a, b & c)).

Figure 2b: Represents FCC image (R = IBD at 1µm, G = IBD at 2 µm and B = albedo at 1500 nm) showing olivine rich Beaumont L crater in pink to red tone.

Figure 2c: Represents spectra collected from the marked places in Figure 2b display strong absorption around 1µm.

Composition of Central peaks of Large Lunar Craters and Discovery of New Lunar Minerals:

Central peaks of the large complex craters on the Moon are considered as important science targets. The peaks of these complex craters contain deep seated crustal material formed as a result of elastic rebound of the upper crustal material. Tycho (~110 Ma old) is a young impact crater having well developed central peak with an altitude of ~2 km situated in the southern nearside highlands of the Moon. This crater was studied in detail using TMC, HySI and M3 data. New aspects about its morphology and composition were reported by Chauhan et al. (2011b, 2012). Their analysis of high resolution remote sensing data provided clear morphological evidences of volcanic vents, lava ponds and channels of lava showing distinct cooling cracks and viscous flow fronts on the central peak of Tycho crater. Compositionally, M3 data suggest that high-Ca pyroxene rich rocks with sparse distribution of olivine dominate the lava ponds and channels on the summit of the central peak. Similar results on the composition of this central peak have also been reported using the combined analysis of HySI and SMART-1 SIR data (Bhattacharya et al. 2011b). On the Moon, spinels range between spinel (MgAl₂O₄),

Figure 3a: Crater Endymion imaged from M3' with the location of Mg-Spinel rich lithology and OOS rich areas marked. (b) FCC prepared using IBD-1µm as red channel, IBD-2µm as green and 1.58µm albedo as blue channel.

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hercynite (FeAl$_2$O$_4$), Chromite (FeCr$_2$O$_4$) and ulvöspinel (Fe(FeTi)$_2$O$_4$). On lunar surface, Mg-Spinel (MgAl$_2$O$_4$) was discovered first time remotely at the central peak of Crater Theophilus using spectral reflectance data from M$^3$ (Lal et al. 2011, 2012a). These newly identified Mg-Spinel rich rock types have been defined by their strong 2-µm absorption and the absence of 1-µm absorption in spectral reflectance curve. The exposures of this mineral i.e. spinel along with other lunar minerals i.e. olivine and plagioclase has also been reported from young lunar complex crater, Tycho (Kaur et al. 2012). Spinel has been reported for the first time using Chandrayaan-1 data from a highly silicic evolved dome namely Hansteen Alpha, and from the anorthositic hills surrounding Mare Ingenii basin (Kaur et al. 2013). This new finding of spinel exposures from two different geologic terrains has lead lunar scientists to work out new theories explaining the formation of spinel in these unique geologic settings. Pink-Mg spinels occur in Troctolites formed after the initial ferroan anorthositic (FAN) crust as a minor phase. Mg-Spinels which would sink during crystallization due to their higher density can later on, be a part of the highland intrusive formed by the deep serial magmatism within the anorthositic crust with upward intrusion.

A unique assemblage of OOS (orthopyroxene-olivine-spinel) lithology has been reported from the southern rim of crater Endymion (Bhattacharya et al. 2012). This crater is of 25km, situated on the northeast limb of the Moon and has been analyzed using M$^3$ data (Fig. 3 (a & b)). The presence of OOS lithology suggests excavation of crustal lithology due to large basin formation event.

**Gullies and Landslides on Moon:**

Gullies and landslides provide important information about the water drainage and movement of material in the past. However, in case of Moon where liquid water is not stable, these features were explained by avalanches of dry granular material. Kumar et al. (2013) has presented some of these features imaged from Terrain Mapping Camera (TMC) from Chandrayaan-1 and Narrow Angle Camera (NAC) and Lunar Reconnaissance Orbiter Camera (LROC) on LRO. Based on the spectral information derived using HySI and M$^3$, composition, extent of space weathering and presence of immature material exposed on the surface were studied. This new study on gullies and landslides concludes that role of water in their formation is insignificant unlike the processes occurring on Earth and Mars. These features are not the direct results of small impacts. However, vibrations from nearby large impacts can trigger large scale mass-wasting on the steep slopes of crater interior, giving rise to landslides.

**Water on Moon:**

Presence of water on Moon is still dubious after 50 years of study of lunar surface. Analysis of Apollo samples suggested dry or completely anhydrous nature of the Moon. With the advancement in the instrumental techn-

ology, detection of water from lunar volcanic glasses provided clues that Moon is not as dry as thought previously. Recent detection of OH/H$_2$O absorption features on the Moon based on remote measurements supports the hydrous nature of the Moon. Bhattacharya et al. (2013) recently reported endogenic magmatic water from Compton–Belkovich Thorium Anomaly (CBTA) region, a volcanic construct on the far side of the Moon (Fig. 4 (a & b)). The water detected is associated with non-mare silicic volcanism based on Chandrayaan-1 Moon Mineralogy Mapper (M$^3$) observations.

**Lunar Morphology Studies:**

TMC data was also used to study the morphological features such as lava tubes, sinuous rilles, volcanic domes etc. Crater counting technique is being widely used for possible determination of relative age determination of lunar and other planetary surfaces. TMC images were used in this respect.
for relative dating crater of some regions of lunar surface by employing Crater-Size-Frequency-Distribution (CSFD) technique. This method was evaluated over regions of Apollo Landing sites 14, 15 and 17 and extended to part of Oceanus Procellarum and other regions of the Moon (Arya et al. 2012). The technique was successfully validated by applying it to Apollo 14 and 17 landing sites, and the age obtained through CSFD technique matched with the obtained from radiometric dating of the returned samples as well as with the earlier reported results. This technique was further extended to south of the Apollo 14 landing site, Imbrium basin, Nubium basin and east of the Copernicus crater. The corresponding ages obtained using this technique were 3.77 Ga, 3.43 Ga, 3.02 Ga, 895 Ma respectively, which are in good agreement with the earlier reported ages. Derived age of 895 Ma suggest a young activity on lunar surface.

Lunar Lava Tubes and Sinuous Rilles:
Lunar surface is known to have presence of sinuous rilles, which are probably collapsed, lave tubes. A Lunar volcanic tube around ~4 km long in the Oceanus Procellarum region of the Moon was identified using TMC images and digital elevation data as a potential site of future human settlement on the Moon (Arya et al. 2011).

Lunar Domes and Silicic Volcanism:
Recent studies using the Diviner data onboard Lunar Reconnaissance Orbiter (LRO) mission, in thermal infrared region of electromagnetic spectrum have shown various regions on the lunar surface (previously described as “red spots”) exhibiting spectral features in the mid-infrared that are best explained by quartz, silica-rich glass, or alkali feldspar. These lithologies are consistent with evolved rocks similar to lunar granites in the Apollo samples. The spectral character of these spots is distinct from surrounding mare and highlands material. Kusuma et al. (2012) have used spectral information from the M² and DIVINER Lunar Radiometer onboard LRO for geochemical and mineralogical characterization of the Gruithuisen region on the Moon along with morphometric information. Based on these data analysis, they have delineated silica saturated lithology from silica under-saturated rocks, their spatial spread and non-mare nature of the Gruithuisen domes. Studies have also been done to understand the lunar non-mare volcanism around domes. Few such domes were identified in the Mare Procellarum region of the Moon.

Lunar Topography:
Terrain Mapping Camera (TMC) was a stereoscopic camera that had provided 3D maps of the Moon. A scheme was developed using the photogrammetric technique to generate the three dimensional information on the Moon’s surface (Gopala Krishna et al. 2009). Using this methodology, entire data collected by TMC have been processed and a three dimensional atlas of the lunar surface has been generated. Lunar Laser Ranging Instrument (LLRI) used infrared laser pulses to provide altimetry data that accurately map the topography of the Moon (Kamalakar et al. 2009). In addition to the data acquired by previously flown lunar altimeters, the LLRI has obtained topographic data close to the lunar Polar Regions. High resolution LLRI topography data have been used for preparation of topographic maps over major lunar basins. Besides, these data could also be used for terrain correction for computation of Bouguer gravity anomalies, which can be further used for gravity inversion modelling of lunar crustal thickness over major lunar basins.

Exploration of Ice in Lunar Poles:
Mini-SAR data from Chandrayaan-1 were analyzed extensively to study the signatures of ice deposits in Polar Regions. The Polar Regions of the Moon contain permanently shadowed craters, which are potential source of surface or sub-surface ice. Some of the studied craters like Peary (North pole) and Amundsen (South pole) have anomalous scattering properties as they have elevated Circular Polarization Ratio (CPR) values within their interiors, characteristic of ice deposits, but not exterior to their rims (Shiv Mohan et al. 2011). However, elevated CPR values were found inside and outside the equatorial crater i.e. Kopff crater. The high CPR values were suggestive of rough surface scattering mechanism and attributed to scattering from very rough surfaces, such as a rough, blocky lava-flow. Similar scattering conditions in few of the craters in the Polar Regions where elevated CPR was found both inside and outside the craters.

Lunar Elemental Chemistry Studies:
The Chandrayaan-1 X-ray Spectrometer (C1XS) flown on-board Chandrayaan-1 was used to measure X-ray fluorescence spectra to derive the elemental chemistry of the lunar surface. During its operational period of ~9 months, solar flares were not powerful enough to stimulate detectable surface fluorescence. Hence, C1XS measurements were not sufficient to produce a global map because of little solar activity during this unusually prolonged solar minimum. The accompanying X-ray Solar Monitor (XSM) provided simultaneous spectra of solar X-rays incident on the Moon which are essential to derive elemental chemistry. Surface abundances of Mg, Al, Si, Ca and Fe derived from C1XS data for a highland region on the southern nearside of the Moon was measured by Narendranath et al. (2011). Plagioclase feldspar with lower amounts of mafic minerals represents the major mineralogy of lunar highlands. C1XS derived Mg and Fe content are slightly higher due to additional mafic content redistributed by impacts. The main deviation is in the C1XS derived Ca/Al ratio. Many possible reasons of this deviation have been explained in the study. In another study Lal et al. (2012b) have also developed algorithms to quantify Iron (FeO) and Titanium (TiO₂) abundance in lunar rocks using the reflectance ratios of Chandrayaan-1 HySI data.

Detection of Lunar Mini Magnetosphere:
Moon does not have a global magnetic field of its own. However, lunar surface has patches of localized low magnetic field known as ‘magnetic anomalies’ having
strength of a few tens of nano-tesla with spatial coverage ranging from few km to few hundred kms. The Sub-keV Atom Reflecting Analyzer (SARA) instrument discovered a mini-magnetosphere above magnetic anomaly regions by means of backscattered Energetic Neutral Atoms (ENA) (Wieser et al. 2010; Bhardwaj et al. 2005). The ENA flux above the anomaly region showed a decrease compared to the regions which are not affected by the anomaly (undisturbed regions), thus confirming existence of a magnetosphere. Some of these localized magnetic fields on the Moon also show relatively high albedo and are known as Lunar Swirls.

**Future Perspective for Lunar Geosciences:**
As described in previous sections a large amount of scientific work using various instruments from Chandrayaan-1 data have resulted in an improved understanding of our closest celestial neighbor. The next lunar mission of India, Chandrayaan-2, is planned to be launched during the year 2014-15 to provide more details of lunar surface using improved sensors (Goswami & Annadurai, 2011). The satellite will be carrying an orbiter, a lander and a rover. Payloads for the orbiter include Imaging IR Spectrometer (IIRS) for the mineralogical mapping over a wide wavelength range (0.8-5.0 μm) along with the study of absorption bands of water molecules or hydroxyl ions present in the lunar regolith. A repeat of TMC instrument is also planned. Analysis of IIRS and TMC-2 data will be carried out for better understanding of lunar crustal evolution of major basins and Polar Regions. The polar regions of the Moon are now known to have hydroxyl (OH) and water (H2O) molecules discovered by Chandrayaan-1 M3 data. Using the spectral region of 2 to 5μm Chandrayan-2, IIRS spectrometer will be able to confirm these findings and will map these features at much higher spatial resolution. The modified TMC data from Chandrayaan-2 will provide complete coverage of Moon’s surface along with 3D information which could not be completed by Chandrayaan-1. The proposed dual frequency SAR onboard Chandrayaan-2 will be a continuity of the S-band Mini-SAR of Chandrayaan-1 and will help in finding subsurface ice deposits on the lunar poles.

**Further Reading:**
11. Chauhan, P. et al., 2011b, 42nd LPSC, Abs no. 1341 B.
22. Kiran Kumar, A. S. et al., 2009b, Current Sci., v.96, no. 4, p. 492-495.

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