Semester report 1

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PhD Program: Astronomy and Space Physics

Supervisors: Zsolt Regály and Zsolt Mózes Sándor

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

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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 analysed 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. This module is already implemented in the GFARGO2 code.

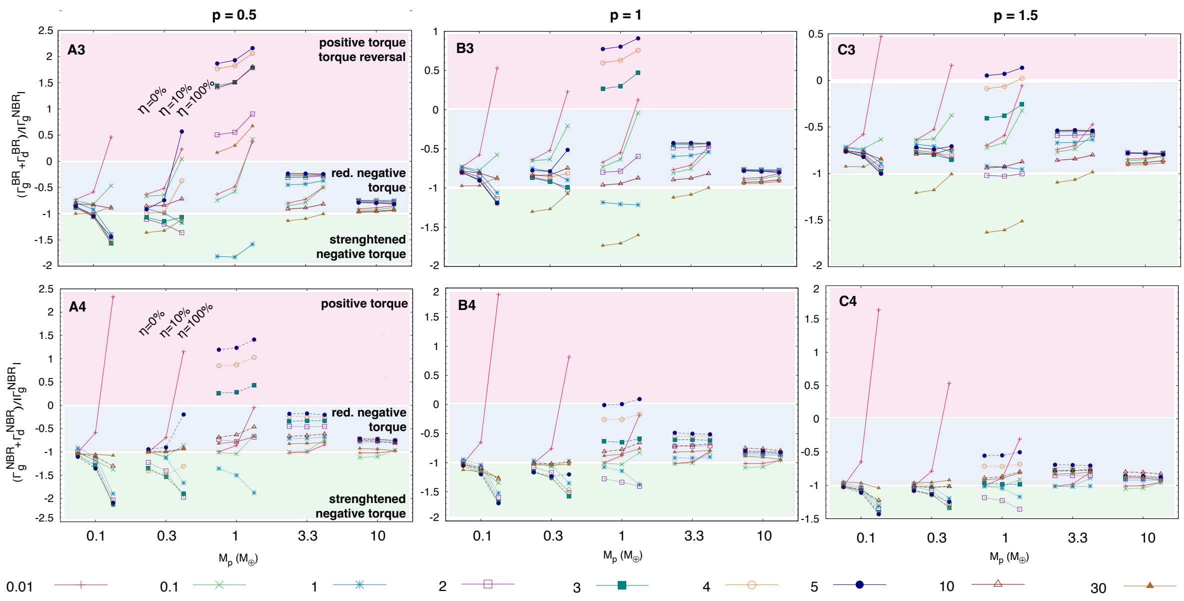

Figure 1: Top: Models where the back-reaction of solids is taken into account. Bottom: Models from Regaly (2020) where the back-reaction was neglected. Panels A, B and C show three set of models assuming p = 0.5, 1.0 and 1.5, respectively. For each planet mass three accretion strength are investigated: $\eta =\ 0,\ 0.1$ and 1. Green, blue and red shaded regions correspond to strengthened negative, reduced negative, and positive torques, respectively.

Our models use an arithmetic grid with the numerical resolution $N_R\ X\ N_\phi$= $1536\ X\ 3072$. In all models, the planet moves on a fixed circular orbit around its host star, thus migration is not allowed. We handled solid material with fix Stokes number throughout the simulation and modelled multiple solid species in nine bins: $\mathrm{St} =\ 0.01,\ 0.1,\ 1,\ 2,\ 3,\ 4,\ 5$ and 30. Five different planet mass ($0.1,\ 0.3,\ 1,\ 3$ and 10 $M_\oplus$) are investigated with three different strength of accretion, $\eta =\ 0,\ 0.1$ and 1 (during an orbit the planet accretes 0%, 10% and 100% of the solid content inside its Hill sphere, respectively). Fig. 1 shows the net torques (A3, B3, C3) measured at the end of simulations, after 200 orbits of the planet. For comparison, the bottom row (A4, B4, C4) shows the net torques (without solid back-reaction) from Regaly (2020). The figure shows that models accounting for solid back-reaction are shifted more towards the positive net torque and reduced negative torque regions. This effect is most noticeable for planets with masses $M_\mathrm{p} =\ 0.3$ and 1 $M_\oplus$. This indicates that the planet can also experience a positive net torque due to the back-reaction of solids. We also found that due to back-reaction of certain species positive gas torque can arise, which was not seen before in locally isothermal disk models. This means that the gas can slow down the planet's migration into the central star and may even cause the planet to migrate outwards.

I also analysed the spatial distribution of gas and solids around an Earth mass planet. Fig. 2 shows the distribution of solid material around a planet in non-back-reaction (NBR) and back-reaction (BR) cases. At first glance, the NBR and BR cases do not show notable changes in the distribution of solid material around the planet. However the ratio of the distributions reveal that the back-reaction changes the distribution considerably. A similar result has been found for the gaseous component of the disk (Fig. 3). 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.

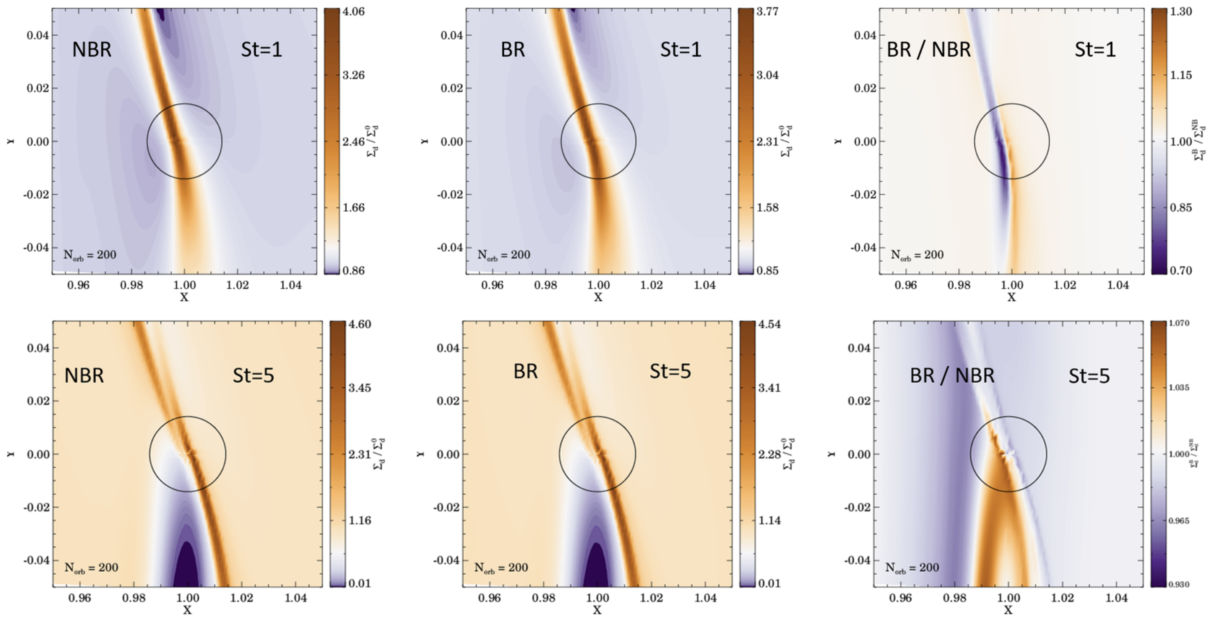

Figure 2: Comparison of the solid density distribution of species having $\mathrm{St} = 1$ and 5 in the vicinity of 1 $M_{\oplus}$ planet in NBR and BR models. The third column shows the ratio of the densities of the two models. The black circle indicates the planetary Hill sphere.

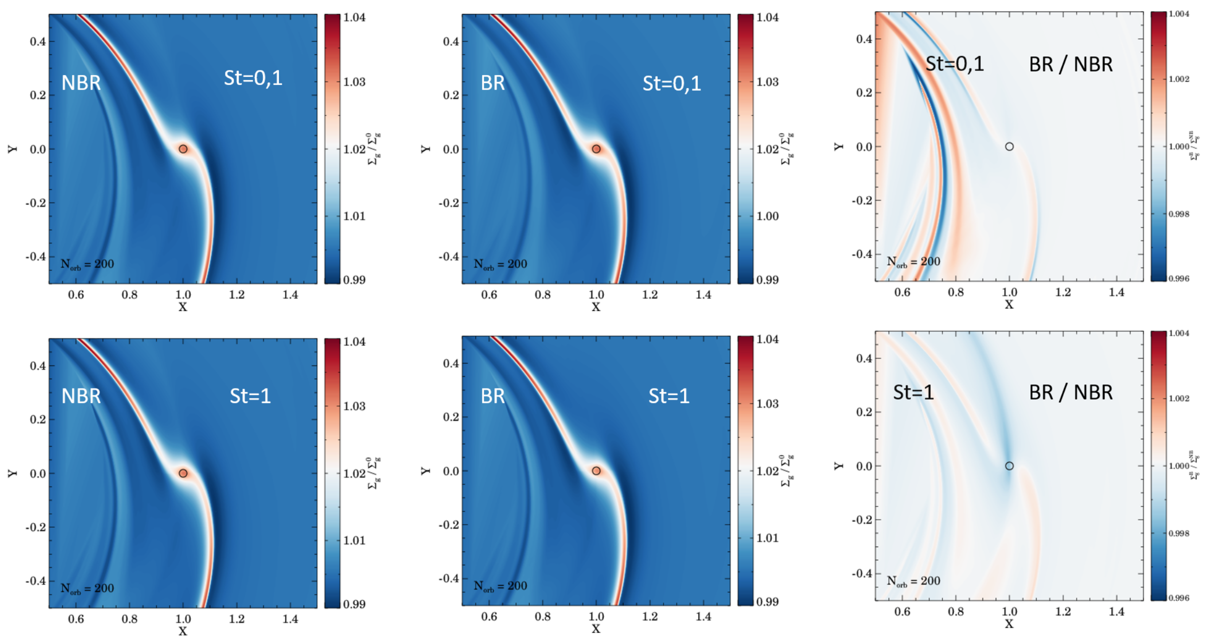

Figure 3: Gas surface density in the vicinity of 1 $M_{\oplus}$ planet in NBR and BR models assuming $\mathrm{p} = 0.5$. The third column shows the ratio of the densities of the two models. The black circle indicates the planetary Hill sphere.

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. Our proposal was submitted and is currently under evaluation. I already started selecting the target exoplanetary systems suitable for the simulations.

Publications

In this semester I contributed to the following paper:

Regály, Zs., Krupánszky, G. and Németh, A.: Effect of solid back-reaction on torques felt by low-mass planets *(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/5/031 The physics of interstellar matter I.
FIZ/5/043 (Exo)planetary atmospheres seminar I.
FIZ/5/047 At the edge of the Solar System 1.

References

Masset, F. S. (2000). FARGO: A Fast Eulerian Transport Algorithm for Differentially Rotating Disks. In Garzón, G., Eiroa, C., de Winter, D., and Mahoney, T. J., editors, *Disks, Planetesimals, and Planets*, volume 219 of *Astronomical Society of the Pacific Conference Series*, page 75.

Regály, Z. (2020). Torques felt by solid accreting planets. , 497(4):5540–5549.