SEMESTER REPORT

2ND SEMESTER, 2025/26/2

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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*

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INTRODUCTION

Large-scale rotating flows often produce stable, well-organized structures, such as Saturn's hexagonal flow pattern. One proposed mechanism is barotropic instability, where shear between differentially rotating layers generates organized large-scale waves — a process testable through laboratory and microgravity experiments. Building on the experimental pipeline developed during the previous semester, this semester I focused on extending the theoretical interpretation of the measured flow fields. To this end, I explored a two-constant-vorticity framework, in which the equatorial and polar regions are each assumed to possess their own constant vorticity, allowing the corresponding zonal velocity profile to be derived analytically and compared with the measurements [1, 2]. In parallel, I investigated the use of the Kuramoto model [3] to describe the phase synchronization of the waves emerging in the flow.

RESEARCH WORK IN THE CURRENT SEMESTER

Following up on the theoretical directions outlined above, I worked on fitting the two-constant-vorticity model [1, 2] to the measured zonal velocity profiles, treating the equatorial and polar vorticities as fit parameters and comparing the resulting analytical profile to the PTV-derived data. In parallel, I fitted a Kuramoto model [3] to the data in order to describe the phase synchronization of the waves observed in the flow, treating the coupling strength and natural frequencies of the oscillators as the relevant fit parameters. On the technical side, I modernized the particle recognition step of the analysis pipeline by replacing the previous detection method with a machine-learning-based approach, which substantially improved the particle detection rate compared to the earlier algorithm. Using the Kommondor supercomputer, I also ran the full Physics-Informed Neural Network on the complete dataset, allowing the velocity field to be reconstructed across the entire domain rather than only between detected particles (Figure 1).

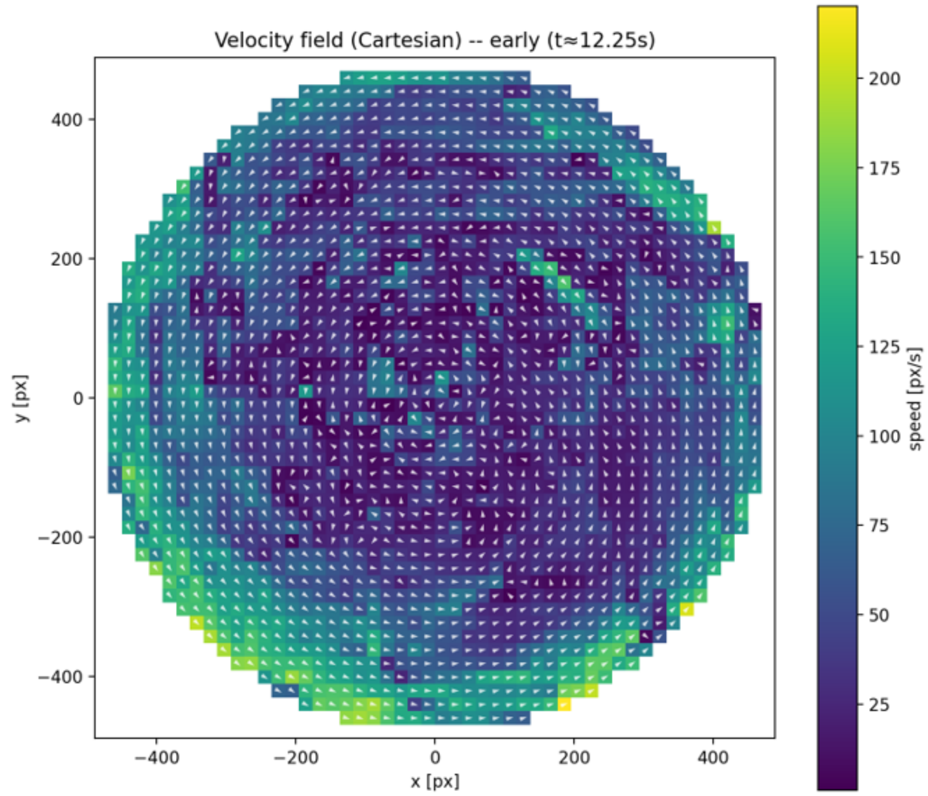

Figure 1: Reconstructed velocity field obtained from the full PINN model trained on the complete dataset (Kommondor).

PUBLICATIONS IN THE CURRENT SEMESTER

These results, together with the contributions of the broader DiRoS collaboration, were compiled into a manuscript reporting the full set of flow instability measurements from the experiment, which has recently been submitted as a preprint [4]. In this work, I contributed to the development of refined particle tracking methods used in the analysis of the experimental data.

STUDIES IN THE CURRENT SEMESTER

This semester I enrolled in several courses covering topics in experimental nuclear physics, machine learning, environmental fluid dynamics, and supervised research. The courses Experimental Methods in Nuclear Physics (FIZ/2/022), and Advanced Machine Learning Laboratory (FIZ/3/093) have already been completed; however, the final grades have not yet been officially recorded in the Neptune system. The Physics of Environmental Flows (FIZ/3/017E) exam is scheduled for later this week, and therefore the course is still in progress.

CONFERENCES IN THE CURRENT SEMESTER

During the current semester, I participated in the XXIX Spring Wind Conference (XXIX. Tavaszi Szél Konferencia), organized by the National Association of Doctoral Students (DOSZ) and hosted by the Faculty of Law of the University of Pécs between 19–21 June. I took part in the Physics Section, which provided an excellent opportunity for interdisciplinary discussions and scientific networking.

My presentation, entitled "From Microgravity Experiments to Saturn's Hexagon," focused on alternative theoretical approaches to the evaluation of the DiRoS experiment. The presentation highlighted multidisciplinary aspects of the research and explored different perspectives beyond the conventional interpretation of the experimental results.

On the second day of the conference, I presented a poster describing the DiRoS experiment in greater detail. During the poster session, I introduced the experimental setup and discussed the traditional methodology used for evaluating the collected data. The session provided valuable feedback from researchers with diverse scientific backgrounds and led to several constructive discussions about the theoretical and experimental aspects of the project.

REFERENCES

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[2] García, C., Hassainia, Z., & Roulley, E. (2023). Dynamics of vortex cap solutions on the rotating unit sphere. arXiv preprint arXiv:2306.00154.

[3] Acebrón, J. A., Bonilla, L. L., Pérez Vicente, C. J., Ritort, F., & Spigler, R. (2005). The Kuramoto model: A simple paradigm for synchronization phenomena. Reviews of Modern Physics, 77(1), 137–185.

[4] Vincze, M., Balázs, B., Hevesi, L., Kadlecsik, Á., Kapu, T., Kiefer-Szabó, R., Szabo, P. S. B., Takács, Á., Vass, B., Whitson, P., & Vizi, P. G. (2026). Flow instabilities in a microgravity model of differentially rotating planetary atmospheres. Research Square preprint, DOI: 10.21203/rs.3.rs-9142223/v1.