Small binary asteroids and prospects for their observations with Gaia

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Submitted to Planetary and Space Science on 2011 July 21.

Proposed running head: Small binary asteroids and Gaia

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Abstract

We studied a capability of Gaia to detect binary systems among small asteroids (with diameters $\lesssim$ 10 km) by observing their photocenter oscillation. The closest binary systems with orbit periods about 1 day or shorter show mostly a too low amplitude of the photocenter oscillation and Gaia will not be able to detect most of them with its expected astrometric performance. Wider binaries with orbit periods on an order of several days or longer shall be detectable with their amplitudes of the photocenter oscillation on an order of 10-times greater than the expected standard uncertainty of their Gaia astrometric measurements. A confusion of binaries with slowly rotating asteroids that show a rotational photocenter variation of a similar magnitude will not be significant unless the satellite is small or very large; in the range of medium-distance binaries (with the orbit periods on an order or several days), we shall be able to uniquely distinguish binaries with the diameter ratio D_2/D_1 between ~ 0.1 and ~ 0.95. Gaia will be the first survey to sample the largely unknown population of medium-distance binary systems among small main-belt asteroids where the present detection techniques (photometric and AO observations) are inefficient. A combination of Gaia binary observations with measurements with other techniques will be needed to eliminate existing degeneracy of the astrometric binary detection and to provide unique estimates of parameters of the binary systems.

Key words: Asteroids, binary;

1 Introduction: Binary systems among small asteroids

There exists a significant population of binary systems among asteroids with diameters $\lesssim 10$ km. Binary systems were found among near-Earth asteroids (Pravec and Hahn 1997, Pravec et al. 1998, Pravec et al. 2000. Mottola and Lahulla 2000, Margot et al. 2002, Pravec et al. 2006) as well as among small main-belt asteroids (Pravec and Harris 2007, and references therein). A fraction of binaries with a secondary-to-primary mean diameter ratio $D_2/D_1 \geq 0.18$ among near-Earth asteroids (NEAs) larger than 0.3 km was estimated to be $15 \pm 4\%$ (Pravec et al. 2006). A similar fraction of binaries was estimated among small main-belt asteroids (MBAs) with $D = 3$–8 km as well (Pravec et al. 2011).

Several interesting properties of NEA and MBA binaries were found by photometric and radar studies. One of the most important findings was that the binaries have a total angular momentum content close to the critical limit for a single body in gravity regime (Pravec and Harris 2007). Primary components of the binaries were found to have near-spheroidal, top-like shapes (Ostro et al. 2006, Shepard et al. 2006, Pravec et al. 2006, Taylor et al. 2008, Benner et al. 2010). Secondary rotations are mostly synchronous with the orbital motion. Eccentricities of mutual orbits between binary components are small and the orbit planes appear close to primary equatorial planes (e.g., Ostro et al. 2006, Scheirich and Pravec 2009, Pravec et al. 2011). Albedos of the components of a binary system are similar to within 20% (Pravec et al. 2006), consistent with being of a similar composition. Binaries appear to be ubiquitous; they were found everywhere (in all asteroid zones, groups and among all major taxonomic classes) we searched thoroughly enough. There were found also ternary systems among NEAs as well as MBAs (Brozovic et al. 2011, Marchis et al. 2008). A special case of a "quadruple" system (3749) Balam having a primary, a close satellite, a distant satellite, and a separated component (paired asteroid) was found by Vokrouhlický (2009; see references therein).

Binary systems among small asteroids (primary diameters $D_1 \lesssim 10$ km) appear to form from parent bodies spinning at a critical rate by some sort of fission or mass shedding process (Scheeres 2007, Pravec and Harris 2007, Walsh et al. 2008). A mechanism to spin the parent asteroid up to its critical rotation frequency is provided by the Yarkovsky-O'Keefe-Radzievskii-Paddack (YORP) effect (e.g., Bottke et al. 2006). Gravitational interactions of strenghtless asteroids during close encounters with the terrestrial planets cannot be a primary mechanism of formation of the binaries, but it may affect properties of the NEA part of the binary population (Walsh and Richardson 2006).

Though we have found some interesting properties of small asteroidal binary systems and developed initial theories for their origin and evolution during the past decade, getting a better knowledge of the binary asteroids will require to get a more complete description of the binary population. Present methods of detecting binary systems among small asteroids —the photometric, radar, and adaptive optics techniques— have significant selection effects. With radar, we can efficiently study only NEA binaries during their close approaches due to the echo strength decreasing with the 4th power of distance from the radar. A probability of binary detection

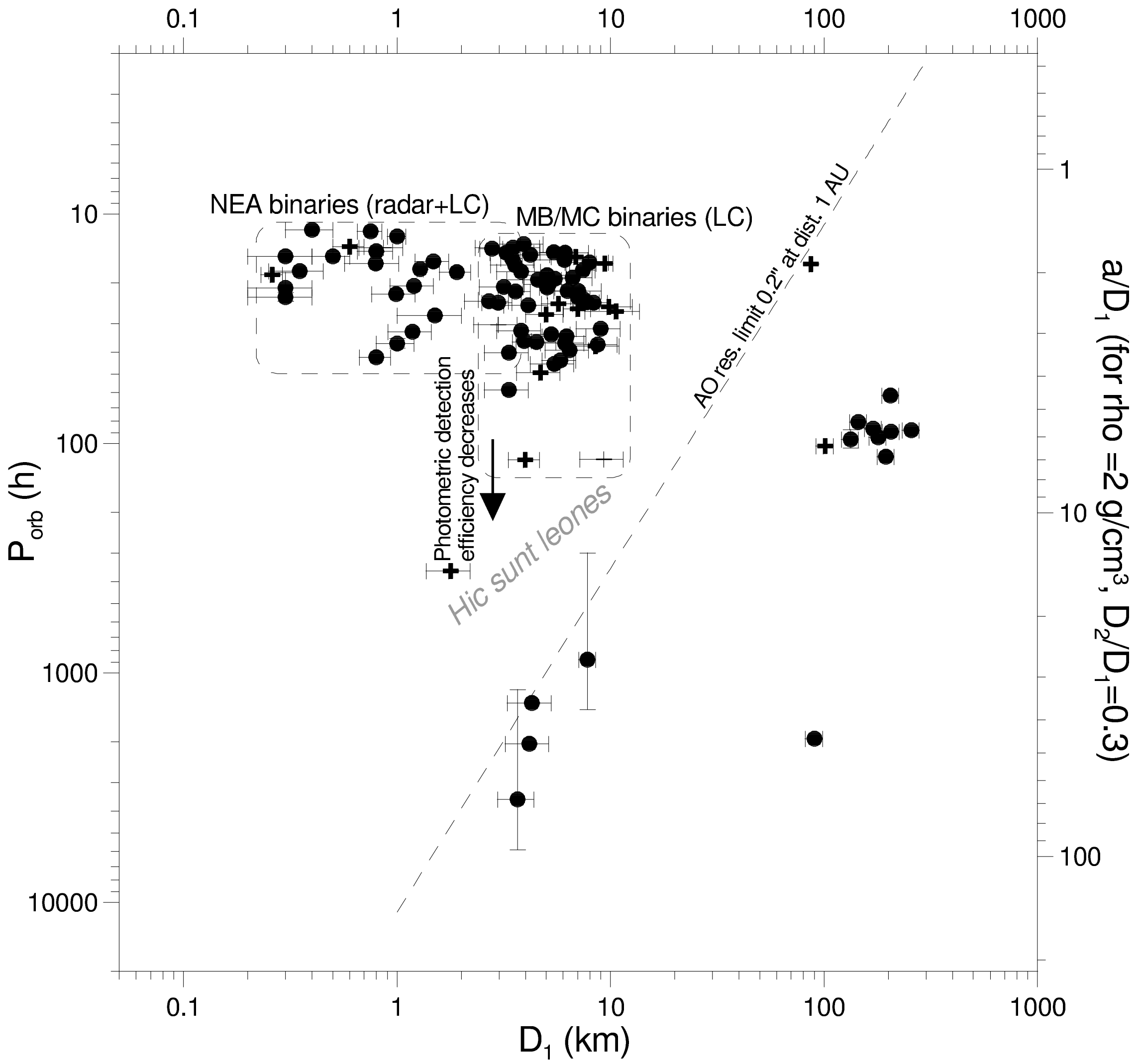

Fig. 1. Data on orbit periods vs primary diameters for known binary systems detected with radar, photometric (LC), and AO techniques. In the primary size range 1–10 km, there is an apparent gap between the group of close binaries ($P_{\rm orb}$ = 10–50 hours) detected with the photometric method and the group of wide binaries ($P_{\rm orb} \gtrsim 1000$ hours) where there is a lack of observed binary systems — the *Hic sunt leones* range. This largely unknown population of medium-distance asteroid binaries will be sampled by Gaia.

with the photometric method decreases with increasing separation between binary components, allowing an efficient study of binaries with orbit periods not longer than a few days. Present adaptive optics (AO) systems have a resolution limit of 0.1–0.2 arcseconds, depending on a magnitude difference between the two bodies (with the higher value for the resolution limit applying to binaries with greater magnitude difference and hence size ratio between the components).

In Fig. 1, we plot estimated orbit period vs primary diameter data for known binaries from our database (Pravec and Harris 2007, updated, available at web page http://www.asu.cas.cz/∼asteroid/binastdata.htm). Points to the right from the dashed line which gives the approximate AO resolution limit are binaries detected with direct imaging. Points to the left from the dashed line are binaries observed by the photometric and radar technique. In the primary size range 1–10 km, there is apparent a gap between the points for close binary systems with orbit periods mostly in the range 10–50 hours that were detected by the photometric technique and the points for wide binaries with orbit periods around 1000 hours or longer that were 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 orbit periods on an order of several days are too close to be resolved with AO observations and too wide to be efficiently detected with photometric observations of mutual events between their components. We show in this paper that Gaia will be the first survey capable of filling in this gap in our knowledge of the binary population.

2 Binary asteroid detection through photocenter oscillation

The center of mass and the center of light of a binary system are

$$\mathbf{r}_\mathrm{g} = \frac{M_1\mathbf{r}_1 + M_2\mathbf{r}_2}{M} \tag{1}$$

and

$$\mathbf{r}_\mathrm{p} = \frac{I_1(\mathbf{r}_1 + \delta\mathbf{r}_{\mathrm{p}1}) + I_2(\mathbf{r}_2 + \delta\mathbf{r}_{\mathrm{p}2})}{I} = \frac{I_1\mathbf{r}_1 + I_2\mathbf{r}_2}{I} + \frac{I_1\delta\mathbf{r}_{\mathrm{p}1} + I_2\delta\mathbf{r}_{\mathrm{p}2}}{I}, \tag{2}$$

respectively, where $M_i, I_i, \mathbf{r}_i, \delta\mathbf{r}_{\mathrm{p}i}$ are a mass, a light flux, a gravity center position vector, and a vector of apparent disk's photocenter offset from center of mass of the ith component, $M \equiv M_1 + M_2$ is the total mass and $I \equiv I_1 + I_2$ is the total light of the system. The second fraction on the right side is a correction term for the offsets of the photocenters of the apparent disks of the components; we will denote it with $\mathcal{O}_\mathrm{p}$ hereafter.

The center of light ("photocenter") is generally displaced from the center of gravity. The displacement vector is

$$\mathbf{\Delta r} = \mathbf{r}_\mathrm{p} - \mathbf{r}_\mathrm{g} = \left(\frac{I_2}{I} - \frac{M_2}{M}\right)\mathbf{r} + \mathcal{O}_\mathrm{p}, \tag{3}$$

where $\mathbf{r} = \mathbf{r}_2 - \mathbf{r}_1$ is a radius vector from the center of the primary to the center of the secondary.

In a case of spherical homogeneous components with the same density, albedo and a magnitude of the phase effect, the photocenter displacement vector is

$$\mathbf{\Delta r} = [(1 + X^{-2})^{-1} - (1 + X^{-3})^{-1}]\mathbf{r} + \mathcal{O}_\mathrm{p}, \tag{4}$$

where $X \equiv D_2/D_1$ is a ratio of diameters of the binary components. [1]

[1] An alternate form of the factor in brackets in Eq. (4) is $[(1 + X^3)^{-1} - (1 + X^2)^{-1}]$.

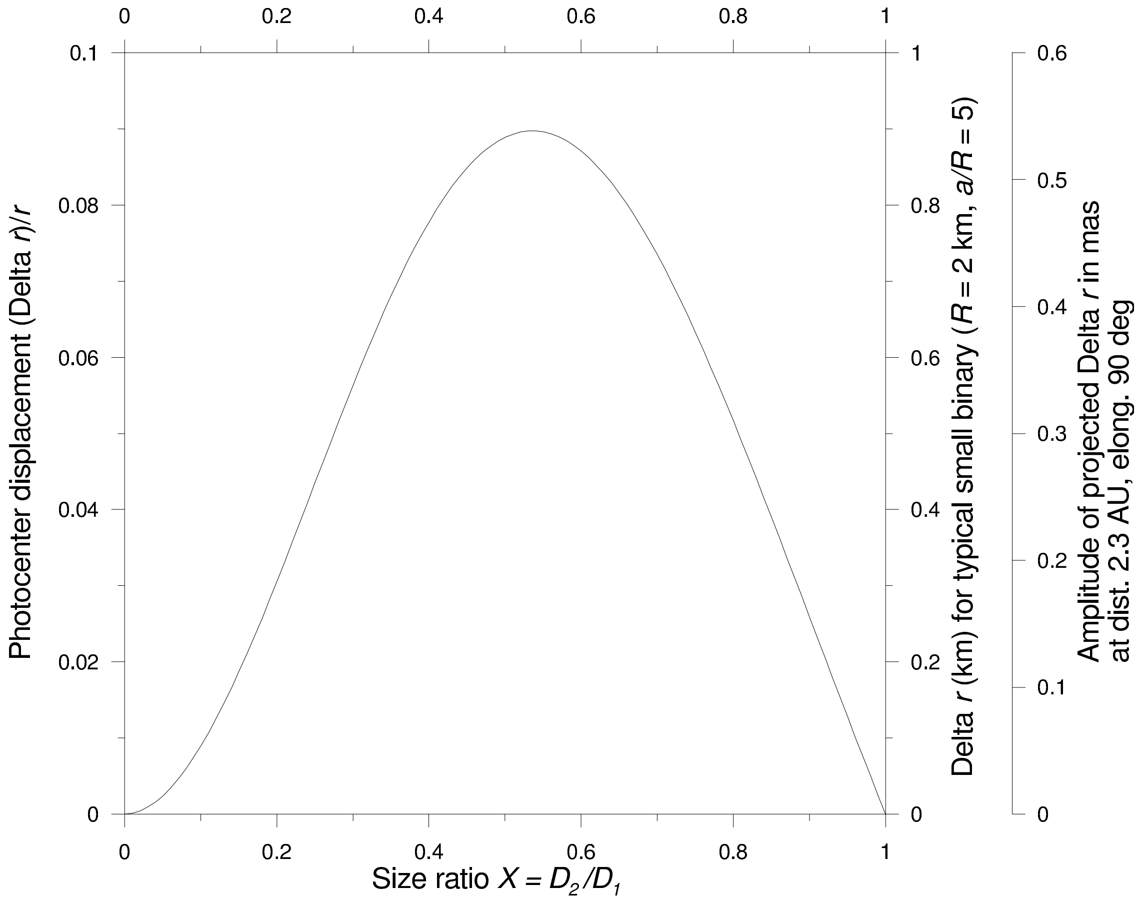

Fig. 2. Magnitude of the photocenter displacement as function of the diameter ratio for a binary system with spherical homogeneous components with the same density, albedo, magnitude of the phase effect, and zero correction term $\mathcal{O}_\mathrm{p}$.

The radius vector circulates with a mutual orbit period of the binary system, and so does $\mathbf{\Delta r}$ around the system's center of mass. This periodic motion of the photocenter around the center of mass, which itself moves around the sun on the asteroid's heliocentric orbit, can be detected with accurate astrometric observations.

3 Detectability of the photocenter oscillation

In Fig. 2, there is plotted a magnitude of the relative photocenter displacement $\Delta r/r$ as function of the diameter ratio X for a case of $\mathcal{O}_\mathrm{p} = 0$; the function is the term in brackets in Eq. (4). The photocenter displacement reaches the maximum $\max(\Delta r/r) \doteq 0.0897$ at $X \doteq 0.536$. The plot shows that a relatively high amplitude of the photocenter oscillation occurs in systems with satellites about half the primary size, while systems with small satellites or with satellites approaching the size of the primary ("double asteroids") show much smaller amplitudes of the photocenter oscillation. The y-axes on the right side of Fig. 2 show corresponding Δr in kilometers for an example of a typical small binary with the primary diameter of 4 km and the radius of the mutual orbit $r = 10$ km, and the amplitude of the

Table 1
Expected standard error of a single-epoch measurement by Gaia vs object's apparent V magnitude (P. Tanga, personal communication).

V	σ (mas)
12	0.02
14	0.06
16	0.15
18	0.38
20	1.00

projected displacement vector in miliarcseconds when the binary is observed at a distance of 2.3 AU and at solar elongation 90°. A sub-miliarcsecond astrometric accuracy is needed to detect the photocenter oscillation in a typical small main-belt binary.

An expected astrometric accuracy of Gaia, like for any properly designed observational project, depends on an apparent magnitude of observed object. Table 1 gives the expected standard uncertainty σ of Gaia single-epoch measurement of a target with the apparent V magnitude from 12 to 20. We represent the dependence of σ on V with following formula:

$$\sigma = 0.15 \times 10^{0.2(V-16)}, \tag{5}$$

where σ is in miliarcseconds (mas). The $\sigma(V)$ function is plotted in Fig. 3.

To investigate a capability of Gaia to observe small binary asteroids through oscillations of their photocenter, we used data from our database of parameters of known asteroid binaries (see Sect. 1) and for each binary with the primary diameter $D_1 < 20$ km, we computed a ratio between its amplitude of the photocenter oscillation $A_{\rm pc} \equiv \max(\Delta r)$ and the uncertainty of the Gaia astrometric measurement $\sigma(V)$ for asteroid's apparent V as seen from the Earth when the asteroid is at quadrature (solar elongation 90°) and with the heliocentric distance equal to the semi-major axis ($a_{\rm h}$) of its heliocentric orbit. Four known binaries on Aten-type orbits were omitted as their solar elongation is $< 90°$ when their heliocentric distance is equal to $a_{\rm h}$. We plotted resulting data $A_{\rm pc}/\sigma(V)$ vs the orbit period $P_{\rm orb}$ for 77 binaries in our sample in Fig. 4.

Most of the closest asteroid binaries with orbit periods less than 1 day have $A_{\rm pc}/\sigma(V) \lesssim 1$, thus they will be impossible or difficult to detect with Gaia unless a high number of points is obtained to beat down the noise. Close-ish binaries with orbit periods in the range 1–2 days have $A_{\rm pc}/\sigma(V) \sim 1$ or greater, so they should be barely detectable. The four wide binaries ($P_{\rm orb}$ of tens of days) with satellites detected with AO observations will be easily detectable as they have $A_{\rm pc}/\sigma(V) \sim 10$ or greater. Most interesting should be Gaia's work in the *Hic sunt leones* range of asteroid binaries with medium-distance satellites with $P_{\rm orb}$ on an order of several days.

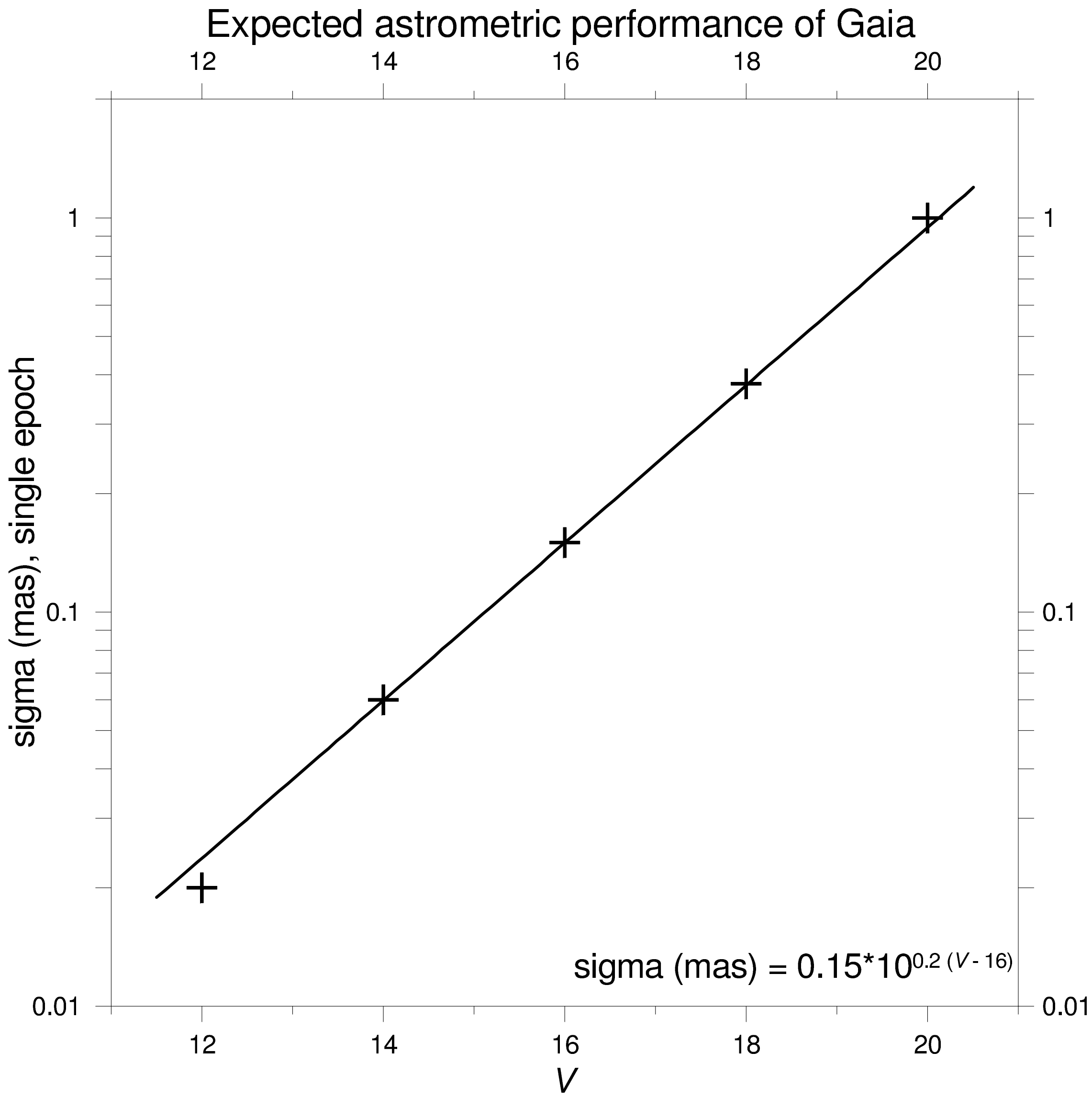

Fig. 3. The expected uncertainty of Gaia's single-epoch measurement vs object's apparent V magnitude. The crosses are the data from Table 1 and the line is the function given by Eq. (5).

4 Limitations of binary detection through photocenter oscillation

4.1 Degeneracy of the astrometric detection

With observations of the photocenter oscillation only, we cannot separate the components' distance r and the size ratio X from Eq. (4). An observed photocenter oscillation could be due to a small (or very large) satellite orbiting the primary on a large distance, or it could be equally well due to a more moderately sized satellite with a smaller separation from the primary.

A combination of Gaia binary observations with measurements by other tech-

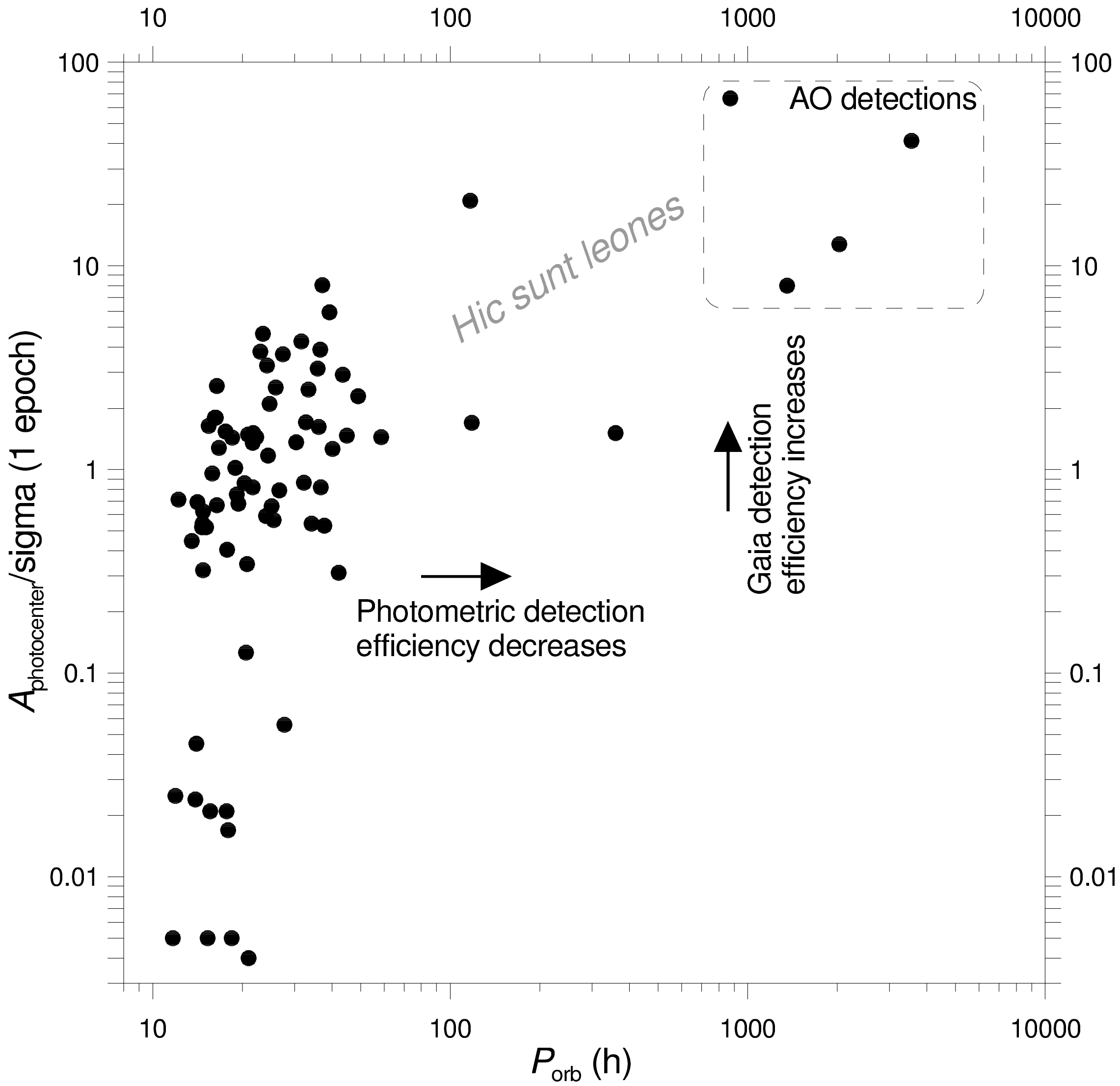

Fig. 4. Expected performance of Gaia on detection of binary asteroids is measured with a ratio between the estimated amplitude of the photocenter oscillation and the uncertainty of Gaia astrometric measurements σ. The estimated ratios for 77 small binaries vs their orbit periods are plotted.

nique(s) may provide constraints on the binary parameters. For instance, with $P_{\rm orb}$ determined from observations of the photocenter oscillation and a size estimated from observations, e.g., in thermal infrared, the system's semi-major axis r can be constrained using Kepler's Third Law, assuming a plausible range of bulk densities. Estimating the size ratio X from Eq. (4) will, however, still remain largely ambiguous.

4.2 Rotational variation of the photocenter

In real asteroid observations, the correction term $\mathcal{O}_{\rm p}$ in Eq. (4) is not zero. Unless the satellite is nearly equal in size to the primary, we can neglect the offset of the

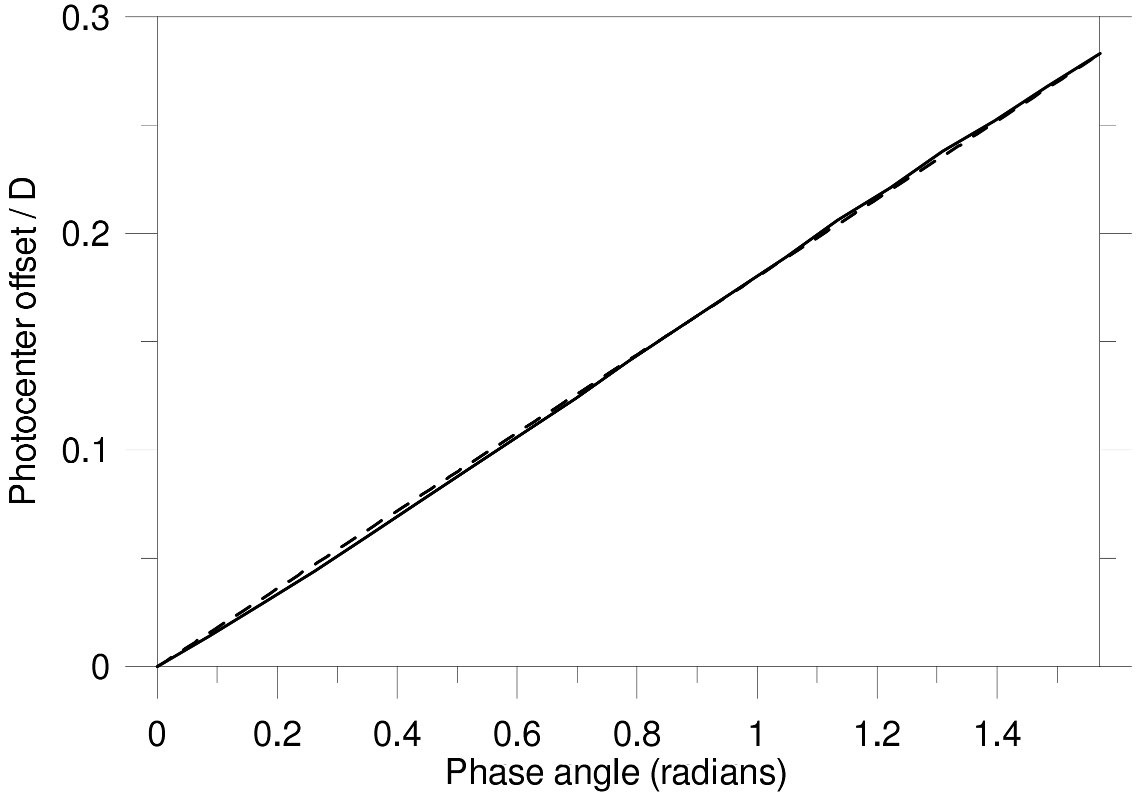

Fig. 5. The photocenter offset for a sphere with the Lommel-Seeliger scattering law as a function of phase angle (solid curve). The linear function eq. 6 is plotted as the dashed line.

photocenter of the secondary's disk (the last term in Eq. 2) and the correction term is $\mathcal{O}_\mathrm{p} \approx I_1 \delta \mathbf{r}_{\mathrm{p}1}/I$.

In a given geometry with respect to the Earth and Sun, the primary disk's photocenter offset vector $\delta \mathbf{r}_{\mathrm{p}1}$ generally has a constant and a periodic term due to rotation of the primary. For a sphere with the Lommel-Seeliger scattering law (see, e.g., Kaasalainen and Torppa, 2001), the projected (the plane-of-sky component of) offset vector is

$$\delta \mathbf{r}_{\mathrm{p}1} \simeq 0.180 D \alpha, \tag{6}$$

where D is the diameter of the sphere and α is a phase angle (in radians), see Fig. 5. The offset vector points towards the sun and there is zero periodic term of rotation of the body.

For a non-spherical primary, the periodic component of the offset vector $\delta \mathbf{r}_{\mathrm{p}1}$ is non-zero. To estimate a distribution of amplitudes of the periodic component of the offset vector in asteroids that will be observed by Gaia, we run a series of simulations with asteroid shapes represented with ellipsoids as well as with gaussian random spheres (Muinonen and Lagerros 1998).

A typical Gaia detected main-belt asteroid will be observed at solar phase about 24°. For this phase angle, a prolate spheroid (the semiaxes $R_\mathrm{a} \geq R_\mathrm{b} = R_\mathrm{c}$) with

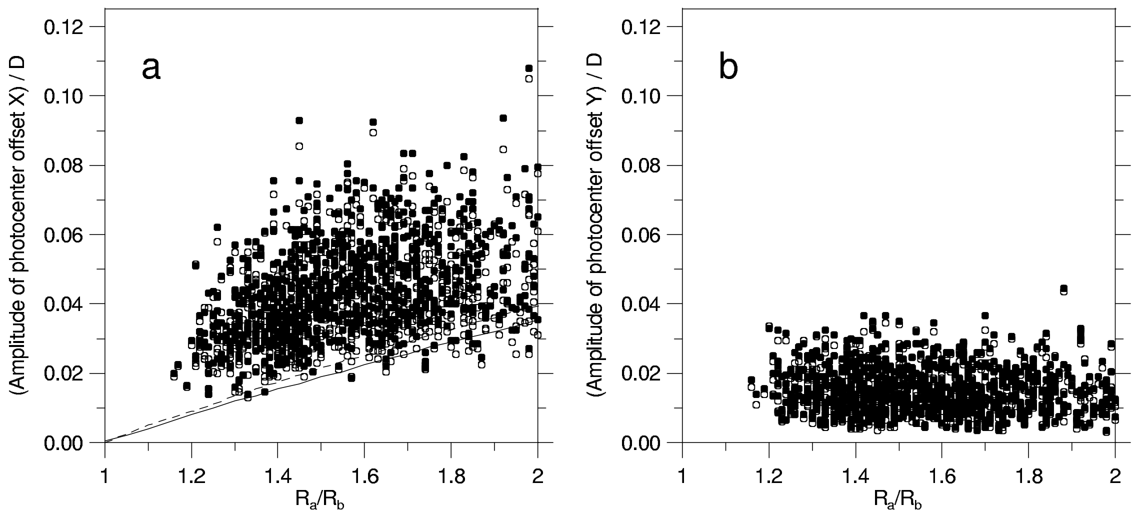

Fig. 6. Rotational amplitudes of the asteroid disk's photocenter offset of simulated asteroid shapes at phase angle of 24° as a function of the ratio between the largest and the smallest equatorial dimensions. Amplitudes of the component of the offset vector in direction towards the Sun are plotted in the left panel, and those of the transversal component are plotted in the right panel. The solid and the dashed curves are the functions for a prolate ellipsoid with the Lommel-Seeliger and the Hapke's scattering law for macroscopically rough surface, respectively. The open and filled points are simulated amplitudes for 1000 gaussian random spheres with the Lommel-Seeliger and the Hapke's scattering law, respectively.

the Lommel-Seeliger scattering law has a rotational amplitude of the asteroid disk's photocenter offset of $0.02D$ and $0.04D$ for $R_{\mathrm{a}}/R_{\mathrm{b}} = 1.5$ and 2.0, respectively, where D is the diameter of a sphere with equal volume. For the Hapke's law for macroscopically rough surface (Bowell et al., 1989), we get the rotational amplitude increased by a few percent (see Fig. 6, left panel). For consistency with the amplitude of the photocenter oscillation A_{pc} in Sect. 3, we define the rotational amplitude as half of a difference between the maximum and the minimum values of the photocenter offset component.

While for the ellipsoid the offset vector $\delta\mathbf{r}_{\mathrm{p1}}$ points towards the Sun, for an irregular shape it has a transversal component as well. We computed amplitudes of both components for 1000 gaussian random spheres rotating around axis with the maximum moment of inertia and observed at phase angle 24°. The results, presented in Fig. 6, show that the photocenters of irregular bodies oscillate with amplitudes typically between $0.02D$ and $0.08D$ in the direction towards the Sun. For $D = 4$ km and a typical geometry of Gaia detected MB asteroid ($a_{\mathrm{h}} \sim 2.5$ AU; solar elongation $\sim 90°$), this corresponds to a range from 0.05 to 0.20 mas. The transversal component oscillates with amplitudes up to $\sim 0.04D$, corresponding to ~ 0.10 mas.

The amplitudes of the rotational variation of the photocenter offset of asteroid disks are similar in magnitude to amplitudes of the photocenter oscilation due to the orbital motion of components of binary systems with small (or very large) secondaries. Thus, we may not be able to resolve, unless perhaps with extensive

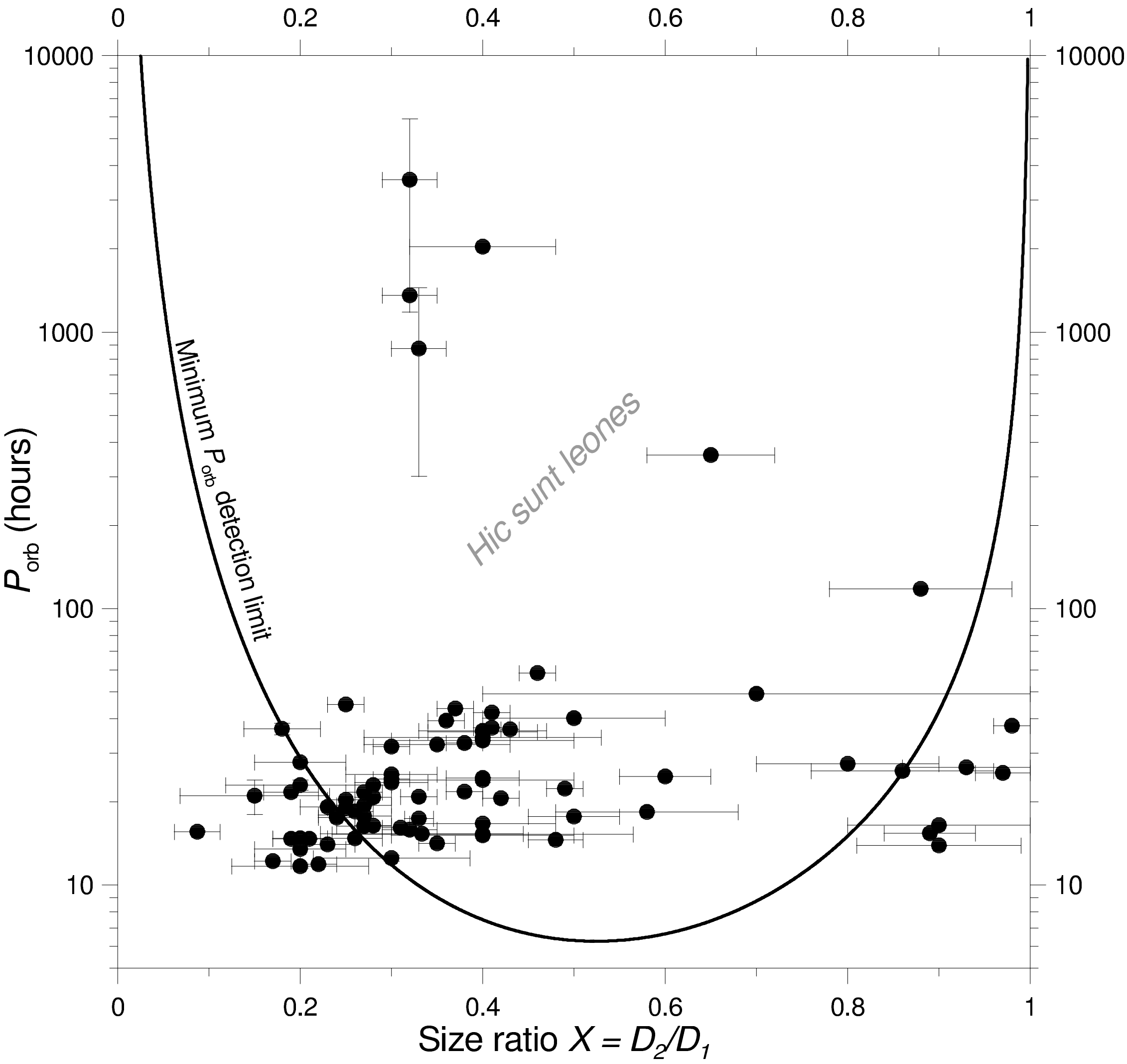

Fig. 7. Dependence of the minimum orbit period on the size ratio for a binary system to be uniquely distinguishable from a slowly rotating asteroid showing rotational photocenter variation with similar amplitude. The points (filled circles) are data for known binary systems.

data and modeling, whether an observed low-amplitude oscilation of the photocenter of an asteroid, with a period of tens or hundreds of hours, is due to a rotational variation of the photocenter in a slowly rotating single asteroid or an oscilation due to the orbital motion of components in a binary system. The simulations presented above suggest that a binary can be uniquely identified with observations of the photocenter oscilation when

$$A_{\rm pc} \gtrsim 0.08 D_{\rm eff}, \tag{7}$$

where $D_{\rm eff} = D_1\sqrt{1+X^2}$ is an effective diameter of the binary system. Using Eq. 4 and assuming circular mutual orbit of the binary, the inequality becomes

$$[(1+X^3)^{-1} - (1+X^2)^{-1}] \gtrsim 0.08 \frac{D_1\sqrt{1+X^2}}{r}. \tag{8}$$

Using Kepler's third law and assuming the mass ratio between system's components $q = X^3$, it is

$$[(1+X^3)^{-1} - (1+X^2)^{-1}] \gtrsim 0.08\sqrt{1+X^2}\sqrt[3]{\frac{24\pi}{G\rho(1+X^3)P_{\rm orb}^2}}, \tag{9}$$

where G is the gravitational constant and ρ is the primary's bulk density. After further processing, we get

$$P_{\rm orb} \gtrsim 0.212\frac{(1+X^2)^{\frac{3}{4}}}{\sqrt{\rho(1+X^3)[(1+X^3)^{-1} - (1+X^2)^{-1}]^3}}, \tag{10}$$

with the numerical constant 0.212 computed for $P_{\rm orb}$ in hours and ρ in g/cm^3.

In Fig. 7, we plot the curve representing the minimum $P_{\rm orb}$ vs size ratio X dependence according to Eq. 10, assuming $\rho = 2$ g/cm^3. It is apparent that only systems with small or very large satellites, with $X \lesssim 0.2$–0.3 or $X \gtrsim 0.8$ for close systems (which we detect in the main belt using the photometric technique), and $X \lesssim 0.1$ or $X \gtrsim 0.95$ for medium-distance systems with orbit periods on an order of several days (the *Hic sunt leones* range of binary parameters) may not be uniquely distinguishable from slowly rotating single asteroids showing similar photocenter variation due to their rotation.

5 Conclusions

Gaia will be the first survey to sample the largely unknown population of medium-distance binary systems among small main-belt asteroids where the present detection techniques (photometric and AO observations) are inefficient. For close systems with orbit periods about 1 day or shorter, which represent a majority in the current sample of asteroid binaries and which were detected with the photometric method of observations of mutual events between binary components, Gaia will provide only limited data as the close systems show low amplitudes of the photocenter oscillation comparable with or lower than the Gaia's expected astrometric accuracy.

Acknowledgement

The work was supported by the Grant Agency of the Czech Republic, Grant 205/09/1107.

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