**Doctoral School of Physics - Eötvös Loránd University (ELTE)**

# 1st semester report

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

## Introduction

When studying the origins of the Solar System, the footprints carried by minor planets cannot be neglected and can help to answer some of the evolutionary questions (Halliday et al. 1996). Up until 2021, we have mostly obtained data from ground-based telescopes, but these are generally very poorly sampled and this usually leads to a very inhomogeneous dataset. However, we already have high-quality light curves for about 10.000 asteroids from DR1, based on data from a single sector (Pál et al. 2020). In contrast, space-borne data can provide better coverage, such as exoplanet missions like Kepler and TESS. These measurements are uninterrupted and can provide continuous photometric time series for a longer period, without diurnal variations (Kiss et al. 2020). It was in 2021 that the field of view of the TESS was rotated into the plane of the ecliptic, multiplying the high-quality photometric data, with orders of magnitude, for the minor planets in the main belt. This allows us to obtain better coverage for a given minor planet, which can then be used for the light curve inversion method. This allows us to determine the shape and polar orientation of the asteroids (Muinonen et al. 2020).

Furthermore, TESS will also provide more precise light curves for Hildas and Jupiter Trojans than previous studies. These populations have undergone significant collisional evolution. From TESS measurements, we can determine the rotational characteristics, then these can be compared with evolutionary models to investigate the differences between background populations and collisional families.

TESS will provide data measured from several directions for approximately in the order of hundreds of thousands of main belt asteroids and during my PhD studies, I plan to perform the light curve inversion procedure on this complete TESS database, taking into account the effects of surface scattering. In addition, using the complete TESS database to date, I plan to determine the rotational characteristics of the Hilda and Jupiter Trojans.

## Description of research work carried out in current semester

During my first semester of PhD studies, I worked on improving and automating further my existing Python code. This code takes all the available TESS light curves for our 43 selected, main belt asteroids as an input. For the selection of these targets, I have established three criteria. First, TESS must have measured it in at least 3 sectors. Second, it must have a brightness of 18 magnitude or less in the TESS bandpass and finally, it must have a shape model in the DAMIT database. I perform a rotation period search, then fold the light curves and attempt to solve the problem through $chi^2$ minimization. For each object, there are at least three measurements, from which we obtain the amplitudes of the folded light curves. These amplitudes are then compared with the model amplitudes for a specific set of parameters. By minimizing the residuals, we can find the best-fitting values for the direction of the axis of rotation. In the simplest shapemodeling process, that I also use, the minor planet is modelled using a three-axial ellipsoid. In addition, my supervisors and I have been investigating the scattering phenomena of the surface of minor planets since the surface reflection depends on the angle between the observer and the Sun as seen from the coordinate system of the minor planet, called the alpha phase angle. We have successfully included the Lommel-Seeliger scattering model in the calculation of the results, which is the best approximation of the scattering of small planets in reality and one of the most popular scattering models, giving more accurate solutions (Muinonen & Lumme 2015; Muinonen et al. 2015). The results for the 43 minor planets we selected were then compared with the results from the `DAMIT` (Database of Asteroid Models from Inversion Techniques) database, which uses a more complex shape determination procedure, but for ground-based measurements (Durech et al. 2010). By further developing this procedure we were able to perform this comparison for 4 objects. For the others, unfortunately, there were not enough observations in the optical range.

One example of the four objects mentioned above is the asteroid (1572) Posnania. Figure 1 shows the results obtained for TESS and DAMIT data. For the TESS data, we used light curves from three sectors scattered over 50% of the orbit of the minor planet, while for the DAMIT data, we used all the light curves which we could extract meaningful amplitudes from. This gave us 15 measurements covering 40% of the orbit. However, these are much shorter and more incomplete measurements compared to the TESS data, plus since different parts of the orbit are sampled by the two techniques, we got a small difference in the results. Apart from this, however, our results for the TESS data are close to the results for the rotation axis direction in DAMIT.
In the future, I plan to do this whole procedure for the entire TESS minor planet database, where it will no longer be a criterion that there must be a solution for the given object in DAMIT. This full light curve sample is roughly on the order of hundreds of thousands of minor planets.

During a three-day workshop, organized by the Konkoly Thege Miklós Astronomical Institute, where me and five additional researchers involved (Emese Plachy, Zsófia Bognár, Dóra Takács, Róbert Szakáts and László Molnár), tried to determine the rotational period of Jupiter Trojans. We used all the available TESS data for these types of objects which gave us 220 minor planets. For these, we used a Python code by Attila Bódi, which can determine periodicities using photometric data. It can filter out the noise using the LOWESS Smoother algorithm, thus increasing the chance of distinguishing the true signal. We checked the results and found that we were able to successfully determine the rotation period for more than half of the Trojans, while the others need further improvements as they are still absorbed by the noise. This was performed initially only on objects that are 19 magnitude or brighter, but we found that the period can be clearly seen in the light curves of fainter planets as well. In the future, I plan to select these and carry out the procedure and the check on them, and I plan to do the same for the entire Hilda light curve database, which will result in rotation periods of similar magnitude.

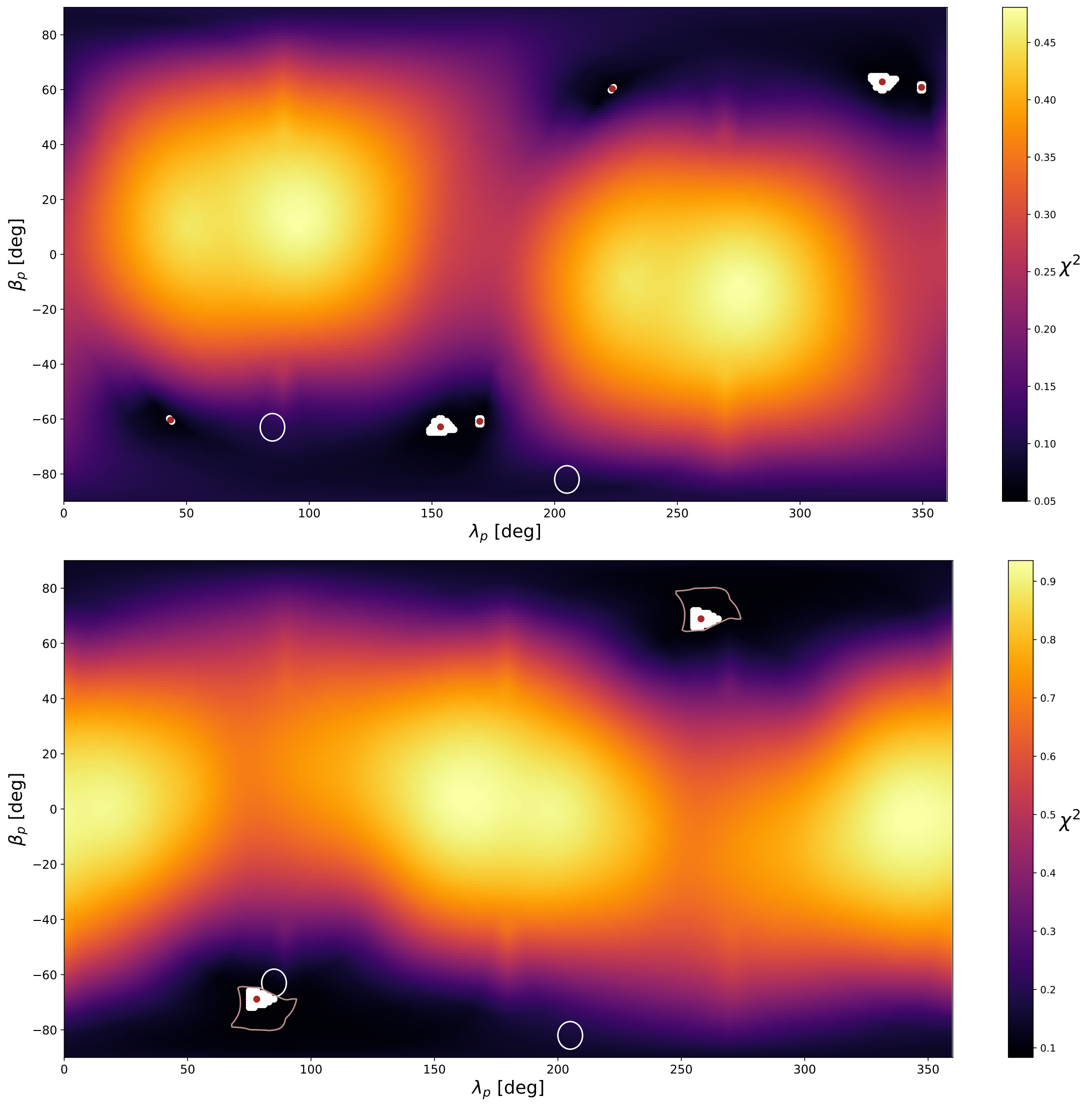


Figure 1: Possible axis of rotation solutions for asteroid (1572) Posnania. The top panel shows the results obtained using TESS data, while the panel on the bottom uses the same procedure but for DAMIT data. The dark areas indicate the possible directions of the axis of rotation. The white dots show the smallest 100 chi$^2$ values. The three contour levels show the 1, 2 and 3% of the maximum value. The red dots in the middle of the minimum areas show the median of those. And the white circles represent the DAMIT coordinates for the axis of rotation.

# 1 Publications

- We have nearly completed a paper that presents the results of our study on the shape and rotational axis orientations of 43 small planets using the light curve inversion method and TESS data. In the paper, we also compare our findings with Damit. Currently, the paper is in the pre-publication stage. We have prepared the data and figures, and the only remaining task is to complete the written part before submission.

- The article on the determination of the period of the larger amount of Jovian Trojans is still in the data retrieval phase. This will, in turn, provide the basis for a similar paper on the case of the Hildas.

## 2 Studies in current semester

During my first semester, I completed the following subjects, all with excellent grades,

- At the edge of the Solar System 1 (FIZ/5/047)
- Radio astronomy I (FIZ/5/009)
- Solar System plasma physics (FIZ/5/055)

I also submitted my application to the 2023 NEON Observing School, which was accepted. However, the organizers moved the date to 4-16 February 2024.

## 3 Further activities

I participated in the Konkoly Thege Miklós Astronomical Institute's workshop in November, which dealt with current issues in the study of the Solar System. I was also involved in its organisation.

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