Semester report 2

András Németh (nearaat@gmail.com)

PhD Program: Astronomy and Space Physics

Supervisors: Zsolt Regály and Zsolt Mózes Sándor

Title of the thesis: Orbital perturbations resulting from planet-disk interactions

2024.06.19

Introduction

The aim of my PhD research is to investigate planet formation through numerical hydrodynamical simulations. Specifically, the focus of this research is on modelling the interaction between a protoplanetary disk and a low-mass planet (1-10 Earth masses) in a two-dimensional approximation. This interaction causes a perturbation in the disk, resulting in a gravitational effect that alters the planet's semi-major axis, leading to migration. Previous studies have neglected orbital perturbations caused by the solid component in the protoplanetary disk. However, recent studies by my supervisor (Regály, 2020) show that dust in the protoplanetary disk can stop or even reverse planetary migration. My goal is to investigate the multifaceted effects of the solid component of the protoplanetary disk. Specifically, I plan to examine: 1) the impact of fully accounting dust-gas interaction on planetary migration; 2) the process of accretion heating by larger dust particles (pebbles) and its effect on the protoplanetary disk; 3) the influence of accretion heating on planetary migration; and 4) the effect of these phenomena on planetary growth. To achieve this, numerical simulations will be performed using the GFARGO2 code, which is a modern version of the FARGO code (Masset, 2000) developed by my supervisor. The GFARGO2 code utilizes a GPU accelerator, enabling a large number of simulations to be performed with high numerical resolution. The numerical simulations are run on the supercomputers of the 3D Numerical Astrophysics Laboratory (3DNAL) at the HUN-REN Research Centre for Astronomy and Earth Sciences Konkoly Thege Miklós Astronomical Institute.

Description of research work carried out in current semester

Effect of solid back-reaction on the total net torque

Recently, it has been shown that although the total solid mass is negligible compared to that of gas in protoplanetary disks, a positive torque can be emerged by a certain size solid species. The torque magnitude can overcome that of gas which may result in outward planetary migration. In this semester, I continued to analyse how the torque on a planet changes when the hydrodynamic equations include the back-reaction of the solid component to the gas in addition to the drag force of the gas.

I analysed the change in the spatial distribution of gas and solids due to back-reaction around an Earth mass planet. As an example, Fig. 1 shows the comparison in the distribution of gaseous material around an Earth-mass planet due to the interaction with 3 different solid species in non-back-reaction (NBR) and back-reaction (BR) cases.

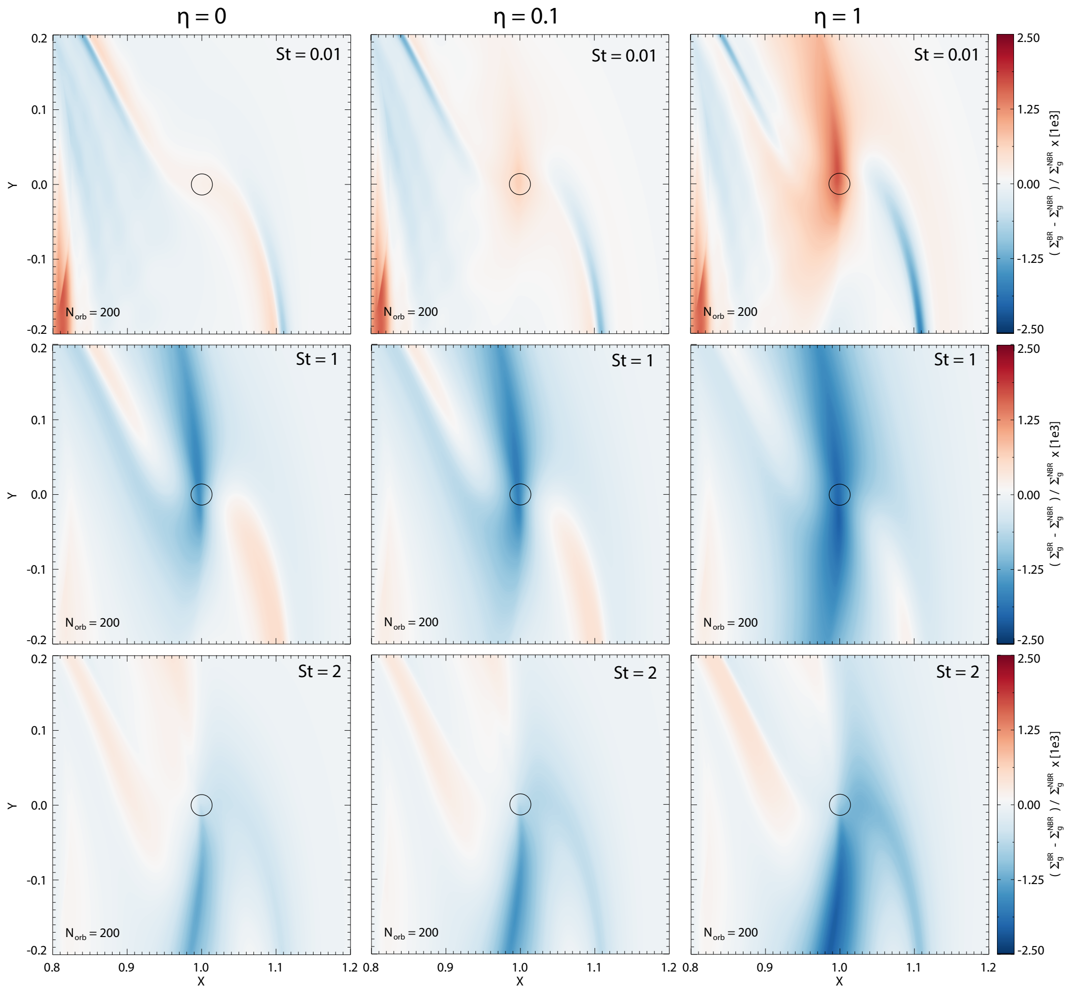

Figure 1: Comparison of gas density distribution for $\mathrm{St} = 0.01,\ 1$ and 2, with three different accretion efficiencies ($\eta = 0,\ 0.1$ and 1), in the vicinity of 1 $M_\oplus$ planet in NBR and BR models. The comparison is calculated as $(\Sigma_g^{BR} - \Sigma_g^{NBR})/\Sigma_g^{NBR}$. The colors ranging from dark blue to dark red represent increasing gas densities in BR models. Regions where the two models are the same appear in white.

For $\mathrm{St} = 0.01$, with increasing accretion efficiency, the amount of gas in the co-rotation region in front of the planet increases up to 0.2% when $\eta = 1$. Meanwhile, the amount of gas in the spiral arms decreases by a similar magnitude, resulting in a reduced negative torque ($\eta = 0$ and 0.1) and in a positive torque ($\eta = 1$) due to accretion compared to the NBR scenario. The back-reaction of species with $\mathrm{St} = 1$ causes the spiral arms in the gas to become less prominent as the accretion efficiency increases, and the amount of gas in the co-rotation region before the planet decreases by 0.2% compared to the NBR case when $\eta = 0$ and 0.1. As a result, the planet experiences a strengthened negative torque from the gas. The co-rotation region behind the planet also depletes in gas when $\eta = 1$, which leads to a reduced negative torque in the BR case. For $\mathrm{St} = 2$, the region behind the planet get depleted in gas due to back-reaction and accretion by up to 0.25% when $\eta = 1$. This leads to a positive gas torque felt by the planet in the BR case regardless of accretion efficiency.

It should be noted that the values on the figures and the color panels were multiplied by 10^3 for clarity. The simulations show that the back-reaction of solid material to the gas alters the distribution of both the gas and solid material around the planet, resulting in the torques observed in our models. These alterations, however slight, can have a profound impact on the forces affecting the planets and thus on their migration.

Effect of solid back-reaction on planetary migration

Following the aforementioned studies, I conducted an analysis of models in which the planet's semi-major axis was not fixed at a constant value. The parameters used are the same as those used previously, but due to lack of capacity, I only considered models with density profile, $\mathrm{p} = 0.5$. In these simulations, in addition to allowing migration, I employed an adaptive mesh grid (AMR) developed by my supervisor. In order to obtain a more precise representation of the change in the semi-major axes of the planets, the orbital period of the migration models was set to 1,000 years. Subsequently, the quasi-stationary and outward migration models were examined on a 10,000 year time scale. Figure 2 shows the migration of an Earth mass planets when interaction with different species of solids and subject to different accretion efficiencies. These simulations allowed for a comparison between the migration patterns predicted by the torque studies and the actual migration observed.

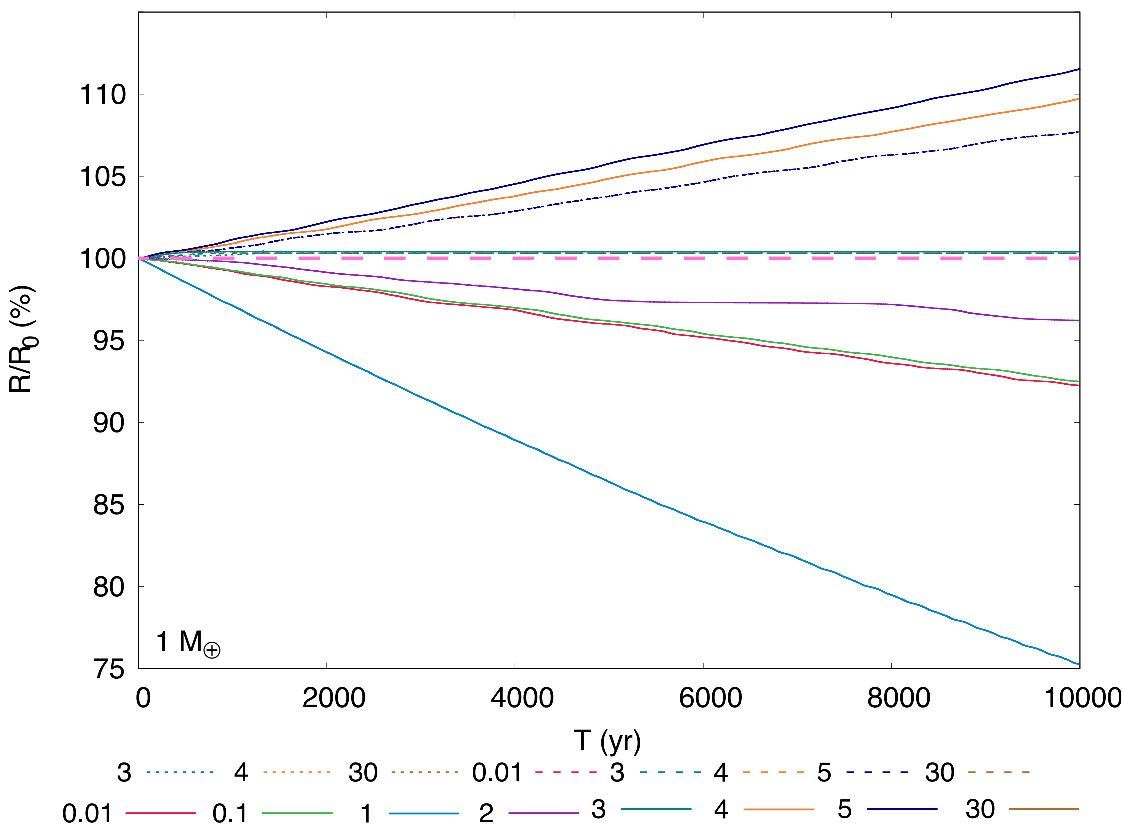

Figure 2: The migration of Earth-mass planets, due to the interaction with species having different Stokes numbers, over 10,000 orbital periods. The horizontal axis represents the time in years, while the vertical axis depicts the change in the orbital distance of the planet over time, expressed in percentages. The densely dashed line shows models with $\eta = 0$, the less dashed line shows models with $\eta = 0.1$ and the solid line shows models with $\eta = 1$.

Eccentricity of Warm Jupiters

In december, together with my supervisor Zsolt Mózes Sándor and MSc. student Viktória Fröhlich, we submitted a proposal for a bilateral Hungarian-French science and technology cooperation. Our goal is to examine the evolution of orbital properties of Warm Jupiters, which are gas giants with orbital periods of more than 30 days and masses between that of Saturn and Jupiter. Specifically, we will map their eccentricity distribution using hydrodynamical simulations. The proposal was accepted, and we are eager to begin collaborating with the French team in the upcoming semester.

Publications

In this semester I contributed to the following papers:

Regály, Z., Németh, A., Krupánszky, G., Sándor, Z.: Effect of solid back-reaction on torques felt by low-mass planets *(In preparation)*

Németh, A., Regály, Z., Krupánszky, G.: Migration of low-mass planets due to solid back-reaction *(In preparation)*

We plan to publish our results in the Astronomy & Astrophysics journal in the following months.

Studies in current semester

In this semester I completed the following courses:

FIZ/5/032 The physics of interstellar matter II.
FIZ/5/045 Formation of planets and planetary systems
FIZ/5/048 At the edge of the Solar System 2.

References

F. Masset. Fargo: A fast eulerian transport algorithm for differentially rotating disks. *Astronomy and Astrophysics Supplement, v.141, p.165-173*, 2000.

Z. Regály. Torques felt by solid accreting planets. *MNRAS, 497, 5540*, 2020.