Semester report 3

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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 planetary migration

This semester I continued the analysis of models in which the semi-major axis of the planet was not fixed at a constant value. To get a more accurate representation of the change in the semi-major axis of the planets, the orbital period of the migration models was set to 1,000 years. Figure 1. shows the migration of planets with different masses, interacting with different types of solids, and subject to different accretion efficiencies. These simulations allowed a comparison between the migration patterns predicted by the torque studies and the actual observed migration. It can be seen that the change in the semi-major axis of the planets increases with increasing planetary mass. For Earth-mass planets, several cases of both inward and outward migration can be identified.

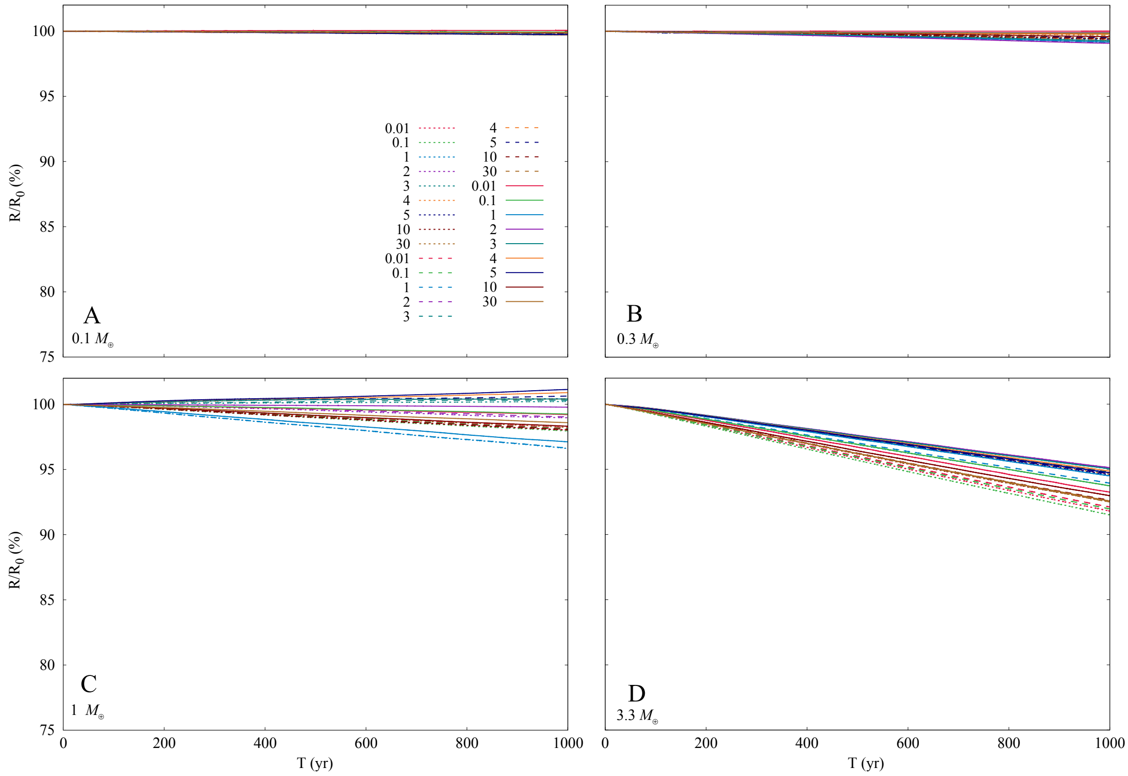

Figure 1: The migration of low-mass planets, due to the interaction with species having different Stokes numbers, over 1,000 orbital periods. The horizontal axis represents the time in years, while the vertical axis depicts the change in the orbital distance of the planet over time, expressed in percentages. 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 $\eta = 1$.

Effect of back-reaction in dusty disks

Based on the results of our previous study, it was reasonable to assume that the effect of the back-reaction of solid material on gas would be enhanced in disks containing higher amount of solid material. To test this theory, 2D global hydrondynamic simulations were performed using the code GFARGO2. To account for the higher solid content, disks with metallicities of $Z = 0.03$ and 0.1 were simulated and the results compared to the torques measured in the $Z = 0.01$ disk. Figure 2. shows the measured and predicted total torques in disks with different amounts of solid matter. The torque predictions for $Z = 0.03$ and 0.1 disks were calculated by multiplying the effect of the back-reaction on the solid and gas torque in $Z = 0.01$ disks by the difference in metallicity (three and ten times, respectively) compared to the canonical value. It can be seen that there are qualitative differences in the predicted and measured torques for species with $\mathrm{St} = 1$ and 2, regardless of accretion efficiency. For the $Z = 0.1$ disk, there is also a qualitative difference for the smallest Stokes number ($\mathrm{St} = 0.01$) when the planet is efficiently accreting this species. The solid torque does not change qualitatively compared to the prediction, but the gas torque varies significantly. These changes also vary with the value of the steepness of the initial gas profile, p. For the other species, small quantitative changes can be seen.

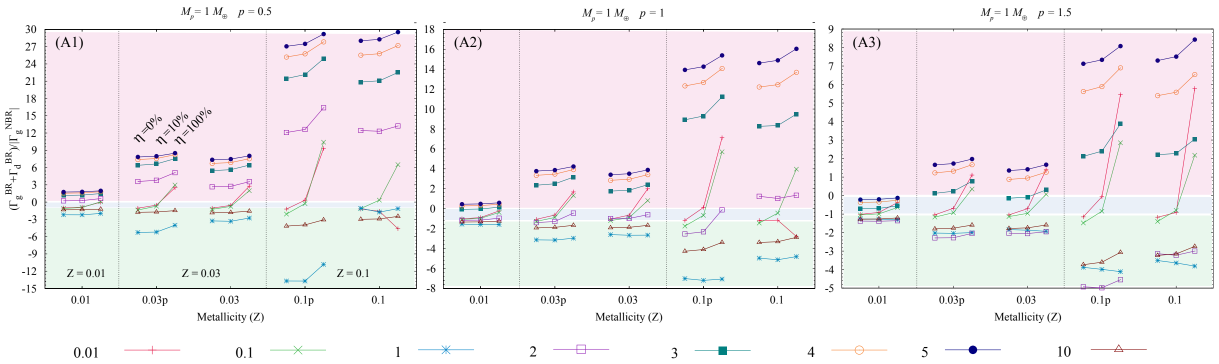

Figure 2: Parameter study of the measured and predicted saturated total torques felt by an Earth-mass planet (1 $M_{\oplus}$) in disks with metallicities of $Z = 0.01, 0.03$, and 0.1. The predicted torques are denoted by the letter "p". For each planet mass three accretion efficiencies are examined: $\eta = 0,\ 0.1$, and 1. The colors indicate the different Stokes numbers ($\mathrm{St} = 0.01,\ 0.1,\ 1,\ 2,\ 3,\ 4,\ 5$, and 10) used for the solid species in the parameter study.

Figure 3. displays the difference in the distribution of gaseous material for species with $\mathrm{St} = 0.01$ around an Earth-mass planet in disks with $Z = 0.03$ and 0.1, compared to the canonical disk. For the $Z = 0.1$ disk (lower panels), the distribution of gaseous material remains symmetric to the Y = 0 axis when $\eta = 0$ and 0.1. As a result of the gas torque does not change qualitatively due to the higher metallicity of the disk. However, for $\eta = 1$, the amount of gas behind the planet increases, while the amount of gas in front of the planet decreases. As a result, the planet experiences an enhanced negative gas torque instead of the weakened one measured in the canonical disk due to the effect of the solid back-reaction. Interestingly, for the $Z = 0.03$ disk we do not see this trend, and the effect of back-reaction increases with accretion efficiency.

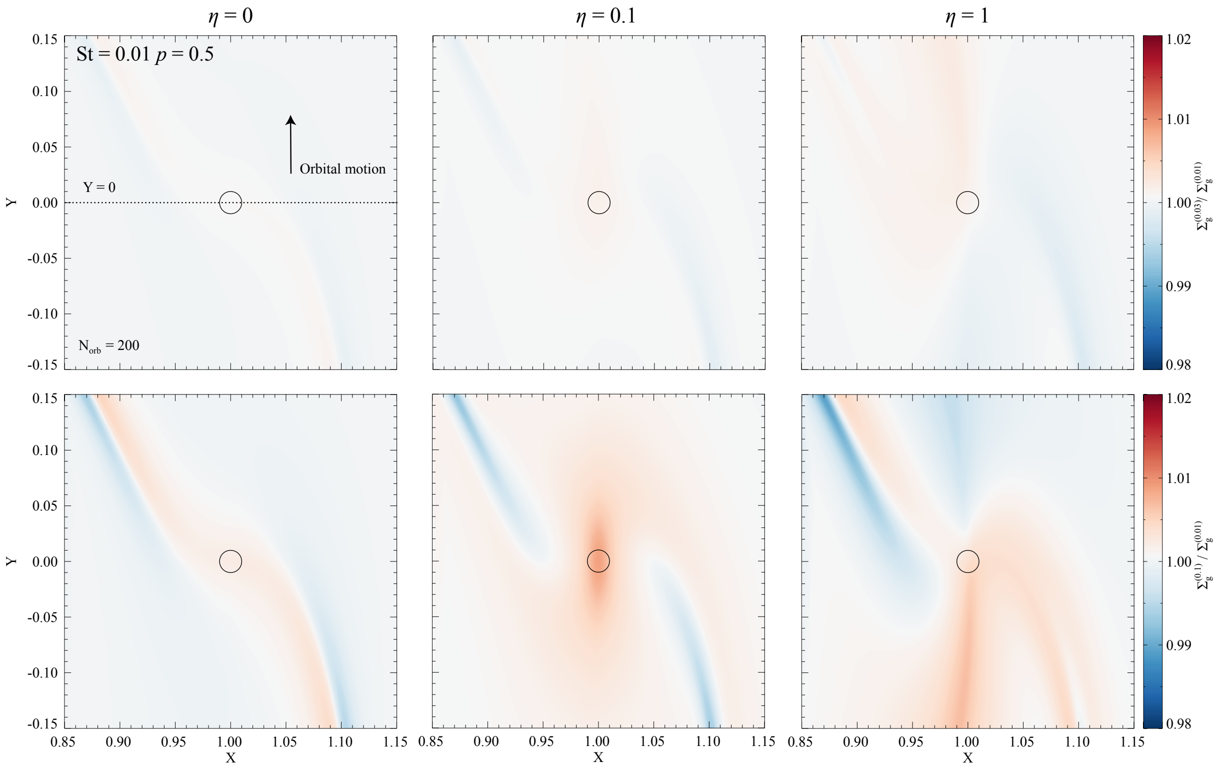

Figure 3: Difference in gas distribution around an Earth-mass planet for disks of different metallicities relative to the canonical metallicity, assuming $\mathrm{St} = 0.01$ and $p = 0.5$.

Publications

In this semester I contributed to the following papers:

Regály, Z., Németh, A., Krupánszky, G., and Sándor, Z.: Dusty disks as a safe heaven for terrestrial planets: Effect of the back-reaction of solid material on gas *(Accepted in A&A)*

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

Regály, Z., Németh, A.: Effect of the back-reaction of solid material on the torques felt by low-mass planets in high metallicity disks *(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/5/053 Fejezetek a modern égi mechanikábó
FIZ/5/017 Fejezetek a modern csillagászatból és kozmológiából

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.