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Giant planet formation: Recurring envelope ejection by episodic impacts

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Abstract

We describe the growth of gas giant planets in the core accretion scenario. The core growth is not modelled as a gradual accretion of planetesimals but as episodic impacts of large mass ratios, Such impacts could deliver the majority of solid matter in the late oligarchic and giant collision growth regime. We focus on the thermal response of the envelope to the energy delivery.

Results show that in such a scenario, each giant impact ejects most of the gaseous envelope of the giant planet. This is a very efficient method to spend the impact energy and is therefore immediately followed by rapid envelope accretion. As an important side-effect, the episodic ejection of the envelope will reset the envelope composition to nebula conditions.

1. Introduction

We study the formation of gas giant planets in the core accretion scenario [1, 2, 3]. In this scenario, a planetary embryo grows by accreting from a swarm of planetesimals. At some point the embryo becomes massive enough to gravitationally attract a gaseous envelope. The growth process, both in terms of solid and gas accretion, is controlled by the planetesimal accretion, which is typically modeled as a gradual accretion of small planetesimals. However, in the oligarchic and later growth phases, the accretion process can be dominated by relatively large impacts [4]. This is confirmed by Monte-Carlo planet formation models (T. Schröter et al., in preparation) and recent results from N-body simulations [5, 6]. In such cases, while the collisions are less frequent, each one increases the mass of the protoplanet by a significant amount (typically of order 10%). This possibility led us to investigate the importance of the nature of the solid accretion process in the overall growth of giant planets. In particular, we want to investigate if episodic but large impacts result in changes in the mass and structure of the envelope when compared to gradual core growth.

2 Methods

In the core accretion scenario in which we place our studies, a growing giant planet is composed of a solid core surrounded by a gaseous atmosphere. To model such a structure, we solve the standard so-called equations of stellar structure. The equations are the same as in [7], except for the envelope which is considered to be in quasi-hydrostatic equilibrium and the fact that we take into account its contraction:

$$\begin{aligned} \nabla \cdot F &= \rho(\epsilon_{ac} - \dot{q}), \quad \text{or} \\ \frac{\partial l}{\partial r} &= 4\pi r^2 \rho(\epsilon_{ac} - \dot{q}), \quad \text{where} \\ \dot{q} &= T ds = c_p dT - \frac{\delta}{\rho} dP, \qquad l = 4\pi r^2 F. \end{aligned} \tag{1}$$

We assume the envelope to be of solar composition and use the equation of state from [8]. For the opacity we use tabulated values: [9] (for $\lg T < 2.3$) combined with molecular opacities from [10] and high temperature opacities from [11].

We study impacts of 0.02 - 1 $M_\oplus$ onto cores of 1-15 $M_\oplus$ in the growth phase of the giant planet. To model this scenario, we spread the impact energy deposition over a time that is long compared to the sound crossing time, but very short compared to the Kelvin-Helmholtz time. The simulations are done in spherical symmetry and assume quasi-hydrostatic equilibrium.

3. Results and Conclusions

We present a series of computations that aim at exploring the case in which episodic impacts by large bodies rather than a steady flux of small planetesimals provide the bulk of the core mass accretion. The resulting envelope structure, in particular the mass of the envelope, is compared to the 'normal' case at the same core masses. We find that the large impacts or sudden energy input, while briefly reducing the envelope mass, allow for a larger gas accretion rate leading for all sizeable impactors to a significantly more massive envelope.

This is caused by the main effect of this episodic accretion: the recurring ejection of envelope material and subsequent fast re-accretion of new envelope gas. The amount of envelope ejected by each impact is shown in Figure 1.

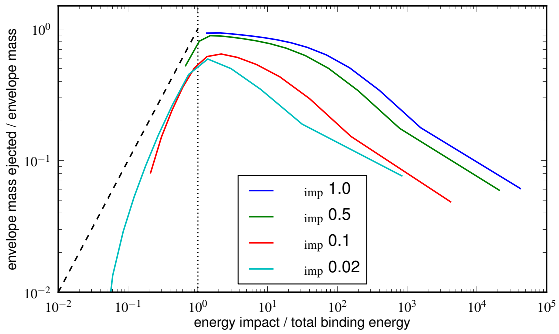

Figure 1: The fraction of envelope mass ejected by the impact as a function of available energy. The abscissa shows the ratio of impact energy to total binding energy of the envelope. Left of the vertical dashed line the impact energy is insufficient to remove the entire envelope. The other dashed line shows the ejected mass ratio for 100% efficient processes. Note that large target cores are to the left, small targets to the right.

The increased envelope accretion rate can be understood by comparing with a stop of core accretion: In that case, the lack of core accretion energy leads to faster envelope accretion. In the impact case, between each impact, we de-facto also turn off core accretion. Because the impact energy has been practically consumed by the envelope ejection, the ensuing behaviour is similar to the case where core accretion is simply stopped. This continues up to the next impact when the process begins again. In summary, the gas accretion can be very fast while the core continues to grow sporadically by large steps.

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