Limits to a Lunar Ionosphere

By

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Abstract

In an exosphere like that of the Moon an ionospheric layer with a peak above its surface cannot form since the ionising radiation penetrates unattenuated to the surface. The ionisation of exospheric species in equilibrium with recombination could lead to appreciable concentrations of electron/ion pairs at the surface, because of the extremely slow loss of atomic ions by radiative recombination, if there were not a competing transport process. This is actually provided by the pick-up of ions by the solar wind leading to an extremely low surface concentration of ionospheric plasma. Russian radio occultation observations on their Luna spacecraft showed an increase in integrated electron content as the radio ray path traversed the dayside of the Moon, which had been interpreted as a lunar ionosphere. It is shown here that these observations are better explained by the *photoelectron layer* (observed by the US Apollo missions) that is the result of the liberation of electrons from the lunar surface by solar env radiation, leaving the dayside of the Moon with a positive charge. Since radio waves are affected by electrons, the measured photoelectron concentrations may limit future radio astronomical observation from the dayside of the Moon to frequencies above 1 MHz.

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The Moon like the planet Mercury possesses an extremely tenuous gaseous envelope originating from sputtering of the surface materials by

solar wind protons, photons and from micrometeorite vaporization (e.g., Morgan and Shemansky [6]; Lammer and Bauer [4]. The observed constituents and their dayside lunar surface densities (atoms cm^{-3}) are < 10, $\lesssim 2 \times 10^3$ and $\sim 10^3$ for H, He and Ar, respectively (Hodges et al. [3]) and ~ 50, ~ 60 and ~ 15 for O, Na and K, respectively; the typical column content of these species is $\mathcal{N} \lesssim 10^{10}$ cm^{-2} (Morgan and Shemansky [6]).

Because of the low concentration of the gaseous constituents this situation represents an essentially "collisionless atmosphere" that is called an exosphere. Such an exosphere is defined by the criterion that the probability for radially outward travelling particles suffering a collision is e^{-1} at its base (the "exobase") corresponding to the condition that the mean free path $\lambda = (n\sigma)^{-1}$, where n is the particle concentration and σ the gas kinetic collision cross section, is of the same order as the "atmospheric" scale height $H = kT/mg$ with k the Boltzmann constant, T the temperature, m the molecular mass of the gas and g the acceleration of gravity.

The above "exospheric criterion" is also equivalent to a column content $\mathcal{N} \equiv nH = \sigma^{-1}$; i.e., for typical collision cross sections $\sigma = 5 \times 10^{-15}\, cm^2$, the column content of an exosphere is $\mathcal{N}_\infty \leq 2 \times 10^{14}\, cm^{-2}$ (e.g. Bauer [1]).

According to the observations summarized above the column content for all species discovered on the Moon and also on Mercury satisfies this criterion; i.e. the surface of these bodies is already the base of the exosphere.

In an exosphere no ionospheric layer with a peak above its base can form since this requires that the ionising radiation should reach unit-optical-depth ($\tau \equiv \sigma_a \mathcal{N} = 1$, where σ_a is the absorption cross section and $\mathcal{N}$ is the column content of the ionizable constituent).

Since, typically $\sigma_a = 10^{-17}/10^{-18}\, cm^2$ and exospheric column contents are $< 10^{14}\, cm^{-2}$, the optical depth is extremely small ($\tau \to 0$) so that the ionising radiation can penetrate almost unattenuated to the surface of the Moon or Mercury (Bauer [2]; Lammer and Bauer [4]). Ion pair production, however, will still occur through interaction of the ionising radiation with the neutral exospheric constituents. In this case the ion pair production function q is given by

$$q = \sigma_i \Phi_\infty n = Jn \qquad (1)$$

where σ_i is the ionisation cross section, Φ_∞ the unattenuated photon flux, and the product $\sigma_i \cdot \Phi_\infty = J$ represents the ionisation rate coefficient or ionisation frequency (s^{-1}). For atomic ions, chemical loss of electron/ion

pairs occurs via radiative recombination

$$L = \alpha_r N^2 \tag{2}$$

where $\alpha_r \approx 10^{-12}\,\mathrm{cm}^{-3}$ is the radiative recombination coefficient and $N = N_e = N_i$ is the plasma density (electron/ion density). For chemical equilibrium $q = L$, the electron/ion concentration near the surface would be

$$N = \left(\frac{Jn}{\alpha_r}\right)^{1/2} \tag{3}$$

and for appropriate values of the dayside lunar exosphere could amount to $N \lesssim 10^4\,\mathrm{cm}^{-3}$. This concentration would be present when only photochemical processes are of importance and transport processes can be neglected. However, since the lunar dayside, because of the absence of a global magnetic field, is subjected to a direct interaction of the solar wind having a flow velocity $v_{sw} \approx 400\,\mathrm{km/s}$, ions can be "picked up" by the solar wind. Because of the finite, though large exospheric ion gyroradii of the order of several lunar radii (R_m) in the interplanetary magnetic field B_{IMF}, the solar wind will accelerate these ions with a Lorentz force $\vec{E} = \vec{v}_{sw} \times \vec{B}_{IMF}$; some ions will impact on the lunar surface and be lost by sputtering or accommodation, whereas the majority will be removed from the lunar environment by the solar wind flow (Manka and Michel [5]). The Lorentz force is about 1000 times stronger than the lunar force of activity. This "transport term" can be represented by

$$\mathrm{div}\,(Nv_{sw}) \approx \frac{Nv_{sw}}{L} \tag{4}$$

where L is the interaction length of the solar wind with the lunar exosphere. To assess the importance of this transport (ion-pick up) relative to the photochemical processes we have to compare the relevant time constants, the ionisation time constant $\tau_{ion} = 1/J$, the recombination time constant $\tau_{rec} = 1/\alpha_r N$ and the solar wind ion pick up time $\tau_{sw} = L/v_{sw}$. For the appropriate numerical values we obtain $\tau_{rec} \approx 10^8\,\mathrm{s}$, $\tau_{ion} \approx 10^7\,\mathrm{s}$ and $\tau_{sw} \approx \sec$, for an interacting length $L \approx R_m$. Thus, exospheric ions once formed will be immediately picked up by the solar wind. In this case the steady state concentration of "ionospheric plasma" can be derived from $q \approx \mathrm{div}\,(Nv_{sw})$ and thus using equations (1) and (4)

$$N \approx \frac{JnR_m}{v_{sw}} \lesssim 1\,\mathrm{cm}^{-3} \tag{5}$$

Under these circumstances no thermal ionospheric *plasma* (equal number of electrons and ions, $N_e = N_i$) resulting from photo-ionisation of neutral exospheric species should be expected.

This conclusion seems to contradict the limited observational evidence. Russian two-frequency radio occultation observations with Luna 19 and 22 (Vyshlov [8]) indicated a change in the line-of-sight electron content of a few times 10^{10} cm^{-2} as the ray path traversed the lunar dayside. These observations were interpreted, assuming spherical symmetry and a "triangular layer shape", i.e. having a peak, as an "ionospheric layer" with a maximum electron density ~ 400 cm^{-3} close to and extending some 25–50 km above the surface (Vyshlov and Savich [9]). Determining the vertical electron content of their "layers" yields $\mathcal{N}_e \approx 2 \times 10^9$ cm^{-2}.

As mentioned before, the dayside lunar surface is exposed to solar euv radiation which liberates photoelectrons from the surface leaving it positively charged. Observations on the Apollo Lunar Science Experiment Package (ALSEP) have indeed measured a "photoelectron layer" with $N_e \approx 10^4$ cm^{-3} extending over several hundreds of meters (Reasoner and Burke [7]). This photoelectron layer would also correspond to an electron column content of $\mathcal{N}_e \approx 10^9$ cm^{-2}. Thus, the Russian radio occultation observations of electron *content* may possibly be interpreted as due to the *photoelectron layer* (not an "ionospheric layer" with equal numbers of electrons and ions). Since radio wave observations are affected by the electrons only, a surface concentration of *photoelectrons* of $N_e \approx 10^4$ cm^{-3} would also imply a low frequency cut-off of about 1 MHz for radio astronomical observations from the lunar dayside, whereas the nightside would be suitable for observations at even lower frequencies.

Acknowledgements

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