The future of stellar occultations by distant solar system bodies: perspectives from the Gaia astrometry and the deep sky surveys

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Abstract

Distant objects in the solar system are crucial to better understand the history and evolution of its outskirts. The stellar occultation technique allows the determination of their sizes and shapes with kilometric accuracy, a detailed investigation of their immediate vicinities, as well as the detection of tenuous atmospheres. The prediction of such events is a key point in this study, and yet accurate enough predictions are available to a handful of objects only. In this work, we briefly discuss the dramatic impact that both the astrometry from the Gaia space mission and the deep sky surveys – the Large Synoptic Survey Telescope in particular – will have on the prediction of stellar occultations and how they may influence the future of the study of distant small solar system bodies through this technique.

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1. Introduction

Stellar occultation is a powerful technique that allows the determination of sizes and shapes of distant solar system objects with kilometric accuracy \cite{1,2,3,4,5,6,7} (leading to albedos, densities), an investigation of their immediate vicinities \cite{6,7,8} (telling about the presence of rings, satellites, jets), and that may reveal tenuous - down to few nanobars - atmospheres \cite{2,3,6,9}.

Accurate predictions\footnote{Where and when, on the Earth, an occultation event can be observed.} of occultation events are the very first step for the full success in the use of the technique. The relevance of this step is such that its improvement inevitably – and positively – affects the future of the study of distant small solar system bodies through stellar occultations.

Thanks to the astrometry from the Gaia space mission and the deep sky surveys, a huge advance in this study is closer than ever. More specifically, the first will provide over 1 billion stars with unprecedented (sub milli- to micro-arcsecond) astrometric accuracy (see, for instance, \cite{10,11}), while the latter, like the Large Synoptic Survey Telescope (LSST), will provide images from which short-term accurate ephemerides\footnote{Ephemerides whose uncertainties, for 1-3 years after the most recent observation used in the determination of these ephemerides, are smaller than the angular size of the respective occulting bodies as seen from the Earth.} of faint (down to $r \sim 24.5$ in the case of the LSST \cite{12}) solar system bodies can be determined. As a result, this will lead us to milli-arcsecond (mas) level - or better - predictions to tens of thousands of TNOs as explained in the next two sections.
Table 1: Quantities from Fig. [4] lower panels

| Technique          | $\Delta \alpha \cos \delta$ | $\Delta \delta$ | Dots | Code | Gaia |
|--------------------|-------------------------------|-----------------|------|------|------|
| Occultation        | 0 (±8)                        | −1 (±4)         | 15   | red  | Y    |
| Direct imaging     | 6 (±23)                       | −3 (±10)        | 8    | light blue | Y |
| Direct imaging     | 22 (±42)                      | 14 (±36)        | 15   | dark blue | N |

Technique: way that positions were determined (from occultation or from direct imaging); $\Delta \alpha \cos \delta$ and $\Delta \delta$: average of the differences in the sense position minus NIMA. Values between parenthesis are the respective standard deviations; Dots: number of measurements used to derive the values in the two previous columns; Code: colour code as given in Fig. [1] Gaia: Gaia-based position? Yes/No. Angular measurements are in units of mas.

2. The power of Gaia

Figure [1] shows the improvement in accuracy, thanks to Gaia, of the ephemeris of (10199) Chariklo as determined by our orbit fitting tool NIMA [13]. In that figure, the most relevant difference between its upper and lower panels is that the first is based on pre-Gaia astrometry, whereas the latter is dominated by Gaia DR1 [14] -based positions [15] (but see also [16] for a foretaste of the impressive data that will be delivered by the Gaia Data Release 2 from April 2018).

It should be noted that the uncertainty in the most recent version[4] of that ephemeris (lower panels) is significantly smaller than the angular size of Chariklo throughout 2018. And there are more accurate data and orbits to come! Note that all positions of Chariklo used here are from ground-based observations and that Gaia DR1 does not provide positions of small solar system bodies. Thousands of them, however, will be available in Data Release 2 [16], [17].

Currently, orbits determined by NIMA discriminates observational data (po-

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[4]On the date this paper was written.
Figure 1: Orbit improvement for Chariklo. Versions 8 (2016/JUN, upper panels) and 13 (2017/JUL, lower panels, the most recent one on the date this paper was written) of Chariklo’s orbit as determined by NIMA. In all plots we have: differences in right ascension and declination (black curves) in the sense NIMA ephemeris minus the Jet Propulsion Laboratory (JPL) ephemeris (version: JPL20); 1-σ uncertainty (grey area) of NIMA ephemeris; red points: differences between positions obtained from stellar occultations and those from the JPL ephemeris; dark/light blue points: differences between positions obtained from direct imaging of Chariklo and those from the JPL ephemeris; red vertical segments are provided for an easier visual correspondence between the dots and the dates associated to them; error bars represent the standard deviation of the observational residuals from the same night and same observatory. Red dots, in particular, represent one observation each so that no error bar is attributed to them. In the upper panels, all positions are based on pre-Gaia astrometric catalogues. In the lower panels, red and light blue points are now Gaia DR1-based. Some of these light blue points are a re-reduction of the non Gaia-based dark blue points in the upper panels. Note how well the Gaia-based positions agree with the orbit. Chariklo and its rings are also roughly represented in the lower right panel.
Figure 2: Logarithm of the weights ($\sigma^{-2}$) attributed to the points shown in the lower panels of Fig. 1. The same colour code is used.

Figure 2 indicates the different weights attributed to the positions mentioned above. Astrometric data from an occultation is obtained from the relative position of the occulting body with respect to that of the occulted star. This relative position is determined with mas level accuracy (see, for instance, [18]). Therefore, accurate stellar positions, as those given by the Gaia mission, provide mas level accurate positions of the occulting (solar system) body. In this context, it is natural that these points (red dots in Fig. 2) have the largest weights.

Table 1 quantifies the effect of the weighing scheme (see [13] for more details), that results in an orbit heavily dominated by the Gaia-based positions with emphasis to those from occultations.
The impact of the use of Gaia DR1-based positions from occultations can be seen in Fig. 3, from which the occultation data have been withdrawn. As compared to the lower panels of Fig. 1, we note not only a non negligible (at least in the context of predictions) difference between both ephemerides to those dates after that of the last observation but also a considerable increase in the uncertainty (grey zone). It is also important to note that, adding the occultation data, the ephemeris better fits the light blue (and also Gaia DR1-based) points, as expected. In this way, in the absence of occultation data, higher weights to the light blue points could be considered.

3. The power of LSST

The Minor Planet Center lists, to date, around 2600 transneptunian objects (TNOs) and Centaurs. The LSST, whose full science operations are scheduled to begin in 2023, will record the entire visible sky from Cerro Pachón about twice a week and observe millions of solar system objects, ~40 000 TNOs among them [12].

The survey expects to deliver astrometry accurate to 10 mas per exposure depending, among others, on the seeing and signal-to-noise ratio. In some cases, however, mas level accuracies may be required by stellar occultation predictions.
to observe satellites, grazing events by rings, topographic features, and bodies that may retain atmosphere. Therefore, a more careful astrometry may also be needed in specific cases and the previous section showed that this is possible.

It should be noted that many thousands of TNOs are expected to have more than one hundred observations along the ten years of operations of the survey [12]. These observations are crucial to, in association with the astrometry from Gaia, orbit fitting tools, and careful weighing schemes (e.g. [13]), obtain accurate enough short-term ephemerides to all those objects.

4. Comments and conclusions

A stellar occultation event is magnitude independent, in the sense that it only needs to record the flux variation of the star in an interval of time that contains its occultation. Therefore, the technique is suitable to also investigate the faintest occulting bodies. With Gaia and deep sky surveys we can expect the need to select events by focusing on, for instance, small groups of objects with different physical/dynamical features, instead of trying to observe them all. On the other hand, with the increasing amount of successful observations, we could also envisage a data-driven approach in the study of small solar system bodies uniquely from the occultations! The full profit of this exciting and quickly approaching scenario will, among others, rely on accurate predictions, on the amateur community, and on the availability of networks of small (20-40 cm) telescopes (e.g. [19]) with fast readout detectors around the world, as well as the appropriate support to storage and data processing (big data context).

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