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Dust growth in the vicinity of Jupiter-mass planet

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Abstract

We used a state-of-the-art numerical model, which couples hydrodynamic evolution of a protoplanetary disk and dust coagulation, to study dust evolution in the vicinity of a Jupiter-mass planet. We compared our results to the commonly used, fixed dust size approach, and found significant differences. Fragmentation of large pebbles captured in the pressure maximum outside of the planetary gap limits the effect of trapping and increases the gap permeability.

1. Introduction

Dust growth plays a major role in shaping the evolution and observational appearance of protoplanetary disks. However, it is often neglected in models due to its complexity and computational expense. We self-consistently include dust coagulation in hydrodynamic simulations of a protoplanetary disk including a massive planet.

2. Methods

We performed 2-D models of protoplanetary disk using a grid-based hydrodynamic code which is part of `LA-COMPASS` described by [1, 2]. The code solves hydrodynamic equations for the coupled evolution of gas and dust, which are both treated as fluids. We include the effect of aerodynamic drag and the back-reaction of dust onto the gas.

In the standard version of the code, dust is treated as a single fluid with a fixed particle size. We run a series of models covering dust sizes between 1 micron and 10 centimeter.

We modified the default version of the code to include multiple dust fluids (we used 151 dust fluids in the model shown here) representing different dust sizes, from 1 micron to 1 meter. Collisional evolution of dust is solved by explicitly integrating the Smoluchowski equation: the mass is shifted between the fluids to account for dust growth and fragmentation. Impact velocities are calculated taking into account Brownian motion, turbulence, differential radial and azimuthal drift, and vertical settling. The values of radial and azimuthal velocities are obtained from the hydrodynamic solver and the other sources are calculated in the same way as in [3]. We assume that grains are compact with constant internal density of $\rho_\mathrm{s} = 1.2$ g cm^{-3}. Fragmentation threshold velocity is set to $v_\mathrm{f} = 10$ m s^{-1}.

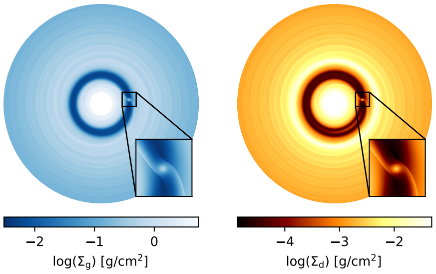

Figure 1: Surface density of gas and dust (left and right panel, respectively) obtained in the model including dust coagulation. The inserts zoom in the planet region.

We performed models of a protoplanetary disk with a Jupiter-mass planet at a fixed, circular orbit with the semi-major axis of 10 AU. The initial surface density of gas and dust follow the Minimum-Mass Solar Nebula model with a solids-to-gas ratio of 1%. We assumed a viscous disk with $\alpha = 10^{-3}$.

3. Results

Figure 1 shows a snapshot of the gas and dust densities obtained in the model including dust coagulation. As expected, the massive planet opens a gap, but some accretion flow is retained around the planet (visible in the inserts). A pressure bump is formed at the outer edge of the gap, which causes the enhancement in dust density.

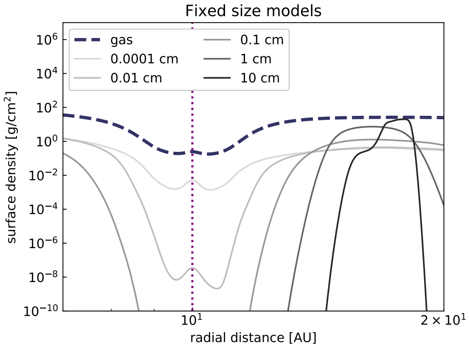

Figure 2: Azimuthally averaged gas and dust densities obtained in models assuming fixed dust size after 4000 orbits of the planet. The vertical dotted line marks the planet position.

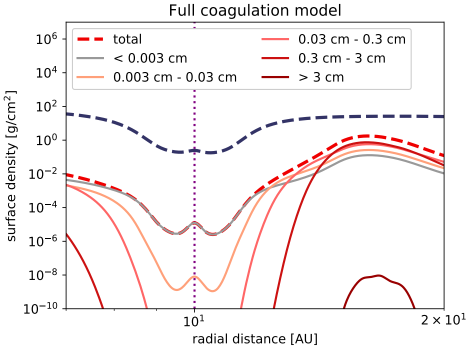

Figure 3: Azimuthally averaged gas and dust densities obtained in the model including the full coagulation prescription. The solid lines show the contributions to the total density from grains of different sizes.

Figure 2 shows azimuthally averaged gas and dust densities obtained in the models assuming one fixed dust size each. The smallest grains are tightly coupled and follow the evolution of the gas. The larger the grains, the clearer and wider gap that is opened.

Figure 3 is an analogical plot for the model including dust coagulation, where the dust sizes are set self-consistently. The dust distribution resulting from the interplay between multi-size advection and coagulation shows both the peak outside of the planetary gap, characteristic for large grains, and the partially filled gap region, characteristic for small grains. This is because large grains can only grow inside of the pressure bump. However, these grains constantly fragment and replenish the population of small grains, which can pass through the gap. Because of the continuous fragmentation, the density of the smallest grains in the pressure trap is enhanced compared to the single size models.

4. Conclusions

We considered dust evolution in the neighborhood of a massive, gap-opening planet. The model including dust coagulation evolves differently than models, in which a fixed dust size was assumed. The continuous fragmentation of pebbles replenishes the population of small grains, which can pass through the planetary gap and thus the effect of dust filtering by the planet is reduced. This may potentially lead to increase of the so-called pebble isolation mass [4].

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