CERES ICE SUBLIMATION AS A SOURCE OF AN EXOSPHERE: MODEL RESULTS. M.E. Landis[1*], S. Byrne[1], N. Schorghofer[2], B. Schmidt[3], P. Hayne[4], J. Castillo-Rogez[4], M. V. Sykes[5], C. Raymond[4], C. Russell[6], [1] Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ (*mlandis@lpl.arizona.edu), [2] Institute for Astronomy, University of Hawaii, Honolulu, HI, [3]Georgia Institute of Technology, Atlanta, GA, [4]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, [5]Planetary Science Institute, Tucson, AZ, [6]Institute of Geophysics and Planetary Physics, Department of Earth and Space Sciences, University of California, Los Angeles, CA

Motivation: Several detections of an H_2O exosphere around Ceres have been reported [1-3], suggesting possible sources from a coincidental impact to outgassing from a subsurface ice table. Ceres likely contains a large volume fraction of water ice [4], making sublimating ice an intriguing potential explanation for the detections. Production rates of vapor reported by [2] were ~10^{26} molecules/second and their observations suggest there could be spatial variability in vapor production on Ceres.

The presence of deposits with significantly brighter albedo than the surroundings was detected by Dawn on approach to Ceres. Some of these deposits were determined to be salts [5] and one (at 42°N) has been confirmed to be water ice [6]. [5] also suggests there may be a diurnally varying haze present at the Occator crater (~20°N) bright deposits. Exposed surface ice and possible diurnally varying phenomena make ice near or at the surface of Ceres a possible explanation for these additional observations. Additionally, Dawn's GRaND instrument has detected latitudinal variations in hydrogen enrichment over the surface of Ceres [7] consistent with a desiccated top ~1m layer equatorward of ~40°N.

We present results from a coupled thermal and vapor diffusion model that explores three possible sources of sublimating water vapor that could explain these observations: 1) pore-filling ice, 2) excess (>50% by volume) ice, and 3) exposed surface ice (Fig. 1). Only the first of these three cases has been considered in [9]. We discuss the order of magnitude vapor production in each of these sources, and whether or not they are possible sources of the exosphere.

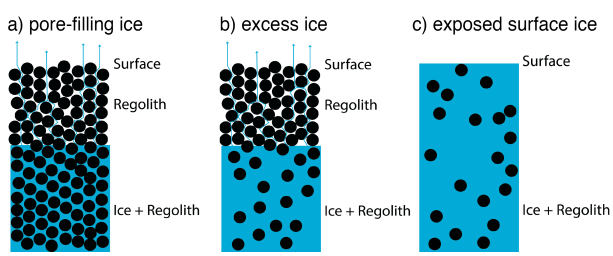

Fig. 1 Diagrams of the three different possible sources of possible water vapor explored in this abstract.

Model description: We model the three configurations of water ice and regolith in Fig. 1. As vapor sublimates from the ice table, the depth to ice increases over time (Fig. 2), thereby increasing the amount of dry regolith overlying the ice table and reducing the rate at which vapor diffuses to the surface. We model this decrease in water vapor diffusion to examine the plausibility of a global ground ice table providing the water vapor observed by [2]. For the exposed surface ice model, we do not include a dry regolith layer at the surface and assume the ice only exists in small patches.

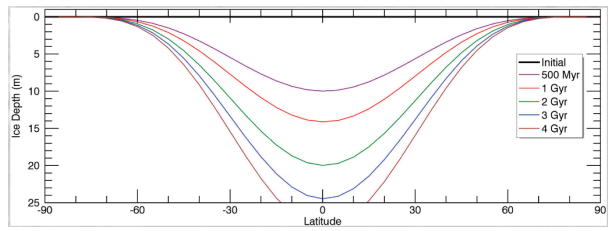

Fig. 2 Global retreat of an ice table starting at 3cm depth over 4Gyr.

Our 1D thermal model solves the thermal diffusion equation from the surface downwards. We use an albedo of 0.09 and thermal inertia of 15 J m^{-2} K^{-1} $s^{-1/2}$ for the regolith and an albedo of 0.135 [6] and a thermal inertia of 2100 J m^{-2} K^{-1} $s^{-1/2}$ for exposed surface ice. We also use a sky-view factor in order to determine the amount of empty sky available for a patch of ice within a crater to radiate back to, which is related to the integral of the horizon height with azimuth.

We use a vapor diffusion model based on [8]. Results shown here assume a regolith grain size of 100μm, a porosity of 0.5, a tortuosity of 2, and vary the volume fraction of regolith (C) in different cases for the retreating ice table. C<0.5 is considered excess ice, and C≥0.5 is pore-filling ice. [9] suggests that <100μm grain sizes are likely on Ceres, and so the vapor production rates presented here can be considered upper limits.

For global ice table calculations (pore-filling and excess ice), we start a global ice table at depth of 3cm. In this model, the ice table retreats at a rate proportional to 1/h.

Pore-filling ice: In this end member case, C equals 1-regolith porosity (C=0.5). We use the annual-

average temperature of the material at depth from the thermal model to calculate ice table sublimation rates. We let the model run for 4.5 Gyr and plot the global production of vapor over time (Fig. 3). We plot the [2] vapor production rate for reference. At no time in the recent past does the vapor production from this source equal the observation by [2]. We eliminate this as a source of the present day exosphere [2].

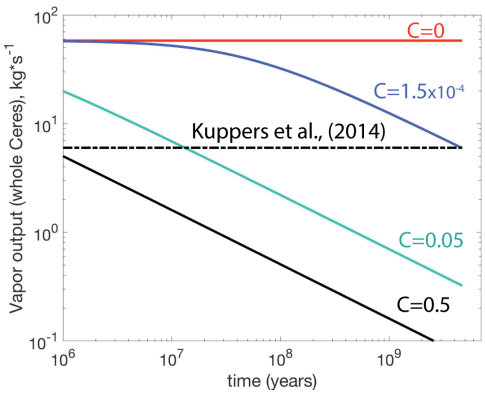

Fig. 3 Vapor production from a subsurface ice-regolith matrix on Ceres over time, varying the dust volume fraction (C). The dashed line represents the vapor output observed by [2]. All ice tables are initially placed 3cm below the surface and allowed to sublimate for 4.5 Gyr. C=0 corresponds to a pure water ice table, C=0.5 to a pore-filling ice table.

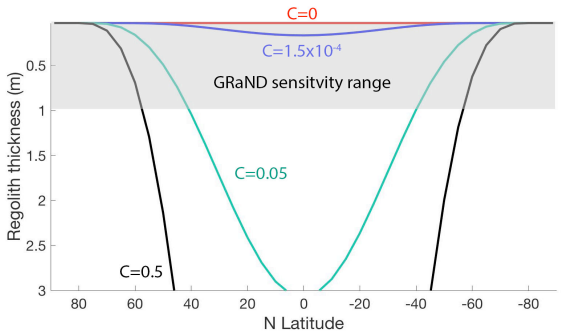

Fig. 4 Ice table depth is plotted with latitude after running the model for 4.5 Gyr for the same values of C plotted in Fig. 3. The gray box represents the depth range where GRaND is sensitive.

Excess ice: Using the same model, we allow C to vary as long as it is <0.5. It is possible that a pure water ice table (C=0) can produce the amount of water vapor detected in [2] (Fig. 3), but it is unlikely that pure water ice still exists 3cm below Ceres' surface.

We explore two realistic cases: one where the modern vapor observation is reproduced by excess ice, and one that, after 4.5 Gyr of retreat, is consistent with GRaND detecting enrichment of H at >40°N latitude (an upper limit, assuming no other H bearing compounds are present).

After 4.5Gyr of sublimation, C=1.5x10^{-4} corresponds to an ice table that would produce 6 kg/s of water vapor globally on Ceres (Fig. 3), but that would also mean a too shallow ice table (Fig. 4) to be consistent with GRaND results. If C=0.05, after 4.5 Gyr of sublimation, the excess ice table will be deeper than 1m equatorward of 40°N (Fig. 4), but will produce <1/10 of the water vapor needed to match [2] (Fig. 3). Therefore, excess ice alone cannot produce the detection of [2] and remain consistent with GRaND observations.

Exposed surface ice: Exposed surface ice at the equator of Ceres can produce water vapor at the rate of ~1s of kg s^{-1} km^{-2} near perihelion, but the rate varies significantly throughout the ceresian year (Fig. 5).

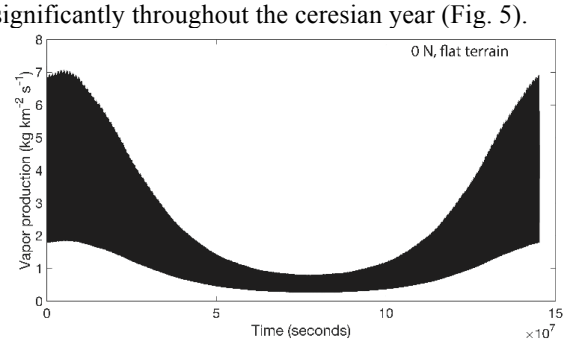

Fig. 5 Sublimation for exposed surface ice at the equator on flat terrain over 1 Ceres year (t=0 at perihelion).

The surface water ice reported by [6] is within a crater, on a poleward-facing slope at 42°N. This reduces vapor produced in our model to a maximum of ~10^{-3} kg s^{-1} km^{-2}. This suggests that while exposed surface ice can explain the [2] observation, vapor produced varies extremely with latitude, time, and local topography. Exposed surface ice only remains bright (sublimation lag is <20µm thick) for ~1 Earth year at 40°N for ice with 5% regolith. We will present fading lifetime and vapor production rate results as a way of constraining the frequency of exposure mechanisms (e.g. small craters, landslides) and report the possible regolith particle sizes lofted by vapor from surface ice.

References: [1] A'Hearn and Feldman, 1992. *Icarus* 98, 54 [2] Kuppers et al., 2014. *Nature* 505 [3] Roth et al., 2016. *GRL* 43, 2465 [4] McCord and Sotin, 2005. *JGR* 110, E05009 [5] Nathues et al., 2015. *Nature* 528 [6] Combe et al., 2016. *Science* 353, aaf3010 [7] Prettyman et al. 2016. *Science,* aah6765 [8] Schorghofer, 2008. *ApJ* 682, 697. [9] Schorghofer, 2016. *Icarus* 276, 88

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