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Radial evolution of a gap-opening planet within a protoplanetary disk

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Abstract

A large planet such as Jupiter in a protoplanetary disk opens a density gap along its orbit due to the strong disk–planet interaction. It is expected that in the ideal case, a gap-opening planet migrates at the viscous drift speed (type II migration). However, recent hydrodynamic simulations have shown that in general, the gap-opening planet is not locked to the viscous disk evolution. A new physical model is required to explain the migration speed of the gap-opening planet. For this reason, we re-examined the migration of a planet in the disk, by carrying out the two-dimensional hydrodynamic simulations in a wide parameter range [1]. We have found that the torque exerted on the gap-opening planet depends on the surface density at the bottom of the gap. The planet migration slows down as the surface density of the bottom of the gap decreases. Using the gap model developed in our previous studies, we have constructed an empirical formula of the migration speed of the gap-opening planets, which is consistent with the results given by the hydrodynamic simulations.

1. Introduction

When the planet is sufficiently large, the planet forms a density gap along with its orbit due to the strong disk–planet interaction. If the gap is clean, the migration of the gap-opening planet is referred to as the type II migration, in which the planet is locked within the gap [2]. However, recent hydrodynamic simulations of the migration of the gap-opening planet [3, 4] have shown that gas can easily cross the gap and the planet is not locked to the viscous disk evolution. Moreover, these hydrodynamic simulations have demonstrated that the migration speed of the gap-opening planet can be faster than the speed of the viscous gas accretion, which cannot be explained by the 'classical' picture. In order to understand the migration of the gap-opening planet, a new physical model is required.

2. Methods

By using the two-dimensional hydrodynamic simulations, we explore the migration timescale of the planet by varying the mass of the planet ($5 \times 10^{-6} < M_{\rm p}/M_* < 1 \times 10^{-3}$), the disk aspect ratio ($0.03 < H_0 < 0.07$), and viscosity ($10^{-2} < \alpha < 10^{-3}$) (98 runs).

3. Results

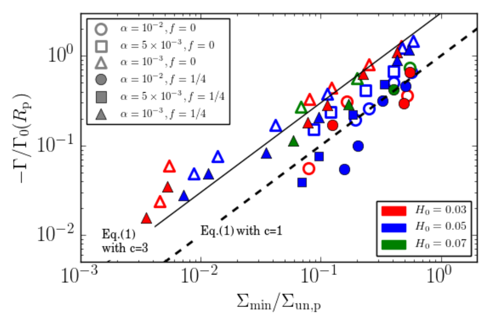

Figure 1: The torque as a function of the surface density at the bottom of the gap.

In Figure 1, we show the torque exerted on the planet when the gap is relatively deep. As can be seen in the figure, the torque is roughly proportional to the surface density at the bottom of the gap ($\Sigma_{\rm min}$) and might be expressed as follows,

$$\Gamma = -c \frac{\Sigma_{\rm min}}{\Sigma_{\rm un,p}} \Gamma_0(R_{\rm p}), \tag{1}$$

where c is a proportionality coefficient, $R_{\rm p}$ is the orbital radius of the planet, $\Sigma_{\rm un,p}$ is the unpertubed surface density at $R = R_{\rm p}$, and Γ_0 is the characteristic torque. In the type I regime, the torque exerted on the planet can be given by $\Gamma \sim -\Gamma_0$. This result indicates that the decrease in the torque exerted on the planet is simply because of the decrease of the surface density at the bottom of the gap.

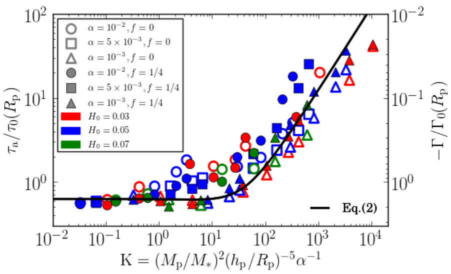

Figure 2: Migration timescales versus K.

By using the empirical relation of Equation (1), we may express the migration timescale of the gap-opening planet τ_a^{II} as

$$\tau_a^{II} = \left(\frac{\Sigma_{min}}{\Sigma_{un,p}}\right)^{-1} \tau_a^{I}, \tag{2}$$

where τ_a^{I} denotes the migration timescale of the type I migration. The relation between Σ_{min} and the planet mass, the disk aspect ratio, and the viscosity are investigated by the work of [5] as

$$\frac{\Sigma_{min}}{\Sigma_{un,p}} = \frac{1}{1 + 0.04K}, \tag{3}$$

where $K = (M_p/M_*)^2(h_p/R_p)^{-5}\alpha^{-1}$ and h_p the disk scale height at $R = R_p$. As can be seen in Figure 2, Equation (2) with Equation (3) can reasonably reproduce the migration timescales given by our numerical simulations.

4. Summary

We have investigated the migration of the planet in the protoplanetary disk by performing over hundred runs of two-dimensional hydrodynamic simulations. We found that the torque exerted on the gap-opening planet is proportional (with some scatter) to the surface density at the bottom of the gap. Considering the reduction of the torque due to the gap formation, we present the simple model of the planetary migration, which can reasonably well reproduce the migration speed given by the hydrodynamic simulations.

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