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GAIAMOONS : STUDY OF BINARY ASTEROIDS WITH STELLAR OCCULTATION AND GAIA ASTROMETRY

R. Lallemand[1], J. Desmars[1,2], B. Sicardy[1] and P. Tanga[3]

Abstract. The latest releases from the *Gaia* mission of the European Space Agency have significantly increased the precision of the position of stars and of Solar System objects, especially asteroids. In this context, the *GaiaMoons* project aims to use GAIA data to detect oscillations in the trajectory of some asteroids, revealing the potential presence of a satellite. This method has produced a list of about 360 potentially binary systems, to be added to the objects already identified as such. This work will focus on the observational part of the project which consists in confirming the binary nature of these systems and their characteristics through stellar occultations, and the first associated results.

Keywords: Occultation, Minor planets, Binary objects, Characterization, Method: Observational

1 Introduction

In the process of planetary system formation, planetesimals are formed in the first few million years. Among these planetesimals, pairs of proto-asteroids (Nesvorny et al. 2021). Understanding the nature of these objects enables us to learn more about the formation processes of planetary systems as in the Streaming Instability model Nesvorny et al. (2019). Due to the lack of observational data, our knowledge is mostly limited to simulations. Indeed, we know very little about the actual number of binary objects in our solar system. Several observational campaigns have been carried out to try and identify them Merline et al. (2004), but unfortunately the results of these studies are biased by our observational techniques, like high resolution imaging that reveals mostly large objects with very small satellites that are far enough apart to be resolved Nesvorny et al. (2010). Moreover most of the asteroids are too small to be observed directly it is then difficult to confront simulation results.

During its movement across the sky plane, an asteroid with a satellite will have its trajectory oscillate periodically from the observer's point of view. This little wobble which derives from the difference between the center of mass and the photocenter can sometimes be measured thanks to the accuracy of Gaia data. Liberato et al. (2024) developed an astrometric method based on this phenomena to establish a list of 352 new potential binary system to be observed (the list is available online*).

Occultations are the alignment of three bodies. The observer (here from Earth's surface), an obscuring object (generally a Solar System object) and an obscured object (a distant star). Such phenomena are visible on a small part of the Earth's surface and for a short period of time. In particular, when observed from multiple places and by performing a photometric analysis of the data from each observer (a chord), occultations can reveal details such as the physical characteristics of the system (size, orientation, shape) with a kilometric precision, find its precise astrometric position at the time of occultation, but also to probe its immediate environment and in particular the presence of satellites, rings or atmospheres.Braga-Ribas et al. (2013). For binary system, physical and orbital parameters of the mutual system can be constrained by occultation. Therefore, we can use stellar occultation to confirm and study the binarity of objects. (Tanga et al. 2023) made an analysis of (4337)

[1] Institut de Mécanique Céleste et de Calcul des Ephémérides, IMCCE, Observatoire de Paris, PSL Research University, CNRS, Sorbonne Universités, UPMC Univ Paris 06, Univ. Lille, 77 Av. Denfert-Rochereau, F-75014 Paris, France.
[2] Institut Polytechnique des Sciences Avancées IPSA, 63 boulevard de Brandebourg, F-94200 Ivry-sur-Seine, France.
[3] Université Côte d'Azur, Observatoire de la Côte d'Azur, CNRS, Laboratoire Lagrange, Bd de l'Observatoire, CS 34229, 06304 Nice Cedex 4, France
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Arecibo's orbit using *Gaia* astrometry to derive its associated wobble whereas a satellite was found by stellar occultation. It is important to note that, however, the presence of a satellite was already known here. This paper will present the occultation prediction method for GaiaMoons targets, the organisation of observation campaigns and outline some recent results.

2 Method

2.1 Prediction

For all the 352 targets of the project, we have computed predictions of occultations of stars in the GaiaDR3 catalogue. For each of them, the input ephemeris prediction is the latest JPL prediction from *Horizons System*. When a system has been observed by occultation, the prediction of its orbit is updated using the NIMA code developed by (Desmars et al. 2015). The website `gaiamoons.imcce.fr` sums up these predictions, with circumstances of occultations, maps and observational information. On the map, zones where the satellite can be detected is also indicated between red lines.

Liberato et al. (2024) provides limits to the distance of the satellite based on assumptions on the density and the use of the wobble. This limit is indicated by red lines around the primary body on the prediction map (see Fig. 1). In a second phase, if previous occultations detected a satellite and constrained its position, it is represented in its relative position to the main body. All predictions take in account the uncertainty in the radii of these bodies in order to help potential observers.
This website offers access to events related to the *GaiaMoons* project worldwide. Users can browse a yearly list of events and filter them by factors such as the target star's magnitude, occultation duration, asteroid system, event date, and region of observation. A list of "important" events is also available, encouraging observation campaigns for events with optimal conditions. For each event, the site provides detailed occultation parameters, including time, duration, star position, object orbit, and other relevant characteristics.

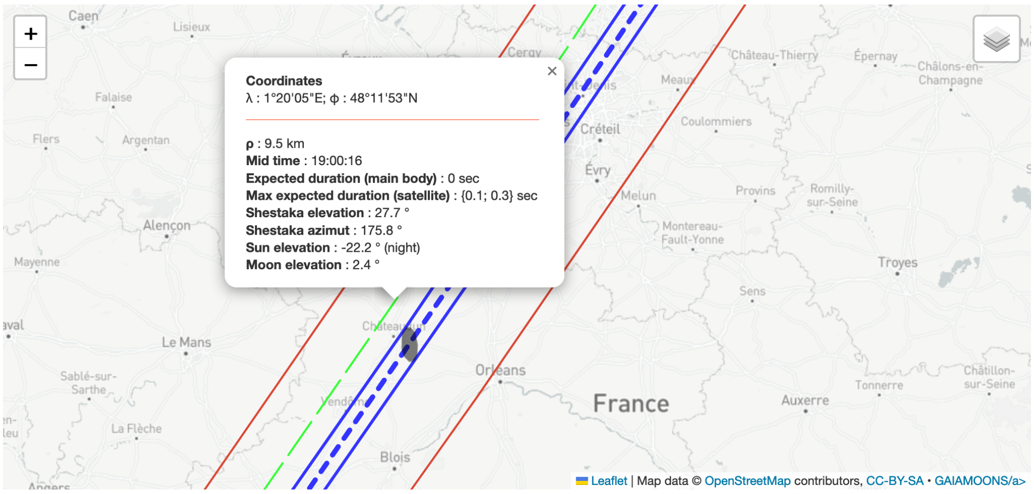

Fig. 1. Screenshot of the interactive map of the prediction of (5044) Shestaka occultation over France and Spain on 10/23/2024 - λ and ϕ are the coordinates of the pointed location. ρ is the closest geocentric distance from the shadow of the object. Mid time is the middle instant of occultation at this location. Expected duration (main body) and (satellite) are respectively the occultation duration expected for the main body and the satellite. Elevation and azimuth of the object are displayed as well as the elevation of the Moon and the Sun.

2.2 Observation campaign

Today, project such as Roadies (Desmars et al. 2022) are set up to provide equipment loans for observations such as TimeBoxes, cameras and computers in the near future. This is an important asset for the GaiaMoons project in particular, which will be able to use this advantage to increase the number of observers of occultation events, thereby increasing the resolution of the data.

Still, observing this type of event requires to face up to a number of challenges. First, since the size of the potential satellites (and sometimes the main body) are expected to be quite small, the associated mean occultation duration is expected to be less than 2 seconds for the most (see Fig. 2). Thus we need to use a short exposition time in order to be able to catch the lightdrop of the event. Plus, this requires to focus on rather bright stars (maximum apparent magnitude of 13) in order to work with a manageable Signal to Noise Ratio (SNR).

Moreover, it is essential to have a dense network of observers, including collaboration with amateur astronomers. This coverage on the ground allows for more comprehensive data collection. Precise localization using GPS coordinates and accurate timing of measurements are critical for obtaining reliable results. Observers must have the necessary resources, including training, to contribute effectively, and must remain committed to the project while having access to real-time information. These elements are vital to maximizing the accuracy and efficiency of observations, making the most of each observer's availability and expertise.

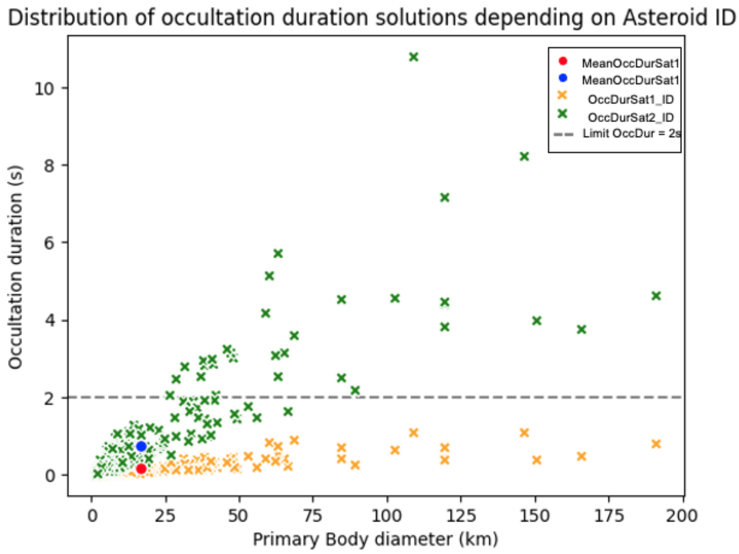

Fig. 2. Distribution of occultation durations for events between June and December 2024. Since Liberato et al. (2024) calculations leads to two differents solutions for satellites diameters, the distribution is divided in 2 subdivisions. For each asteroid, Yellow crosses stands for solution 1 with mean value on red dot $(x, y) = (16.6, 0.16)$. Green crosses stands for solution 2 with mean value on blue dot $(x, y) = (16.6, 0.73)$. The grey line represent the limit occultation duration at 2 seconds (arbitrary).

3 First results & analysis

The following table (see Tab. 1) provides a non-exhaustive summary of the occultation events of some asteroids observed among the GaiaMoons list in the period from February 2023 to August 2024. The derived diameter of the main body, geometric position derived in the sky plane, number of chords and the dates of the occultations are presented. Particular attention should be paid to (35420) 1998AG6, which is the object that has benefited from the most successful campaign to date, preliminary results highlight a particular shape that may be associated to a satellite or a very irregular object. Analysis of the observation data is still underway, and for the moment no conclusions can be drawn on its nature. Further observations will be necessary in the months to come.

4 Conclusions

During the last few months, we have developed a method for efficiently organising observation campaigns for targeted objects, giving different observers access to as much information as possible. The link between professional astronomers and amateurs network is a significant advantage and the result of several years of collaboration. The results presented in this work testify to the effectiveness of this method and are encouraging

Occultation results			
(ID) Object	**Date**	**Number of chords**	**Primary Diameter**
(31) Euphrosyne	2024/07/01	2 positives	**267.18 ± 4.15 km**
(146) Lucina	2023/02/22	1 positive	**131.28 ± 15.50 km**
(476) Hedwig	2024/03/10	1 negative	119.28 ± 9.37 km
(476) Hedwig	2024/04/16	1 positive	**113.808 ± 1.61 km**
(488) Kreusa	2024/04/15	1 negative	165.54 ± 3.33 km
(550) Senta	2024/03/21	2 positives	**37.87 ± 1.02 km**
(550) Senta	2024/07/06	1 negative	37.91 ± 1.09 km
(550) Senta	2024/08/21	1 positive	37.91 ± 1.09 km$^{(*)}$
(1024) Hale	2024/05/07	1 positive	41.90 ± 1.55 km
(1024) Hale	2024/06/30	1 negative	41.90 ± 1.55 km
(1509) Esclangona	2024/07/26	1 negative	9.53 ± 0.58 km
(4875) Ingalls	2024/03/12	1 negative	5.49 ± 0.10 km
(10418) 1990MC	2024/05/15	1 positive / 1 negative	5.99 ± 0.34 km$^{(*)}$
(35420) 1998AG6	2024/07/17	3 positives / 3 negatives	6.63 ± 0.12 km$^{(*)}$

Table 1. Non exhaustive synthesis of observation of asteroids in the *GaiaMoons* list. Displayed data are ID and name of the asteroid system, occultation date, number of positive and negative chords and the equatorial diameter of the primary body derived from this occultation with 3-σ uncertainty. **Bold** values are derived from occultation, values with a $^{(*)}$ are still under analysis and the rest come from the most recent literature using SsODNet Berthier et al. (2023).

for the periods to come. In the future, more observations are about to be organized and numbers of asteroids are to be characterized with precision. This characterization will serve for statistics of binaries and composition in the Solar System. In the end, dynamical studies of binary system using collected data may be performed.

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