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Asteroid physical studies with GAIA

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Abstract. GAIA is expected to produce a major breakthrough in planetary science, particularly in the field of asteroid studies. Several teams working in the GAIA Solar System Working Group are carrying out simulations of the predicted performances of GAIA as a powerful tool to determine the most important physical properties of large samples of the asteroid population. Here, we focus particularly on the expected performances of GAIA for what concerns the determination of asteroid sizes, spin properties, overall shapes, and taxonomic classification. The importance and the implications of the expected results are briefly discussed.

1. Introduction

GAIA is scheduled to be launched in 2012 and will be operative for five years. The main goal of the mission is an assessment of the dynamical structure of the Milky Way. Accordingly, GAIA will be primarily an astrometric mission, reaching a level of unprecedented accuracy in the measurement of star positions and parallaxes. Moreover, it will have important spectroscopic (for the purposes of precise measurements of radial velocities) and photometric capabilities.

According to current plans, the general design of the GAIA payload should be the following. Two astrometric telescopes will have a common focal plane (De Boer et al. 2000). The optical axes of the two telescopes will be at a fixed angle from each other, and both will be perpendicular to the direction of the spin axis of the satellite. In this way, the fields of view of the two astrometric telescopes will scan the celestial sphere along a great circle. The spin axis will not be fixed in the sky, but it will slowly precede, being forced to make a constant angle with the direction of the Sun. In this way, each point of the sky will be observed several times by the GAIA detectors during the mission lifetime, the exact number of observations depending on the celestial coordinates, as a consequence of the adopted scanning strategy.

The focal plane will consist of a mosaic of CCDs. Star images will move sequentially across the CCD array, due to the spin motion of the satellite. A first group of CCDs constitutes the so-called *astrometric sky mapper*, used for target detection and determination of the expected path of the target transit across the focal plane. A second, larger array of CCDs is devoted to the actual astrometric measurement. During the transit of the target in the astrometric focal plane, only a limited window of pixels centered on the moving center of the image, around the path initially determined by the

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astrometric sky mapper, is really read-out and recorded. The bidimensional astrometric signal inside the pixels window is then integrated (binned) along the direction normal to the scan motion, so that only the along-scan astrometric information will be actually collected. A Time-Delayed Integration (TDI) mode of CCD read-out will be implemented in order to transfer the collected photoelectrons along the along-scan direction at the same rate of motion of the image across the focal plane. The resulting duration of an elementary integration, producing a "snapshot" signal measurement consisting of the photoelectrons collected in six or twelve adjacent bins according to the star's magnitude, is about 3.3 seconds, while the total duration of the transit of an object in the GAIA astrometric focal plane will be of about 20 seconds. The last columns of the CCD array will be devoted to photometric measurements of the collected flux in the GAIA Broad Band Photometric system (BBP).

The spectroscopic capability of GAIA will be made possible by the presence in the payload of a separate, dedicated instrument. The viewing direction of this spectroscopic telescope will lay in the same plane as the two astrometric telescopes. In turn, the spectroscopic telescope will be divided into two distinct focal planes: the Radial Velocity Spectrometer (RVS) and the Medium-Band Photometer (MBP). According to current plans, the calibration of the RVS will be steadily checked by means of observations of bright, well known asteroids, for which the inferred radial motion, derived from measurement of the shift of the major absorption lines in the solar spectrum, will be compared with the expected radial motion known from knowledge of the asteroid orbital parameters. The MBP will be, on the other hand, a major tool for asteroid taxonomic classification (see below).

As we will show in what follows, GAIA is expected to produce a major breakthrough in our knowledge of asteroids. One major advantage of observing from an orbiting platform with respect to conventional ground-based observations is that in principle from space it is easier to observe the objects in a wide range of observational circumstances, not limited to an observing window around the epoch of opposition. In particular, from space the asteroids can be seen at small solar elongation angles, which are hardly achievable from the ground. The satellite will typically observe Main Belt asteroids tens of times during five years of expected operational lifetime. The simulations indicate that during the mission each object will be detected in a wide variety of ecliptic longitudes, corresponding to a wide range of aspect angles (the aspect being the angle between the direction of the asteroid as seen by the observer, and the direction of the spin axis of the object), that are not achievable by means of ground-based observations covering a time span of only five years. Accordingly, GAIA will provide extremely accurate and homogeneous astrometric, photometric and spectrophotometric measurements of a large number of objects seen in a wide variety of observing circumstances. This will make it possible to derive a large amount of information on the most important physical and dynamical properties of the objects. This will include, in particular, also the determination of masses for an expected data-base of about 100 Main Belt asteroids, derived from measurements of tiny orbital deflections caused by mutual close encounters. Although this particular topic does not constitute the main subject of the present paper, it nicely complement the amount of physical information described in the following Sections.

2. Colors and taxonomy

A first, immediate exploitation of the GAIA MBP spectrophotometric data will certainly be a new taxonomic classification. In this respect, GAIA will have a couple of major advantages: first, a huge spectrophotometric database of about 200,000 objects observed down to a V magnitude of 20 will be obtained using a unique, homogeneous photometric system. Second, the spectral coverage of the MBP will certainly include also the blue region of the reflectance spectrum, that currently tends to be missed by the most recent spectroscopic surveys, like SMASS and SMASS2 (Bus & Binzel 2002).

This is a problem, because the blue region is very useful to distinguish between several different sub-classes of primitive objects (Bus & Binzel 2002). GAIA spectrophotometric data are expected to be better to discriminate among different subclasses of the big *C* complex, and to determine the relative abundance of these different subclasses, also as a function of heliocentric distances. This will be important for studies of the compositional gradient of the solid matter in the Solar System (Cellino 2000).

3. Disk-integrated photometry

Disk-integrated photometry at visible wavelengths has been extensively used since many years to derive information on the rotational state (spin period and pole orientation) and shapes of asteroids. Different techniques, based on the lightcurves analysis, have been developed for this purpose (Magnusson et al. 1989) and the predictions concerning asteroid shapes and spin axis directions based on ground-based photometry have been found to be quite good, according to the results of *in situ* investigations carried out by space probes (Kaasalainen et al. 2002).

GAIA disk-integrated photometry will be a very powerful tool to derive the poles of the objects, as well as the sidereal periods and the overall shapes. The main difference with respect to the situation usually occurring in traditional asteroid photometry, is that in the case of GAIA we will not have at disposal full lightcurves, but only a number of sparse photometric measurements lasting a few seconds, obtained according to the law that determines the scanning rate of the sky as seen by the satellite. This would seem in principle a crucial limitation, but it is more than compensated by the high number of homogeneous photometric measurements for each object. It is easy to see that GAIA data taken in only five years of mission will be much denser than ground-based data obtained by means of observations spanning over intervals of tens years.

Experience gathered from ground-based photometry indicates that as a first, preliminary approximation it is sufficient to describe the shapes of the objects by means of triaxial ellipsoids. In this case the number of unknowns (the value of the spin period, two coordinates for the pole axis orientation, the two axial ratios describing the shape, and an initial rotation phase) is much smaller than the number of observations. Other parameters to be derived must also include a description of the photometric behavior exhibited by real objects, including the magnitude-phase relation and the lightcurve amplitude-phase relation. In principle it is possible to develop techniques of inversion of sparse photometric data. Different approaches are possible in principle, and have been independently considered by different teams.

In order to solve this inversion problem, the Torino group has explored both semi-analytical techniques and fully numerical options. The latter approach seems to be particularly promising. This idea is implemented by means of a numerical algorithm, which initially generates a large number of completely random solutions, saving in memory only a limited subset, corresponding to those producing the smallest residuals. In general, these preliminary solutions are very bad, as one would expect a priori from a set of completely random attempts. At this time, a "genetic" mechanism is switched on. This consists in random coupling of the parameters of the saved solutions, and in random variations ("genetic mutation") of some of the parameters constituting the "DNA" of a single solution. If the newly born "baby" solution is better than some of those saved until that step, it enters the "top list", whereas the previously worst solution is removed from the same set. In this way, after a number of the order of one or two millions of "genetic experiments", a very good solution is usually found, which produces small residuals and basically solves the inversion problem.

The tests have been performed so far using different simulators of GAIA photometric data developed independently by different teams in the GAIA Solar System Working Group. The fits of the single data are generally very good when simulations of triaxial ellipsoid objects are performed, and when very simple light scattering laws are considered (geometric scattering). When more irregular shapes, and/or more realistic light scattering laws are used in the generation of simulated observations, the genetic algorithm still finds the correct solution, although the fit of the single simulated measurements obviously becomes significantly worse.

Another fully independent approach, adopted by M. Kaasalainen, is also being tested for the treatment of GAIA photometric data. The method is based on photometry inversion techniques developed by the above author (Kaasalainen et al. (2002) and references therein). According to preliminary simulations, also this approach should be very effective.

4. Sizes

Many asteroidal sources detected by GAIA will have the property to be extended sources. In other words, they will not appear as purely point-like sources when observed by the GAIA astrometric telescopes. The measurement of asteroid sizes will then be possible in principle, down to a limit of apparent angular size that must be determined.

An assessment of the capability of GAIA in determining asteroid sizes is obviously based on a detailed simulation of the actual signals that will be produced by asteroids in the focal plane and in particular, for the purposes of size determinations, the GAIA Astrometric Focal Plane.

The big advantage of GAIA, with respect to ground-based telescopes of larger aperture, will be obviously the fact of being diffraction-limited. The image of an object on the GAIA focal plane will be the result of the convolution of the incoming wave front with the optical system of GAIA, described by the Point Spread Function (PSF) of the instrument. In addition, several other subtle effects will play a role in the generation of the final signal recorded by the detectors. In particular, in addition to the properties characterizing the GAIA optics and detectors, one has also to model some intrinsic properties of the signals. Asteroid emission at visible wavelengths consists of sunlight scattered by the surface. The exact flux of photons incident on the GAIA focal plane will then be the final result of a complex interaction of solar photons with the asteroid surface. The object's size, albedo, shape, macroscopic and microscopic roughness, and light-scattering properties will all play a role in the final properties of the recorded signal. This complex process is currently not fully tractable by means of purely analytic means, and no definitive theory of light scattering is presently available, although several models describing the most general properties of realistic light scattering properties are available.

Therefore, the formation of an asteroid signal on the GAIA astrometric focal plane has been modeled by means of a numerical algorithm, in which all the effects mentioned above are taken appropriately into account, within the limits posed by current understanding of the involved physics. In particular, an algorithm based on a ray-tracing approach, and a Monte Carlo implementation, has been developed.

The basic idea of a size measurement is to discriminate the properties of the signal coming from an extended source with respect to the signal coming from typical point-like sources, and to be able to distinguish among signals produced by extended objects of different angular sizes. The basic property of the signals that can be used for these purposes is simply the resulting signal width (the standard deviation σ of the photon distribution over the recorded channels). In other words, if one can derive an expected angular size *versus* signal width relation, a simple measurement of the signal width would be in principle sufficient to derive the angular size of the asteroidal source.

Apart from a number of effects that must be taken into account in the case of the observation of an asteroid, including primarily the motion of the object in the focal plane, and a number of more subtle effects due to the general features of the procedures of GAIA signal measurement, the most important effect that has to be taken into account, in this respect, is photon noise. Due to photon noise, the angular size *versus* signal width relation is not a rigorous one-to-one relation, but it is affected by a random variation due to photon statistics. As a consequence, when one measures a given signal width, due to the intrinsic uncertainty of the measurement due to photon noise, there is a corresponding range of angular sizes which are compatible with the measured signal width. This uncertainty is increasing for decreasing angular sizes and increasing magnitude (decreasing apparent brightness).

The complex interplay of magnitude (signal intensity), apparent angular size and resulting signal width has been explored by means of extensive numerical simulations. The final result of these studies can be summarized by noting that the apparent-magnitude *versus* apparent angular size plane can be divided into two distinct domains, according to the possibility to derive an angular size measurement having a relative accuracy better or worse of a given accuracy limit.

A more instructive way to present the results of these simulations, is to take also into account the results of available simulations of detections of known Main Belt asteroids in a simulated GAIA survey lasting five years. Every object will be observed many times (typically several tens) in different sky locations, during the operational lifetime of the mission. For each observation we can establish the accuracy in size measurement.

The results of the simulations show that above 30 km in diameter, more than one half of the known Main Belt asteroids will have their size measured at least once during the GAIA operational lifetime. The number of useful measurements rapidly increases for increasing size. Between 20 and 30 km, a fraction larger than 20% of the objects will also be measured at least once, or even a few times. The number of objects that will be measured is thus of the order of 1,000. That such a result will not be possible using any other observing facility existing today or planned to be operative in the next ten years.

5. Conclusions

The multi-band observations carried out by GAIA for tens of thousands of objects will be useful not only to derive a new taxonomy, but also to add spectral reflectance data as a further constraint to identify asteroid families. These are groupings of objects having similar orbital properties, which constitute the outcome of catastrophic events of collisional disruptions of single parent bodies. Families have been so far identified mostly on the basis of similarities in the orbital proper elements of their members (Bendjoya & Zappalà 2002), but it has become evident that spectral properties can be added as an additional element to identify objects having a common collisional origin (Bus 1999).

The results of the simulations performed so far indicate that, whatever choice will be made of the most suitable algorithm of inversion of photometric data, the GAIA data-set of disk-integrated photometry will be a major resource to derive spin properties and overall shapes for a number of objects that will not be smaller than 10,000, to be conservative. The determination of the rotational state for a set of more than 10,000 Main Belt asteroids will make it possible to use the spin properties of Main Belt objects as a new powerful constraint to the models of the collisional evolution of this population. So far, the models have been mainly constrained by the size distribution, but since collisions strongly affect the spins, GAIA data will add a new full dimension to the problem.

At the same time, the spin properties derived for family objects will allow us to test the possible existence of preferential alignments in the spin properties, which have been recently found to likely exist in the case of the Koronis family (Slivan et al. 2003). The same techniques of photometric inversion that are being developed for GAIA will be also useful for other surveys like Pan-STARRS or the Large-Aperture Synoptic Survey Telescope. The main difference, however, is that GAIA will be able to sample the possible range of ecliptic longitudes (hence, aspect angles) of the objects at a much faster pace than ground-based surveys.

The direct measurement of sizes will allow us to have an improved knowledge of the asteroid size distribution down to 20 km in diameter. Today, the only size data we have come from indirect measurements (thermal radiometry, polarimetry) and are subject to considerable uncertainties. Direct size measurements, on the other hand, will allow us to derive the albedos of the same objects. In this way, we will check whether there are dependencies of albedo upon size, as old results of IRAS radiometric observations seem to indicate (Cellino 2000). An albedo variation due to space weathering processes has been convincingly shown to exist for S-type objects by the Galileo close-range images of asteroid 243 Ida (Chapman 1996) but it is not completely clear if the same processes can alter also the reflectance properties of objects belonging to other taxonomic classes (*i.e.,* having different surface compositions). GAIA will give the correct answers to these major open questions. The post-GAIA scenario in the physical study of asteroids will be much more advanced in many fundamental respects. GAIA astrometry will provide us reliable measurements of mass for about 100 objects. For these same objects we will know also the size and the overall shape, again obtained from GAIA data, then we will have at disposal reliable estimates of average densities. These objects will belong to different taxonomic classes, then it will be possible to assess the relation between density and taxonomy, to be possibly interpreted in terms of overall composition and structural properties. This will be a kind of knowledge that we cannot be realistically expect to achieve by any other means in the next two decades.

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