IMPACT MIXING OF ICE-RICH REGOLITH ON CERES AND THE MOON.

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Introduction: On Ceres, ice is still present within the top ~0.5 m of the regolith [1], after more than 4 Gyr of impact history. This may be due to insulation of the ice by a mantle of very fine-grained material (dust) and/or recharging of ice excavated from greater depths by impactors. Measurements by the Dawn spacecraft provide unique insight into impact mixing and devolatization of ice-rich regolith. The very same types of processes are expected to affect the ice content of lunar cold traps.

Gamma Ray and Neutron Spectrometer (GRaND) measurements on Ceres revealed a latitude-dependent H-concentration indicative of an ice table governed by sublimation loss, with little retreat near the poles and greater retreat at the equator [1]. The equator-pole difference of [H], interpreted as ice rather than non-volatile hydrous material, reaches up to ~11 wt%, which corresponds to ~23 vol%. Gradual sublimation and impacts have not fully depleted the polar and mid-latitude regions of Ceres of ice to ~1 m depth. The measurement of the hydrogen concentration of crater ejecta around Occator Crater on Ceres [2] illustrate that ice has survived in the ejecta.

Loss by sublimation: Water vapor inevitably diffuses through porous regolith. The lower the temperature and the smaller the pore spaces, the slower the loss of ice to space. Dust mantles are particularly effective at protecting ice from sublimation. Smaller grains can have smaller pore spaces, and therefore act as strong barrier to vapor diffusion. Moreover, the low thermal conductivity of dust leads to large diurnal and seasonal surface temperature amplitudes and therefore to increased infrared emission to space, which cools even the subsurface.

Model calculations with various grain sizes and porosities suggest grain sizes of ~1 µm are most consistent with the GRaND measurements [1,3]. Much larger grain sizes would cause retreat beyond the sensing depth of GRaND of ~1 m.

Small grain size is also consistent with the very low thermal inertia of Ceres of ~15 $JK^{-1}m^{-2}s^{-1/2}$ [4]. This value implies that grain sizes are far below 100 µm, on a global (disk) average [5]. Spectrophotometric modeling also suggests the presence of micron-sized particles on Ceres [6].

The sublimation-only model that best matches the GRaND data implies a total loss of only 10 cm GEL (Global Equivalent Layer) of ice over 4 Gyrs and corresponds to a current outgassing rate of 0.003 kg/s.

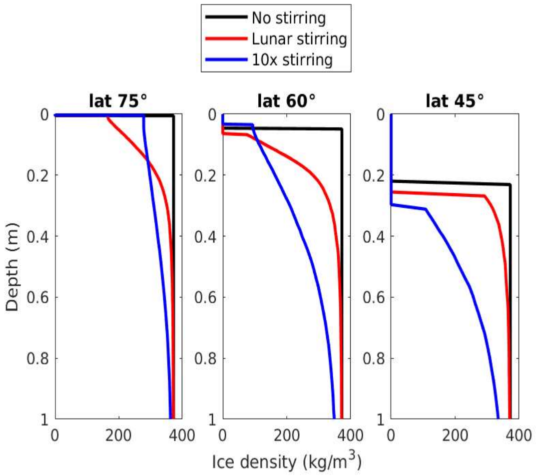

Figure 1: Ice content as a function of depth based on model calculations with sublimation and impact mixing for latitudes 45°, 60°, and 75° on Ceres. Mixing leads to an increase of ice-content with depth, but an abrupt ice table is preserved. At latitude 75°, strong stirring leads to a higher near-surface ice content than moderate stirring. Shown are ensemble-averages.

Loss by impact mixing combined with sublimation: Impacts can excavate ice from greater depth. Unless the ejecta are nearly pure ice, which is inconsistent with other constraints for the crustal composition of Ceres, total ice loss must be small, otherwise the surface would be covered with ejecta that are devolatilized beyond the GRaND sensing depth.

A one-dimensional model of temperature and sublimation loss is combined with a one-dimensional model of impact stirring [7]. Impacts homogenize the ice content over a depth $0<z<zmax$, where $zmax$ follows a probabilistic power-law distribution. As time increases, so does the mean turnover depth. The impactor frequency can be set to obtain the desired average stirring depth (e.g., 10 cm/Gy [8,9])

Impactors on Ceres are expected to be slower but more frequent than on Earth's Moon, due to Ceres' location in the middle main belt. The resulting mixing rates have not yet been quantified, and here we will simply consider the mixing rate a model parameter.

In the model, mixing stirs ice to shallower depth and ice loss is due to sublimation. Ice loss through the heat generated by the impact is neglected (and probably small). The model asynchronously couples temperature (with time steps of minutes), ice loss (Myrs), and impact stirring (sporadic) [7]. At each latitude, the results for 1000 random impact histories are simulated and averaged.

Figure 1 shows results of the model calculations at several latitudes, after 4 Gyr of combined sublimation and mixing. The model calculations begin with a porosity's worth of ice. The mixing dilutes the ice content at the ice table relative to that at greater depths. The dilution provides a possible explanation for the measured ice content of ~23 vol% on Ceres, as it is a value intermediate between a typical porosity's worth of ice (42 vol%) and the completely devolatilized surface.

The depth of the ice table, however, changes only little due the mixing (Fig. 1). The mixing does increase the total ice loss. With strong stirring (stronger than on the lunar surface), the total loss becomes 30 cm GEL, three times that without stirring. Hence, the majority of the water outgassing is sporadic rather than continuous.

Very small grain sizes are still needed to explain the shallow ice table depths. Another effect, not yet included in these calculations, may be at work: deflation of the regolith. If the ice is in the form of chips, created by impacts, just as silicate rocks are made up of fragments, then their disappearance by sublimation will lead to deflation. This in turn leads to shallower ice table depths (Illustration).

Application to Lunar Cold Traps: The lunar cold traps are small (<~50 km) and only somewhat colder than Ceres (<120 K vs. <140 K [10]). Based on the observations on Ceres, it is reasonable to expect that impact ejecta within the lunar cold traps have also been able to retain much of their ice [11]. In particular, the ice concentration at depth may be much higher than on the surface (Fig. 1) [12]. On Ceres, exposures of ice on the very surface are rare [13,14]. Sporadic exposure of ice in the cold traps of the Moon might explain why spectroscopic and albedo observations have detected so little exposed ice in the lunar cold traps [e.g., 15].

The ice in the lunar cold traps is thought to be delivered from above, through the exosphere, whereas Ceres formed water-rich. Nevertheless, mixing and sublimation of ice-rich regolith acts to create a thin devolatilized layer on the very surface distinct in ice content from the deeper layers.

Conclusions: The combined action of sublimation and impact mixing may explain the near-surface ice concentration on Ceres. This ice concentration is less than at depths below the mean single-turnover depth. Micron-sized grains are still required to explain the presence of near-surface ice on much of the surface of Ceres, but deflation may relax this requirement. If these lessons also apply to ice in the cold traps of the Moon, then these devolatilization processes can explain the paucity of exposed ice in the lunar cold traps. Like on Ceres, the distribution of exposed ice may bear little resemblance to the distribution of buried ice. This would be key for designing a strategy for mapping ice on the Moon.

Acknowledgements: This material is based upon work for the TREX team supported by NASA through the SSERVI Cooperative Agreement NNH16ZDA001N.

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