A Wunda-full world? Testing the plausibility of CO_2 frost on Umbriel

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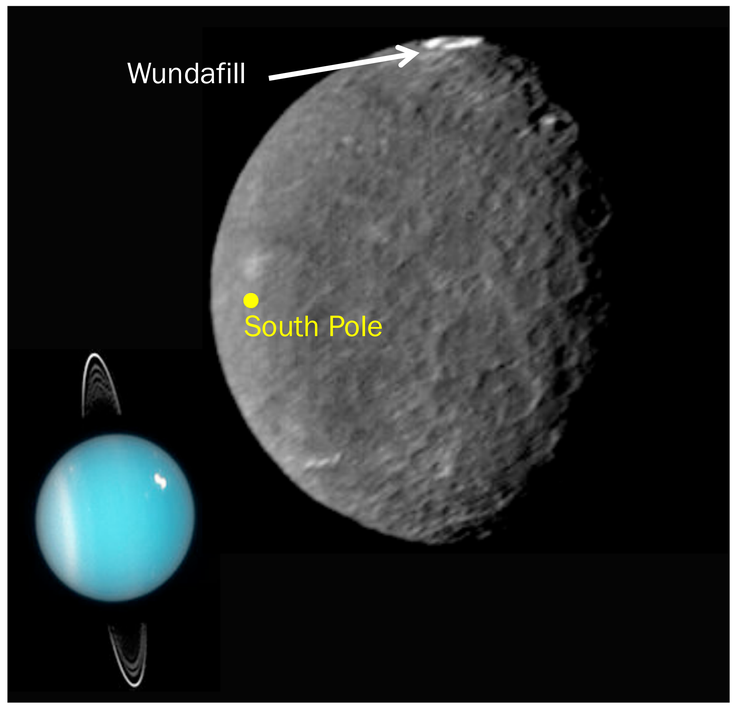
Umbriel and Uranus

Umbriel is one of five large (r = 584.7 km) Uranian moons. It is dark (average bond albedo ~0.1), but has a noticeable bright (~0.5) annulus inside the ~130 km diameter equatorial crater Wunda [1–3]. We hypothesize that the bright annulus, which we call "Wundafill," represents a deposit of carbon dioxide frost.

Recent detections of CO_2 on the trailing hemispheres of Uranian satellites [4,5] support this hypothesis. The CO_2 may be produced radiolytically [6]. We test our hypothesis using a combination of thermal modeling and ballistic transport models.

The extreme obliquity of the Uranian system (~98°) makes our study fundamentally different from similar work on other planets [e.g., 7].



Above: Uranus as seen from the Hubble Space Telescope and Umbriel as seen from Voyager 2 (not to scale or during the same season).

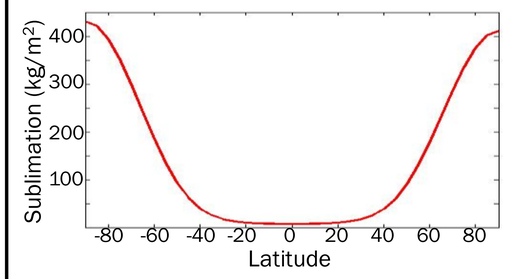
Thermal Modeling

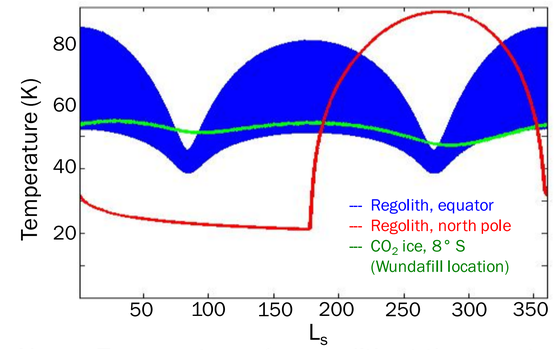
We use a 1D semi-implicit thermal conduction model to calculate surface temperatures. We use I = 15 J m^{-2} K^{-1} s$^{-0.5}$ for regolith [8] and I = 940 J m^{-2} K^{-1} s$^{-0.5}$ for pure CO_2 ice. Based on temperature results we estimate sublimation rates, which are given by:

$$i = p\sqrt{\frac{\mu}{2\pi RT}}$$

I	thermal inertia	R	gas constant
c	heat capacity	T	Temperature
E	escape velocity	r	Umbriel radius
p	vapor pressure	μ	molecular mass
i	sublimation rate	k	Boltzmann constant
g	surface gravity	v	velocity

Above: Table of parameters used.





Above: Temperatures for regolith at the equator, north pole, and thick CO_2 ice at Wunda.
Left: Sublimation of CO_2 ice per Uranian year on a surface with regolith thermal properties.

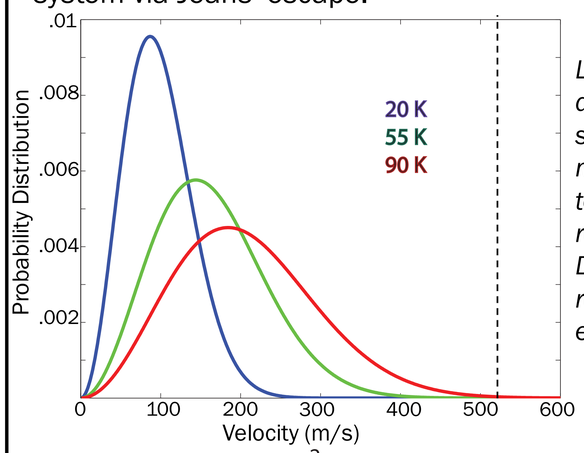
The sublimation on a surface with thermal properties of thick CO_2 ice at Wunda is < 3×10^{-7} kg/m^2 per Uranian year (~84 Earth years).

Ballistic Transport

When a molecule sublimates, it is launched on a ballistic trajectory with a random direction and launch angle, and with a velocity according to the Maxwell-Boltzmann probability distribution:

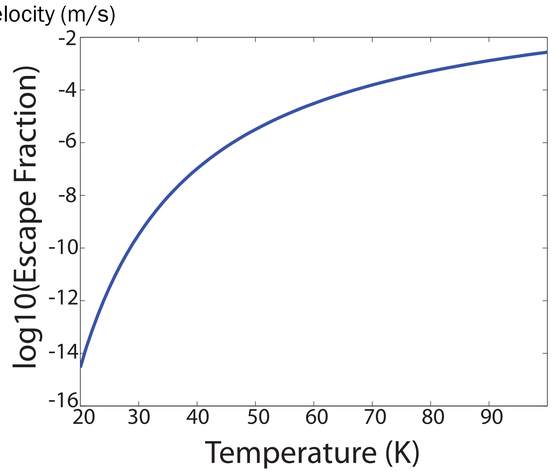
$$f = 4\pi\left(\frac{\mu}{2\pi kT}\right)^{\frac{3}{2}} v^2 e^{\frac{-\mu v^2}{2kT}}$$

If a molecule's velocity exceeds Umbriel's escape velocity of $E = (2gr)^{0.5}$ = 517 m/s, it is lost from the system via Jeans' escape.



Left: Velocity distributions of sublimated CO_2 molecules at temperatures relevant to Umbriel. Dashed line represents the escape velocity.

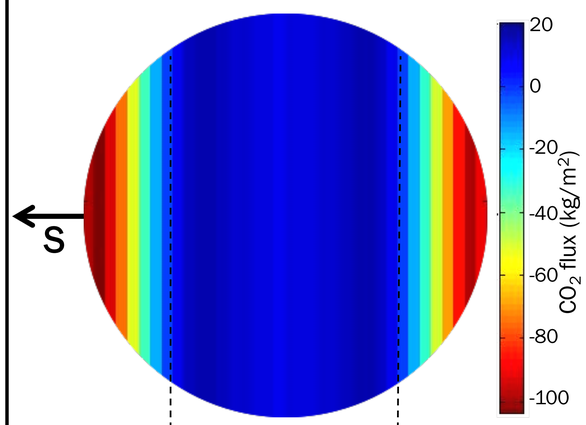
Right: Fraction of sublimated CO_2 molecules that are lost to Jeans escape versus temperature.

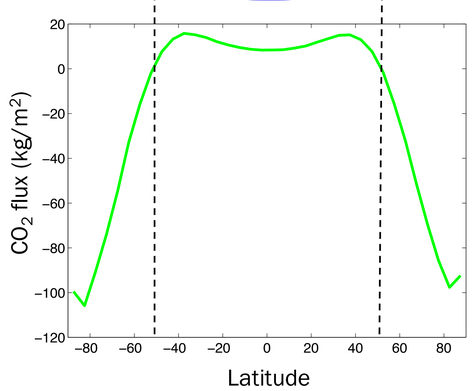


We do not calculate the effects of CO_2 frost adsorbed onto the surface of regolith grains, which we expect to be much less important than sublimation.

Carbon Dioxide Budget

Using the temperatures and sublimation rates from our thermal model as an input for our ballistic transport model, as has been done for other planets [e.g., 7] we calculate how an initial distribution of surface CO_2 evolves over time.





Left: Flux of CO_2 molecules at a given location on Umbriel's surface over one Uranian year, starting from an initial condition of CO_2 everywhere on the surface, but the surface has thermal properties of regolith. Top shows results displayed over one hemisphere, bottom shows flux as a function of latitude. Dashed lines represent zero net flux.

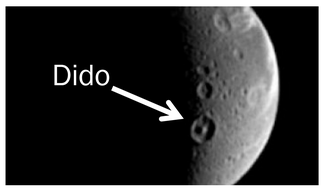
Once CO_2 starts migrating, the above results change as the polar regions are rapidly depleted of CO_2; we expect the latitudinal band experiencing net CO_2 influx to narrow as the system evolves.

We also ran simulations where equatorial regions had the thermal properties of CO_2 ice, not regolith. These runs show sublimation rates are negligible: once Wundafill forms, it is stable throughout the age of the solar system.

Discussion

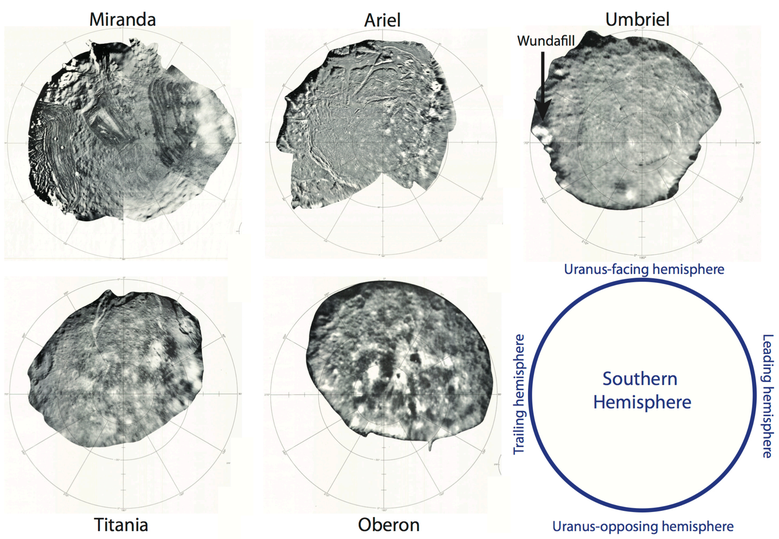
CO_2 frost migrates equatorward on geologically short timescales. Why does Wundafill appear in a crater, and not in a band around a low latitude? Two possibilities:

1. Wunda is a complex crater, and the flat area around the central peak is a relative cold trap.
2. Wunda is near the center of the trailing hemisphere, where CO_2 may be produced [5, 6].



Left: Cassini image of Dione. The crater Dido has a central peak. Relevant parameters are very similar between Dione/Dido and Umbriel/Wunda, so we expect Wunda to have a central peak.

Miranda's escape velocity (~1.93 m/s) is too low to retain CO_2, but it is possible the other large Uranian moons have Wundafill-like deposits which are not yet observed. Umbriel is the only moon where we have visually observed the center of the trailing hemisphere.



Above: Photomosiacs produced by the USGS showing Voyager imagery coverage of the 5 large Uranian moons.

We conclude Wundafill plausibly represents a CO_2 frost deposit. It need not be geologically young.

[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* 257, 428–456. [8] Howett, C.J.A. et al. (2010), *Icarus* 195, 434–446.