国立天文台天文シミュレーションプロジェクト

成果報告書

研究課題名 利用者氏名 (所属機関)

利用カテゴリ XC-MD

以下に成果の概要を記入してください。ページ数に上限はありませんが、最終的に提出される PDF のファイルサイズの上限は 2 MB です。

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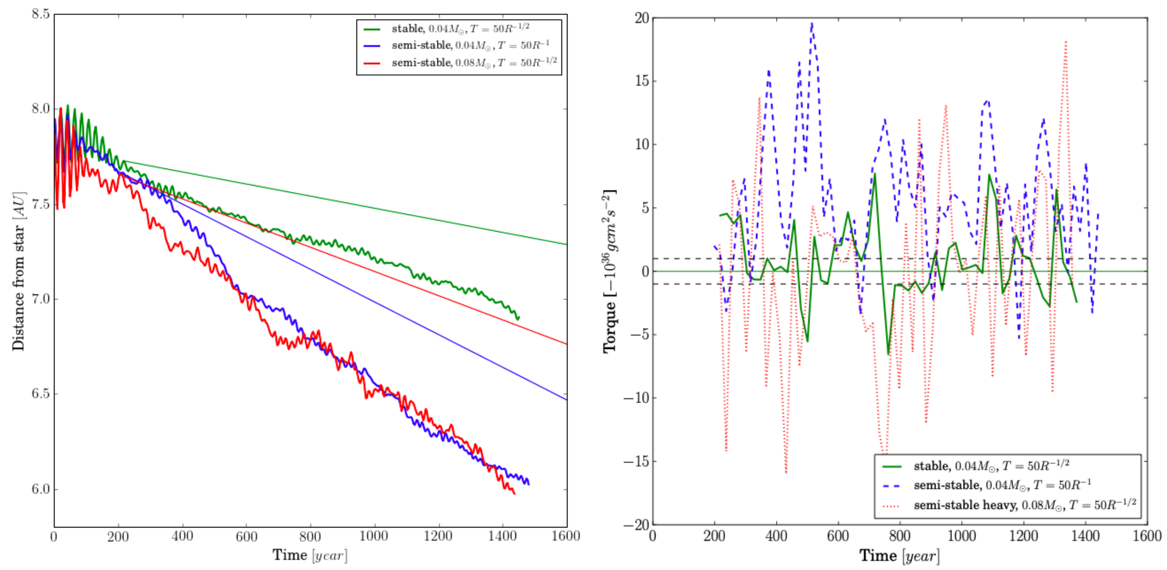
Our Solar System is a crucial planet nursery for scientists to study the formation and evolution of planets, from which two main theories have been proposed to explain these popular phenomena in galaxies. Core accretion process including a series of collisions results in terrestrial planets close to the Sun and lack of thick atmosphere. On the other hands, gas and ice planets are expected to form far from their host stars as a consequence of quick formation of solid core beyond the frostline thanks to water ice. However, observational results of exoplanets, especially hot Jupiters - a Jupiter sized exoplanet, is much closer to its host star than our Jupiter does, suggested something was seriously amiss with the theory. These empirical evidences arouse a possibility of migration.

Planets are natural by-products of the star formation process, form around the protostar when the disk is still largely gaseous. Gravitational instability is thus likely to occur early when protoplanetary disks are still massive and at large radii (typically a few percent or more of the stellar masses). The disk may settle into a quasi-steady, saturated state of self-gravitating turbulence in which trailing spiral arms yield an outward transport of angular momentum via gravitational torques. Or, it may fragment and break up into distinct bound objects. On the other hands, previous research has considered clumps in unstable disks as a way of forming giant planets. But we do not know if these disk instabilities affect smaller planets undergoing type I migration (or may halt this quite fast process) since other simulations assumed a fairly light disk (e.g. 0.005 solar mass in Ayliffe et al. 2010) where no structure was shown.

To investigate this issue, we have utilized ChaNGa, a SPH code with 1e6 particles to simulate different degrees of stability of protoplanetary disks by changing disk mass and temperature. Then, we grew a planet seed to 0.01 Jupiter mass in about ten orbits at 5.2 AU, and let it interact with the gas disk and migrate.

We set up 3 disks which have relatively massive masses (0.04 and 0.08 solar mass) and temperature profiles ($T \sim 50R^{-1}$ and $T \sim 50R^{-1/2}$), corresponding to different stability with spiral structures. The simulations present the low-mass planet (~33 Earth mass) in these semi-stable disks moves toward the star along a fluctuation trajectory and faster than analytical prediction (blue and red lines in Figure 1 left). On the other hands, total torque on planet varies strongly and much larger than Tanaka+ (2002) calculation (right plot of Figure 1). This result was presented in the conference in Okinawa.



Firgure 1. Type 1 planet migration in unstable disk. Left: planet movement with straight lines are predicted migration timescale for linear estimation. Right: Torque on planets, in matching colors with the left plot.

To understand this variation of the torque, we have added an option of gravitational potential of fixed star and planet in the code and implemented a range of runs with stable disks to reproduce results from previous work. These tests perform the torque on 10, 20 and 33 Earth-mass planets in a 0.005 solar-mass stable disk close to analytical calculation when excluding vicinity of the planet (Figure 2). These results confirm the torque of the light stable disk on the planet and propose any addition of disk structure could result in the change of migration rate.

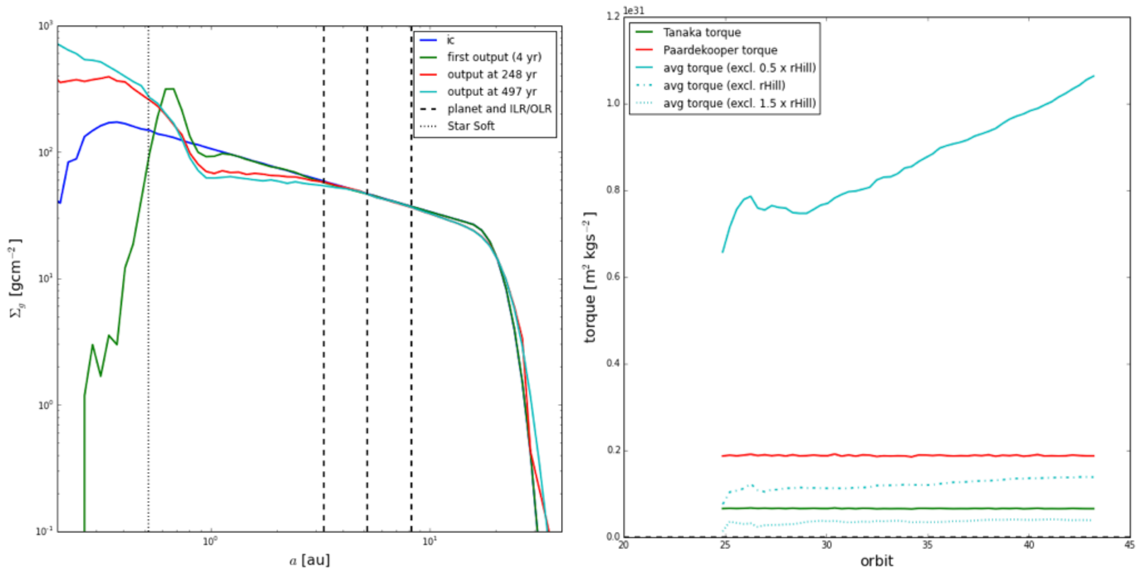


Figure 2. Simulation of fixed star and planet in a MMSN-mass disk. Left: disk density profile evolution. Vertical dashed lines are planet position (middle) and Lindblad resonances. Vertical dotted line is the inner boundary of the disk. Right: Torque on 33 Earth mass planet, excluding regions within 0.5, 1 and 1.5 Hill radius around planet (blue straight, dashed, dotted lines, respectively), compared to analytical calculation from Tanaka+ 2002 (red line) and Paardekooper+ 2010 (green line).

In attempt to fit the analytical torque result, we rerun the moving planet (33 Earth mass) simulation in stable light disk (0.005 solar-mass) (Figure 3). While the torque of light stable gas disk on planet is quite close to analytical estimation from Tanaka+ 2002, planet migrates faster than expectation but the interaction of stable gas disk and planet is negligible and unchanged. We need to test the planet in massive structured disks.

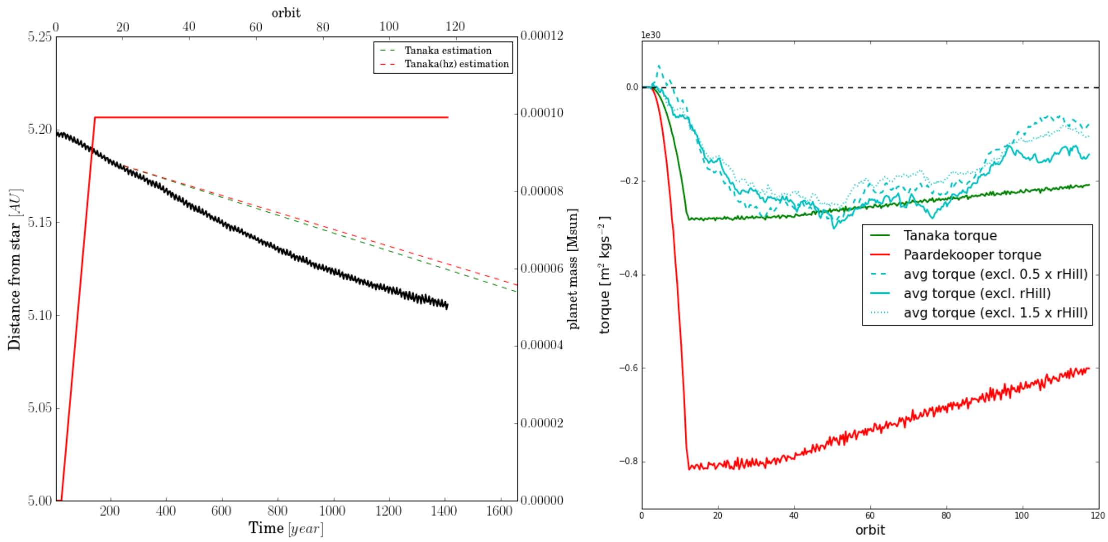


Figure 3. Planet migration in a stable 0.005 solar-mass disk. Left: planet movement (black line) and estimated analytical calculation (dashed lines) and planet mass growth (red line). Right: Torque on planet, excluding regions within 0.5, 1 and 1.5 Hill radius around planet (blue straight, dashed, dotted lines, respectively), compared to analytical calculation from Tanaka+ 2002 (red line) and Paardekooper+ 2010 (green line).