Icarus 276 (2016) 88–95

Contents lists available at ScienceDirect

Icarus

journal homepage: www.elsevier.com/locate/icarus

Predictions of depth-to-ice on asteroids based on an asynchronous model of temperature, impact stirring, and ice loss

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ARTICLE INFO

Article history:
Received 20 December 2015
Revised 21 April 2016
Accepted 25 April 2016
Available online 2 May 2016

Keywords:
Asteroid Ceres
Ices
Regoliths

ABSTRACT

Water ice near the surface of main belt asteroids is gradually lost to space. A mantle of low thermal conductivity causes large surface temperature amplitudes, and thus increased cooling by thermal reradiation, lowering temperatures well below the fast-rotator limit. A computational barrier for modeling this ice loss is the multi-scale character of the problem: accurate temperatures require many time steps within a solar day, but ice retreats slowly over billions of years. This barrier is overcome with asynchronous coupling: Models of temperature, ice loss, and impact stirring each use their own time steps and are coupled with one another. The model is applied to 1 Ceres and 7968 Elst-Pizarro. On Ceres, ice can be expected in the top half meter poleward of 60° latitude on both hemispheres, even if excursions of the axis tilt took place, and even in the presence of impact gardening. At the poles, ice can be expected within a centimeter of the surface. The retreating ice crust leads to emission of water from the surface, mainly at the equator; the gradually retreating ice supplies a water exosphere less dense than has been observed by the Herschel telescope. For Main Belt Comet Elst-Pizarro, depths to ice depend on the properties of the surface mantle. For a dust mantle estimated depths are on the order of a decimeter; for a rocky surface the depth at the pole is on the order of one meter. Hence, it could have been activated by a small impact that exposed buried ice.

1. Introduction

Water ice may reside near the surface of main belt asteroids. For example, dwarf planet Ceres is thought to have an icy mantel (McCord et al., 2011; Rivkin et al., 2011). Fanale and Salvail (1989) have studied the rate of ice loss from Ceres with a detailed temperature and vapor diffusion model. And Prialnik and Rosenberg (2009) have modeled the evolution of ice in main belt comet 7968 Elst-Pizarro.

On an atmosphereless body the temperature difference between its dayside and night side can be large. A mantle of low thermal conductivity causes large surface temperature amplitudes, and enhances radiative cooling, because the time average of T^4 is significantly larger than the 4th power of the time-averaged temperature. This nonlinearity effect lowers the body's mean temperature (Schorghofer, 2008). Fig. 1 shows the mean surface temperature at the equator of a spherical body with zero axis tilt as a function of thermal inertia. The thermal inertia of Ceres is estimated as $\sim$15 $\mathrm{J\,m^{-2}K^{-1}s^{-1/2}}$(Lebofsky et al., 1986; Rivkin et al., 2011; Spencer, 1990), consistent with a mantle of dust-sized particles. Due to this very low thermal inertia, the mean temperature is about 20 K lower than for the fast rotator model that assumes temperature at each latitude is independent of local time. In terms of sublimation rate (or vapor pressure), 20 K correspond to two orders of magnitude (!) difference. Hence, to accurately determine desiccation rates, at any depth, it is crucial that the diurnal temperature variations be resolved.

The multi-scale character of the problem leads to a computational barrier for modeling the ice loss: accurate temperatures require many model time steps within a solar day, but ice retreats slowly over billions of years. This barrier can be overcome with "asynchronous coupling" between a thermal model and an ice evolution model. This makes it feasible to integrate the retreat of the ice over billions of years using rotationally resolved temperatures. A similar asynchronous numerical method was developed for martian subsurface ice by Schorghofer (2010).

As is well-known from the lunar surface, small impactors garden or stir the uppermost surface (Heiken et al., 1991). On icy bodies, this impact stirring may devolatilize the surface. In addition, stirring/gardening may smooth an otherwise abrupt transition from a dry surface layer to an ice rich layer (ice table). Impact stirring is also implemented in the model, and this component uses its own time step as well. Hence, there is asynchronous coupling

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http://dx.doi.org/10.1016/j.icarus.2016.04.037
0019-1035/

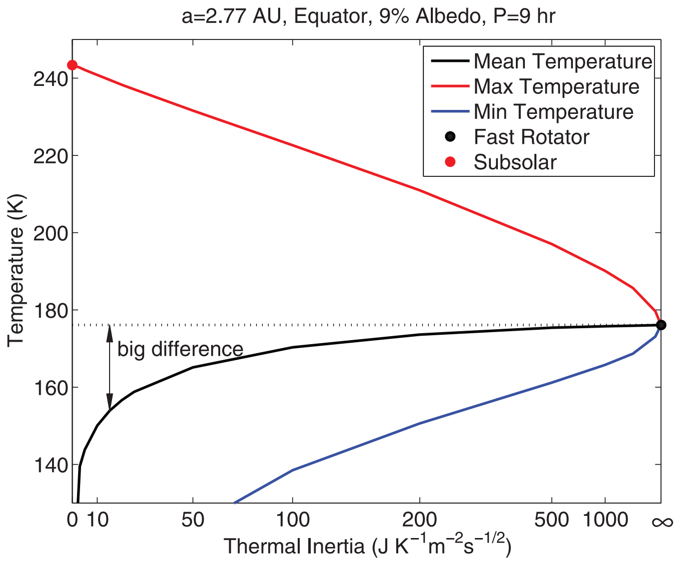

Fig. 1. Maximum, minimum, and mean temperature experienced over a solar day at the equator of a body with the orbit of Ceres. The nonlinear horizontal axis is thermal inertia; infinite thermal inertia corresponds to the fast rotator model, and zero thermal inertia corresponds to an instantaneous equilibrium between insolation and surface temperature. At high thermal inertia (rocky mantel), mean temperature is well approximated by the fast rotator model. At low thermal inertia (dust mantle), mean temperature is significantly lower than in the fast rotator approximation, due to enhanced amplitude-dependent radiative cooling caused by night-day surface temperature variations. Ceres has an estimated thermal inertia of 15 J m^{-2}K^{-1}s$^{-1/2}$.

between three types of models. Ordered by increasing time step, they are: thermal, impact stirring, and ice evolution.

The model is applied to two main belt bodies that are of current interest: Dwarf planet 1 Ceres, that the Dawn spacecraft has begun to orbit in 2015 (Russell and Raymond, 2012), and 133P/Elst-Pizarro, the best studied of the Main Belt Comets. For Ceres, the H-content in the uppermost decimeters will be measured by the Gamma Ray and Neutron Detector (GRaND) on board the Dawn spacecraft (Prettyman, 2011).

2. Numerical method

2.1. Thermal model

The temperature on and near the surface is determined by the surface energy budget. This energy balance is calculated using the incident solar flux and the one-dimensional heat diffusion equation (Delbo et al., 2015). The thermal properties of a regolith-ice mixture are a combination of its components (Siegler et al., 2012), and are allowed to change with depth and time. The heat equation is solved with a Crank-Nicolson method with a nonlinear upper radiation boundary condition, as described in the notes distributed with the online version of the code (Schörghofer, 2015). The model domain is a thin shell, typically 20 m thick, with zero heat flux at the lower boundary. The time scale for thermal equilibration within this layer is short compared to the time scale for ice volume changes; it is also short compared to the age of the body. Changes of solar luminosity with time are taken into account (Gough, 1981).

2.2. Ice loss

A crucial component of the "fast" or asynchronous numerical method are time averaged quantities. Long-term averages, practically averages over one whole orbit after thermal equilibrium has been reached, are denoted with overbars, e.g. $\bar{\rho}_{sv}$ is the time-averaged saturation vapor density. For any non-zero temperature amplitude, $\bar{\rho}_{sv} > \rho_{sv}(\bar{T})$.

Ice is lost from a buried ice table to space. The vapor flux between the surface and the ice table at depth z_p is,

$$\bar{J}_{\rm dry} = -\hat{D}\frac{\bar{\rho}_{sv}(z_p)}{z_p} \tag{1}$$

where the effective diffusion coefficient $\hat{D}$ is given by

$$\frac{z_p}{\hat{D}} = \int_0^{z_p} \frac{dz}{D(z)} \tag{2}$$

and the local diffusion coefficient D by

$$D = (1-f)^2 \frac{\pi}{8+\pi}\frac{\Phi}{1-\Phi}\frac{\bar{v}}{\tau}\frac{d}{2} \tag{3}$$

where Φ is the porosity of the dry medium, $\bar{v}$ the mean thermal speed of molecules, $\tau = 2$ tortuosity, and d the grain size (Schorghofer, 2008). When pores are filled to a fraction f with ice, the vapor flux is reduced by a constriction factor (Hudson et al., 2009).

Where ice is present, the local vapor flux is governed by the saturation vapor pressure,

$$\bar{J}_P = -D\frac{\partial \bar{\rho}_{sv}}{\partial z}. \tag{4}$$

Ice is lost to the outside and vapor may also move downward. The equation for the motion of the ice table is

$$\sigma(z_p)\frac{dz_p}{dt} = -\bar{J}_{\rm dry}(z_p) + \bar{J}_P(z_p) \tag{5}$$

where $\bar{J}_P$ is the "pumping" contribution (often small) and σ is the (mass) density of ice. The ice table moves downward at a speed dz_p/dt.

Eqs. (1) and (5) lead to

$$z_p\frac{dz_p}{dt} = \frac{\hat{D}}{\sigma}\bar{\rho}_{sv}(z_p) + \bar{J}_P\frac{z_p}{\sigma}. \tag{6}$$

Integration from 0 to Δt_B leads to a time stepping scheme,

$$z_p^2(\Delta t_B) - z_p^2(0) = 2\int_0^{\Delta t_B}\frac{1}{\sigma}\left[\hat{D}\bar{\rho}_{sv} + z_p\bar{J}_P\right]dt \tag{7}$$

To keep the problem linear, $\bar{\rho}_{sv}$, $\bar{J}_P$, and $\hat{D}$ are evaluated at the beginning of the time step. The change from time step (n) to time step $(n+1)$ may be written as

$$z_p^{(n+1)} = \sqrt{{z_p^{(n)}}^2 + \frac{2}{\sigma}\left[\hat{D}\bar{\rho}_{sv} + z_p\bar{J}_P\right]^{(n)}\Delta t_B} \tag{8}$$

Evaluating σ at the beginning of the time step is potentially problematic if there is a rapid increase in relative σ, not at but below z_p. The scheme proceeds by first evaluating σ at the computational grid point beneath $z_p^{(n)}$, and if z_p crosses more than one grid point, it subdivides Δt_B into smaller steps using the appropriate values for σ. Subdivision into two steps replaces (8) with

$$\begin{aligned}
{z_p^{(n+\frac{1}{2})}}^2 &= {z_p^{(n)}}^2 + \frac{\Delta t_B}{\sigma^{(n)}}\left[\hat{D}^{(n)}\bar{\rho}_{sv}^{(n)} + z_p\bar{J}_P^{(n)}\right] \\
{z_p^{(n+1)}}^2 &= {z_p^{(n+\frac{1}{2})}}^2 + \frac{\Delta t_B}{\sigma^{(n+\frac{1}{2})}}\left[\hat{D}^{(n)}\bar{\rho}_{sv}^{(n+\frac{1}{2})} + z_p^{(n)}\bar{J}_P^{(n)}\right]
\end{aligned}$$

where $\sigma^{(n)}$, $\bar{\rho}_{sv}^{(n)}$, and $\bar{J}_P^{(n)}$ are evaluated at the first grid point beneath $z_p^{(n)}$, and (n) may be replaced with $(n+1/2)$. Not all quantities on the right-hand side of the equation for the second half step are evaluated at $(n+1/2)$ for mere convenience. And no temperatures are re-computed for the sub-steps; otherwise one may as well decrease Δt_B from the outset.