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Pre-impact thermochemical state of planetesimal interiors

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Abstract

Understanding the formation and composition of major and minor bodies of the Solar System requires a comprehensive toolkit to represent the physical and chemical processes during accretion. Here, we present numerical models of the internal evolution of planetesimals during the earliest phase of the Solar System, during and shortly after the protoplanetary disk phase. We consider the magmatic evolution of silicate phases, metal-silicate separation, and volatile losses due to degassing, and discuss how these results may be of use in collision models to advance our understanding of the formation and evolution of the Solar System planets and asteroids, and for planetary systems in general.

Introduction

The collisional processing of rocky bodies during accretion fundamentally shaped the orbital architecture and compositional properties of the Solar System objects we observe today [1]. So far, key chemical signatures were studied in a variety of potential impact scenarios [2, 3] that may have influenced the structural and evolutionary history of major and minor bodies and left behind crucial traces that can help us to piece together the early history of the Solar System.

However, the final composition of collisionally processed bodies is a complex function of both the pre-impact thermophysical and -chemical state, and the specific impact configuration during potentially repeated evolution-collision-reaccretion cycles. This notion necessitates coupled models of thermochemical evolution and collisional processing [4].

Methods

In recent years, developments in the geodynamical community have enabled physically comprehensive numerical tools that advance beyond simple thermal models of planetesimal interiors by solving for the time-dependent internal deformation and fluid flow, allowing estimates on the evolutionary processes that shape both the thermo-mechanical and -chemical state of the system [5, 6, 7, 8]. Using a combination of direct numerical integration of the internal evolution and post-processing of the advection and thermal history of tracer particles, we derive first order estimates on the chemical and structural evolution of planetesimals that were formed during the protoplanetary disk phase.

Results

We present recent results from large suites of numerical models that quantify the thermophysical and thermochemical state of planetesimals heated from the radioactive decay of ^{26}Al during the main accretion phase of the Solar System planets [5–14, Fig. 1]. These simulations cover the degassing rate and retention of volatiles [12, 13], such as H_2O, CO_2, CO, N_2, the redistribution of major rock phases and incompatible elements [7], as well as information on the timescales and potential for incomplete metal-silicate segregation due to percolation or metal rain-out during internal magma ocean stages [9, 11].

Our numerical models reveal distinct evolutionary pathways of the internal chemical evolution of planetesimals that are controlled by the accretionary regime and growth history of major Solar System bodies. Early formation time and large size promote high melt regimes, which results in interior magma oceans above the rheological transition [6], rapid core formation from raining-out of Fe,Ni particles [9], and extreme devolatilization of bodies formed beyond the water snowline [12, 13]. Bodies formed around 1 Myr after Ca,Al-rich inclusions may undergo a bifurcation of internal magma flow: bodies that accrete from particles with large mineral grain size (or develop such during melting) experience efficient magma ascent and thermal inversions, which may result in large magma pooling beyond a cold and stable lid, potentially re-

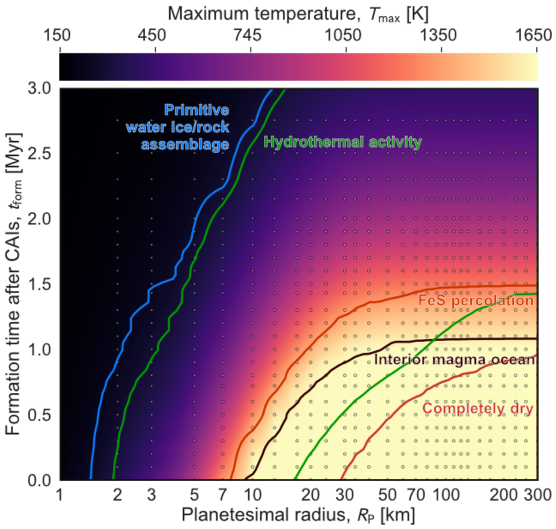

Figure 1: Planetesimal evolutionary parameter space integrated through the first 10 Myr after the formation of the Solar System. The formation time after Ca,Al-rich inclusions defines the heating rate due to incorporated ^{26}Al. Thermochemical regimes are indicated with multi-colored isolines.

leased via surface volcanism [7].

Summary

Our simulations can be combined with recent findings from the geochemical community to constrain astrophysical accretion models, which underlines the importance to consider the thermochemical state of planetesimal interiors to understand the formation of the Solar System [9]. We will present how various accretionary parameters, such as planetesimal formation time, composition, or grain size, can be used to reliably estimate the pre-impact thermo-chemical state of planetesimal interiors, with the ultimate goal of deriving scaling relations for use by the impact community [14]. Finally, we will discuss how these results may be used to extrapolate from Solar System accretion scenarios to the more diverse realm of the extrasolar planet population [13].

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