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Conditions for Sublimating Water Ice to Supply Ceres' Exosphere

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1. Introduction

OH^- and water vapor has been detected around Ceres [1,2], suggesting an exosphere. However, not all observations of Ceres have shown this exosphere [2], suggesting it is transient. One hypothesis to explain these detections is solar energetic particle events [3]. Another possible hypothesis is water ice sublimation. We model the conditions under which water ice sublimation can explain the transient detections of water vapor around Ceres. We conclude that surficial water ice exposures can produce the amount of vapor needed to match the observations of [2], if certain realistic constraints are met.

2. Model Description

We use a one-dimensional heat diffusion model in order to determine the temperatures in the near surface and surface. For water ice, we use an albedo of 0.135 [4], a heat capacity of 1615 J kg^{-1} K^{-1}, a thermal inertia of 2100 J m^{-2} K^{-1} $s^{-1/2}$, and a density of 925 kg m^{-3}. For regolith, we use an albedo of 0.09 [5], heat capacity of 837 J kg^{-1} K^{-1}, thermal inertia of 15 J m^{-2} K^{-1} $s^{-1/2}$ [6], and density of 1388 kg m^{-3}. We use a semi-implicit Crank-Nicholson scheme for stability and speed [e.g. 7].

We use a vapor production and diffusion model described by [8] in order to model global ice tables and locally exposed surface ice (Figure 1). For buried ice tables, we include the effects of a diffusive barrier to vapor release, composed of regolith grains with a porosity (ϕ) of 0.5 and a radius of 50 μm. We initially assume a depth to ice in this case of 3 cm, many diurnal skin depths such that $T_{depth}=\langle T_{annual}\rangle$. For exposed surface ice, we do not include the granular barrier to diffusion. We allow the volume fraction of regolith (C) to vary and assume the regolith content of the ice does not affect the ice thermal properties. Unless otherwise noted, we assume Ceres is a smooth oblate spheroid with an obliquity of 4°.

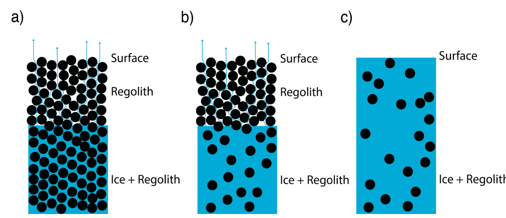

Figure 1: The different ice configurations explored in this paper: a) global buried pore-filling ice table, b) global buried pore-filling ice table, and c) exposed surface ice.

3. Sublimation from Buried Ice

We first examine the rate at which water vapor will be produced by buried ice (Figure 1a&b). As time increases, the amount of regolith that builds up on top of the ice increases and vapor escaping the surface decreases. We consider the C value of 0.5 (1-ϕ) for pore filling ice first. While pore-filling ice globally can produce close to the vapor production rate reported by [2] for a few million years, at 4.5 Gyr the vapor production falls several orders of magnitude short (Figure 2).

For excess ice, we consider C<(1-ϕ). We test two cases where: 1) the ice table can match the observed vapor output, and 2) the regolith build-up over 4.5 Gyr is consistent with the GRaND observations of hydrogen distribution [9] (Figure 2).

$C=7x10^{-5}$ is sufficient for a global ice table to produce the observation of [2] but would result in an ice table detectable everywhere by GRaND, inconsistent with reported hydrogen depletion in the upper 1m equatorward of 20°. C=0.02 would produce an ice table consistent with the GRaND results after 4.5 Gyr, but produces only about ~0.3 kg/s of water vapor (a factor of 10 too small). We cannot rule out some vapor production from a global ice table, but we can rule out a buried ice table (either excess or pore-filling ice) as a source of [2]'s observation.

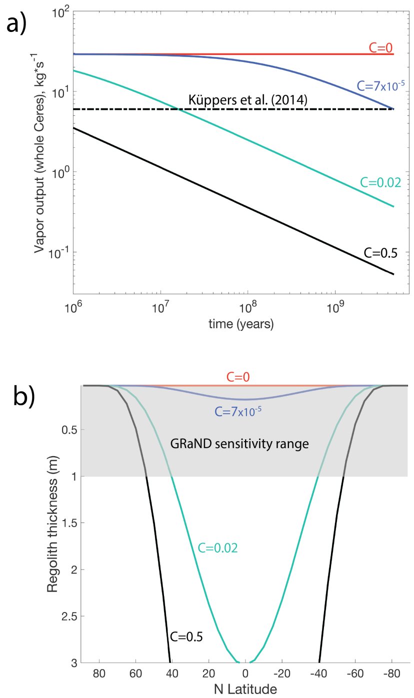

Figure 2: Results of vapor output (a) and regolith lag build up (b) with time for buried ice tables with varying regolith content.

4. Sublimation from Exposed Ice

If exposures of water ice (e.g. similar to the one reported in [4]) occurred close enough to the equator, the vapor produced over 1 km^2 is close to the vapor production rate of [2] (Figure 3). However, there are major seasonal and diurnal variations. Also, the effect of a crater similar to Oxo (latitude at 42.2° N, diameter 10 km, depth 1.5 km, parabolic shape) on the vapor flux is significant. This reduction is ~100 in the case of the approximate location of the Oxo exposed surface ice (maximum of ~0.5 kg s^{-1} km^{-2} on flat terrain to ~6 $x10^{-3}$ kg s^{-1} km^{-2} on a poleward facing slope 3.3 km from the center of the crater).

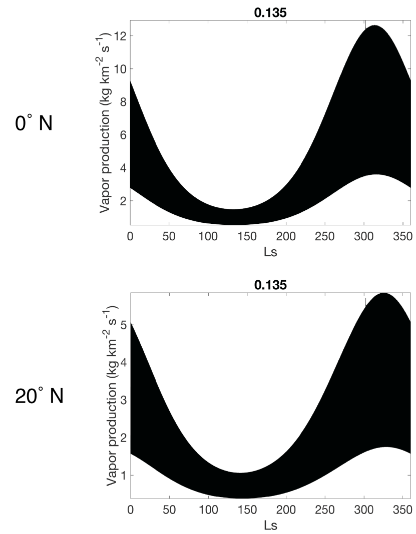

Figure 3: Vapor produced by exposed surface ice depending on latitude (labeled at left).

We calculate the amount of time it takes for a 100 μm (monolayer of regolith particles) lag to build up on these water ice exposures, reducing their albedo (0.135) to the background of Ceres (0.09). This is sensitive to the amount of regolith contamination assumed, but we find generally that water ice exposures close to the equator (the most likely to be able to produce the vapor reported by [2]) have lifetimes of less than ~3 terrestrial years. Therefore, if an ice exposure caused the vapor detection reported in [2], the ice would have faded to the background albedo by the time of the Dawn spacecraft's arrival.

References: [1] A'Hearn and Feldman, 1992. *Icarus* 98, 54 [2] Kuppers et al., 2014. *Nature* 505 [3] Villarreal et al., 2017, *AJL*, 838(1), doi: 10.3847/2041-8213/aa66cd/ [4] Combe et al., 2016. *Science* 353, aaf3010 [5] Li et al., 2016. *AJL*. doi: 10.3847/2041-8205/817/2/L22 [6] Rivkin et. al., 2011. *Space Sci. Reviews*, *163*(1), pp.95-116. [7] Parker, I. B., & Crank, J. (1964). *Computer Journal*, *7*(2), 163-167. doi: 10.1093/comjnl/7.2.163 [8] Schorghofer, 2008. *ApJ* 682, 697. [9] Prettyman et al. 2017. *Science,* aah6765