



Publication Year	2021
Acceptance in OA	2025-07-03T16:36:56Z
Title	Potential asteroid discoveries by the ESA Gaia mission. Results from follow-up observations
Authors	Carry, B., Thuillot, W., Spoto, F., David, P., Berthier, J., Tanga, P., Mignard, F., Bouquillon, S., Mendez, R. A., Rivet, J. -P., Le Van Suu, A., DELL'ORO, Aldo, Fedorets, G., Frezouls, B., Granvik, M., Guiraud, J., Muinonen, K., Panem, C., Pauwels, T., Roux, W., Walmsley, G., Petit, J. -M., Abe, L., Ayvazian, V., Baillié, K., Baransky, A., Bendjoya, P., Dennefeld, M., Desmars, J., Eggl, S., Godunova, V., Hestroffer, D., Inasaridze, R., Kashuba, V., Krugly, Y. N., Molotov, I. E., Robert, V., Simon, A., Sokolov, I., Souami, D., Tarady, V., Taris, F., Troianskyi, V., Vasylenko, V., Vernet, D.
Publisher's version (DOI)	10.1051/0004-6361/202039579
Handle	http://hdl.handle.net/20.500.12386/43052
Journal	ASTRONOMY & ASTROPHYSICS
Volume	648

Potential asteroid discoveries by the ESA *Gaia* mission

Results from follow-up observations

B. Carry^{1,2}, W. Thuillot¹, F. Spoto^{2,3}, P. David¹, J. Berthier¹, P. Tanga², F. Mignard², S. Bouquillon⁴, R. A. Mendez⁵, J.-P. Rivet², A. Le Van Suu⁶, A. Dell’Oro⁷, G. Fedorets^{8,9}, B. Frezouls¹⁰, M. Granvik^{8,11}, J. Guiraud¹⁰, K. Muinonen^{8,12}, C. Panem¹⁰, T. Pauwels¹³, W. Roux¹⁰, G. Walmsley¹⁰, J.-M. Petit¹⁴, L. Abe², V. Ayvazian^{15,16}, K. Baillié¹, A. Baransky¹⁷, P. Bendjoya², M. Dennefeld¹⁸, J. Desmars^{1,19}, S. Eggel^{1,20}, V. Godunova²¹, D. Hestroffer¹, R. Inasaridze^{15,16}, V. Kashuba²², Y. N. Krugly²³, I. E. Molotov²⁴, V. Robert^{1,19}, A. Simon^{25,26}, I. Sokolov²⁷, D. Souami^{28,29}, V. Tarady²¹, F. Taris⁴, V. Troianskyi²², V. Vasylenko^{25,26}, and D. Vernet²

(Affiliations can be found after the references)

Received May XX, 2020; accepted June XX, 2020

ABSTRACT

Context. Since July 2014, the *Gaia* mission of the European Space Agency has been surveying the entire sky down to magnitude 20.7 in the visible. In addition to the millions of daily observations of stars, thousands of Solar System Objects (SSOs) are observed. By comparing their positions, as measured by *Gaia*, to those of known objects, a daily processing pipeline filters known objects from potential discoveries. However, owing to *Gaia*’s specific observing mode, which follows a pre-determined scanning law designed for stars as *fixed* objects on the celestial sphere, potential newly discovered moving objects are characterized by very few observations, acquired over a limited time. Neither can those objects be specifically targeted by *Gaia* itself after their first detection. This aspect was recognized early in the design of the *Gaia* data processing.

Aims. A daily processing pipeline dedicated to these candidate discoveries was set up to release calls for observations to a network of ground-based telescopes. Their aim is to acquire follow-up astrometry and to characterize these objects.

Methods. From the astrometry measured by *Gaia*, preliminary orbital solutions are determined, allowing to predict the position of these potentially new discovered objects in the sky accounting for the large parallax between *Gaia* and the Earth (separated by 0.01 au). A specific task within the *Gaia* Data Processing and Analysis Consortium (DPAC) has been responsible for the distribution of requests for follow-up observations of potential *Gaia* SSO discoveries. Since late 2016, these calls for observations (nicknamed *alerts*) are published via a Web interface with a quasi-daily frequency, together with observing guides, freely available to anyone world-wide.

Results. Between November 2016 and the end of the first year of the extended mission (July 2020), over 1700 alerts have been published, leading to the successful recovery of more than 200 objects. Among those, six have provisional designation assigned with the *Gaia* observations, the others being previously known objects with poorly characterized orbits, precluding identification at the time of *Gaia* observations. There is a clear trend for objects with a high inclination to be unidentified, revealing a clear bias in the current census of SSOs against high inclination populations.

Key words. Astrometry and celestial mechanics – Minor planets, asteroids: general

1. Introduction

The main science driver of the European Space Agency (ESA) *Gaia* astrometric mission is the study of the structure and the dynamics of the Milky Way (Perryman et al. 2001). Building upon the heritage of HIPPARCOS, *Gaia* was designed to conduct a survey of the full celestial sphere (Brown et al. 2016), at an absolute precision of 25 micro-arcseconds (μas) for the parallax for $V=15$ mag, solar-type stars, and 13 $\mu\text{as}/\text{yr}$ for the proper motion. *Gaia*’s on-board image processing detects and measures all celestial sources brighter than ≈ 20.7 mag in G, *Gaia* wide visible filter (Jordi et al. 2010). It also measures the photometry in the G filter and low-resolution spectroscopy for all sources.

To achieve such accuracies, *Gaia* eliminates systematic errors by adopting the same strategy as its predecessor HIPPARCOS, i.e., by measuring simultaneously with high precision the epochs of transit of all sources in two fields of

view separated by a wide angle (the *Basic Angle*) of 106.5° , during a continuous scan at a constant rate (period of 6 h). The practical realization (e.g., pixel scale, binning) implies a widely different astrometric precision between the “*along scan*” (AL) direction (tangent to the great circle scanned by the rotation) and the perpendicular “*across scan*” (AC) direction.

Multiple transit observations of the same portion of the sky, with varying scanning directions, are therefore required to measure the positions at the required μas precision. This is realized through the precession of the spinning axis¹ in 64 days, always pointing 45° away from the Sun. The so-called Astrometric Global Iterative Solution (AGIS) produces the astrometric model of the whole sky, corresponding to the combination of all star positions and proper motions, plus calibration parameters. For a complete description of the

¹ which is anyway required to cover the entire celestial sphere.

satellite and its operation we refer the interested reader to Prusti et al. (2016); below we summarize some features that are relevant for the present work.

The two 1-m telescopes of *Gaia* are mounted on a structure pointing to the two fields separated by the Basic Angle, and produce an image on a single focal plane. The CCDs composing the focal plane operate in Time-Delayed Integration mode (TDI), in which electrons are moved from pixel to pixel at the same rate as the sources (hence the photo-electrons) drift along the CCD pixel lines (i.e., the AL direction).

Gaia's focal plane contains several instruments, each corresponding to different “strips” of 7 CCDs each. First, the SkyMapper (SM) instrument identifies the sources from each telescope and discriminates their origin between the two fields of view, by two CCD strips. It is followed by nine CCD strips for astrometry (the Astrometric Fields, AFs). Hereafter, *observations* refer to the positions on each of these 9 CCDs, while *transit* encompasses these observations, as in Spoto et al. (2018). Then two strips provide slitless low-resolution spectroscopy, splitting the visible spectrum in a blue and a red component, named BP and RP (Riello et al. 2018). A more restricted portion of the focal plane is devoted to the three CCD strips of the radial-velocity spectrometer RVS (Cropper et al. 2018), collecting high-resolution spectra of bright stars ($V < 17$). With each of these 16 CCD strips containing 7 CCDs (except the 3 RVS strips with only 4 CCDs each) and a few technical CCDs, *Gaia*'s focal plane is the largest ever operated in space in terms of the number of pixels.

The resulting large data volume poses a challenge for the telemetry. Since the start of its operations in July 2014, *Gaia* has been located at the Sun-Earth L2 Lagrangian point (0.01 au from the Earth). Upon detection by the SM, only small windows around each source are tracked along the focal plane. Most frequently, these windows have 6×12 pixels² only. Most of them are also binned in the AC direction so that only a unidimensional signal is transmitted to the ground. A notable exception is for sources brighter than $G < 13$, for which larger 2-D windows are preserved.

All the aforementioned characteristics of *Gaia* have strong consequences on its observation of Solar System Object (SSO) transits such as:

- Source tracking on the focal plane follows closely the rate of stars. For this reason, SSOs may drift with respect to the centre of the assigned windows in the AF, and ultimately leave it if the apparent velocity is large enough. A typical main-belt asteroid drifts by 1 pixel in AL during a transit over a single CCD (4.4 s) if it moves at a typically rate of 13 mas/s along the same direction.
- The motion of the SSOs produces a distortion of the signal, the shape of which is no longer well-represented by a pure stellar point-spread function.
- As a consequence, the astrometric and photometric processing must be adapted to cope with the resulting flux loss, variable and increasing over the transit.
- Each measured position of an SSO is strongly constrained in the AL direction (at the 0.1–20 mas level, depending on the astrometric solution used to reduce the data, see below) but much worse in the AC direction (~ 600 mas).

- The identification of SSOs, due to their motion relative to stars, cannot be determined by the internal cross-matching of sources (which is the root of the creation of the stellar catalog, Fabricius et al. 2016) but must rely on a specific processing requiring an external catalogue of orbits.

The potential for Solar System research of the absolute and extreme-precision astrometry, photometry, and low-resolution spectroscopy of *Gaia* was recognized early on (Mignard et al. 2007). Furthermore, early estimates considering the limiting magnitude of *Gaia* and the completeness of SSO catalogs, predicted about a hundred discoveries of SSOs per week (mainly main-belt asteroids, with potentially a couple of near-Earth asteroids, and no objects in the outer Solar system: Mignard et al. 2007; Carry 2014).

While large ground-based surveys (e.g., Pan-STARRS, Catalina Sky Survey, Legacy Survey of Space and Time) are expected to discover and gather multiple observations of most objects, the specific location of *Gaia* and the small solar elongation (45°) reached by its observations allows the discovery of near-Earth asteroids (NEAs) with small aphelion distances.

Within the *Gaia* Data Processing and Analysis Consortium (DPAC), the potential for SSO discoveries led to a specific workflow for SSOs, consisting in two chains. A short-term processing pipeline (named SSO-ST) runs daily to identify SSOs in the latest (72 h) transits (Tanga et al. 2016), and to trigger follow-up observations from the Earth. A ground-based follow-up network of telescopes (*Gaia*-FUN-SSO) was established to ensure observations and confirm *Gaia* discoveries (Thuillot & Deneffeld 2018). The long-term processing pipeline, named SSO-LT, benefiting from the full global astrometric solution of *Gaia*, runs on longer timescales to produce the catalogues with the best astrometry, photometry, and spectroscopy of SSOs for the various Data Releases (DRs, of which the first with SSOs was *Gaia* DR2, see Spoto et al. 2018).

We focus here on the results of the SSO-ST over the course of the *Gaia* nominal mission (July 2014 – July 2019) and the first year of the extended mission (July 2019 – July 2020). The article is organised as follows. Section 2 summarizes the main steps of the daily processing (beyond the description of the chain provided by Tanga et al. 2016). Section 3 presents the system through which calls for observations of potential discoveries are released. The network of ground-based telescopes is presented in Section 4, and a summary of the successful SSO recoveries in Section 5. We discuss the orbital properties of the alerts in Section 6.

2. The SSO-ST daily processing

We briefly summarize the daily processing of *Gaia* observations in the framework of the SSO-ST. For a full description of the pipeline, we refer to Tanga et al. (2016) and *Gaia* documentation³. We focus here on its differences with the long-term processing, which is thoroughly documented in Spoto et al. (2018).

An Initial Data Treatment (IDT) of the *Gaia* data is performed upon reception on Earth (Fabricius et al. 2016). After obtaining the signal parameters that describe the position of a source on the focal plane at the observing epoch,

² The angular size on the sky of the pixels of the Astrometric Fields is 59×177 mas.

³ <https://gea.esac.esa.int/archive/documentation/>

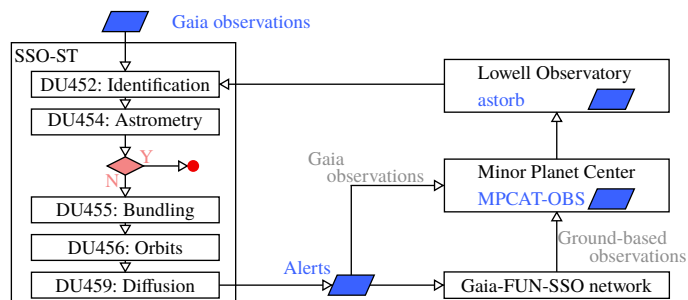


Fig. 1: Simplified workflow from *Gaia* observations to alert dissemination, reporting to the Minor Planet Center, and update of *astorb*, the database of orbital elements used for the identification.

IDT uses a preliminary great-circle attitude solution to derive its position on the sky, and executes a first cross-matching to sources previously observed. Typical sources that fail cross-matching are either artifacts (e.g., cosmic ray, diffraction spikes from bright sources, spurious detections), sources at the limit of detection (detected only on certain transits), or transients such as genuine moving objects from our Solar System. The position of the latter always changes on the sky. In these cases, the unmatched sources are removed from the main stellar data processing, and are available for a special processing for SSOs (Figure 1).

The first task of this processing is to identify if the source corresponds to a known SSO (task performed by the Development Unit DU452 of *Gaia* DPAC). Potentially, all unmatched sources are SSO candidates. However, SSOs constitute a very minor fraction of all the sources continuously transiting the focal plane of *Gaia*. By taking a somewhat optimistic number of 350,000 asteroids that *Gaia* can observe during the entire duration of its mission, *Gaia* observes on average 1 SSO for every 4,000 stars. It is clear that any inefficiency in the IDT cross-matching for stars can produce an overwhelmingly large number of false SSO detections (for instance, at a 99.9% efficiency, there are 4 unmatched stars for each genuine SSO).

Furthermore, a very large number of contaminants at the CCD level was found to heavily populate the sample of unmatched detections, making the task of SSO identification impossible without appropriate cleaning of the data set. The appropriate filtering was made possible by introducing in IDT the computation of the AL velocity of the source (and AC whenever possible) on the focal plane. All sources without a detectable motion are discarded. The threshold is dynamically adjusted on the base of the velocity distribution for each 1-day data chunk and is typically of the order of ± 2 mas/s.

For an object that passes through the filter, its positions are checked against the predicted positions of known SSOs at the corresponding epochs. Weekly, the catalogue of oscillating orbital elements of the minor planets *astorb*⁴ (Bowell 2014; Bailen et al. 2020) is updated, the ephemerides for all SSOs are pre-computed and stored in a database (this is a version of the SkyBoT software dedicated to *Gaia*, see Berthier et al. 2006, 2016, for more details). If not linked with a known SSO, the source may still be either a known SSO with a poorly characterized orbit (which precludes

identification), an unknown SSO, or an artifact as listed above. Because the identification relies on an external catalogue, it is crucial to keep the latter up to date. Similarly, any bias in the current census of SSO populations will affect the identification.

A suite of different tasks are then performed in chain on each unidentified source. The suite of observations (i.e., SM+AF, up to ten) defining a transit is converted into sky coordinates by DU454, after being subjected to a quality filtering to mitigate the distortion effects, due to the motion, on the accuracy of the centroid determination (DU453). The only attitude (the transformation from pixel coordinates to sky coordinates) available hours after the observations is the *poor* (by *Gaia*'s standards) Oga1 attitude, containing many irregularities. One of the tasks of DU454 is to smooth the attitude and remove these irregularities, which is necessary to check whether a linear motion in the sky can be fit to the transit. The obtained smoothed attitude has typical uncertainties of 25 mas in AL and 40 mas in AC, which is still much larger than the uncertainties on the high-quality Oga3 attitude that will be determined by AGIS, months later (hence too late to be used for alerts) for the data releases. Next, DU454 will try to fit a linear motion on all positions of a transit, and remove those that do not fit on the linear motion, and that are either of too bad quality, or not detections of the SSO. If no linear motion can be fit at all on the transit, the entire transit is rejected, and is supposed to be a contaminant.

A procedure (DU455) then attempts to link together transits, in order to identify which ones belong to the same source. Based on current census of asteroids, their typical apparent motion on the sky as a function of solar elongation (the most important parameter for this task) is determined. The linking procedure then performs an efficient search to find all possible links that satisfy this typical motion. The result is further filtered on similarity of the measured apparent magnitude, and compatibility of the apparent motion with the instantaneous velocity produced by IDT. This process is applied daily on the last 48 hours worth of data. Once at least two transits are linked together, the source may be a genuine moving object. However, a few transits by *Gaia* (two or three only, in 45% and 10% of the cases, providing less than 6 h of observations, Tanga 2011) are not enough to compute an accurate orbital solution. The uncertainty associated to these preliminary orbit solutions are inversely proportional to the number of transits (Figure 2).

A short-arc solution, valid for a limited interval of time, is, however, required for ground-based follow-up, which is essential to secure the orbit. The proximity of SSOs compared to the Earth-*Gaia* distance implies large parallaxes: from an arcminute for the distant Kuiper belt at 30 au from *Gaia* to over a *degree* for nearby (less than 0.5 au) Mars-crosser and near-Earth asteroids. Because the distance of SSOs is unknown upon first observation, the parallax cannot be accounted for to convert the coordinates measured by *Gaia* into Earth-based coordinates. Preliminary orbits based on *Gaia* short arcs are thus computed within the SSO-ST (in the processing unit named DU456) to allow short-term predictions (Muinonen et al. 2016) and to guide ground-based observations. These preliminary orbits are determined through a random-walk independent sampling of ranges of SSOs. This provides 2000 candidates orbits (represented by Keplerian elements) for each new source. We refer to Fedorets et al. (2018) for details.

⁴ Based on the world-wide catalog of observations maintained at the Minor Planet Center (MPCAT-OBS, Rudenko 2016).

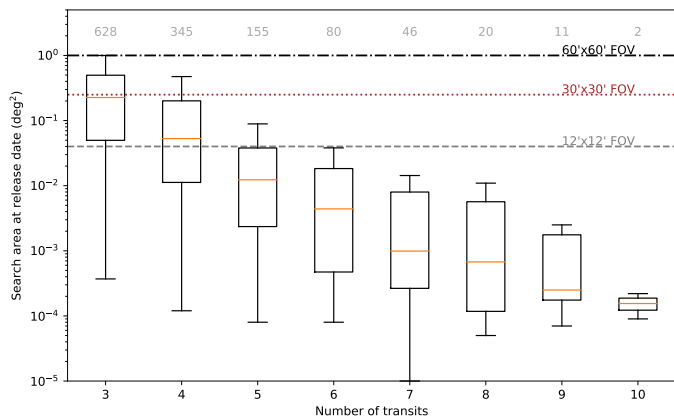


Fig. 2: Area on sky (present as 25-50-75% whiskers and 3σ min,max) covered by the preliminary orbits as function of the number of *Gaia* transits used. The gray numbers at the top correspond to the number of alerts released with the associated number of transits.

These short-term orbital elements, improved by ground-based follow-up, adds enormous value to *Gaia* observations. First, without follow-up observations, these *Gaia* observations are “lost” as they cannot be linked with any known object. Second, without an orbit, the observed properties (position, apparent G magnitude, BP and RP spectra) of these asteroids cannot be appropriately studied or understood in the context of SSO populations. Such situations can arise in modern surveys and can lead to a significant loss of valuable data. As a matter of example, the latest release (2008) of the moving object catalog of the Sloan Digital Sky Survey (Ivezic et al. 2001) contains over 470,000 observations of moving objects of which only about 220,000 are linked with known SSOs.

The SSO-ST was set up to avoid such a situation. Its main goal is to release calls for observations (*alerts*) of these unidentified sources, allowing for observations from the Earth and hence the determination of a preliminary orbit, and update of the database of orbits (Figure 1).

The pre-launch plans for the SSO-ST were to process all SSOs with at least two transits by *Gaia*. The majority of cases represent the situation where only two transits exist for an object. However, the spread of orbital solutions for these cases typically results in a large spread of solutions on the sky. This renders any follow-up efforts unfeasible. Therefore, we operate the pipeline for objects with a minimum of three transits (Figure 2).

3. The alert release interface

An interface to release the calls for observations (*alerts*) to the community of observers was set up. This is the last task of the SSO-ST (DU459), the workflow of which is described in Figure 3.

All sources are treated independently. For each, the geocentric ephemerides of the 2000 orbits are computed for 30 days starting at the current epoch, with a time step of one day. At each computed epoch, the different orbits result in a cloud of different positions on the sky. The median position with the estimated apparent velocity vector, the convex hull of the cloud, and its angular surface are computed at each time step, and stored in a database.

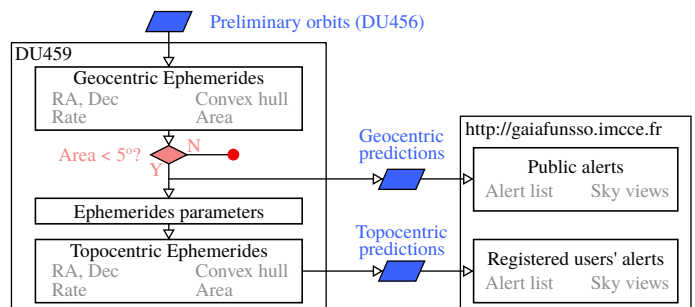


Fig. 3: Simplified workflow of alert processing and diffusion. Alerts are selected based on geocentric ephemerides. For each alert below the area threshold, topocentric ephemerides are computed for each observatory in the system. All ephemerides are stored in a database which is used by the Web pages.

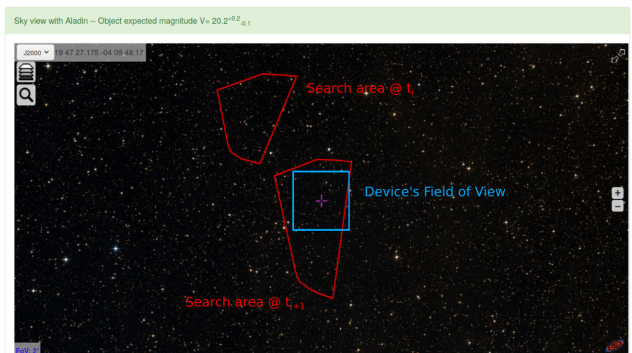


Fig. 4: Example of the sky view of alerts with AladinLite. The red polygons correspond to the convex hull of the cloud of predicted position at different dates, and the blue square represents the field of view of the device defined by the user (only available upon registration).

Given the spread in the initial orbital elements, the dispersion of the cloud of predicted positions increases over time. When the search area has grown beyond a certain size, a very large field of view or a time-consuming search strategy would be required. For this reason, the alerts are considered to be valid only between the epoch of computation and the epoch at which the area on sky becomes larger than five square degrees. If at the first epoch, the area is already larger than this threshold, the corresponding alert is skipped and the pipeline processes the following entry in the alert list.

Topocentric ephemerides (for each observatory registered in the system, see below) are then computed. The time step and duration of prediction are adapted to each observatory, according to each user’s preference (i.e., maximum search area on the sky). Similarly to the geocentric ephemerides, the area, median position, and convex hull of the cloud of predictions are computed for each alert, observatory, and time step; and stored in a database.

All these predictions are published online through a suite of online portals⁵. A public page lists all the alerts whose area is smaller than one deg² and the apparent magnitude brighter than $V=21$, based on their geocentric ephemerides. For each alert, the dates of release and end

⁵ <https://gaiafunso.imcce.fr/>

of validity are given, together with an identifier⁶, the predicted median Right Ascension and Declination, area, and apparent magnitude. The details of each alert are accessible on specific pages, in particular a display of the convex hull of the predictions at each time step with *AladinLite* (Figure 4, Bonnarel et al. 2000).

These geocentric predictions are available to everyone. More functionalities are, however, provided to registered users. Anyone can register for free to the system, by filling a simple form. Upon registration, users can easily list their observing devices (i.e., observatories). The main characteristics of each device are its location on Earth (either by entering its longitude, latitude, altitude, or IAU MPC observing code⁷), its field of view, and the thresholds in apparent magnitude and area on sky to consider for alerts. Hence, for registered users, the list of alerts proposed by the Web pages contains only those fulfilling the user’s observability criteria: apparent magnitude brighter than the threshold, area on sky smaller than the threshold, declination observable from the observatory. Furthermore, the pages presenting the details provide additional features:

- the *AladinLite* sky view shows the field of view of the device, to help preparing the observations (Figure 4);
- the convex hull at each time step can be downloaded (to be used in *Aladin* or user in-house software);
- a simple page is proposed to observers to report on the status of their observation (success or target not found).

4. The *Gaia*-FUN-SSO ground-based network

As explained in Section 2, the necessity of follow-up observations from ground-based stations was recognized early on. Two aspects, closely related to the specificity of *Gaia*, required multiple stations, widely spread over the globe to cover a large range of longitude and latitude. First, *Gaia* is an all-sky surveyor, hence requiring follow-up stations in both the northern and southern hemisphere. Second, the strong yet unknown parallax between *Gaia* and the Earth carries a significant uncertainty on the sky coordinates of any new detections (Bancelin et al. 2012), which increases with time (Figure 5). Observations as early as possible after detection by *Gaia* are therefore more likely to succeed than delayed ones, calling for a wide coverage in longitudes.

Before the launch of *Gaia*, efforts were conducted to build this large network. The early assessment of the magnitude range of potential discoveries opened the possibility of alerts observable with modest apertures (0.5 to 1 m). Our requests for volunteers were warmly received, and over 150 participants, including amateur astronomers, had registered in the alert release system by the time of *Gaia*’s launch. We consolidated and interacted with the network of volunteers (observations were to be conducted on the best-effort basis) through three workshops, held in Paris Observatory in 2010, 2012, and 2014 (Tanga & Thuillot 2010, 2012, 2014). We also trained the network to react to alerts by releasing calls for observations on NEAs (Thuillot et al. 2015).

⁶ The nomenclature is gYwNNN, with Y the year of *Gaia* operations, w the week of the year, NNN the incremental number of alerts in that week.

⁷ <http://vo.imcce.fr/webservices/data/displayIAUObsCodes.php>

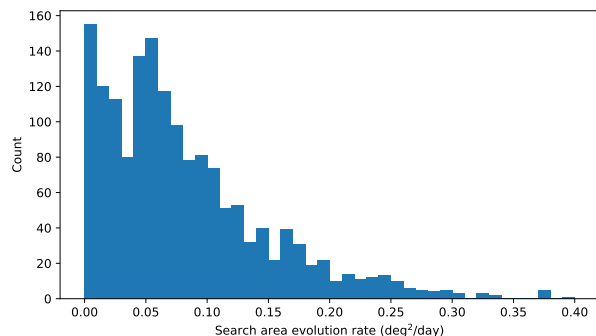


Fig. 5: Distribution of the growth rate of the search regions, in deg^2/day , for all alerts released since November 2016. The median growth rate is $0.06 \text{ deg}^2/\text{day}$ with a standard deviation of $0.08 \text{ deg}^2/\text{day}$.

However, the contribution of the network has been concentrated in only a few observatories since 2016, with fewer detections per week than foreseen. First, between the early assessment of the *Gaia* capabilities for SSOs in 2007, the start of the *Gaia* operations in 2014, and the effective daily processing of alerts in November 2016 (see below), wide surveys (Pan-STARRS, WISE) had discovered most of the SSOs observable by *Gaia* ($V \leq 20.7$). The bulk of alerts hence corresponds to objects fainter than $V \approx 20$, seldom brighter (Figure 6). Telescopes larger than typically 1 m are therefore required, and cameras with large field of views are favoured, which strongly limits the potential contribution by amateurs. Second, the areas to search within increase with time due to the lack of constraints on the short-term orbit (Figure 5, Figure 7). Owing to delays from the observation on-board to the downlink to Earth, to the initial data treatment and finally to the many steps in the SSO-ST, alerts are released at the earliest about 48 h after the observations. The area and its evolution with time are strongly tied to the number of transits observed by *Gaia*. With increasing delay, it is often required for observers to scan the area to search with multiple exposures as it becomes larger than their instrument field of view.

Although that fact limited the kind of facilities participating to the network, the numerous discoveries by other surveys did not reduce the interest in the SSO-ST. First, *Gaia*, being an all-sky survey observing at solar elongation between 45° and 135° , provides the opportunity to discover SSOs in region of the sky poorly covered by ground-based telescopes. Second, SSOs with poorly characterized orbits are likely not recognized and hence are processed by the SSO-ST as new sources. Observations by the network provide new constraints which improve their orbit, allowing the MPC to link them with known SSOs, and hence a subsequent identification by *Gaia* or by ground-based observatories.

5. Results

Soon after the start of *Gaia*’s regular operations in September 2014⁸, the SSO-ST faced several issues, which did

⁸ The scanning law during the first three months, called Ecliptic Pole Scanning Law (EPSL), was different (Clementini et al. 2016)

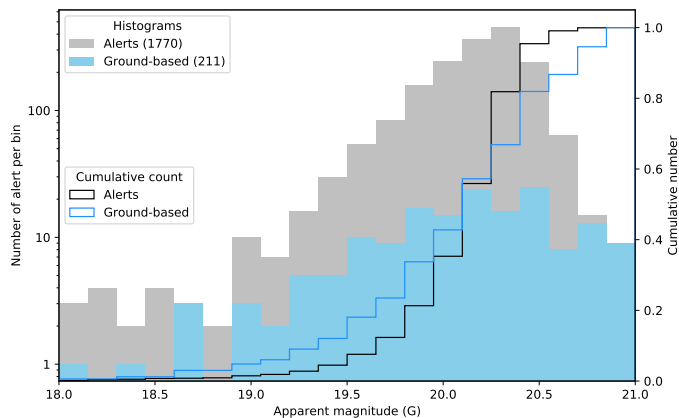


Fig. 6: Distribution of the G magnitude of all alerts and of ground-based observations.

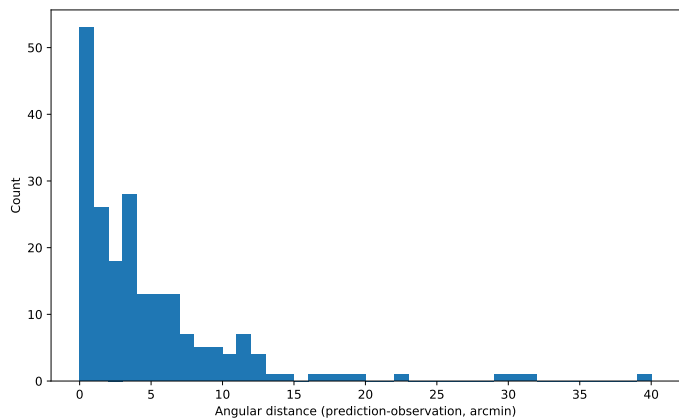


Fig. 8: Distribution of the angular distance between the predicted median (RA,Dec) coordinates and the observed position measured from the ground.

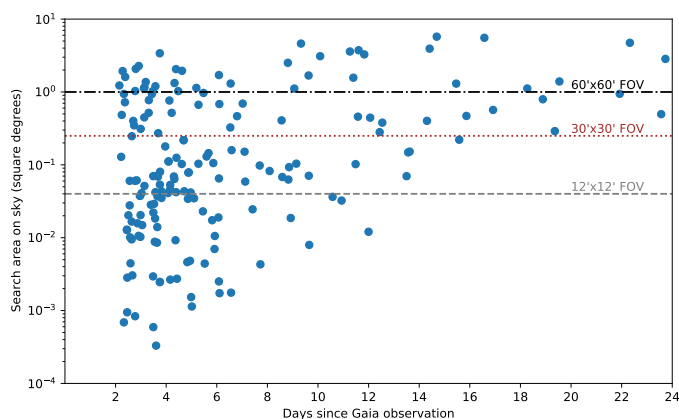


Fig. 7: Extent (in square degrees) of the search regions of alerts at the time of their observations by the network, counted in days since *Gaia* observations.

not show up in the pre-launch simulations. The major issue which delayed the release of alerts was the number of contaminants, several orders of magnitude above expectations. Filtering these contaminants required several cycles of tests and adaptations of the SSO-ST pipeline, so that the pipeline became fully functional no earlier than November 2016, which is a delay of 24 months with respect to the expectations. Since then, the pipeline has been very robust, running continuously on the computation facilities of CNES, in Toulouse, France, with the exception of a few technical breaks. It has also proved to produce a clean set of alerts in the output, effectively rejecting the contaminants.

Since the start of the automated operations, more than 1700 alerts have been released. Observations from the ground have been performed for almost 250 of them, leading to the successful observation of 227 *Gaia* discovery candidates. Most of these observations were performed by a small number of observatories (Table 1) and an even smaller number of astronomers (the observations at C2PU, OHP, and LCOGT being carried out by the same observers, within a concerted effort to follow-up alerts from *Gaia*, for SSOs as described here but also photometric alerts, e.g., Simon et al. (2019)).

This limited number of participants with respect to the large network built before launch, is the result of two effects.

First, the delay between the launch of *Gaia* and the starting date of alert releases lowered the interest of observers in the alerts. Second, the distribution of apparent magnitude and area of sky (Figure 6 and Figure 7) limited the participants to those using large aperture telescopes with optical configurations providing large fields of view.

As such, most of the ground-based follow-up has been performed by the co-authors of the present article. Early observations were mainly performed at the OHP 1.2-m telescope, of which field of view ($12' \times 12'$) seldom covered the entire search region. Hence, we had to scan the search area with multiple exposures, slowing the process. We soon started to use the C2PU 1-m telescope, whose field of view ($38' \times 38'$) was more adapted to our needs. The successful recovery of the alerts g1P024 and g1j03C (2012 VR₈₂), at these telescopes in 2017 showed the pipeline was delivering real SSO alerts which could be confirmed from the ground, starting from the receipt of alert and up to almost ten days after (Carry et al. 2019).

While the number of recoveries increased, we noted that most objects are found well within the search area, on average at only $3'$ from the median of the predicted coordinates (Figure 8). In other words, the area in the sky of alerts can be large, but the reported medians (RA,Dec) are good estimators of the positions. Therefore, we continued to observe with the 1.2 m at the OHP. Following these first recoveries, the number of successfully observed alerts dramatically increased with the use of the Las Cumbres Observatory Global Telescope (LCOGT) network, which offers 1-m telescopes with large fields of view ($27' \times 27'$) spread worldwide, hence perfectly adapted to the distribution of alerts on the celestial sphere (Figure 9) and to the large search area.

Before sending ground-based astrometry to the MPC, we always test whether the observation indeed corresponds to the object detected by *Gaia*. To this end, we compute an orbit based on both the *Gaia* transits and the ground-based astrometry (the latter measured with the *Gaia* Ground Based Optical Tracking software, Bouquillon et al. 2014). We use a modified version of `OrbFit` (Orbfit Consortium 2011), used to validate the astrometry of SSOs in *Gaia* DR2 (Spoto et al. 2018).

The MPC has been collecting the minor planet astrometry acquired worldwide for decades. Upon reception of astrometry of a unidentified object, such as a *Gaia* alert, the

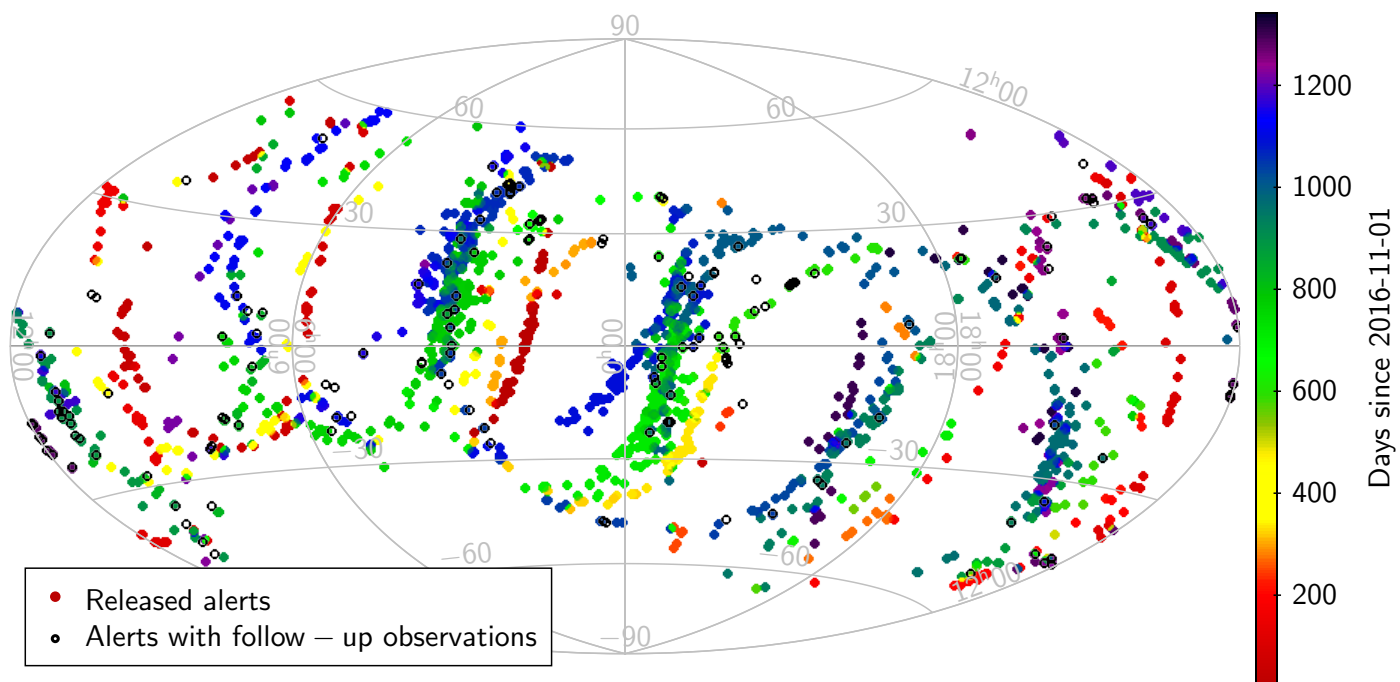


Fig. 9: Distribution of the alerts in equatorial coordinates (dots, colour-coded by epoch), together with the ground-based observations (open circles). The black line represents the ecliptic plane.

Table 1: Most-participating observatories of the network, with their numbers of detection (up to July 2020).

Observatory	Code	Country	Apert.(m)	Detections
Observatoire de Haute Provence (OHP)	511	France	1.2	44
C2PU, Observatoire de la Côte d’Azur)	010	France	1.0	23
Terskol Observatory	B18	Ukraine	0.6 & 2.0	27
Kyiv Comet station	585	Ukraine	0.7	21
Odessa Mayaki Observatory	583	Ukraine	0.8	18
Abastumani Observatory, Tbilisi	119	Georgia	0.7	
	V37	USA	1.0	
	V39	USA	1.0	
	W85	Chile	1.0	
Las Cumbres Observatory	W86	Chile	1.0	
	W87	Chile	1.0	
Global Telescope Network	Q63	Australia	1.0	113
	Q64	Australia	1.0	
	K91	South Africa	1.0	
	K92	South Africa	1.0	
	K93	South Africa	1.0	

MPC tries to link it with known objects, based on its observation database, including its unpublished part. Several cases are possible: the alert can correspond to a new object never observed before, an object recently detected by another observatory and not yet ingested in the `astorb` database, or a known object with a poorly determined orbit (which precluded its identification within the SSO-ST and from the ground).

The MPC is the sole international organization collecting astrometry, and we entirely rely on it to know if the *Gaia* alerts were hitherto unknown objects or recoveries of newly/poorly characterized SSOs. The *results*⁹ page of the *Gaia*-FUN SSO Web interface lists the designations of all recovered alerts. Of the 250 follow-up observations, 139 have

received a designation, but only 6 are attributed to *Gaia* (2018 XL₂₀, 2018 XL₄, 2018 YK₄, 2018 YM₄, 2019 CZ₁₀, 2019 HO₄). However, the others were poorly-characterized SSOs, and their observation in the context of the *Gaia*-FUN-SSO drastically improved their orbital elements.

6. Orbital distribution

We use the designations assigned by the MPC to retrieve the orbital elements of the SSOs that led to alerts. We compare their distribution in semi-major axis, eccentricity, and inclination in Figure 10.

As of July 2020, all the recovered *Gaia* alerts concerned main-belt asteroids. Considering that 139 alerts were assigned a designation and that the incidence of NEA was expected to be 1–2%, it is not surprising. Moreover, the SSO-

⁹ <https://gaiafunssso.imcce.fr/stats/network.php>

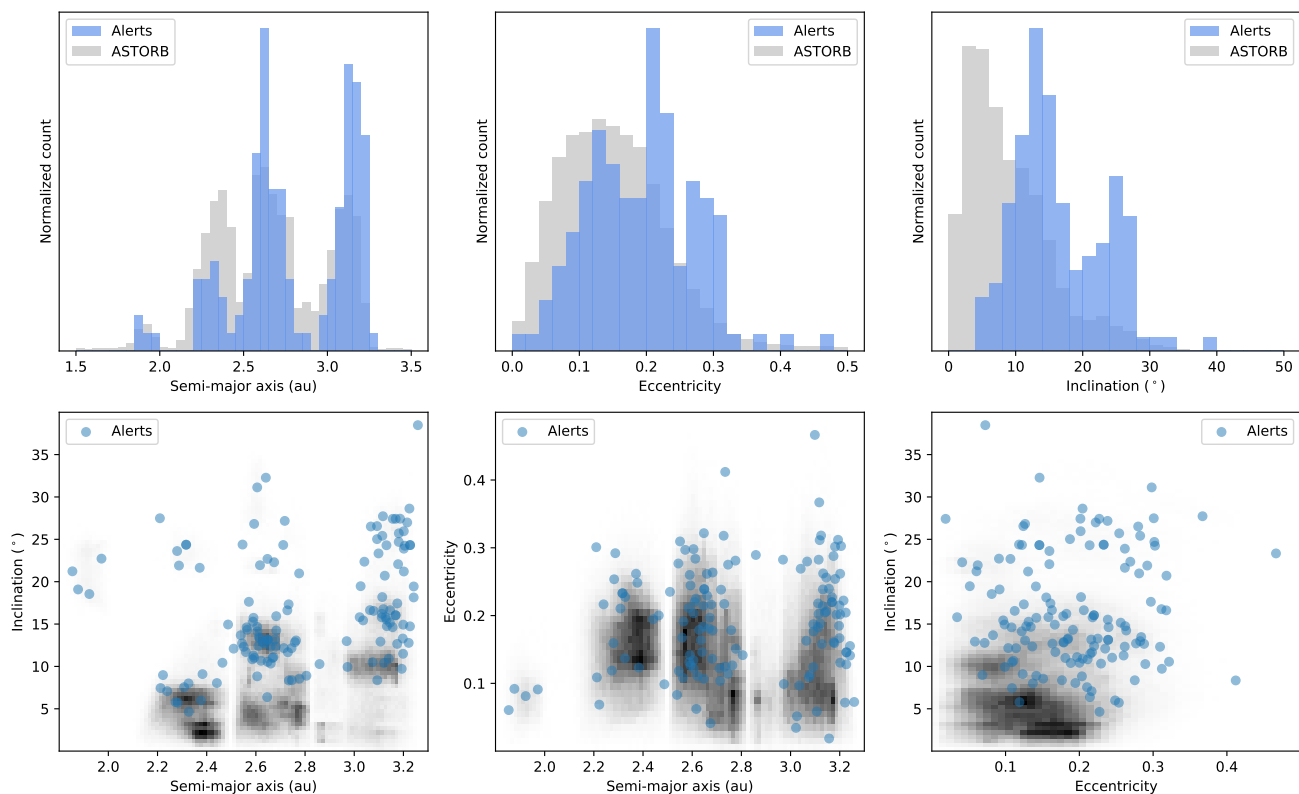


Fig. 10: Comparison of the distribution of the detected asteroids with the current census of SSOs as represented by the `astorb` database.

ST may be biased against NEAs for several reasons. First, as NEAs present a higher apparent motion than main-belt asteroids, they will smear and move faster outside the transmitted windows. Their transits will hence contain less observations, which may lead to rejection of the transit at the DU54 level. Second, their motion combined with the *Gaia* scanning law may result in fewer overall transits, leading to more rejections of NEAs at the DU59 level. We can, however, attest the SSO-ST capability of processing NEAs: we tested it with known NEAs, and it successfully led to simulated alerts (not released).

Regarding the distribution of orbital elements, the sample of alerts is different from the current census of asteroids, taken from `astorb`. By applying 1D Kolmogorov-Smirnov test on semi-major axis, eccentricity, and inclination in turn (Figure 10, top line), to test whether the distribution of alerts and `astorb` are similar, we find it highly unlikely that the distributions are similar, since the K-S p-values are 10^{-4} , 10^{-9} , and 10^{-33} respectively, well below the typical threshold of 0.2 for similar distributions.

The alerts are typically located in the outer main-belt, and have more inclined and more eccentric orbits than the known population (Figure 10, bottom line). There is a weak correlation between semi-major axis and inclination (hence alerts are preferentially for high-inclined outer main belt asteroids).

The outer main belt being further, and populated by darker asteroids than the inner parts of the belt, its completeness at a given size is lower (DeMeo & Carry 2013). The bias in the current census against high-inclination orbits has already been reported by Mahlke et al. (2018), based on deep images obtained by the KiDS survey. Here,

the distribution of alerts clearly skewed towards high inclinations, highlights the strength of *Gaia*'s all-sky survey. With the final release of SSO catalogue by *Gaia*, efforts to debias the current census of SSOs will be possible.

7. Conclusion

Since the beginning of *Gaia*'s operations in 2014, a specific pipeline has been running daily to process unidentified Solar System Objects observed by *Gaia*. Since 2016, about 1700 calls for observations, called alerts, have been released to trigger ground-based follow-up observations of these unidentified objects. Among these, 250 recovery observations have been attempted, resulting in the detection of 227 of them. Their astrometry has been sent to the Minor Planet Center, which assigned a preliminary designation to 139 of these objects, including six attributed to *Gaia*. The orbital distribution of these alerts confirms the bias in the current census of the asteroid population against highly inclined objects. This bias is even more pronounced in the outer asteroid belt.

The daily processing pipeline is still running and will continue until the end of *Gaia*'s operations, that have been extended to the end of 2022 by ESA, and possibly until end 2024 (approval pending).

Acknowledgements. We are indebted to the engineers of the European Space Agency and of the Data Processing Center CNES in Toulouse, France, who made possible this mission and these observations. We thank CNRS-INSU (France) and the scientific council of the *Gaia* observing service ANO1 for the yearly funding allowing us to observe periodically at Haute-Provence Observatory (OHP). This work presents results from the European Space Agency (ESA) space mission *Gaia*. *Gaia* data are being processed by the *Gaia* Data Processing

and Analysis Consortium (DPAC). Funding for the DPAC is provided by national institutions, in particular the institutions participating in the Gaia MultiLateral Agreement (MLA). The Gaia mission website is <https://www.cosmos.esa.int/gaia>. The Gaia archive website is <https://archives.esac.esa.int/gaia>. RAM acknowledges support from CONICYT/FONDECYT Grant Nr. 1190038 and from the Chilean Centro de Excelencia en Astrofísica y Tecnología as Afines (CATA) BASAL PFB/06. We are grateful for the continuous support of the Chilean National Time Allocation Committee under programs CN2019A-3, CN2019B-16, and CN2020A-20. We thank all the observers participating in this program. This work has financially been supported by Agenzia Spaziale Italiana (ASI) through contracts I/037/08/0, I/058/10/0, 2014-025-R.0. The observations at Abastumani were supported by the Shota Rustaveli National Science Foundation, Grant RF-18-1193.

References

- Bailen, M. et al. 2020, in 51st Lunar and Planetary Science Conference, Vol. 51, 2078
- Bancelin, D., Hestroffer, D., & Thuillot, W. 2012, *Planet. Space Sci.*, 73, 21
- Berthier, J., Carry, B., Vachier, F., Eggl, S., & Santerne, A. 2016, *MNRAS*, 458, 3394
- Berthier, J., Vachier, F., Thuillot, W., et al. 2006, in *Astronomical Society of the Pacific Conference Series*, Vol. 351, *Astronomical Data Analysis Software and Systems XV*, ed. C. Gabriel, C. Arviset, D. Ponz, & S. Enrique, 367
- Bonnarel, F., Fernique, P., Bienaymé, O., et al. 2000, *A&AS*, 143, 33
- Bouquillon, S. et al. 2014, in *Proceedings of the SPIE*, Vol. 9152, 03B
- Bowell, E. 2014, vizier.u-strasbg.fr/viz-bin/VizieR-2
- Brown, A. G. A., Vallenari, A., Prusti, T., et al. 2016, *A&A*, 595, A2
- Carry, B. 2014, in *Gaia-FUN-SSO workshop 2014*
- Carry, B. et al. 2019, in *EPSC-DPS Joint Meeting 2019*, Vol. 13, 1409–1, 2019
- Clementini, G., Ripepi, V., Leccia, S., et al. 2016, *A&A*, 595, A133
- Cropper, M., Katz, D., Sartoretti, P., et al. 2018, *A&A*, 616, A5
- DeMeo, F. E. & Carry, B. 2013, *Icarus*, 226, 723
- Fabrizius, C., Bastian, U., Portell, J., et al. 2016, *A&A*, 595, A3
- Fedorets, G., Muinonen, K., Pauwels, T., et al. 2018, *A&A*, 620, A101
- Ivezić, Ž., Tabachnik, S., Rafikov, R., et al. 2001, *AJ*, 122, 2749
- Jordi, C., Gebran, M., Carrasco, J. M., et al. 2010, *A&A*, 523, A48
- Mahlke, M., Bouy, H., Altieri, B., et al. 2018, *A&A*, 610, A21
- Mignard, F., Cellino, A., Muinonen, K., et al. 2007, *Earth Moon and Planets*, 101, 97
- Muinonen, K., Fedorets, G., Pentikäinen, H., et al. 2016, *Planet. Space Sci.*, 123, 95
- Orbfit Consortium. 2011, *OrbFit: Software to Determine Orbits of Asteroids*
- Perryman, M. A. C., de Boer, K. S., Gilmore, G., et al. 2001, *A&A*, 369, 339
- Prusti, T. et al. 2016, *A&A*, 595, A1
- Riello, M., De Angeli, F., Evans, D. W., et al. 2018, *A&A*, 616, A3
- Rudenko, M. 2016, in *Asteroids: New Observations, New Models, Proceedings of the International Astronomical Union IAU Symposium*, Vol. 318, 265–269
- Simon, A., Pavlenko, E., Shugarov, S., et al. 2019, *Contributions of the Astronomical Observatory Skalnaté Pleso*, 49, 420
- Spoto, F. et al. 2018, *A&A*, 614, A27
- Tanga, P. 2011, in *Solar System Science Before and After Gaia*, 2
- Tanga, P. & Thuillot, W., eds. 2010, *Proceedings of the Gaia-FUN SSO workshops*, IMCCE, Paris Observatory
- Tanga, P. & Thuillot, W., eds. 2012, *Proceedings of the Gaia-FUN SSO workshops*, IMCCE, Paris Observatory
- Tanga, P. & Thuillot, W., eds. 2014, *Proceedings of the Gaia-FUN SSO workshops*, IMCCE, Paris Observatory
- Tanga, P. et al. 2016, *Planet. Space Sci.*, 123, 87
- Thuillot, W. & Dennefeld, M. 2018, in *SF2A-2018: Proceedings of the Annual meeting of the SF2A*, ed. P. Di Matteo, F. Billebaud, F. Herpin, N. Lagarde, J. Marquette, A. Robin, & O. Venot, 463–465
- Thuillot, W. et al. 2015, *A&A*, 583, 59
- ¹ Institut de Mécanique Céleste et de Calcul des Éphémérides IMCCE, Observatoire de Paris, Université PSL, CNRS, Sorbonne Université, Université de Lille, 77 av. Denfert Rochereau, 75014 Paris, France
- ² Université Côte d’Azur, Observatoire de la Côte d’Azur, CNRS, Laboratoire Lagrange, Boulevard de

- l'Observatoire, CS34229, 06304, Nice Cedex 4, France
e-mail: benoit.carry@oca.eu
- ³ Harvard-Smithsonian Center for Astrophysics, 60 Garden St., MS 15, Cambridge, MA 02138, USA
- ⁴ SYRTE, Observatoire de Paris, PSL Research University, CNRS, Sorbonne Université, UPMC Univ. Paris 06, LNE, 61 avenue de l'Observatoire, 75014 Paris, France
- ⁵ Departamento de Astronomía, Facultad de Ciencias Físicas y Matemáticas, Universidad de Chile, Casilla 36-D, Santiago, Chile
- ⁶ Aix Marseille University, CNRS, Institut Pytheas-Observatoire Haute Provence, F-04870 St-Michel-l'Observatoire, France
- ⁷ INAF - Osservatorio Astrofisico di Arcetri, Largo Enrico Fermi 5, 50125 Firenze, Italy
- ⁸ Department of Physics, Gustaf Hällströmin katu 2, University of Helsinki, PO Box 64, 00014, Finland
- ⁹ Astrophysics Research Centre, School of Mathematics and Physics, Queen's University Belfast, Belfast BT7 1NN, UK
- ¹⁰ CNES Centre Spatial de Toulouse, 18 avenue Edouard Belin, 31401 Toulouse Cedex 9, France
- ¹¹ Asteroid Engineering Lab, Onboard Space Systems, Luleå University of Technology, Box 848, S-981 28 Kiruna, Sweden
- ¹² Finnish Geospatial Research Institute, Geodeetinrinne 2, 02340, Masala, Finland
- ¹³ Royal Observatory of Belgium, Avenue Circulaire 3, B-1180 Bruxelles, Belgique
- ¹⁴ Observatoire de Besançon, UMR CNRS 6213, 41 bis avenue de l'Observatoire, 25000, Besançon, France
- ¹⁵ Kharadze Abastumani Astrophysical Observatory, Ilya State University, K. Cholokashvili Avenue 3/5, Tbilisi 0162, Georgia
- ¹⁶ Samtskhe-Javakheti State University, Rustaveli Street 113, Akhaltsikhe 0080, Georgia
- ¹⁷ Astronomical Observatory, Taras Shevchenko National University of Kyiv, 3 Observatorna str., Kyiv, 04053, Ukraine
- ¹⁸ Institut d'Astrophysique de Paris, Sorbonne Université, CNRS, UMR 7095, 98 bis bd Arago, 75014, Paris, France
- ¹⁹ Institut Polytechnique des Sciences Avancées IPSA, 63 bis Boulevard de Brandebourg, F-94200 Ivry-sur-Seine, France
- ²⁰ Vera C. Rubin Observatory/DIRAC Institute, Department of Astronomy, University of Washington, 15th Ave. NE, Seattle, WA 98195, USA
- ²¹ ICAMER Observatory of NASU, 27 Acad. Zabolotnogo str., Kyiv, 03143, Ukraine
- ²² Astronomical Observatory of Odessa I.I. Mechnikov National University, 1v Marazlievska str., Odessa, 65014, Ukraine
- ²³ Institute of Astronomy, V.N. Karazin Kharkiv National University, Sumska Str. 35, Kharkiv, 61022, Ukraine
- ²⁴ Keldysh Institute of Applied Mathematics, RAS, Miusskaya sq. 4, Moscow, 125047, Russia
- ²⁵ Astronomy and Space Physics Department, Taras Shevchenko National University of Kyiv, 60 Volodymyrska str., Kyiv, 01601, Ukraine
- ²⁶ National Center "Junior Academy of Sciences of Ukraine", 38-44, Degtyarivska St., Kyiv, 04119, Ukraine
- ²⁷ Terskol Branch of INASAN RAN, 48 Pyatnitskaya str., Moscow, 119017, Russia
- ²⁸ LESIA, Observatoire de Paris, Sorbonne Université, Université PSL, CNRS, Univ. Paris Diderot, Sorbonne Paris Cité, 5 place Jules Janssen, F-92195 Meudon, France
- ²⁹ naXys, University of Namur, Rempart de la Vierge, Namur 5000, Belgium
- ³⁰ Astronomical Observatory Institute, Faculty of Physics, A. Mickiewicz University, Słoneczna 36, 60-286 Poznań, Poland