Thermal Evolution of Planetesimals Beyond the “Snow-Line”

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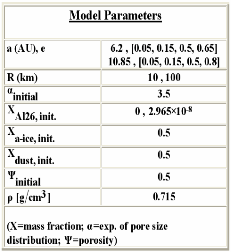
Cometary-like bodies are believed to be porous, icy-rich (crystalline or amorphous), relics from the early phases of planetary system formation.
The early evolution of such bodies, in terms of composition, structure and thermal balance, may have strong implications for planet formation scenarios.

We set several distinctions in our models

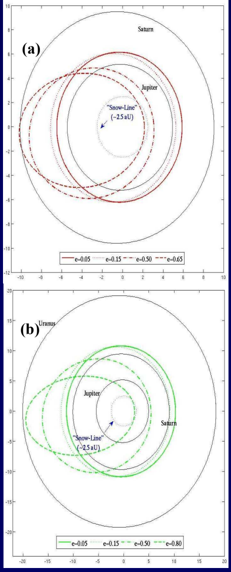
- **(I) Orbit – average distance near the Jupiter-Saturn center of mass, and near the Saturn-Uranus center of mass (with varying eccentricities).**
- **(II) Size – radius of 10 km and 100 km, where a hydrostatic scheme is implemented, affecting porosity and thermal conduction.**
- **(III) Thermal input – insolation alone, and insolation+26Al heating.**
- **(IV) Time span – ~10 Kyr for bodies heated by insolation alone, and ~100 Kyr for those heated by insolation+Al26. These timescales are on the order (or less) of the “survival” lifetime of planetesimals (e.g. Grazier et al. 1999)**



Model Parameters	
a (AU), e	6.2 , [0.05, 0.15, 0.5, 0.65] 10.85 , [0.05, 0.15, 0.5, 0.8]
R (km)	10 , 100
α_{initial}	3.5
$X_{\text{Al26, init.}}$	0 , 2.965×10^{-8}
$X_{\text{a-ice, init.}}$	0.5
$X_{\text{dust, init.}}$	0.5
Ψ_{initial}	0.5
ρ [g/cm^3]	0.715
(X=mass fraction; α=exp. of pore size distribution; Ψ=porosity)	

Tab. 1 – Key physical parameters used in our models.
The initial mass fraction of Al26 is taken with the assumption of ~3 Myr of prenatal decay.

Fig. 1 – Schematic representation of the orbits chosen for the thermal models in:
(a) The Jupiter-Saturn region.
(b) The Saturn-Uranus region.



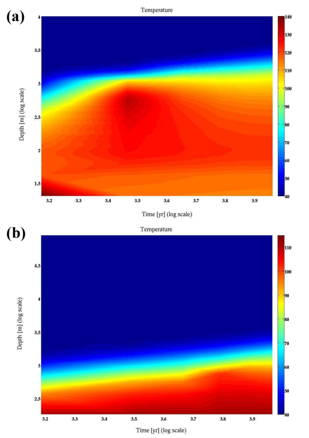


Fig. 2 – Internal Temperature profiles for:
(a) A body of 10 km, J-S zone, extreme eccentricity (0.65), no 26AL.
(b) A body of 100 km, J-S zone, low eccentricity (0.05), no 26AL.

Note the different depth & temperature scales.
In the high-e case there is a “bump” around 30 Kyr, due to rapid onset of a crystallization front.
In the low-e case the heat front slowly penetrates from the surface.

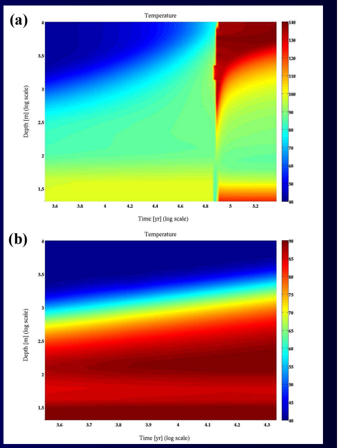


Fig. 3 – Internal temperature profiles of a 10 km, S-U zone, extreme eccentricity (0.8) body, for:
(a) Radioactive heating by 26 Al.
(b) Heating solely due to solar radiation.

Note the different time & temperature scales.
In the 26Al case there is a ‘‘cusp’’, at around 80 Kyr, associated with a very rapid onset of crystallization, driven from the heat flow of both the surface and the interior.
In the insolation case the heat front slowly penetrates from the surface, after hastily crystallizing the amorphous ice to a depth of ~50 m.

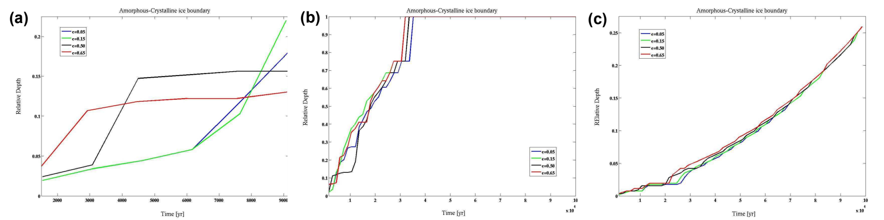


Fig. 4 – Evolution of the amorphous-crystalline boundary, which is defined as the depth where more than half of the initial mass fraction of amorphous ice has crystallized. The plots compare the different orbital configurations (eccentricities) for:
(a) A 10 km, J-S zone body, without radioactive heating.
(b) A 10 km, J-S zone body, with radioactive heating.
(c) A 100 km, J-S zone body, with radioactive heating.

Note the different timescales for the cases with, and without, radioactive heating. This highlights the fact that radioactivity is a bulk heating source, acting homogeneously from the interior outwards.
The ‘‘bumps’’ and ‘‘knees’’, clearly visible in (a) and (b), are due to crystallization, which is a local transient source within a body. This is an induced source, necessitating other means of temperature raising. The exoergic nature of this source implies that it may induce a runaway process. This is partly what happened in Fig. 3a.

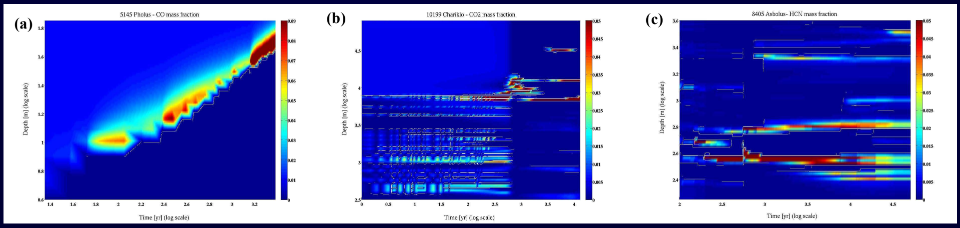


Fig. 5 – Mass fraction profiles of retained volatiles (as ices), during a thermal evolution. These are more “realistic” models of Centaur objects:
(a) **5145 Pholus**, with [a,e]=[20.43,0.57]: CO mass fraction, from an initial 10% mass fraction of CO ice.
(b) **10199 Chariklo**, with [a,e[=[15.87,0.18]: CO2 mass fraction, from an initial 1% fraction of occluded CO2 gas in amorphous ice.
(c) **8405 Asbolus**, with [a,e]=[17.97,0.62]: HCN mass fraction, from an initial 0.5% of occluded HCN gas in amorphous ice.

Thermal evolution of planetesimals beyond the “snow-line”

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The early thermal and structural processes that affect planetesimals have strong implications for planet formation scenarios. 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.

Modeling the internal evolution of cometary bodies takes into account various heat sources, such as insolation, crystallization, collisional effects and radioactive elements. In terms of composition, these models deal with a composition of dust and a mixture of volatiles, this may be either in solid or gaseous state. In terms of structure, the negligibility of self-gravity is taken as a general rule for all cometary bodies. As a result of the above assumptions, the equations that govern the structure and evolution are those of mass and energy conservation. A prescribed density profile usually replaces the demand for momentum conservation. In large enough bodies (~100 km and larger) self-gravity is not necessarily negligible, at least not for the entire body. Hydrostatic balance may play an important role in the evolution of internal structure in large bodies, affecting compaction and the continuous re-distribution of pore sizes. We combine in our models the thermal processing of volatiles, due to radionuclides (predominantly, 26Al and 60Fe) and insolation (which is negligible for orbits far enough from the “snow-line”), with a hydrostatic scheme for the solid matrix.

We present some preliminary results and considerations, regarding the thermal and structural state of bodies occupying the region where the outer planets were formed and accreted. Emphasis is put on the emerging structure, amorphous-to-crystalline ice transition, and possible volatile retention.

(More results of this research will be presented in future papers and on the internet, on ***http://geophysics.tau.ac.il/personal/gal_sarid/****)*