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Short Communication

The spatial distribution of molecular Hydrogen in the lunar atmosphere—New results

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ABSTRACT

The measurements carried out by Chandra's Altitudinal Composition Explorer (CHACE) onboard the Moon Impact Probe (MIP) of Chandrayaan I mission is used to obtain information on the 2-D distribution of the lunar atmospheric H_2 by a novel approach that makes use of the basic fact that the Moon has a Surface Boundary Exosphere (SBE).These are the ‘first’ daytime in situ measurements of lunar H_2 covering the 20°S to 88°S latitude region centered ~14°E longitude. A critical examination of the observed spatial features of the surface number density of H_2 vis-à-vis the surface topography delineated from the Lunar Laser Ranging Instrument (LLRI) in the main orbiter Chandrayaan-I, indicates that that lunar surface process may be important in introducing small scale variations in the H_2 number density. Another constituent which exhibited spatial variation in the observed partial pressure is ^{40}Ar and it was hypothesized that it is indicative of the spatial heterogeneity in the radiogenic activity of the Lunar interior (Sridharan et al., 2013a). The absolute number density at the surface and also the latitude/altitude variation of the densities that are reported for the first time, highlight the complexities of the sunlit lunar atmosphere.

1. Introduction

The lunar atmosphere is known to be extremely tenuous and falls in the category of Surface Boundary Exosphere (SBE), implying that the scale height is much smaller than the mean free path, which means there are no inter-molecular collisions and *the region is nearly isothermal*. The first in situ measurements of the composition of the lunar atmosphere were made during the Apollo-17 mission using a mass spectrometer—the Lunar Atmosphere Composition Experiment (LACE), which was physically deployed by the astronauts on the lunar surface (~20°N latitude). The LACE ran into saturation during sunlit times mainly for want of a larger dynamic range and, due to this limitation, it had provided data only during night time conditions. The LACE night time data confirmed the existence of Helium, Neon and Argon in the lunar atmosphere, and the several other detected species were doubted to be of non-lunar origin, essentially from the out-gassing during the astronauts′ extra-vehicular activity and also from the materials left behind, including the Lander (Hoffman et al., 1973). It was suggested that most probably molecular Hydrogen [H_2] existed in the lunar atmosphere, and it must have had its origin in the lunar surface (Hoffman et al., 1973). In fact, the LACE had measured a H_2 surface density of $6.5 \times 10^4\ cm^{-3}$ at night, which agreed with the predictions by Hodges (1973). On the other hand, the ^{40}Ar number density reported by LACE was $\sim 10^4\ cm^{-3}$ during pre-dawn hours.

Apart from LACE, there was a UV spectrometer on Apollo 17, which also detected similar levels of H_2 ($\sim 10^4\ cm^{-3}$). On the other hand, the estimated atomic Hydrogen abundance was too low, i.e., $\sim 10\ cm^{-3}$ (Fastie et al., 1973). This was interpreted as an indication for the conversion of the majority of the solar wind protons as H_2 at the lunar surface and its re-emission to the atmosphere in accordance with the lunar surface temperature. The upper limits of H_2 at the Apollo-17 site (Hodges et al., 1974) also qualitatively agreed with this hypothesis. Later, using the Apollo-17 UV spectrometer data, Feldman and Morrison (1991), provided more stringent upper limits to the number densities of H ($17\ cm^{-3}$), and H_2 ($9000\ cm^{-3}$). On the other hand, Wurz et al. (2012), based on the previously reported upper limits, arrived at H_2 number density of $\sim 5 \times 10^4\ cm^{-3}$ and ^{40}Ar number density of $\sim 4 \times 10^4\ cm^{-3}$ near 10 km above the lunar surface on the dayside, at a temperature of 400 K.

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Recently, the twilight observations of the lunar atmosphere made by the LAMP instrument aboard NASA′s Lunar Reconnaissance Orbiter provided upper limits for 27 species, primarily neutral atomic and molecular, which are significantly lower than the previous upper limits (Cook Jason et al., 2013). They reported an upper limit of $2.3 \times 10^4\ \mathrm{cm}^{-3}$ for Argon, which is ~1.5 times lower than the upper limit given by LACE. Their observations also showed that the abundance of H_2 is lower by more than an order of magnitude compared to the previous reports, with a surface density of $1.7 \pm 0.4 \times 10^3\ \mathrm{cm}^{-3}$ at dusk increasing to $2.1 \pm 0.3 \times 10^3\ \mathrm{cm}^{-3}$ at dawn. Using the same dataset, Stern et al. (2013) reported the presence of H_2 in the native lunar atmosphere, and obtained an ‘effective’ vertical column density of $\sim 6 \times 10^9\ \mathrm{cm}^{-2}$. From these values, they arrived at a surface density of $\sim 1.2 \times 10^3$ at 120 K, which is significantly lower than the previously reported values. However, it must be mentioned here that the spectrum used for the above estimation has been averaged over many different column lengths throughout the mission, and hence they are referred to as an ‘effective’ (averaged) vertical column density.

The most recent attempt to study the tenuous lunar atmosphere is through the Lunar Atmospheric and Dust Explorer Experiment (LADEE) that has just completed its mission and the results are yet to become available. LADEE is expected to provide the significant differences between the day and night side of the Moon due to its near equatorial orbit in addition to providing data on the altitude/longitude variation of the number densities of the different species. In view of the prevailing uncertainties regarding the lunar atmospheric H_2 abundances and the dearth of in situ measurements in the lunar daytime, our understanding on these species still remains incomplete.

India's first mission to Moon, the Chandrayaan-I had made several new findings. As mentioned earlier, the Sub-keV Atom Reflecting Analyzer (SARA) instrument on Chandrayaan-I showed that up to 20% of the impinging solar wind protons are reflected from the lunar surface back to space as neutral Hydrogen atoms (Wieser et al., 2009; Vorburger et al., 2013). The SARA instrument also provided the first image of a lunar magnetic anomaly in backscattered Hydrogen atoms (Wieser et al., 2010). However, the above measurements pertain only to the energetic neutral atoms. The Chandrayaan-I had also carried a stand-alone micro-satellite (34.6 kg) riding piggy back on it. This micro-satellite called as the Moon Impact Probe (MIP) (Ashok kumar et al., 2009) had three experiments viz., i) a *radar altimeter*, ii) a *Moon imaging system* and iii) a *mass spectrometer* referred to as Chandra's Altitudinal Composition Explorer (CHACE). The main objective of CHACE had been to explore ‘for the first time’ the tenuous atmospheric composition in the sunlit side. On 14th November 2008, the MIP was released from the mother spacecraft at 13.3S which took an oblique trajectory and finally impacted near the South Pole region, and while doing so, CHACE made measurements of the latitudinal and altitudinal variation of the lunar atmospheric composition till its impact on the lunar soil. One of the significant discoveries of CHACE had been the *first direct* detection of H_2O (in vapor phase) in the tenuous lunar atmosphere, over an extended latitudinal region (Sridharan et al., 2010a). Apart from the detection of H_2O, CHACE also provided the details of the atmospheric composition in the sunlit side in addition to the total pressure in-situ. Initially the overall pressure on the dayside of the lunar atmosphere as indicated by the laboratory calibrated ionization gauge was found to be of the order of 10^{-7} Torr ($\sim 10^{-5}$ Pa) with 44 (CO_2) and 18 (H_2O) amu as the dominant constituents (Sridharan et al., 2010b). At a first cut it may appear that these values indicated a much denser atmosphere than previously presumed (e.g., Dollfus, 1956; Stern, 1999 and the references cited therein). It had been clarified through a note (Sridharan et al., 2014) that what has actually been recorded is without taking the velocity of the probe through the medium into account and when one wants to estimate the actual number density of any of the measured species this factor has to be accounted for. The volume correction factor turns out to be 10^4 implying that the actual pressure values were $\sim 5 \times 10^{-11}$ Torr ($\sim 6.5 \times 10^{-9}$ Pa). The total number densities corresponding to this pressure, after duly accounting for the calibration factors of the instrument, turns out to be $\sim 10^6\ \mathrm{cm}^{-3}$. The sum of the relative amplitudes of different mass constituents has to be normalized to this value and only then individual densities could be estimated. While the significant presence of the heavier species (around 60 and 90 amu) was also detected by CHACE (Sridharan et al., 2013b) the CHACE data further revealed large spatial heterogeneity in the radiogenic activity of the lunar interior inferred using the measurements of the relative composition of the isotopes of Argon (Sridharan et al., 2013a). When the total densities are of the order of $10^6\ \mathrm{cm}^{-3}$, the mean free path λ i.e., the distance traveled by any atom or molecule turns out to be ($\lambda = 1/n\sigma$; where n is the number density and σ is the collision cross section) $> 3 \times 10^3$ km confirming the existence of a surface bound exosphere of the Moon. Making use of this basic fact, we obtain the spatial distribution of molecular Hydrogen (H_2) and Argon-40, and study their correspondence with the lunar surface features.

2. Methodology

CHACE is a quadrupole mass analyzer which had a dynamic range spanning ~9 orders of magnitude with the mass resolution better than unity in the entire range 1–100 amu and was operated with a scan rate of one scan in every 4 s yielding a total of 650 high quality mass spectra covering the entire range along the track of the MIP. CHACE had an in-built ionization gauge, which was an integral part of the ion source and had been independently calibrated with an industry standard. This combination enables one to convert the individual amplitudes to partial pressures by normalizing the sum of all the peaks up to 100 amu to the total pressure and then estimating the partial pressure due to any species of interest. The uniqueness of this experimental set up is that the mass spectrometer data are used to update the ionization gauge calibration and the corrected total pressure is used in the normalization of the spectrum to finally arrive at the partial pressures. In other words, the availability of calibrated ionization gauge makes further analysis straightforward. The ultimate detectable partial pressure was $< 10^{-13}$ Torr for the present instrument. The instrument details, calibration procedures and a detailed discussion on the out-gassing issues have been presented elsewhere (Sridharan et al., 2010a, 2010b). All the necessary corrections like ionization gauge correction for the dominant species (CO_2), quadrupole mass discrimination factor, the mass dependence of the gain of the channel electron multiplier and also due correction for the large velocity of the probe through the medium have been applied before arriving at the partial pressure due to any particular species at any given altitude. For the determination of absolute number densities of the species, the partial pressures are converted to the respective number densities at any altitude/latitude, using surface temperature estimates. Since the Moon has a surface boundary exosphere, the atmospheric region over any particular location is essentially isothermal. The latitudinal temperature profile at the lunar surface has been obtained using the variation of ^{36}Ar (Figure 9, Sridharan et al., 2010b) and expressed in a best-fit analytical form as follows:

$$T_\lambda = T_{eq}(\alpha + (1-\alpha)\cos\lambda) \tag{1}$$

where T_λ is the temperature at any latitude (λ) of interest and T_{eq} corresponds to that over the equator (~400 K). In this case ‘α’ has