VOLATILE TRANSPORT ON ARIEL AND IMPLICATIONS FOR A RADIOLYTIC ORIGIN OF CARBON DIOXIDE.

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Introduction: Uranus and its moons have only been directly observed by the Voyager 2 spacecraft flyby in 1986. However, Earth-based observations still give us important information about volatile presence and activity on the large Uranian moons. Telescopic observations of Uranus' moons [1, 2] have revealed a spectral signature of carbon dioxide (CO_2) on their surfaces. This signature was found to be much stronger on the trailing hemispheres of the moons as compared to the leading hemispheres. Additionally, this detection signature has a planetocentric trend on the large Uranian moons, with moons closer to Uranus displaying a stronger signature of CO_2 and moons farther from Uranus displaying an increasingly weaker signature (excluding Miranda, which is too small to gravitationally retain CO_2). Previous work [1–4] has suggested that this dichotomy between the leading and trailing hemisphere is the result of an exogenic formation process, through the radiolytic production of CO_2 ice preferentially on the moons' trailing hemispheres by interaction with charged particles from Uranus' magnetosphere.

Ariel shows the strongest signature of CO_2 of all the Uranian moons (and is the closest large moon to Uranus excluding Miranda). Furthermore, the spectral signature of CO_2 ice is stronger in reflectance spectra collected over low sub-observer latitudes (30°S–30°N) [4]. These stronger absorption bands likely indicate that on the trailing hemisphere there is a higher concentration of CO_2 ice near Ariel's equator. Models of volatile transport can be used to determine how CO_2 ice would migrate on the surfaces of the Uranian moons and how to interpret the observed CO_2 distributions with respect to hypotheses on their origin. For example, volatile transport modeling of Uranus' moon Umbriel has shown that a bright deposit in Wunda, a complex crater near Umbriel's equator, may represent a large CO_2 ice deposit [5]. The high obliquity of the Uranian system (~98°) likely drives higher CO_2 sublimation near the poles of Umbriel and lower rates near its equator [5]. Due to Ariel's similar obliquity, we expect CO_2 ice to behave qualitatively similarly on its surface.

Here, we seek to characterize the transport of CO_2 molecules on Ariel through numerical modeling. We hypothesize that the current observed distribution of CO_2 ice on Ariel is consistent with radiolytic production on the trailing hemisphere and subsequent transport across Ariel's surface to the equator.

Surface Temperature Modeling: Surface temperature is a key control on CO_2 ice transport, but spacecraft observations of this parameter do not exist beyond one measurement at a single point in space and time from the Voyager 2 fly-by [6]. We used a modified thermal model [7] to determine the surface temperature on Ariel both spatially and temporally. As expected, we find Ariel's poles undergo large changes in surface temperature over the course of a Uranian year (Figure 1), allowing the poles to be continuously illuminated for long stretches of time during Uranian polar summers. At Ariel's equator, surface temperature varies less throughout a year, but diurnal temperature fluctuations are larger.

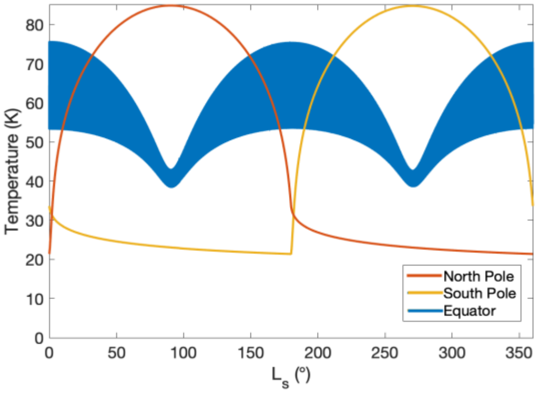

Figure 1. *Surface temperatures on Ariel's surface at the equator and both poles throughout the Uranian year (L_s = 90°: northern hemisphere summer solstice; L_s = 270°: southern hemisphere summer solstice).*

Volatile Transport of CO_2 Ice: We quantified the total amount of sublimation that occurs at each latitude throughout a Uranian year on Ariel.

At Ariel's poles, the sublimation rate of CO_2 ice is high (~80–90 kg/m^2 or ~10^{-2} m/Uranian year), whereas sublimation rates at Ariel's equator are much lower (< 1 kg/m^2 or ~10^{-4} m/Uranian year), although still high enough for ice migration on geologic timescales. Sublimation rate by latitude is shown in Figure 2. These sublimation rates suggest that any CO_2 ice deposited at Ariel's poles will quickly migrate away from these latitudes.

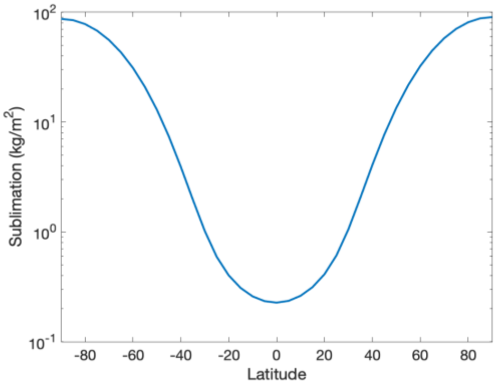

Figure 2. *Total sublimation of CO_2 ice (in kg/m^2) on Ariel per Uranian year versus latitude. Sublimation rate of carbon dioxide ice at Ariel's poles is much higher than at Ariel's equator (note log scale on vertical axis).*

To determine the likelihood of where CO_2 ice is most likely to condense, we conducted a volatile transport model of 10^5 particles using a Monte Carlo method to determine a probability distribution of what latitudes CO_2 molecules will migrate to, depending on starting latitude. We considered the case of a small (~1 m thick) CO_2 ice deposit located at the center of the trailing hemisphere (0°N, 270°E) of Ariel, matching the expectations of where CO_2 ice would originate if it is produced radiolytically [3, 4]. At this location, the sublimation rate is low (~10^{-4} m/Uranian year) compared to the poles. Of the molecules that do sublimate in a Uranian year, 36% stay within 5° of the equator, and 55% remain within 5° of the starting longitude. Figure 3 shows the ending latitudes of 10^5 sublimated CO_2 particles after one hop.

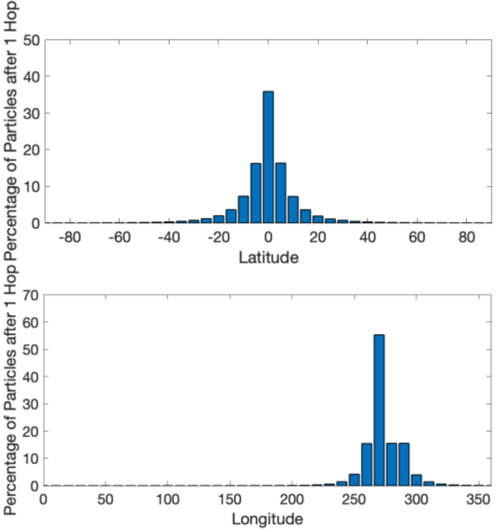

Figure 3. *Distribution of what latitude (top panel) and longitude (bottom panel) a carbon dioxide particle is most likely to migrate to after one hop, starting from the center of Ariel's trailing hemisphere (0° N, 270°E).*

CO_2 ice that is radiolytically produced at the center of the trailing hemisphere will "spread out", but still remain relatively close to its origin after one Uranian year (Figure 3). However, although sublimation rates at the equator are much lower than at the poles (Figure 2), they are still high enough such that a 1-m-thick CO_2 deposit could sublimate to other locations in <1 Myr. In this case, we would expect that CO_2 ice would still preferentially be located at low latitudes (because of the latitudinal distribution in sublimation rates shown in Figure 2), but with a uniform longitudinal distribution if ancient CO_2 has been left to migrate on Ariel over 1 Myr with no production. The observed trend in CO_2 on Ariel might therefore require active CO_2 production.

Conclusions and Future Work: Volatile transport modelling demonstrates that CO_2 ice on Ariel's surface, regardless of starting latitude, will migrate towards Ariel's equator. If CO_2 ice began migrating across Ariel's surface starting randomly at any longitude, CO_2 ice would be distributed more uniformly across Ariel's leading and trailing hemispheres. If CO_2 begins migrating in our model beginning on Ariel's trailing hemisphere, the end distribution of CO_2 ice is uniform in longitude after long timescales but remains confined to Ariel's trailing hemisphere after only a few Uranian years (1 Uranus year = 84 Earth Years). Therefore, the observed distribution of CO_2 ice might be consistent with active radiolytic production of CO_2 molecules on Ariel.

Our work assumed flat topography, and future work will explore how canyons observed on Ariel's surface [8] could potentially act as a cold trap for CO_2 ice, especially near its equator. Our predictions of volatile transport on Ariel could be tested with spatially resolved observations collected by instruments onboard a future Uranus orbiter that studies the system and its moons [9].

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References: [1] Grundy et al. (2003) *Icarus*, 162, 222–229. [2] Grundy et al. (2006) *Icarus*, 184, 543–555. [3] Cartwright et al. (2015) *Icarus*, 257, 428–456. [4] Cartwright et al. (2022) *Planetary Sci. Journal*, 3, 8. [5] Sori et al. (2017) *Icarus*, 290, 1–13. [6] Hanel et al. (1986) *Science*, 233, 70–74. [7] Bramson et al. (2017) JGR: Planets, 122, 2250–2256. [8] Plescia (1987) Nature, 321, 201–204. [9] Cartwright et al. (2022) *Planetary Sci. Journal*, 2, 120.