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Observation of Neon at mid and high latitudes in the sunlit lunar exosphere: Results from CHACE aboard MIP/Chandrayaan-1

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ABSTRACT

The distribution of neutral Neon at the mid and high latitudes in the sunlit lunar exosphere observed by CHandra's Altitudinal Composition Explorer (CHACE) aboard the Moon Impact Probe (MIP) of the Chandrayaan-1 is reported. The CHACE observation was made when Moon was in the Earth's magnetotail. The upper limits of the surface number density are found to vary from (7–22) × 10^3 cm^{-3} at the pole, to (3–5) × 10^3 cm^{-3} in mid (50°S) latitudes and to (0.5–1.1) × 10^3 cm^{-3} in lower (20°S) latitudes. The surface number densities estimated at lower latitudes from CHACE observations are consistent with the LADEE Neutral Mass Spectrometer (NMS) observations.

1. Introduction

The study of the noble gases in the surface boundary exosphere (SBE) of the Moon is of paramount importance, as they are potential tracers of the internal and surface processes. For example, Neon and Helium are of solar wind origin (Benna et al., 2015; Heiken et al., 1991), implanted into the lunar surface, although ∼ 10% of the Helium is known to be radiogenic and of lunar in origin (Hodges, 1975). Lunar Argon is mostly Argon-40, which is a radiogenic daughter of the radioactive Potassium-40 available in the interior of the Moon (Heiken et al., 1991). The lightest among them, Helium, is lost mostly by thermal escape. Neon and Argon are lost through photoionization and ion-pick up by the solar wind (Johnson et al., 1972). Argon-40 is also prone to be lost through cold trap condensation in the day–night terminators and the permanently shadowed regions on the lunar surface (Heiken et al., 1991). In situ measurements of noble gases in the lunar atmosphere using mass spectrometers are given more importance since they are free from contamination due to outgassing.

In situdetection of the lunar exospheric noble gases traces back to the Apollo era, when the mass spectrometers flown aboard the Apollo 15 and 16 spacecraft probed the lunar exosphere (Hoffman et al., 1972), but with limited success. A significant step to study the lunar exospheric composition was achieved by the Lunar Atmospheric Composition Experiment (LACE) (Hoffman et al., 1973), deployed on the lunar surface as a part of the Apollo Lunar Surface Experiment Package (ALSEP) in the Apollo-17 mission. LACE analyzed the constituents of the lunar neutral exosphere at the surface. The LACE instrument ran into saturation during lunar days and hence provided useful scientific information only during lunar nights. It continued to operate for nine lunations. The noble gases detected unambiguously in the lunar exosphere were Helium and Argon. The Neon-20 signature observed by LACE was believed to be contaminated by the signal of $H_2^{18}O$ from Apollo equipment (Hodges et al., 1973). There was an attempt to estimate the possible abundance of the neutral Neon-20 from the measurements of the fluxes of ionized Neon from the Suprathermal Ion Detector Experiment (SIDE) emplaced by Apollo 12, 14 and 15 missions (Benson et al., 1975; Freeman and Benson, 1977). The estimated surface abundance of Neon at the terminator crossing was 10^5 cm^{-3}. Owing to the different uncertainties involved in the estimation of the abundance of neutral Neon from its ion fluxes and also due to the lack of the observations on neutral Neon, the inference on Neon-20 from SIDE data was largely ignored in later analyses (Stern, 1999).

Since there was no reliable observation from LACE on Neon, work resorted to model calculations (Hodges, 1973; Hodges et al., 1973) and the concentration of Neon during the lunar day was estimated as (4–7) × 10^3 cm^{-3}. In the decade of 1970s, abundances of different constituents of the lunar exosphere including Neon-20 were calculated by several researchers (Hodges, 1973; Hodges et al., 1974; Hoffman and Hodges, 1975; Johnson et al., 1972; Mukherjee, 1975) and the Neon-20 abundances of 4 × 10^3 to 10^4 cm^{-3} for lunar day-time and 10^5 cm^{-3} for lunar night-time

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were reported in the lunar sourcebook (Heiken et al., 1991). Wurz et al. (2012) calculated the lunar Neon based on solar wind implantation as 4900 cm^{-3}.

Later, Cook et al. (2013) reported an upper limit of 4400 cm^{-3} for the surface number density of Neon based on the observation of 63 nm and 73.5 nm spectral lines from the Lyman Alpha Mapping Project (LAMP) aboard Lunar Reconnaissance Orbiter. Recently, the Neutral Mass Spectrometer (NMS) instrument aboard the Lunar Atmosphere and Dust Environment Explorer (LADEE) has reported the longitudinal variation of Neon at lower latitudes (Benna et al., 2015) during the observations in February 2014. The derived surface number densities are found to vary from 10^3 cm^{-3} in the day–night terminators to 3.5×10^4 cm^{-3} at 240° meridian (0° is the subsolar meridian).

In this context, the observations by the quadrupole mass spectrometer-based CHandra's Altitudinal Composition Explorer (CHACE) experiment aboard the Moon Impact Probe (MIP) in the Chandrayaan-1 mission are significant as they provide the latitudinal and altitudinal variations of Neon-20 (hereafter to be referred to as Neon) in the sunlit lunar exosphere. The CHACE experiment studied for the first time the constituents of the sunlit lunar exosphere with broad latitudinal (45° North to the South pole) and altitudinal (∼ 98 km to the surface) coverage (Sridharan et al., 2015; 2010a; 2010b; 2013b; 2013a; Thampi et al., 2015). The observation of Neon by CHACE is reported in this paper. The derived surface number densities from CHACE are compared with those obtained from the NMS/LADEE observations.

2. Observation

The CHACE instrument is a quadrupole mass spectrometer with 1–100 amu mass range and unit mass resolution, equipped with a Bayard Alpert gauge to measure the total pressure. The details of the CHACE experiment are reported earlier (Sridharan et al., 2010a; 2010b; 2013a). CHACE was housed in the MIP, which descended from 100 km (∼ 13.6°S latitude) to impact in the South pole at 89°S on 14 November 2008. Hence, the measurements made by CHACE are a convolution of both altitude and latitude variations. The latitude variation brings in the variation of the local surface temperature, which, in turn, controls the altitude distribution of the exospheric species and is used to derive the number density. It is assumed here that the neutrals detected by CHACE were in thermal equilibrium with the lunar surface and the contribution of the sputtered neutrals in the lunar exosphere, if any, is less (Wurz et al., 2007). The raw signals for the detected species are corrected for the mass-dependent factors, like the gain of the channel electron multiplier detector and the relative transmission efficiencies through the quadrupole mass analyzer. The absolute partial pressures are obtained by normalizing the sum over all the peaks to the total pressure measured with the Bayard-Alpert gauge.

The CHACE instrument used 70 eV electrons to impact-ionize the ambient neutrals. The doubly ionized Argon-40, i.e. Ar^{++}, would contribute to the $m/q = 20$ bin of the mass spectra. The National Institute of Standards and Technology (NIST) has listed a value of the Ar^{++}:Ar^{+} ratio as 0.13. The laboratory calibration data of the CHACE instrument acquired by inserting laboratory grade Ar-40 in the vacuum chamber yielded a ratio of 0.145 at 70 eV electron energy. Montanari and Miraglia (2014) compiled the experimental work of several workers to determine the electron impact ionization cross sections of Argon and compared the results with theoretical calculations, suggesting a value of the Ar^{++}:Ar^{+} ratio as 0.087, which is on the lower side. Since the present work is to investigate the upper limits of the Neon density, the value of 0.087 of the Ar^{++}:Ar^{+} ratio is used for the removal of the Ar^{++} contribution to the amu 20 signal to obtain the Neon number density. Also, results of the sensitivity analysis presented in Section 4 show that the number density of Neon is not very sensitive to the Ar^{++}:Ar^{+} ratio at the high latitudes.

Two important instrument calibration factors are the relative gain of the CEM detector and the relative transmission efficiency of the quadrupole mass analyzer (due to quadrupole mass discrimination) at amu 20 with respect to amu 40. For the CHACE instrument, the relative gain of the CEM detector and the relative transmission efficiency of the quadrupole mass analyzer at amu 20 with respect to amu 40 are 1.25 and 1.6, respectively. In addition to these calibration factors, the relative (with respect to N_2) ionization sensitivity factors of Argon-40 and Neon (1.11 and 0.28, respectively) are also taken into account. The total number density was derived by accounting for the local surface temperature on the Moon and also by applying the correction for the ram pressure enhancement due to the velocity of the MIP (Sridharan et al., 2015).

Significant information on the lunar global surface temperature distribution was provided by the Diviner Lunar Radiometer Experiment aboard the Lunar Reconnaissance Orbiter (LRO), which brought out the diurnal and latitudinal variabilities of the lunar surface temperatures by mapping the albedo of the Moon at infrared wavelengths (Paige et al., 2010b). Accordingly, a cosine model of the lunar surface temperature variation is adopted in the present analysis with the equatorial temperature of 382 K and polar temperature of 95 K, based on the Diviner temperature map at the Local Solar Time (LST) relevant to the CHACE observations. The Diviner observations have revealed distinct variations of the lunar surface temperature at higher lunar latitudes including patches of very low temperature regions (from 80° towards poles), ranging down to 25 K (Paige et al., 2010a) at the permanently shadowed regions (PSR) on the lunar surface. In addition, the local surface temperatures at higher lunar latitudes have significant spatial and temporal variations due to the variations of the solar incidence angle owing to the local topography. Due to the inhomogeneity of different surface parameters that govern the local surface temperature, any analytical model would deviate from the actual values. Analytical modeling of the lunar surface temperatures for exospheric modeling using Diviner observations deviate from the measured lunar surface temperature near the terminators and higher lunar latitudes (Hurley et al., 2015) due to local variations in the solar incidence angle. The local fluctuations of the surface temperature at higher lunar latitudes translate to fluctuations in the spatial distribution of the number density observed by CHACE, as discussed in Section 3.

3. Results

Fig. 1 presents the number densities of Neon as a function of the lunar altitude and latitude derived from the partial pressure measurements and accounting for the corrections as mentioned above. The temperature model assumed here is based on the Diviner temperature map, relevant to the LST corresponding to the CHACE observations, where the equatorial and polar temperatures are taken as 382 K and 95 K, respectively.

The Fig. 2 shows the surface number density of Neon as a function of the lunar latitude, derived using the scale heights at different latitudes assuming a cosine model of temperature consistent with the Diviner observations (Hurley et al., 2015). The surface number densities from the CHACE observations are seen to vary (1σ variation) from 7×10^3 to 22×10^3 cm^{-3} near the pole, 3×10^3 to 5×10^3 cm^{-3} in mid (50°S) latitudes, and 0.5×10^3 to 1.1×10^3 cm^{-3} in lower (20°S) latitudes. This is due to the non-condensible behavior of Neon at Moon. The filled circles in the figure represent the mean of the number densities derived from 10 consecutive spectra acquired by CHACE, leading to a latitudinal binning of ∼ 2°. The error bars are standard deviations on the observations within a bin. The higher values of the standard