Database on detected stellar occultations by small outer Solar System objects

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Abstract. Observation of stellar occultation by objects of the Solar System is a powerful technique that allows measurements of size and shape of the small bodies with accuracies in the order of the kilometre. In addition, the occultation star probes the surroundings of the object, allowing the study of putative rings/debris or atmosphere around it. Since 2009, more than 60 events by trans-Neptunian and Centaur objects have been detected, involving more than 34 different bodies. Some remarkable results were achieved, such as the discovery of rings around Chariklo and Haumea, or the high albedo of Eris, the lack of global atmosphere around Makemake and the discovery of the double shape of 2014 MU$_{69}$, among others. After the release of Gaia catalogues, predictions became more accurate, leading to an increasing number of successful observations of occultation events. To keep track of the results achieved with this technique, we created a database to gather all the detected events worldwide. The database is presented as an electronic table (http://occultations.ct.utfpr.edu.br/), where the main information obtained from any occultation by small outer solar system objects are listed. The structure and term definitions used in the database are presented here, as well as some simple statistics that can be done with the available results.

1. Introduction
Small outer Solar System objects are remnants of our system formation that are orbiting the Sun at average distances equal to or greater than that of the giant planet Jupiter. They are divided into different groups according to their dynamical properties. They are known as Trojans, Centaurs and Trans-Neptunian Objects (TNOs for short).

The study of these small distant bodies is relevant in the context of the Solar System dynamical evolution. It is believed that they are pristine objects of an evolved planetesimal
During the early ages of the Solar System, the planetary migration would have left signatures on the small objects orbital distribution and physical properties such as sizes, shapes, and densities. Therefore, the determination of their physical properties is key to understand the history and evolution of the outer solar system. It is believed that many of the giant planet satellites and Trojan objects were captured during the solar system formation, so they are also formation remnants [3]. As a consequence, the knowledge of their physical properties is also essential to better understand their origin.

The stellar occultation technique is suitable to deliver measurements of sizes and shapes with precision on the order of the kilometre, from Earth-based observations. When associated with other methods, it allows the determination of accurate albedos and densities. For a given observer, during an occultation, the solar system object obstructs the light of the star, which then acts as a probe allowing for the study of its environment. We can thus study or search for rings, dust, satellites or atmosphere around these small bodies [4, 5].

Other observational techniques, such as radiometric and direct observations, can deliver a large number of physical properties measurements for these objects. Apart from resolved imaging, sizes determined from these techniques are model dependent. These models can be calibrated with the use of precise measurements such as those obtained with stellar occultation observations [6, 7, 8], and applied in a systematic manner to other bodies.

The first stellar occultation by a TNO was observed on October 2009 [9]. Since then, a total of 55 events were already detected\(^1\). Adding to this the occultations by Pluto system, Centaurs, Trojans and giant planets satellites, more than 155 events were already detected. This number is rapidly increasing (Figure 1), thanks to the precise star positions from Gaia DR2 catalogue now available [10], and to observational efforts and ephemeris computation improvements of these objects, allowing for better predictions [11].

Since 2010, efforts have been made to keep track of the results obtained from these occultation events [13, 12]. Due to its increasing number, a database was developed and presented as an online interactive table. It is meant to be a common and easy place to find the main results of each detected event as well as the respective references. To achieve that, we provide all the detected occultations worldwide\(^2\) by small outer solar system objects\(^3\), independent of the prediction source or group that led an observation campaign.

In section 2, we describe the web page structure and tools. The technical terms used to define the elements presented in the database are defined in section 3. In section 4, a few results are presented as well as a general discussion.

2. Database description and presentation

The database is presented as a dynamic table in page ‘Results’ of the web page hosted at http://occultations.ct.utfpr.edu.br/. It provides the main results, such as size and shape, albedo, density and astrometric position for each observed stellar occultation (when available). It also indicates whether any feature was detected on its surroundings or surface, and if the star was also occulted by the main body or only by a feature, such as a satellite or a ring.

All provided results are given as obtained from the respective events, so objects with more than one detected occultation may present different results, accordingly to the quality and assumptions on the specific data sets. It is up to the user to select the best result and access the respective references, also provided on the table, to understand and analyse it. If many events were interpreted together for a common finding, they will present the same values for

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\(^1\) Pluto system detections are not counted here, as significant efforts have been made to observe these events since the year 2000.

\(^2\) Anyone can suggest the inclusion of an event or reference through contact tab and filing the result form.

\(^3\) Serendipitous events or occultations observed by space probes are not included, as they require different techniques and usually have different objectives.
Figure 1. Example of interactive graph available in the database web page, showing the number of detected stellar occultations by small outer Solar System objects per year. Here the histogram starts in 2009 when the first detection of an occultation by a TNO (other than Puto) happened. For 2019 counts are up to April (time of the writing of this paper). We see the growing number of events detected per year, thanks to specific efforts and the publications of first Gaia catalogues.

The table can display all the reported events, or the user can select tabs with preset filters on a different class of objects, namely: TNOs, Centaurs, Dwarf-Planets, Trojans, Planet Satellites, Pluto and (detected) Features. At the bottom of each column, the user can choose to display only one of the entries. On the tab with all the events, filters on the event date, number of detected chords, equatorial and equivalent radius, albedo and density can also be used to select a subset of results. Finally, a case sensitive search box can be used to find any specific term or number.

The table can be copied, exported or printed with the desired columns, as chosen by the user in the "View more Columns" button. A simple statistic on the number of detected events by the different class or individual objects is displayed on the top of the page. It is important to note that the total number of detections does not agree with the simple sum of it from the different classes, as, for instance, Chariklo is counted in Centaurs and Features classes.

Notes and a glossary with the term definitions of the columns are available at the top of the page. Finally, interactive graphs can be displayed presenting all the reported events in eccentricity versus semi-major axis or inclination versus semi-major axis (Figure 2), from which the user can have a clear idea of the distribution within the dynamical classes of the bodies already observed in a stellar occultation event.

3. Term definitions
A glossary with terms used to describe the number presented on the columns is available. This is important for the user to clearly understand the values, units and results given along with the table. All the terms are defined here with a discussion on the assumptions when applicable.
Figure 2.  *Left:* eccentricity versus semi-major axis of the objects detected on a stellar occultation event. The red curves represent the perihelion distances of 30 and 40 au.  *Right:* Inclination versus semi-major axis of the detected objects. The vertical dashed-lines represent the mean motion resonances of Neptune.

- **Provisional Designation:** object’s provisional designation (when available) as assigned from its discovery date [14];
- **Number:** object’s number as designated by Minor Planets Center [15];
- **Name:** object’s name as designated by the International Astronomical Union [16];
- **Date:** date of the event in the format year-month-day;
- **Local:** countries acronyms from where the event was detected;
- **Chords:** number of positive detections. This represents the number of detections, or telescopes, that provided light curves. If they were at the same site, or over the same line on the shadow path, they might not improve the knowledge of the object profile, but they are counted here anyway;
- **Radius (equatorial) (km):** equatorial radius in kilometre of the object as derived from the observed event, or as given in the respective reference. If it is a single chord event, this represents the half-length of the observed chord;
- **Error Radius (equatorial):** error, in kilometre, of the equatorial radius. If it is a single chord event, it represents the lower limit of the equatorial radius, and is represented by the ‘>’ symbol;
- **Equivalent Radius (km):** this is only available when a shape could be obtained from the occultation, that is, when three or more chords where detected, or two chords when a spherical shape can be assumed. If the object is oblate, this represents the same surface that a disk with this radius would have. For an oblate or Maclaurin [17] object it can be calculated from $R_{eqv} = \sqrt{R_{equa} \cdot R_{pol}} = R_{equa} \sqrt{1 - e}$ where $R_{pol}$ is the polar semi-major axis and $e$ is the oblateness. If the object has a tri-axial shape or a Jacobi [7] shape then $R_{eqv} = (a \cdot b \cdot c)^{1/3}$, were $a$, $b$ and $c$ are the three axis of rotation symmetry. Here we use the values derived from the occultation if the equivalent radius is not given in the corresponding reference;
- **Error Equivalent Radius:** error, in kilometers, of the equivalent radius;
- **Oblatness:** object’s oblateness. Can be obtained from $e = (a - c)/a$, where $a$ is the equatorial radius and $c$ is the polar radius (or semi-minor axis). The value can be apparent, as measured from the occultation, or real according to the respective reference;
• **Error oblateness**: oblateness error;

• **b/a**: assuming $a > b > c$, the three axis of rotation symmetry for a tri-axial body, the ratio $b/a$ is a relation of the two equatorial radius. It is equal to unity for a Maclaurin equilibrium shape;

• **c/a**: following the same definitions as above, it is a relation between the biggest equatorial radius and polar radius;

• **Albedo (V)**: visual albedo of the object, as derived from the surface area obtained from the detected stellar occultation and given in the respective reference;

• **Error Albedo**: error of the derived albedo;

• **Density ($g/cm^3$)**: object’s density, as given in the respective reference, considering the derived or assumed volume from the occultation result. The density can be derived from the knowledge of its mass. Alternatively, it can also be obtained under the assumption of hydrostatic equilibrium, using the body oblateness associated with its rotation period can be used to derive its density [17, 5];

• **Error Density**: density error in $g/cm^3$ units;

• **Atmosphere (nbar)**: derived atmosphere surface pressure, or at a given distance, in nanobars. When the number is preceded by the symbol ‘<’, it represents an upper limit to the presence of a putative atmosphere;

• **Atm_gas**: atmospheric gases used to study the atmosphere and derive the given pressure;

• **Detected feature**: if any feature was detected, like rings, chasm, atmosphere, dust, jets, satellite, if the object is double or a binary, if an unknown secondary star was occulted, or any other physical property measured thanks to the stellar occultation;

• **Shape**: derived or assumed shape as obtained from the particular event, or as given on the respective reference. It can be equilibrium figures like Maclaurin, Jacobi or simply spherical, oblate, tri-axial, irregular, binary or undetermined shape. Single or double chord detections will most probably lead to an undetermined shape;

• **Kind**: what was detected, the main body, or only a satellite, only the ring(s), only the atmosphere, only jets/dust. Alternatively, it can indicate that the event was double, i.e. the occultation has probed two components of the system;

• **DynClass**: object’s dynamical class. Trojans are small bodies orbiting the Lagrangian points of a major body. Planet satellites are small bodies orbiting a planet. There is no consensus or formal definition on the dynamical classes of Centaur and Trans-Neptunian Objects (TNOs), so we decided to base our classification on the Deep Ecliptic Survey [18]. Centaurs are small solar system objects that have unstable orbits with perihelia greater than 5.2 astronomical unity (au) and orbital semi-major axis smaller than that of Neptune ($a < 30.1$ au). TNOs are objects with an orbital semi-major axis ($a$) greater than that of Neptune ($a > 30.1$ au); they are divided into different classes according to their orbital properties. In this work, these classes are defined as follows. The Kuiper Belt is a region extending from 30 to 50 au and is divided into three sub-classes, the Cold-classical and Hot-classical populations (also known as Cubewanos) [19], and the Resonant objects that are locked by Neptune in integer orbital period ratio with it. Among the resonant, we can find the Plutinos, which are in 2:3 resonance, such as Pluto. The Cold-classical objects have orbital eccentricity smaller than 0.2 and inclination smaller than 12 degrees; in contrast, the Hot-classical members have higher eccentricity and inclination values [20]. The Scattered population objects are those highly perturbed by Neptune, as they have perihelia between 30.1 and 40 au with high eccentricity. The Detached objects are well beyond Neptune’s orbit, away from any perturbation from it, with perihelia greater than 40 au.
• Delta (au): distance of the object centre to the geocentre, in astronomical units, at the event date;
• Star G mag.: magnitude of the occulted star in the ‘G’ wavelengths, as given by Gaia DR2 [10];
• Object G mag.: magnitude of the occulting object in the ‘G’ wavelengths;
• Position date: date and time in UTC of the object’s astrometric position as derived from the stellar occultation;
• Semi-major axis (au): Object’s orbital semi-major axis in astronomical units;
• Eccentricity: object’s orbital eccentricity.
• Inclination: object’s orbital inclination with respect to the ecliptic plane;
• Lucky Star project: if the event was predicted, observed and/or analyzed by a Lucky Star project4 collaborator;
• Reference: reference to the publication from which the information was obtained. The references are active links to the journal or any other kind of publication. When only a preliminary result was obtained, the event is indicated as preliminary and should be used with caution;
• DOI: Digital Object Identifier (DOI) number of the reference.

4. Results and Discussion

From the database, we can see that more than a hundred and fifty events have already been reported involving 61 different objects. The quantity of all reported events, separated by the different classes, is given in table 1. It is also possible to see that 57 of the detected events had more than two observed chords, enabling size and shape determinations. Interestingly, many different features have been discovered, such as high albedo, rings, dust, chasm and atmosphere, showing that we have a lot to learn from these distant small bodies.

| TNOs | Pluto | Dwarf-planets* | Centaurs | Trojans | Planet Satellites | Features* | Total |
|------|-------|---------------|----------|--------|-------------------|----------|-------|
| 54   | 28    | 4             | 27       | 21     | 23                | 31       | 154   |

Table 1. Total of events ever observed in a stellar occultation, per group. Dwarf-planets are those officially assigned by IAU [16]. Interesting to notice the high number of discovered features like rings, double stars, dust and even chasm. The * symbol indicates that the events promoted by Pluto system are not counted.

From the histogram of detections per year (Figure 1) it is possible to see a decrease in 2015 and 2016. This was partially caused by the end of the availability of the ”WFI” catalogue [21, 22, 23]. This catalogue consisted of star positions obtained from images made at the 2.2-meter telescope at La Silla/Chile from the Max Planck Institute, using the Wide Field Imager (WFI). The observations covered the apparent path of 49 TNOs and Centaurs from 2009 to 2015, with the aim of providing a high-precision position of stars fainter than those available in the UCAC catalogues [24]. With that, prediction of stellar occultations by these bodies could be made with higher accuracy. During these two years (2015-2016), the best star position catalogues

4 The Lucky Star project aims at predicting, observing worldwide and analyzing stellar occultations by small objects of the outer solar system. It receives funding from the European Unions Horizon 2020 Research and Innovation Programme (ERC), under the supervision of Prof. Bruno Sicardy (http://lesia.obspm.fr/lucky-star/).
available had errors on the order of 50 milliarcseconds (mas). This error, associated with the even bigger ephemeris errors, did not allow for precise predictions. An accurate prediction with errors smaller than the objects apparent angular size (about 30 mas) is needed for a successful campaign. As a consequence, many events were lost during these two years.

In September 2016 the Gaia DR1 catalogue was released [25]. Astrometric positions of TNOs could be obtained in the frame of Gaia DR1 and compared to DR1 star positions, leading to reliable predictions and an increasing number of detections. In April 2018 the second release of Gaia catalogue became available [10], with astrometric positions, proper motions and parallaxes of stars up to magnitude $G = 20$. This allowed not only accurate predictions thanks to the knowledge of the star position with sub-mas accuracy, but also accurate measurements of the target in the same frame [26].

Consequently, the number of positive detections has greatly increased. It is noteworthy that multi-chord detections have also increased, allowing for accurate size determinations, with remarkable results such as the detection of the plutino Huay, when more than 20 positives where detected, or the observation of Triton with more than 80 chords.

In Figure 2 we can also notice that at least one member of each of the dynamical classes was already probed with a stellar occultation event, allowing for a better understanding of the relations between their physical characteristics with their dynamics. It is also true that many of them are single chord detections, so a lower limit to their equatorial radius was obtained, but with the growing number of positive observations, due to precise predictions, it is clear that more and more objects will be precisely characterized in the near future.

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