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The effects of large planetesimals on giant planet formation

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Abstract

1. Introduction

We study the formation of gas giant planets in the core accretion scenario ([11], [3], [12]). In this scenario, a planetary embryo grows by colliding with a swarm of planetesimals. At some point the embryo becomes massive enough to gravitationally attract a gaseous envelope and it becomes the core of the planet. The growth process is controlled by the planetesimal accretion, which is typically modeled as a gradual accretion of small planetesimals at a given rate. However, in the oligarchic growth phase under certain conditions, the accretion process could be dominated by relatively large impacts [13]. This is confirmed by our Monte-Carlo planet formation model and recent results from N-body simulations. In such cases, the majority of the mass is deposited by impacts having a large mass ratio. This led us to investigate the importance of the nature of the accretion process. Do episodic impacts change the envelope structure when compared to gradual core growth? Few studies have addressed this issue.

One study of a giant impact on a gaseous planet is concerned with the stripping of the envelope of Uranus, a planet having a very small atmosphere [10]. Due to computational difficulty, the authors could not follow the long-term behavior of the post impact planet. Another study [1] tries to assess the effect of a huge impact with a 3-dim SPH calculation focusing on the subsequent change in luminosity in the long-term evolution of the giant planet. Other studies investigate the influence of the solid core in terms of thermal energy content and energy provided by the contraction of the core [2]. Another group studied the response of the envelope to a sudden shut-off of the core accretion [7].

The effect of sporadic, relatively massive impacts in the growth phase of the core has not been studied properly. We want to study the thermal response of a gas giant on the impact of a large planetesimal and compare it to the nominal case of constant accretion.

2. Method and validation

To be able to model this scenario, we developed a new numerical code that solves the standard equations of stellar structure [9] on a self-adaptive 1-dimensional grid [6] using an implicit BDF for the time evolution. We have successfully tested the code in a series of calculations: In the static case we exactly reproduce [8] or [4]. The long-term evolution of the planet HD209456b, a very close-in planet with extremely hot atmosphere, agrees with established calculations by T. Guillot (pers. comm.). We also applied the code to the evolution of CoRoT-9b. The radius at present is in good agreement with observations, obtaining a best fit for a 10 Earth mass core – like they do in the discovery paper [5]. Furthermore, we computed the formation of Jupiter following Pollack (1996, case J1). While it is not possible to do a quantitative comparison[1], qualitatively we get the same results and peak luminosities are very similar to [12]. Furthermore, our calculation can follow the evolution of Jupiter to present day without changing the equation system[2]: we get a radius slightly larger than Jupiter (+3%) and the luminosity is 76% of Jupiter's present day value. Since our code has not been designed with accurate long-term evolution in mind, but focuses on the growth of the planet in the early phases, this is a very good agreement.

An large planetesimal impact is simulated by a Gaussian peak of the core accretion rate dM_z/dt. We use the equivalent width τ_{EW} as the timescale of the impact. The equivalent width of the Gauss curve gives the time during which the same amount of mass is deposited as when using the maximum accretion rate. So $\tau_{EW} = \sigma\sqrt{2\pi}$ where σ is the standard deviation of the Gauss curve.

3. First results

To test the applicability of the quasi hydrostatic assumption, we have simulated impacts of 10 Earth

[1] we don't compute the capture radius and gravitational focusing
[2] To stay in the quasi hydrostatic regime we have to limit the gas accretion rate to 10^{-4} Earth masses per year

masses on a possible CoRoT-9b–like planet[3]. The planet is at the beginning of the contraction phase and therefore rather large compared to Jupiter. The Kelvin-Helmholtz time of the test planet is 55 Myr and the dynamical timescale is on the order of a fraction of a year. Therefore we expected to be able to calculate impacts with impact timescales of about 1000 years. Indeed, we manage to simulate such an impact as long as the impact time is 5000 years or larger. For shorter impact times, the mach number becomes larger than one in thousand and the numerical code is not applicable any more. We simulated a sequence of 4 such impacts every 10 Myr and compared it with a constant, smooth accretion of 10^{-6} Earth masses in one year. First results indicate, that both cases give very similar results for quantities such as radius or luminosity when compared exactly at the middle of the impact, i.e. when the total accreted mass is equal.

Currently, we are studying the effect of episodic planetesimal accretion on small embryos that are in the process of building up an envelope of gas. The outcome is compared to a proto-planet having accreted small planetesimals in a gradual fashion. We are doing this for a range of core and planetesimal sizes. This will let us draw conclusions whether or not using a smooth accretion rate is justified in planet formation models.

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[3] 0.84 Jupiter masses, 0.4 AU from host star