ON LOW-MASS PLANETARY MIGRATION IN AN OPTICALLY THICK DISK.

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Introduction: Planets form in a disk surrounding a young star. A low-mass protoplanet interacts with a gas disk gravitationally, which leads to a decrease in its semi-major axis. This is called the Type I migration of a protoplanet. The Type I migration is caused by the torques acting on a protoplanet by a disk. Recently, it was shown that a protoplanet is possibly trapped in a disk [1,2]. Hasegawa & Pudritz comprehensively examined various mechanisms to halt the protoplanet migration in a disk [3]. They showed that a planet might be trapped at the ice line, inside of which all the ice is evaporated and solid particles are composed of rocks and metals. The different opacity laws are used inside and outside of the ice line, resulting in a steep and shallow temperature distributions in the inner and outer regions, respectively. The large corotation torque acting on a protoplanet due to the steep temperature distribution suppresses the negative Lindblad torque in an inner region. On the other hand, the corotation torque on a protoplanet is too weak to cancel the negative Lindblad torque in an outer region. A protoplanet inside and outside of the ice line moves toward the ice line and is expected to accumulate at the ice line. However, it was found that the corotation torque is dependent on dissipation processes such as viscosity and/or radiation [4]. It is not clear if protoplanets accumulate at the ice line even when we include dissipation processes in a disk. We make global two-dimensional hydrodynamic simulations and systematically examine the total torque acting on a planet by an optically thick accretion disk, taking dissipation processes in a dsk into account.

Numerical method and setting: We use a cylindrical coordinate where the star is located at the center of the coordinate. The problem is limited to 2D flow. Governing equations for the gas are the mass conservation, the Navier-Stokes equations, and the energy equation with dissipative terms due to viscosity and radiation. These equations are solved simultaneously using the finite volume method with an operator splitting procedure. The source terms, which include the gravity, the viscous force, and the radiation, are computed with a second order Runge-Kutta scheme. The advection terms are calculated with a second order MUSCL-Hancock scheme and an exact Riemann solver [5,6].

The initial disk surface density distribution is given by the power-law distribution: $\Sigma = 100\tilde{r}^{-1}\,\mathrm{g/cm^2}$, where $\tilde{r}$ is the distance from the star normalized by a_0=1AU. The viscosity ν is expressed by a power-law function of the distance from the central star to satisfy the constant accretion rate of a disk as $\nu = \xi_\mathrm{v}\nu_0\tilde{r}$, where ν_0 is the kinematic viscosity at a_0 and we set $\nu_0 = 10^{-4}a_0^2\Omega_0$ and ξ_v is a viscous strength factor. The accretion rate of a disk with the kinematic viscosity, ν_0, is 6.3×10^{-8} solar mass/yr. Observations of disks suggest that the accretion rates of disks are approximately 1×10^{-8} solar mass/yr [7]. We treat ξ_v as a parameter to consider disks with various accretion rates of $0.1<\xi_\mathrm{v}<1$. Let us determine the temperature distribution of an optically thick accretion disk. The optical depth of a disk is defined as $\tau = 0.5\xi_\mathrm{gr}\kappa_0\Sigma$, where κ_0 is the best fit function of the opacity [8] and ξ_gr is the grain content factor. Micron size dust particles are the main source of the opacity. Collisions between particles might produce a large number of small dust particles, increasing the opacity of a disk. Conversely, the opacity might decrease due to capture of small dust particles by large particles. It is valuable to study the torque acting on a planet in a disk with various values of ξ_gr. We treat ξ_gr as another parameter of the simulations and consider the disks with $0.1<\xi_\mathrm{gr}<100$. We adopt the opacity distribution derived from the available opacity data [8], which incorporates small particles found in an interstellar medium. Dust particles are composed of rocks and metals in a region of disk with T>210K, while ice is added to form dust particles in a region of disk with T<170K. In the transition region between the cold and the hot region, the ice is evaporating. We divide a disk into three regions: the region 1 with T$\geq$210K, the region 2 with 170K<T <210K, and the region 3 with T$\leq$170K. The resulting density and temperature distributions are displayed in Fig.1. The larger viscosity and/or opacity increase the temperature of the disk. The boundary positions move outward with increases in the viscosity and/or opacity. The location of the boundary is expressed by the two parameters, ξ_gr and ξ_v, and the boundary position between the regions 1 and 2 is given by $\tilde{r}_{12} = 1.4\left(\xi_\mathrm{v}\xi_\mathrm{g}\right)^{1/4}$

Results: We perform a number of numerical simulations of gravitational interactions between the planet and the optically thick accretion disks. Figures 2 and 3 show the magnitude and sign of the total torques exerted on the planet with 5 Earth masses in the regions 1 and 3 of the disks with various values of two parameters. The planet is located at 1 AU when $\tilde{r}_{12}$=2.4, at 0.9AU when $\tilde{r}_{12}$= 1.4 and 1.2, and at 0.7AU when $\tilde{r}_{12}$=0.8, respectively, in Fig.2. The planet is located at 5AU when $\tilde{r}_{12}$=2.4, at 3AU when $\tilde{r}_{12}$=1.4, 1.2, and 0.8, respectively, in Fig.3. The open and filled marks denote the positive and negative total torques acting on the planet, respectively. We find the largest magnitude of the total torques, $|\tilde{\Gamma}_{\max}|$, from the simulations with the same boundary position of $\tilde{r}_{12}$. The total torques are plotted as circles, squares, and triangles when $|\tilde{\Gamma}| > 0.5|\tilde{\Gamma}_{\max}|$, $0.5|\tilde{\Gamma}_{\max}| > |\tilde{\Gamma}| > 0.1|\tilde{\Gamma}_{\max}|$, and $0.1|\tilde{\Gamma}_{\max}| > |\tilde{\Gamma}|$, respectively. The total torque becomes positive in both regions if the dissipation is small. We find that the total torque becomes zero when the timescale for the viscosity is about three times as long as the turnover time of the planet in the horseshoe orbit. In the optically thick accretion disk with ξ_{gr}=1, the accretion rate of the disk is required to be smaller than 2×10^{-8} solar mass/yr for the planet to move outward in both regions. On the other hand, in region 2, the total torque always becomes negative, leading to the inward migration of the planet. Our study suggests that planets with 5 Earth masses might accumulate and drive further growth of the planets at the boundary between the regions 1 and 2 in the optically thick accretion disk.

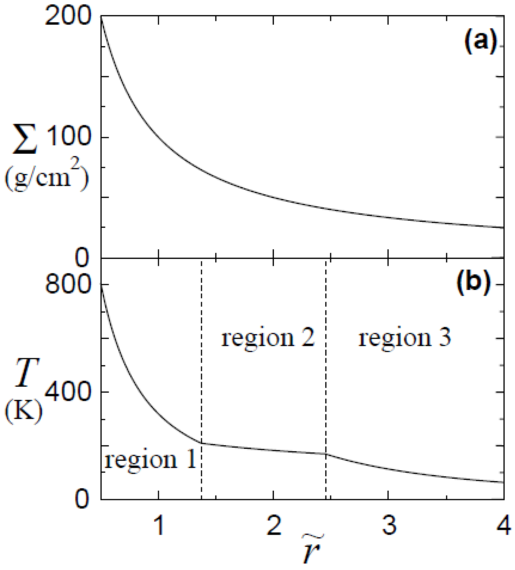

Figure 1: (a) the surface density distribution and (b) the temperature distribution of the disk. The temperature distribution of the disk is determined by the balance between the viscous heating and the radiative cooling. The temperature distribution is described by the power-law distributions with three different gradients. The power-law index of the temperature distribution strongly depends on the opacity of the disk, which varies due to the evaporation of ice. The power-law indexes of the temperature distribution change at 1.4 and 2.5 AU.

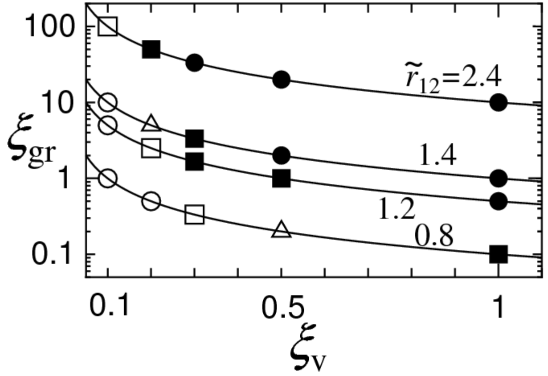

Figure 2: The diagram of the total torques exerted on the planet with 5 Earth masses by the disk with various parameter sets. The planet moves outward in the region 1 of the optically thick accretion disk with ξ_{gr}=1 when the accretion rate is smaller than 2×10^{-8} solar mass/yr.

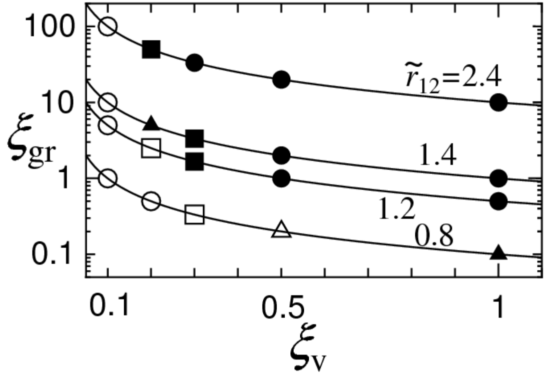

Figure 3: The diagram of the total torques exerted on the planet with 5 Earth masses by the disk with various parameter sets. The planet moves outward in the region 3 of the optically thick accretion disk with ξ_{gr}=1 when the accretion rate is smaller than 2×10^{-8} solar mass/yr. The boundary position between the regions 2 and 3 is given by $1.8\tilde{r}_{12}$.

References: [1] Masset et al. (2006), ApJ, 642, 478; [2] Morbidelli et al. (2008), A&A, 478, 929; [3] Hasegawa Y. & Pudritz R.E., (2011), MNRAS, 417, 1236; [4] Yamada K. & Inaba S., (2011), MNRAS, 411, 184; [5]Toro E.F., (1999), in Riemann solvers and numerical methods for fluid dynamics(Springer); [6] Inaba et al. (2005), A&A, 431, 365; [7] Hartmann et al. (1998), ApJ, 495, 385; [8] Lin D. N. C. & Papaloizou J., (1985), Protostars and planets II, 981