A WUNDA-FULL WORLD? TESTING THE PLAUSIBILTY OF CARBON DIOXIDE FROST ON UMBRIEL
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Introduction: Umbriel is an icy, dark, and heavily cratered [1] satellite of Uranus (Figure 1). It has an especially low bond albedo (~0.1), but contains one particularly bright feature: Wunda, a large (~130 km) impact crater, contains an annulus-shaped (lesser and greater radii of ~10 km and ~40 km) high-albedo feature [2, 3]. Carbon dioxide has been detected on the largest satellites of Uranus, principally on their trailing hemispheres [4, 5]. A leading hypothesis is that CO_2 is produced radiolytically by charged particles caught in the Uranian magnetosphere [6]. Because the albedo of CO_2 ice is consistent with the albedo of the bright feature in Wunda (hereafter called "Wundafill"), it is tempting to identify Wundafill as CO_2 ice, but this idea has not been rigorously tested.

Here, we quantitatively test the hypothesis that Wundafill represents a deposit of CO_2 ice in a "cold trap" by combining a thermal model to estimate the spatial and temporal temperature distributions on Umbriel with a ballistic transport model to determine the expected migration of CO_2 molecules similar to Iapetus [7]. The cold trap hypothesis is attractive because Wunda lies at approximately the equator, where we expect Umbriel to have the lowest total CO_2 sublimation over a Uranian year due to the planet's extreme obliquity (98°), and because Wunda lies at approximately the center of the trailing hemisphere, where CO_2 detection is strongest [5]. Questions we seek to answer in this work include (1) Do CO_2 molecules tend to migrate to Wunda's location? (2) If so, do we expect them to remain there perennially? (3) What is the lifetime of CO_2 molecules due to escape? (4) Why is Wundafill an annulus? (5) Why do we not observe similar bright features on the surfaces of the other large Uranian moons or elsewhere near Umbriel's equator?

Thermal Model: We use a 1D semi-implicit thermal conduction model to calculate expected surface temperatures. Using the orbital properties of Uranus and rotation rate and pole-vector of Umbriel, we calculate solar fluxes at each latitude and local-time on the moon's surface throughout an Umbriel year, assuming a bond albedo of 0.1. There are no thermal inertia data available for Uranian moons; here we assume a thermal inertia of 15 $Jm^{-2}K^{-1}s^{-0.5}$ for our nominal case, which is a value typical of icy satellites [8], but also test the sensitivity of our results to this parameter. We use the same model to simulate a CO_2 ice deposit at the latitude of Wunda (7.9° S) with an albedo of 0.5 and thermal inertia of 940 $Jm^{-2}K^{-1}s^{-0.5}$.

Ballistic Transport: Using the temperature and sublimation rate outputs from our thermal model as inputs for a ballistic transport model, we calculate the expected distribution of CO_2 on Umbriel throughout a Uranian year. At a given temperature T, the velocity v of a particle will be random according to the Maxwell-Boltzmann probability distribution. The distribution of directions a particle takes is assumed to be isotropic.

If a molecule's velocity exceeds the escape velocity (517 m/s), then the molecule is lost from the system via Jeans escape. Figure 2 shows the fraction of sublimated CO_2 molecules that are lost in this way for a range of temperatures relevant to the Umbrielian system. Knowledge of the fraction of CO_2 lost allows us to constrain the lifetime of any CO_2 feature, or the rate at which new CO_2 must be produced to sustain it.

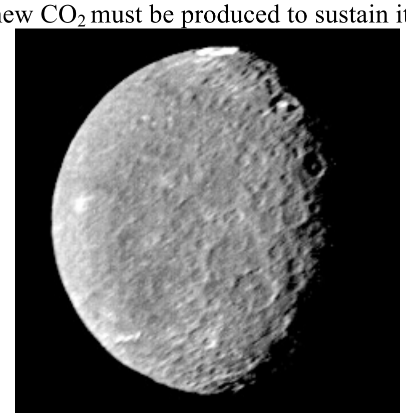

Figure 1. Voyager 2 image [2] of Umbriel. Wundafill is the bright feature at the top (which is at the equator).

Results: Results of our thermal model are shown in Figure 3, showing our calculated temperature as a function of time throughout the Umbrielian year for our nominal case. At the equator, temperatures range between ~40–80 K and may experience a diurnal temperature change of up to ~20 K, depending on the time of year. At the poles, temperatures range from ~20 K to ~90 K. Due to the relatively low eccentricity of Uranus and the timing of perihelion near Umbriel's fall equinox, there is no strong difference between northern and southern summers.

Figure 4 shows the total annual sublimation of CO_2 ice as a function of latitude. While our models show that the annual-average temperatures on Umbriel as a function of latitude lie within a relatively narrow range, sublimation rate (sensitive to the peak temperatures) is strongly dependent on latitude. We tested our ballistic transport model and found that during extreme temperature distributions (at solstices, Figure 3), a sublimated CO_2 molecule is more likely to spend time in the winter hemisphere, due to colder temperatures and resulting lower velocities.

Discussion: Our results reveal a tendency for CO_2 ice to reside near the equator. Combining an estimated equatorial sublimation rate of 6 kg m^{-2} per Umbrielian yr (Figure 4) with the expected loss rates due to Jeans escape (Figure 2), we estimate that Wundafill, if it were a deposit of CO_2, would experience a loss rate of at least 0.5 mm/Myr assuming the low albedo and thermal inertia typical of Umbriel and no replenishing CO_2 source. With these assumptions, Wundafill could not persist throughout solar system history.

However, although most of Umbriel's surface has a low albedo, Wundafill itself is bright (albedo of 0.49 [3]), and icy deposits have a much higher thermal inertia than regolith. The higher albedos and thermal inertias result in lower peak surface temperatures. Thus, a feedback effect may be at play, increasing the stability of CO_2 ice; accumulation of ice in a cold spot increases albedo, which decreases temperature and makes the location more suitable for further accumulation. We ran a thermal model for CO_2 ice at Wunda's location, and find that temperatures range between 47–55 K (Figure 3). The smaller range is due to the increased thermal inertia of CO_2 ice compared to typical airless body surfaces. At these temperatures, the sublimation rate is nearly zero, and we find that a large patch of bright CO_2 ice is stable near Umbriel's equator over the age of the solar system. Indeed, these sublimation rates are so low that Wundafill may be actively accumulating from CO_2 sourced elsewhere on the body.

Though we have shown stability, to satisfyingly answer the question as to whether Wundafill could be CO_2, we need an explanation for why ice would build up inside Wunda specifically and not everywhere near the equator. We expect, based on studies of impact crater morphology on other icy satellites [e.g., 9, 10], that Wunda is a complex crater with a central peak. Such morphology could explain the annular shape of Wundafill; a central peak has surface slopes (which alter the amount of incident sunlight upon its surface) and positive relief (which could provide shade to nearby flat surfaces in an annular pattern). If these effects are important, it is possible that we observe Wundafill because Umbriel fortuitously contains a large complex crater very close to its equator and near the center of the trailing hemisphere where CO_2 may be radiolytically sourced [6]. Alternatively, similar features could exist on other Uranian moons or the unseen portions of Umbriel's equator, but have not been observed.

Our models differ from previous work on volatile migration on other bodies [e.g., 7] due to the high obliquity and relatively low gravity of Umbriel and the importance this has on temperature distributions and escape rates. Our work could be useful in understanding volatiles on other high-obliquity bodies, like the other large satellites of Uranus or Pluto.

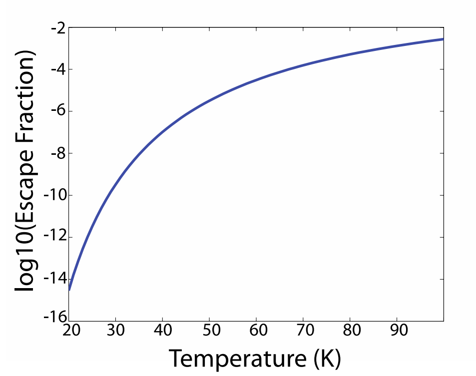

Figure 2. Fraction of sublimated CO_2 that thermally escapes the Umbriel system as a function of surface temperature.

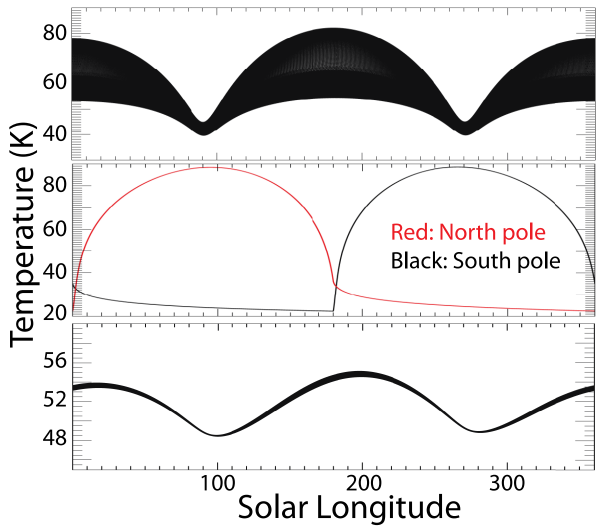

Figure 3. Example outputs of our thermal model, displaying the temperature throughout an Umbrielian year for regolith at the equator (top) and poles (middle), and CO_2 ice at Wunda (bottom).

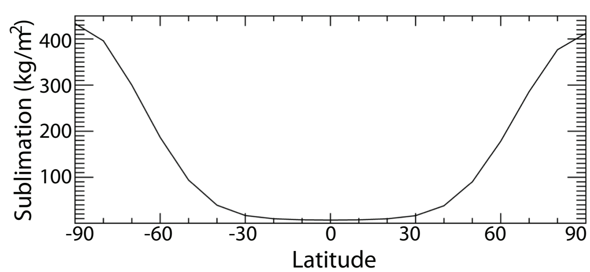

Figure 4. Total sublimation of CO_2 ice over an Umbrielian year as a function of latitude.

References: [1] Plescia, J.B. (1987), *JGR* 92, 14918-14932. [2] Smith, B.A. et al. (1986), *Science* 233, 43-64. [3] Helfenstein, P. et al. (1989), *Nature* 338, 324-326. [4] Grundy, W.M. et al. (2003), *Icarus* 162, 222-229. [5] Grundy, W.M. et al. (2006), *Icarus* 184, 543-555. [6] Cartwright, R.J. et al. (2015), *Icarus* 257, 428-456. [7] Palmer, E.E. and R.H. Brown (2008), *Icarus* 195, 434-446. [8] Howett, C.J.A. et al. (2010), *Icarus* 206, 573-593. [9] Schenk, P.M. (1989), *J. Geophys. Res.* 94, 3813-3832. [10] Moore, J.M. et al. (2004), *Icarus* 171, 421-443.