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論 文 要 旨

THESIS SUMMARY

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要旨（英文 800 語程度）
Thesis Summary（approx.800 English Words ）

Planets form in protoplanetary disks. The outcome of planetary growth depends on the environment of disks. The current observed period-mass distribution of exoplanet suggests the dominance of low-mass planets. Recent high-spatial-resolution observations have revealed dust substructures in disks such as rings and gaps, which do not always correlate with gas. The interaction between the planet and the disk would be a key for interpreting the diversity of exoplanets and observations of protoplanetary disks. A growing planet embedded in a disk interacts with the surrounding disk gas and induces three-dimensional gas flow. Small dust grains are abundant in a disk, and they are sensitive to the gas flow. Planets accrete these small dust grains. Because gas flow induced by embedded planets could affect dust dynamics, it potentially affects the growth of planets and forms the observed dust substructures in disks.

In this thesis, we investigate dust dynamics influenced by the planet-induced gas flow and the potential of the planet-induced gas flow to sculpt the rings and gaps in the dust profiles. Assuming a nonisothermal, inviscid sub-Keplerian gas disk, we first perform three-dimensional hydrodynamical simulations, which resolve the local gas flow past a planet. We then numerically integrate the equation of motion for dust particles to calculate the trajectories of dust influenced by the planet-induced gas flow. We used the obtained hydrodynamical simulation data to calculate the gas drag force acting on the dust particle. Finally, we compute the steady-state dust surface density by incorporating the influences of the planet-induced gas flow into a one-dimensional dust advection-diffusion model.

We find that the gas flow induced by embedded planets affect dust dynamics around planetary orbits and the spatial distribution of dust changes significantly. Throughout this thesis, the key physics is the outflow of the gas. A substantial amount of gas from the disk enters the gravitational sphere of the planet (inflow) and exits (outflow). The outflow induced by the embedded planet occurs in the radial direction to the disk.

The outflow of the gas toward the outside of the planetary orbit inhibits the radial drift of dust, leading to dust accumulation (the dust ring). The outflow toward the inside of the planetary orbit enhances the inward drift of dust, causing dust depletion around the planetary orbit (the dust gap). Under weak turbulence ($\alpha_{\rm diff}\lesssim 10^{-4}$, where $\alpha_{\rm diff}$ is the turbulence strength parameter), the gas flow induced by the planet with $\gtrsim 1\ M_{\oplus}$ (Earth mass) generates the dust ring and gap in the distribution of small dust grains ($\lesssim 1$ cm) with a radial extent of $\sim$1—10 times the gas scale height around the planetary orbit without creating a gas gap and pressure bump.

We find that the response of the spatial distribution of dust to the planet-induced gas flow varies significantly depending on the location of the planet within the disk, resulting in the differences in the growth efficiency of planets. The dust gap formation by the planet-induced gas flow is susceptible to occur in the inner region of the disk ($\lesssim 1$ au), where the growth of the planet via the accretion of dust onto the planet is suppressed due to the dust gap. The dust ring formation by the planet-induced gas flow is susceptible to occur in the outer region of the disk ($\gtrsim 10$ au), where the efficient growth of the planets via dust accretion would be achieved.

Our results suggest that: (1) the gas flow induced by embedded planets can be considered a possible origin of the observed dust substructures in disks whose dust substructures were found not to correlate with those of the gas, and (2) the planet-induced gas flow could determine the architecture of planetary systems, which may be helpful in explaining the current observed period-mass distribution of exoplanets in which the low-mass planets are more frequent than giant planets at <1 au. The dust rings and gaps formed by the planet-induced gas flow might be probed by future observations using a next-generation Very Large Array (ngVLA) and a possible future extension to the Atacama Large Millimeter/submillimeter Array (ALMA). Our future work will include more quantitative discussions of both a comparison between our results and ptoroplanetary disk observations using synthetic images and the influence of the planet-induced gas flow on the planetary growth with additional physics such as dust growth and planet migration.