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Combined modeling of thermal evolution and accretion of trans-neptunian objects—Occurrence of high temperatures and liquid water

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Abstract

We have calculated the early thermal evolution of trans-neptunian objects by means of a thermal evolution code that takes into account simultaneous accretion. The set of coupled partial differential equations for ^{26}Al radioactive heating, transformation of amorphous to crystalline ice and melting of water ice was solved numerically for small porous icy (cometary-like) bodies growing to final radii between 2 and 32 km and accreting between 20 and 44 AU. Accretion within a swarm of gravitationally interacting small bodies was calculated self-consistently with a simple accretion algorithm and thermal evolution of a typical member of the swarm was tracked in a parameter-space survey. We find that including accretion in numerical modeling of thermal evolution leads to a broad variety of thermally processed icy bodies and that the early occurrence of liquid water and extended crystalline ice interiors may be a very common phenomenon. The pristine nature of small icy bodies becomes thus restricted to a particular set of initial conditions. Generally, long-period comets should be more thermally affected than short-period ones.

Keywords: Accretion; Asteroids; Comets; Kuiper Belt objects; Thermal histories

1. Introduction

NASA's *Deep Impact* mission to Comet P/Tempel 1 attests to the increasing interest in questions related to internal thermal processing and the possible pristine nature of small icy bodies of the Solar System. Comets as well as Kuiper Belt objects (KBOs) formed far away from the Sun at heliocentric distances of more than 20 AU. Given the low ambient temperature of that region (Bell et al., 1997), they are expected to reveal an original (or *pristine*) composition. Thus space missions to comets may be considered a way to obtain information about the very early stages of the Solar System.

Alterations of icy planetesimals, however, have taken place. Impacts, insolation and particle radiation are examples of factors that can affect the surface and the outermost layers of icy planetesimals. But more importantly, radioactive decay of isotopes contained in dust, providing a volume-energy source, may lead to changes in the deeper interior, eventually progressing outward, such as crystallization of amorphous ice and phase transitions of volatile species. In comparison to planets, radiogenic heating of comets (and asteroids) is less effective due to their large surface-to-volume ratio. However, if the heat source is strong enough, this picture may change. An ideal candidate for altering comets and asteroids is the radioactive isotope ^{26}Al, abundant in the dust of the early Solar System (MacPherson et al., 1995). On the timescale of planetary evolution, this isotope is short-lived (with a half-life of 0.72 Ma). Therefore, it cannot alter planets, which appear much later than planetesimals in the accretion scenario of planetary bodies, after most of the ^{26}Al nuclei have already decayed.

However, it was shown that an early heat pulse generated by ^{26}Al decay may have significantly modified asteroids (e.g., Wood, 1979; Miyamoto et al., 1981; Ghosh and McSween, 1998; Akridge et al., 1998; Merk et al., 2002). In the case of comets, the work by Irvine et al. (1980) and Wallis (1980) predicted possible melting of water ice and prompted a series of studies devoted to radiogenic heating of comets and icy satellites (Schubert et al., 1981; Ellsworth and Schubert, 1983; Prialnik et al., 1987; Haruyama et al., 1993; Yabushita, 1993; De Sanctis et al., 2001; for a review cf. Podolak and Prialnik,

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1997). A more recent work by Choi et al. (2002) led to the conclusion that insolation and radiogenic heating might lead to a substantial loss of volatiles within KBOs.

These investigations have shown that perhaps the pristine nature of small icy bodies should not be taken for granted. Rather, what is required is a closer study of the early stage of evolution of planetesimals, when formation (accretion) and early radiogenic heating by ^{26}Al could have altered the original material out of which comets and KBOs eventually formed. Usually, accretion of small bodies and heating by ^{26}Al are treated separately in numerical calculations, although these processes actually take place in parallel. The half-life of ^{26}Al and typical formation times of small bodies are both of the order of 1 Ma (Wetherill and Stewart, 1989).

The common procedure adopted for including accretion in the framework of thermal evolution calculations has been to impose a time shift to the decay law of ^{26}Al, allowing for the span of time needed for the small bodies to accrete to their final sizes (e.g., Ghosh and McSween, 1998). The justification was that the surface-to-volume ratio of accreting seed bodies is such that any alteration of the material *during* accretion could be neglected (Miyamoto et al., 1981). Furthermore, the long accretion times calculated for objects in the outer Solar System (Kenyon and Luu, 1998), led to the conclusion that major changes of small icy bodies could be neglected altogether. However, more recently, both analytical and numerical calculations have demonstrated the significant influence of the accretion process on the thermal history of small planetary bodies (Merk et al., 2002; cf. Merk and Prialnik, 2003, in the case of trans-neptunian objects). Thus consideration of accretion in thermal evolution calculations may lead to a revision of the common picture of the early thermal behavior of these bodies and, consequently, of their pristine nature.

2. Modeling simultaneous internal heating and accretion

2.1. Estimates

In a previous work (Merk and Prialnik, 2003, hereafter Paper I), we addressed the question whether the combined effect of accretion and radioactive heating of icy planetesimals can be estimated analytically. To this purpose, it is sufficient to consider a simple accretion law that shows saturation for $t \to \infty$. Such simple law for the planetesimal mass $M_{\rm p}(t)$ is, for example

$$M_{\rm p}(t) = M_{\rm pmax}\left(1 - e^{-t/\theta}\right). \tag{1}$$

Here, θ is the accretion time constant of the respective body. The accreted material contains radioactive ^{26}Al within a mass fraction

$$X(t) = X_0 e^{-t/\tau}, \tag{2}$$

where τ denotes the time constant of radioactive ^{26}Al nuclei. Thus we showed in Paper I that, because planetesimal accretion and radioactive decay proceed in parallel and on the same time scale ($\theta \approx \tau$), effective heating starts already when a planetesimal has yet to accrete half of its final mass while the accreted material still contains half the original amount of live ^{26}Al. It is therefore necessary to treat radioactive heating and spatial growth (accretion) of planetesimals simultaneously.

In technical terms, this means that the governing set of partial differential equations has to be formulated on a domain whose boundary changes with time. Such boundary value problems are often referred to as *moving boundary problems* and their mathematical and numerical treatment is known to be non-trivial (Ockendon and Hodgkins, 1975; Albrecht et al., 1982; cf. Merk et al., 2002, in the case of moving boundary problems of asteroids).

2.2. Governing equations

The thermal evolution model used here was already described in Paper I. To summarize, we have developed a 1D code that numerically solves the heat transport equation written in terms of energy density u, depending on mass (m) and time coordinate (t). We assume a spherically symmetric body, consisting of ice (in a mass fraction $X_{\rm ice}$) and dust (in a mass fraction $X_{\rm d}$). We consider only water ice; the dust component is assumed to include any non-volatile material present in icy bodies. Given the specific densities of the components and the porosity p, the bulk density $\rho_{\rm p}$ is obtained. The model allows for amorphous-ice crystallization and melting of water ice, amorphous ice being contained within a fraction $X_{\rm a}$ and liquid water within a fraction $X_{\rm w}$ of the water ice. Heat sources are due to radioactive ^{26}Al within the dust fraction (associated with the radioactive energy per unit mass $\mathcal{H}$) and to the latent heat released in the transition from amorphous to crystalline ice (associated with the energy $H_{\rm ac}$). Significant impact heating during formation can be ruled out as a first approximation, as was already shown in earlier studies (Merk et al., 2002; Squyres et al., 1988; Orosei et al., 2001). This is justified by the low relative velocities of planetesimals in comparison to velocities found in the belts of small bodies nowadays (Wetherill and Stewart, 1989). A rough estimate of the increase in surface temperature ΔT due to impact events during the accretion stage gives $\Delta T = v^2/c_{\rm p} < 1$ K, with v and $c_{\rm p}$ denoting impact velocity and specific heat of ice, respectively, assuming $v \approx 100$ m/s (Wetherill and Stewart, 1989).

In the following, the local heat balance is expressed in terms of the divergence of the heat flux $F(m,t)$, which is determined by the temperature-dependent thermal conductivity $K(T)$

$$\frac{\partial u}{\partial t} = -\frac{\partial F(m,t)}{\partial m} + X_{\rm ice}\dot{X}_{\rm a}(m,t)H_{\rm ac} + \frac{1}{\tau}X_{\rm d}X_0\mathcal{H}e^{-t/\tau}, \tag{3}$$

$$F(m,t) = -K(T)\left[4\pi\left(\frac{3m}{4\pi\rho_{\rm p}}\right)^{\frac{2}{3}}\right]^2\frac{\partial T}{\partial m}. \tag{4}$$

The propagation of cystallization is described by an additional differential equation, which is solved in parallel during the course of thermal evolution. With the crystallization rate $\lambda(T)$ (cf. Table 1 and Schmitt et al., 1989) and planetesimal mass $M_{\rm p}$, the equation reads

$$\dot{X}_{\rm a} + \frac{\dot{M}_{\rm p}}{M_{\rm p}}X_{\rm a} = -\lambda X_{\rm a}. \tag{5}$$