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Hydrodynamic effects on the accretion of gas and dust onto protoplanetary cores

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Abstract

A protoplanetary core embedded in a protoplanetary disk induces recycling flow: disk gas enters the Bondi/Hill sphere at high latitudes and leaves through the mid-plane regions. Our simulations revealed that, whereas the recycling flow does not limit the accretion of disk gas, the midplane outflow prevents small dust particles from accreting onto the core. These results, combined with inefficient dust growth beyond CO_2 snow line due to reduced stickiness, suggest that gas giants must have formed predominantly at ~1-10 au, between H_2O and CO_2 snow lines.

1. Introduction

Gas giants are typically found to have separations of ~1-10 au from their host stars. About 10% of stars possess this type of planets [4] with a peak between 2-3 au, which may correspond to H_2O snow line [2]. In contrast, hot Jupiters (<~0.1 au) and distant planets (30-300 au) are rare, with the occurrence rates being only ~1% [1,3]. The origin of this trend has not been elucidated.

Hydrodynamics of disk gas around a protoplanetary core has been considered to influence the accretion of gas and dust onto the core. Recycling flow was proposed to limit the runaway gas accretion onto cores at close-in (~0.1 au) orbits [10]. The flow may also prohibit small dust particles from accreting as shown for 2D in [9].

We simulated gas flow around an embedded planet and the trajectories of accreting solid materials. We discuss the implications for the origin of the orbital distribution of gas giants.

2. Model

We performed a series of 3D hydrodynamic simulations of gas flow around a core. We focused on the influence of non-isothermality on the recycling flow [5] and the dependence on planetary mass [6]. We also computed the trajectories of accreting dust particles in the simulated gas flow for a range of particle sizes [7].

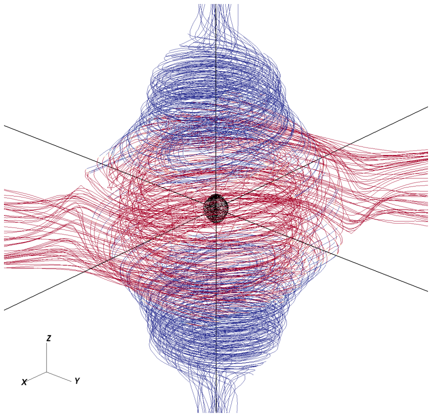

Figure 1: Streamlines around a planet embedded in a disk. Color represents where the radial speed is negative (blue) or positive (red). The inner black lines show the protoplanetary core [5].

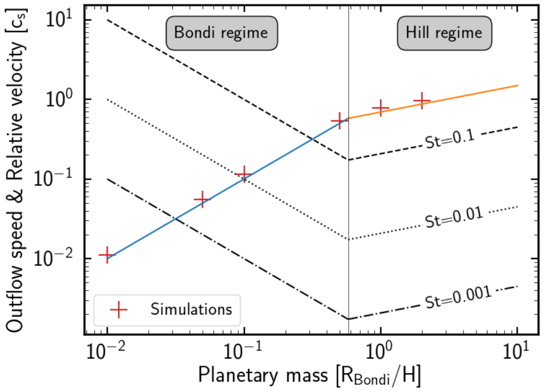

Figure 2: Speed of the midplane outflow (Points: simulations, solid lines: analytical estimate) and the terminal velocity of accreting dusts at Bondi/Hill radius (black lines) [6].

3. Results

We found that, in contrast to the isothermal case where the recycling flow reaches the deeper part of the envelope [10], the inflow is inhibited from reaching the deep envelope in the non-isothermal case (Figure

1). Once the atmosphere starts cooling, buoyant force prevents the high-entropy disc gas from intruding into the low-entropy atmosphere. Therefore, we suggest the recycling flow cannot prevent the runaway gas accretion [5].

The midplane outflow prohibits small dust particles from accreting onto the core (Figure 2). The condition for successful accretion was analytically derived to be,

$$m < \mathrm{St}^{1/2} \qquad (1),$$

where m is the dimensionless planetary mass (the ratio of the Bondi radius to the disk scale height) and St is the Stokes number of dust (the stopping time times the Kepler frequency) [6]. Assuming the minimum-mass-solar-nebula (MMSN) temperature profile leads to,

$$M_\mathrm{p} = 12\, m\, (\mathrm{a} / 1\ \mathrm{au})^{3/4}\, M_\mathrm{Earth} \qquad (2).$$

Accretion of small dust particles not satisfying Equation 1 is significantly reduced (Figure 3).

4. Discussion

Equation 1 defines the *outflow isolation mass* $m_\mathrm{iso} = \mathrm{St}^{1/2}$, where further growth of the core via accretion of small (in terms of St) particles is limited. The outflow isolation mass depends on St, which is controlled by the growth and migration of dust in a global disk.

Recent polarimetric observations of the HL Tau circumstellar disk are consistent with the self-scattering by dust as small as ~100 µm. The inferred size is considerably smaller than predicted by dust growth models assuming a high particle sticking efficiency. This discrepancy suggests inefficient growth due to non-sticky CO_2-ice mantle beyond the CO_2 snow line [8].

Assuming that silicates and CO_2-mantled particles are poorly sticky, one can expect that gas giants' cores ($>\sim 10\ M_\mathrm{Earth}$) only form between the H_2O and CO_2 snow lines. (Figure 4). We suggest that the rareness of close-in and distant gas giants may be explained by the interplay between the inefficient dust growth and the reduction of accretion of small dust particles via local recycling flow.

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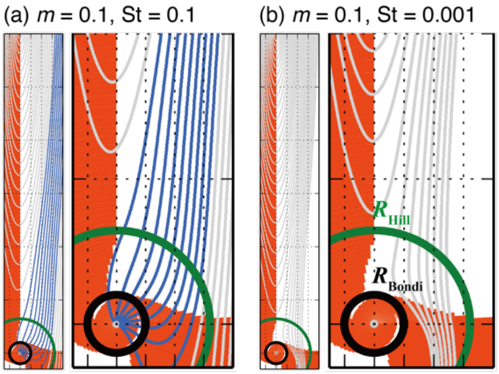

Figure 3: Trajectories of pebbles in the midplane (blue: accreted, grey: not accreted). The outflow is indicated by red regions.

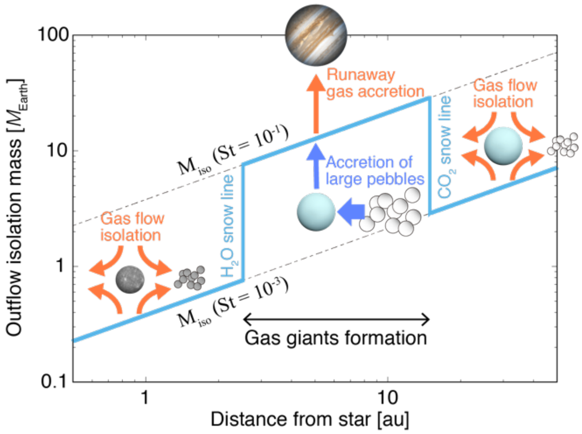

Figure 4: Outflow isolation mass. We assumed the MMSN temperature profile. The dust size distribution is St = 10^{-1} between H_2O and CO_2 snow lines and St = 10^{-3} in the other part (motivated by the results of [8]).

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