Influence of protoplanet-induced gas flow on pebble accretion: Implications for the dichotomy between inner super-Earths and outer gas giants

*Ayumu Kuwahara[1,2], Hiroyuki Kurokawa[2]

1. Tokyo Institute of Technology, 2. Earth-Life Science Institute

Pebble accretion model (Ormel & Klahr 2010, Lambrechts & Johansen 2012, 2014), a new model of planet formation, has become a focus of attention in recent years. Accreting mm—cm-sized particles, called pebbles, onto the proto-cores can form the massive cores faster than accreting the planetesimals. Pebbles not only experience the gravitational interaction with the growing planet but also a gas drag force from the surrounding protoplanetary disk gas. The hydrodynamic influence is important when we consider planet formation via pebble accretion. A growing planet embedded in a disk induces three-dimensional (3D) gas flow (Ormel et al. 2015), which may influence pebble accretion. However, so far the conventional pebble accretion model has mostly been discussed in the unperturbed (sub-)Keplerian shear flow.

When the disk gas rotates in a Keplerian fashion, previous study has found that the accretion of mm-sized pebbles is suppressed due to the planet-induced gas flow (Kuwahara & Kurokawa 2020). The planet induces the horseshoe and recycling flows. These flows have the vertically symmetric structure. The horseshoe flow, extending in the orbital direction of the planet, have a characteristic vertical structure like a column. The disk gas enters the gravitational sphere of the planet at high latitudes (inflow) and exits through the midplane region (outflow). The horseshoe and outflow alter the motion of the pebbles, which leads to a reduction of the accretion probability of mm-sized pebbles. In a realistic protoplanetary disk, the disk gas rotates in a sub-Keplerian fashion due to the pressure gradient of the gas. Since the planet rotates with the Keplerian frequency, the planet moves against the headwind of the gas. In the minimum mass solar nebula model, Mach number of the headwind increases with the orbital radius. The strong headwind of the gas changes the structure of the planet-induced gas flow significantly. The positions of the inflow and the outflow is reversed (Ormel et al. 2015, Kurokawa & Tanigawa 2020), and the horseshoe flow shifts to inside the planetary orbit keeping its configurations. It is unclear that how the influence of the planet-induced gas flow on pebble accretion depend on the speed of the headwind of the gas.

In this study, we performed 3D hydrodynamical simulations on the spherical polar grid, which has a planet located at its center. We then numerically integrated the equation of motion of pebbles in 3D using hydrodynamical simulation data. We investigated how the description of the pebble accretion changed in the planet-induced gas flow on the dimensionless planetary mass, $m=R_{\rm bondi}/H$, Mach number of the headwind, $M_{\rm hw}$, and the pebble size, where $R_{\rm bondi}$ and H are the Bondi radius of the planet and disk scale height.

We found that the structure of the 3D planet-induced gas flow depends on the ratio of the dimensionless planetary mass to the Mach number of the headwind, $m/M_{\rm hw}$, and the trajectories of pebbles in the planet-induced gas flow differs significantly from those in the unperturbed flow for a wide range of pebble sizes. When $m/M_{\rm hw}\gg1$, the 3D planet-induced gas flow has the vertically symmetric structure. In this case, the accretion of mm-sized pebbles is suppressed due to the horseshoe flow and the outflow (Kuwahara & Kurokawa 2020). When $m/M_{\rm hw}\ll1$, pebble accretion is not suppressed regardless of the pebble size. The vertically symmetric structure of the planet-induced gas flow is broken. Thus, pebbles are less susceptible

to the horseshoe flow and the outflow. Since Mach number of the headwind increases with the orbital radius, the influence of the planet-induced gas flow on pebble accretion becomes prominent in the inner region of the disk. Based on our results, we discuss the implications for the origin of dichotomy between inner super-Earths and outer gas giants in exoplanetary systems.

References:

Ormel, C. W., & Klahr, H. H. 2010, A&A, 520, A43
Lambrechts, M., & Johansen, A. 2012, A&A, 544, A32
Lambrechts, M., & Johansen, A. 2014, A&A, 572, A107
Ormel, C. W., Shi, J.-M., & Kuiper, R. 2015, MNRAS, 447, 3512
Kuwahara, A., & Kurokawa, H. 2020, A&A, 633, A81
Kurokawa, H., & Tanigawa, T. 2018, MNRAS, 479, 635

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