

ESTIMATION OF ION ESCAPE RATES FROM NON-MAGNETIC EARTH: ON CONTRIBUTION OF TERRESTRIAL ION FLOWS TO NON-SOLAR COMPONENTS IMPLANTATED IN LUNAR SOILS.

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Introduction: Physical and chemical mechanisms responsible for the atmospheric escape from a planet dramatically change with the strength of its intrinsic magnetic field [1,2]. When the planet has substantial global intrinsic magnetic field as in the case of the present Earth, the planetary magnetic field provides a barrier against the solar wind (continuous and dynamic supersonic plasma flow from the Sun) and the solar wind cannot blow directly into the upper atmosphere. In the present Earth, the solar wind approaching to the Earth is stopped by the terrestrial magnetic field at the magnetopause (at about 10 Earth radii), where the magnetic pressure balances the kinetic pressure of the solar wind.

On the other hand, when the planet has no global intrinsic magnetic field as in cases of present Mars and Venus, the solar wind directly interacts with the planetary upper atmosphere and may cause efficient loss of heavy atmospheric constituents such as Nitrogen and Argon under certain solar wind conditions. In this study, we estimate the escape rates of H^+ , He^+ , N^+ , O^+ , Ne^+ , and $^{36}Ar^+$ from the non-magnetic Earth, i.e., under assumption that the Earth does not have its intrinsic magnetic field, through the solar wind induced escape. In order to access whether these escaping ions contribute to non-solar components implanted in lunar soils, fluxes of the terrestrial ions at lunar orbit are discussed.

Ion Escape Rate Above Ionopause: At altitudes above ~ 80 km, terrestrial atmosphere starts ionized by solar radiation and these atmospheric electrons and ions form the ionosphere, a dense plasma layer in the upper atmosphere. If the Earth does not possess any intrinsic magnetic field, the solar wind would approach to the Earth until its kinetic pressure was balanced by the ionospheric pressure and this boundary of the solar wind entry is called the “ionopause”. Above the ionopause, the terrestrial ions are accelerated by the electric field induced by the magnetized solar wind flow and flow away from the Earth together with the diverted solar wind flow around the planet. This picked-up process can efficiently remove terrestrial ions created above the ionopause. The solar wind induced ion escape from unmagnetized planets has been observed at Mars and Venus, which have no permanent global magnetic dipole [3, 4, 5].

In order to estimate the ion escape rates due to this pick-up process above the ionopause, we first

calculated the ion production rates around the Earth using MSIS00 model [6], an empirical model of the terrestrial upper atmosphere, as an input. From the given neutral atmospheric density and temperature, the ion production rate of each ion species are calculated based on previously studies of the photon ionization by solar radiation [7,8] and photoelectron impact ionization [9]. Figure 1a displays the resultant production rates for H^+ , He^+ , N^+ , O^+ , Ne^+ , and Ar^+ , respectively. If one assumes that ions produced above the ionopause escape from the Earth, the total ion escape rate can be estimated by integrating the ion production rate over the dayside Earth surface area above the ionopause.

The picked-up planetary ions flow away from the Earth with the solar wind, and spread over the “tail region” in the anti-sunward direction from the Earth. From the observations at Mars and Venus, it is known that the “tail region” has a cylinder shape with the radius of about two planetary radii [10]. Assuming a circular escape area with the radius of

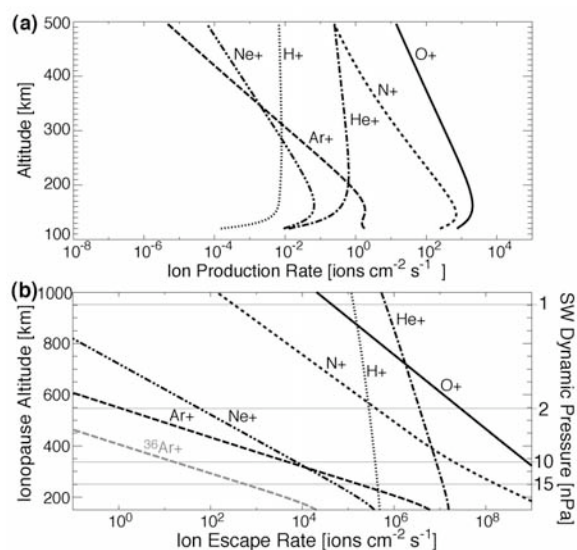


Figure 1: (a) Ion production rates calculated from an empirical model of the present Earth's atmosphere (MSIS00 model) under normal EUV flux ($F_{10.7} = 150$) condition. (b) Escape fluxes of Ar^+ , Ne^+ , O^+ , N^+ , He^+ , and H^+ ions normalized with the tail width of two Earth radii. Gray dashed line shows the $^{36}Ar^+$ flux (1/300 of the total Ar^+ escape flux) for convenience of comparison with lunar samples. The ordinate represents both the ionopause altitude (left) and corresponding solar wind dynamic pressure (right) derived from IRI model.

two Earth radii in the anti-sunward direction of the Earth, we can obtain a rough estimate of the average ion escape flux in the nightside tail region. Figure 1b shows the estimated escape flux of each ion species as a function of the ionopause altitude (and also SW dynamic pressure). If we take the typical (active) solar wind conditions with solar wind dynamic pressure of 1 (15) nPa, which corresponds to velocity of 500 (1000) km/s and density of 5 (15) cm^{-3} , it would balance with the ionospheric plasma pressure estimated inferred from IRI (International Reference Ionosphere) model [11] at the altitude of 950 (250) km. As shown in Figure 1b, the escape rates of heavier ions are more sensitive to the ionopause altitude as expected.

Terrestrial Ion Flux at Lunar Orbit: If Earth did not have no permanent global magnetic field in the past, some fraction of the escaping ions would hit the Moon, creating potentially observable effects that last even to the present day. If we assume the ionopause altitude of 500 km which is expected for the present Earth without global magnetic field under normal solar wind conditions, N^+ flux in the Earth's tail is expected to be $\sim 10^6$ ions/ cm^2/s as shown in Figure 1b. Assuming 10^6 ions/ cm^2/s N^+ escape flux from the early non-magnetic Earth, we next estimate the fraction of the escaping ions that will hit the lunar surface. A circular cross section with two Earth radii is assumed for the escaping area of terrestrial ions (hereafter referred as Earth's tail or tail region).

In evaluating the probability of Moon's passage through the Earth's tail, we also considered the variation of Earth-Moon distance with time. The distance between the Earth and Moon has been increasing due to tidal dissipation since the formation of the Earth-Moon system [12]. For example, the Earth-Moon distance was ~ 40 Earth radii about 4 Ga ago. If we take account of the fraction of time that the lunar orbit stays inside the Earth's tail (Figure 2), about 0.3% of the terrestrial ion flux would hit the lunar surface, i.e. it corresponds to $\sim 3 \times 10^3$ N^+ ions/ cm^2/s on average. The N^+ ions will then be implanted on lunar soils with the same velocity as that of the solar wind. As shown in an accompanied paper by Ozima *et al.* [14], the above estimated average N flux (about 3×10^3 atoms/ cm^2/s) that could be transported to the Moon from the non-magnetic Earth is close to the non-solar implanted N flux observed at the lunar surface ($> 2 \times 10^3$ atoms/ cm^2/s). It should be noted that the escape fluxes in Figure 1 may be underestimated, since terrestrial ions can escape also at and below the ionopause through other processes [1].

Figure 1b also shows that if the solar wind dynamic pressure changes from 2 to 15 nPa, the ionopause altitude decreases drastically from 500 km

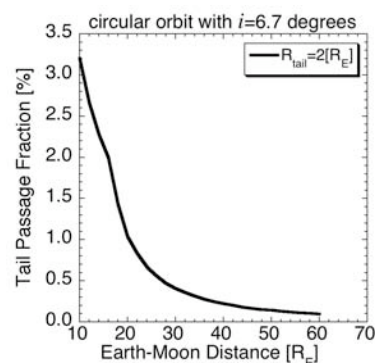


Figure 2: The fraction of time that the lunar orbit stays inside the “tail region” of the Earth (see text) is shown as a function of the Earth-Moon distance. In estimating the probability, we assume that the Moon's orbital plane is inclined to the ecliptic plane by $i=6.7^\circ$ (the present value). For the Earth's tail, we assume a circular cylinder with a radius of $2R_E$.

down to ~ 250 km, and accordingly the escaping ion flux, especially of heavy ions, undergo significant increase. If the solar wind pressure exceeds 15 nPa, the ionopause becomes even closer. When the ionopause altitude decreases from 500 to 200 km, for example, the average terrestrial N^+ flux at lunar surface increases from 3×10^3 to 2×10^6 , Ne^+ from 0.5 to 5×10^2 , and $^{36}\text{Ar}^+$ from 7×10^{-5} to 13 ions/ cm^2/s , respectively. Such high solar wind pressure as assumed above is still within the present variation and hence even higher solar wind flux would be expected from an active young Sun [13]. In addition, low O_2 pressure (and possibly CO_2) in the paleoatmosphere further brings the ionopause closer to the Earth. All these factors tend to enhance the ion escape rate especially of heavy components. The high terrestrial ion fluxes from the ancient non-magnetic Earth with low atmospheric O_2 (or CO_2) pressure can be the source of non-solar components of N and light noble gases implanted in lunar soils [14].

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