Doctoral School of Physics - Eötvös Loránd University (ELTE)

4th semester report

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PhD Program: **ELTE Astronomy and Space Physics doctoral program**

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Ph.D. Thesis title: **Exploring the physical properties of asteroids with the TESS space telescope**

Introduction

Minor planets, such as main-belt asteroids, Hildas, and Jupiter Trojans, preserve important clues about the formation and long-term evolution of the Solar System. Their physical characteristics—especially shapes, rotational properties, and spin axis orientations—can be determined from the detailed analysis of their photometric light curves. These properties reflect processes such as collisional histories and migration events (Halliday et al., 1996).

Until recently, light curve data were primarily obtained from ground-based surveys, which often suffer from sparse sampling and diurnal interruptions. In contrast, the Transiting Exoplanet Survey Satellite (TESS) offers continuous, high-precision photometric time series that are particularly advantageous for asteroid studies. The first data release already included high-quality light curves for approximately 10,000 asteroids (Pál et al., 2020). In 2021, for Sectors 42-46, TESS's field of view was rotated into the ecliptic plane, multiplying the high-quality photometric data by orders of magnitude, for the minor planets in the main belt (Kiss et al., 2020).

By applying light curve inversion techniques (Muinonen et al., 2020), it is possible to reconstruct the shapes, rotational periods, and spin axis directions of a large number of asteroids. In my research, I make use of these improved datasets to investigate the physical properties and rotational states of selected populations of minor planets. This approach enables the identification of extreme rotators, potential non-principal axis rotators, and previously unmodeled objects, contributing to our broader understanding of asteroid evolution across different dynamical groups.

Summary of research work carried out in the previous three semesters

In the previous semesters, I focused on the photometric analysis of main-belt, Hilda, and Jupiter Trojan asteroids using light curves from the TESS space telescope (Ricker et al., 2015). I wrote and continuously improved a Python code that automates the process for TESS light curves, searching for rotation periods, and models asteroid brightness variations assuming a triaxial ellipsoid shape. The code fits the amplitudes of the observed light curves using chi-square minimisation, taking into account the geometry of the observations. The Lommel–Seeliger scattering law is also implemented into the model to improve the fits and better reproduce realistic surface scattering, which led to more accurate results for the pole orientations and shape parameters (Muinonen & Lumme, 2015; Muinonen et al., 2015).

Using this tool, I selected 44 main-belt asteroids with accessible DAMIT shape models that were observed in at least 3 TESS sectors and had a brightness of at most 18 magnitudes (Durech et al., 2010). For these targets, I calculated spin-axis orientations based on TESS data and compared the results with DAMIT models. In four cases, including (22) Kalliope and (1572) Posnania, the TESS-based and DAMIT-based results showed good agreement. For validation, I also extracted amplitude values from the DAMIT light curves and ran them through my code to compare the solutions based on TESS and DAMIT amplitudes (Takács et al., 2025).

In the future, I plan to apply my pipeline to a much larger number of targets by removing the initial selection criteria based on DAMIT and brightness. This will allow the spin-axis modelling of thousands of asteroids, offering a new, large-scale statistical view of asteroid rotation and shape distributions based on TESS photometry.

I also participated in determining the rotation periods of Jupiter Trojan asteroids, based on TESS measurements. For this project, we used a separate Python tool developed by Attila Bódi, which applies LOWESS smoothing to TESS light curves to identify rotation periods. By analysing the light curves, identifying rotation periods, and comparing them with previous ground-based data, we were able to determine the rotational characteristics for over 300 Trojans. This work led to the discovery of the three fastest-rotating Jupiter Trojans – (13383) 1998 XS3, (38615) 2000 AV121 and (228155) 2009 SF61 – known to date. These exceptional objects rotate in less than 5 hours, challenging the typical spin barrier expected for such large, low-density bodies. Our results suggest that some Trojans may have higher densities or more cohesive internal structures than previously thought, and they provide valuable constraints for models of Trojan formation and evolution (Kiss et al., 2025).

Description of research work carried out in current semester

In the current semester, I focused on analysing the rotational properties of Hilda asteroids using data from the Transiting Exoplanet Survey Satellite (TESS). Hilda asteroids, which orbit in a 3 : 2 mean-motion resonance with Jupiter, serve as key tracers of dynamical processes in the early Solar System. Understanding their spin rates is crucial for constraining their internal structure, density, and collisional history (Brož & Vokrouhlický, 2008; Roig & Nesvorný, 2015).

Three fast-rotating Hildas—(42237), (91273), and (237321)— were identified with spin periods in the 3.2–3.7 hour range. These periods are significantly shorter than the previously known limit of $\sim$5 hours for $\sim$10 km Hildas derived from ground-based observations (Warner et al., 2009; Mottola et al., 2024), and approach the $\sim$3-hour breakup limit for small Hildas established by the FOSSIL survey (Chang et al., 2022). Our findings were supplemented with two earlier-identified fast rotators from the Kepler/K2 mission, (207644) and (208290) (Szabó et al., 2020), to establish a complete sample of fast-spinning Hildas in this size regime (see Fig. 1).

The light curves were extracted using elongated apertures and corrected for systematics using LOWESS smoothing, iterative sigma-clipping, and phase angle corrections. Rotation periods were determined using Lomb-Scargle periodograms and validated with higher-order Fourier fits. We ruled out instrumental contamination by analysing correlations between brightness and CCD coordinates, following the method of Kiss et al. (2024).

The results suggest that a subset of Hilda asteroids may have either higher-than-expected densities or notable internal cohesion. Interestingly, C-type asteroids—common in the outer main belt and possessing $\rho \sim 1.5$ g,cm^{-3}—are believed to constitute $\sim$10–15% of the Hilda population. The frequency of fast rotators in our sample is consistent with this fraction, supporting the hypothesis that such objects were mixed into the Hilda population during early dynamical reshuffling involving the giant planets (Wong et al., 2017; Yoshida et al., 2019).

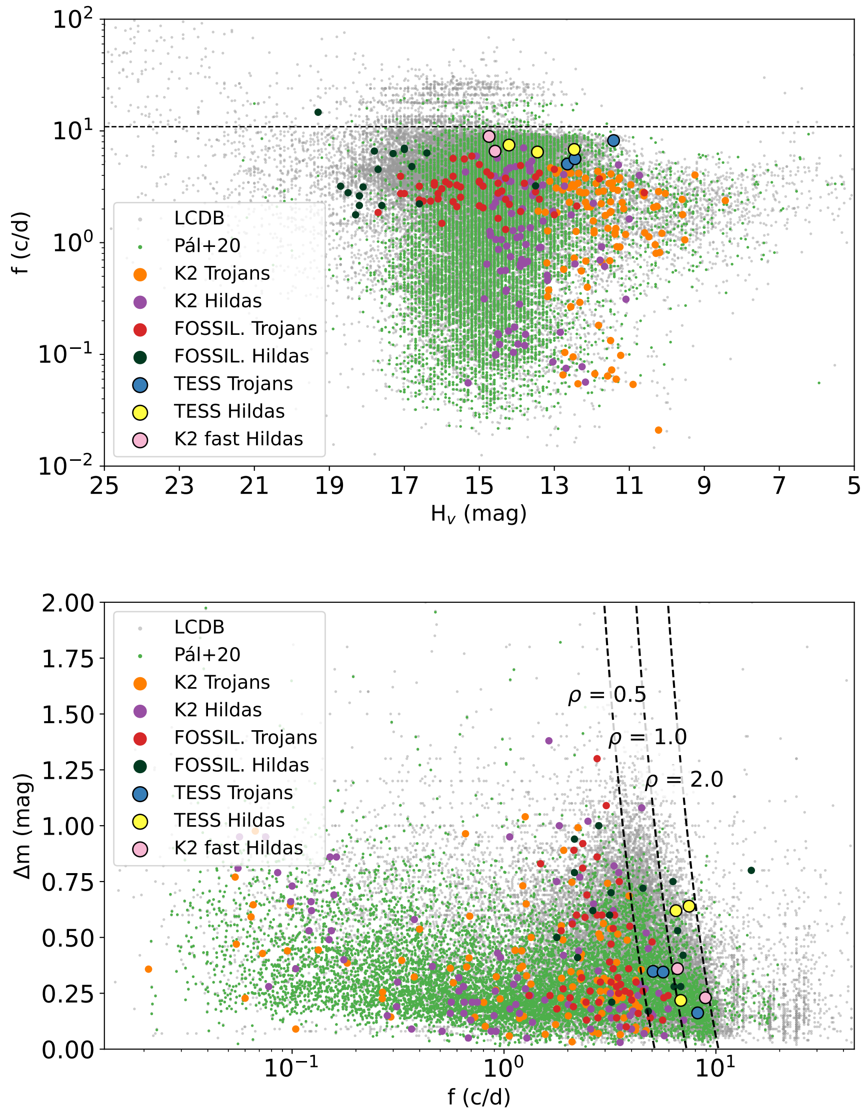

Figure 1: Rotational properties of inner Solar System asteroids. Top panel: rotational frequency vs. absolute magnitude, with the 2.2-hour breakup limit shown as a dashed line (Pravec & Harris, 2000). Bottom panel: light curve amplitude vs. rotational frequency, with dashed curves marking constant critical densities (Pravec & Harris, 2000). The three Hildas in this study are highlighted in yellow, K2 fast rotators in pink, and fast-rotating Trojans from Kiss et al. (2025) in blue.

Publications

- Submitted and accapted articles
  - Takács N., Kiss C., Szakáts R., Pál A., 2025
    Solar System Objects Observed with TESS—Early Data Release 2: I. Spin-shape Recovery Potential of Multi-epoch TESS Observations
    Publications of the Astronomical Society of the Pacific, Volume 137, Issue 4, id.044401, 11 pp.
  - Kiss C., Takács N., Kalup C. E., Szakáts R., Molnár L., Plachy E., Sárneczky K., et al., 2025
    Three fast-rotating Jovian trojans identified by TESS set new population density limits
    Astronomy & Astrophysics, Volume 694, id.L17, 5 pp.
  - Choukroun A., Marciniak A., Ďurech J., Perła J., Ogłoza W., Szakats R., Molnar L., et al., 2025
    Asteroid sizes determined with thermophysical model and stellar occultations
    eprint arXiv:2505.09437
  - Takács N., Kiss C., Kalup C. E., Szakáts R., Molnár L., Plachy E., Sárneczky K., et al.
    Three fast-spinning medium-sized Hilda asteroids uncovered by TESS
    The paper has been accepted in the Astrophysical Journal Letters
- Papers in preparation
  - A paper about optical phase curve analysis of four selected transiting hot Jupiters, based on TESS data, based on the Transit and Light Curve Modeller (TLCM) is before submission.

Studies in current semester

During my fourth semester, I completed the following subjects with an excellent grade,

- (Exo)planetary atmospheres seminar II. (FIZ/5/044)
- Exoplanetary research (FIZ/5/040)

Conference participations during the doctoral studies

- In October 2023, I attended the ARIEL Consortium Meeting, held in Budapest.
- I attended the TESS Science Conference III held in Boston from July 29 to August 2, 2024, with a 15-minute presentation and a poster.
- I attended the Europlanet Science Congress 2024, held in Berlin from 8 to 13 September 2024, by contributing a 15-minute presentation and a poster.

- I have applied for and was accepted to the Europlanet Science Congress EPSC-DPS Joint Meeting 2025, held in Helsinki, Finland, from 7 to 12 September 2025, by contributing a 15-minute presentation.

- I was also invited to give a seminar talk on my research at the Konkoly Thege Miklós Astronomical Institute the following semester.

Teaching activities during the doctoral studies

- During my third semester, I entirely lectured the first-semester MSc course 'Astronomical information technology' (cscsillinfg17gm).

Professional activities during the doctoral studies

- During my first semester, I participated in the Konkoly Thege Miklós Astronomical Institute's workshop in November, which dealt with the issues in the study of the Solar System.

- In my second semester of studies, from 4 to 16 February 2024, I participated in the 2023 NEON Observing School programme, during which I had the opportunity to learn how to use local instruments, telescopes and systems and to carry out the reduction of my own measurements.

  Also, on 6 March, with Zsófia Bora, we had the opportunity to give an astronomical demonstration to a group of high school students in the ELTE planetarium.

- During the third semester, from 16 to 20 September 2024, I participated in the EXOHOST summer school "Planet formation and populations" programme, where I had the opportunity to attend a diverse array of presentations on exoplanet formation and observation.

- Recently, in my fourth semester of Phd studies, I was invited to give a talk to 2-3 visiting groups at the planetarium of Eötvös Loránd University on 19 June.

- For three years now, I have been going to the Piskéstető Observatory for an average of 1 whole week per month to make observations with the largest telescope in the country, and from this January, I was also hired as one of the observatory's support astronomers.

References

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