CARBON DIOXIDE COLD TRAPS ON THE MOON.

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Introduction: Ices, such as H_2O and CO_2, are delivered to the Moon by impacting comets [1]. Among those common volatiles, the strongly polar water molecule has the lowest vapor pressure, and is expected to be trapped in permanently cold regions near the lunar poles [2,3]. Other ices ("super-volatiles") are trapped at lower temperatures, close to the lowest temperatures measured within the lunar PSRs (Permanently Shadowed Regions). We determine the thermal stability of carbon dioxide in the south polar region of the Moon based on 11 years of surface temperature measurements by Diviner, a radiometer onboard the Lunar Reconnaissance Orbiter (LRO) [4], considering their time variation over lunations and seasons.

Methods: The rotation axis of the Moon is tilted by at most 1.57° relative to the normal of the ecliptic, and some craters in the lunar polar regions are permanently shadowed. A portion of these PSRs are cold enough (<~110 K) to trap water ice [2,3]. The sublimation rate of CO_2 ice becomes negligible (<~10 kg/m^2/Gyr) at around 50 K [5]. Dry ice cold traps, if they exist at all [6,7], would lie within the water ice cold traps.

The extent of cold traps is commonly determined by a peak temperature threshold, whereas it is fundamentally defined by the time-integrated sublimation loss [9]. The time-average of the sublimation rate E, $\mathrm{mean}_t(E)$, can be significantly smaller than $\max_t(E)$, and use of the maximum temperature criterion may fail to identify cold traps. The relative difference in cold trap area as determined by these two criteria is 24% for H_2O [8], but is found to be much larger for CO_2.

Diviner provides high-resolution surface temperature and has extensive time coverage [4,9,10]. Diviner bolometric temperatures over 11 years are processed to calculate the time-integrated sublimation loss of CO_2. During the draconic year (346.6 Earth days), the declination of the sun changes between ±1.5°, the equivalent of seasons [10]. For each pixel in the south polar region, the radiances are partitioned into 24 bins within a lunation, based on subsolar longitude (λ_s) and 6 seasonal bins based on ecliptic longitude (L_s). Time-domain interpolation along the diurnal and seasonal axes is used to fill data gaps and frequency-domain filtering is used to smooth the data [8]. Details about the temperature data reduction are provided in Ref. [8], and we are still refining the data processing for the temperature range relevant for CO_2 cold traps.

Measurements of vapor pressure and of the sublimation rate need to be extrapolated to low temperatures. For solid CO_2, a sublimation rate of 10 kg m^{-2}Gyr^{-1} is reached at about 51 K, which corresponds to a 6 mm thick layer of dry ice. (At low temperature, the density of solid CO_2 is 1.7 g/cm^3 [11].) The supply rate of CO_2 to the lunar cold traps is hardly constrained by direct observations, but CO_2 is abundant in comets [1]. Moreover, exosphere models suggest CO_2 is captured by cold traps at high efficiency, due to its low photo-destruction rate [12].

Results: Figure 1 shows the time-averaged sublimation rate of CO_2 ice in the south polar region. The dry ice cold traps include several spatially contiguous pockets, such as in Haworth crater and Amundsen crater. Considering a threshold (delivery rate) of 10 kg m^{-2}Gyr^{-1}, the total area of dry ice cold traps is 286 km^2. If the threshold is lowered to 1 kg m^{-2}Gyr^{-1}, the area decreases to 145 km^2.

If only the maximum temperature were considered, then the total area <10 kg m^{-2}Gyr^{-1} would only be 79 km^2, a factor of 3.6 lower, which demonstrates that using only the peak temperature would dramatically underestimate the extent of super-volatile cold traps.

Discussion: Carbon was found at low concentration, ~100ppm, in Apollo samples [13,14], and may have been implanted in the lunar surface by solar wind. When trapped in unusually cold areas near the lunar poles, the concentration can be far higher. The LCROSS (Lunar CRater Observation and Sensing Satellite) probe impacted a CO_2 cold trap in Cabeus crater [15,16], and the impact plume contained CO_2 [16] in excess of the carbon content measured in Apollo samples, consistent with the theoretical predictions made here.

The availability of carbon would be valuable for In-situ Resource Utilization (ISRU). Future surface missions can utilize CO_2 for scientific studies and the production of hydrocarbons, steel, and biological materials.

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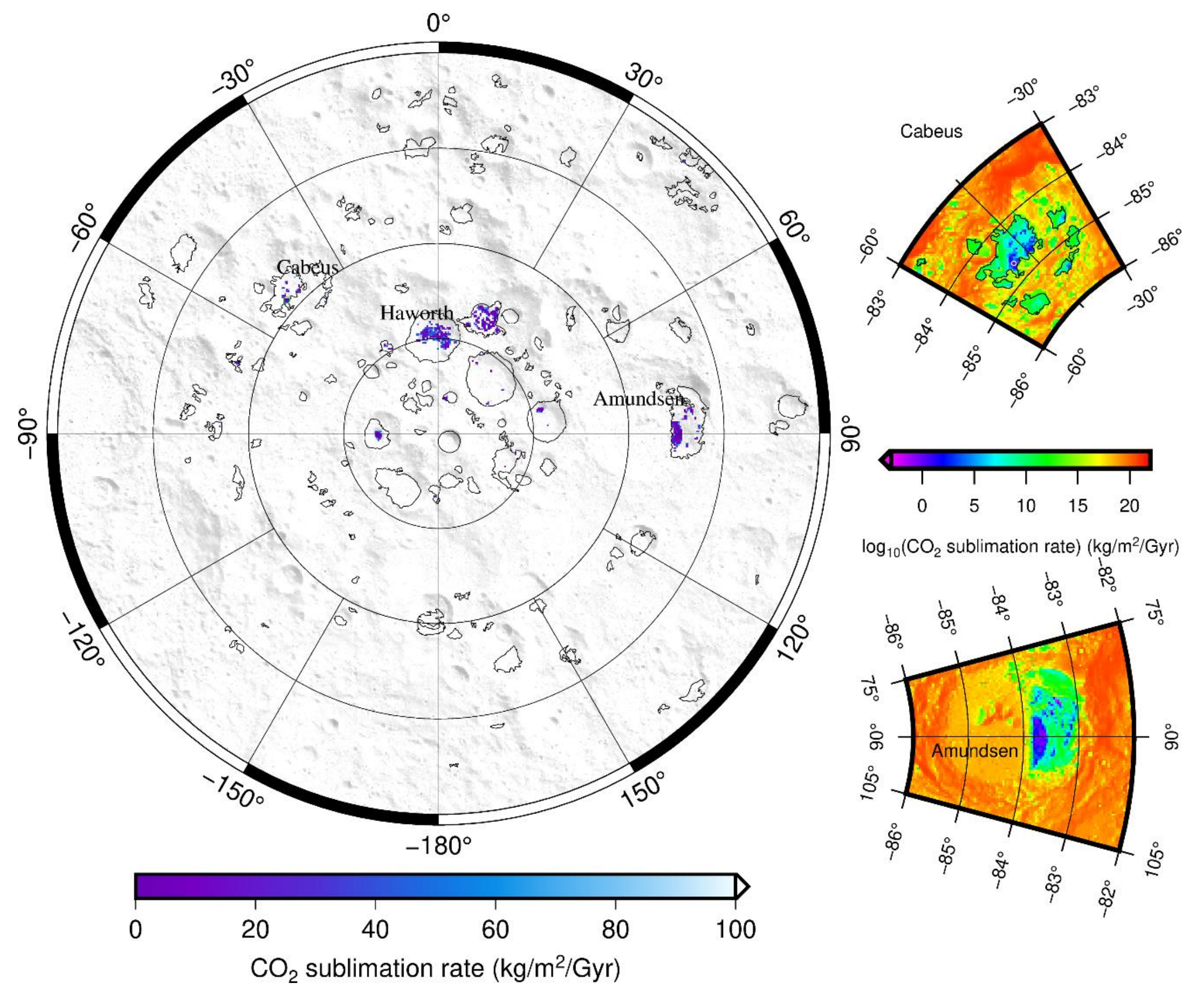

Figure 1: Long-term average of the potential sublimation rate, *E*, of CO_2 in the south polar region of the Moon, poleward of 80°S. Areas where $\text{mean}_t(E)<100\ \text{kg m}^{-2}\text{Gyr}^{-1}$ are colored. Black contours show the boundaries of H_2O cold traps with a threshold of 100 kg $m^{-2}Gyr^{-1}$. The background map is shaded relief. Enlarged maps of Cabeus and Amundsen craters with a logarithmic color scale are also shown. The LCROSS impact site location at Cabeus is marked with a circle.