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Pebble pile-up and planetesimal formation at the snow line

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Abstract

The planetesimal formation stage represents a major gap in our understanding of planet formation process. Because of this, the late-stage planet accretion models typically make arbitrary assumptions about planetesimals and pebbles distribution, while the state-of-the-art dust evolution models predict no or little planetesimal formation. With this contribution, I present a step toward bridging the gap between the early and late stages of planet formation by models that connect dust coagulation and planetesimal formation. With the aid of evaporation, outward diffusion, and re-condensation of water vapor, pile-up of large pebbles is formed outside of the snow line that facilitates planetesimal formation by streaming instability.

1. Introduction

Our understanding of planet formation is limited by the disconnection between its early and late stages. This is because the growth barriers: the dust growth is inhibited at centimeter sizes and some particular conditions are needed for the formation of larger, gravitationally bound planetesimals and planetary embryos [1]. We cannot really explain how and where planetary embryos form. As a consequence, models that deal with the late-stage planet accretion, when a planetary embryo grows to its final size and structure, typically use the same input models for the radial distribution of gas and solids as the early-stage models dealing with dust growth and planetesimal formation, which is obviously inconsistent.

Probably the most widely accepted planetesimal formation scenario at the moment is called the streaming instability. It leads to formation of dense filaments of pebbles that subsequently become gravitationally unstable and collapse to planetesimals. This scenario allows us to bypass the fragmentation barrier and form gravitationally bound object directly from cm-sized pebbles that can be obtain from dust coagulation.

In a realistic disk conditions needed by the streaming instability (which include existence of large pebbles and high dust-to-gas ratio) are not easily met. Such disks typically start their evolution with dust-to-gas ratio of 1%, which gets lower because of removal of solids by the radial drift. Dust pile-ups are necessary to allow for planetesimal formation in gas-rich phase of protoplanetary disk [2] while disk dispersal may allow for late planetesimal formation [3]. Both of these processes may be needed to explain the existence of different types of planets and debris belts, for instance in the Solar System.

2. Models

I developed one dimensional model for evolution of protoplanetary disk that includes:

- gas disk evolution: I tested several different models, both with and without stellar irradiation, obtaining qualitatively similar results; the non-irradiated models are based on the work of [4] and the irradiated models on [5];
- dust growth, fragmentation, and radial drift: the dust evolution model closely follows the algorithm proposed by [6]. This algorithm was designed to reproduce full dust growth simulations at much lower computational expense. One significant modification is that the so-called collective drift effect is considered, which means that the radial drift velocity decreases with increasing dust-to-gas ratio;
- evaporation, diffusion, and re-condensation of water following treatment proposed by [7];
- planetesimal formation via streaming instability using semi-analytical prescription similar to [8].

3. Results

Processes happening around the snow line facilitate planetesimal formation via streaming instability. Ice evaporation and outward diffusion of water followed by its re-condensation increases abundance of icy pebbles that triggers planetesimal formation just outside of the snow line. Typical evolution in an irradiated protoplanetary disk is showed in Fig. 1. An annulus of planetesimals is formed between 2 and 10 au. The total mass of these planetesimals is over 100 $M_\oplus$. For the non-irradiated disk models, the snow line typically falls closer to the central star and thus the inner edge of planetesimal belt is shifted inwards.

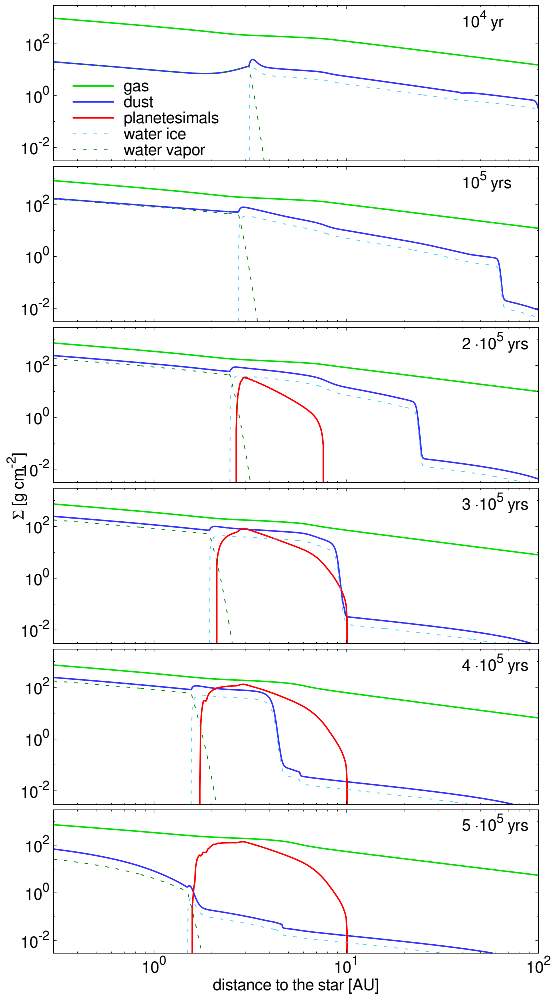

Figure 1: Temporal evolution of gas (green solid line), dust (blue solid line), and planetesimals (red solid line) surface densities radial distribution. Water ice and vapor contributions are also showed with the dashed lines.

4. Summary and Conclusions

This contribution addresses the connection between dust growth and planetesimal formation, which corresponds to a major gap in the state-of-the-art planet formation models. Planetesimal formation is possible in a smooth protoplanetary disk thanks to the pile-up of icy pebbles outside of the water snow line. This massive annulus of planetesimals will trigger formation of planetary embryos that can benefit from the high surface densities of both planetesimals and pebbles.

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