PREDICTIONS OF DEPTH TO ICE ON ASTEROID CERES. N. Schorghofer, Institute for Astronomy and NASA Astrobiology Institute, University of Hawaii, 2680 Woodlawn Drive, Honolulu, HI 96822, USA (norbert@hawaii.edu).

Introduction: A primary reason for the scientific study of minor planet 1 Ceres is its putative icy mantel [e.g.,1,2]. Bodies in the main asteroid belt are generally too warm to retain near-surface ice over billions of years, but the axis tilt of Ceres is (at least currently) almost zero, so that the polar regions are very cold. Fanale and Salvail (1989) have studied the rate of ice loss into space using a detailed temperature and vapor diffusion model [3]. The model predicted surface and subsurface temperatures, water fluxes, and ice depths as a function of time, latitude, and assumed regolith properties. Their model calculations suggest that ice could have survived for 4.5 Gyr at depths of 10–100 m near the equator and less than 1.0 to 10 m at latitudes greater than 40°.

Depths-to-ice can be expected to be smaller than previously predicted due to the presence of a mantle of very low thermal conductivity that leads to large surface temperature amplitudes, and thus to enhanced cooling by the T^4-effect. Figure 1 shows the mean surface temperature at the equator of a spherical body with zero axis tilt as a function of thermal inertia. The very low thermal inertia of Ceres, ~15 $Jm^{-2}K^{-1}s^{-1/2}$ indicates a mantle of dust-sized material [5]. Mean temperature is about 20 K lower than for the fast rotator model, due to the enhanced radiative cooling caused by day-night surface temperature variations. In terms of sublimation rate, 20 K correspond to two orders of magnitude (!) difference [6]. Hence, to accurately determine desiccation rates, at any depth, it is crucial that the diurnal temperature variations be resolved.

We calculate the expected depth to ice with thermal and ice evolution models that simulate the desiccation of the surface over time. The depth to ice will be observationally constrained by the Gamma Ray and Neutron Detector (GRaND) on board the DAWN spacecraft [4]. Here, predictions are presented *before* DAWN arrives at Ceres in 2015.

Model: The model simulates the retreat of ice over time-scales of billions of years. A computational barrier is the multi-scale character of the problem: accurate temperatures require many model time steps within a solar day, but ice retreats slowly over billions of years. This barrier is overcome with "asynchronously coupling" between a thermal model and an ice evolution model. An asynchronous numerical method of this type was developed for Martian subsurface ice [7], and is here adapted to asteroids. The thermal model (time step ~5 minutes) is evolved with a static ice distribution for twenty orbits until the temperature has equilibrated, and a time-averaged sublimation rate is calculated. This information is then used to advance the ice content with a time step of up to many Myr. In other words, the temperature model and the ice evolution model use vastly different time steps, which makes it feasible to integrate the retreat of the ice over billions of years using rotationally resolved temperatures.

The temperature in the upper surface is determined by the surface energy budget. This surface energy budget is calculated using common thermal model equations and widely used thermal properties. Vapor transport at low temperature and low pressure is based on common expressions for the diffusivity and compiled data on sublimation rates.

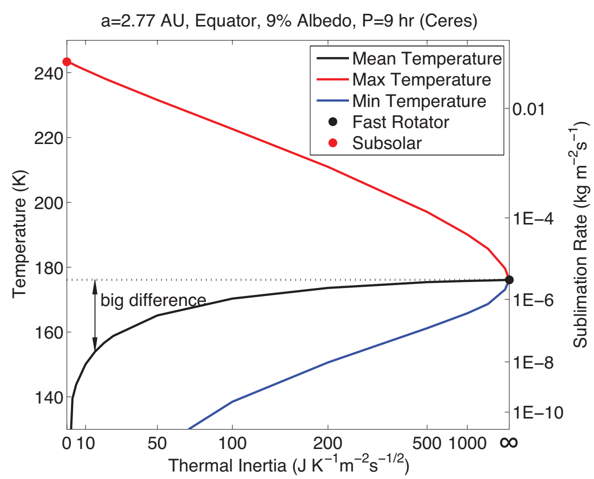

Figure 1: Maximum, minimum, and mean temperature experienced over a solar day at the equator of a body with the orbit of Ceres. The horizontal axis is thermal inertia; infinite thermal inertia corresponds to the fast rotator model, and zero thermal inertia corresponds to an instantaneous equilibrium between insolation and surface temperature. At high thermal inertia, mean temperatures are well approximated by the fast rotator model. At low thermal inertia (dust mantle), mean temperatures are significantly lower than in the fast rotator approximation, due to enhanced amplitude-dependent radiative cooling caused by night-day surface temperature variations. Ceres has a thermal inertia of 15 $Jm^{-2}K^{-1}s^{-1/2}$ [5], and its desiccation rate is two orders of magnitude less than for a fast rotator. The

sublimation rates shown on the right axis are into vacuum and proportionally lower for buried ice.

The preliminary model calculations use a simplified version of the asynchronous model for asteroids, without impact stirring and without partial ice contents (ice and silicates, but no voids). Only the depth of an ice table is tracked. Changes of solar luminosity with time are taken into account.

Results: The zonally averaged model calculates the desiccation of the surface over 4.5 Gyr and is initialized with a 50% mixture of ice and dust. Figure 2 shows the main result, ice depths after 4.5 Gyr of desiccation. The current obliquity (axis tilt) of Ceres is estimated as ~3° [e.g.,8,9]. There is very shallow ice in the polar regions, within the sensing depth of the GRaND instrument. For a sensing depth of ~0.5m, ice would be detected to about 60° on both hemispheres.

Because the history of the axis tilt is unknown, model calculations are also carried out for higher obliquities (Fig. 2). At these higher obliquities, the near-surface ice stretches farther equatorward. If the rotation axis wobbles, the latitudinal extent of the shallow ground ice is thus determined by the *lowest* obliquity. Hence, the prediction that the surface is ice-rich within the uppermost 0.5 m equatorward of about 60° is robust even if the axis tilt has varied.

The shallowest depths will be devolatilized by impact stirring. On the Moon, the disturbed depth is ~1 m after 1 Gyr [10]. If this rate also applies to Ceres, there has been significant turnover and devolatization within the sensing depth of GRaND, although the shallow model ice depths suggest only ice brought very close to the surface will be lost. In any case, the latitude boundary predicted by the model should remain valid.

Over the last 100 Myr, the dessication rate was nearly 10^6 kg/yr (10^{24} molecules/s). Once a water molecule reaches the surface, it is briefly gravitationally bound, which results in a water exosphere. Observations suggest the presence of an exosphere at $>10^{26}$ molecules/s [11].

Conclusions: Asynchronously coupled numerical methods enable us to calculate desiccation rates and depth to ice on Ceres, without neglecting surface-temperature-amplitude-dependent thermal emission. This leads to desiccation rates and ice depths shallower than previously predicted. An otherwise simplified model, that does not include impact stirring, predicts that ice can be expected to have survived within the uppermost 0.5 m polewards of 60° latitude on both hemispheres. Excursions of the axis tilt, from its present near-zero value, do not change the latitude of this boundary. The retreating ice also feeds a tenuous water exosphere, not quite as dense as the one observed.

Discussion: A more advanced model could incorporate impact stirring and partial ice contents. It could make specific predictions of ice content as a function of depth, which would be useful for the interpretation and inverse modeling of the neutron and gamma ray measurements by the GRaND instrument. Another factor missing from the preliminary model calculations is the ice loss due to continued radioactive heating from below, after the icy mantel has formed. Quick formation of a dust layer, presumably caused by space weathering, is also assumed, but only a few cm thick layer of dust is required for the enhanced cooling. Shallow ice depths also suggest that small impacts in the polar regions could expose ice to the surface that would feed a temporary water exosphere.

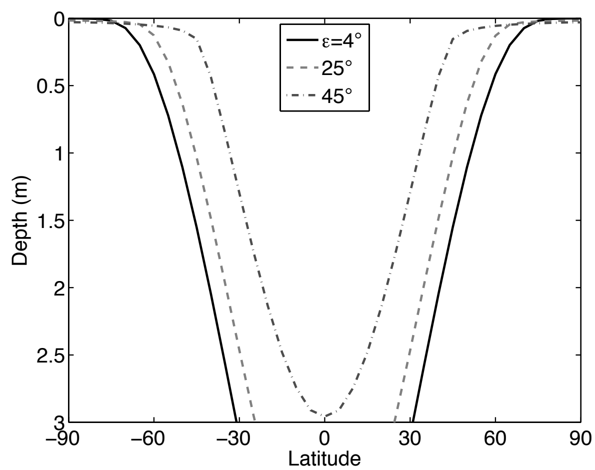

Figure 2: Model-predicted depth-to-ice after 4.5Ga of desiccation for obliquities ε of 4° (best estimate of current value), 25°, and 45°. In all cases, there is shallow ice in the polar regions. The depths are the same on both hemispheres, because the rotation axis is assumed to precess due to perturbations by other bodies. Not taken into account is devolatization by impact gardening.

References: [1] Rivkin A. S. et al. (2011) *Space Sci. Rev., 163*, 95–116. [2] McCord T. B. et al. (2011) *Space Sci. Rev. 163*, 63–76 [3] Fanale F. P. & Salvail J. R. (1989) *Icarus, 90,* 1151–1154. [4] Prettyman T. H. et al. (2011) *Space Sci. Rev., 163*, 371–459. [5] Muller, T. G. & Lagerros J. S. V. (1998) *Astr. Astrophys., 338*, 340–352. [6] Schorghofer N. (2008) *Astrophysical J., 682,* 697–705. [7] Schorghofer N. (2010) *Icarus, 208*, 598–607. [8] Tedesco E. F. et al. (1983) *Icarus, 54*, 23–29. [9] Drummond J. D. et al. (2014) *Icarus, 236*, 28–37. [10] Arnold J. R. (1975) *Proc. Lunar Sci. Conf. 6*, 2375–2395. [11] Küppers, M. et al. (2014). *Nature, 505*, 525–527.