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Status Report

Lunar Geosciences using Chandrayaan-1: Indian Perspective

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The successful launch of Chandrayaan-1 satellite allowed Indian lunar scientists to get firsthand experience of working with higher resolution lunar data sets in unprecedented details to look into various lunar science studies. Data from different instruments on-board Chandrayaan-1 have been used to assess lunar surface morphology, mineralogy, elemental abundance and detection of water/ice in the polar regions and these results were supported with high resolution topographic data from more than one sensor. This paper attempts to provide an overall summary of various science results obtained using Chandrayaan-1 data to answer questions related to lunar science.

Key Words : Moon; Chandrayan-1; Mineralogy; Morphology; Lunar Water/Ice

Introduction

During the last four decades, India has developed a successful space based Earth Observation (EO) program, and has accomplished 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 Chandaryaan-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 of 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). During the last three years, a significant contribution to newer aspects of lunar geosciences has been addressed using data provided by Chandrayaan-1 instruments. 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 enhanced thoughtful views regarding lunar evolutionary processes. These studies initiated ultimately lead to an understanding of the conditions in early solar system.

Out of eleven instruments, three instruments, Hyperspectral Imager (HySI) by Indian Space Research Organisation (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 composition by measuring reflectance in an extended range of 0.4 to 3.0 μm of electromagnetic spectrum (Kiran Kumar *et al*. 2009a*;* Pieters *et al*. 2009a; Mall *et al*. 2009). A high-resolution camera called Terrain Mapping Camera (TMC) provided stereoscopic images of the lunar surface at 5m spatial resolution for photo-geological 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). Moon Impact probe (MIP) data analysis also resulted in a significant finding of presence of water molecules in the tenuous atmosphere of the Moon (Sridharan *et al*. 2010). This review attempts to provide a glimpse of achievements during 2008-2012 by Indian researchers in the broad area of lunar science.

Lunar Surface Composition Studies

The thermal and chemical evolution of planetary bodies has been the major guiding theme in planetary sciences and exploration. Planetary bodies cool in a number of ways, including magma ocean processes density stratification through differentiation, internal convection, and volcanism. These processes affect the chemical evolution of planetary surfaces, as the composition and mineralogy of zones within

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the bodies evolve as thermal evolution progresses. Thus, study of lunar surface composition and mineralogy is of prime importance in understanding the crustal evolution.

Compositional mapping of the lunar surface based on spectroscopy was carried out using reflectance spectra from HySI, Moon Mineralogy Mapper (M3) and SIR-2 spectrometers. The absorption features in the reflectance spectra of the minerals arise due to the electronic and vibration processes taking place at different crystallographic sites at atomic and molecular level, respectively (Burns *et al*. 1970). Towards the generation of science data, spectral lunar surface radiance data was converted to obtain surface reflectance in sixty-four bands of HySI imager in the spectral region of 0.4 to 0.95 µm and corrections for photometric effects were done to normalize the lunar reflectance to a common viewing geometry. The important lunar minerals such as Olivine, low Ca-pyroxene, high Ca-pyroxene and crystalline plagioclase could be identified using the hyperspectral data from all the three instruments. (Mall *et al*., 2009; Pieters *et al*., 2009; Bhattacharya *et al*., 2011a)

Characterization of Mare Basalts

The science data in terms of apparent reflectance was subsequently 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 basin soils, ancient mature mare, highland contaminated mare, buried lava flows with low Ca-pyroxene and young mare units were also identified. A detailed mineralogical analysis of Crater Le Monnier, situated on the eastern edge of the Mare Serenitatis on the near side of the Moon, was carried out using the M3 data. It was found that this impact crater is compositionally rich in high Ca-pyroxene basalts in comparison to surrounding highland rock of anorthositic composition (Kaur *et al*. 2011).

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 situated (~ 5 km diameter) on the western edge of Mare Nectaris on the Moon 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. 1 shows the geological setting of the Beaumont-L carter and TMC image of this crater along with topographic data.

Composition of Central Peaks of Large Lunar Craters

Central peaks of the large complex craters on the Moon are considered as important science targets as they are conjectured to contain deep seated crustal material and, thereby provide an ideal locale to study the lunar deep inner crustal material. Tycho is a young impact crater of (~110 Ma) in the southern highlands of the Moon. The crater has a well-developed central peak with an altitude of ~2 km. The central park of Tycho 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, domes, pyroclastics, 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. The base of the central peak is anorthositic in nature. These new findings suggest that Tycho's central peak has undergone multiphase post-impact modifications. Fig. 2 show a three dimensional view of the central peak of Tycho crater and associated composition data derived from M3 sensor. Similar results on the composition of this central peak have also been reported using the combined analysis of HySI and SMART-1SIR data (Bhattacharya *et al*. 2011b).

A new Lunar mineral Mg-Spinel was discovered at the central peak of Crater Theophilus on the near side of the Moon using spectral reflectance data from M3 (Lal *et al*. 2011, 2012a). These Mg-Spinel rich rock types have been identified by their strong 2 µm absorption and the absence of 1 µm absorption in spectral reflectance curve. Such lithology was previously reported at inner ring of Mare Moscoviense on far side, apart from the above mentioned central peak of crater Theophilus. Fig. 3 shows the Crater Theophilus and exposures of Mg-Spinel on its central peak. The presence of spinel group of minerals at the central peak confirms the fact that the crater central peaks mostly represent uplifted mass of the deep crustal material and therefore acts as a window to study the deep crustal and/or upper mantle composition and may lead to a fresh aspect about the crustal composition of Moon. Recent work on another young lunar complex crater, Tycho, have also reported to have exposures of this newly discovered lithology, i.e spinel along with other lunar mineral i.e. olivine and plagioclase (Kaur *et al*., 2012).

Lunar Magma Hypothesis Confirmation

Scientifically interesting regions of the lunar farside were studied in details using HySI and TMC derived digital

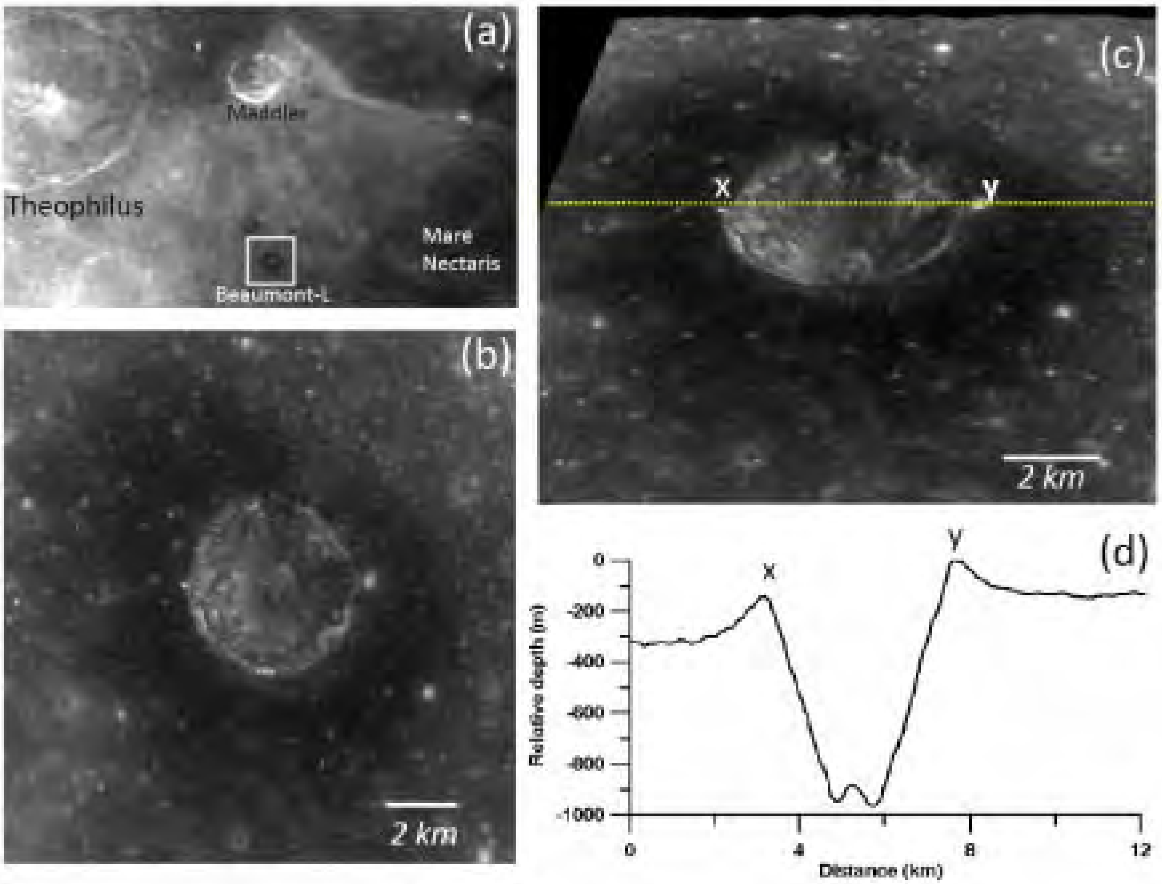

Fig. 1 : (a) Geological setting of dark haloed crater Beaumont-L (~ 5 km diameter) on the western rim of Mare Nectaris on the Moon, large Craters such as Theophilus and Madler are in close vicinity, (b) TMC image of crater Beaumont-L, c) 3D image and d) elevation transect across the crater showing raised rims and elevated centre, characteristics of an impact crater

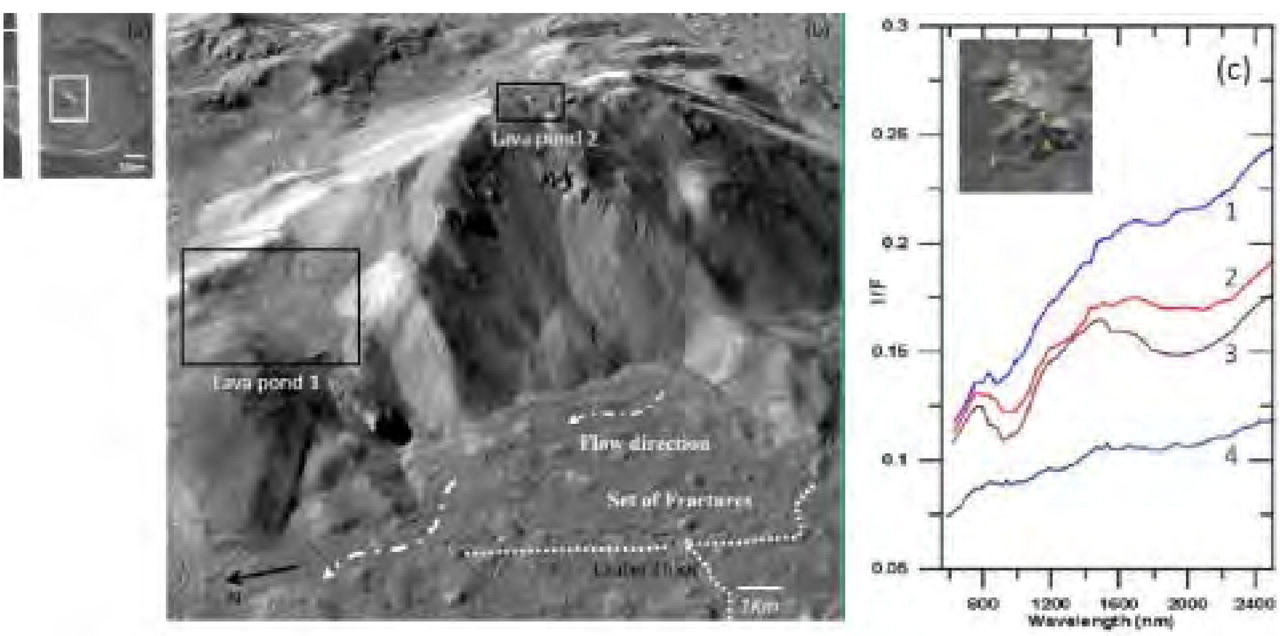

Fig. 2: (a) TMC mosaic over the Tycho crater. This young crater has a diameter of ~85 km, (b) three dimensional image of the central peak of Tycho crater using TMC data, (c) spectral reflectance data over four locations on Tycho crater, location 2 and 3 shows presence of mafic minerals

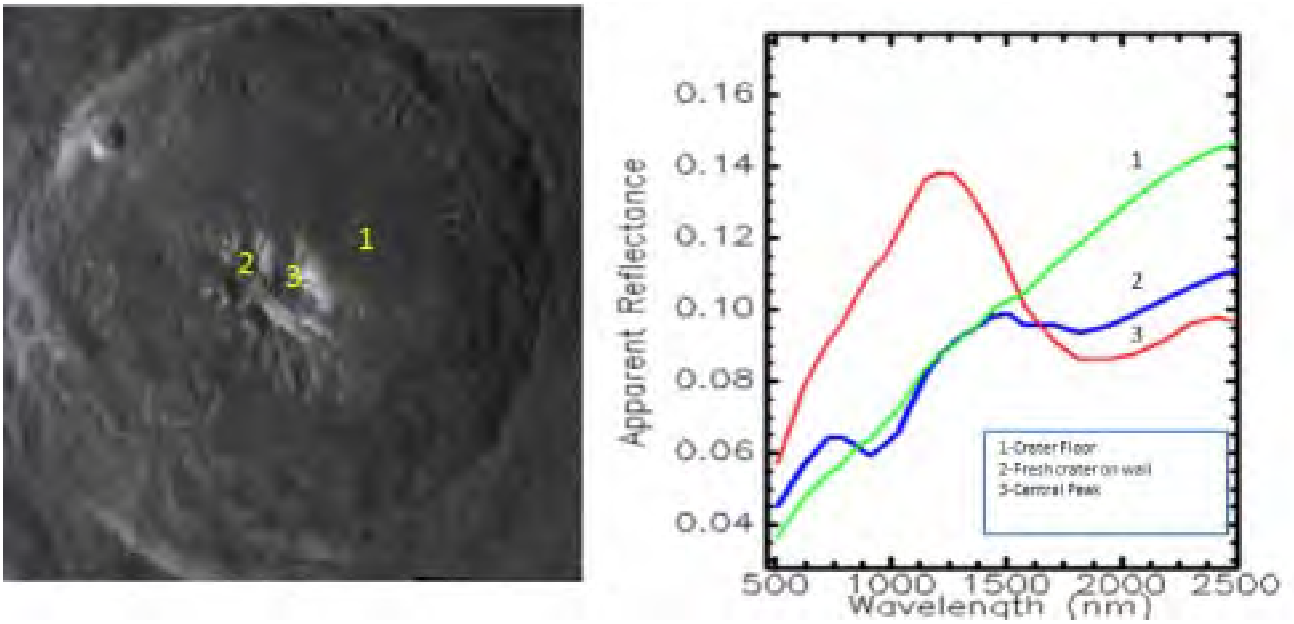

Fig. 3: (a) TMC image of lunar crater Theophilus showing a well developed central peak, (b) reflectance spectra from M3 data for Mg-Spinel mineral (in red colour), showing no absorption at 1.0 µm

elevation models (DEM) for Mare Orientale. Orientale basin is a young and most well-preserved large multi ring basin on the Moon. Its central portion has areas covered by mare basalt and the impact melt deposits. Pristine ring structures of this impact basin are also relatively well preserved. Using spectral reflectance derived from HySI data, various lithological units of mare basalts and plagioclase bearing high lands rocks could be discriminated. The identification of plagioclase blocks in Mare Oreintale is scientifically significant as it provide evidences for the Lunar Magma Ocean (LMO) hypothesis for the crustal evolution of the Moon (Kumar *et al*. 2009).

Lunar Regolith (Soil) Characterization

Using TMC and hyperspectral sensors, a study of chemical and mineralogical composition of lunar soil and its physical properties (including degree of maturation and space weathering) were carried out for various characteristic sites, representing both Highlands and Maria regions. Using the high-resolution data of TMC and associated stereoscopic data the disturbance caused by the Apollo-15 lander could be identified around the Apollo-15 landing site (Chauhan *et al*. 2009). It was observed that lunar regolith show increased albedo around the landing site. It was concluded that the disturbance caused by the Apollo-15 lander, has led to exposure of fresh material of higher reflectance.

Lunar Morphology Studies

Very high spatial resolution TMC data (~ 5 m resolution) had been used extensively for studying the morphology of impact craters and to understand the impact cratering mechanism over lunar highlands and mare basalts. TMC data was also used to study other morphological features such as lava tubes, sinous rills, volcanic domes etc. The number of craters on a surface increases with the length of time that surface has been exposed to space. These rather being simple ideas are the basis for a very powerful tool, called crater counting, that planetary scientists use to unravel the age of a planetary surface. TMC data was used for absolute dating 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 matches with that 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.

Secondary Impact Crater formation Process Studies

Ejecta ray deposits around large impact craters on the Moon are one of the most spectacular geologic features. These ray deposits largely comprise materials ejected from primary impact craters. Impact of ejecta fragments produces secondary craters surrounding the primary craters. These secondary craters occur usually in the form of clusters, chains and loops. In a recent study using TMC data, Senthil Kumar *et al*. (2011), has observed a big cluster enclosing thousands of fresh and buried impact craters in the size range of 20-1300 m within a 20 km x 27 km area in the Mare Imbrium region. It has been concluded that majority of the large fresh craters having diameter ranging from 160 to 1270 m exhibit near-circular mounds on the crater floor, and their size depends on the host crater size. Based on global lunar images and the analysis of Chandrayaan-1 HySI data the possible origin of this cluster of secondary craters was suggested to be Copernicus crater. These findings provide new evidence of low velocity impacts by the clustered fragments of primary impact ejecta which results in the formation of secondary impacts.

Lunar Lava Tubes and Sinous Rilles

Lunar surface is known to have presence of sinous rilles, which as suggested are collapsed lave tubes. A Lunar volcanic tube (Fig. 4) around ~4 km length was identified as a potential source of future human settlement on the Moon using TMC images and digital elevation data in the Oceanus Procellarum region of 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 (Glotch *et al*. 2011; Jolliff *et al*. 2011). 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

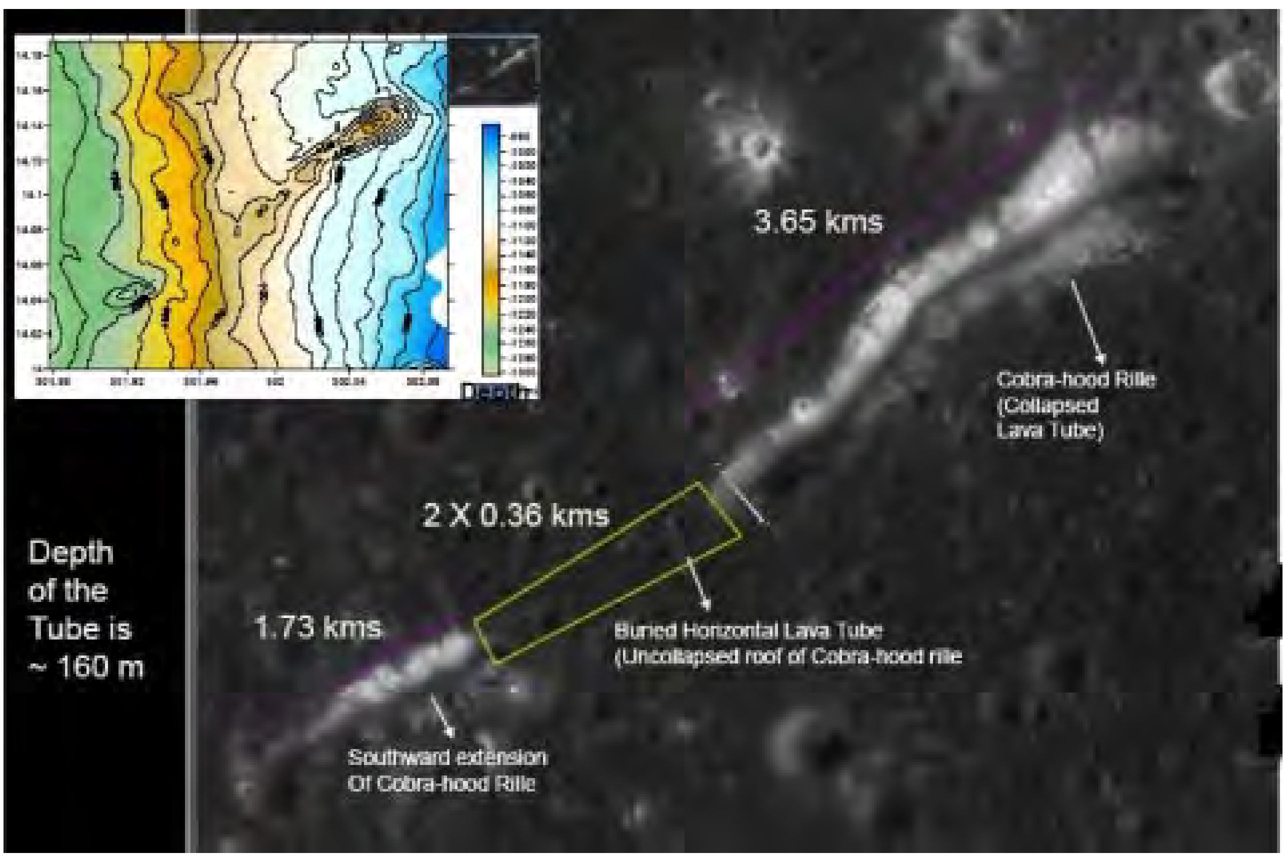

Fig. 4: Lunar volcanic tube identified using TMC data in Mare Procellrum

information from the M3 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 the silica saturated lithology from silical under-saturated rocks, their spatial spread and non-mare nature of the Gruithuisen domes. Studies have also been done to study the lunar non-mare volcanism around domes and 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. TMC was a line scanner with three CCD arrays, Fore, Nadir and Aft looking at +26, 0 and –25 degrees, respectively. The camera provided three images (triplet) of the same object having three different view angles. The swath and resolution of TMC were 20km and 5m, respectively. A scheme was developed using the photogrammetric technique to generate the three dimensional information on the Moon 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 is generated. Fig. 5 shows an example of the digital elevation model (DEM) derived from TMC data.

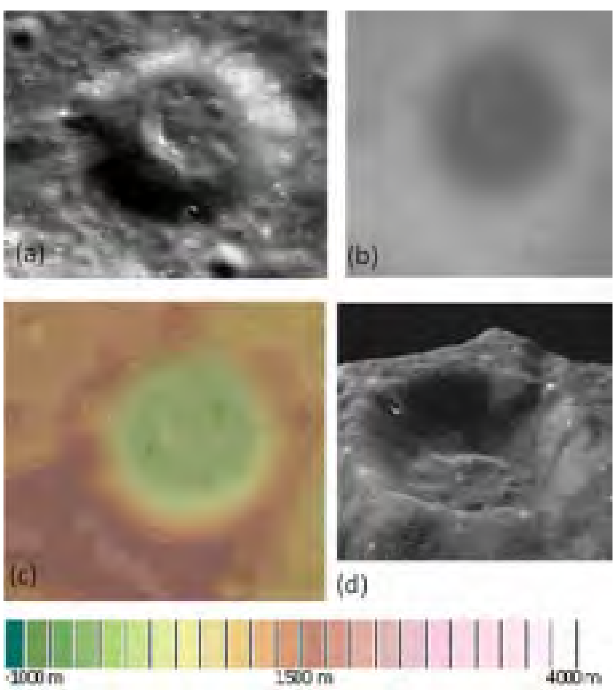

Fig. 5: (a) TMC data from Chandryaan-1 of Coloumb –C crater, (b) derived DEM from the stereo data, (c) colored contour map and (d) the 3D visualization for Coloumb C crater

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 data acquired by previously flown lunar altimeters, the LLRI has obtained topographic data close to the lunar Polar Regions. High resolution LLRI topography data used for preparation of topographic maps over major lunar basins. Besides that this data could also be used for terrain correction towards computation of Bouguer gravity anomalies, which can be further used for inversion of lunar crustal thickness over major lunar basins. Fig. 6 shows the LLRI derived global topography of the Moon surface along with boundaries of the major lunar basins. The dark blue color in the Fig. 6 shows the deepest parts of the Moon, known as South Pole Aitkin (SPA) basin.

Exploration of Ice in Lunar Poles

Mini-SAR data from Chandrayaan-1 was 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 these crater in this region have anomalous scattering properties as they have elevated Circular Polarization Ratio (CPR) values within their interiors (Fig. 7), but not exterior to their rims, as revealed by the hybrid polarimetric Mini-SAR data (Shiv Mohan *et al*. 2011). However, elevated CPR values were also observed in some non-polar areas and also from fresh craters and thus, elevated CPR values may not be a unique signature of water ice deposits. This issue can be settled by dual frequency SAR data from Chandrayaan-2.

Lunar Elemental Chemistry Studies

The Chandrayaan-1 X-ray Spectrometer (C1XS) flown on-board was used to measure X-ray fluorescence spectra during several episodes of solar flares during its operational period of ~9 months. 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). These were consistent with a composition rich in plagioclase with a slight mafic mineral enhancement and a Ca/Al ratio that is significantly lower than measured in lunar returned samples. In another study Lal *et al*. (2012b) have also developed algorithms to quantify Iron (FeO) and Titanium (TiO_2) 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,

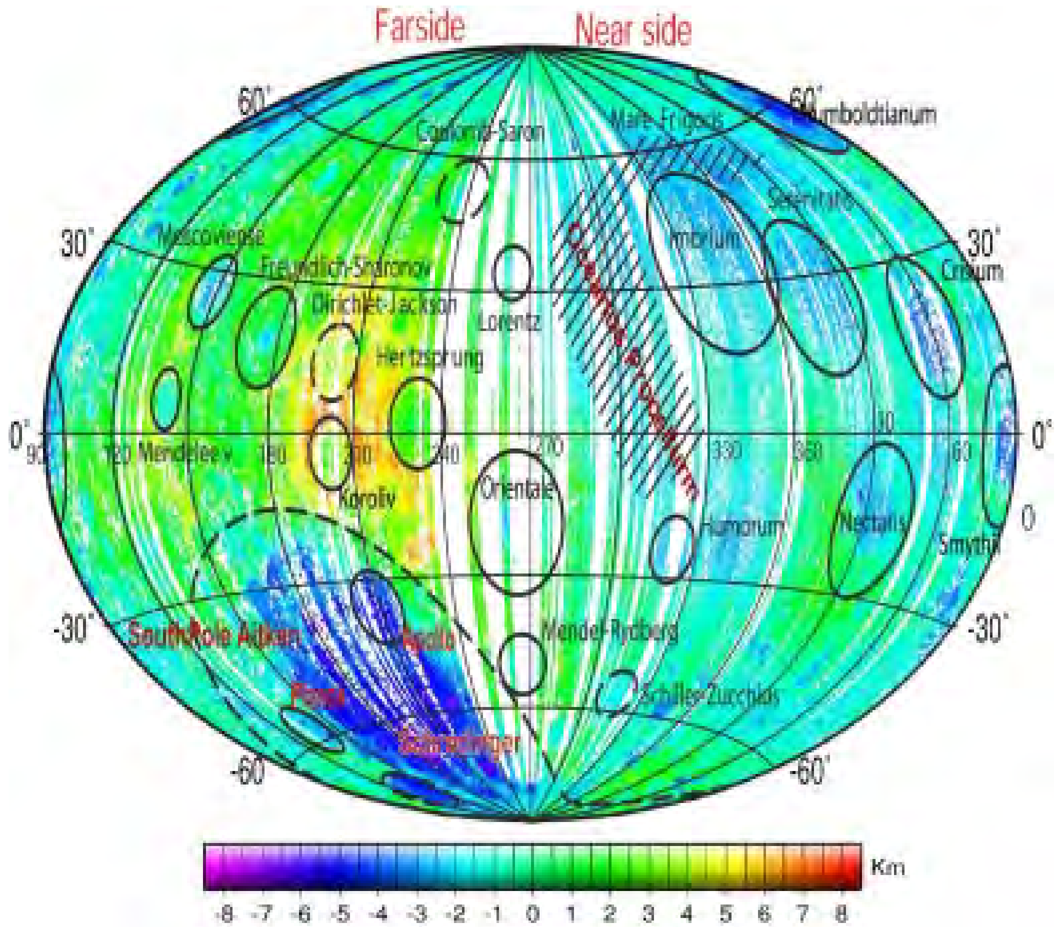

Fig. 6: Lunar Laser Ranging Instrument (LLRI) derived global topographic map of the Moon surface along with the boundaries of the major lunar basins. Data gaps in the image are due to lack of Chandrayaan-1 coverage

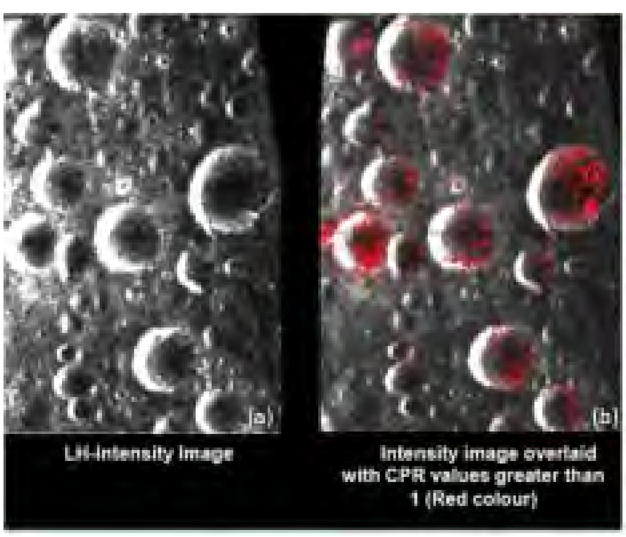

Fig. 7: Interior of Peary crater at the lunar North Pole as seen by the Mini-SAR. Regions shown in red show high CPR values

however, lunar surface has patches of localized magnetic field known as 'magnetic anomalies' of strength few tens of nano-tesla with spatial coverage ranging from few km to few 100 km. The Sub-keV Atom Reflecting Analyzer (SARA) instrument observed for the first time a mini-magnetosphere above the magnetic anomaly region by means of the backscattered Energetic Neutral Atoms (ENA) (Wieser *et al*., 2010; Bharadwaj *et al*. 2005). The ENA flux above the anomaly region indeed showed a decrease compared to the regions which are not affected by the anomaly (undisturbed region). 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 data from various instruments of Chandryanan-1 have resulted in an improved understanding about our closest celestial neighbour. The next lunar mission of India, Chandrayaan-2, is being targeted for launch during the year 2013 to provide more details of lunar surface using improved sensors (Goswami & Anna Durai, 2011). Chandrayaan-2 will have an orbiter, a lander and a rover. Payloads for this mission includes Imaging IR Spectrometer (IIRS) for the mapping of lunar surface over a wide wavelength range (0.8-5.0 µm) for the study of minerals, water molecules and hydroxyls 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 known to have presence of hydroxyl (OH) and water (H_2O) molecules as discovered by Chandrayaan-1 M3 data (Pieters *et al*. 2009b). Using the spectral region of 2 to 5 µm Chandryaan-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 surface along with 3D atlas which could not be done using the 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 our subsurface ice deposits on the lunar poles.

References

Arya, A. S., Rajasekhar, R. P., Thangjam, G., Ajai and Kiran Kumar, A. S., 2011. Detection of potential site for future human habitability on the Moon using Chandrayaan-1 data. Curr. Sci., v. 100, no. 4 p. 524-529.

Arya, A. S., Thangjam, G., Rajasekhar, R. P., Ajai, Gopalkrishna, B., Amitabh, Kiran Kumar, A. S. and Navalgund, R. R., 2011. Morphometric and rhelogical analysisof an effusive dome in Marius Hills using Chandrayaan-1 TMC data. 42nd Lunar Planet. Sci. Conf., Abs no. 1470.

Arya, A. S., Rajasekhar, R. P., Thangjam, G., Gujrati, A., Amitabh, Trivedi, S., Gopala Krishna, B., Ajai, and Kiran Kumar, A. S., 2012. Lunar surface age determination using Chandrayaan-1 TMC data, Curr. Sci., v. 102, no. 5, p.783-788.

Burns, R.G., 1970. Mineralogical Applications of Crystal Field Theory. Cambridge Univ. Press, N.Y.

Bhattacharya, S., Chauhan, P., Rajawat, A. S., Ajai and Kiran Kumar, A. S., 2011a. Lithological mapping of central part of Mare Moscoviense using Chandrayaan-1 Hyperspectral Imager (HySI) data, Icarus, 212, p. 470-479.

Bhattacharya, S., Nathues, A., Reddy, V., Dannenberg, A., Chauhan, P. and Ajai, 2011b. Combined analysis of Chandrayaan-1 HySI and SMART-1 SIR data over central peak of Tycho, EPSC Abstracts, 2-7 October 2011, Nantes, France, v.6, p.1842.

Bhandari, N., 2005. Chandrayaan-1 Science goals, Jour. Earth Sys. Sci. (ESS), v.114, no.6, p. 701-709.

Bhardwaj, A., Barabash, S., Futaana, Y., Kazama, Y., Asamura, K., McCann, D., Sridharan, R., Holmstrm, M., Wurz, P. and Lundin, R., 2005. Low energy neutral atom imaging on the Moon with the SARA instrument aboard Chandrayaan-1 mission. Jour. Earth Syst. Sci., v. 114, no. 6, 749760.

Chauhan, P., Ajai and Kiran kumar, A. S., 2009. Chandrayaan-1 captures Halo around Apollo-15 landing site using stereoscopic views from Terrain Mapping Camera. Current Sci., v.97, no. 5, p. 630-631.

Chauhan, P., Kaur, P., Srivastava, N., Bhattacharya, S., Lal, D., Ajai and Kiran Kumar, A. S., 2011a. Studies of lunar dark halo craters in northwestern Mare Nectaris using high Resolution Chandrayaan-1 data. 42nd Lunar Planet. Sci. Conf., Abs No. 1338.

Chauhan, P. Srivastava, N., Kaur, P., Bhattacharya, S., Ajai, Kiran Kumar, A. S., Goswami, J. N. and Navalgund, R. R., 2011b, Evidences of multiphase modification over the central peak of Tycho crater on moon from high resolution remote sensing data, 42nd Lunar Planet. Sci. Conf., Abs no. 1341 B.

Chauhan P., Kaur, P. Srivastava, N. Bhattacharya, S., Ajai, Kiran Kumar, A.S. and Goswami, J. N., 2012. Compositional and morphological analysis of high resolution remote sensing data over central peak of Tycho crater on the Moon: Implications for understanding Lunar Interior. Curr. Sci., v. 10, no.7, p. 1041-1046.

Glotch *et al*., 2010. Highly Silicic Compositions on the Moon. Science, v. 329, p. 1510-1513.

Gopala Krishna, B., Amitabh Singh, S. Srivastava, P.K. and Kiran Kumar, A. S., 2009. 40th Lunar Planet. Sci. Conf., Abs No. 1694.

Goswami, J. N., 2010. An overview of Chandrayaan-1 mission. 41st Lunar Planet. Sci. Conf., Abs No. 1591.

Goswami, J. N. and Annadurai, M., 2009. Chandrayaan-1: India's first planetary science mission to the moon. Current Sci., v.96.no. 4, p.486-491.

Goswami, J. N., and Annadurai, M., 2011. Chandrayaan-2 mission. 42nd Lunar Planet. Sci. Conf., Abs no. 2042.

Jolliff, B., *et al*., 2011. Non-Mare silicic volcanism on the lunar farside at Compton–Belkovich. Nature Geosci. v. 4, p. 566-571.

Kamalakar, J. A., Prasad, A. S. Laxmi, Bhaskar, K. V. S., Selvaraj, P., Venkateswaran, R., Kalyani, K., Goswami, A., Raja, V. L. N. and Sridhar, 2009. Lunar Laser Ranging Instrument (LLRI): A tool for the study of topography and gravitational field of the Moon. Curr. Sci, v. 96, no. 4 .p.512-516.

Kaur, P., Chauhan, P., Bhattacharya, S., Ajai and Kiran Kumar, A. S., 2011. Detailed mineralogical analysis of crater Le Monnier on Lunar surface using Chandrayaan-1 hyperspectral data. 9th Low Cost Planet. Sci. Mission conf.

Kaur· P., Chauhan, P., Bhattacharya, S., Ajai and Kiran Kumar, A. S., 2012. Compositional diversity at Tycho crater: Spinel exposures detected from M^3 data. Lunar Planet. Sci. Conf., Abs no. 1434.

Kiran Kumar, A. S., Chowdhury, A., Banerjee, A., Dave, A. B., Sharma, B. N., Shah, K.J., Murali, K. R., Joshi, S. R. and Sarkar, S. S., 2009a. Hyperspectral Imager for Lunar mineral mapping in visible and near infrared band, Curr. Sci., v. 96, no. 4, p. 496-499.

Kiran Kumar, A. S., Chowdhury, A., Banerjee, A., Dave, A. B., Sharma, B. N., Shah, K. J., Murali, K. R., Joshi, S. R., Sarkar, S. S. and Patel, V. D., 2009b. Terrain Mapping Camera: A stereoscopic high-resolution instrument on Chandryaan-1, Current Sci., v. 96, no. 4, p. 492-495.

Kumar, A. S., Kiran Kumar, A. S., Goswami, J. N., Pieters, C. M., Krishna, B. G. and Chauhan, P., 2009. Lunar Orientale Basin: Topology and morphology of impact melt region from Chandrayaan-1 TMC and HySI. 40th Lunar Planet. Sci. Conf., Abs. No. 1505.

Kusuma, K. N., Sebastian, N. and Murty, S.V.S., 2011. Geochemical and mineralogical analysis of Gruithuisen region on Moon using M3 and Diviner images. Planet. Space Sci. v. 67, no. 1, p. 46-56.

Lal, D., Chauhan, P., Bhattacharya, S., Shah, R. D., Ajai and Kiran Kumar, A. S., 2012a. Detection of Mg-Spinel lithologies on central peak of crater Theophilus using Moon Mineralogy Mapper (M3) data from Chandrayaan-1. Jour. Earth Sys. Sci., v. 121, no. 3, p. 847-853.

Lal, D., Chauhan, P. and Ajai, 2012b. FeO and TiO_2 abundance analysis around Apollo-17 landing site using reflectance spectra from HySI sensor on-board Chandryaan-1. Current Sci. v. 102, no. 11, p. 1560-1564.

Mall, U., Banaszkiewicz, M., Brønstad, K., McKenna-Lawlor, S., Nathues, A., Søraas, F., Vilenius, E. and Ullaland, K., 2009. Near Infrared Spectrometer SIR-2 on Chandrayaan--1. Current Sci., v. 96, no. 4, p. 506-511.

Narandranath S, Athiray P. S., Sreekumar P., Kellett B. J., Alha L., Howe, C. J., Joy, K. H., Grande, M., Huovelin J., Crawford, I. A., Unnikrishnan, U., , Lalita, I.S., Subramaniam, S.,Weider, S.Z., Nittler, L. R., Gasnault, O., Rothery, D., Fernandes, V. A., Bhandari, N., Goswami, J.N., Wieczorek, M.A. and the C1XS team, 2011. Lunar X-ray fluorescence observations by the Chandrayaan-1 X-ray Spectrometer (C1XS): Results from the nearside southern highlands. Icarus, v. 214, p. 53-66.

Navalgund, R. R., Jayaraman, V. and Roy, P. S., 2007. Remote Sensing Applications: An Overview. Curr. Sci., v. 93, no. 12, p. 1747-1766.

Pieters, C. M., Boardman, J., Buratti, B. J., Chatterjee, A., Clark, R., Glavich, T., Green, R., Head, J. W., Isaacson, P. J., Malaret, E. McCord, T. B., Mustard, J. F., Petro, N. E., Runyon, C., Staid, M., Sunshine, J., Taylor, L., Tompkins, S., Varanasi, P. and White M., 2009a. The Moon Mineralogy Mapper (M3) on Chandrayaan-1. Curr. Sci.,v. 96, no. 4, p. 500-505.

Pieters, C. M., Goswami, J. N., Clark, R. N., Annadurai, M., Boardman, J., Buratti, B. J., Combe, J. P., Dyar, M. D., Green, R., Head III, J. W., Hibbitts, C. A., Hicks, M. D., Isaacson, P., Klima, R. L., Kramer, S., Kumar, S., Livo, E., Lundeen, S., Malaret, E., McCord, T. B., Mustard, J. F., Nettles, J. W., Petro, N., Runyon, C., Staid, M., Sunshine, J., Taylor, L. A., Tompkins, S. and Varanasi, P., 2009b, Character and spatial distribution of OH/H2O on the surface of the Moon seen by M3 on Chandrayaan-1, Science, v. 326, p. 568-572.

Senthil Kumar P., Kumar, A. S., Keerthi, V., Goswami, J. N.,Krishna, B. G. and Kiran Kumar, A. S., 2011. Chandrayaan-1 observations of distant secondary craters of Copernicus exhibiting central mound morphology: evidence for low velocity clustered impacts on the Moon. Planet. Space Sci., v. 59, no. 9, p. 870-879.

Shiv Mohan, Das. A. and Chakarborty, M., 2011. Studies of polarimetric properties of lunar surface using Mini-SAR data. Curr. Sci., v. 101, no. 2, p.159-164.

Spudis, P., Nozette, S., Bussey, B. , Raney, K., Winters,H., Lichtenberg, C. L., Marinelli, W., Crusan, J. C. and Gates, M. M., 2009. Mini-SAR: an imaging radar experiment for the Chandrayaan-1 mission to the Moon, Curr. Sci., v. 96, no. 4, p.533-539.

Sridharan, R., Ahmed, S. M., Das, T. P., Sreelatha, P., Pradeepkumar, P., Naik, N. and Gogulapati S., 2010. Direct evidence for water (H_2O) in the sunlit lunar ambience from CHACE on MIP of Chandrayaan-1. Planet. and Space Sci., v. 58, p. 947-950.

Wieser, M., Barabash, S., Futaana, Y., Holmstrm, M., Bhardwaj, A., Sridharan, R., Dhanya, M. B., Schaufelberger, A., Wurz, P. and Asamura, K., 2010. First observation of a mini-magnetosphere above a lunar magnetic anomaly using energetic neutral atoms, Geophys. Res. Lett., v. 37, L05103, doi: 10.1029/2009GL041721.