SEMESTER REPORT

1ST SEMESTER, 2025/26/1

by Árpád Takács (takacsarpad@student.elte.hu)

PH.D. PROGRAM: Statistical Physics, Biological Physics and Physics of Quantum Systems

THESIS TITLE: *Reconstruction and Forecasting of Large-scale Flow Fields Using Advanced Numerical and Machine Learning Methods*

SUPERVISOR: Dr. Miklós Vincze

INTRODUCTION

Large-scale rotating flows in geophysical and astrophysical systems are known to produce surprisingly stable and well-organized structures. However, the physical mechanisms responsible for their formation are still not fully understood. A well-known example is the hexagonal flow pattern observed around Saturn's north pole, which has remained almost unchanged for several decades.

The fact that such structures are so stable suggests that simple and fundamental fluid-dynamical mechanisms may be responsible for their formation. One possible mechanism is barotropic instability. This type of instability can occur in rotating flows when neighboring fluid layers rotate at different speeds. The resulting shear can generate waves that may organize into large-scale coherent patterns. Laboratory and microgravity experiments provide an ideal way to study these processes under controlled conditions. This makes it possible to isolate the key physical mechanisms and to directly relate our experimental results to large-scale geophysical flows.

RESEARCH WORK IN THE CURRENT SEMESTER

During the first semester of my doctoral studies, I mainly worked on the analysis of experimental data obtained from the DiRoS (Differential Rotation and Shear Instabilities) experiment. It was carried out in microgravity on board the International Space Station during the Axiom Mission–4 scientific program.

In the experiment, a free-surface, spherical layer of water was set into differential rotation, with the equatorial region rotating faster than the polar regions, mimicking flow conditions relevant to stars and gas giant planets.

Velocity fields developing at different rotation rates were measured using either Particle Image Velocimetry (PIV) or Particle Tracking Velocimetry (PTV), depending on the seed density of the flow and the quality of the video. My primary focus was the processing and analysis of these datasets using PTV. I developed a pipeline for the analysis of the flow, which includes several steps such as preprocessing, particle tracking, outlier correction, velocity profile calculation, and numerical simulations.

I created an algorithm for automatically detecting the particles using PTV and experimented with various outlier correction methods to obtain the best results. After this, I also determined the zonal velocity profile. We are also interested in how the flow slows down when the rotation of the sphere is stopped. A video was recorded of a spin-down experiment, which allows us to determine the time evolution of the zonal velocity and to characterize the deceleration of the flow.

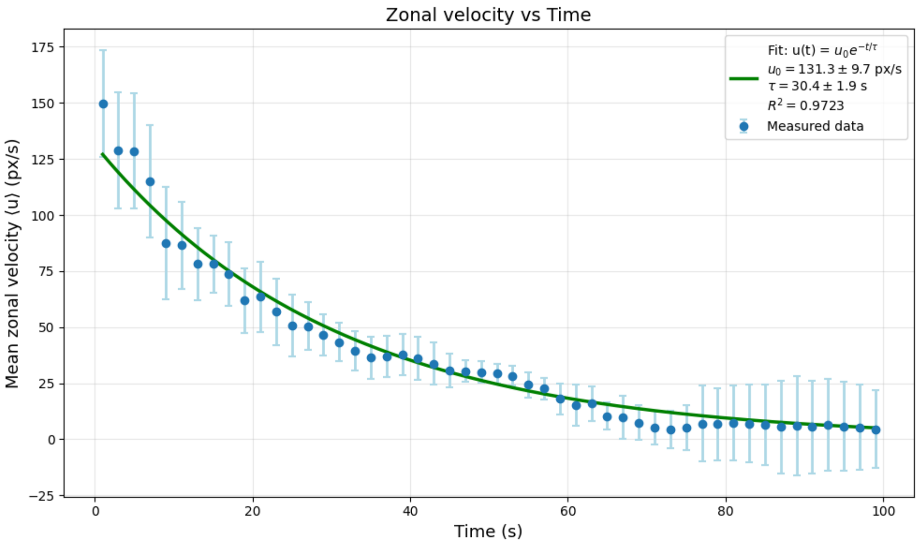

Figure 1: Mean zonal velocity time dependence.

I prepared the environment for the numerical simulation using a Physics-Informed Neural Network (PINN), which will be helpful for predicting the velocity profile between the detected particles.

Our next goal is to interpret the experimental and numerical results using existing theoretical models [1]. In particular, we would like to compare our measurements with theoretical predictions and provide experimental evidence supporting these models. We plan to submit a paper describing these results to a peer-reviewed international (interdisciplinary) journal in the near future.

TEACHING & STUDIES IN THE CURRENT SEMESTER

At the beginning of the semester, I was responsible for the Wednesday morning laboratory classes ("Klasszikus fizika laboratórium" (fizlab2f19la)) and supervised three different measurement stations. During the semester, I kept regular contact with the students and graded a total of 16 submitted laboratory reports.

As described in the previous sections, a significant part of my time during the semester was dedicated to the DiRoS experiment. In addition to this, I took on a leading role in a larger project at my workplace. In my position as a data scientist, I worked on data processing tasks, implemented outlier handling logic, and tested forecasting machine learning models.

Due to these parallel responsibilities, I only only in the course "Irányított kutatómunka 1., 2., 3., 4. szemeszter", as taking additional courses during the semester would not have been possible at a sufficient level. The remaining two courses are planned to be completed in one of the following semesters, when the workload related to the experiment and my professional obligations is expected to decrease, likely around the spring period.

References

[1] Kim, S.-C., & Sohn, S.-I. (2021). Linear stability and nonlinear evolution of a polar vortex cap on a rotating sphere. European Journal of Mechanics / B Fluids, 85, 102–109.

[2] Vallis, G. K. (2017). Atmospheric and oceanic fluid dynamics. Cambridge University Press.

[3] Baines, K. H., Momary, T. W., Fletcher, L. N., Showman, A. P., Roos-Serote, M., Brown, R. H., ... & Nicholson, P. D. (2009). Saturn's north polar cyclone and hexagon at depth revealed by Cassini/VIMS. Planetary and Space Science, 57(14-15), 1671-1681.