SF2A 2025
A. Siebert, K. Baillié, M. Béthermin, F. Cantalloube, E. Josselin, N. Lagarde, J. Malzac, J. Richard, L. Selliez, O. Venot (eds)

FIRST GAIAMOONS OCCULTATION RESULTS WITH FEATURES SUGGESTIVE OF BINARITY

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

Abstract. *Context.* Binary asteroids play a key role in understanding the formation and evolution of the Solar System, through their dynamics and composition.

Method. Gaiamoons is a program that aims to detect and characterize such objects by using Gaia astrometric data and stellar occultations.

Results. Between October 2023 and February 2025, 113 occultation campaigns targeting 51 asteroids were conducted with professional and amateur observers worldwide, each providing precise constraints on asteroid positions, shapes, and potential satellites. Notably, some of these data exhibit features attributable to binary systems, such as (1127) Mimi.

Keywords: Occultation, Shape, Satellite, Object : Asteroids, Method : Observational.

1 Introduction

As 15% of Near-Earth asteroids (Pravec & Harris 2007) and many Trans-Neptunian Objects (TNOs) are expected to be binary systems (Noll et al. 2008), several studies have been carried out to look for undiscovered binary systems among known objects in the Solar System (Kovalenko et al. (2017), Ondřejov Asteroid Photometry Project* among many others). Gaiamoons is one of these projects, aiming to detect and characterize binary asteroids using Gaia's unprecedented astrometric precision and stellar occultations (Lallemand et al. 2024). As described in Tanga et al. (2023) thanks to Gaia observations, the offset between the photocenter and the center of mass of asteroids can be measured with high precision. For some objects, this offset exhibits a periodic oscillation that can be attributed to the presence of a satellite. As a result, a list of binary candidates has been established as explained in Liberato et al. (2024), providing a set of targets for further monitoring. Given its effectiveness and accuracy, stellar occultation has been selected as the preferred method to observe these objects.

Binary asteroids represent a key population for understanding the formation and evolution of small bodies in the Solar System. The presence of a satellite provides a natural way to determine the primary's mass through dynamical studies of the mutual orbit, which in turn allows the estimation of its bulk density and internal structure. Comparisons between densities and compositions offer crucial constraints on accretion processes, collisional history, and possible differentiation. Moreover, the fraction of binaries among different asteroid populations (Main Belt, near-Earth, trans-Neptunian) is an important tracer of their dynamical and collisional evolution.

Therefore, occultations allow these objects to be tracked with precision, enabling them to be studied in order to expand the current sample of known binaries, particularly in the Main Belt, which is currently biased by traditional observation methods (direct imaging, photometry, radar). This paper reports on the progress of Gaiamoons, presenting statistics on the observations performed and highlighting a specific system whose data indicate a potentially binary nature. The paper concludes with a discussion on the methodologies for conducting such observations and their further development.

[1] LTE, Observatoire de Paris, Université PSL, Sorbonne Université, Université de Lille, CNRS UMR 8028, 77 avenue Denfert-Rochereau 75014 Paris, France

[2] Polytechnic Institute of Advanced Sciences-IPSA, 63 boulevard de Brandebourg, 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

*https://space.asu.cas.cz/ ppravec/

2 Latest Updates from Gaiamoons

Since the beginning of the project, from October 2023 to September 2025, a total of 113 stellar occultation observations have been conducted, each involving at least one observer. Some planned campaigns were hampered due to adverse weather conditions or technical issues, which occasionally limited the data collection. Nevertheless, 62 of these events yielded at least one observed chord (positive or negative).

These campaigns targeted 51 different asteroids. Observations have been carried out across all five continents, with the largest contribution coming from Europe, particularly from France, Spain and Belgium. This is followed by contributions from East Asia (mainly Taiwan and Japan), the United States, Latin America, Australia, and a few events observed from North Africa. Several campaigns achieved multichord detections, which are crucial for resolving the shape and possible binarity of the targets. A notable campaign was an occultation by (5044) Shestaka, which yielded about 30 chords with 7 positive and 17 negative chords. These multichord observations provide highly accurate information on the position and shape of the targeted asteroids, which will be invaluable for future campaigns, as each observation helps refine the astrometry for subsequent events, see Appendix A of Sicardy et al. (2024)

3 The Case of (1127) Mimi

Among the various observations carried out, several systems exhibit characteristics consistent with those of a binary system, although this cannot yet be confirmed with certainty. One such system is (1127) Mimi, which has been observed four times since the start of the observational campaigns. Notably, two of these events were multichord observations, providing particularly interesting results that will be presented in the following sections.

3.1 Predictions & Observations

For (1127) Mimi, four occultation events were successfully recorded between October 2024 and February 2025. The first two events, observed in Japan on October 30th and November 7th, in 2024, yielded a single positive chord. In 2025, two additional events were recorded in France: the first, on February 16th, resulted in three positive chords and one negative detection, while the second, on February 26th, produced three positive and four negative chords. These two latter events provide the richest datasets for this target to date. The corresponding chord distributions and ephemeris prediction for each of these two events are presented in Figure 1. It should be noted that the number of participating observers was limited, partly due to adverse weather conditions and partly because of the large positional uncertainty of the suspected satellite, which constrained the geographical deployment of observing stations.

The predictions were produced using a dedicated code developed at the LTE[†] , which combines the Gaia star catalogue with the available ephemeris of the target object. The subsequent organization of observation campaigns was carried out in close collaboration with the amateur astronomy community (notably IOTA and Planoccult). Alerts containing detailed information about each event[‡§] were distributed to observers through a web platform specifically developed for this project, facilitating the coordination and preparation of the observing campaigns.

The collected data are subsequently hosted by the Occultation Portal (Kilic et al. 2022). The heterogeneity of the datasets represents a significant challenge, as in some cases the observations are provided as pre-processed products, while in others only the raw data are available, often in a variety of formats (e.g., .avi, .adv, .ser, .fits). When possible, a cross-check analysis is carried out using PRAIA (Assafin 2023) and PyMovie (Anderson 2019) in order to process and validate the observations. The reduced data are then analyzed using the SORA library (Gomes-Júnior et al. 2022) and existing information database on asteroids (Berthier et al. 2023). For each recording, the final lightcurve is reduced to retrieve the associated immersion and emersion time. The astrometric accuracy ultimately achievable from stellar occultations relies largely on the timing precision of the recorded events. To ensure this, most observers are equipped with modules that provide precise time-stamping of their measurements, typically via GPS-based systems or equivalent solutions. However, these systems may vary from one observer to another, and this variability must be carefully considered during the data analysis.

[†]Laboratoire Temps Espace, Paris Observatory
[‡]`https://gaiamoons.imcce.fr/occ.php?p=31761` (16 Feb. 2025)
[§]`https://gaiamoons.imcce.fr/occ.php?p=31764` (26 Feb. 2025)

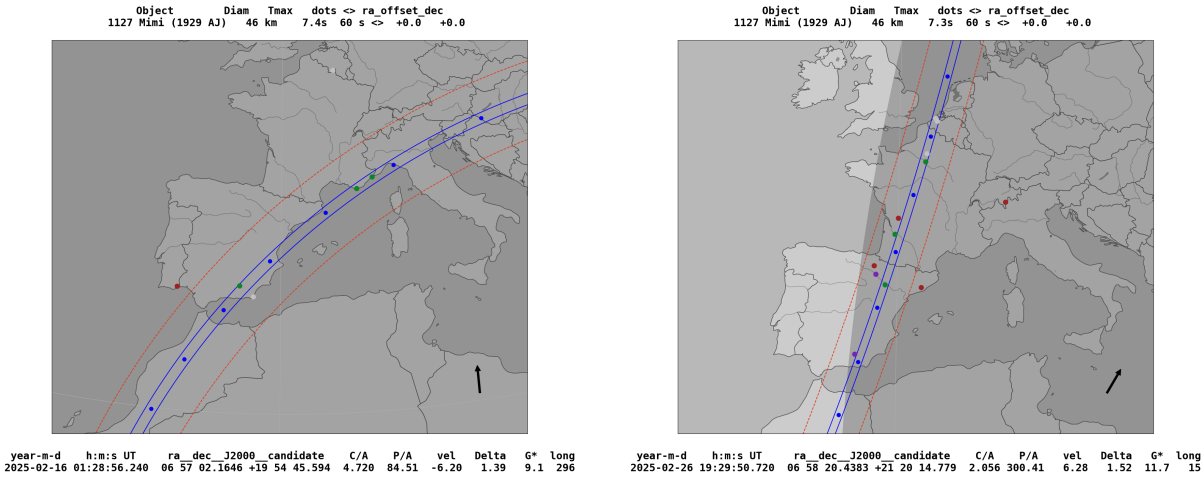

Fig. 1. Occultation shadow paths computed for stellar occultations by (112) Mimi. The blue lines indicated the shadow path borders, blue points within the path show the primary's position at one-minute intervals. The red dotted lines cover the estimated satellite uncertainty region. Observers are displayed with different colors depending on the associated observation status ; Red - Negative, Green - Positive, White - Overcast, Purple - Technical issues. Both event are presented with the relevant observational parameters at the bottom of the figure.**a) Left:** Occultation path for the February 16th Mimi **event** after the observation. **b) Right:** Occultation path for the February 26th stellar occultation by Mimi after the observation.

3.2 Preliminary reduction & analysis

The data obtained in February 2025 are presented in Figure 2. For the February 16th 2025 event, we note a significant offset between the measured occultation chords and the predicted shadow path, of the order of one predicted-radius distance - an offset that is noteworthy given the expected ephemeris accuracy. In this case, three chords were recorded on the primary body, together with one negative observation located well outside the predicted shadow track.

For the February 26th 2025 event, three positive chords were obtained, relatively well separated from one another. A preliminary analysis assuming a single-body model suggests an effective diameter significantly larger than expected, which points to the possibility that the event involved the detection of a satellite. A more detailed analysis of this occultation event will be presented in Lallemand et al. (2025).

3.3 Discussions

Stellar occultation observations present several intrinsic challenges. The vast majority of events have extremely short durations (less than about 2 s in 90% of cases; Lallemand et al. 2024), which requires the use of high-speed cameras by each observer and consequently limits the accessible target star magnitude to about 14. Obtaining detailed shape of the occulting body demands a dense network of observers, whose effective deployment depends on both the size of the primary and the often poorly constrained orbit of the suspected satellite. To answer to these, international coordination is necessary, often involving professional and amateur astronomers across multiple countries and time zones, as well as by the heavy reliance on the Gaia data for accurate predictions of the satellite's position.

These factors lead to heterogeneous datasets that can be difficult to interpret in isolation, frequently preventing firm conclusions from a single event. Progress therefore relies on the multiplicity of observations, which gradually improves the characterization of each potentially binary system and creates a virtuous cycle, where refined predictions lead to more successful campaigns and progressively better constraints. In addition, exploring archival occultation data may reveal previously overlooked signatures of candidate satellites; this approach will be further discussed in Lallemand et al. (2025).

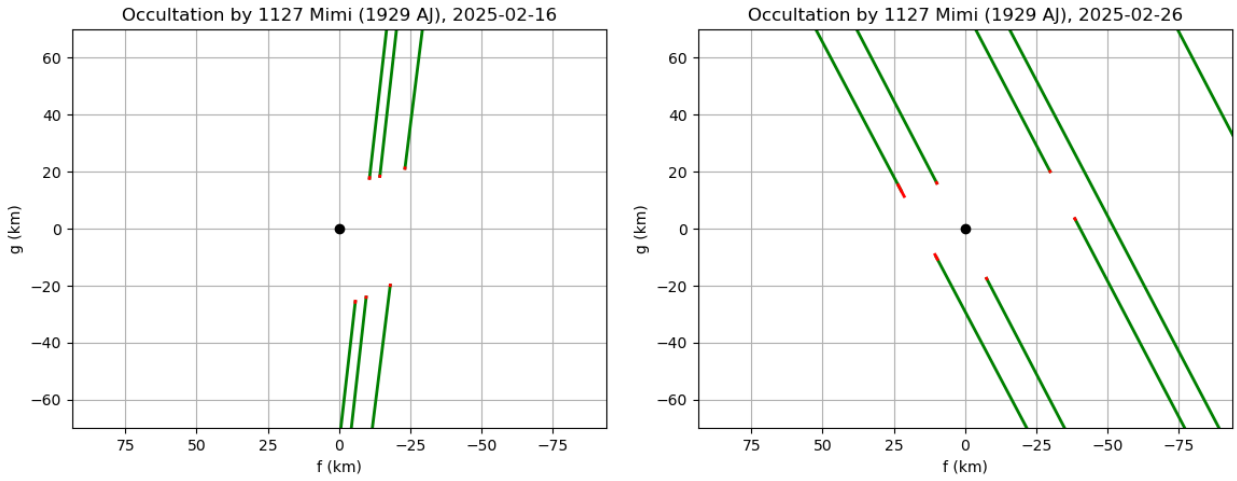

Fig. 2. Chords of the stellar occultations by (1127) Mimi on February 16th and February 26th, in the left and right panels, respectively. The observation chords are displayed in green. The empty spaces near the center correspond to the occultation. The ingress and egress uncertainties are displayed in red. The black dot is the center of the prediction used to construct the chords, based on the JPL#68 ephemeris.

4 Conclusions

The first results of the Gaiamoons occultation campaigns have been presented, which to date have targeted 51 asteroids in 62 successful events, delivering unprecedentedly precise astrometric, environmental, and shape data. Stellar occultations have proven to be one of the most effective techniques for detecting and characterizing binary asteroids. While no satellite has yet been definitively confirmed, several systems - notably (1127) Mimi - show features consistent with close or contact binaries. Each new observation enhances predictions for subsequent events, creating a virtuous cycle that refines our understanding of these systems. Progress relies on detecting astrometric shifts, securing multichord events, and exploiting negative chords to constrain satellite geometry. Ongoing efforts, supported by improved predictions and sustained collaboration, will be crucial to confirm candidate satellites and deepen our understanding of this population.

The Gaiamoons project is supported by the Agence Nationale de Recherche (France), grant ANR-22-CE49-0002. We thank the ROADIES program throught the API ProAm of Paris Observatory. We also thank all the observers who participated to the stellar occultation campaigns of the project. Especially Wolfgang Beisker, Mirel Birlan, Roland Boninsegna, Ferran Casarramona, Deborah Smith, Patrice le Guen, Eric Barbotin, Wolfgang Beisker, Jean Bourgeois, Oscar Canales-Moreno, Guillaume Langin, Philippe Henarejos, José-Luis Maestre, Pedro Martorell, Javier Prat, Carles Schnabel, Olivier Schreurs, Joël Souchu, Corine Yahia, Denis Bourdens, Stefano Sposetti.

References

Anderson, B. 2019, Journal for Occultation Astronomy, 9, 9

Assafin, M. 2023, Planet. Space Sci., 239, 105816

Berthier, J., Carry, B., Mahlke, M., & Normand, J. 2023, A&A, 671, A151

Gomes-Júnior, A. R., Morgado, B. E., Benedetti-Rossi, G., et al. 2022, MNRAS, 511, 1167

Kilic, Y., Braga-Ribas, F., Kaplan, M., et al. 2022, MNRAS, 515, 1346

Kovalenko, I. D., Doressoundiram, A., Lellouch, E., et al. 2017, A&A, 608, A19

Lallemand, R., Desmars, J., Sicardy, B., & Tanga, P. 2024, in SF2A-2024: Proceedings of the Annual meeting of the French Society of Astronomy and Astrophysics, ed. M. Béthermin, K. Baillié, N. Lagarde, J. Malzac, R. M. Ouazzani, J. Richard, O. Venot, & A. Siebert, 483–486

Lallemand, R. et al. 2025, In prep.

Liberato, L., Tanga, P., Mary, D., et al. 2024, A&A, 688, A50

Noll, K. S., Grundy, W. M., Stephens, D. C., Levison, H. F., & Kern, S. D. 2008, Icarus, 194, 758

Pravec, P. & Harris, A. W. 2007, Icarus, 190, 250

Sicardy, B., Braga-Ribas, F., Buie, M. W., Ortiz, J. L., & Roques, F. 2024, A&A Rev., 32, 6

Tanga, P., Pauwels, T., Mignard, F., et al. 2023, A&A, 674, A12