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Dependence of the planet mass on type I migration in a radiative disk

Kou Yamada[1*], Satoshi Inaba[2]

[1]Center for Planetary Science, [2]Waseda University

Gravitational interaction between a low-mass planet and a protoplanetary gas disk is one of the important physical processes in the formation of planetary systems. A planet embedded in a disk migrates toward a central star on a shorter timescale than a lifetime of a disk. This process is known as the type I migration. Gravitational interaction between a planet and a disk excites density waves in a disk. The tidal torque of the density waves acts on a planet and generally leads to the migration of the planet. Formed density waves are significantly affected by thermal structure of a disk. Most of previous studies assumed a disk with constant temperature and did not take into account the energy equation. Recent studies with the energy equation showed that a planet migrates even outward in a disk if the entropy of the gas decreases with an increase in the distance from a central star. A torque on the planet is greatly influenced by cooling effect of a disk (e.g., radiative energy transfer in a disk). We investigate how the radiative energy transfer affects migration of a planet in an optically thin disk with the use of global hydrodynamic simulations. We find that the planet migration is sensitive to the efficiency of the radiative transfer.

The isothermal equation of state adopted by previous studies assumes the constant temperature of a disk due to the efficient loss of excess energy generated by compression and shocks. However, the cooling ability of a disk is strongly dependent on the opacity of a disk. We performed two dimensional global hydrodynamic simulations of a disk with various opacities including the gravitational forces of a star and a planet. The basic equations are solved simultaneously using the finite volume method with an operator splitting procedure. The source terms are computed with a second order Runge-Kutta scheme, while the advection terms are obtained with a second order MUSCL-Hancock scheme and an exact Riemann solver.

We find that the total torque exerted by a disk increases with the planet mass and it is roughly proportional to the square of the planet mass. The total torque significantly decreases with an increase in the opacity of a disk. In an adiabatic disk with the negative power law distribution of the entropy, a planet migrates outward. A planet does not migrate inward or outward in a disk with opacity that we call the critical opacity. The critical opacity is weakly dependent on mass of a planet.

Keywords: type I migratoin, adiabatic disk, radiative, protoplanet, gravitational interaction, density wave