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Early Thermal Evolution of Planetesimals Beyond the Snow Line

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Abstract

We present here simulations of the early evolution of icy planetesimals, before they are incorporated into giant planets or ejected from the planetary system. The volatile composition and interior structure of these objects change considerably prior to interaction with the giant planets, due to intrinsic thermal evolution of the different planetesimals. Some volatiles may survive throughout (until incorporated in planetary atmospheres or ejected further outside), but the varied thermal histories may impose an additional composition gradient to that inherent from the disk's physical-chemical evolution.

1. Introduction

The early thermal and structural processes that affect planetesimals have strong implications for planet formation scenarios and the attributes of large dusty aggregates in proto-planetary disks. The record for the evolution of these "building blocks" may be interwoven in the profiles of nowadays cometary bodies of various sizes, compositions, and presumed source regions. We present some preliminary results and considerations, regarding the thermal and structural state of objects occupying the region where the outer planets were formed. Representative examples of the meter-scale and km-scale populations are presented, with varying orbits and compositions. Emphasis is put on the emerging structure, heat input history, amorphous-to-crystalline water ice transition, and possible volatile retention.

2 Modeling issues

We model the objects in question as cometary-like – porous aggregates of ices and dust [7]. Modeling the internal evolution of such bodies takes into account various heat sources, the most important being, crystallization and radioactive decay (of either short-lived radionuclides or long-lived ones). In terms of composition, these models deal with a composition of refractory silicate-mineral solid grains and a mixture of volatiles, either in solid (ice) or gaseous (trapped) state. Here we restrict our simulations to consider only CO2, CO and HCN as representatives of the volatile species, other than water, as they are the most common in planetary environments [1] and are among the most abundant cometary volatiles observed [2]. The equations that govern the structure and evolution are those of mass and energy conservation (sublimation/gas flow and heat transfer), coupled with a hydrostatic scheme, for a 1-D spherical body [6]. We combine in these models the thermal processing of ices, due to radioactive heating, solar radiation (may be negligible for surface compositions in the trans-Neptunian region) and crystallization of amorphous water ice (as a triggered source of internal energy), and the treatment of gas flow and densification of a varying porous medium. The early presence of organic compounds in the interiors of planetesimals may affect the heat balance and phase transitions of water [3]. This is examined self-consistently, as the abundances and locations of these species evolve. We set several distinctions in our models, to account for some of the breadth of possible configurations: (i) Orbit - Heliocentric distance near the Jupiter-Saturn center of mass ("J-S zone") and near the Saturn-Uranus center of mass ("S-U zone"), with varying eccentricities; (ii) Size - Radii of 10 m to 100 km, where a hydrostatic scheme is implemented for the larger objects, affecting porosity and thermal conductivity; (iii) Thermal input - Solar radiation alone and combination with radioactive heating, where only the larger objects can be effectively heated by radionuclides [6]; (iv) Time span - $\sim$10 Kyr for bodies heated by solar radiation alone and $\sim$100 Kyr for those heated by radionuclides as well. These timescales are on the order (or less) of the dynamical lifetime of planetesimals in these regions [4, 5].

3 Longevity of Volatiles

We show, in Fig. 1 how an evolving temperature profile may look like, for smaller planetesimals, not experiencing radioactive heating. Both planetesimals are from the "J-S zone" and have high eccentricities, so that they venture within the snow line, where sublimation timescales are rapid. The 10 km object has a bump at $\sim$30 Kyr, due to rapid onset of a crystallization front. However, from that point on, the temperature gradient changes and the interior below a few km is pristine. The 10 m object exhibits the effect the heat diffusing throughout the whole body, sublimating most of the ice at very early times. This is due to the fact that the orbital thermal skin depth is of the order of the size of the object.

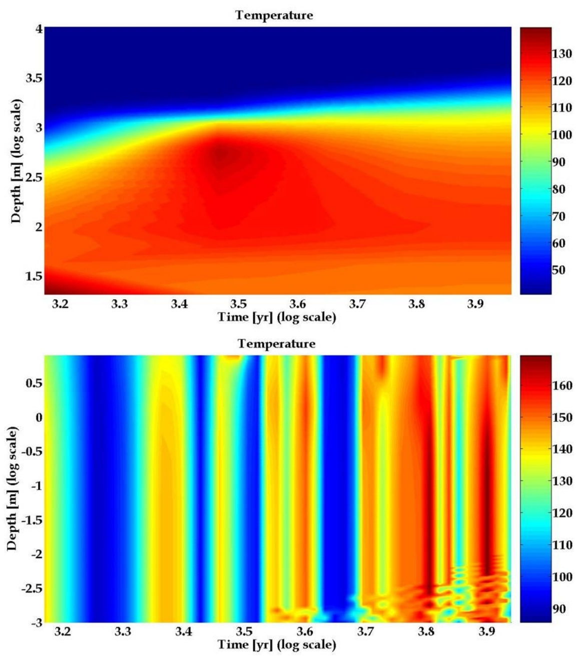

Figure 1: Internal Temperature profiles for a 10 km (top) and 10 m (bottom) object in the J-S zone with high eccentricity and no radioactive heating.

The survival of species more volatile than water, will also depend on their initial phase. If occluded in amorphous water ice, they will survive until a crystallization process will be triggered. From that time on, they will flow through the pores towards the surface and will either escape and be lost or freeze at the colder layers near the surface. However, the sublimation timescales for volatile ices, under the conditions we explored here is shorter than the dynamical lifetime, so they will effectively become lost. Thus, for larger objects, heated from the inside by radioactive decay, volatiles may survive closer to the surface, but will be lost almost as soon as the perihelion distance starts decreasing and well before incorporated into planets. The smaller objects could retain some of their pristine composition, to be deposited wherever they may go.

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