EPSC Abstracts
Vol. 13, EPSC-DPS2019-236-2, 2019
EPSC-DPS Joint Meeting 2019

EPSC
EPSC-DPS Joint Meeting 2019
15–20 September 2019 | Geneva, Switzerland

Suppression of pebble accretion by planet-induced gas flow: The implication for the origin of super-Earths

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Abstract

A growing proto-core embedded in a protoplanetary disk induces three-dimensional gas flow. Disk gas enters the Bondi/Hill sphere at high latitudes and exit through the midplane region. Our simulations showed that this flow field reduces the accretion rate of small pebbles onto the core. We also derived the size-threshold for the suppression analytically. Our results suggest that proto-cores of super-Earths have avoided becoming gas giants due to the suppression of core growth by the planet-induced gas flow.

1. Introduction

The *Kepler* mission revealed that about 50% of Sun-like stars harbor short-period super-Earths with orbital period less than 85 days and radii of 1—4 R_{Earth} [e.g., 2]. The timescale of runaway gas accretion is shorter than the lifetime of protoplanetary disk for some of these super-Earths (having ~5—10 Earth masses) [8,10], which means that they should have formed in the late stage of disk evolution to avoid becoming gas giants.

Previous studies [1,3,4,5,9] have found the three-dimensional (3D) structure of the gas flow around embedded planets (Fig. 1). Disk gas enters at high latitude of the Bondi/Hill sphere of the planet (inflow) and exits through the midplane region (outflow). This outward gas flow was considered to suppress the accretion of ~mm—cm-sized particles, called pebbles, and delay the core growth [4,5].

We calculated the trajectories of pebbles in the 3D gas flow field obtained from non-isothermal hydrodynamical simulations. We discuss the effect of gas flow on pebble accretion and the implication for the origin of short-period super-Earths.

2. Model

We performed a series of non-isothermal hydrodynamical simulations with different dimensionless planetary masses expressed by the ratio of the Bondi radius to the disk scale height, $m = R_{Bondi}/H$.

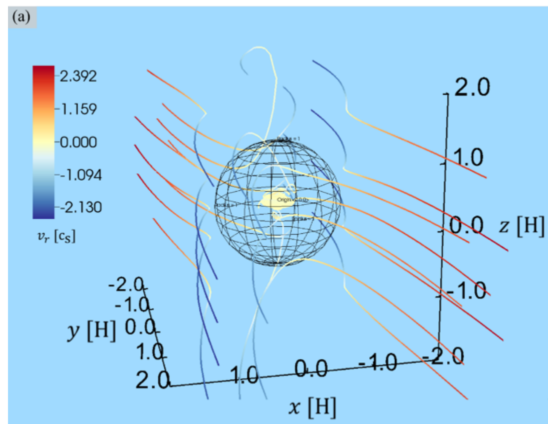

Figure 1: Streamlines of planet-induced gas flow around an embedded planet. The color shows the radial velocity normalized by the isothermal sound speed. The sphere is the Bondi region. The regions where v_r has a positive (outflow) or a negative value (inflow) are shown in blue and red, respectively [5].

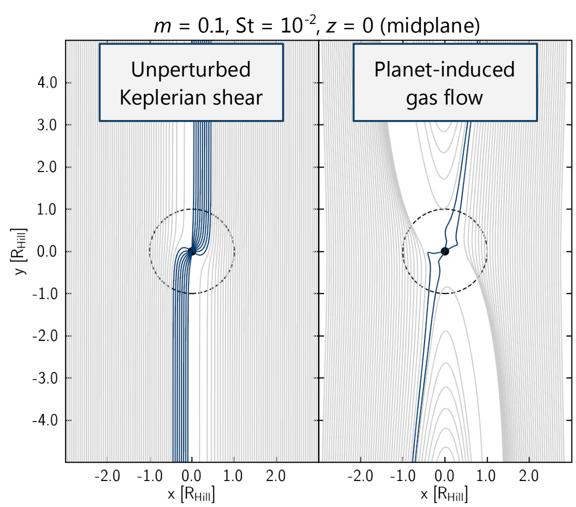

Figure 2: Trajectories of pebbles (blue: accreted, grey: non-accreted) in the unperturbed Keplerian shear flow (left) and in the three-dimensional planet-induced gas flow (right) [6]. The dashed lines are the Hill sphere of the planet.

We also calculated the trajectories of pebbles with various Stokes numbers, St (the stopping time times the Keplerian frequency), using the above-mentioned simulation results.

3. Results

The efficiency of pebble accretion is lower in the planet-induced flow than in the unperturbed Keplerian shear flow (Fig.2). In the midplane, pebbles coming from a window between the horseshoe and shear regions can accrete onto the core if the pebble size is sufficiently large. Otherwise the outflow prohibits pebble from accreting. Because the horseshoe flow extends well above the midplane, pebbles coming from high altitudes are also influenced. In general, when the pebble accretion in the midplane is suppressed, their accretion from higher altitudes is also limited.

We analytically derived that the size-threshold for the suppression of accretion efficiency is given by [5]:

$$m \geq \sqrt{\mathrm{St}}\,. \qquad (1)$$

This means that, for a given pebble size (in terms of St), a growing proto-core starts to suppress the accretion of those pebbles as the core reaches the mass given by Equation 1.

4. Discussion

We suggest a scenario for the formation of super-Earths as follows (Fig. 4).

1. Proto-cores form in the protoplanetary disk at ~1 au under the influence of the flow field. Due to the planet-induced gas flow field, the growth of proto-cores may halt when $m \sim \sqrt{\mathrm{St}}$.
2. When the growth of the proto-cores halts, they begin to migrate inward. A number of proto-cores are arranged at the inner edge of the disk.
3. Super-Earths are formed by giant impact during disk dispersal. In a short time, until the gas has disappeared completely, an envelope forms around each super-Earth, which has ~1—10% of the total mass.

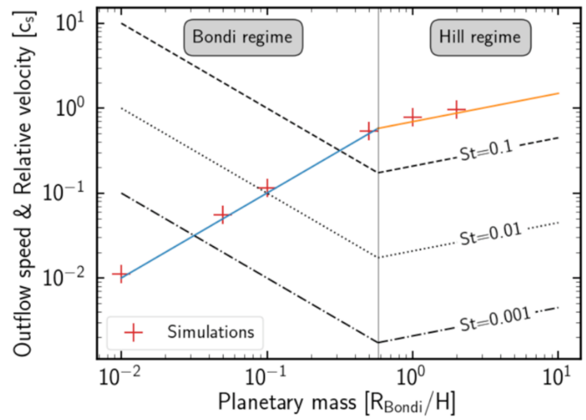

Figure 3: Outflow speed in the midplane (the cross symbols are the simulation results and the solid lines are the analytic estimate) and the terminal velocity of pebbles at Bondi/Hill radius (black lines) [5].

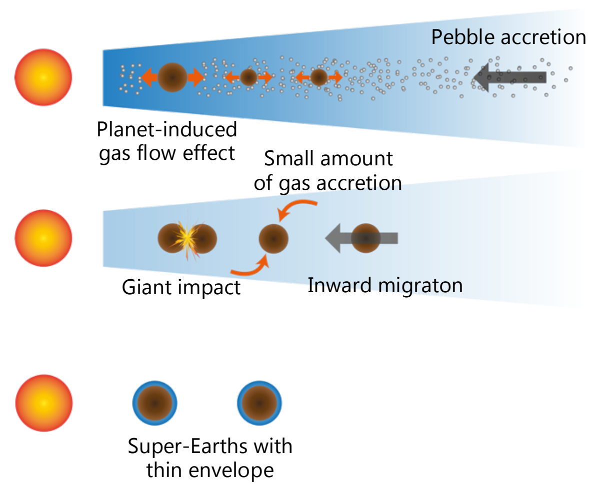

Figure 4: A plausible scenario for the formation of super-Earths.

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