EPSC Abstracts,
Vol. 4, EPSC2009-139-1, 2009
European Planetary Science Congress,

Computational modeling a protoplanetary system formation from a flattened dust-gas protoplanetary cloud

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Abstract

As it has been mentioned in some recent works (see for example [1], [2]) within the last decade, a coherent scenario has arisen for the formation of terrestrial planet from an initial dusty protoplanetary disc (a flattened dust-gas protoplanetary cloud). The modern insight is the result of numerous N-body computational simulations of the solar system formation [3], [4], [5], [6] and numerical high-resolution hydrodynamic as well as magneto-hydrodynamic calculations [7], [8].

A contemporary understanding consists in that the evolution from dust to planet can be divided into *three successive phases* [2], [9]. The *first* main stage is the coagulation of micrometer-sized grains into kilometer-sized *planetesimals* [10], [11]. This stage is currently the least-understood phase of planet formation, with several competing theories [9]. The first is that planetesimals form as the result of gravitational instability in the solar nebula, in which solids are sufficiently concentrated that planetesimals are able to form purely by self-gravity [11]. The second is that planetesimals form by the direct collisional accretion between colliding particles [10], i.e. grains are assumed to stick together if an impact occurs a critical, threshold velocity. While this phase of a planet formation still remains to be fully quantified, the key point is that once these planetesimals reach a size where they can gravitationally perturb each other, generally on the order of a few km, their orbits begin to cross [9].

As the planetesimals grow, they decrease in number, and collisions become less frequent. Due to the stochastic nature of growth, not all planetesimals grow at the same rate and some will become more massive than others. More massive bodies are more effectively able to accrete the surrounding planetesimals.

This quickly leads to a *runaway* accretion process [4] beginning the *second* main phase. In a swarm of planetesimals, the relative velocity v_{rel} is governed by their frequent encounters with one another, and given their small gravity, is kept low [9]. Runaway growth is stalled somewhat when the planetary embryos grow large enough that their gravitational perturbations on the planetesimals become the dominant influence on v_{rel} . The system enters a regime called *oligarchic growth* where the largest bodies in each region of disc come to dominate, growing much larger than the surrounding “planetesimal sea” [4]. At this occurs, planetesimals decouple from gaseous disk and start to interact gravitationally with each other. This catalyses the second phase completely: a runaway growth leading to the formation of *planetary embryo* with masses 1-10% of that of Earth M_E. These embryos accrete material locally and form a dense population distributed throughout the solar system. When a body starts to grow larger than its neighbors, it begins to increase the v_{rel} of planetesimals in its vicinity, decreasing its accretion efficiency, and thus letting its neighbors catch up. The end result of this stage is a system of roughly comparably sized and spaced planetary embryos embedded in a swarm of planetesimals with a total mass roughly comparable to the total mass of embryos [9].

In the *third* and final stage of terrestrial planet accretion, the gravitational effect of the planetesimals begins to fade as their numbers decrease, and the planetary embryos begin to perturb one another onto crossing orbits. Planets then begin to grow from collisions between embryos and the accretion of remaining planetesimals. This stage is characterized by relatively violent, stochastic large collisions as compared to the previous stages, where the continual accretion of small bodies dominates [9].

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At the same time, while the number of embryos involved (on the order of 50) it is easily modeled by direct numerical simulation. Direct N-body simulations (e.g., [5], [6]) incorporating 50–200 bodies generally form about the right number of planets (although generally not a small 'Mercury' and 'Mars'), but those planets are significantly more dynamically excited (i.e., larger eccentricity *e* and inclination *i*) than the terrestrial planets in our solar system [9]. While of 10^4 years more are needed to form the embryos, the final mass of the Earth is reached with 50-150 Myears [6] according to numerical simulations. Thus, this time can be interpreted as a mean differentiation time for the embryos that made the Earth. These embryos can incorporate into a planet several AU from their formation region. This third step of the planetary accretion makes the novelty of the scenario: the Earth is no longer formed continuously by accreting planetesimals formed around 1 AU [2]. Therefore, the last three decades of research in this area showed that numerical modeling has become a major part in understanding the evolution of the protoplanetary systems.

This work investigates a protoplanetary system forming with usage of computational modeling based on modern program packages [12]. Pictures of fields for pressure and velocity into a gravitating and rotating gas-dust cloud (around of a protostar) are obtained. Here it is shown how evolution of rotating gas-dust disc (a flattened dust-gas protoplanetary cloud) forms planetary embryos in the centrally symmetric gravitational field. This work also develops an analysis of dust-gas flows into a rotating protoplanetary cloud with usage of nonlinear dynamics methods into state-space [13]. This analysis permits to reveal and investigate chaotic regimes of protoplanetary system formation into a dust-gas protoplanetary cloud.

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