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On the possibilities of the existence of molecular ions in the lunar ionosphere: a study using results from Chandrayaan-I S-Band Radio Occultation Experiment and a photochemical model

K M Ambili*(1), R K Choudhary(2), and Anil Bhardwaj(2)
(1) Indian Institute of Space Science and Technology,Valiamala, Trivandrum, India-695547, Email: ambilisadasivan@gmail.com
(2) Space Physics Laboaratory, VSSC, ISRO, India

Abstract

Using Chandrayaan-1 communication link between orbiter and ground (S-band frequency), the presence of ionosphere at Moon has been explored using Radio Occultation technique. Results obtained from the observations conducted between July 30 and August 14, 2009 show evidence for a possible existence of the Ionosphere at Moon. A few seconds before the occultation of Chandrayaan-1 radio signals, extra fluctuation in the rate of change of difference between the theoretically estimated Doppler and observed Doppler was observed. Using standard âĂIJonion-peelingâĂİ technique to invert the phase changes in radio signals to the refractivity of the medium, we obtained the electron density profiles for the Lunar medium. The estimated electron density near the Lunar surface was of the order of 400 - 1000 cm^3 which decreased monotonically with increasing altitude till about 40 km above the surface where it became negligible. The obseved electron density was compared with the results from a model which was developed based on CHACE measurements abroad Moon Impact Probe of Chandrayaan-I. The model included the photo chemical reactions and solar wind interactions of the lunar plasma. We propose that the ionosphere over Moon could have molecular origin with H_2O^+,CO_2^+ and H_3O^+ as dominant ions.

1 Introduction

The existence and characteristics of atmosphere and ionosphere at Moon has remained an enigmatic question in front of the scientific community. Debates are still going on among scientists on various explanations and observations of lunar ionosphere [2]. Very old belief was that the lunar ionosphere is produced by the photoionization of the tenous lunar atmosphere consisting of Ar and He with a dayside density of the order of 10^5 cm^{-3} [3]. The density of the lunar ionosphere, in turn, was considered to be about a few cm^{-3} in the range from surface to 100 km altitude. It was believed that such a low plasma density at Moon was because the solar wind magnetic field prevented any accumulation of ions near the lunar surface by sweeping across the interplanetary space [4].

The stellar radio experiments however put forward a different picture of ionosphere at Moon. They observed large angular shifts when the waves are occulted by the dayside lunar limb. The explanation for such a large angular shift was proposed to the existence of lunar ionosphere with electron density of the order 1000 cm^{-3} and thickness of several kilometers. The existence of ionosphere was later further confirmed by several radio occultation experiments [2].

The first occultation experiment for studying Lunar ionosphere was performed by the Pioneer-7 probe in the year 1966. This experiment proved the existence of a thin ionosphere around Moon. The electron density determined at that time was of the order of 10^2 el/cm^3. The later Soviet missions Luna-19 and Luna-22 revealed the presence of a 10 km plasma layer having electron densities of the order of $0.5–1.0 \times 10^3$ el/cm^3. The estimated columnar density of the Lunar ionosphere falls in the range of 3-5 x 10^{14} el/cm^2. Radio occultation of moon's ionosphere by SMART-1 has shown the exitence of ionosphere with columnar density of the order of 10^{13} el/cm^2 [5] which was later further confirmed by SELENE RO measurements [2]

In this study, we have used measurements from Chandrayaan-I to revist the Ionosphere at Moon and its possible origin. India's Chandrayann-I mission, which was launched on 22nd October 2008, had two components, namely the orbiter revolving around Moon at the altitude of 100 km, and a standalone micro-satellite known as Moon Impact Probe (MIP) which was allowed to fall free from the orbiter to Moon's surface. The orbiter had a suit of experiments to explore Moon's topographical features and mineralogical composition. The details of the experiments are available elsewhere [6]. The composition of the tenuous atmosphere was studied with the help of Chandra's Altitudinal Composition Explorer (CHACE), a mass spectrometer based instrument, which was a part of MIP. Results obtained from CHACE are well described in [7]. An important result from the CHACE measurements is the signature of large background neutral pressure on the sunlit side of the lunar atmosphere with significant amount of CO_2 and H_2O beyond 20°. It is worth mentioning that CHASE was the first experiment which provided first direct evidence for water in its vapour phase.

According to the CHACE results,the 50% of the atmo-

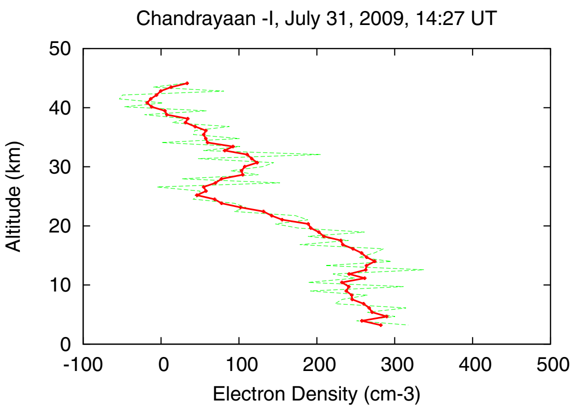

Figure 1. Altitude profile of electron density at Moon using RO

sphere is contributed from CO_2 and H_2O and the rest of 50% is from other neutrals. Since the composition of the neutral atmosphere determines the characteristics of the ionosphere, the observed CO_2 and H_2O molecules should have a direct impacts on the lunar ionosphere. None of the previous studies reported CO_2 or H_2O dominated atmosphere. Here we discuss results from a photochemical model for the lunar ionosphere based on the Chandrayan-1 results. The following sections we describe measurements that from Chandrayan's RO, followed by the photochemical model and their intercomparison.

2 Results and discussions

2.1 Radio occultation results

Chandrayaan's TTC signals at S band frequency was used in the Occultation experiment. The S-band (2.3 GHz) radio signal, stabilized at the ground station and transmitted using the High Gain Antenna, was used in two-way mode of operation for this experiment. In the ingress mode (satellite going behind the Moon), the satellite revolving around Moon in 100 km orbit with a velocity of 2 km/s, takes around 1 min to cross the Lunar ionosphere. The RO measurements however were initiated 15 min before the actual occultation. It allowed us to separate phase change in the radio signals due to the Lunar ionosphere from the classical Doppler shift. A brief description of method used to estimate the residual Doppler (Δf) is in order. As already stated, only three minutes of data before the actual signal loss were considered in the analysis. The effects due to Ionosphere/ Atmosphere of Earth, however, were still to be removed from the Doppler Residuals. In order to do that, a fit was applied to the first two minutes of Doppler residuals (Δf) data prior to occultation and the fit was extended for last one minute of the observations. The fitted data, thus obtained, was subtracted from the actual Doppler residuals which eventually nullified the contribution prior to Occultation and reflected the contribution during the Occultation period only. If the phase changes during the occulted period exceeded one sigma of the fluctuation during first two min, then only we assumed that the extra phase change in the signal was due to occulted planetary medium. Further processing of the data to obtain the bending angle of radio signal, refractive index, and electron density profiile was done using Onion Peeling Technique as described by [8] which assumes that the atmosphere is spherically symmetric. In Figure 1, we show a sample of elecron density profile at Moon as observed on July 31, 2009 at 1427 UT (Occultation time with respect to the Earth).

2.2 Photo chemical model

The RO measurements by Chandrayaan-I showed that the maximum plasma density at Moon on July 31 2009 was near ground with a magnitude as low as 400 cm^3 (40×10^7 m^{-3}). The photochemical model for the lunar ionosphere, used in this study, has been developed based on the mass spectrometer on the Moon Impact Probe (CHACE) measurements. The CHASE measured the neutral density from 20°1S and right up to the south pole and finally imapcted very close to the south pole at 89°S latitude and 30°W longitude. The mass spectrometer detected the abundance of CO_2 and H_2O along with the inert gases in the lunar atmosphere [?]. In this model, therefore, we considered that the Moon has an atmosphere mainly composed of CO_2, H_2O, OH, O, Ar, Ne, He and H_2.

The main sources of ions in the lunar ionosphere is considered to be the photo ionization of the neutral atmosphere. The ions and electron density densities are calculated by considering the continuity equation which includes all the production and loss reactions of these ions. The divergence term in the continuity equation is also considered via by including the solar wind interactions of the lunar plasma. Hence, in the model, calculations have been done for two separate cases. (a) The ionosphere at moon is in the photo chemical equilibrium and there is no dynamical interactions. (b) The ionosphere is continuously interacts with the solar wind.

Followings are the assumptions used in this model.

1. The calculations have been done at the poles with Temperature = 150 K and Solar Zenith Angle= 80deg. The neutral density are obtained at the ground at 89° S and 30° W coordinates from CHASE measurements [7].
2. The altitudinal profile of the neutral density is calculated based on the assumption that the atmosphere is assumed to be in hydrostatic equilibrium, ie the individual neutral species are exponentially decreasing in density with scale height,

   H_{CO_2}=17 km, H_{H_2O}=42 km, H_O=48 km, H_{OH}=45 km, H_{Ne}=38 km, H_{He}=192 km, H_{H_2}=384 km
3. Photo ionization, photo dissociative ionization, solar wind protons charge exchange reactions and solar wind electron impact ionization reactions have

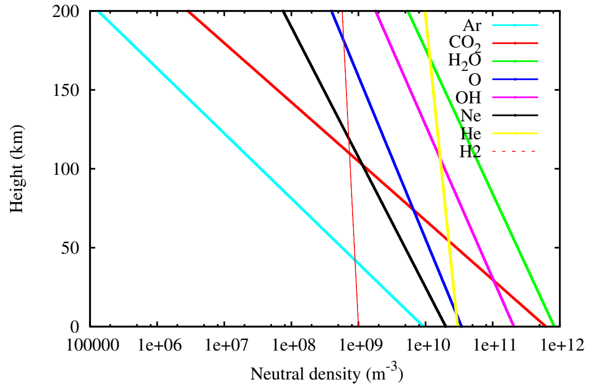

Figure 2. Height profile of Neutral density

been considered for the production of plasma. Photo ionozation of CO_2, H_2O, OH, O, He and H_2 and photo dissociative ionization of H_2O, CO_2 and H_2 have been calculated using Chapman function. The method used to calculate the function is similar to the method used in the model for Earth's ionosphere.

4. The important sources of loss of ions are recombination reactions such as ion atom charge exchange reactions and dissociative recombination reactions of CO_2^+, H_2O^+, H_3O^+, OH^+, O_2^+,O^+, Ar^+, Ne^+, He^+, H^+, H_2^+.

The ions density (CO_2^+, H_2O^+, H_3O^+, OH^+, O_2^+,O^+, Ar^+, Ne^+, He^+, H^+ and H_2^+) are calculated for two different cases as discussed above, (1) each individual ion is considered to be in photo chemical equilibrium. (2) The divergence due to the solar wind interaction is incorporated. In both cases, the total electron density is the sum of all the individual ions density.

Since the atmosphere is assumed to be in hydrostatic equilibrium, each species are distributed with their own scale height. Figure 2 represents the distribution of each molecules upto 200 km. It is clear from the above figure that water vapour content is larger than CO_2. At around 150 km, atomic density is higher than molecular density. For the above stated neutral densities, the density of individual ions and finally that of electrons are calculated for the above two cases.

2.3 Case 1: Photo chemical equilibrium

The calculated density, if the lunar ionosphere is in photo chemical equilibrium, is given in Figure 3. As shown in the figure dominant ions are atomic ions such as Ar^+,Ne^+ and He^+. The peak electron density is 35000 cm^{-3} at the ground. The density is decreasing until 100 km, after that the density is more or less constant or shows a slight increase. The reason for such a distinct behaviour above 100 km is because of the He^+ ions. At the lower altitudes, the rate of recombination of He^+ and CO_2 is high because of the high density of CO_2. As the height increase, CO_2 falls

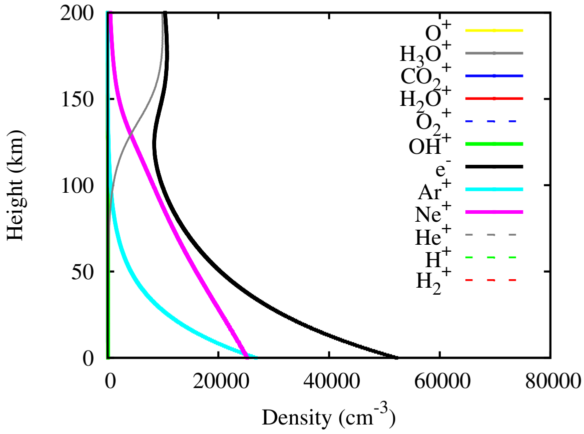

Figure 3. Individual ion density and electron density

very quickly due to its lower scale height. Such a drop in the CO_2 is reflected as increase in He^+. Thus, if the lunar ionosphere is in photo chemical equilibrium, we can expect the electron density as high as 35000 cm^{-3} with Ar^+,Ne^+ and He^+ as the domination ions. In reality however we do not get such a high plasma density at Moon. Instead the density is maximum up to 1000 cm^{-3} and decreases very fast to almost zero around 50 km its self.

In order to understand the observed features we considered the dynamical interaction between the moon and solar wind.

2.4 Case 2: Solar wind interaction

As discussed above, one of the important factor which determines the electron density at the Moon is its interaction with the solar wind. Since, Moon does not have a magnetic field as in the case of Earth, the solar wind directly impinges on the lunar surface. Such high speed solar wind particles have enough strength to pick up ions from the lunar atmosphere. Hence in the model we incorporated the solar wind interaction. The following method was used to solve the problem.

1. The system is considered to be in steady state, so $\delta N/\delta t$ =0.

2. The divergence term in the continuity equation is due to the solar wind interaction. The ions formed due to photo ionization are picked up by the solar wind electric field and it gets removed. It is given by NV_{ion}/L, where N is the ion density, V_{ion} is the velocity of the ions after the soalr wind interaction and L is the scale length of interaction (which of the order of several lunar radii).

3. V_{ion} has been included in the model for each ion based on the real measurements from SIDE experiment associated with Apolo missions. They observed that the maximum electron velocity can be 100 eV. Based on

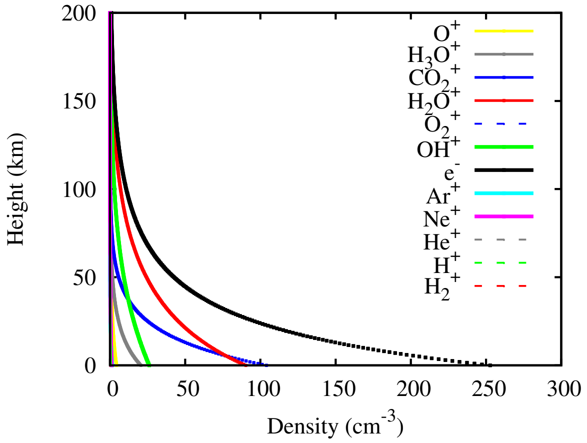

Figure 4. Individual ion density and electron density

this energy, the velocity of each particle is calculated and is listed below. V_H= 139 km/s, V_{H_2}= 98 km/s , V_{CO_2}= 21 km/s, V_{H_2O}= 33 km/s, V_O= 35 km/s, V_{O_2}= 25 km/s, V_{Ar}=22 km/s, V_{Ne}= 31 km/s, V_{He}= 69 km/s, V_{OH}=34 km/s.

4. Hence the density can be calculated as, N = P/(Vsw /L + Lf), where Lf is the loss factor and L is taken of the order of Lunar radii.

The Figure 4 presents the electron density at the lunar ionosphere a s a result of solar wind interaction. As shown in the figure, the maximum density is around 250 cm^{-3} at the ground for the conditions given above. We can expect an increase in the density up to 1000 cm^{-3} as the scale length of interaction increases. The modeled electron density matches well with the results from radio occultation measurements given by [2].

3 Summary and Conclusions

The presence of ionosphere at Moon was explored by Radio Occultation technique using Chandrayaan-1 communication link between orbiter and ground (S-band frequency). The observed electron density was compared with results from a model which was based on measurements of neutral density from a mass spectrometer based instrument, ChACE aboard Moon Impact Probe of Chandrayaan-I. The model included photo chemical reactions and solar wind interactions of the lunar plasma. According to the model calculations the surface electron density at Moon could be as high as 35000 cm^{-3} if dynamical interaction between solar wind and lunar plasma is considered absent. The dominant ions would then be Ar^+,Ne^+ and He^+. The absence of any intrinsic magnetic field , however, leads the ionosphere at Moon to interact continuously with the solar wind, resulting in the sweeping of plasma thereat. This in turn leads to a negligible presence of plasma at Moon. Still, our calculations suggest that the Moon can have a ionosphere which has molecular origin with H_2O^+, CO_2^+ and H_3O^+ being dominant ions. Our modeled electron density matches well with the results from radio occultation measurements.

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