LABORATÓRIO NACIONAL DE ASTROFÍSICA

SOAR TELESCOPE - Brazilian National Office

Observing Time Application Form (Version 5.0.0)
Semester: *2026B* (Aug/2026 - Jan/2027)

Proposal ID : **SO2026B-002**
Data Received : 14/04/2026 11:16

A.M.(<=)	Any	**Moon P.**	Gray
Image Quality		Seeing < 1.3"	
Cloudy Cover		Thin Cirrus (<70%)	

Title of Proposal: ***Photometric Characterization of Centaurs: (10199) Chariklo, (5145) Pholus and (32532) Thereus.***

Abstract:

Understanding the physical properties of small bodies is a step toward understanding the current configurations of the Solar System, including the distribution of ices and silicates, sizes, shapes, and the maintenance of structures such as rings. One dynamically active class in the Solar System is the Centaurs, objects orbiting between Saturn and Neptune with orbits perturbed by the giant planets. The largest is Chariklo, which possesses a complex ring system. We intend to increase our knowledge of this object and this family, thus, we selected three targets for improved characterization, which are Chariklo, Pholus, and Thereus. All three share very similar characteristics, such as size, color, spectrum, and orbit, and may also possess hidden structures like rings. We aim to perform the photometric characterization of these objects by obtaining their rotational light curves at SOAR.

Category: Solar System: Small Bodies (Asteroids, Comets, Moons, Kuiper Belt, Near Earth Objects)

Time requested: 56 hours.

Minimum time accepted: 16 hours.

Observing Mode: Classical Remote (CR)

Program Type: Regular Proposal (RP)

Principal Investigator (PI): Giuliano Margoti

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Is there a thesis or dissertation that will benefit from the data?: YES

Student	E-mail	Degree	Defense
Giuliano Margoti	giulianomargoti@on.br	PhD student	11/2028
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Instruments:

Goodman (Imaging)

Detectors	- Red Camera
Filters	- g´ SDSS 4x4 - r´ SDSS 4x4 - i´ SDSS 4x4 - z´ SDSS 4x4

Optimal dates:

Between: September 04 to 18, August 05 to 21 or Octuber 03 to 17 (Chariklo + Pholus); /nAugust 05 to 21 or Decemb

Impossible dates:

NaN

Scientific Justification

The study of small bodies, such as Centaurs, is a step toward understanding the dynamical evolution of the Solar System. Due to their distances to Sun and sizes, the physical characterization of these objects remains challenging, therefore, we uses stellar occultation data for this purpose. While occultations provide the projected size and shape of a body at a specific moment with kilometer-level precision, they struggle to constrain rotational properties or orientation, as the temporal distribution between events often spans months or even years. Consequently, it is necessary to include rotational properties such as rotation period, initial phase, and pole orientation as priors when determining the triaxial shape of the body. These properties are effectively obtained through rotational light curves, which are also sensitive to albedo variations and surface features (Sicardy, et al. 2024; Margoti, G. 2024).

Therefore, the objective of this propose is to conduct a rotational photometric study of three Centaurs: (10199) Chariklo, (5145) Pholus and (32532) Thereus. These are particularly compelling objects that share similarities in size, orbital characteristics, and colors (Tegler, et al. 2005; Rabinowitz, et al. 2007; Fornasier, et al. 2014). Chariklo and Pholus have available stellar occultation data, with Chariklo being the most observed, and Thereus is a candidate of a large number of occultation in the next years. By combining rotational and occultation data, we developed a code to determine the triaxial shape. The model's variables include the equatorial (a and b) and polar (c) semi-axes, rotational parameters (rotation period and initial phase), and orientation parameters (pole right ascension, declination and center projection position) (Margoti, G. 2024, 2025). Furthermore, as rotational light curves can reveal albedo variations, we have also developed a code that incorporates the latitude, longitude, radius, and multiplicative factor of surface spots (Margoti, G. 2026).

The Centaur Chariklo is one of the most interesting objects of its class. While it has an equivalent radius of approximately 130 km, the biggest one, its most remarkable feature is a system of dense and well-confined rings, discovered via stellar occultations (Morgado, et al. 2021). Given the multiple ring occultations recorded and the assumption of circularity, it is possible to achieve a determination of the rings' pole. Since a disk forming a ring system is expected to align rapidly with the body's equator, resulting in zero inclination, we can use the orientation of the rings' pole as a prior, assuming it is aligned with Chariklo's rotational pole. Consequently, one of the primary variables for the physical characterization of the object is already constrained (Margoti, G. 2024).

Several rotational light curves are already available for this object (Fornasier, et al. 2014, Galiazzo, et al. 2016; Leiva, et al. 2017). A key characteristic of a light curve is its amplitude, the brightness difference between peak and valley. As the object moves along its orbit, its aspect angle changes, consequently, there are periods when the pole is nearly pointed toward Earth, leading to a minimum in the light curve amplitude. This is currently the case for Chariklo. While its rotation period is reasonably well-constrained by existing data, the primary focus of this project is that its triaxial dimensions remain poorly determined (Morgado, et al. 2021).

A well-determined three-dimensional shape for Chariklo has yet to be established. Morgado et al. (2021) suggested semi-axes of $143.8\times135.2\times99.1$ km. However, as demonstrated by Margoti (2024), Chariklo's dimensions should be $144.3\times125.4\times110.5$ km, due to a discrepancy in the rotational light curve amplitude calculation in the Morgado et al. (2021) work. We contend that Chariklo's dimensions differ from previous estimates, a key piece of evidence is the predicted amplitude for 2026, which is 0.02 mag according to Morgado et al. (2021), whereas the Margoti G. (2024) model predicts 0.05 mag. Therefore, monitoring the amplitude during this period is essential to accurately determine Chariklo's dimensions. Given Chariklo's current magnitude ($V\approx19.1$) and the expected low amplitude, only the SOAR telescope can provide the precision required for this characterization. Figure 1 illustrates the amplitude differences between the Margoti and Morgado models. Consequently, these SOAR observations will be decisive in validating one of the proposed models.

Our other two targets, Pholus and Thereus, have more limited datasets. For Pholus, we have one observed (though currently unpublished) stellar occultation from the 1.6-m telescope at OPD-Brazil, along with access to four rotational light curves (Buie, M. W. & Bus, S. J. 1992; Tegler, et al. 2005; Farnham, 2001; Hoffmann, et al. 2014). Through this work, we aim to constrain the model for Pholus, providing the first characterization of its dimensions and pole orientation. And for Thereus we only have rotational light curves in literature (Rabinowitz, et al. 2007).

These SOAR observations are critical for completing a manuscript currently in preparation, which details the physical characterization of these Centaurs.

Experimental Design

The selection of targets begins with Chariklo, the Centaur with the largest number of stellar occultation events (11 published and 2 unpublished). Between 2013 and 2020, Chariklo passed through a dense region of bright stars, which facilitated this high number of occultations (Morgado, et al. 2021). Since then, only two additional occultations involving fainter stars (V>16) have been recorded. During this period, several attempts to obtain rotational light curves were made; however, the object's proximity to background stars frequently compromised the results (Fornasier, et al. 2014, Galiazzo, et al. 2016; Leiva, et al. 2017). Even when employing Image Differencing techniques, only partial results were obtained. Since 2025, Chariklo has moved into a increasingly sparse stellar region, providing more favorable conditions for high-quality rotational monitoring.

Given the observational requirements for Chariklo and the necessary night coverage, we selected additional targets that also require complementary rotational data for three-dimensional shape modeling. We searched for objects with pre-existing multi-epoch stellar occultations and rotational light curves, prioritizing those within the Centaur class that share similar orbital and color parameters with Chariklo. Furthermore, these targets were chosen because their observation specifically requires the capabilities of a telescope like SOAR.

Consequently, we have finalized the selection of our priority targets as follows: Chariklo, Pholus and Thereus, the last one with potential to be monitoring by a large number of stellar occultations in the next years. Among these, Pholus is the most challenging target, currently, there are no high-quality rotational light curves or models sufficient to predict its amplitude for the 2026. Given that Pholus will reach an apparent magnitude of V≈22.2 during 2026, the SOAR telescope is uniquely positioned to provide the sensitivity required for these observations. Pholus estimated rotational period is of 9.98 hours (Buie, M. W. & Bus, S. J. 1992; Tegler, et al. 2005; Farnham, 2001; Hoffmann, et al. 2014).

Thereus has more data then Pholus for rotational light curves. It has a rotation period of approximately 8.30 hours (Rabinowitz, et al. 2007) and will reach an apparent magnitude of V≈18.9 during the 2026.

Our observation strategy is adaptable and can be executed across several fronts, depending on the number of nights allocated. Since Chariklo is our primary target, we request that the observation window be scheduled between September 04th and September 19th to maximize observational efficiency. If allocated three or more consecutive nights, our strategy will be as follows: on the first night, we will observe Chariklo for as long as possible, dedicating the remaining time to Pholus. On the second night, we will focus on Pholus and Thereus. On the third night, we will return to prioritizing Chariklo for the maximum available duration, followed by Thereus, and so forth.

Our primary constraint, however, is the requirement for at least two consecutive nights per run. Under this configuration, we would prioritize maximum coverage for Chariklo on both nights, dedicating the remaining time to Pholus. This approach ensures full coverage of Chariklo's rotational light curve while providing a preliminary estimate of Pholus's amplitude. Should additional blocks of nights be granted, we will perform a preliminary data reduction to assess the phase coverage achieved for Chariklo and Pholus. If Chariklo's light curve reaches the required quality, the focus of subsequent night blocks will shift toward Pholus and Thereus.

Observations will be conducted with exposure times ranging from 200 to 600 seconds to achieve a signal-to-noise ratio of 200, obtaining the maximum possible number of frames per night. From this dataset, we will extract the target's flux over time, convert it to magnitudes, and apply the Lomb-Scargle technique to generate a periodogram for rotation period determination. The light curves will then be phased to determine their amplitude and morphology (e.g., identifying single-peak or double-peak behavior). All data processing will be performed using our softwares, PRAIA package for aperture photometry and custom-developed codes for light curve analysis. Standard image calibrations, such as bias and flat-field corrections, will also be carried out using our software pipeline (Margoti, G. 2024).

Regarding sky conditions, it is preferable to observe during dark time or with a lunar illumination of no more than 65%. To achieve our scientific goals, we require monitoring durations of 13 to 15 hours for Chariklo, 8 to 10 hours for Pholus, and 9 to 18 hours for Thereus. These observation windows are essential to provide sufficient phase coverage for the rotational light curves of each target.

Technical Description

In this propose, we intend to use the Goodman (Imaging mode) with the Red Camera to obtain rotational light curves, as it offers excellent throughput and image quality. The g', r', i' and z' SDSS filters will also be employed for specific frames to determine the objects' color indices. These targets exhibit reddish colors, with Chariklo showing a slight albedo variation toward the blue, therefore, imaging in the R band is required.

Chariklo has a rotation period of 7.0 hours. For the project's feasibility, we require a phase coverage of at least twice its period (14h). In September, Chariklo will have an apparent magnitude of 19.1, with a predicted rotational amplitude between 0.02 and 0.05 mag. To accurately detect this amplitude, a Signal-to-Noise Ratio of at least 500 is necessary to achieve a photometric uncertainty of 0.002 mag. Consequently, an exposure time of 400 seconds per frame is required.

Our preferred window for observing Chariklo is from September 4th to September 19th, when the Moon's illumination is below 65% and the object remains above the 20° for over 8 hours. Alternative windows include August 5th to August 21st and October 3rd to October 17th. However, these periods are less favorable: in the former, Chariklo is closer to the Moon, and in both, the maximum nightly visibility decreases to approximately 6 hours.

However, for the observational blocks dedicated to Thereus, the preferred window is between August 5th and August 20th. Consequently, our requested dates are split between August and September to optimize the observation of different targets.

Chariklo's requirements impose a minimum observation block of two consecutive full nights. During intervals when Chariklo is not observable, our priority target is Pholus. Pholus has an estimated rotation period of 9.98 hours, requiring one dedicated full night for complete coverage. When combined with the time Chariklo is unavailable, we request one additional full night for Pholus. Furthermore, to include Thereus (period of 8.3h) in our sample, two more full nights would be necessary to complete its phase coverage.

All targets will be visible during the requested preferred period for more than 6 hours per night. Accordingly, we request a minimum of 2 nights (16h) for Chariklo, 3.5 nights (28h) for Chariklo and Pholus, or 6 nights (48h) for the full sample (Chariklo, Pholus, and Thereus). To account for potential weather losses, we request an additional night, totaling 7 nights (56h). We anticipate that these data will be ready for publication by late 2026.

For Pholus, we intend to use exposure times of 500 seconds, and for Thereus, 250 seconds, aiming for a precision of 0.01 mag. While partial cloud cover or variable sky quality would hinder observations, they would not necessarily invalidate them, though exposure times might need to be increased. We prefer the nights to be distributed in blocks of at least two consecutive nights during the specified windows; however, larger blocks of consecutive nights would also be highly advantageous.

In the context of this proposal, we have also identified three backup targets to ensure observational efficiency in the event of any unforeseen issues with our primary targets. These objects are (55576) Amycus, (95626) 2002 GZ32, and (120061) 2003 CO1. All three meet the selection criteria established for our primary sample: they are Centaurs with similar color and spectral characteristics, and they possess either existing stellar occultation data or high-probability occultation events predicted for the coming years.

Figures and Tables

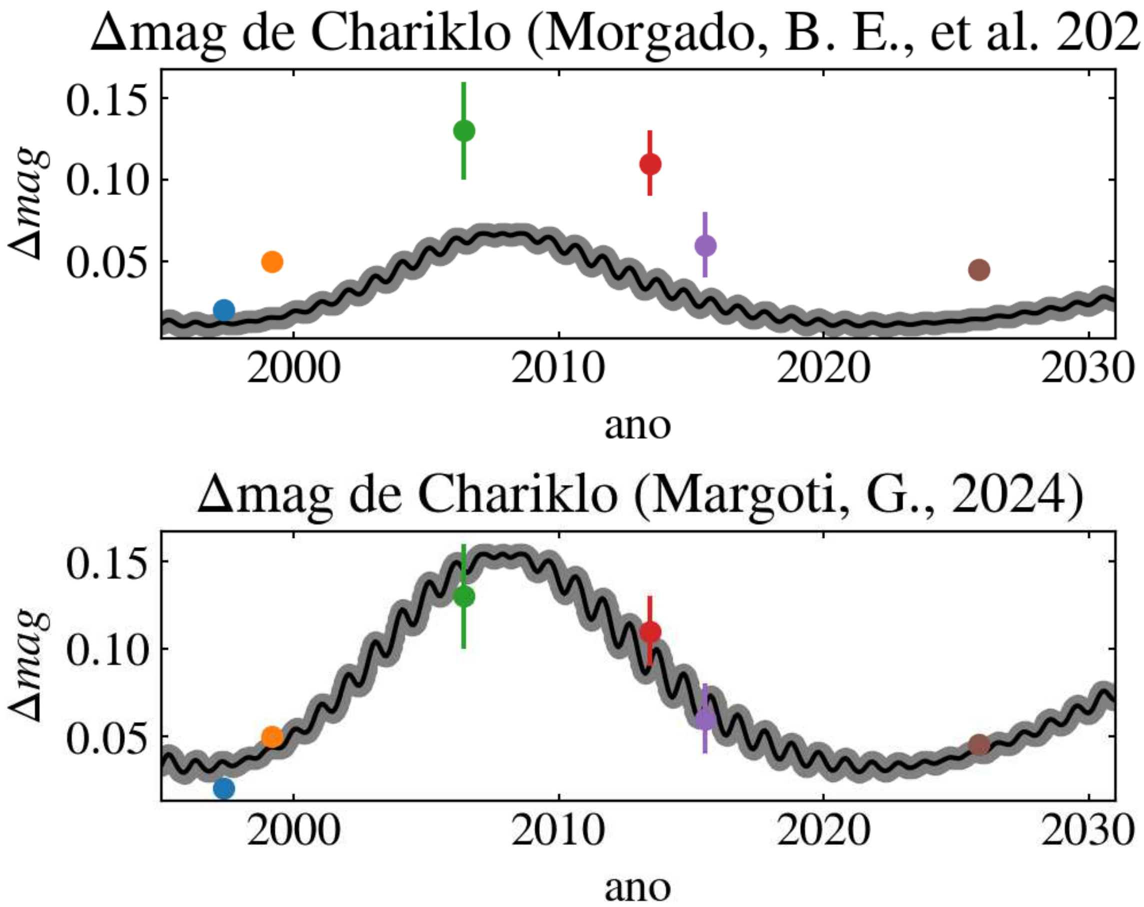

Figure 1: Comparison between the amplitudes derived from the models of Morgado et al. (2021) and Margoti, G. (2024). The points displayed in the figure correspond to Table 1. The brown point in 2026 represents the expected 2026B SOAR observation based on the model by Margoti, G. (2024).

Date	Δmag	**Reference**
1997–05	< 0.02	Davies et al. (1998)
1999–03	< 0.05	Peixinho et al. (2001)
2006–06	0.13 ± 0.03	Galiazzo et al. (2016)
2013–06	0.11 ± 0.02	Fornasier et al. (2014)
2015–07	0.06 ± 0.02	Leiva et al. (2017)

Table 1: Summary of Chariklo's Δmag

References

- Sicardy, B., Braga-Ribas, F., Buie, M. W., Ortiz, J. L., & Roques, F. 2024 A&A Rev., 32, 6.
- Margoti, G. 2024, Master's Thesis, Universidade Tecnológica Federal do Paraná (UTFPR). "Determinação da forma tridimensional de (50000) Quaoar por ocultações estelares utilizando algoritmo genético para minimização".

- Margoti, G., Braga-Ribas, F., Sicardy, B., et al. 2025, ApJ, submitted. ”Size, shape, density, and atmospheric limit of (50000) Quaoar revealed from 14 years of stellar occultations”.
- Margoti, G., Braga-Ribas, F., Ortiz, J. L., et al. 2026, in prep. ”A Methodology for Deriving Ellipsoidal Shape Models for Small Bodies using Multi-epoch Stellar Occultations and Rotation Curves: The Notable Case of the TNO (50000) Quaoar”.
- Morgado, B. E., Sicardy, B., Braga-Ribas, F., et al. 2021 A&A, 652, A141.
- Tegler, S. C., Romanishin, W., Consolmagno, G. J., et al. 2005, icarus, 175, 390.
- Rabinowitz, D. L., Schaefer, B. E., & Tourtellotte, S. W. 2007 AJ, 133, 26.
- Farnham, T. L. 2001 icarus, 152, 238.
- Hoffmann, M., Fink, U., Grundy, W. M., & Hicks, M. 1993 J. Geophys. Res., 98, 7403.
- Fornasier, S., Lazzaro, D., Alvarez-Candal, A., et al. 2014 A&A, 568, L11.
- Galiazzo, M., de la Fuente Marcos, C., de la Fuente Marcos, R., et al. 2016 Ap&SS, 361, 212.
- Leiva, R., Sicardy, B., Camargo, J. I. B., et al. 2017 AJ, 154, 159.
- Peixinho, N., Lacerda, P., Ortiz, J. L., et al. 2001 A&A, 371, 753.
- Buie, M. W. & Bus, S. J. 1992 icarus, 100, 288.

Previous missions of this proposal to this telescope

This proposal has not been submitted before.

Previous missions of other proposals to this telescope

- ”Rotational Characterization of Trans-Neptunian Object 90568 Goibniu (2004 GV9)” (SO2026A-007): One night (8h) for observation on May 10, 2026. PI: Giuliano Margoti.
- Obtaining rotation light curves of Neptune and Uranus Trojans to determine their 3D shapes (SO2026A-008): Two nights (16h) on June 14 and 15, 2026. PI: Eros De Oliveira Gradovski.
- ”Chiron’s rotation light curve for 3D shape characterization” (SO2023B-017): four half-nights of data obtained. The results is in analisys. PI: Chrystian Luciano Pereira
- ”Rotation light curve for the high-inclination TNO 2004XR190” (SO2021B-012): six half-nights of data obtained. Results from these observations were presented at the XLV Meeting of the Brazilian Astronomical Society (2022). PI: Flavia Luane Rommel

Previous results in the field by the Principal Investigator

The PI’s Master’s thesis focused on the physical characterization of Centaurs and Trans-Neptunian Objects. The thesis introduced a methodology implemented for Chariklo and Quaoar, addressing the difficulty of modeling irregular shapes for distant objects that lack observations across diverse aspect angles. It proposes a streamlined formulation for triaxial shape, incorporating hydrostatic equilibrium constraints and discussing Maclaurin, Jacobi, and Jeans figures.

This methodology was applied to Chariklo and revealed a significant discrepancy with previously published data. Specifically, the thesis identified an error in the rotational amplitude calculation presented by Morgado et al. (2021). This finding led to the direct formulation of this proposal, as new observations are required to validate the results of the thesis.

Derived from this research, two manuscripts are currently submitted to The Astrophysical Journal (ApJ). The first presents the stellar occultations of Quaoar and its Maclaurin shape, while the second highlights the importance of rotational curves in determining Quaoar’s shape. This second paper describes a double-peaked light curve with unequal amplitudes, modeled by incorporating albedo variations on the body’s surface.

The PI is an active collaborator in determining the physical properties of various Solar System objects, resulting in several relevant publications:

- Evidence of a New Arc or a Belt of Small Satellites around (50000) Quaoar
- Constraining the size, shape, and albedo of the large trans-Neptunian object (28978) Ixion with multi-chord stellar occultations
- The rings of (2060) Chiron: Evidence of an evolving system
- Nsf-doe vera c. rubin observatory observations of interstellar comet 3i/atlas (c/2025 n1)
- Investigating the formation of small Solar System objects using stellar occultations by satellites: present, future and its use to update satellite orbits
- Physical characteristics of Jupiter’s Trojan (1437) Diomedes from a tri-chord stellar occultation in 2020 and dimensionless three-dimensional model
- Kilometer-precise (UII) Umbriel physical properties from the multichord stellar occultation on 2020 September 21
- A large topographic feature on the surface of the trans-Neptunian object (307261) 2002 MS4 measured from stellar occultations
- Constraints on (2060) Chiron’s size, shape, and surrounding material from the November 2018 and September 2019 stellar occultations

- The two rings of (50000) Quaoar
- A dense ring of the trans-Neptunian object Quaoar outside its Roche limit
- A multi-chord stellar occultation by the large trans-Neptunian object (174567) Varda

These works demonstrate the PI's commitment to studying the physical properties of small bodies, particularly 3D modeling of Centaurs like Chiron. Furthermore, the PI led a previous observation run at the 1.6-m telescope of the Pico dos Dias Observatory (OPD):

- Fotometria rotacional multibanda de pequenos corpos do Sistema Solar. (2025B - P005). Five nights between October 23 and 27, observed in person at the OPD (Pico dos Dias Observatory). PI: Giuliano Margoti.

During this 2025B run, we attempted to observe Chariklo's rotation. However, due to its magnitude (V>19) and very low amplitude, the data did not yield the precision required for rotational parameters, providing only a upper limit for the amplitude (¡0.08 mag). This confirms that a precise characterization of such small factors can only be achieved with larger telescopes like SOAR. Nevertheless, the OPD data allowed for the determination of Chariklo's general color index, which will be included in our forthcoming paper.

The same proposal yielded high-quality light curves for the Trojan Thymbraeus, revealing its bilobed nature and no rotational color variation. These data are currently being used to model the irregular 3D shape of Thymbraeus by Co-PI Eros de Oliveira Gradovisky.

Recent presentations regarding the use of rotational data include:

- IAU Symposium 401: Advancing Reference Systems, Ephemeris, and Standards (2025): Three-Dimensional Shape of (50000) Quaoar and Orbit Refinement Using Data from 29 Stellar Occultations
- XLVIII Reunião anual da sociedade astronômica Brasileira (2025): Modeling the Physical Properties of Outer Solar System Objects Using Genetic Algorithms and Multi-technique Observations
- 35° Colóquio Brasileiro de Matemática (2025): Modeling Phisical Propieties of Outher Solar System Objectis.
- XXII Congresso Brasileiro de Dinâmica Orbital e Planetalogia (2024): Equilibrium Figures for Asteroids.

PI and Co-Is publications relevant to this proposal

The co-authors of this proposal have extencive experience with rotational light curves, such as the Master's thesis presented in 2025 by Eros de Oliveira Gradovisky. His work utilized rotational and occultation data to develop irregular, concave shape models for several Jupiter Trojans: "Obtainment of rotational parameters and scale of Jupiter Trojans through rotation curves and occultations". Furthermore, our team has produced numerous studies focused on determining the physical properties of Trojans, Centaurs, and Trans-Neptunian Objects (TNOs), the main ones are:

- A ring system detected around the Centaur (10199) Chariklo
- Size and shape of Chariklo from multi-epoch stellar occultations
- Refined physical parameters for Chariklo's body and rings from stellar occultations observed between 2013 and 2020
- The size, shape, density and ring of the dwarf planet Haumea from a stellar occultation
- A Pluto-like radius and a high albedo for the dwarf planet Eris from an occultation
- Albedo and atmospheric constraints of dwarf planet Makemake from a stellar occultation
- Triplicity and physical characteristics of Asteroid (216) Kleopatra
- The size, shape, albedo, density, and atmospheric limit of transneptunian object (50000) Quaoar from multi-chord stellar occultations
- Study of the Plutino Object (208996) 2003 AZ84 from Stellar Occultations: Size, Shape, and Topographic Features
- Changing material around (2060) Chiron revealed by an occultation on December 15, 2022

- Physical characterization of double asteroid (617) Patroclus from 2007/2012 mutual events observations
- The large trans-Neptunian object 2002 TC302 from combined stellar occultation, photometry, and astrometry data
- Results from a triple chord stellar occultation and far-infrared photometry of the trans-Neptunian object (229762) 2007 UK126
- Physical properties of the trans-Neptunian object (38628) Huya from a multi-chord stellar occultation
- A stellar occultation by the transneptunian object (50000) Quaoar observed by CHEOPS
- Results of two multichord stellar occultations by dwarf planet (1) Ceres
- The Trans-Neptunian Object (84922) 2003 VS2 through Stellar Occultations
- The multichord stellar occultation on 2019 October 22 by the trans-Neptunian object (84922) 2003 VS2
- The 2017 May 20 stellar occultation by the elongated centaur (95626) 2002 GZ32
- Physical properties of Centaur (60558) 174P/Echeclus from stellar occultations

Objects List.

Object	A.R.(h,m)	Dec.(deg)	Mag.	Band	Type	Comments
(10199) Chariklo	21:26:41.08	-04:06:27.46	19.1	V	Sci	Position at 2026-Sep-11 00:00 UTC
(5145) Pholus	18:39:12.39	-14:55:13.72	22.1	V	Sci	Position at 2026-Sep-11 00:00 UTC
(32532) Thereus	12:33:19.61	-07:27:39.12	19.9	V	Sci	Position at 2026-Aug-11 00:00 UTC
(55576) Amycus	21:26:41.08	-04:06:27.46	19.1	V	Sci	Position at 2026-Sep-11 00:00 UTC Backup object
(95626) 2002 GZ32	19:53:44.70	-23:57:39.15	20.1	V	Sci	Position at 2026-Sep-11 00:00 UTC Backup object
(120061) 2003 CO1	22:01:59.09	-31:54:53.88	22.8	V	Sci	Position at 2026-Sep-11 00:00 UTC Backup object