A WUNDA-FULL WORLD? TESTING THE PLAUSIBILITY 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 CO₂ is produced radiolytically by charged particles caught in the Uranian magnetosphere [6]. Barring any abundant CO₂ ice deposit at the top (which is at the equator), it is tempting to identify Wundafill as CO₂ ice, but this idea has not been rigorously tested.

Here, we quantitatively test the hypothesis that Wundafill represents a deposit of CO₂ 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 CO₂ 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 CO₂ 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 CO₂ detection is strongest [5]. Questions we seek to answer in this work include (1) Do CO₂ 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 CO₂ 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⁻²K⁻¹s⁻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 CO₂ ice deposit at the latitude of Wunda (7.9° S) with an albedo of 0.5 and thermal inertia of 940 Jm⁻²K⁻¹s⁻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 CO₂ 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 CO₂ molecules that are lost in this way for a range of temperatures relevant to the Umbrielian system. Knowledge of the fraction of CO₂ lost allows us to constrain the lifetime of any CO₂ feature, or the rate at which new CO₂ must be produced to sustain it.

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 CO₂ 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 CO₂ molecule is more likely to spend time in the winter hemisphere, due to colder temperatures and resulting lower velocities.

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