# IS THERE A DENSE CARBON-DIOXIDE EXOSPHERE AT THE MOON?

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**Introduction:** The influx, neutralization, and recycling of solar wind ions at the surface of the Moon is a key process in the formation of the lunar exosphere. Previous work has shown that several components of the lunar exosphere originate via such a recycling process, including $H_2$, He, Ne, and $^{36}$Ar, for example [1–5]. Similarly, solar wind carbon ions incident on the surface of the Moon are also predicted to neutralize and recycle into various carbon-bearing species in the lunar exosphere such as $CH_4$, CO, and $CO_2$. Indeed, both $CH_4$ and CO have been detected in-situ in the dayside lunar exosphere by the LADEE mission [6,7] while mass-44 ions (presumably $CO_2^+$ ions) have been measured as a slight pre-dawn enhancement by the Apollo 17 Lunar Mass Spectrometer (LMS). The LCROSS impact experiment also detected the presence of $CO_2$ in the Moon's Cabeus crater, presumably from long-term cold trapping in permanently shadowed regions [8]. Finally, recent analyses of the lunar exospheric pickup-ion flux observed by the THEMIS-ARTEMIS mission in orbit around the Moon have suggested a "missing" component in the lunar exosphere that could be provided by a relatively dense (~$10^4$ – $10^5$ cm$^{-3}$) $CO_2$ exosphere at the Moon. Taken together, these measurements hint at a complex set of carbon-recycling pathways at the Moon; however, the detailed physics and chemistry remains poorly understood.

**Background:** While the solar wind is predominantly composed of protons ($H^+$; ~97%), a series of increasingly heavy minor ions are also present. These minor ions include $^3He^{++}$, $^4He^{++}$, $C^{n+}$, $N^{n+}$, $O^{n+}$, $Ne^{n+}$, $^{36}Ar^{n+}$, and $^{40}Ar^{n+}$, among others [9]. When these ions impact the lunar surface, they are thought to rapidly neutralize and lose their energy through a collisional cascade with regolith grains. Those species that are chemically inert will then outgas as neutral atomic gases (e.g., the He, Ne, $^{36}$Ar, and $^{40}$Ar exospheres) while reactive species may potentially undergo more complex chemistry within the regolith. In the case of solar wind carbon, reactions with both solar wind-derived and lunar H and O should yield a mixture of $CH_4$, CO, and $CO_2$, which then diffuse out of the regolith and into the lunar exosphere.

A model put forth by [10] argues that the influx of solar wind carbon to the Moon must be balanced by an equivalent loss rate across all possible loss mechanisms. These loss mechanisms include implantation and burial in the lunar regolith, diffusion into the lunar exosphere followed by ionization and pickup loss back to the solar wind, and long-term cold trapping in lunar polar regions. The formation of carbon-bearing neutral exospheres was also modeled using a Monte Carlo method, an example of which for $CO_2$ is shown in Figure 1. The exact relative loss rates across these mechanisms, as well as the relative branching ratios governing the production of $CH_4$, CO, and $CO_2$ from solar carbon recycled within the lunar regolith nevertheless remain poorly constrained.

A more recent analysis by [11] has compared lunar exospheric pickup ion fluxes at the Moon by the THEMIS-ARTEMIS mission to a comprehensive model of the lunar exosphere, considering all known or predicted species. After accounting for the total pickup ion production rates from the model, the THEMIS-ARTEMIS measurements reveal greater exospheric pickup-ion flux than can otherwise be accounted for. Based on limitations from existing measurements and dynamical features in the pickup-ion flux, [11] suggested that the pickup ion model–which included

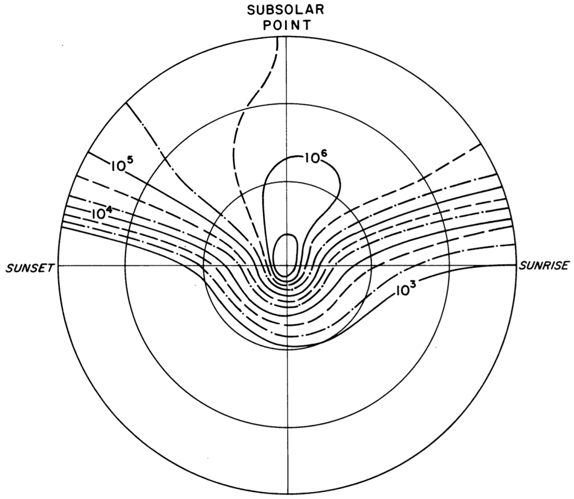

**Figure 1: A Monte Carlo model of the putative $CO_2$ exosphere at the Moon under the assumption that all solar wind carbon converts to $CO_2$ and is emitted into the exosphere. Density contour units are in cm$^{-3}$ and the viewpoint is looking down onto the north pole [10].**

only a limited $CO_2$ exosphere based on pre-dawn Apollo 17 LMS measurements–was missing a relatively heavy ion species, see Figure 2. One possible resolution to this disagreement is the presence of a relatively dense ($\sim 10^4 - 10^5$ cm$^{-3}$) $CO_2$ exosphere at the Moon.

Here, we discuss the neutral exospheric model of [10] and the pickup-ion observations of [11] in the context of establishing our understanding of the nature of solar wind carbon recycling at the Moon. We compare the predictions of [10] for the densities of the $CH_4$, CO, and $CO_2$ exospheres to the LADEE measurements of $CH_4$ and CO [6,7] and the predictions for a $CO_2$ exosphere from [11]. We also discuss the possibility of detecting and/or further constraining the carbon-based exospheric densities and distributions at the Moon via the upcoming *HERMES* instrument suite hosted on the Lunar Gateway, which includes mass-resolved ion measurements. Finally, we touch on implications of this research at the Moon for other airless bodies exposed to the solar wind, including Mercury, which should play host to similar physical and chemical processes regarding solar wind carbon recycling.

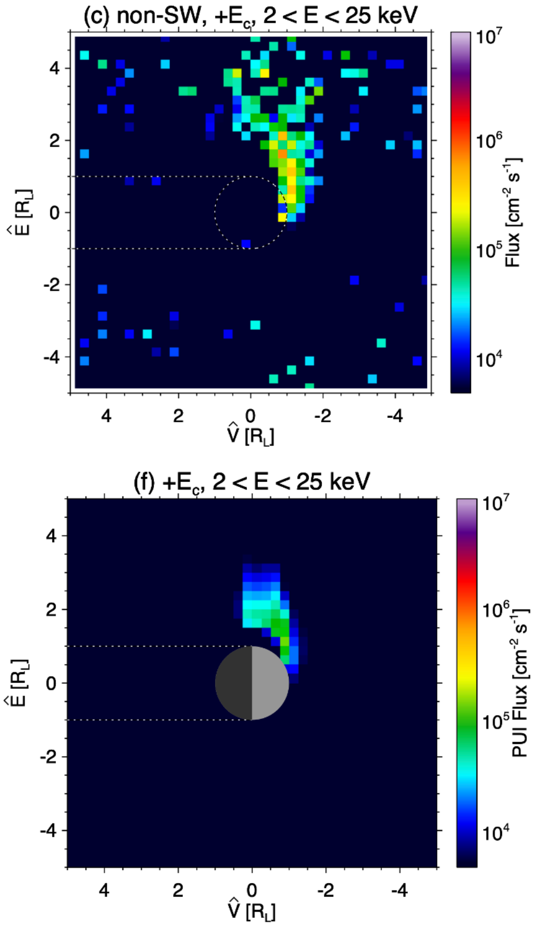

**Figure 2: A comparison of (top) observed and (bottom) modeled lunar pickup ion fluxes [11]. The greater observed pickup-ion flux suggests a missing component in our current understanding of the lunar exosphere.**

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