Radial migration of gap-opening planets in protoplanetary disks

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Introduction
A planet in a protoplanetary disk gravitationally interacts with a surrounding disk gas. When the planet is massive enough, it can create a density gap (disk gap) along its orbit.

It was expected that in the ideal case, a gap-opening planet migrates at the viscous drift speed (Type II migration). But, recent hydrodynamic simulations (e.g., Duffell et al. 2014, Durmann & Kley 2015, 2017) have shown that, in general, the gap-opening planet is NOT locked into the viscous disk evolution.

A new physical model is required to explain the migration speed of such a gap-opening planet.

Migration of a single planet

We performed over hundred runs of 2D hydrodynamic simulations and found that the torque exerted on the gap-opening planet is roughly proportional to the surface density at the bottom of gap.

This proportional relation indicates that the gap is not perfectly clean, and the torque felt by the planet is determined by the interaction with the gas within the gap.

Using our gap model (Kanagawa+15), we construct an empirical formula:

\[ K = \frac{M_p}{M_d} \frac{h_R}{R_p} \left( \frac{\Sigma_{\text{min}}}{\Sigma_{\text{top}}} \right)^{1/2} \frac{1}{\alpha} \]

The gap formation condition can be considered as \( K \sim 20 \), which corresponds:

\[ \left( \frac{M_p}{M_d} \right) = 8 \times 10^{-5} \left( \frac{h_R}{R_p} \right) \frac{1}{\alpha} \left( \frac{\Sigma_{\text{min}}}{\Sigma_{\text{top}}} \right)^{1/2} \]

Migration of a planet pair

When two planets (planet pair) migrate within the disk, they are likely to be captured into a mean-motion resonance, if the outer planet can catch up with the inner one.

Using our empirical formula for the migration timescale for a gap-opening planet, we can make a map of a ratio of the migration timescale of the outer planet to that of the inner one (left panel).

Even in the divergent case, the planet pair can be captured into the resonance at the early phase of the evolution. But, as the gap opens, the outer planet slows down and eventually the evolution of the pair becomes divergent.

Such a divergent evolution can be reproduced by three-body simulations with our empirical formula, as well as by hydrodynamic simulations.

Example of the divergent evolutions.

Although a detail of the evolution is bit different, the evolution of the pair becomes divergent in both the hydrodynamic simulation and three-body simulation.

Varying the masses of the planets, we performed three-body simulations and calculated the period ratios after the migration timescale of the inner planet (left below). Due to the divergent evolutions, the period ratios of the planet pair can take various values from that near the resonance and that is far from the resonance.

This wide distribution may explain the distribution of the period ratio observed by the Kepler mission.

Summary

1. We found that the torque exerted on the planet is proportional to the surface density at the bottom of the gap, which indicate that the migration of the gap-opening planet slows down simply because the gap is formed.
2. Using our gap model, we construct the empirical formula for the migration timescale of the gap-opening planet.
3. Our 3-body simulations incorporating our formula can reproduce the divergent evolution in the same parameter as in the hydro-simulations.
4. The contribution of the divergent evolution may explain the broad distribution of the period ratio given by the observations.