IMPACT OF GAIA ON DYNAMICS AND EVOLUTION OF THE SOLAR SYSTEM

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ABSTRACT

The huge amount of astrometric and photometric data expected by Gaia observations will contain much information on the physical characteristics and past history of the Solar System bodies. For example, Gaia astrometry and photometry of asteroids will provide useful constraints on shapes, masses, spin properties, taxonomy and presence of satellites. In this context, a refinement of our understanding of the collisional evolution and the internal properties of minor bodies can be achieved. The astrometry of several satellites orbiting the main planets gives access to their dynamical properties with an unprecedented accuracy. Masses of several asteroids will be available and a measurement of the Yarkovsky force can probably be obtained. Hints on the physical structure of the Galilean satellites of Jupiter will be derived from the measurement of dissipative (tidal) effects. On a longer term, Earth-based observation of Solar System bodies should also be positively affected by the availability of precise asteroids orbits and star positions, allowing, for example, to predict systematic observations of star occultations by minor bodies with a high rate of success.

Key words: Gaia; Solar System; Dynamics; Asteroids; Satellites.

1. AN OVERVIEW OF OPEN PROBLEMS

Our present knowledge of the Solar System bodies relies on a huge historical record of ground-based observations obtained by exploiting all possible techniques, from traditional astrometry to radar ranging, from photometry to polarimetry. In the last three decades, space probes have allowed us to reach extremely high spatial resolution on surfaces and atmospheres, for bodies belonging to nearly all the different object classes that compose the Solar System. Despite these efforts, however, several fundamental questions wait for a definitive answer, or even for a first observational constraint. That becomes particularly true when a reconstruction of the past history of the Solar System is tried. In this field, several blank spaces remain.

The reason for this situation is the need for new methods of investigation, capable of providing an insight that today remains essentially out of reach. In fact, it is necessary to recall the nearly complete lack of knowledge concerning the internal structure of asteroids. This topic is of extreme relevance, since asteroids are considered to be a natural laboratory for highly energetic impacts, that dominated both the evolution of the major bodies in the last stages of planetary accretion, and the early stages of planetesimals build-up. Even if most of them cannot be said to be 'primordial' in the strict sense, asteroids still hide several secrets of the planetary formation process.

It is widely accepted that asteroid dynamical families are the signature in the orbital elements space of the catastrophic disruption of some parent bodies. However, neither the mechanical properties of rocky bodies involved in the process, nor the internal structure of the fragments that we observe today are directly accessible.

To address this difficulty, several paths have been followed. The extrapolation of laboratory disruption experiments toward the asteroid range of sizes and energies requires several orders of magnitude to be bridged. Without knowing in advance the degree of pre-fragmentation and differentiation, the rock composition and texture, the bulk density of the asteroids, that extrapolation remains a risky exercise. Recently, numerical simulations of the shock propagation and disruption using the Smooth Particles Hydrodynamics scheme, have both underlined the sensitivity from those unknown initial conditions and provided some useful predictions of the fragment ejection velocities (Benz & Asphaug 1999). N-body simulations of the post-fragmentation phase have shown that most of the family members could be loosely bound gravitational aggregates ('rubble piles') with very low internal strength, formed by the reaccumulation of individual fragments (Michel et al. 2003).

However, if the simulated orbital element dispersions of families are considered, it can be seen that the collisional ejection velocities alone are not sufficiently high to explain them. The comparison with observations requires to invoke some additional, non gravitational force. The Yarkovsky thermal effect (Section 3) has good properties to fit this scenario, but it depends upon parameters that remain largely unknown, such as the porosity of the object, the thickness of the regolith cover, etc.

A few asteroids have been closely observed at very high resolution, such as Mathilde (mean radius R$\sim$26.3 km) or Eros (R∼9.3 km) by NEAR. The first one presents impact structures nearly as large as the object itself. Their existence could imply a very weak internal strength typical of a rubble pile, capable of absorbing the impact energy and allowing a plastic deformation. Eros, on the other hand, presents structures that are compatible with a monolith, or with a single collisional fragment that has been shattered but not completely disrupted (Cheng 2004). However, these interpretations are always indirect, being based on the morphological analysis of the surface, as it appears despite the thick regolith covering.

The precise volume of the object being known by direct imaging, the probe telemetry allows, by measuring the gravitational field, to determine the mass and, in turn, the direct computation of the bulk density. The values thus obtained further support the above picture: 2.67±0.3 g cm^{-3} for Eros, and 1.03±0.3 g cm^{-3} for Mathilde (Yeomans et al. 1997).

However, beside these special cases, we can state that the present knowledge of asteroid masses and sizes cannot offer robust constraints. Recent reviews (Hilton 2002) just cite 14 other densities, most of them with uncertainties of 30% or more. Conversely, only a statistically significant sample could have an impact on our understanding of the asteroid belt.

Gaia, thanks to its unprecedented astrometric accuracy, will allow a jump in power of investigation such that the mission alone will be able to provide this sample by accurately measuring asteroid masses (Section 2) and sizes (Cellino 2005; Dell'Oro 2005). Furthermore, a direct measurement of the Yarkovsky force can also be obtained (Section 3).

After a quick look to other examples of fundamental Solar System physics (Section 4) it will be clear that Gaia will be a comprehensive mission for Solar System studies, giving access to some of the most important key elements necessary to understand its formation and evolution.

2. ASTEROID MASSES

2.1. The Current Situation

At present (Hilton 2002), most of asteroid masses (about 15) have been determined by exploiting close encounters between a large body (the unknown mass) and a small test object. Other methods include the measurement of spacecraft trajectories (3 bodies), and the determination of the revolution period of binary asteroids (about 10 bodies). The exploitation of close encounter requires a precise measurement of the orbit of the test asteroid before and after the event. Increasing the length of the observational arc normally helps to improve orbital parameters, but unfortunately the perturbations due to other poorly determined (or completely unknown) masses of the system also grow with the time span of the observations. In most practical cases it is not even possible to identify the interfering bodies. For this reason, even if the uncertainty on the orbit perturbation, when propagated to the mass, remains acceptable, determinations made at different encounters are sometimes in disagreement relative to the corresponding nominal error bars. It can be estimated that the actual uncertainty is of the order of 10^{-11} $M_\odot$. For the largest asteroids, 1 Ceres, 2 Pallas and 4 Vesta, having a mass of some 10^{-10} $M_\odot$ (Pitjeva 2001), this translates into an uncertainty of about 2–10%. Beside these objects, only a very small sample of the measured masses exceeds 10^{-11} $M_\odot$, corresponding to the quoted uncertainty. For smaller bodies the measured mass can be considered to be no more than an estimate, as can be deduced from the detailed analysis of some examples. Table 1 shows the results for the mass of 52 Europa as determined by three different encounters (Michalak 2001). The induced perturbations are measurable from Earth, but the relative uncertainties are high and no solid conclusion can be deduced concerning the real mass of the object.

The only possibility to improve the situation is to increase the accuracy of the single astrometric measurements. It is thus very tempting to investigate the capabilities of Gaia in this field.

2.2. Simulations of Close Encounters During the Gaia Mission

By approximating the perturbation exerted on the test object by an instantaneous impulse, we can evaluate the angular deviation $\Delta\theta$ of its trajectory:

$$\Delta\theta = \frac{2Gm}{V^2\Delta} \tag{1}$$

where m is the mass to be determined, V is the relative velocity of the encounter and Δ is the impact parameter (see also Figure 1). Typical values that are obtained are summarized in Table 2.

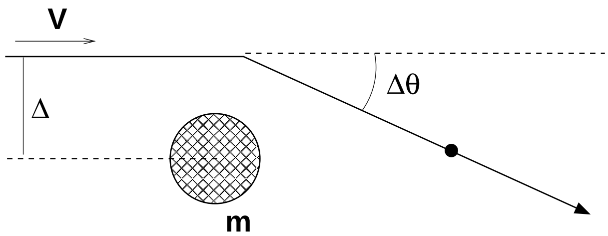

Figure 1. Angular deviation of a small size asteroid by a mass m to be determined, in the impulse approximation. The impact parameter is Δ.

To make the computation we assume a typical encounter velocity in the main belt (3 km s^{-1}) and two possible values for the impact parameter. For a favorable geometry the deviation θ can easily exceed 5–10 mas. Using the Gauss perturbation formalism, one can see that a coplanar encounter affects the semi-major axis and eccentricities. It can be demonstrated that a deviation of the entity given above will produce a change in the orbital longitude that will be detectable by Gaia in observations spanning several weeks.

Table 1. Ground-based mass determinations for 52 Europa from encounters with three different targets.

	Target	Max. pert. arcsec	Num. obs.	Mass $M_\odot$
933	Moultona	2.1	278	$(24.6\pm14.7)\times10^{-12}$
1023	Thomana	4.2	150	$(17.5\pm15.5)\times10^{-12}$
84	Klio	3.5	465	$(85.1\pm16.0)\times10^{-12}$

Table 2. Typical deviations for close encounters involving large asteroids.

m $M_\odot$	D km	Δ AU	V km s^{-1}	$\Delta\theta$ mas
10^{-10}	500	0.1	3	40
		0.05	3	80
10^{-11}	200	0.1	3	4
		0.05	3	8

However, a more general question must be answered. As seen above, the role of perturbing masses not participating in the encounter is not negligible. By performing a simulation of the motion of the asteroid belt objects, the number of deviations produced by distant and close encounters can be estimated, thus allowing to evaluate both the role of disturbing perturbations and the number of binary encounters that are accessible to Gaia over the nominal mission lifetime.

Such a simulation was run over 5.5 years by assuming as initial conditions the positions and velocities at the epoch 2010.5. The statistics associated to the first 500 numbered minor planets (that in a first approximation coincide with the 500 most massive bodies of the belt) were computed, by considering perturbations affecting 20 000 targets (corresponding to asteroids brighter than about V$\sim$18). The masses assigned to the first few bodies were taken from the literature, while the others were derived with order-of-magnitude estimates starting from the measured sizes.

To analyze the results, several diagnostic parameters were taken into account, such as distance, relative speed, instantaneous change in orbital elements, angular deviation. Some statistics on the number of close encounters are presented in Figure 2. The number of encounters with an impact parameter $<$0.1 AU (upper panel) and $<$0.05 AU is plotted for each of the 500 selected bodies. The asteroid identification number is on the abscissa.

It can immediately be seen that a huge number of encounters capable of yielding a detectable signature will take place during the Gaia observations. An even more impressive result is obtained by analyzing deflection statistics. As an example Table 3 presents some results for the first 15 asteroids. The number of deflections larger that certain typical values is given for each body.

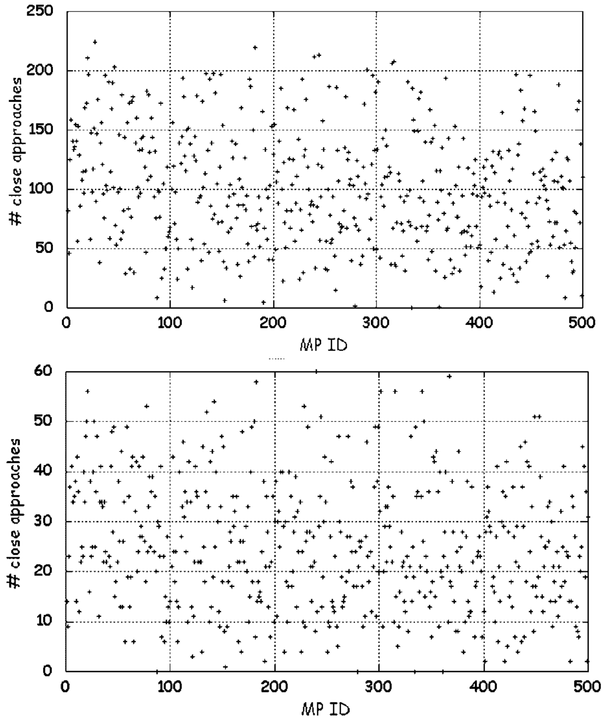

Figure 2. Number of encounters with impact parameter smaller than 0.1 AU (upper panel) and 0.05 AU (lower panel) for the first 500 numbered asteroids, with 20 000 targets. The minor planet identification number appears on the x axis.

The striking feature is the impressive number of ‘small’ (but not negligible) deviations, and the relevant fraction of those with $\theta > 5$ mas. For comparison, the last line gives the number of bodies (among the 500 considered) that produce at least 5 close encounters having the given minimal deviation.

These figures are compatible with those given in the more general study presented in Fienga et al. (2003). They clearly suggest that Gaia-detectable perturbations among masses in the complete system are so frequent that the classical approach of close binary encounters with small perturbations by other distant bodies is not apt to describe the richness of the scenario. The Solar System as seen by Gaia cannot be modelled precisely if a large amount of

Table 3. Number of deflections $\leq \theta_{lim}$ for the first 15 Main Belt asteroids.

	$\theta \geq$ (mas)	1	5	20	100
1	Ceres	8738	4828	1518	163
2	Pallas	275	18	1	0
3	Juno	162	6	0	0
4	Vesta	5772	1575	314	30
5	Astraea	41	6	0	0
6	Hebe	66	9	0	0
7	Iris	382	51	7	1
8	Flora	188	22	2	2
9	Metis	3369	773	144	16
10	Hygiea	3675	901	193	26
11	Parthenope	377	48	8	0
12	Victoria	34	8	2	0
13	Egeria	93	5	2	0
14	Irene	1874	195	24	3
15	Eunomia	377	27	6	0
	N>5	305	120	40	11

mutual perturbations is not taken into account. The complete solution of a single close encounter will most of time involve several other bodies. The classical problem of perturbations during close encounters is thus found again, and amplified, at a higher level of astrometric precision.

This poses new problems for the data reduction of minor planets astrometry. In fact, it must be noted that the determination of a large number of masses is now deeply intermingled with the problem of orbits computation. A global solution, in the frame of a completely new approach in celestial mechanics, must then be found for trajectories and masses of the system, at the same time. The solution of this inverse problem is one of the most important priorities for the Solar System Working Group.

2.3. Gaia Capabilities in the Determination of Masses

To obtain some preliminary hints on the precision in mass determination that can be expected from Gaia, it is still useful to make the hypothesis that a single binary encounter between a large object and a target can be isolated from other interactions. In that case, the system associated to the observations can be written:

$$\mathbf{A}\,[\Delta\mathbf{X}] + \mathbf{B}\,[\Delta m] = \mathbf{O} - \mathbf{C} \qquad (2)$$

in which the matrix of partial derivatives with respect to the orbital elements and to the mass are called **A** and **B** respectively, while the corrections to apply to the mass of the perturbing body (Δm) and to the orbital elements ($\Delta\mathbf{X}$) are the unknowns.

Singular Value Decomposition allows to iteratively solve the system. We assumed for simplicity that the accuracy of each astrometric measurement (single Astrometric Field crossing) is the conservative value of 1 mas. We considered 4 close approaches between the most massive asteroids and small targets. Observing those targets over 5 years yield – for each encounter – a value of the expected accuracy on the unknown mass. The results are summarized in Table 4.

The accuracy of the last encounter, less well observed and producing a weak deviation, is obviously rather low, but in itself it represents a determination of the mass of 1 Ceres to better than 25%. However, the big jump in accuracy for the first three examples is spectacular. Furthermore, it must be taken into account that the final mass value will be determined by a combination of a large number of close approaches. From the statistics discussed above, we still remain on the conservative side stating that an accuracy of $\sim 10^{-14}$ will be reached for 1 Ceres, whose mass will thus be known to better than $\sim 10^{-4}$.

The statistics presented above suggest that Gaia will be able to derive a very precise mass for at least ∼100 asteroids, and a reliable estimate for several of them.

3. THE YARKOVSKY THERMAL EFFECT

3.1. The Role of the Yarkovsky Effect in Solar System Evolution

The Yarkovsky thermal effect is named after the civil engineer who first described it in a pamphlet written around the year 1900. He suggested that the thermal emission of a small spinning body in space would cause a tiny recoil force acting on it inducing a secular evolution in its orbit. Opik (1951) was the first to recognize the possible importance of the Yarkovsky force for the Solar System, but only in recent times (essentially the last decade of the 20th century) detailed studies have shown its role for understanding many unresolved issues in asteroids and meteorites science.

The exact computation of the Yarkovsky effect remains essentially impossible since, as cited above, it depends upon several properties of the asteroid, such as shape, density, thermal inertia of the inside and of surface material. Several useful approximations can be introduced to obtain reasonable estimates and several authors have made a variety of choices: spherical or more complex shapes, linearization relatively to an average internal temperature, etc. For a complete review the author can refer to Bottke et al. (2002).

The important element to note for the following, however, is that the Yarkovsky effect acts primarily by changing the semimajor axis of the asteroid orbit. In practice, if we consider an asteroid with a small spin axis obliquity, the thermal re-emission will be delayed relatively to the local mid-day. The resulting reaction force will thus have a non-zero component tangential to the orbit. This is the so-called 'diurnal effect', that can result in a positive or negative force depending upon the spin direction.

Table 4. Accuracy for single encounters solutions obtained by a variance-covariance analysis.

	Perturber		Perturbed	$\Delta\theta$ mas	Number obs.	σm $M_\odot$
4	Vesta	17	Thetis	400	71	2.6×10^{-13}
1	Ceres	45	Eugenia	50	78	1.1×10^{-12}
1	Ceres	829	Academia	57	103	7.3×10^{-12}
1	Ceres	1765	Wrubel	4	53	1.3×10^{-10}

In the linearized approximation, the diurnal component is separated by the 'seasonal effect', which is similar but referred to re-emission along the orbital motion. The seasonal component reaches its maximum for objects having high obliquities (i.e., maximum seasonal differences) and its direction is always opposed to the orbital motion. The diurnal effect, whose timescale is related to the spin rate, is in general much more efficient than the seasonal one, related to the orbital period. For this reason, in the following, we will consider mainly the diurnal component, as the most plausible candidate capable of yielding an orbit modification detectable by Gaia.

The importance of Yarkovsky can be better understood by recalling the relevant discrepancies that it could help to solve:

- To keep the population of kilometer-sized Near Earth Objects in steady state, it is necessary that fragments produced in the Main Belt by asteroid collisions (i.e., the small family members) be injected into resonances capable of delivering them toward the Earth. However, the small number of families identified in the inner or central Main Belt and their distance from powerful resonances is not compatible with this scenario (Zappalà et al. 2002). Yarkovsky force could cause a gradual drift of kilometer-sized object toward resonances, possibly solving the discrepancy (Bottke et al. 2002).
- The high post-impact ejection velocities that would be needed to explain the present dispersion of families in the orbital element space (Cellino et al. 1999; Tanga et al. 1999) are observed neither in laboratory nor in SPH simulations (Benz & Asphaug 1999). That dispersion, on the other hand, could be explained by the effect of the Yarkovsky force (Bottke et al. 2001).
- Meteorites are supposed to be ejecta of mutual collisions between asteroids. Their transport toward Earth orbit could be operated by their direct injection into resonances (Gladman et al. 1997) with the subsequent orbit modification. The main problem with this scenario is that the lifetime of meteorites into resonances ($\sim10^6$ years) would be much less than the measured Cosmic Rays Exposure ages ($\sim10^7$–10^9 years). A slow Yarkovsky drift could instead deliver meteorites to resonances at a rate compatible with observations (Farinella et al. 1998; Vokrouhlický & Farinella 2000).
- Yarkovsky force can also affect the spin rate of asteroids (YORP effect, (Rubincam 2000)). It could explain the excess of fast and slow rotators among small (D<10 km) asteroids, relatively to the Maxwellian distribution expected for a population in collisional equilibrium.

3.2. Yarkovsky Effect Evaluation and Measurement

It can be useful to recall that in the linear approximation for a spherical body, and assuming negligible orbital eccentricity, we can write for the diurnal and seasonal components (Bottke et al. 2002):

$$\left(\frac{da}{dt}\right)_{\rm diurnal} = -\frac{8\alpha\Phi}{9n}F_\omega(R_l,\Theta)\cos\gamma \qquad (3)$$

$$\left(\frac{da}{dt}\right)_{\rm seasonal} = \frac{4\alpha\Phi}{9n}F_n(R_l,\Theta)\sin^2\gamma \qquad (4)$$

in which n and ω are respectively the orbital and rotational frequencies, γ the obliquity of the spin axis, α a linear function of the albedo, $\Phi = \pi R^2\epsilon_0/(mc)$ the radiation pressure coefficient and F represents a complex function (Vokrouhlický 1998, 1999) mainly depending upon R_l (the radius of the object normalized to the thermal wave penetration depth l) and upon the thermal parameter Θ representing a measure of the relaxation between absorption and reemission. These two last parameters, in turn, depends upon the surface thermal conductivity K and the driving frequency ν (equal to spin or orbital rate depending upon which component is considered). Their behavior is like $l \sim \sqrt{K/\nu}$ and $\Omega \sim \sqrt{K\nu}$. Having defined those parameters, the main factors determining the entity of the Yarkovsky force can be summarized as follows:

- obliquity, as explained above. The diurnal component is at maximum when the rotation axis is perpendicular to the orbital plane.
- Size. For most of the objects in the size range accessible to Gaia, (da/dt)$\sim$1/R. For very large objects, the effect is limited by the body inertia. For small particles, by the fast redistribution of temperature in the interior, resulting in isotropic reemission. Optimal drift is for objects with R$\sim$10–100 meters.

- Surface conductivity K. It can probably assume values in large range, from K$\sim$0.001 W m^{-1} K^{-1} for thick regolith layers to K$\sim$1 W m^{-1} K^{-1} for compact rocks, up to K$\sim$40 W m^{-1} K^{-1} for iron objects. The Yarkovsky force is at maximum when $\Theta \sim R_l \sim 1$.
- Distance from the Sun. For the diurnal effect, in general, it can be demonstrated that $(da/dt) \sim a^{-2}$.

Observational data capable of providing constraints to the different parameters are not available in practice. Today, we probably detect indirectly the effect of the Yarkovsky force over dynamical families dispersion (Nezvornỳ & Bottke 2004).

On the other hand, only one case of direct detection exists at present: radar astrometry of the near-Earth asteroid 6489 Golevka, observed during four close approaches to the Earth: in 1991, 1995, 1999 and 2003. Delay-Doppler measurements were performed by the instruments of Arecibo and Goldstone (Chesley et al. 2003). The observations made during the first three close approaches have been used to predict the nominal Golevka position and velocity at the epoch of the May 2003 observations. Various error sources have been taken into account for the prediction, including the uncertainty related to poorly known planetary and asteroidal masses, and that intrinsic to the radar delay measurement itself. The measured 2003 position falls well outside the 90% confidence ellipse if the Yarkovsky effect is not included, with about a 6σ discrepancy; on the other hand, the prediction including the contribution of the thermal force is fully compatible with measurements. The distance between the two positions results to be about 15 km, but measurements uncertainties are still too large to allow a strict constraint on the entity of the Yarkovsky effect.

We can expect that in the next few years other radar observations of the same object, as well as of other NEOs, will improve the observational constraints for the Yarkovsky force. In any case, the concerned population will remain a very small sample.

3.3. Yarkovsky as Seen by Gaia

It is interesting to note that the Golevka magnitude at the epoch of the 2003 observation was V$\sim$16, and its distance 0.094 AU. Assuming a favorable projection of the displacement of 15 km on the sky, this would correspond to 2 mas for an Earth-based observer. Such a positional difference will be well within the astrometric sensitivity of Gaia at that given magnitude.

More generally, we can infer the role of Gaia in measuring thermal forces starting from current models of the Yarkovsky effect. From the considerations discussed above, we can state that maximum sensitivity will be reached for small objects (<1 km in general) of appropriate composition and low spin axis obliquity. Assuming a 1-km asteroid with 2.5 g cm^{-3}, the average drift rate at 1 AU from the Sun for a spherical body should be $\sim$2 × 10^{-4} AU Myr^{-1} for typical expected K values for Main Belt objects (Morbidelli & Vokrouhlický 2003). That means that over the 5 years duration of the Gaia mission, the semimajor axis change will be Δa $\sim$10^{-9} AU. The main effect of this drift will be a shift in the heliocentric orbital longitude of $\Delta\lambda$ $\sim$5 mas. Observed at a distance of 0.5$\sim$AU with a favorable projection of the orbital motion on the celestial sphere, this can translate to an angle up to 10 mas. Such a small asteroid will be at the limit of detection (around V$\sim$20, depending upon the albedo), but still the single passage in the AF should yield an accuracy better than $\sim$2 mas. With the contribution of several measurements over the mission lifetime and with an appropriate analysis of the orbit, the change in orbital elements should be detectable.

Of course, several assumptions concur to this positive result. For larger (and generally brighter) objects the effect will become too small to be measurable, and the geometry of both close encounters and Gaia observation will be critical. The best candidates are mainly Near Earth Objects with $a \sim 1$ AU. Nevertheless, on the positive side, it must be noted that a non negligible fraction of NEOs (about 5%)will be observed at a distance of 0.5 AU or even less (Mignard, F. 2002).

In other words, the set of objects capable of providing measurements of the Yarkovsky force by Gaia exist. Its weight, depending upon several parameters, must be carefully evaluated by further detection simulations.

4. PLANETARY SATELLITES

Planetary satellites are not only an important element for understanding the evolution of the Solar System, but also a natural laboratory for important dynamical phenomena. Satellites hardly observable from Earth will be easily detected by Gaia (Tanga 2005), but here we want to briefly recall some aspects related to major bodies.

One of the main open problems in the study of the Galilean satellites of Jupiter is related to the determination of the acceleration in their motion due to dissipative effects. Table 5 shows the results of some recent measurements. The discrepancies are relevant, even on the sign of the acceleration in some cases.

Recently, Lainey & Tobie (2004) have shown that Earth-based observations will not be able to constrain tidal dissipation. They performed a numerical simulation of the Galilean satellites motion over 100 years, and computed the difference in position for each body when tidal dissipation is taken into account. Figure 3 shows that, unfortunately, position derived from the dissipative model can be fitted with an appropriate non-dissipating orbital model, thus reducing the residuals well below the accuracy of Earth-based observations (50 mas at best, or $\sim$150 km at the distance of Jupiter).

In order to constrain dissipative effects, an accuracy better than 30 mas (for Io) to 10 mas (Ganimede) would be needed. Gaia will be able to easily go well beyond this requirements, detecting the position difference over a few

Table 5. Recent determination of the mean motion acceleration of Io, Europa and Ganimede (in units of 10^{-10} yr).

Reference	$\dot{n}_1/n_1$	$\dot{n}_2/n_2$	$\dot{n}_3/n_3$
Lieske (1987)	-0.074 ± 0.087	-0.082 ± 0.097	-0.098 ± 0.153
Vasundhara et al. (1996)	2.46 ± 0.73	-1.27 ± 0.84	-0.022 ± 1.07
Aksnes & Franklin (2001)	3.6 ± 1.0		

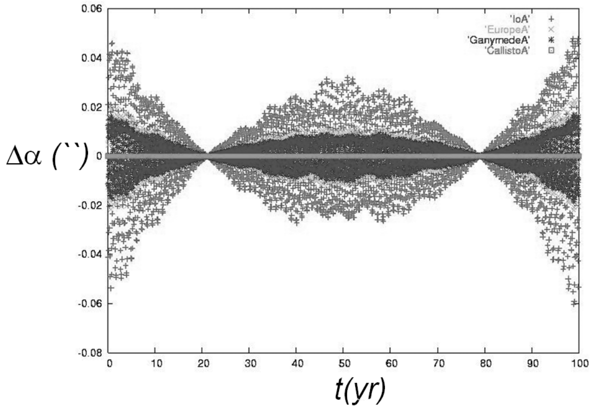

Figure 3. Difference in right ascension between the positions obtained by numerical integration of a model taking into account tidal dissipation, and a best-fitting non-dissipative model. The difference is plotted for the four Galilean satellites (Lainey & Tobie 2004).

years, provided that a suitable strategy for the observation of extremely bright sources is adopted.

5. PERSPECTIVES: AFTER GAIA

Even if not originally designed with Solar System studies as first priority, Gaia can probably be considered a 'global tool' for the study of the Solar System, and for asteroids in particular. Our knowledge of sizes, masses and dynamical properties – all keys to opening the way toward a better theoretical understanding – will make a giant leap forward. After Gaia, new perspectives will open both on the theoretical and the observational sides.

To cite just one example, precise orbits and masses will allow high-precision ephemerides, capable of providing a high degree of confidence to asteroidal occultation predictions. Networks of Earth-based observers will thus be able to increase in a considerable way the precision of shape and size determinations. Together with the knowledge of masses, the internal structure of a large sample of bodies will be within reach, and will be used to refine the thermal models that are the foundation for the study of the Yarkovsky effect.

The examples given in this work do not pretend to be a comprehensive list of topics that Gaia will address concerning Solar System dynamics, but certainly focus some of the most important areas needing improved observational efforts. The interested reader will find other relevant problems addressed elsewhere in this volume as, for example, the independent measurement of the PPN relativistic parameter Γ and of the Sun quadrupole moment J_2 (Hestroffer & Berthier 2005).

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