



## The sunlit lunar atmosphere: A comprehensive study by CHACE on the Moon Impact Probe of Chandrayaan-1

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### ARTICLE INFO

#### Article history:

Received 23 March 2010

Received in revised form

10 June 2010

Accepted 23 July 2010

Available online 6 August 2010

#### Keywords:

CHACE

Lunar atmosphere

Chandrayaan-1

Moon Impact Probe

### ABSTRACT

The altitudinal/latitudinal profile of the lunar atmospheric composition on the sunlit side was unraveled for the first time by the Chandra's Altitudinal Composition Explorer (CHACE) on the Moon Impact Probe, a standalone micro-satellite that impacted at the lunar south pole, as a part of the first Indian mission to Moon, Chandrayaan-1. Systematic measurements were carried out during the descent phase of the impactor with an altitude resolution of  $\sim 250$  m and a latitudinal resolution of  $\sim 0.1^\circ$ . The overall pressure on the dayside and the neutral composition in the mass range 1–100 amu have been measured by identifying 44 and 18 amu as the dominant constituents. Significant amounts of heavier ( $> 50$  amu) species also have been detected, the details of which are presented and discussed.

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### 1. Introduction

The Earth's Moon is known to have a delicate and tenuous atmosphere. Earlier attempts to make an assessment of the surface pressure yielded estimates that varied by several orders of magnitude. One of the earliest attempts (Fessenkov, 1943) through effects on polarization near the terminator estimated an upper limit of  $10^{-4}$  bar. Refined estimates (Dollfus, 1956) indicated pressures of the order  $10^{-9}$ – $10^{-10}$  bar. In addition, there had been several indirect estimates as well. The situation had not improved much till the Apollo era when systematic efforts were made to directly measure the surface pressure to start with and later, to measure the composition. In spite of four decades since the Apollo era, till this date, only the Apollo series measurements remain as authentic, both on the base level pressure and on the composition. This is in spite of the limitation that there had been no reliable measurements from the 'sunlit' side of the Moon due to the saturation of the instruments, which were believed to be due to outgassing from the space modules.

So far, three cold cathode gauges have been placed on the lunar surface by Apollo 12, 14 and 15 missions during the 1969–1971 time frame. While Apollo 12 instrument had a technical problem, Apollo 14 and 15 instruments gave some useful data. One of the serious problems faced by them had been due presumably to the

contamination due to outgassing from the space modules and also the detector, as these systems were left in extreme ultra-high vacuum, which otherwise cannot be created on Earth. The situation would get aggravated due to the enhanced temperatures on the sunlit side. The instruments got saturated right from the sunrise time, leaving a gap in our understanding of the dayside pressures. However, there had been no ambiguity in the nighttime values due to the prevailing low temperatures.

In the last of the Apollo series (Apollo 17), attempts were made to measure the composition using the Lunar Atmosphere Composition Experiment (LACE) by placing a sensitive mass spectrometer that had a mass range 1–110 amu and sensitivity to detect concentration as small as  $200 \text{ cm}^{-3}$ . Unfortunately, the LACE also suffered from saturation problem during lunar daytime (Hoffman et al., 1973) mainly due to the limited dynamic range and also the very slow scan rate. However, very significant results based on the lunar nighttime measurements have been reported in the literatures (Hodges, 1973; Hodges et al., 1972) with positive detection of helium ( $^4\text{He}$ ), which varied by a factor of 20 during a lunar diurnal cycle. The direct experimental confirmation for the  $^4\text{He}$  to be of solar origin has also been obtained (Hodges et al., 1972). The absence of species like H, C and N has been suggested to be due to their reduction to  $\text{H}_2$ ,  $\text{CH}_4$  and  $\text{NH}_3$  (Hodges, 1975). Further, the usage of LACE data for setting up an upper limit for  $\text{H}_2$  had been substantiated by the independent ultraviolet spectrometer, which was free of contamination problems. The Apollo 17 mass spectrometer, though confirmed the existence of helium, neon, argon and possibly molecular hydrogen in the lunar ambience, more favorably during sunrise conditions, upper limits have been arrived at only for helium and neon, which are once

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again model dependent. The model estimates were based on the solar wind as the primary source (Fastie et al., 1973). On the other hand, the isotopes of Ar, i.e.  $^{36}\text{Ar}$  and  $^{40}\text{Ar}$ , exhibited steep predawn enhancement, implying their condensable nature on the night side and getting released at sunrise as the surface warmed up. In fact the amazingly high adsorption potential of the lunar soil has been highlighted by Cook (1972). The total nighttime concentration has been estimated to be  $\sim 2 \times 10^5$  molecules/cm<sup>3</sup> (Fastie et al., 1973).

On the other hand, the spectrometers flown in the orbiters of Apollo 15 and 16 were believed to be so heavily dominated by the contaminants from the orbiter module that no detection or upper limits could be obtained (Hodges et al., 1972). Therefore, it could be seen that all the in-situ measurements attempted in the past encountered problems. Though the Apollo-17 optical techniques operated in the UV, to detect resonance fluorescence emissions characteristic of atmospheric species (Fastie et al., 1973), were void of any contamination effects, they too did not yield any significant positive results (Feldman and Morrison, 1991). They had inferred that nearly 100% of the solar wind protons should have been converted into H<sub>2</sub> and also have arrived at upper limits for H, O, C, N, Kr, Xe, H<sub>2</sub> and CO. Even with improved resonance fluorescence g-factors, little success had been met with Flynn (1998) in these attempts. Further, the claims (Alan Stern, 1999) from Earth based satellite measurements of Ar resonance line (1048 Å) were debated and the final suggestion that solar corona could be a potential source for Ar emerged.

Looking into the sort of the prevailing uncertainties, the need for reliable composition measurements has been repeatedly stressed in the literature (Alan Stern, 1999) and also in the vision documents of space agencies (The Scientific Context for Exploration of the Moon, National Research Council of the Academics, The National Academy Press, 2007).

In the light of the above, the comprehensive result from Chandra's Altitudinal Composition Explorer (CHACE) on the Moon Impact Probe of Chandrayaan-1, India's mission to moon, on the altitudinal/latitudinal composition of the sunlit side of the lunar atmosphere, 'the first of its kind', gains importance. This paper discusses these results from this maiden attempt.

It is worth mentioning here that CHACE provided the 'first' direct evidence for water in its vapour phase in the lunar ambience along with its latitudinal variation thus, complementing the results from the Moon Mineralogy Mapper in Chandrayaan-1 main orbiter (Sridharan et al., 2010).

## 2. Mission details

The Chandrayaan-1, launched on 22nd October, 2008, and captured by lunar gravity on 8th November 2008 had essentially two components, one orbiter intended to orbit the Moon at  $\sim 100$  km polar orbit with 10 experiments to explore the topographical features at high resolution and also the mineralogical composition. The experimental details are available elsewhere (Goswami and Annadurai, 2009). In addition, a standalone micro-satellite (34.6 kg) riding piggy back on Chandrayaan-1 had three experiments viz. a radar altimeter, a Moon imaging system and a mass spectrometer referred to as Chandra's Altitudinal Composition Explorer ((CHACE) (Ashokkumar et al., 2009)) to explore the tenuous atmospheric composition in the sunlit side. On 14th November 2008, this micro-satellite, called the Moon impact probe (MIP), was released from the mother spacecraft and, after a brief maneuver, was directed to impact in the south pole region, near the Shakerley crater, flying over the Malapert mountain *en route*. CHACE was switched on twenty minutes before the release of MIP from 40°N latitude at an orbital

altitude of 98 km. The instrument typically takes  $\sim 20$  min to warm up and the stabilization of the ion source filament emission current, which is essential while attempting to retrieve the actual number densities, revealed that it had become stabilized when the MIP was at 20°S lat. Details of the neutral composition obtained from 20°S and right up to the pole with an unprecedented altitude resolution of 250 m and a latitudinal resolution of 0.1° constitute the subject matter for this paper. The spacecraft, which was spin stabilized at 82 rpm, after separation at 13.3°S and 14°E, took an oblique trajectory and impacted very close to the south pole at  $\sim 89^\circ\text{S}$ – $30^\circ\text{W}$  longitude, thus realizing the mission objectives flawlessly.

Further, in order to have a health check, all the MIP experiments were switched on (except for the release of MIP) and all the spacecraft operations were performed for  $\sim 10$  min. This was carried out five orbits before the actual release of MIP from Chandrayaan-1. During this rehearsal phase, the MIP, mated to Chandrayaan-1, was put on in the actual operation mode and provided data on the total pressure along with the neutral composition in the region of 39°N to 9°N along the 20.8° E-meridian. Since the instrument did not yet reach the stable mode of operation, as revealed by the ion source emission current, the rehearsal phase data could be used only in the context of relative composition. However, the emphasis in the present paper pertains only to the actual mission that occurred after the instrument became stabilized and hence provides clues on the spatial heterogeneity of the lunar atmospheric composition. Fig. 1 depicts the ground track both during the rehearsal and the actual mission phase, along with the impact point of MIP. The previous Apollo landing sites are also marked on the lunar atlas.

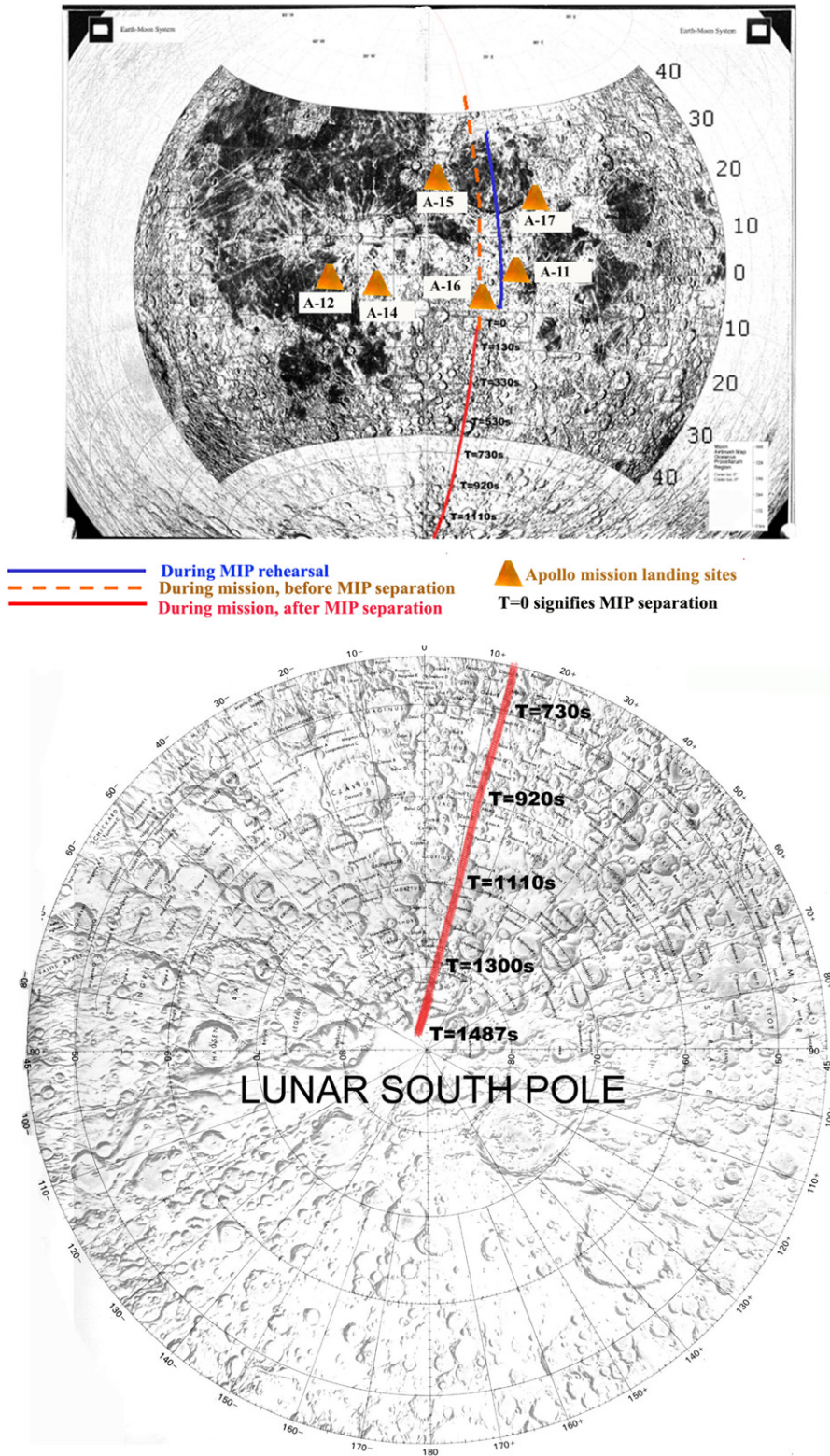
## 3. Methodology

CHACE is a quadrupole mass analyzer based instrument with its own inbuilt ion source and an ionization gauge for total pressure, configured along Bayard–Alpert geometry and calibrated for nitrogen. Fig. 2 depicts CHACE in its actual flight configuration. It featured a highly sensitive electron multiplier in the detector stage along with a conventional Faraday cup. It had a dynamic range that spanned  $\sim 9$  orders of magnitude for both the types of detectors put together. It had better than 'unit mass resolution' in the entire range 1–100 amu and the entire mass range was scanned in 4 s. The ultimate detectable partial pressure was  $< 10^{-13}$  Torr.

## 4. Outgassing issues

When composition measurements are attempted at extremely low pressures i.e., at ultra-high vacuum levels, the measurements getting contaminated by outgassing from the surroundings including the spacecraft and the measuring device cannot be totally avoided. It is all the more so, when measurements pertain to water vapour and its derivatives as they are inherently embedded in the basic materials used in the fabrication of the measuring device itself. It may be recalled that all the earlier attempts to measure the total pressure using a cold cathode gauge and also the atmospheric composition using a mass spectrometer (LACE) during the Apollo era resulted in the saturation of the devices themselves (Alan Stern, 1999 and the references therein). The swarming of the sensors and their eventual saturation by the large number of gaseous species were ascribed to the possible outgassing from the surroundings including the satellite systems. In spite of obtaining good spectra well within the dynamic range of the instrument during lunar nighttime that

### Ground Track of the MIP



**Fig. 1.** Top: ground track of the MIP during rehearsal and mission projected on the lunar atlas at lower and middle latitudes. The Apollo mission landing sites are also marked. Bottom: the ground track at higher latitudes up to the impact point.

extended up to lunar sunrise time, the thought of contamination due to outgassing had outweighed the measurements and hence data other than those corresponding to noble gases were not considered by the previous workers.

All the earlier measurements were from the respective landing sites while in the case of CHACE onboard MIP it provided latitudinal and altitudinal variations of the lunar atmospheric composition. As it had been a ‘one shot’ measurement during



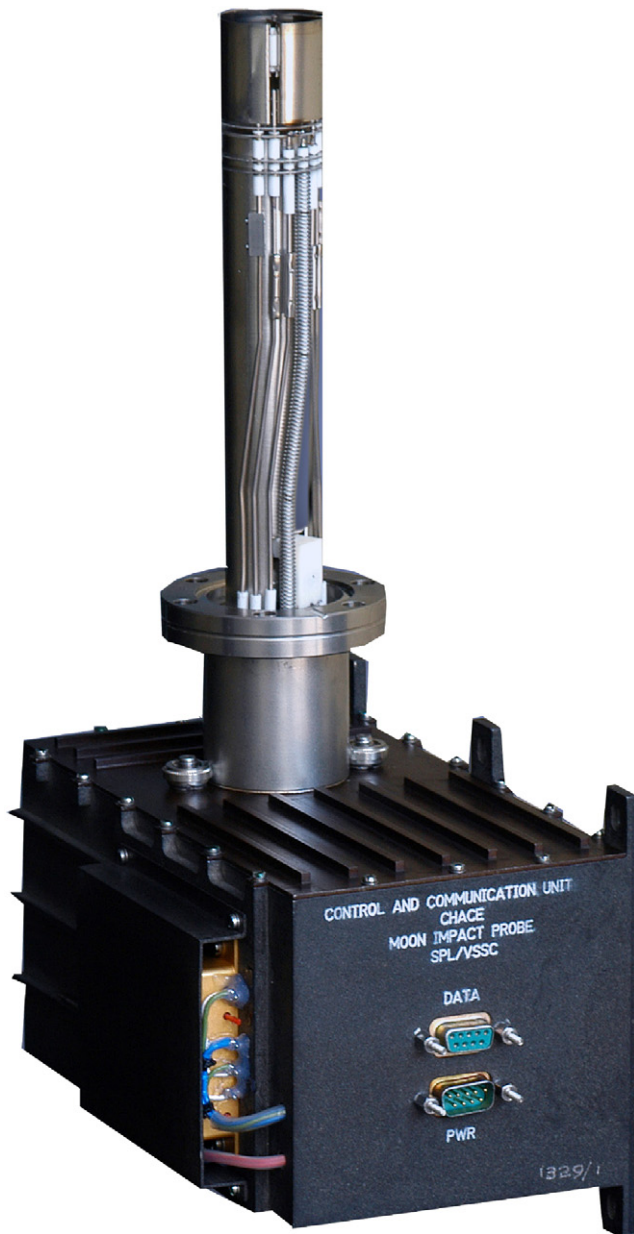


Fig. 2. CHACE payload in its flight configuration.

which it is safe to consider that the instrumental parameters, including outgassing if any, had remained constant thus enabling measurements of the ambient species in the light of its background. While all the care had been taken in the preparation of the instrument, extensive laboratory tests have been carried out at the UHV ( $10^{-8}$ – $10^{-9}$  Torr) levels on the sample materials that have been used in the spacecraft manufacture and that could be a worrisome cause from the degassing point of view. Literally every such sample had been characterized with its outgassing properties, that too at elevated temperatures of  $250^{\circ}\text{C}$ . The characteristic signature peaks had been identified and recorded in the laboratory conditions.

In addition, the exposure of the probe for deep space vacuum *en route* to Moon for  $\sim 3$  weeks, though in a passive condition, is also believed to have helped to reduce the outgassing effects. However, it must be mentioned that the mass spectrometer was switched on only in the lunar environment after the main orbiter Chandrayaan-1 reached 98 km near circular orbit. Since this experiment was a part of the Moon Impact Probe, a micro-satellite riding piggy back on the main orbiter, it had power constraints that did not permit operation of CHACE *en route* to the Moon. Few sample spectra representing the deep space and also the outgassing specie from the satellite system would no doubt have provided a reference, in the backdrop of which one could have easily highlighted only the lunar constituents. It was not to be; leaving the quantification of the contamination issue an open question. In the absence of such a reference, one has to seek recourse to the presence/absence of characteristic features of the substances that have outgassing potential and also looking for significant differences in the concentration of the measured species; (i) when MIP was connected to the main orbiter Chandrayaan-1 that weighed nearly twenty times that of MIP and as much more voluminous and (ii) when it was detached and on its way to the lunar surface.

One would have normally expected a spurt of outgassing from the instrument ion source the moment it is switched on. However, no such effect was seen in the case of CHACE. The behavior was like in the case of an analyzer kept under ultra-high vacuum conditions for a prolonged time before switching on. Under such conditions the spectral peaks would gradually build up and would reach a steady state value rather than decreasing with time. This is more so in an instrument that is dynamically controlled with the emission current forming a part of the feedback loop in the ionizer. It is interesting to note that none of the characteristic features of the potential degassing materials were present in the measured spectra. In addition, there had been no significant change in the spectra (Fig. 3a and b) when the MIP was attached

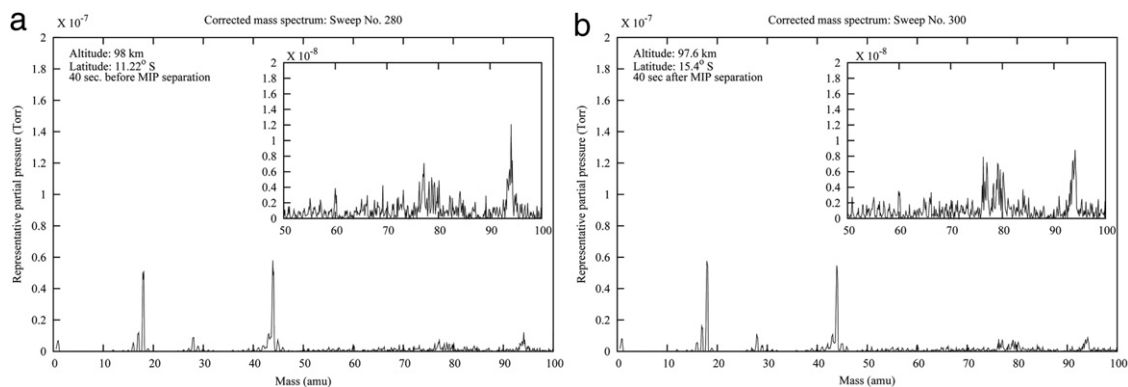
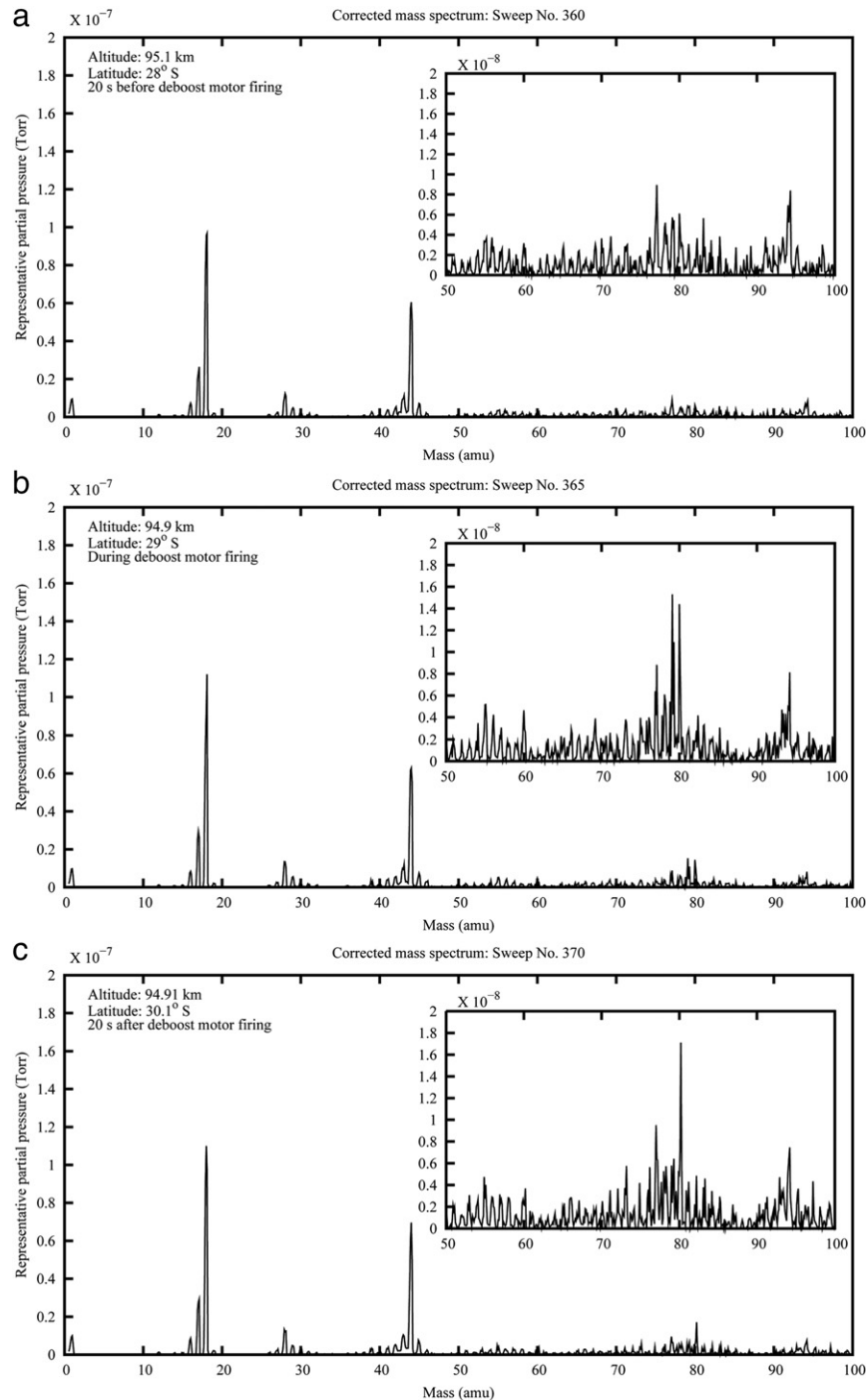


Fig. 3. (a) spectrum from CHACE payload 40 s before the event of MIP separation. (b) spectrum 40 s after MIP separation. The comparison between the spectra indicates that there has been no effects of outgassing on the obtained spectra.

and detached from the main orbiter indicating that the outgassing, if at all there had been any, had not affected our measurements. Further, critical examination of the spectra obtained during the brief firing of the deboost motor for  $\sim 3$  s during the separation of MIP from the main orbiter also revealed practically no change (Fig. 4a–c). Further, the orientation of CHACE having a very narrow acceptance angle and its mounting on MIP was kept such as to avoid the outgassing specie, if any, from directly getting sampled by the instrument. With the spacecraft velocity being  $\sim 1.6$  km/s, any outgassing specie with thermal velocity will not be able to make it to the entrance orifice of CHACE.

All the above clearly indicate that outgassing issues are not any major concern in this experiment. Saturation of the instrument had been avoided ensuring a very large dynamic range  $\sim 9$  orders of magnitude for both types of detectors viz., the electron multiplier and the Faraday cup put together and choosing a fast scan rate of one complete spectra in four seconds.

Another salient feature of CHACE is its in-built hot cathode ionization gauge with Bayard–Alpert configuration, which makes use of the same ion source as that of the mass analyzer. Any change in the ion source parameters would get promptly reflected in both the total pressure and also in the mass concentration. Under stable operating conditions (i.e., when the ion source



**Fig. 4.** (a) spectrum obtained 20 s before deboost motor firing. (b) spectrum during deboost motor firing. (c) spectrum 20 s after deboost motor firing. No significant changes in the spectrum observed.

emission current remains steady and also when the spectral amplitudes remain constant for a given ambient condition), since the ionization gauge has been calibrated against a laboratory standard Bayard–Alpert ionization gauge, normalizing the sum of the individual peaks to the total pressure would enable retrieval of the individual partial pressures. On the other hand, the ionization gauge calibration is dependent on the dominant species in the medium. For laboratory applications it is calibrated to nitrogen. During exploratory investigations of planetary atmospheres including that of the lunar atmosphere, the mass analyzer gives us information about the dominant species using which the ionization gauge values could be corrected before normalizing the sum of all the individual mass peaks. This distinct advantage has been made use of very effectively in CHACE. Further, due care has been taken while normalizing the sum of the individual species as the quadrupole mass filter is known to have mass dependent sensitivity and so is the case with the electron multiplier. The electron multiplier gain (EMG) correction formula for the flight model of CHACE was determined experimentally and was applied over the entire mass range to compensate the mass dependence of the electron multiplier gain. Using a reference sample like perfluoro tributyl amine (PFTBA), whose relative concentrations are well known, the quadrupole mass discrimination (QMD) of the mass analyzer was established. These mass discrimination corrections have been duly applied to the resultant mass peaks before normalizing the sum of the individual peaks.

## 5. Results and discussion

Though CHACE was operated twice during the mission, once for a short duration of 10 min in a rehearsal mode and the second time for  $\sim 44$  min, the data corresponding to the last 24 min during the mission alone are presented in this paper. This is due to the fact that CHACE takes  $\sim 20$  min to stabilize due to the complex feedback system employed invoking the filament emission current in the feedback loop. For any reliable measurements of individual species the emission current has to remain constant. Since during the rehearsal mode when the spacecraft

covered from  $40^\circ\text{N}$  to  $10^\circ\text{N}$  CHACE was operated only for  $\sim 10$  min, far short of the stabilization requirement, these results are not taken up for further discussion in this paper. On the other hand, during the actual mission the spacecraft moved from  $\sim 40^\circ\text{N}$  to  $13.3^\circ\text{S}$  in the first 20 min and the emission current became almost stabilized by then (the MIP was still attached to the main orbiter Chandrayaan-1). At the time of release of MIP, CHACE became stabilized and had provided data up to the point of impact. Though relative composition could still be obtained both during the rehearsal and the initial mission phase, it has not been taken up for further discussion and the data pertaining to the last  $\sim 24$  min alone are presented and discussed in this paper.

One of the striking results is the presence of large number of species in the mass range 1–100 amu in significant concentrations and also the one pertaining to the total pressure indicated by the ionization gauge that had a large dynamic range  $10^{-4}$ – $10^{-10}$  Torr. The ionization gauge readings have been corrected to the dominant species revealed by the mass analyzer. The most significant mass numbers were 18, 44 and 28 amu, out of which the latitudinal/altitudinal distribution of 18 ( $\text{H}_2\text{O}$ ) amu had been investigated earlier and had been provided as ‘direct’ evidence for the presence of water molecules in the tenuous lunar atmosphere by Sridharan et al. (2010). They had shown how CHACE results complemented the discoveries by the Moon Mineralogy Mapper ( $\text{M}^3$ ) (Pieters et al., 2009) in the same mission. Since  $\text{H}_2\text{O}$  and its derivatives cannot be avoided from any measurement system, their presence had been seen all through the operation of CHACE. It would become difficult to separate out the contribution from the lunar ambience. Sridharan et al. (2010), taking recourse to the  $\text{M}^3$  results and also making use of the available data on the saturated vapour pressure of ice with temperature (Wexler, 1977), could bring about the complementarities of CHACE and  $\text{M}^3$  results. Having demonstrated this aspect, it now becomes possible to extend the data up to  $20^\circ\text{S}$  latitude as well. The arguments are based on the fact that outgassing from the instrument, especially from hot areas surrounding the filament, would remain constant all through the short duration missions like CHACE. It would not show any altitudinal/latitudinal variation. Further, in none of the laboratory calibration studies,

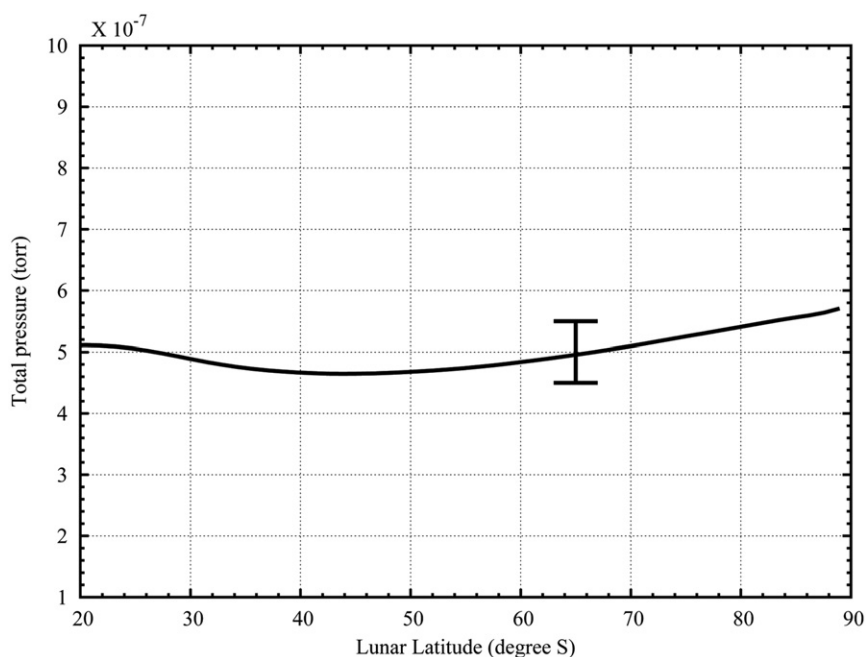
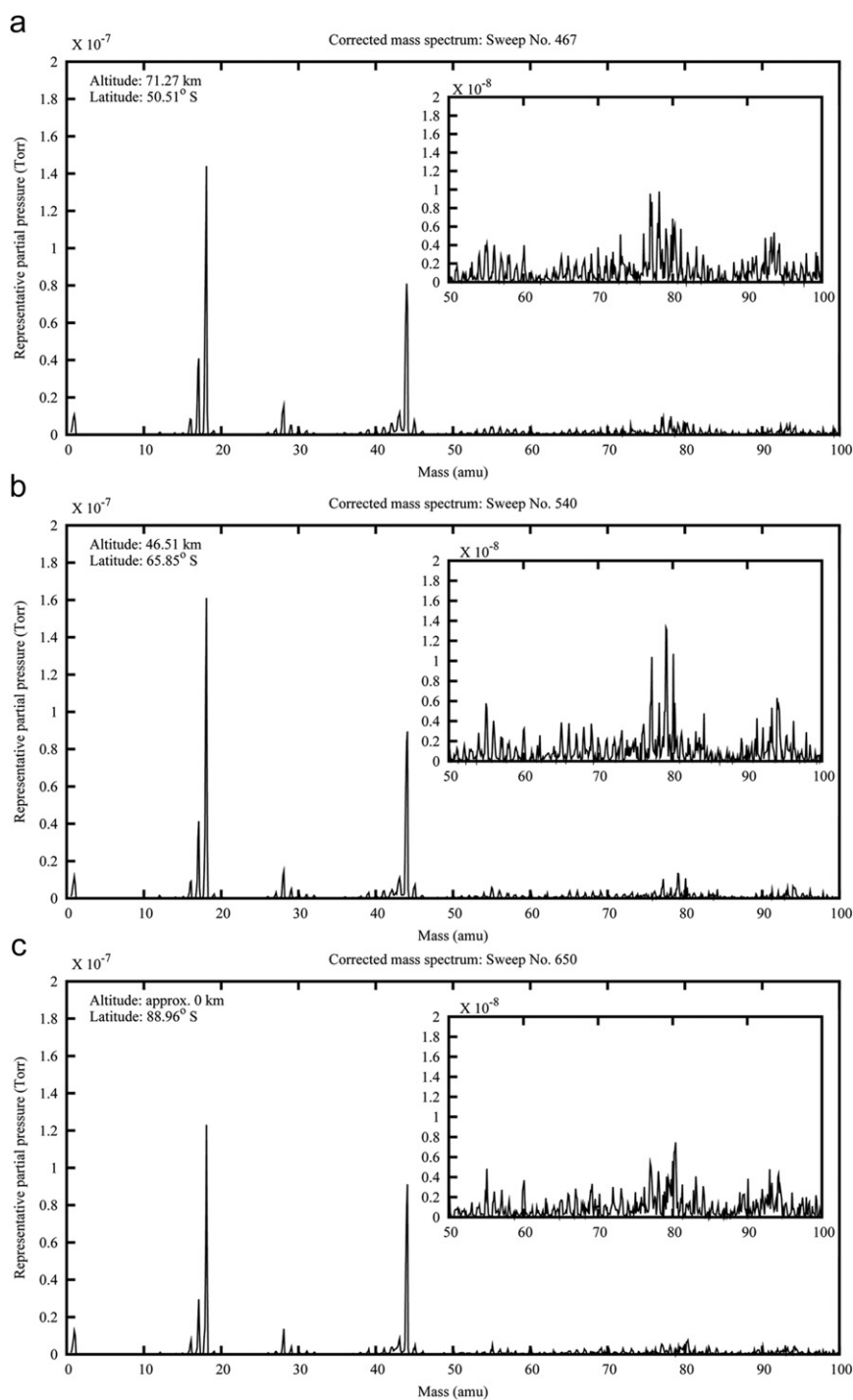


Fig. 5. Latitudinal variation of total pressure in the sunlit side of Moon. Beyond  $20^\circ\text{S}$  the instrument obtained data under fully stabilized condition.

44 amu ( $\text{CO}_2$ ) had come out so explicitly as one of the dominant species. The ratio 44–18 amu in the laboratory had always been  $\leq 0.1$  while in the actual mission it had even gone up as high as 7 during the initial stages i.e., during the first 20 min. Such high values are mentioned as they refer to the relative composition (ratio) and are discussed any further during the discussion on the partial pressures due to individual species. In fact, giving allowance for  $\text{H}_2\text{O}$  of instrumental origin, the ratio is likely to be significantly larger for the lunar ambience. Therefore, it is believed that the  $\text{CO}_2$  detected by CHACE is of lunar origin only, which is the first direct (*in situ*) experimental confirmation of the

prediction regarding the  $\text{CO}_2$  dominance of the sunlit lunar atmosphere (Oepik, 1962). The correction factor of 1.4 corresponding to  $\text{CO}_2$  has been made use of for the ionization gauge readings.

Fig. 5 depicts the variation in the total pressure beyond  $20^\circ\text{S}$  as recorded by the ionization gauge, with the gas correction factor applied. The pressure had remained at  $5 \pm 0.5 \times 10^{-7}$  Torr all through the latitude range, from the equator to the poles. Because it is surface boundary exosphere in the case of the moon, the latitudinal variation of temperature appears to compensate for the altitude as the Moon Impact Probe descended from its release altitude of 98 km. As mentioned earlier, these measurements,



**Fig. 6.** A set of sample spectra obtained during the mission. (a) Spectrum at an altitude of 71.2 km and a latitude of  $50.51^\circ\text{S}$ . (b) Spectrum at an altitude of 46.51 km and a latitude of  $65.8^\circ\text{S}$ . (c) Spectrum at the impact point at lunar south pole.



incidentally, happen to be 'the first set' from the 'sunlit' side of the moon. The pressures are at least two orders of magnitude larger than what had been anticipated based on the night side measurements using the cold cathode gauges in the Apollo missions cited earlier. The significantly higher pressures only indicate the complexity in the desorption process and these aspects are discussed later. Before addressing the trend shown by the individual species, some sample spectra representative of different latitudes/altitudes in a linear scale, are presented through Fig. 6a–c. Though the instrument has a large dynamic range ( $\sim$ nine orders of magnitude) a linear scale is chosen so as to highlight only the major species and those that form  $> 1\%$  of the total. The large number of heavier species  $> 50$  amu, concentrated only in certain locations, revealing significant spatial heterogeneity is considered important. These heavier species are zoomed in (by a factor of ten) and shown as an inset in the above figures. They form 1–2% of the total concentration. It is known that 55, 56 and 57 amu register their presence invariably in any sensitive composition measurements and are generally treated as of instrumental origin. When we compare the ratio of their respective densities in the laboratory spectra for 55/56 and 56/57 (1.75 and 0.88) in the actual mission data it is noted that the ratios are significantly different ( $\sim 1.3$  and  $\sim 1.15$ ) in addition to large latitudinal variation implying that there could be significant lunar contribution of 55 and 56 amu corresponding to manganese and iron. These heavier species could be released due to the interaction of energetic particles with the lunar surface. More detailed analysis is called for.

The latitudinal/altitudinal trends of the partial pressures of the different species that constitute  $> 1\%$  of the total pressures are depicted in Fig. 7. The dominance of  $\text{H}_2\text{O}$  and  $\text{CO}_2$  followed by 28 amu ( $\text{N}_2/\text{CO}$ ) could be clearly seen. The close similarity in the trends of 18 and 17 amu indicates that the latter could in all probability be due to the dissociation of  $\text{H}_2\text{O}$  into OH radical and hydrogen. Similarly fragmentation of  $\text{CO}_2$  into CO and O is also highly probable. From the available literatures (Yukikazu, 2002; McConkey et al., 2008) electron bombardment ionization with an energy of  $\sim 70$  eV,  $\text{CO}_2$  could result in  $\sim 15\%$  of it manifesting as

CO. The observed ratio of 44/28 in the present case is  $\sim 4$ , which would mean contribution to 28 amu from other specie, most probably is  $\text{N}_2$  could be around 40% of the measured concentration. Similarly 16 amu could also be a resultant of the fragmentation of  $\text{CO}_2$  and  $\text{H}_2\text{O}$ . In fact, published literature reveals the ratio 44/16 ratio could be as high as 10 (McConkey et al., 2008). CHACE does not show such high ratios implying loss of O in the system due to its highly reactive nature. Quantification of atomic oxygen becomes rather difficult. Further, the 94 amu peak was one of the significant peaks in the higher mass range, which was not found in any of the laboratory test spectra. Exact identification of the specie may call for detailed analysis. The trend of 94 amu decreased up to  $80^\circ\text{S}$ , and subsequently showed an increasing trend beyond  $80^\circ\text{S}$ . At  $80^\circ\text{S}$  latitude, the altitude of measurement corresponded to 15 km. The scale height of 94 amu in the lunar environment is  $\sim 8$  km assuming a surface temperature of 160 K at  $80^\circ\text{S}$ . Hence, its increasing trend seems to be of lunar origin. The signature of heavier species with such less scale heights at higher altitudes ( $\sim 98$  km) would become possible only through strong interaction with the high energy particles of solar wind origin and through a chain of electro dynamical processes. Once they reach greater heights, they would be suspended in the atmosphere for considerable amount of time before finally settling down. CHACE has highlighted the need for more such measurements before arriving at any firm conclusion.

The individualistic trend shown by the different species only confirms the prevalence of surface boundary exosphere over the moon. These results are discussed below in the context of our present understanding.

## 6. Discussion

From the trend curves it is seen that 18 amu ( $\text{H}_2\text{O}$ ) and 44 amu ( $\text{CO}_2$ ) had remained as the most dominant species. The trend of 18 amu had been shown to be complementary to that obtained through Infrared absorption spectroscopy of water ice in the lunar regolith (Sridharan et al., 2010). When water is available in the

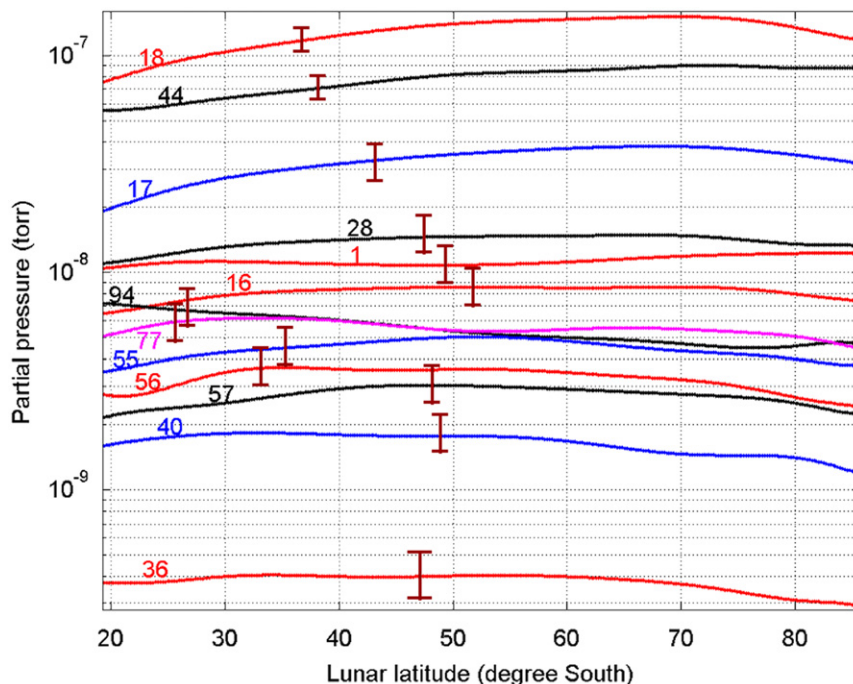


Fig. 7. Latitudinal trends of some significant species as detected by CHACE.



form of ice, water vapour must also be present to the extent of its saturated vapour pressure, which is strongly dependent on temperature as shown in Fig. 8 (Wexler, 1977). Therefore, even at very low polar temperatures of the order 120–150 K, water vapour partial pressures could be of the order of  $10^{-7}$  Torr ( $1.33 \times 10^{-5}$  Pa). CHACE results appear to vindicate the above conclusion.

It is also known that the dayside lunar surface temperature has a very large latitudinal variation with the equatorial region reigning as high as 400 K and the poles going as low as 120–150 K. In the case of surface boundary exosphere all the individual species, due to lack of collisions, have their own scale height mainly dictated by the surface temperature at that location i.e., at a particular lunar latitude in this case. If one is able to get the latitudinal/altitudinal distribution of any inert atmospheric specie one could estimate the latitudinal temperature gradient. The outcome of an exercise with  $^{36}\text{Ar}$  was carried out, with an assumption of an equatorial temperature of 400 K and the expected gradient along with a cosine model based on CHACE measurements, is depicted in Fig. 9. The surface temperature could be inferred to be below 273 K beyond  $60^\circ\text{S}$ . Incidentally, the Moon Mineralogy Mapper on Chandrayaan-1 also revealed the

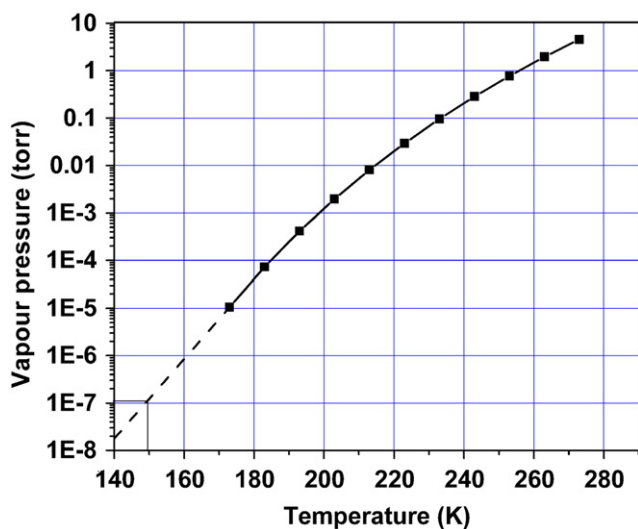


Fig. 8. Variation of the vapour pressure of water with temperature (Wexler, 1977). Near the lunar pole, where the temperature is  $\sim 150$  K, the vapour pressure of water is extrapolated and found to be  $\sim 10^{-7}$  Torr.

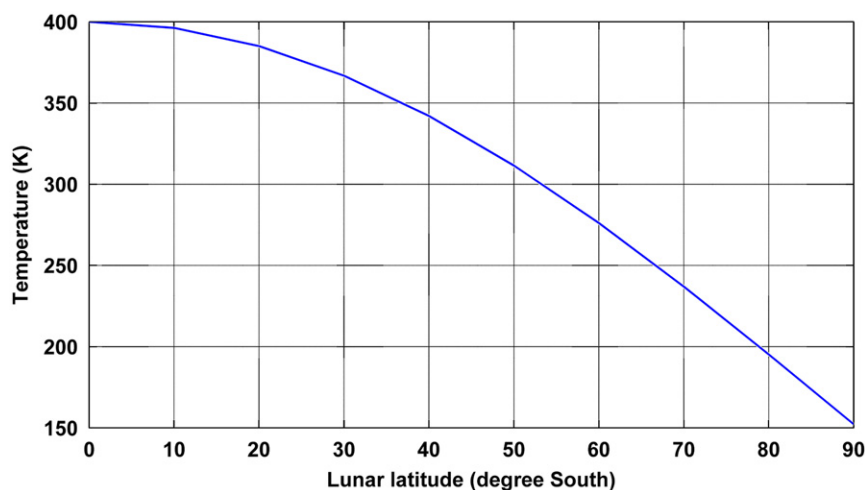


Fig. 9. Lunar surface temperature profile modeled with reference to the variation of the specie  $^{36}\text{Ar}$  with an assumption of the equatorial temperature of 400 K.

presence of water ice on the lunar surface beyond this latitude only (Pieters et al., 2009). This is in addition to the discovery made by the mini SAR experiment in Chandrayaan-1 where in around 40 deep craters in the north pole, that are permanently in the shadow, containing large amount of water ice (Spudis et al., in press) have been reported. The background information provided by CHACE supports these findings.

Further, it is interesting to make a comparative study of CHACE results with the published (Hoffman et al., 1973) Apollo 17 results (Fig. 10). During the Apollo era, measurements during sunrise time happened to be the closest sunlit period measurements. A comparative study of the mass spectra reveals that LACE too had detected quite a few species that included 18, 36, 30 and 44 amu

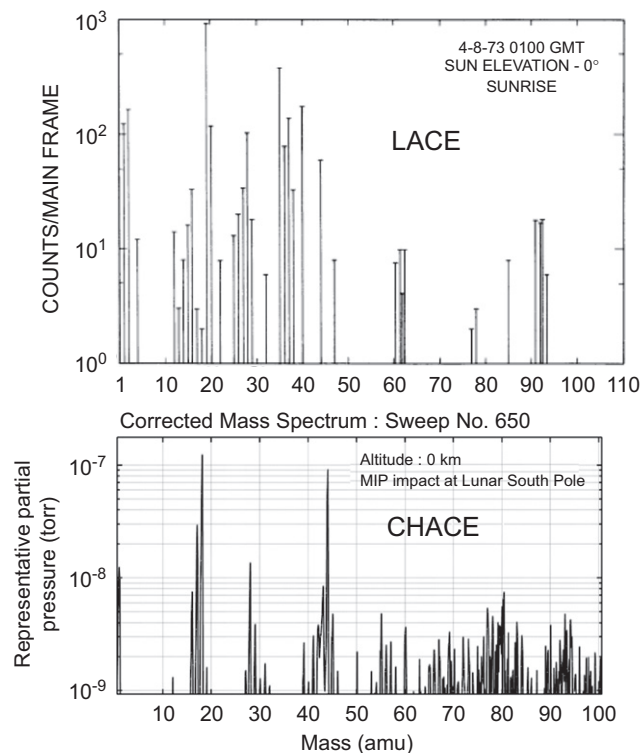


Fig. 10. Comparison between the mass spectra obtained by LACE in Apollo 17 mission (top) (Hoffman et al., 1973) and CHACE in Chandrayaan I mission (bottom). The former corresponds to over the surface, at equatorial region and sunrise time while the latter corresponds to close to the surface over south pole.

and also heavier species ( $>75$  amu) cluttered around 60 and 90 amu. On the other hand, CHACE revealed 18, 28 and 44 amu as the dominant ones in addition to a clutter of species  $\sim 80$  amu. The LACE spectra correspond to over the surface from equatorial region at sunrise hours, when all the loosely adsorbed gaseous species and condensable vapours would be getting desorbed. One would expect to see complex spectra with large concentration of different species. On the other hand, during local noon hours, the desorption process would have become stabilized resulting in relatively simpler spectra. In addition, close to surface measurements by CHACE are from the polar region (Fig. 10) where the desorption effects would be significantly less. CHACE–LACE comparison appears to support the above line of thinking (Fig. 10). The most interesting observation that is highlighted here is the presence of almost all the dominant species in both the spectra though in varying amounts. The nature of the spectra and their comparison indicate that, ruling out all the other constituents apart from the inert gases as contaminants in the LACE measurements, may have to be revisited and in all probability a wealth of data are available even from LACE, in spite of they being restricted only to nighttime conditions.

The very significant observation by CHACE on the total pressure being at least two orders of magnitude larger than that anticipated calls for a viable explanation; whether there had been a real increase in the last four decades or it is due to certain episodic events or it is a natural process that had not been fully accounted for in the previous estimates.

Though the first two mechanisms could not be ruled out based on the limited measurements available and, as on this date no episodic events have been reported, the third possibility needs particular attention. All along in the literature, adsorption, desorption, sputtering, meteoritic and internal sources, etc. have been identified as possible causes for the lunar atmospheric evolution and these have been very comprehensively reviewed by Alan Stern (1999). The day and night sides go through a temperature cycle of 100–400 K during which the lunar regolith, that provides a large surface area could act as an adsorbent material. It has also been reported that there exists enormous adsorbing potential of the volatiles and as well as rare gasses. Cook (1972) had investigated the rare gas data from the lunar solids and found that the accommodation coefficient for rare gases in the lunar regolith and the structural adsorption coefficient on lunar solids were amazingly high. With this property and also due to the intense surface activation of the lunar surface due to the large thermal cycling and the inherent UHV ambience, reduction of the night side pressures by 5 orders of magnitude (from  $10^{-7}$  to  $10^{-12}$  Torr) when cooled to  $\sim 120$  K is indeed feasible. Under such circumstances, one would start experiencing the buildup of the partial pressures, including that corresponding to water vapour, as the sun rises and as the surface warms up. Apollo measurements do confirm such effects. Therefore, the variation of day and nighttime pressures is highly dynamic and would show a natural rhythmic variation. More systematic measurements with a large dynamic range as CHACE had, preferably in a lunar orbiter, would provide clear-cut answers to these questions. The need for such measurements is of utmost priority and has to be carried out before any irreversible changes occurred in the lunar atmosphere, which itself is extremely delicate.

It has been stated that the gas release during the landing and takeoff of a lunar module is comparable to the total lunar atmospheric density. However, it is construed that, within a couple of months the system would revert to its initial state. On the other hand, when large chunks of material are left on the lunar surface, they would become perennial source of outgassing, especially if it happens to be in the sunlit portion and hence

would contribute to the spatial heterogeneity. In the absence of collisions and lack of fluid nature of the tenuous lunar atmosphere, these inhomogeneities would be left undisturbed except for the thermal gradient induced transport (Hodges and Johnson, 1968) that has been invoked to explain the pre-sunrise build-up. In addition, the currently ongoing exploratory missions too would alter the balance. This calls for continuous monitoring of the lunar ambience and the CHACE experiment had been the first step in this direction.

## 7. Conclusion

The significantly large background pressure on the sunlit side of tenuous lunar atmosphere as measured by CHACE highlights the large spatial inhomogeneity surpassing the outgassing from the spacecraft systems if any. The significant amount of  $\text{CO}_2$  and large enhancement in  $\text{H}_2\text{O}$  beyond  $20^\circ\text{S}$  in addition to the significant presence of the heavier species are considered very important results. The distinct possibility of the fragile lunar atmospheric system getting altered due to the impact of the past and present exploratory missions does exist and a systematic investigation is called for addressing this issue.

## Acknowledgements

This work was supported by the Indian Space Research Organization, Department of Space, Government of India. The constant encouragement from Dr. G Madhavan Nair, then Chairman ISRO, Secretary DOS, is duly acknowledged. The significant support extended by the MIP Project Team and Chandrayaan-1 mission team is duly appreciated.

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