A Wunda-full world? Carbon dioxide ice deposits on Umbriel and other large moons of Uranus

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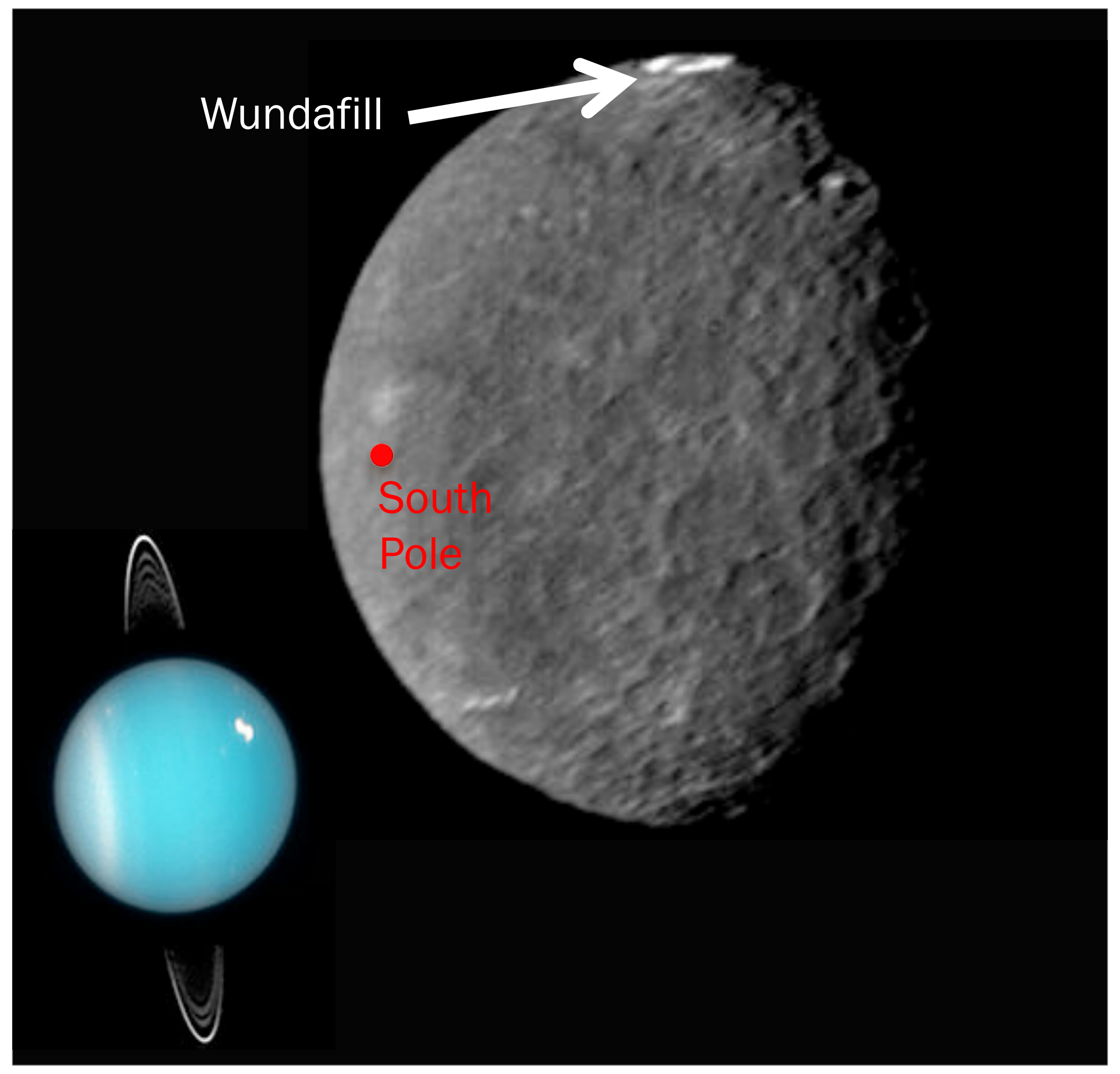
Umbriel and Uranus

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 ice.

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 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

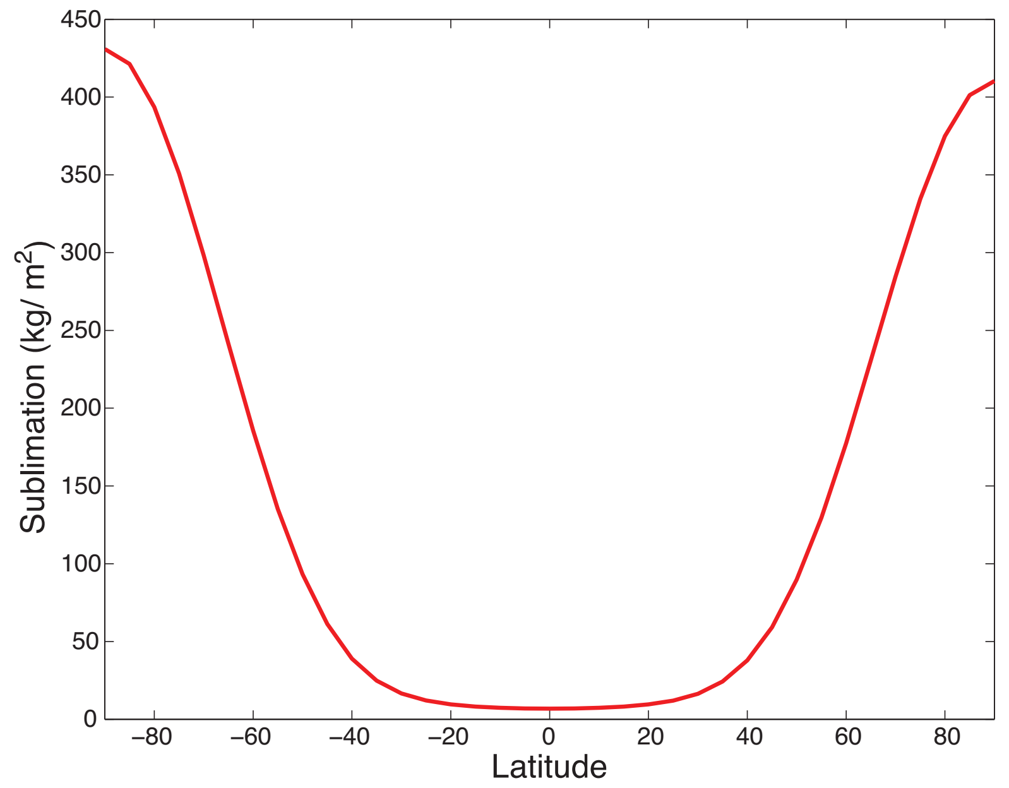
We use a 1D semi-implicit thermal conduction model to calculate surface temperatures. We use I = 15 J m^{-2} K^{-1} s$^{-0.5}$ for regolith [8] and I = 940 J m^{-2} K^{-1} s$^{-0.5}$ for pure CO_2 ice. Based on temperature results we estimate sublimation rates, which are given by:

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

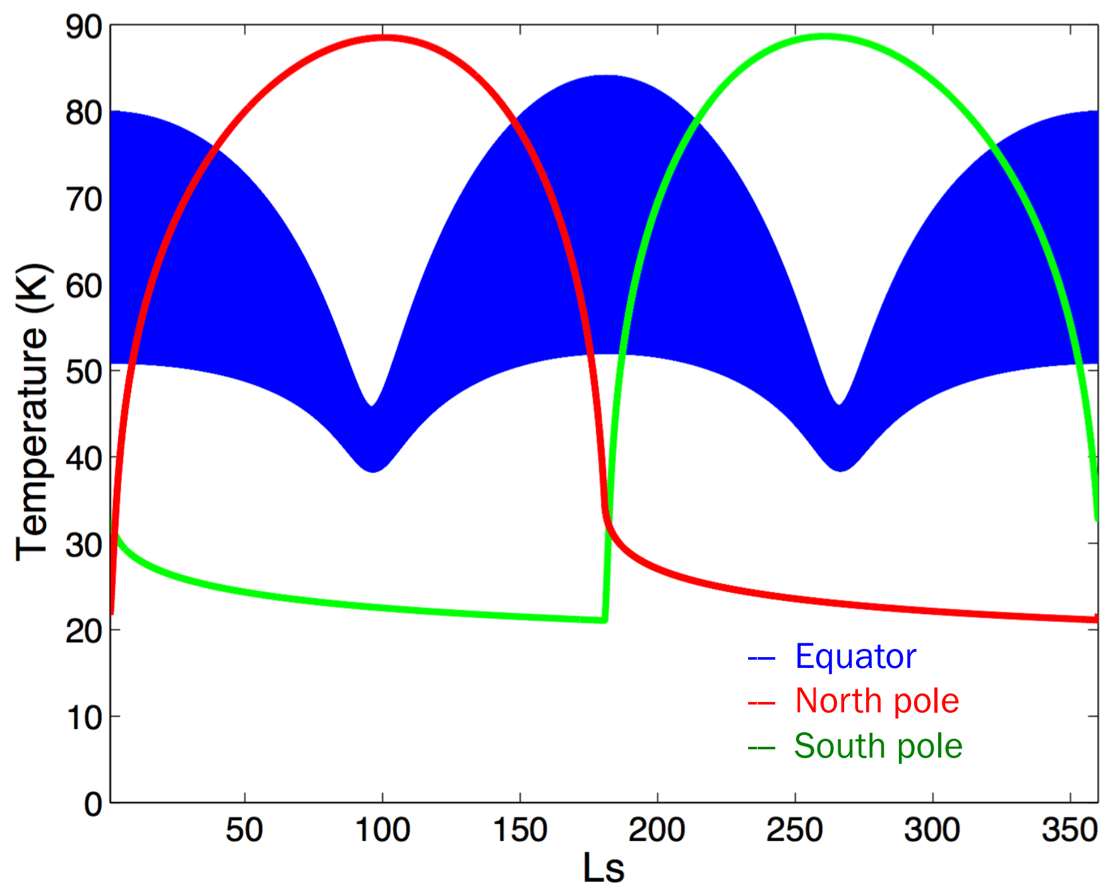
We have performed thermal model simulations at varying thermal inertias and find our results are robust to uncertainty in this parameter.

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

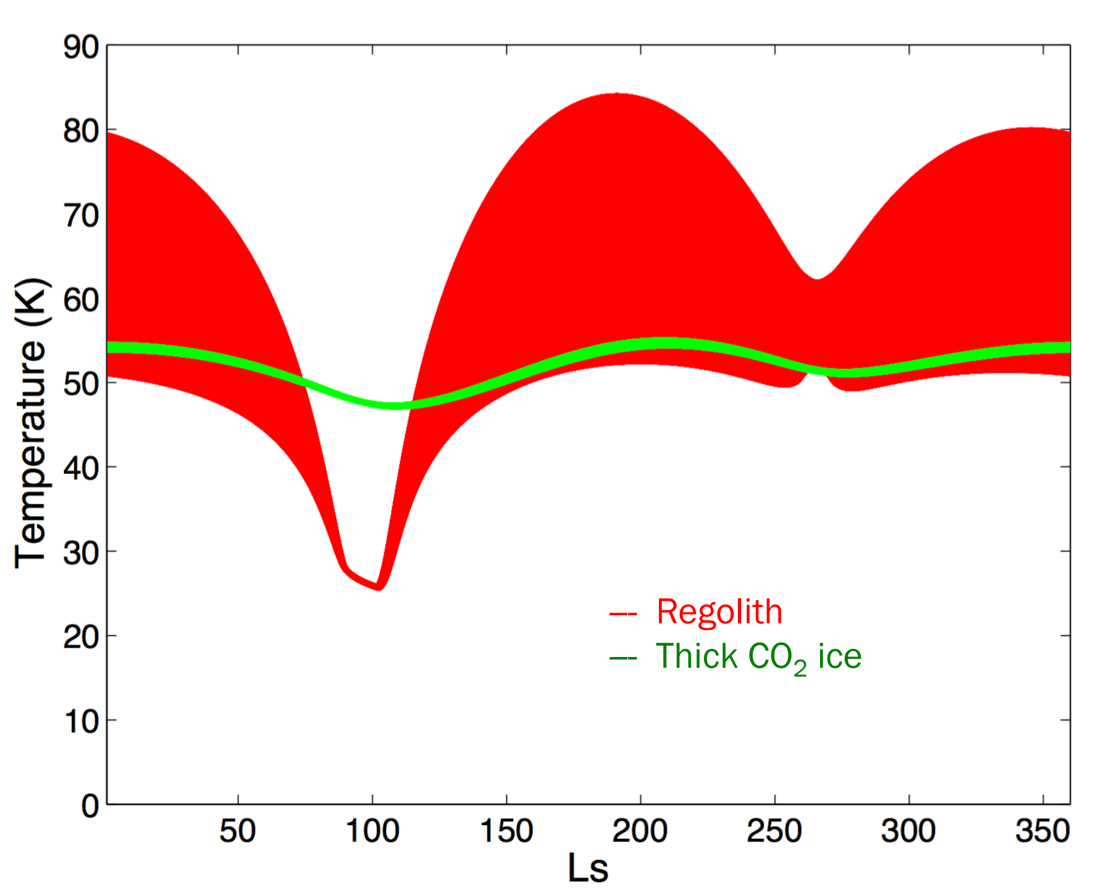
Above: Table of parameters used.



Above: Total annual sublimation of CO_2 ice mixed with regolith on Umbriel.



Above: Temperatures for regolith at the equator, north pole, south pole of Umbriel.



Above: Temperatures for regolith and thick CO_2 ice at Wunda's location.

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).

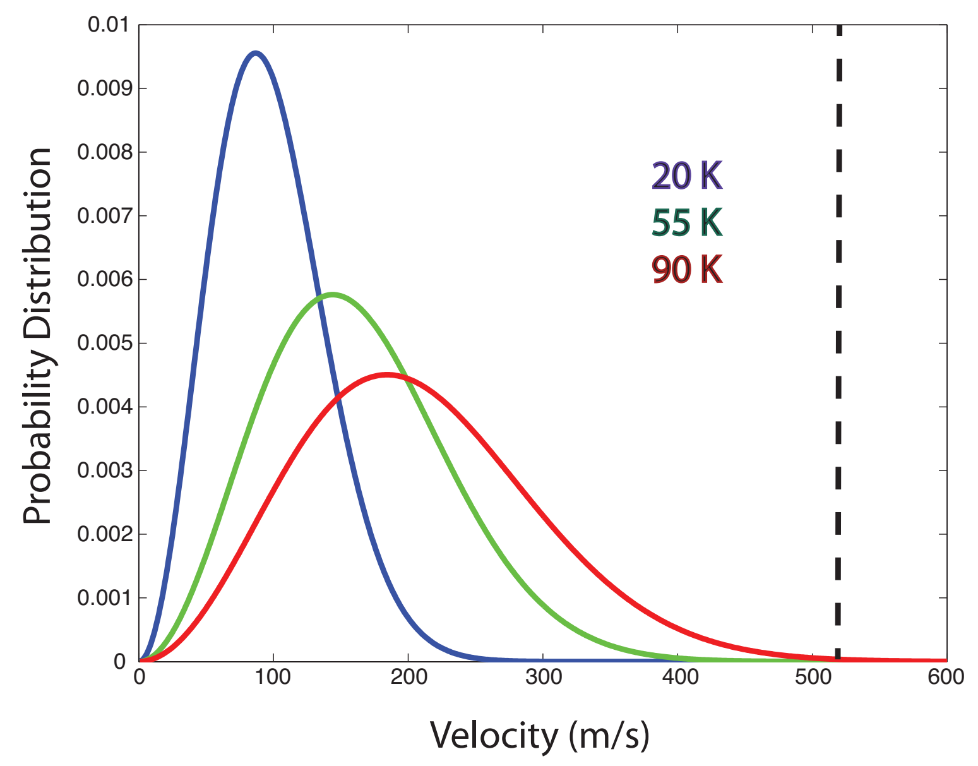
<u>A thick (10s of m) CO_2 ice deposit on Umbriel is stable over the age of the solar system.</u>

Ballistic Transport

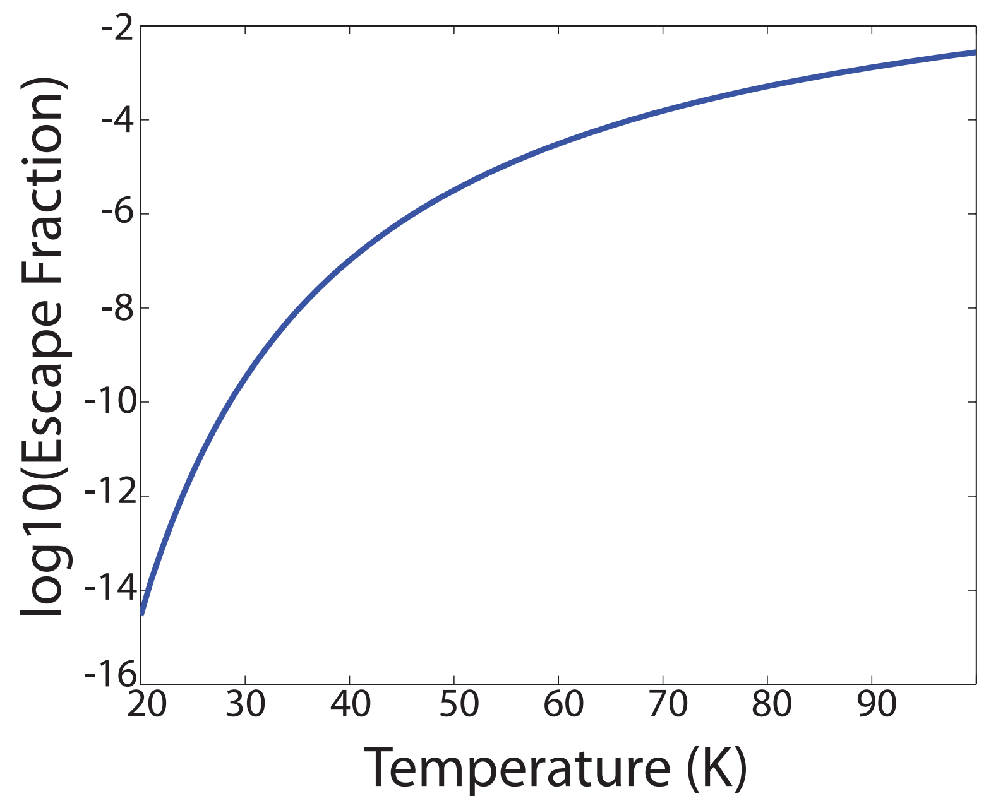
When a molecule sublimates, it is launched on a ballistic trajectory in a random direction, and with a velocity according to the Maxwell-Boltzmann probability distribution:

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

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.



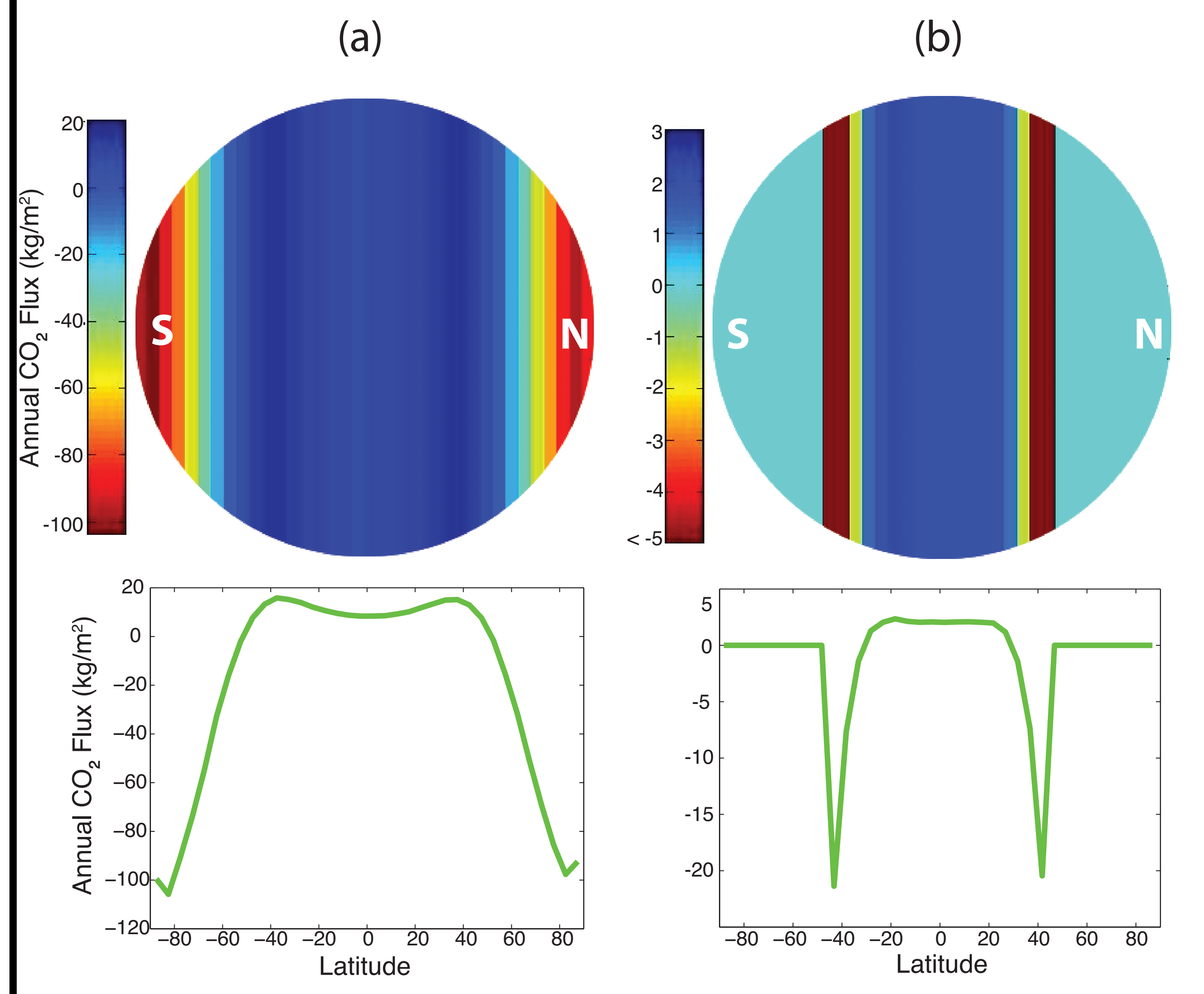
Left: Velocity distributions of sublimated CO_2 molecules at temperatures relevant to Umbriel. Dashed line represents the escape velocity.



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

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.

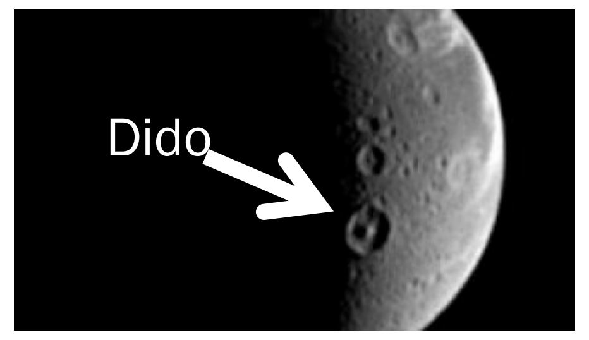


Above: Flux of CO_2 molecules at a given location on Umbriel's surface over one Uranian year, starting from an initial condition of CO_2 everywhere on the surface (left column) or everywhere except depleted from regions poleward of 50° latitude (right column). Top shows results displayed over one hemisphere, bottom shows flux as a function of latitude.

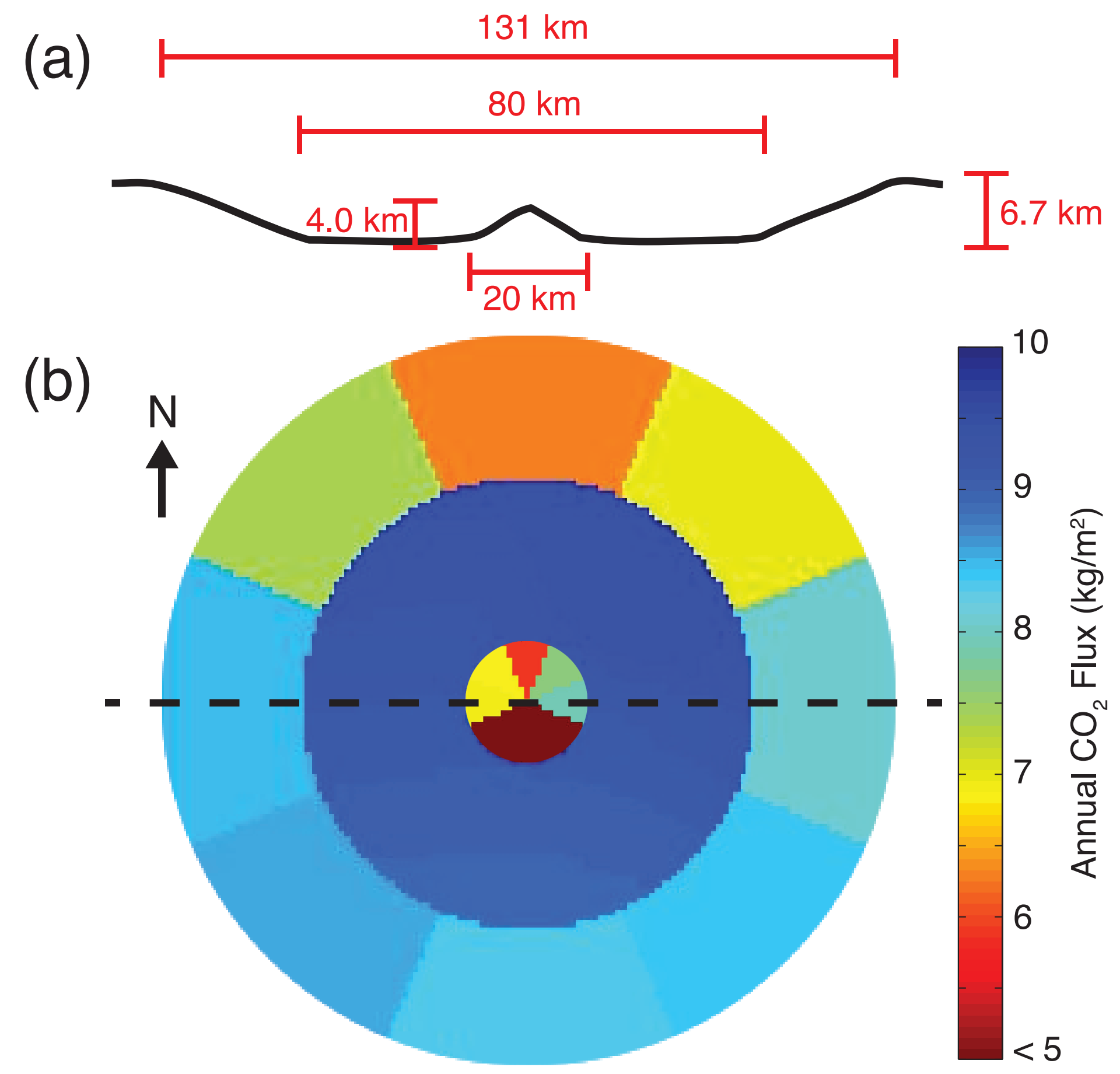
Once CO_2 starts migrating, the the latitudinal band experiencing net CO_2 influx narrows as the system evolves. These results assume the thermal properties of regolith; thick CO_2 ice is instead effectively immobile.

Topographic Effects

Why does Wundafill appear in a crater, and not a latitudinal band? And why is Wundafill in the shape of an annulus? We propose that Wunda is a complex crater, as expected from its size [9]. The crater topography would have 3 thermal effects: (1) sloped terrain would experience different insolation, (2) walls and central peak would provide shadowing to the floor during parts of the year, and (3) crater topography obstructs portions of the sky from reradiation of heat from surrounding topography.



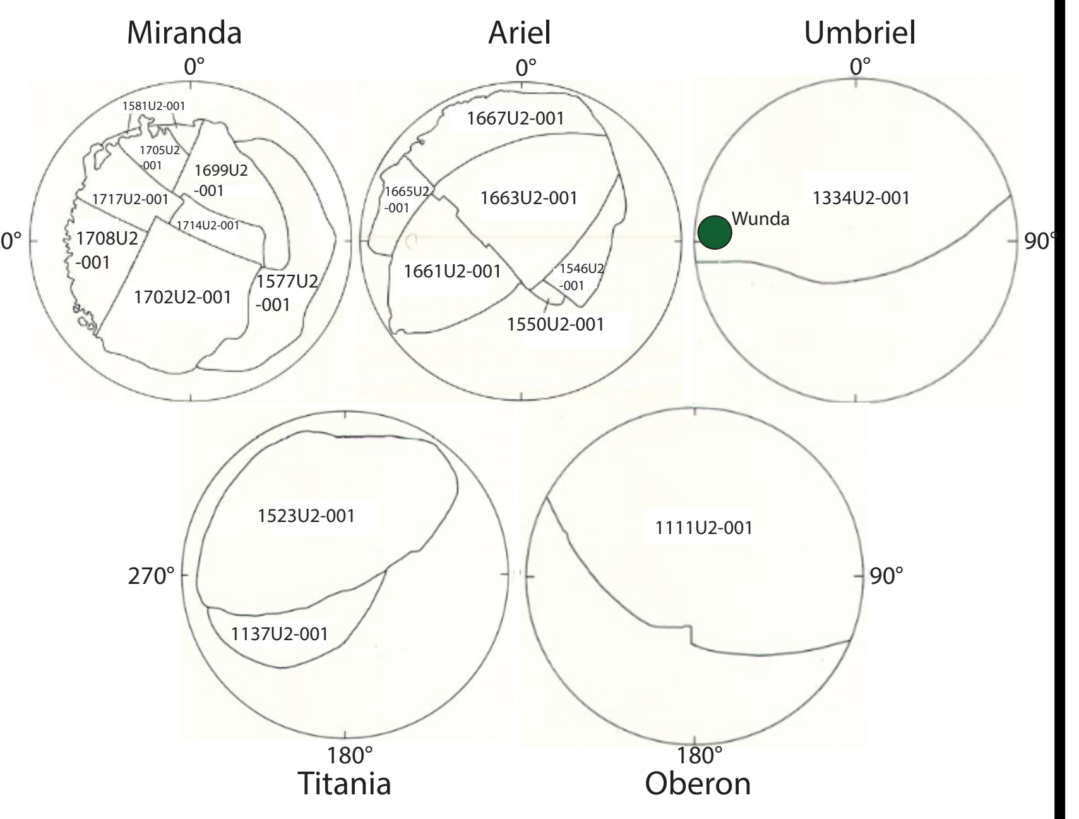
Left: Cassini image of Dione. The crater Dido has a central peak. Relevant parameters are very similar between Dione/Dido and Umbriel/Wunda, so we expect Wunda to have a central peak.



Above: (a) Our estimate of Wunda's topography, extrapolated from Saturnian moons [10]. (b) The CO_2 budget for the walls, floor, and central peak of Wunda crater taking into account the 3 thermal effects listed above.

Other Uranian Moons

Why have we not observed similar bright spots on the other four large moons of Uranus? Miranda is too small to retain CO_2 (E = 193 m/s) and detections of CO_2 on Oberon are uncertain. Voyager 2 was only able to image ~1/3 of the surfaces of Ariel, Umbriel, and Titania, so it is not surprising that we have only observed a bright deposit on 1 of the 3 moons. We predict that complete coverage would reveal a similar bright deposit of CO_2 ice on all three of these moons.



Above: Voyager 2 image coverage of the five large Uranian satellites.

The case for Wundafill as CO_2 Ice

1. CO_2 has been detected on the trailing hemisphere of Umbriel, and Wunda lies very near the center of the trailing hemisphere.
2. CO_2 ice migrates to low latitudes over short timescales, and Wunda lies nearly at the equator.
3. Umbriel occupies a sweet spot for CO_2: it is warm enough for CO_2 to be mobile, cold enough so a thick CO_2 ice deposit is resistant to sublimation over long timescales, and large enough to retain CO_2.
4. The albedo of Wundafill is consistent with CO_2 ice.
5. The annular shape of Wundafill is explained by Wunda as a complex crater.

Why do we care?

1. We make a prediction about the Uranian satellite system that can easily be tested with a Uranus orbiter or fly-by.
2. If correct, bright ice deposits will have implications for other processes on these bodies, e.g. radiolysis or cryovolcanism.
3. Our work helps interpret telescopic observations of other bodies in the outer solar system.
4. "Exotic" ices may actually be common in the outer solar system.

[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. [9] Schenk, P.M. (1989), *J. Goephys. Res.* 94, 3813–3832. [10] Moore, J.M. Et al. (2004), *Icarus* 171, 421–443.