ICE LOSS FROM THE INTERIOR OF SMALL AIRLESS BODIES ACCORDING TO AN IDEALIZED MODEL. N. Schörghofer[1] and H. H. Hsieh[1], [1]Planetary Science Institute, Tucson, Arizona & Honolulu, Hawaii (norbert@psi.edu)

Introduction: Water ice in the interior of asteroids and Near Earth Objects (NEOs) is of scientific and resource exploration interest [1, 2]. Airless bodies gradually lose their ice to space by outward diffusion through the porous material, and the time-scale of this desiccation determines whether or not a body that initially contained ice still retains some of it in its interior. To quantify this process, we obtain analytic solutions for 1) the latitude-dependent temperature field inside a fast-rotating and thermally equilibrated spherical body, and 2) the time-dependent depth to retreating ice in a spherically averaged sense, with the effect of latent heat incorporated. The results provide insight for a wide range of scales and parameters. Previously, several numerical and simple analytical models have been developed for icy bodies [3].

Temperature in body interior: A few diurnal skin depths below the surface, the temperature varies little throughout a solar day, and below a few seasonal skin depths, it varies little even throughout an orbit around the sun. In the interior, the temperature is cylindrically symmetric around the rotation axis of the body. It is assumed that the thermal conductivity is spatially uniform, so the temperature obeys the 2D Laplace equation.

For a body in thermal equilibrium, the total radial heat flux through a sphere around the center must vanish, at any depth. Hence the temperature averaged over the surface of the body, $\bar{T}$, is the same as the temperature at the center of the body. The solution can be written as

$$T(r,\theta) = \bar{T} \sum_{\ell=0}^{\infty} a_\ell \left(\frac{r}{R}\right)^\ell P_\ell(\cos\theta) \qquad (1)$$

where a_ℓ are coefficients determined by the boundary conditions, R is the body radius, r is the distance from the body center, P_ℓ is a Legendre polynomial of degree ℓ, and θ is the zenith angle or co-latitude.

Fast rotator model as surface boundary condition. The fast rotator model [4] assumes the temperature does not change with local time. When the body has zero axis tilt, the surface temperature is proportional to $(\sin\theta)^{1/4}$. In this case, the average surface temperature (area-weighted) is about 1% lower than the effective temperature,

$$\bar{T} = \frac{\pi^{1/4}}{5\sqrt{2}} \frac{\Gamma(1/8)}{\Gamma(5/8)} T_{\text{eff}} \approx 0.98882\, T_{\text{eff}} \qquad (2)$$

where Γ is the Γ-function. If the only source of energy is the sun, then it is always the case that $\bar{T} \le T_{\text{eff}}$.

Solution for interior temperature. We analytically determined the coefficients a_ℓ from the surface temperature. The first few are $a_0 = 1$, $a_2 = -5/26$, and $a_4 = -9/104$. Figure 1 shows the interior temperature distribution. The polar regions are very cold, and the temperature quickly homogenizes with depth.

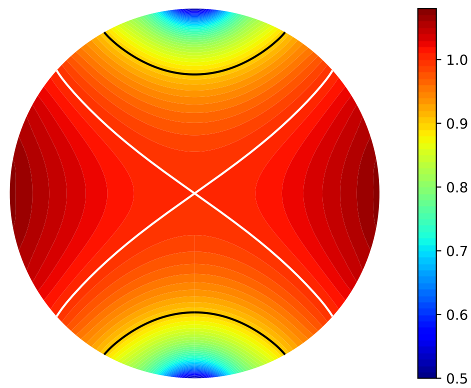

Figure 1: Temperature distribution in the body interior as a function of r and θ, based on 20th order analytic solution. The color scale shows $T/\bar{T}$. The contours show $T/\bar{T} = 1$ (white) and $T/\bar{T} = 0.9$ (black).

$\bar{T}$ determines the interior temperature, and depends on the orbital geometry and the physical properties of the body. Numerical thermal modeling for a range of axis tilts and thermal inertias suggests the fast rotator with zero axis tilt represents a hot end-member case in terms of $\bar{T}$.

Ice retreat for spherically averaged model: For constant temperature, the time to complete desiccation t_D is given by

$$t_D = \frac{R^2}{6D} \frac{\rho_i}{\rho_s(\bar{T})} \qquad (3)$$

where D is the vapor diffusivity of the asteroid interior, ρ_i the density of ice, and ρ_s the saturation vapor density. The radius of the ice-rich interior (i.e. the location of the ice table), $r_i(t)$, is the solution to a cubic equation and given by

$$\frac{r_i(t)}{R} = \frac{1}{2} + \cos\left(\frac{1}{3}\arccos\left(2\frac{t}{t_D} - 1\right) - \frac{2\pi}{3}\right) \qquad (4)$$

Figure 2 shows this universal solution. The ice has receded to half the body radius at $t = t_D/2$. Half the ice volume is lost after 11% of the total desiccation time.

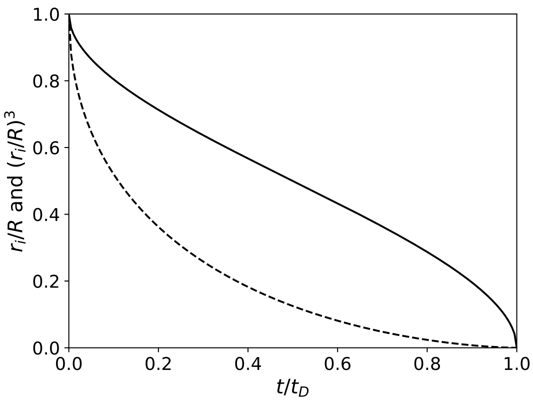

Figure 2: Time evolution of ice retreat in a spherically averaged model according to eq. (4). The retreat is also shown in terms of relative volume retained (dash line).

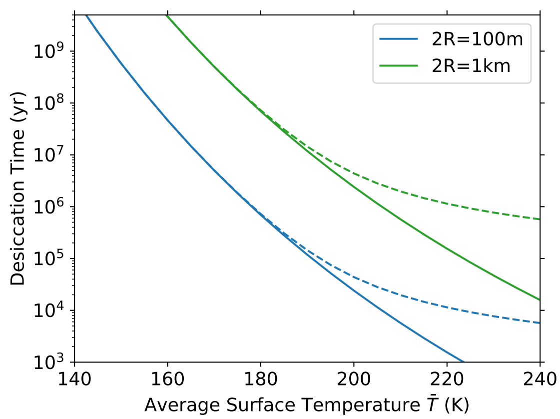

Figure 3: Desiccation time t_D in Earth years as a function of surface temperature $\bar{T}$ for pore size $\zeta = 1$ mm and body diameters $2R$, according to eq. (3). The dash lines are desiccation times with the latent heat effect included.

t_D depends on body size R, body temperature $\bar{T}$, and vapor diffusivity D. The vapor diffusion coefficient D depends on pore size (related to grain size) ζ, which in turn is related to grain size. Figure 3 shows desiccation times as a function of $\bar{T}$ for two body diameters.

The latent heat consumes energy at the ice interface. Since temperature and vapor density both obey the Laplace equation in the same geometry, the solutions for the heat flux and the vapor flux are geometrically similar. It turns out that the temperature difference between the surface and the ice table depends on neither R nor r_i, so the ice table remains at about the same temperate as it retreats.

Application to specific populations: The Beagle family has an estimated age of 10 Ma and is centered at semi-major axis $a = 3.157$ AU [6]. For $\zeta = 1$ mm, the size threshold for complete desiccation is a diameter of 26 m. For $0.11 t_D$, when half the ice is lost, the threshold is 80 m. The known Beagle family members are significantly larger than that, so they should have retained most of their ice.

Most Main Belt Comets (MBCs) fall in the range 3.0–3.2 AU [7]. At 1 km size, typical for MBCs, their desiccation time scale exceeds the age of the solar system.

Most 100 m size objects are ejected over 100 Myr due to the Yarkosky effect [8]. Objects of this size and age retained some of their ice at temperatures below about 170 K, which includes all bodies beyond $a \gtrsim$ 2.7 AU, and hence the outer main belt.

Outside of $a = 2.5$ AU (middle and outer belt), all bodies larger than 10 km were able to retain ice in their interior over the age of the solar system (if they formed with ice and the ice lasted beyond the period of radiogenic heating).

Many NEOs originate in the main belt, and especially from the inner main belt ($a < 2.5$ AU) [9]. Nearly 10^3 NEOs are larger than 1 km, but most are smaller. For a NEO of a km or less in size to have retained ice in its interior, one of the following conditions has to be met: 1) a semi-major axis in the outer belt or beyond, 2) a mantle of very low thermal inertia, which lowers interior temperature, 3) a young age due to a recent break-up from an ice-rich body, or 4) a stable and moderately small axis tilt would maintain cold polar regions.

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