Semester report 4

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PhD Program: Astronomy and Space Physics

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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 the previous three semesters

Over the past three semesters, my research has focused on investigating how the back-reaction of solid material in protoplanetary disks affects the net torque exerted on embedded low-mass planets.

In the first two semester, I explored how solid back-reaction modifies the torque on a non-migrating planet across various solid sizes (St = 0.01–10), planet masses (0.1–10 $M_\oplus$), and solid accretion efficiencies (η = 0–1). The simulations showed that the inclusion of solid back-reaction shifts the net torque toward more positive values, especially for Earth-mass planets. I examined how the back-reaction affects the spatial distribution of gas and the resulting torque contributions in more detail. Depending on the Stokes number and accretion efficiency, the co-rotation region and spiral arm structures of the gas respond differently to the effect of back-reaction. These changes in distribution explain the net torque differences observed in the simulations, including significantly reduced negative gas torques. Our results were published in the Astronomy and Astrophysics journal in February (Regály et al., 2025).

Next, I conducted and analysed simulations 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, p = 0.5.

More recently, I tested how increasing the disk metallicity (Z = 0.03 and 0.1) modifies the effects of back-reaction. Simulations revealed that the scaling of torques with metallicity is not always linear.

Description of research work carried out in the current semester

In February, I attended the Spring School "Birth of Solar Planets" in Bertinoro, Italy. During the 10-day training course, I gained a detailed insight into the structure and observation of protoplanetary disks, which will significantly contribute to the progress of my research. During the school, I presented the results of my research on the impact of protoplanetary dust on the gas dynamics and its consequences on the migration of low-mass planets.

Effect of solid back-reaction on planetary migration

η \ St	0.01	0.1	1	2	3	4	5	10	
0	0.146	0.154	0.147	0.165	0.170	0.169	0.170	0.144	$0.1\,M_\oplus$
0.1	0.079	0.146	0.169	0.189	0.197	0.200	0.200	0.144	
1	0.055	0.065	0.261	0.291	0.300	0.291	0.271	0.129	
0	0.524	0.541	0.680	0.833	0.819	0.738	0.609	0.587	$0.3\,M_\oplus$
0.1	0.444	0.511	0.720	0.865	0.830	0.683	0.471	0.558	
1	0.007	0.176	0.825	0.925	0.731	0.234	0.112	0.414	
0	1.957	2.051	3.387	1.035	0.217	0.382	0.432	1.982	$1\,M_\oplus$
0.1	1.785	1.858	3.363	0.960	0.318	0.413	0.632	1.918	
1	0.789	0.743	2.882	0.219	0.410	0.895	1.138	1.682	
0	8.202	8.493	6.266	5.382	5.301	5.381	5.415	7.485	$3.3\,M_\oplus$
0.1	7.885	8.038	6.061	5.232	5.201	5.283	5.347	7.372	
1	6.748	6.267	5.502	4.868	4.962	5.133	5.261	7.022	
0	22.036	25.222	18.991	18.609	18.517	18.255	17.936	20.958	$10\,M_\oplus$
0.1	21.359	24.389	18.656	18.242	18.309	18.229	17.968	20.868	
1	20.512	23.122	18.069	17.807	18.194	18.265	18.110	20.619	

Figure 1: Comparison of the expected migration from net torques and the actual change in semi-major axis from simulations.

This semester, I continued analysing simulations in which the semi-major axis of the planet was permitted to evolve. This enabled me to investigate the actual direction of migration. The results were compared with predictions based on the net torques obtained from simulations with fixed planetary orbits. Figure 1. shows a comparison of the expected and actual direction of the migration from simulations, for various planetary masses, Stokes numbers and accretion efficiencies. The sign in the bottom left and top left corners of the cells represents the sign of calculated net torque and the change in the planet's semi-major axis, respectively. The values in the cells indicate the absolute value of the change in semi-major axis over 1000 years, in percentages. The models exhibiting the same migration direction are indicated by color blue (for inward) and red (for outward migration). In a mere five instances (indicated by the green cells), the predicted direction of the migration exhibited a discrepancy with the actual change in the semi-major axis. Although in these cases the change in the semi-major axis was below 1 percent. In a single instance (illustrated by the yellow cell), the net torque exerted on the planet was found to predict inward migration, while the planet exhibited outward migration. Nevertheless, the discrepancy in semi-major axis and the net torque value in this instance was so negligible that it could be considered inconsequential. Our results show that the back-reaction of solids on gas dynamics has a significant influence on the migration of low-mass planets. Specifically, we find that Earth-mass planets undergo outward migration when interacting with solid species having Stokes numbers St = 3-5. In contrast, interactions with pebble sized solid species (St = 0.01-1) result in inward migration. However, in these cases, the migration rate is substantially reduced, resulting in only a small percentage change in the planet's semi-major axis over a timescale of 1000 years.

Effect of back-reaction in dusty disks

I continued the investigate of the effect of back-reaction in protoplanetary disks with higher metal content. For species with St = 1, the effect of back-reaction resulted in a positive gas torque in a disk having Z = 0.1 and p = 0.5 (Figure 2.). It is of particular interest, since the interaction of gas with solid species having St = 1 had consistently resulted in a strengthened negative gas torque in all previous simulations. Qualitative differences were also found for other pebble sized species (e.g., St = 0.01). Our results suggest that the effect of the solid back-reaction depends sensitively on the solid-to-gas ratio and the initial steepness of the disk profile. We plan to publish our results in the following months.

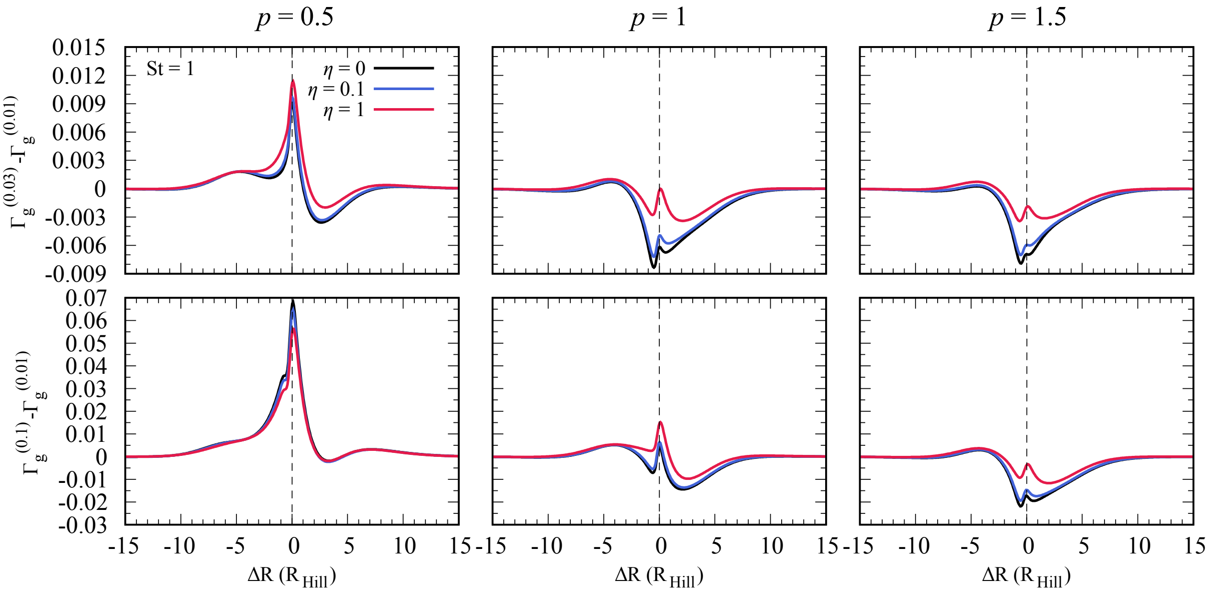

Figure 2: Difference in the azimuthally averaged gas torque profiles for species with $\mathrm{St} = 1$ in disks having different metallicities.

Publications

Published papers:

Regály, Z., Németh, A., Krupánszky, G., & **Sándor, Z. 2025, A**&**A, 694, A279:** Dusty disks as a safe heaven for terrestrial planets: Effect of the back-reaction of solid material on gas

Papers in preparation:

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

Regály, Z., Németh, A.: Effect of the back-reaction of solid material on the torques felt by low-mass planets in high metallicity disks

Studies in current semester:

In this semester I completed the following courses:

FIZ/5/044 (Exo)Bolygólégkörök szeminárium II.
FIZ/5/040 Az exobolygók kutatása

Teaching activity:

cg1c4eg3 Csillagászati Észlelési Gyakorlatok 3. (Practice)

Conference participations during the doctoral studies:

The Art of the Invisible Force: The Dynamics of Equilibria Near and Far. Scientific Conference in Honor of Bálint Érdi, June 2–4, 2025, Budapest, Hungary (Accepted for Contributed talk)

Summer schools and workshops:

"The Birth of Solar Planets" Spring School, February 25th-March 7th, Bertinoro, Italy (Attended, presented a poster)

"A New Era in Exoplanet Atmosphere Observation and Characterisation" Physics School, July 20-25, Bad Honnef, Germany (Registration accepted)

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, A. Németh, G. Krupánszky, and Z. Sándor. Dusty disks as safe havens for terrestrial planets: Effect of the back-reaction of solid material on gas. , 694:A279, Feb. 2025. doi: 10.1051/0004-6361/202452806.

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