7. Asteroids : space- and ground-based observational data

A. Context and state of the art

The ESA cornerstone mission Gaia, that started its 5-years all-sky survey in July 2014, will characterize all astrophysical sources down to V=20, including about 350,000 asteroids, by measuring their position, motion and spectral properties. The ultra-precise astrometry (~25 μas at V=15) is the unbeatable driver for Gaia science, promising a revolution in astrophysics, with the first data release at end 2016. Gaia will continue to operate until 2019 (nominal mission) and probably more (extended).

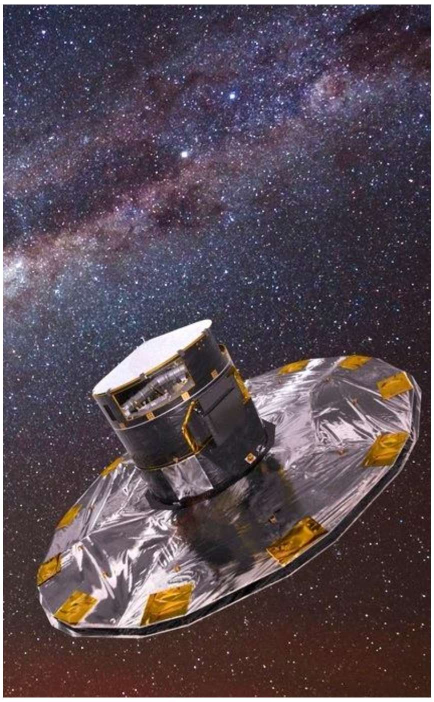


Fig. 1 - The Gaia satellite is continuously scanning the sky from the Lagrangian Point "L2" at 1.5 million km from the Earth. L2 offers a highly stable environment for the observation of cosmic objects, from the Solar System to the Galaxy.

The **Data Processing and Analysis Consortium of Gaia (DPAC)** gathers ~450 scientists and engineers from all over Europe tasked with the mass processing of the data of the mission. The goal of DPAC is to produce a calibrated, first-level data product containing the main properties (positions, proper motions, statistics, classifications, etc.) of the largest possible number of astrophysical objects, as observed by Gaia. More specific analyses, e.g. combination with external data, is excluded from DPAC's scope – although it is needed to really exploit the advances that Gaia will bring in different branches of astrophysics.

Concerning solar system objects, DPAC will produce asteroid positions (by epoch) and provide a first-level physical characterization, including spectral classes from Gaia data. However, unleashing the full potential of Gaia will require levels of processing well beyond the possibilities of DPAC, in terms of available manpower and funding.

The outcome of the processing pipelines is detailed in Tab. 1. It can be clearly seen that the main strengths of Gaia are its capabilities in redefining dynamical properties, in providing bulk shapes and rotation periods for the asteroids.

Table 1 – DPAC Solar System processing : expected outcome. *The impact of Gaia on our knowledge of asteroids is striking, especially concerning orbit accuracy, rotation periods and spectral properties (taxonomy).*

	Before Gaia	*Gaia*
Typ. orbit accuracy (best)	1″	0″.01
Limit for accurate occultation prediction	> 100 km	> 10 km
Mass σ relative < 10%	~20*	60
Ellipsoidal shape, rotation period	~4000	10^5
Density σ relative < 20%	~20*	
Taxonomy and spectra	~2000**	10^5
Binary asteroids	~100 (Main Belt)	?

* From Carry (2012), reduced due to discrepant values for ~50% of the sample
** Excluding the SDSS spectro-photometry, only 4 exploitable wide spectral bands

However, the improvement of the astrometry and of asteroid orbits will have a tremendous impact, disclosing new approaches determining important dynamical and physical properties of the asteroids. Our project is focused on these two key aspects.

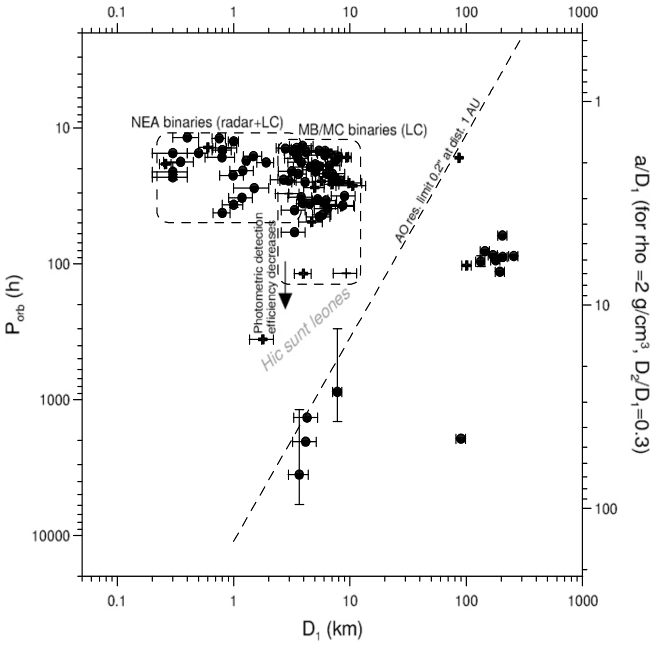


Fig. 2 - Orbital periods vs primary diameters for known binary systems detected with radar, photometric (LC), and adaptive optics (AO) techniques. The inaccessible, empty area in the middle represents an unknown population of medium-distance asteroid binaries that can only be sampled by Gaia.

Asteroids with one or more satellites provide the unique possibility of measuring the total mass of the system, and in some cases the mass of individual components. When the sizes and shapes of the bodies are measured, one can calculate the bulk density. When compared with the densities of meteorites - a partial sample of the building blocks of asteroids that survive the passage through the Earth's atmosphere - one can deduce the nature of asteroid interiors.

Our objective is to discover and characterize a large amount of new satellites around asteroids that have never been searched for satellites before, thus by probing a new population.

In Fig. 2, we plot estimated orbital period vs primary diameter data for known binaries from the database by Pravec and Harris (2007), available at http://www.asu.cas.cz/asteroid/binastdata.htm and updated regularly. Data points on the right of the dashed line (the approximate AO resolution limit at 8-10 m class telescopes) are binaries detected with direct imaging. Points to the left are binaries observed by the photometric and radar technique. In the size range 1–20 km, there is an observational hole between the close binary systems with orbital periods mostly in the range 10–50 h detected by the photometric technique and the wide binaries with orbital periods around 1000 h or longer detected by the AO technique. This *Hic sunt leones* range of binary parameters is where neither of the present binary asteroid detection methods is efficient; the medium-distance binary asteroids with orbital periods on an order of several days are too close to be resolved with AO observations and too wide to be efficiently detected with the photometric observations of mutual events between their components. Gaia will open a completely new perspective by allowing us to employ a method that is out of reach from the ground: *the astrometric detection* (Fig. 5). In this approach the signatures of the presence of satellites and of the orientation of its orbit appear as a wobbling of the binary asteroid photocentre around the centre of mass of the binary system. As the heliocentric orbit of a binary asteroid is the path of the binary's centre of mass, we will ascertain the satellite's presence by detecting offsets (residuals) of the asteroid positions from the best fitting orbit . The candidate binaries will then be further characterized by using ground-based observations and data from the WISE mission.

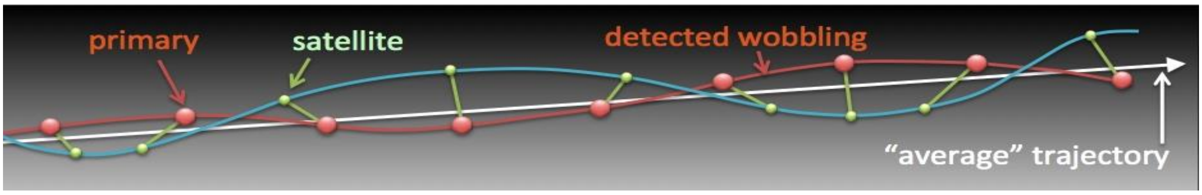


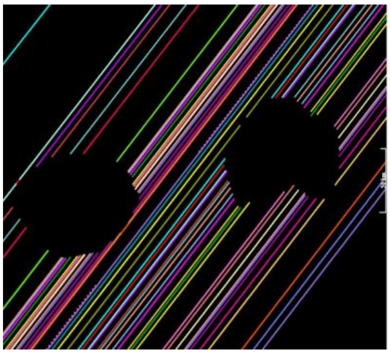
Fig. 3 - Schematics of the method proposed to detect moons around asteroids. The red trajectory is the « signature » of the satellite presence, relative to the unperturbed trajectory that would be followed by the asteroid in the sky.

Asteroid diameters and shapes are primordial physical parameters, fundamental in understanding the mechanism of formation, collisional disruption and evolution of Minor Planets. Currently known diameters have been measured mainly indirectly, by the application of thermal models to infrared observations from the ground and from space., Systematic errors on diameters (albedo) computed from WISE observations are ~5%–10% (~10%–20%) subject to the assumption that spherical effective diameters can be computed for non-spherical shapes (Mainzer et al. 2011). The accuracy of asteroid diameters deteriorates with decreasing size such that for D~20 km as these bodies are significanlty non spherical. The albedo is an important mineralogic indicator, necessary to disentangle asteroids of certain taxonomic types. For example, the X-class in the Bus taxonomy is know to have no unique meteorite analogues and to include both low, moderate and high albedo bodies, with the lowest albedos possibly corresponding to primitive, volatile-rich objects. Primitive asteroids are believed to be the main contributors in water and organics to the terrestrial planets during their formation, and for this reasons they are targets of sample return missions such as OSIRIS-REx (M. Delbo is CoI). The identification of low-abedo primitive bodies is a major challenge for Solar System science.

As detailed further below, we plan to exploit the increased accuracy of asteroid orbits brought by Gaia, and the improved stellar positions, to observe, by a network of robotic telescopes, a large amount of stellar occultations, capable of bringing a wealth of data on diameter, shape, and on the satellite systems that we will discover.

The technique of observation relies upon fast photometry and accurate absolute timing of the observations (by appropriate GPS receivers hardware-coupled to CCD shutters). The occultation by a typical Main Belt asteroid moving at 15 km/s, observed at a frame rate of 20 frames/sec, provides an uncertainty around 0.2-0.7 km (depending upon the SNR), representing 1-2% of the size of a 30 km body. An absolute timing accuracy at the 0.01 s level is targeted.

The availability of the Tycho and Hipparcos catalogues resulted in a 10-fold increase in the annual rate of observed occultations over the period 1997- 2003.



Today, predictions for asteroids are based on Tycho, Hipparcos and UCAC catalogues, for a total of about 4 × 10^6 stars at V<12. A typical site on Earth has ~50 opportunities of observation per year, currently. Only a fraction of them will produce positive events. The best-case accuracy of prediction of the occultation path on the Earth surface for Main Belt asteroids with excellent orbits is 50-100 km. As a result occultations by smaller asteroids have a low probability of success.

We are however at the eve of a revolution in the stellar occultation domain, as the future availability of stellar and asteroid astrometry by Gaia is expected to reduce the prediction uncertainty of >2 orders of magnitude, for all objects (Tanga and Delbo' 2007). This will completely change the approach to - and the exploitation of occultation event. While today the observations mainly rely upon small movable telescope ready to chase the asteroid shadow (Fig. 1), very soon fixed sites will have several tens of events to manage each night (Tab. 1). This evidence opens up the possibility of a systhematic exploitation that has no comparison to what was done in the past.

Isolated sites with ~1 m telescopes will be able to determine accurate, single occultation chords. For the objects >30-40 km in diameter, the position of the chord relative to the barycenter of the asteroid will be known, thanks to the ephemeris accurate at better than ~a few km. Even a single occultation will thus be able to put constraints on their size. Incidentally, these targets include the large perturbers for which mass and density can be determined.

A small network of 3 robotic telescopes, spaced by a few km across the occultation path, can conveniently provide enough chords to measure the size of the much larger population of objects smaller than 20-30 km. During idle time, they can be conveniently employed to observe asteroid light curves, providing constraints on the asteroid orientation at occultation epochs.

Tab 1. Stellar occultations by asteroids, the available sample (Tanga and Delbo' 2007)

Before Gaia	***with Gaia (end 2016 - onward)***
stars V < 13 (mainly the 118.000 Hipparcos stars)	1000 X more stars (V<15)
~200 asteroids D > 50 km	20 X more asteroids (D>10 km)
	= 20000 X more events

Spectral properties of asteroids inform us about the composition and the mineralogy distribution across the belt. Gaia is equipped with two low-resolution spectrophotometers, the Blue and the Red Photometer (BP and RP). that will be used to determine the surface reflectivity of asteroids and to produce a spectral classification for over 100,000 of these bodies, to be compared to the ~3,000 asteroid spectra available today. This large number statistic will allow compositional studies of the whole asteroid belt down to very small sizes and of sub-populations thereof such as the different collisional families (Delbo et al. 2012). Moreover, all spectra will be acquired by the same instrument in a very stable space-based environment. Spectroscopic data are fundamental to identify asteroid collissional familes (Parker et al. 2008). Family members are fragments created during impacts between asteroids. Asteroid families are important because one can time the collisions that generated them. However, the asteroid family chronology shows that the number of identified families formed in a given time interval is not uniform over the age of the solar system, e.g. a lack of old (>1.5 Ga) families is observed while models predict the opposite. There are also indications that the family formation efficiency depends on the composition. For instance, there are no D-type families, and Ceres does not have identified families, although, according to collisional models, it should. The problem is that we do not know what most of the family asteroids are made of. While the mineralogy of the stony (S-types) and basaltic (V-type) asteroids has been deciphered by spectroscopic linking their visible and near-infrared reflectance with those of ordinary chondrite and differentiated (HED) meteorites, respectively, the mineralogy of all other taxonomic types is still unknown. Practically all asteroids belonging to the C- and X-complex, which constitute more then 60% in mass of the main belt and more than 50% of the presently known families4, can not be readily linked to meteorite samples.

An outstanding application consists in mapping the so-called Barbarian asteroids, which display anomalous polarimetric properties. Barbarians are rare, and there are reasons to believe from their extremely high aboundance in Calcium-Aluminum Rich Inclusions, that they could represent the remnants of a primitive asteroid population formed in early times in the Solar System. Their rarity, which is *per se* difficult to explain, limits our ability to characterize a statistically significant sample of them. We want therefore to check whether the several, possibly ancient, Barbarian asteroid families exist. Finding new Barbarians is important to understand their origin and evolution, which are still quite enigmatic, and to better assess their real abundance and distribution throughout the asteroid main belt.

B. Current activity

Laboratoire Lagrange/OCA have been involved in Gaia since the preparatory phase, with the contribution of F. Mignard, former member of the Gaia Science Team and chair of the DPAC (2006-2012). Today, within DPAC, OCA has the leadership of Solar System data processing and validation (P. Tanga), of asteroid spectra processing (M. Delbo), of detection simulation (F. Mignard).

By exploiting preliminary data, we have shown that the astrometric accuracy of Gaia meets the expectations and have started to implement initiatives for preparing the scientific exploitation.

We coordinate the DPAC effort in the development of the software algorithms devoted to the treatment of Gaia observations of asteroids.

Our group is also carriyng out spectroscipic ground-based obsevrtions focused, in particular, in understanding asteroid familes. We have used a novel method to identify asteroid familes which resulted in the discovery of the "Eulalia" and the "new Polana" familes. These familes are sources of the primitive near-Earth asteroids Bennu, Ryugu, and 1996 FG3 the baseline targets of the sample return space missions, OSIRIS-REx, Hayabusa-II. Although these two familes are certainly related to two different asteroid break-up events, we found that their members are spectrscopically homogenous between them (de Leon et al. 2016), implyting some kind of common origin.

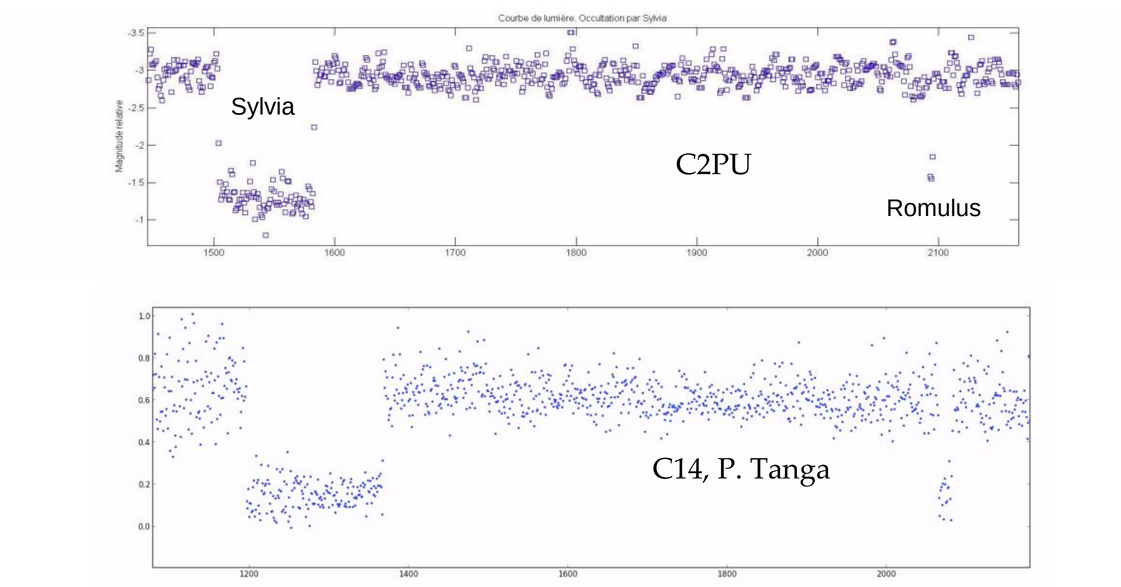


Fig. 5 – Two occultation light curve registered for the asteroid 87 Sylvia on Jan 6, 2013 by our team, at C2PU (upper panel; Bendjoya, Devogele, Suarez) and at a 35 cm C14 telescope at about 20 km (Tanga). Time is on the x axis, brightness on the y. The light dips are associated with the passage of the main body in front of the star (left) and of its satellite Romulus (right). The contemporary observation at two different sites has allowed to obtain the first precise size measurement of Romulus.

Concerning asteroid occultaions, we have established a team interested, now inserted in the international collaborations in the field. We recently hired Federica Spoto (2-years CNES post-doc starting on Dec. 1st, 2015) who is working on the exploitation of Gaia astrometry (first release published in 2016), for the prediction of stellar occultations. We also hired Josef Hanus on another post-doctoral grant from CNES. Hanus' work was partailly devoted to derive accurate shape models for those asteroids for which masses will be derived from Gaia precision astrometry. At the moment these shape models are based on inversion of optical lightcurves, but occultation choords can be added to improve the final shape and size of the asteroid model (Hanus et al. 2016).

Among our results in the field we recall that we were able to unambiguously determine the shape of the candidate binary (234) Barbara, to observe the first occultation by a TNO from Europe (50000 Quaoar, on February 17th, 2012, P. Tanga) and to obtain the first size measurement of a satellite of an asteroid (Romulus, satellite of 87 Sylvia, on January 6th 2013, from two sites including C2PU).

Our observation at C2PU of the occultation of a star by the multiple asteroid 87 Sylvia (Fig. 5) is particularly meaningful since although it is positive, it points out the known limitations of the equipment we used (standard CCD video camera with GPS time inserter and external digitizer), resulting in a timing uncertainty of 0.2 s, and a systematic timing discrepancy relative to other observers. C2PU is capable of a much higher time resolution (factor 10X, depending upon star brightness), if the appropriate camera and timing device are used[1].

Coupling spectroscopy to stellar occultations can give to Calern an unprecedented power of investigation in the domain of asteroid physical porperties.

We also have an intense, ongoing program of photometry, spectroscopy and polarimetry of Barbarian asteroids, by using C2PU and a large international collaboration.

We are also preparing the forthcoming era of big asteroid surveys, that will require crossing and searching data bases for asteroid dynamical and physical properties.

In the last few years we witnessed a large growth in the number of asteroids for which we have physical properties. However, these data are dispersed in a multiplicity of catalogs. Extracting data and combining them for further analysis requires custom tools, a situation further complicated by the variety of data sources, some of them standardized (Planetary Data System) others not.

We thus created a new Virtual Observatory service named "Minor Planet Physical Properties Catalogue" (abbreviated as MP3C - http://mp3c.oca.eu/). MP3C is a portal allowing the user to access selected properties of objects by easy queries. At present, orbital parameters, photometric and light curve parameters, sizes and albedos derived by IRAS, AKARI and WISE, SDSS colors, SMASS taxonomy, family membership, satellite data, stellar occultation results, are included.

Plans are to expand MP3C capabilities, for instance by allowing the access to multi-dimensional quantities (such as spectra, lightcurves, shapes, images…). Also, it will allow the user to browse in the Gaia asteroid data, and in the measurements obtained during our own campaigns.

C. Future steps

C4PO offers an unique opportunity to bridge this gap between Gaia mass processing and the genuine science exploitation. A specific exploitation of the unique accuracy in asteroid astrometry by Gaia, not only brings an added value to the mission itself, but also enables an unprecedented advance in our comprehension of the asteroid belt.

We thus **propose to build upon the output from Gaia, and to exploit it jointly with data produced by new approaches to asteroid observations that Gaia will enable, such as the massive exploitation of stellar occultations by dedicated, robotic telescope networks. We will thus be able to determine unknown physical properties such as the bulk density and infer the internal structure for an unprecedented number of asteroids and for populations of these bodies never explored before**.

The main consequence will be **an amplification of the impact of Gaia scientific results triggering a wave of publications in peer-reviewed journals, an increased visibility for the mission, an enhanced access to the data and – more in general – a positive return of the investment in the mission at different level : at OCA, the leading centre for asteroids in Gaia ; at French level, given the strong committment of a large French community in Gaia ; and eventually at Europen level, the context in which Gaia is being operated.**

An important goal that we pursue in the context of C4PO is to **boost the synergy between those Solar System experts that can best contribute to this breakthrough in asteroid research, putting together scientists involved in Gaia and knowing the mission idiosyncrasies with other experts in different domains.**

Our results will provide new observational evidence to drive several activities inside C4PO, such as the exploration of the asteroid formation and composition, related to the accretion of the first solids, the regolith formation or the the mineralogy of meteorites. **We will also trigger collaborations in the domain of high resolution imaging (shape determination, satellite measurements), of software engineering (remote telescope observations and automated data processing), database maintenance (data repositories, Virtual Observatory tools) and of robotic, high-precision mechanics (telescopes).**

Thus accurate orbits or recent reference points, together with better stellar positions, will be used for high quality prediction of stellar occultations. **Such dramatic improvement on the accuracy of stellar and asteroid astrometry by the Gaia mission will trigger a real revolution in the approach to the observation of occultations.** This change of perspective has been investigated by Tanga and Delbo' (2007), showing that for all asteroids larger than 10 km occultation predictions will be highly reliable. For larger asteroids the position of the chord relative to the object barycentre will be known, thus directly opening the way to size measurements by observing a very small number of occultation chords.

Also, predictions will be fairly accurate also for stars that are much fainter than those considered in current predictions (mag. ~15-16 or higher) thus strongly increasing the population of occultation target stars. Following the publication of Gaia astrometry, a given site with a 0.5-1 m telescope will then have ~tens of events to observe each night.

For this reason an epochal change in the approach to this methodology is going to take place, shifting from nomadic telescopes of small size, mainly managed by amateur astronomers, to fixed instruments of larger diameters and professional installations. With the increase of the prediction accuracy, occultations are going to become a very rewarding method of observation. We plan to exploit this opportunity for performing a large census of asteroid sizes, and for validating the binary systems that we could discover in Gaia data.

The detectability of binary asteroids by photocentre wobbling, including the performance, efficiency and selection effects of this technique applied to Gaia astrometric data, was studied by Pravec and Scheirich (2012b). They found that it will be particularly efficient in detecting binary asteroids with medium separation between the components, i.e., it will explore the population of binaries that is largely unknown so far, because of the inefficiency of the ground-based observing techniques. An example of the expected signature is shown in Fig. 5 as a result of simulations performed at CNRS and ASU, on a known binary asteroid. We expect that we could detect some ~10^3 candidate binary asteroids.

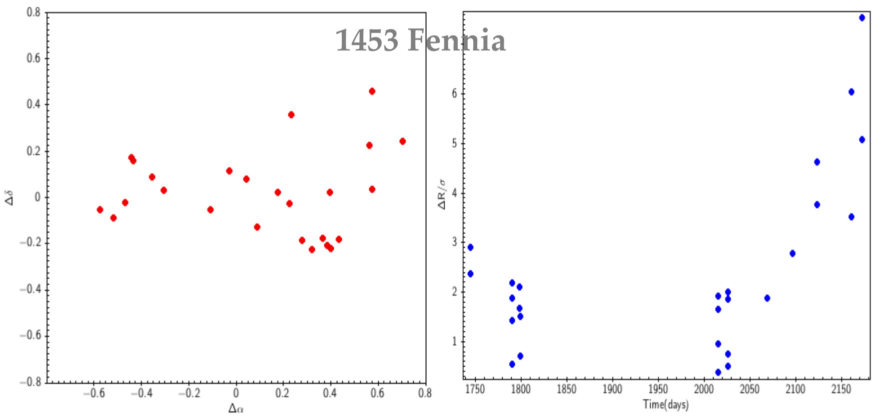


Fig. 6 - Simulations of the wobbling induced on the photocentre of the asteroid 1453 Fennia (diameter ~7 km) by its satellite, over 1 year of simulated Gaia observations. On the left, the displacement in mas, in equatorial coordinates relative to the barycentre of the system. On the right, the total displacement normalized by the expected astrometric uncertainty on the single observation as a function of time.

Local networks of telescopes spaced by a few km can be used to obtain several chords at the same time, while isolated instruments will operate on larger objects for which a single occultation chords provides good size constraints.

We already have at our disposal the C2PU 1m telescopes at Plateau de Calern (OCA/CNRS), but this instrument is not well suited to a continuous, fully robotized operation. We thus plan to build a local network by complementing C2PU with other two 50 cm telescopes, fully robotic and whose priority is intensively focused on Solar Sytem observations (lightcurves and occultations).

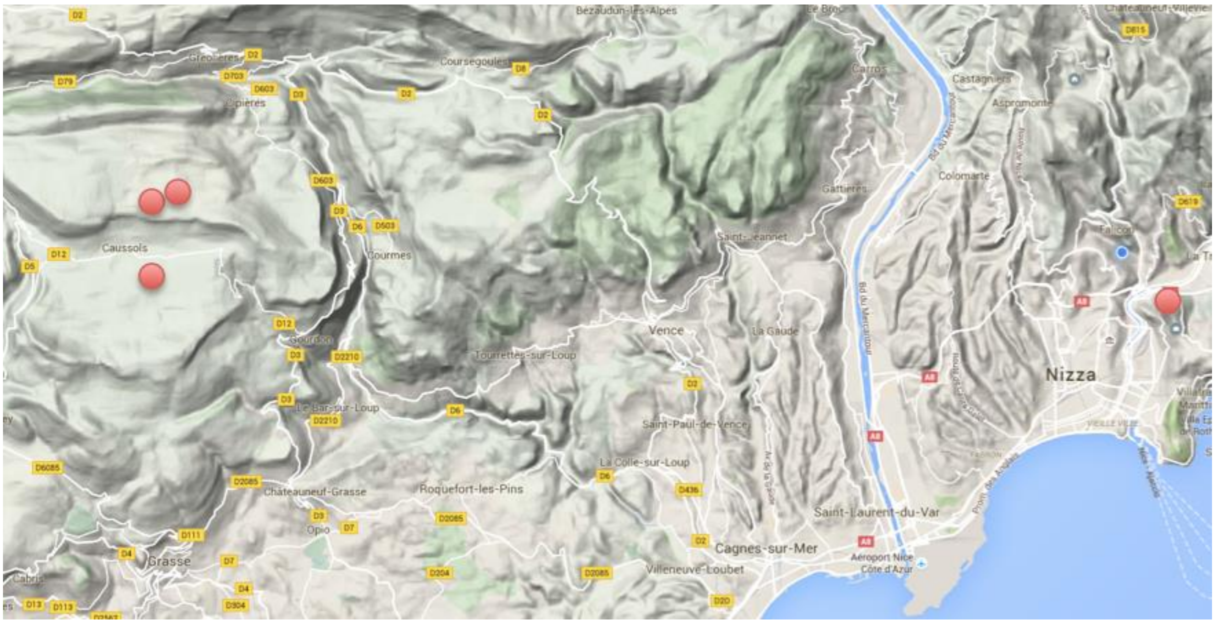


Fig. 7 - A tentative hypothesis on the distribution of telescopes for the occultation network (red dots). The site on the left correspond to Calern, while OCA site at Mont Gros is on the right. These instruments are completely fitted out for this task and have already been trained to observe stellar occultations. They represent a unique facility that we can operate for implementing an efficient and semi-automated coverage of the interesting occultation events. Being spaced of distances between ~4 and ~24 km on the ground, the scale of such a network is well suited to operate with the targets of interest for this project.

Such telescopes can either be built by exploiting off-the-shelf components, or can be the core of a specific development to develop prototypes. Prototyping could be of interest to develop special applications such as:

- A demonstrator of an autonomous telescopes operating on low-energy consumptions with batteries and solar panels, for an application to unattended observations (for example, from the Moon surface)
- A lightweight, modular instrument, of commercial interest. We have preliminary contacts with local small firms that are interested in a joint development.

Concerning Gaia asteroid spectroscopy, two are the major future steps. The first is an accurate validation of a carefully selected subset of the asteroid reflectancies produced by our algorithms of Gaia data treatment that are running on the computer clusters at the CNES. This will typically done, by comparing Gaia's results with data obtained during the last 20 years by the different ground based asteroid spectroscopic surveys such as the SMASS of the Massachusetts Institute of Technology. We also expect that the spectroscopic classification that we will produce from Gaia data will have some differences with the previously and well-established ones (e.g. Bus, Bus and DeMeo, DeMeo and Carry etc etc). The reason is that Gaia observes asteroids under illumination conditions typically different than ground based surveys. In addition, Gaia spectrometers will produce data in a range of wavelengths bluer than from the ground.

The second topic concerns the combination of Gaia spectra with other physical parameters, such as the albedo. Gaia spectrophotometric observations will refine the compositional map of the Main Belt to an unprecedented detail. However, it is well known that classes of asteroids built from visible spectroscopy are affected by degeneracies in their compositional interpretation. For instance, the X-class (in the Bus taxonomy) does not define a compositional class nor has a unique meteorite analog. It is known that asteroids of the X-class can have very different albedos from low (defining the P-class), to moderate (defining the M-class), to high (defining the E-class). In order to remove degeneracies in the Gaia classification of asteroids, we will add auxiliary data to the BP-RP spectrophometry. These data can come from telescopic surveys in the near infrared, or more likely from the catalogue of asteroid observations of the NASA WISE mission.

Implications for high-level education

The development and operation of our network of robotized telescopes and the exploitation of Gaia data offer fertile ground for educational and didactic activities. In particular, we could propose short-duration stages to Master students in science or engineering, and practical activities of support to teaching in both areas. We tentatively identify the following topics: (a) Processing of Solar System data and exploitation; (b) High-accuracy astrometry and photometry from space- and ground-based observatories; (c) Development of equipment for automation, system control, unattended equipment operations; (d) Software engineering and optimization for robotic observations; (e) Automated data reduction pipelines; (f) Big data mining.

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D. International collaborations

In the framework of the Data Processing and Analysis Consortium of Gaia, our group has several close collaborations : e.g. with the Executive team (DPACE) the ESA Science Manager (Timo Prusti) of the ESA Project Office, and several members of different development units such as researchers at the Institute of Astronomy of Cambridge (UK) , the Leiden Observatory in the Netherlands and the INAF Osservatorio Astronomico di Torino, Italy (A. Cellino, M. Aprile).

Concerning the topic of stellar occultation by minor bodies, we collaborate with researchers worldwide that develop techniques of stellar occultaion prediction : e.g. the Rio de Janeiro (Brazil) group (F. Braga-Ribas), and the group at the LESIA Observatoire de Paris (B. Sicardy).

Regarding asteroid spectroscopy we collaborate with the South-West Research Institute in Boulder CO, USA (K. Walsh), the Instituto de Astrofisica de Canarias in Tenerife, ES (J. Licandro, J. de Leon), the University of Central Florida in Orlando FL, USA (H. Campins, N. Pinilla-Alonso)

E. List of people involved in the project

Permanent: *L. Abe (50%), Ph. Bendjoya (30%), B. Carry (40%), M. Delbo (40%), F. Mignard (100%), J.P. Rivet (50%), P. Tanga (75%),*

Engineers: L. Galluccio (100%)

Post-doc: F. Spoto (2015-2017)

PhD: *M. Devogele (- 2017), B. Bolin (2015-2017)*
Contact : tanga@oca.eu

F. Most significant publications of the team

[1] Delbo, M., Ligori, S., Matter, A., Cellino, A. & Berthier, J. First VLTI-MIDI Direct Determinations of Asteroid Sizes. *ApJ* **694,** 1228–1236 (2009).
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[5] Ali-Lagoa V. 2016. Visible spectroscopy of the Polana-Eulalia family complex: Spectral homogeneity. Icarus, 266, 57-75.

Short CV of participants

Paolo Tanga, senior astronomer at OCA. HDR in 2014. Leader of the Solar System data processing within the Gaia DPAC. Expertise on physical properties of asteroids and planetary atmospheres. Polarimetry, spectroscopy, astrometry of Solar System objects. Chevalier de l'Ordre des Palmes Academiques.

Marco Delbo, CNRS research scientist, expert of the physical characterisation of asteroids, ground- and space-based astronomical observations, modelling, and laboratory experiments on meteorites and other asteroid analogs. He is CoI of space missions: ESA's Gaia (responsibility of asteroid spectroscopy) and NASA's asteroid sample return OSIRIS-REx mission. Author of 80 reviewed publications, ~1,000 citations and an H-index = 19 (ADS). Asteroid (16250) was named after "Delbo".