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THE DETERMINATION OF ASTEROID PHYSICAL PROPERTIES FROM GAIA OBSERVATIONS. GENERAL STRATEGY AND A FEW PROBLEMS

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Abstract. Gaia observations are expected to produce a real revolution in asteroid science. Apart from major improvements in the determination of orbital elements, Gaia data will make it possible to derive for large numbers of objects a determination of the most important physical properties, including mass, size, average density, rotational period, spin axis direction, overall shape, and geometric albedo. Here, we focus mainly on the determination of sizes, rotational properties and shapes, and show some of the main problems that are encountered in the data analysis procedures.

1 Introduction

In spite of the tremendous progress that has been made in recent years in the field of the determination of physical properties of the minor bodies of our Solar System, our knowledge of these bodies is still not satisfactory due to the difficulty in getting detailed physical information about them, due to their intrinsic faintness, and also due to the fact that both asteroids and comets are extremely heterogeneous, and include bodies characterized by great diversity in many respects. Fundamental physical parameters including masses and sizes are mostly unknown for the vast majority of the objects, since they are extremely difficult or impossible to obtain by means of remote observations. For instance, only for a handful of objects which are either among the biggest members of the asteroid population, or have been visited *in situ* by space probes, we have reasonable measurements of the mass. As a consequence, also the average density is largely unknown for the vast majority of the population. What is done usually is only some tentative estimate based on extrapolations of the values found for a handful of objects observed *in situ* by space probes. Since the asteroid population exhibits a heterogeneity of spectral reflectance properties, likely related to differences in overall composition and thermal histories, such extrapolations are mostly tentative and quite uncertain in most cases. Needless to say, it is very frustrating to carry out astrophysical studies of objects for which even the average density is essentially not known. Unfortunately, even in this new era of development of increasingly large telescopes and increasingly sensitive detectors at different wavelengths, it is very difficult to expect that ground-based remote observations can produce in the near future a big wealth of new accurate measurements of the fundamental physical parameters of a large sample of asteroids and comets. In this respect, this branch of Planetary Sciences is still waiting for a revolution.

In this paper, we show that the forthcoming Gaia mission can be this much expected revolution, especially for what concerns the studies of the physical properties of the asteroids. This is a consequence of the fact that Gaia will be in many respects a major step forward in the history of the tools available for remote observations of bodies as the asteroids. Due to its unprecedented performances in terms of astrometric accuracy, Gaia will produce a huge improvement in the determination of the orbits of the minor bodies, eventually leading to the measurement of the mass for a significant number of large asteroids, and to the direct measurement of non-gravitational effects affecting the orbital motion of several small near-Earth objects. Moreover, the direct measurement of the size for a big sample of main-belt objects is also expected to be possible. Combined estimates of mass and size will lead to reliable estimates of the average density for a sizeable sample of objects belonging to different taxonomic classes. In addition, the excellent photometric and spectroscopic performances of Gaia

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are expected to produce a wealth of data including the determination of the rotational properties, the overall shapes (useful to improve the reliability of density estimates), the reflectance spectra at visible wavelengths and a taxonomic classification for a significant sample of the asteroid population.

In the following sections we present more in detail some of the results we expect to obtain from Gaia observations of asteroids, and we point out some technical problems that are relevant for a thorough exploitation of the future Gaia data.

2 Asteroid signals in the GAIA astrometric field

In this Section, we assume that the reader is familiar with the overall design of the Gaia scientific payload, in particular the optical design, the scanning law of the satellite, the design of the CCD matrix in the focal plane, and the TDI (transfer delay integration) mode of data acquisition. This general information is given in several papers, including Mignard et al. 2007.

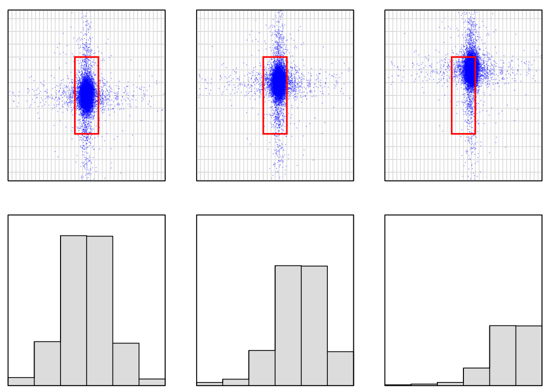

Fig. 1. Signal collected in the observing window of three consecutive CCDs in the astrometric field of view, for an asteroid moving 15 mas/sec in the along-scan direction, and 45 mas/sec in the across-scan direction. The corresponding recorded signals are shown at the bottom.

Figure 1 shows the simulated signal of an asteroid moving across the field of view of Gaia, as it transits in the observing window in different CCDs. The Figure summarizes some important problems related to the observation of moving objects. In particular, the collected photons tend to shift outside the observing window during a single transit in the Gaia field of view, and the corresponding signal recorded by different CCDs progressively changes as the object tends to exit the window. Since the position and size of the observing window in each different CCD in the focal plane is fixed at the beginning of the object's transit, a moving object tends to move progressively off-center in the observing windows of adjacent CCDs, and may in principle even exit the window if the apparent motion is sufficiently fast. Note that the recorded signal is the sum of all the photoelectrons integrated over each column of the observing window. In Figure 1 an observing window consisting of 6 columns is shown as an example. This corresponds to the most general case, wider windows being automatically selected on the basis of increasing apparent brightness of the source when it is first detected at the beginning of its transit across the Gaia field of view. The analysis of the signal is carried out by the routines of CCD processing, which are based on a standard signal model, solving simultaneously for the apparent angular size of the asteroid, and for its apparent motion, generally only in the along-scan direction.

The signal of an asteroid is fit by a model which takes into account the object's motion and apparent angular size. In particular, at a preliminary stage, the signal is fit to a very simple and not very realistic model of a spherical object seen at zero phase angle, i.e., at perfect sun opposition. In a second step, when the result of the inversion of disk-integrated photometry is available (see below), a more realistic model of a triaxial ellipsoid object with semi-axes $a > b > c$, seen at the correct phase angle is applied. If the number of collected photoelectrons is sufficiently large, i.e., when the object is sufficiently bright, and at the same time the angular size of the object is not negligible, it is possible to solve for the largest semi-axis of the triaxial ellipsoid shape (the b/a and c/a axial ratios being already known from photometric inversion). The measurement of the size gives reliable results whenever favorable conditions are met in terms of the apparent angular size of the object, and its apparent brightness. For a given object, these conditions can be met or not in different transits, depending on its absolute size and on the observing circumstances. In cases in which it turns out that the signal analysis can produce an estimate of the size with an uncertainty better than 10%, we speak of an actual size measurement. Based on an extensive simulations of five years of Gaia observations, Figure 2 shows, as a function of the diameter in km, how many times the size of different asteroids will be measured with an accuracy better than 10%. As it can be seen, the results are very encouraging, and show that direct measurements of the sizes of asteroids will be possible for all objects down to sizes a little above 20 km. This corresponds to a number of objects of the order of 1,000 for which Gaia is expected to provide direct size measurements, a very impressive result.

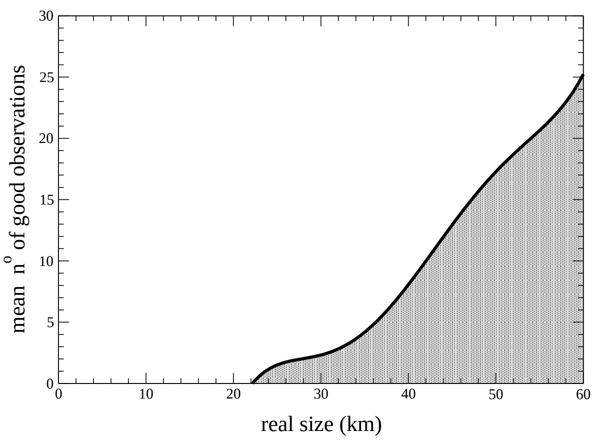

Fig. 2. Number of "good observations", namely transits for which the size can be measured with an accuracy better than 10%, for objects of different sizes. Based on an overall simulation of the Gaia detections of known main belt asteroids.

When the apparent angular size of an object will be measurable, the signal being different with respect to that of a point-like source, another very important parameter will be derived, mainly the amount of the difference between the apparent position of the photocenter of the signal, and that of the sky-projected barycenter of the object, taking into account its apparent projected shape and defect of illumination. The amount of this so-called "photocenter shift" will be important, since it will be used to correct the astrometric measurement of the object resulting from the photocenter position. When applicable, this correction will be used to improve the accuracy of the astrometric measurement, and will lead to a more accurate computation of the object's orbit.

3 Masses, densities and Yarkovsky effect

Every main-belt asteroid will be observed on the average about 70 times during the five-years operational lifetime of Gaia. While the usual astrometric accuracy of ground-based asteroid observations ranges between 0.05 and 1.0 arcsec, the astrometric accuracy of Gaia measurements for each single transit will range between 0.1 and 1.0 milli-arcsec (mas). As a consequence, the uncertainties in the orbital elements of the asteroids observed by Gaia will decrease by a factor of about 100. This will make it possible to measure tiny dynamical effects that are usually beyond the limit of ground-based observations. In particular, the deflections experienced by small asteroids when having close encounters with the largest objects in the main belt will be measurable, leading to the derivation of the masses of the perturbers. According to simulations, in this way the masses of about 100 among the largest asteroids will be measured. The accuracy of each single mass measurement is expected to be of the order of 10^{-12} solar masses, but combining different mass measurements for a single asteroid, corresponding to close approaches with different smaller objects, the accuracy should sensibly improve, possibly reaching values of the order of 10^{-14} solar masses. In the case of (1) Ceres, this would correspond to an accuracy of 0.01% in the mass determination, a very impressive result.

Having at disposal masses, sizes and overall shapes for about 100 asteroids, the average densities of these objects will be also determined with good accuracy. This will be another tremendous improvement in our knowledge of the physical properties of asteroids, taking also into account that among these 100 objects there will be asteroids belonging to a wide variety of taxonomic classes. For the first time, we will have the possibility to assess whether different taxonomic classes correspond also on the average to different densities, determined by differences in overall composition and/or internal macro-porosity.

Another consequence of the excellent astrometric accuracy of Gaia measurements will be the direct measurement of the effect of non-gravitational mechanisms on the orbital motion of small asteroids. In particular, the Yarkovsky effect is known to produce a small, steady drift in semi-major axis of small asteroids. This will produce a measurable effect on the recorded positions in some cases. According to simulations by Delbò et al. 2008, a measurement of the Yarkovsky drift should be possible for a number of about 35 near-Earth asteroids that will be observed by Gaia. Since the Yarkovsky effect depends on many physical parameters of an object, including size, spin axis orientation, rotation period and thermal inertia, the direct measurement of the effect for these objects will be a very important achievement for the physical studies of the asteroid population.

4 Spin, shape, taxonomy

Gaia will have remarkable photometric and spectrophotometric capabilities. For thousands of asteroids, disk-integrated photometric data, corresponding to different transits in the Gaia field of view, will be recorded. For each object, this will be a series of photometric snapshots taken over a five-years time span. As explained by Cellino et al. (2007, 2009) these data will be used to obtain information on the rotational properties of the objects (spin period, spin axis direction) and on their overall shapes. As explained in the above papers, the procedure developed to perform the photometric inversion of Gaia data is based on a genetic algorithm, and will use a simple triaxial ellipsoid model to fit asteroid shapes. According to the tests carried out so far, the spin properties are expected to be derived with good accuracy, of the order of fractions of a second for the rotation period, and a few degrees in the coordinates of the spin pole. As for the shapes, the results should be more qualitative, due to the simple shape model adopted to minimize CPU time. The number of objects for which we can expect to derive an accurate photometric inversion should be of the order of $10,000$. This will be another major result of Gaia, and will make it possible to carry out studies of the distributions of spin properties among dynamical family members, with important consequences on our overall understanding of asteroid collisional evolution. The determination of overall shapes will also be very useful to improve the accuracy of volume computations, needed to compute average estimates of density for the largest asteroid in the main belt (see previous Section).

Spectrophotometric data will range between 0.33 and about 1 μm, and will be used to derive a new taxonomic classification based on Gaia data. The sample should include several tens of thousands objects. Interestingly, the blue region of the visible spectrum, that has been largely lost in recent taxonomic classifications, will be included in Gaia data. This will be very important to identify distinct sub-classes of objects having a generally primitive composition, including the very interesting F class. Objects of this class have been found to be interesting in many respects, and might share asteroidal and cometary properties (Cellino et al., 2001). In addition to being *per se* an important resource, the taxonomy obtained by Gaia will be also an excellent tool to discriminate among membership of asteroids to mutually overlapping dynamical families.

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