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Close encounters of asteroids before and during the ESA GAIA mission*

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Abstract. Observation of close encounters of asteroids is a powerful method to determine their masses. A systematic search of such close encounters of asteroids with diameters larger than 40 km has been made thanks to a procedure to select the most efficient phenomena by means of the observable gravitational deflection. This study allows us to give lists of such single (one encounter) and multiple (several encounters between two pairs of asteroids) phenomena that will be observable from ground based astrometric telescopes from 2003 to 2022. We also give lists of single and multiple phenomena spanning 2010-2022 and implying less sensitive deflections only accessible by space astrometry. These last encounters may be observed during the ESA GAIA space mission.

Key words. minor planets, asteroids – astrometry – celestial mechanics – methods: observational

1. Introduction

The determination of the masses of asteroids remains a primordial problem to be solved in order to improve our knowledge of the dynamics of the asteroid families. Such progress could provide information on their origin and on the formation process of the solar system. Furthermore it could also give opportunities to improve the accuracy of the theory of motion of Mars which is now limited by the uncertainties on the asteroid masses (Standish & Fienga 2001).

Unfortunately, direct determination of asteroid masses is difficult. Less than twenty of them are currently available (Michałak 2001). Furthermore the uncertainties remain high, even for the largest asteroids Ceres, Pallas and Vesta (Hilton 1999). The analysis of the perturbing effects of the mass of an asteroid on the orbit of a target asteroid is the usual method to perform direct mass determination. For this purpose close orbits of asteroids involving one or several encounters have to be detected and computed. These resonant orbits are thus able to accumulate weak perturbations all along large periods of time of the order of ten or hundred years (Schubart 1974).

After the first determination of the mass of Vesta by Hertz (1968), the number of direct mass determinations using resonant orbits increased, leading to several determinations of the mass of Ceres (Schubart 1971; Landgraf 1988; Goffin 1991; Williams 1983; Viateau & Rapaport 1998; Michałak 2001). With similar methods, several papers recently led also to the determination of the mass of smaller asteroids from ground-based observations (Viateau & Rapaport 2001, 1997; Viateau 2000; Michałak 2001). Today, the ground-based observations seem to be of limited use for the search for new opportunities of mass determination. Favourable close encounters are rather rare. A systematic search was carried out by Kuzmanoski & Knežević (1993), who have computed opportunities of very close encounters spanning 1993–2043. Hilton et al. (1996) published their prospects for determining masses of large asteroids based on their own computations of close encounters from 1950 to 2017. More recently Galád (2001), and Galád & Gray (2002) studied much longer lists of asteroids and gave dates of close approaches from 1967 to 2023.

The accuracy of recent ground-based observations by CCD astrometry, reduced using astrometric catalogues, can reach 50 milliarcsec or mas (see for example Fienga 1998). Unfortunately, the need to include older and less accurate observations, performed with other techniques, imposes a strong restriction on the detection of perturbing effects of a given orbit by another asteroid. Furthermore, the next important step for asteroid mass determination will be achieved thanks to the new observational methods: mainly adaptive optics and space astrometry. The recent advent of adaptive optics has lead to the discovery of new satellites of asteroids and subsequently will us to get new determination of masses (Merline et al. 2000; Margot et al. 2000). But, beyond a deflection, the mass determination requires one to observe large enough arcs of the

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* Tables A.1–A.8 are only available in electronic form at the CDS via anonymous ftp to
cdsarc.u-strasbg.fr (130.79.128.5) or via
http://cdsweb.u-strasbg.fr/cgi-bin/qcat?J/A+A/406/751
or http://www.imcce.fr

Table 1. Main characteristics of the GAIA mission.

Magnitude limit		21
Number of objects:	stars	1.3 billions (to $V = 20$)
	asteroids	10^5 to 10^6
Accuracy:	stars	10 μmas
	asteroids	0.1 mas
Mission duration		≥5 years

satellite orbit in order to deduce the mass through the measurements of its orbital period. Considering these new techniques of observations and the new accuracy of the astrometric reductions, we think that close encounter observations remain very valuable and we give, in this paper, several dates of favourable close encounters from 2003 to 2022 which could allow us to determine asteroid masses thanks to such 50 mas ground-based observations.

From space, two kinds of mass measurements are possible. On the one hand, spacecraft can furnish opportunities for in situ asteroid mass determinations. This was the case with the fly-by of the small asteroid 243 Ida by Galileo (Belton et al. 1995), 253 Mathilde and 433 Eros by NEAR (Yeomans et al. 1997, 2000). On the other hand, data obtained by astrometric satellites have been proved to be helpful for mass determinations, due to the very good accuracy they provide in a short time in comparison with ground-based observations. The ESA satellite Hipparcos (ESA 1997) was the first instrument devoted to astrometric measurements of positions of stellar and solar system objects. Among them, the astrometric data of minor planets led an estimation of the mass of asteroid 20 Massalia (Bange & Bec-Borsenberger 1997; Bange 1998) which was the first determination of an asteroid mass using the short time span of close encounter observations. The GAIA mission is now planned by ESA to follow the Hipparcos mission in this way. Providing many more observations of greater accuracy (see Table 1), its data, planned to be taken between 2010 and 2022, will be of the greatest interest to study close encounters among asteroids. This project will allow a limiting accuracy two orders of magnitude better than its predecessor, Hipparcos. It is presently estimated to lead to positions, proper motions and parallaxes of about one billion objects, with an expected accuracy of 10 microarcseconds, along with multicolour multi-epoch photometry of each object.

In the first section of this paper, we define criteria and parameters used to identify close encounters efficient for mass determinations. In Sect. 3, we give the dates of encounters between asteroids and the intervals of time where the most efficient gravitational deflections have to be surveyed in order to provide masses of several asteroids from ground-based CCD astrometry. This study is done on the 2003–2022 period. In Sect. 4, we study the opportunities for close encounters involving fainter effects and occurring during the GAIA mission, from 2010 to 2022.

2. The selection procedure

In order to study close encounters of asteroids, we computed the orbital motions of 900 asteroids with a diameter greater than 40 km (among the first 8000 objects) taken from the ASTORB database (Bowell 2001). We used the orbital elements from this database as integration constants with the Bulirsch and Stoer algorithm (1966) of numerical integration. The planetary perturbations of all the planets were taken from the VSOP ephemerides (Bretagnon 1982)

It is an essential requirement for asteroid mass determinations to evaluate the characteristics of the gravitational event efficient for mass determination and to provide an estimate of their efficiency.

From 1971 till now, different criteria were considered. The minimal distance between the two asteroids, i.e. the impact parameter, is the usual criterion. The necessity of finding close enough orbits can explain this choice. But actually, the minimal distance is not the most determining parameter. As pointed out by Hoffman (1989) and Kuzmanoski & Knežević (1993), the relative velocity at close encounter (or "encounter velocity") is also an important characteristic to be considered. The masses of the bodies involved in a close approach is another parameter of importance. Thus, a criterion of maximal deflection, a number directly related to the deviation occurring in a close approach between two asteroids, can also be used as a selection criterion.

Bange (1998) defined a criterion of deflection proportional to $m_{\rm p}/r_{\rm m}v_0^2$, where v_0 is the relative velocity between the two bodies, $m_{\rm p}$ is the mass of the perturbing asteroid and $r_{\rm m}$ is the minimal distance at close encounter. This criterion is more sensitive to the encounter velocity than the other criteria described in literature. This method was already used to study and select close encounters of minor planets observed by Hipparcos (Bange & Bec-Borsenberger 1997).

Related to these characteristics, we define the concept of a mutual gravitational event (MGE). A mutual gravitational event occurs when the relative velocity becomes minimum or the impact parameter becomes minimum or the criterion of deflection becomes maximum. These events (minimum of relative velocity or impact parameter, or maximum of criterion) could occur at different epochs or within a delay of several days. In such cases, we have chosen to consider separately each event. This type of gravitational event is then seen as multiple events. In the case where the minimum of relative velocity, the minimum of the impact parameter and the maximum of the criterion of deflection occur once at the same time, then one can consider the event as a single event.

Furthermore, as described by Michałak (2001), the criterion we have finally chosen for the selection of asteroids suitable for mass determinations is the maximum difference in right ascension or in declination between the perturbed and unperturbed orbits of the asteroid. If the difference is large (greater than 50 mas for modern ground-based observations and greater than 1 mas for GAIA observations) and the available observations cover a long enough time before and after the MGE, the asteroid is a good candidate for mass determination.

The main sources of uncertainties in mass determination are in most cases the limited number of high accuracy observations framing the events. A good way to overcome this problem is to compute the mass determination over several different

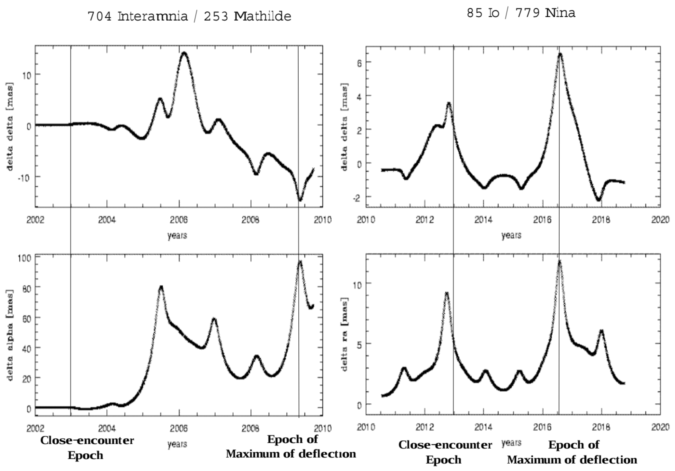

Fig. 1. Perturbations in right ascension and declination induced by the encounter between 704 Interamnia and 253 Mathilde and between 85 Io and 779 Nina. On the first plot, the estimated epoch of encounter is 2003, but the maximum impact would be observed in 2009. The estimated epoch of encounter for the second encounter is 2013, but the perturbations on the observed angles are maximum in 2016.

MGE with the same perturbing asteroid. When the number of MGE is large, the effects caused by systematic errors in the observations, gaps in the time distribution of observations, or mismodeling in the dynamical model can cancel out and not affect too seriously the mass determination. Considering this, we will emphasis such MGE.

Usually, one can see a delay between the epoch of the MGE and the deflection of the induced perturbations on the perturbed orbit. The delay between the MGE and the impact on the observable quantities (α, δ) could be very important as one can see in Fig. 1. The estimation of the mean epoch of the maximum deflection in (α,δ) is then a very important parameter.

For our computations, the initial epoch for all numerical integrations is t_0 = JD 2 450 000.5. The calculated position of a minor planet is obtained by numerical integration of the motion equations. The perturbations from major planets Mercury to Neptune are taken into account when integrating these equations of motion.

As 1 Ceres and 4 Vesta were intensively studied by radar and stellar occultation observations, as several dynamical mass determinations were already done, and mainly because of the NASA space mission Dawn (Russell et al. 2002), which is a Ceres and Vesta orbiter mission planed to be launched in 2006, the masses of these two asteroids will be quite well estimated in the near future (around 2010). We do not think that GAIA will be very useful in the mass determination of such big objects. In this paper, we would like to analyse more closely other possible mass determinations.

Finally, selections were also made considering the values of the solar elongation of the perturbed objects when perturbations become detectable (greater than 50 mas for ground-based surveys and greater than 1 mas for GAIA observations). For ground-based observations, the limit value is 50 degrees and for GAIA observations, the limit value is 35 degrees. In some cases, at the epoch of the maximum perturbations, the object is not observable. However, a few months before or after the epoch of the maximum, the object could have a good elongation and the perturbations on the orbit could be large enough to be detected. In the Appendix, two types of tables are published. The first type of table presents the main characteristics of the MGE. The second type of table gathers all the MGE that could be observed during periods when induced perturbations of orbits are large enough to be detected. Furthermore, we will present separately the single MGE and the multiple MGE.

3. The selection for ground-based observations

Determination of asteroid masses by close encounters from ground-based observations is a heavy task. However, if asteroids are observed during an appropriate period of time and with an efficient accuracy, the mass determination is possible, as it was demonstrated by Viateau & Rapaport (1997). Two criteria could be used to predict such success: a great deflection of the asteroid orbit detected by great changes in observable quantities (right ascension and declination) or a permanent modification of the Keplerian elements of the orbit noticed after a long period of mean accurate observations or a short period of very accurate observations. This second criterion will fit the space missions, even if it is difficult to estimate how accurate the mass determination could be after such deflection. If only ground-based observations are used, the first criterion seems to be the less uncertain indicator of success.

After computing possible close encounters over a 2003-2022 period (before and during the GAIA mission), we estimate for each of them the deflection induced on the orbit of the perturbed asteroid in computing the resulting variations in geocentric right ascension and declination. These variations were determined by comparison between the perturbed and unperturbed orbits 1000 days before and 2000 days after the MGE, in the case of a single MGE or, for multiple MGE, 1000 days before the first MGE and 2000 days after the last MGE in the limits of the time span of the numerical integration.

We have made a selection using the criterion of change in angular quantities detectable from the ground. The value of minimum change in right ascension or declination is 50 mas. The results for the selected phenomena are given in Appendix A. In Tables A.1 and A.3, the so-called epoch of MGE is given as well as the impact parameter, the relative distance and the criterion of maximum deflection (see Sect. 2). The epoch of MGE is defined as the epoch when the relative distance or velocity between the two asteroids become minimum or the criterion of deflection becomes maximum.

The ($\Delta\alpha$, $\Delta\delta$) given in tables are the maximum differences in right ascension and declination between the perturbed and the unperturbed orbits and the epoch of maximum ($\Delta\alpha$, $\Delta\delta$) is defined as the mean epoch for the maximum values of ($\Delta\alpha$, $\Delta\delta$). Finally, in Tables A.2 and A.4, we give the observability of each MGE. We give the periods when the asteroids have a mean solar elongation greater than 50 degrees and when the perturbations of the orbits induced by the MGE are greater than 50 mas. Mean values of these perturbations in right ascension and declination computed over the corresponding periods are given in Cols. 4 and 5.

3.1. Results

To simplify the analysis, we present the single MGE and multiple MGE in two different tables. Furthermore, in the following analysis, we stress over MGE induced by asteroids other than 1 Ceres and 4 Vesta.

For multiple MGE (Table A.1), there is 199 perturbed asteroids involving 10 perturbing asteroids, 1 Ceres (64%), 4 Vesta (24%), 10 Hygiea (4.5%), 16 Psyche (4%), 29 Amphitrite (1%) and 22 Kalliope, 31 Euphrosyne, 52 Europa, 65 Cybele, 511 Davida (1 MGE). There are 9 asteroids perturbed by 10 Hygiea inducing perturbations greater than 50 mas. All the MGE related to these 9 asteroids are observable and for 7 of them over more than one period of time. 10 Hygiea is then a very good candidate for mass determination. For the same reason, 16 Psyche is also a good candidate. 31 Euphrosyne has only one multiple MGE observable over a quite small period (from November 2017 and March 2018). However it is a very interesting case because, as one will note in the following, it would be the only observable event allowing mass determination of the asteroid 31 Euphrosyne.

For single MGE, we obtain 160 different MGE observable from the ground estimated over the 2003-2022 period. These encounters involve 12 different perturbing objects: 1 Ceres (69%), 4 Vesta (18%), 10 Hygiea, 16 Psyche, 19 Fortuna, 511 Davida and 704 Interamnia with 2 different MGE, and 2 Pallas, 48 Doris, 52 Europa, 87 Sylvia and 804 Hispania with 1 MGE. Most of them would also be observed during the GAIA mission. However one can have a closer look at the encounters of 10 Hygiea and 75 Eurydike, 16 Psyche and 1082 Pinola, 704 Interamnia and 253 Mathilde, and finally 87 Sylvia and 846 Lipperta. These 4 MGE would induce observable modifications of the angular quantities (α,δ) before the GAIA mission: the periods of observations of these MGE happen before January 2011 and the mean perturbations during these periods of observations in observable quantities are greater than 50 mas. It will be very interesting to begin now accurate astrometry of the target objects for these cases in order to perform an accurate modelling of their orbits.

The main advantage of the ground-based observations is their constant availability to observers. If an asteroid needs follow-up observations for a long period before and after the encounter, only small ground-based telescopes can provide such data sets. On the other hand, the accurate information given by GAIA observations can be very useful. Considering the Tables A.1–A.4, it is possible to set up a strategy which would combine long-time span modern ground-based observations with very accurate observations made by the GAIA space telescope during a very short period of time. Such strategy would allow to estimate very accurately new asteroid masses. As an example, an accurate mass determination of 1 Ceres was obtained by Viateau & Rapaport (1998) with combination of very accurate Hipparcos observations and ground-based data.

4. The selection for the GAIA mission

Following the success of the Hipparcos mission, the GAIA project, Global Astrometric Interferometer for Astrophysics, has been proposed (Perryman et al. 2001) for high precision astrometric measurement. This five year mission was selected as a cornerstone mission within European Space Agency's scientific programme in October 2000, to be launched before 2010.

The accuracy reachable by GAIA for solar system objects will nevertheless remain lower (0.1 mas) than the expected accuracy of star observations (10 microarcseconds), because of their apparent daily motion (Mignard 2002) and because of the offset between the observed photocenter and the real center of mass of the object (Evans & Tabachnik 2000). Simulations to define exactly what the error function induced by such defects could be are still in process. However, 10^5 to 10^6 asteroids could be observed with an astrometric accuracy of 100 μas (0.10 mas) (see Table 1).

Then, almost all the minor planets known today are expected to be observed at the sub-milliarcsecond level by GAIA. High precision photometry data would also be provided. As a great number of these asteroids are expected to be resolved, determinations of their diameters in the optical domain could be made.

In this paper we have studied the possibilities of direct mass determinations using close encounters between asteroids during the GAIA mission. For this purpose, following the method explained in the previous section, we performed a selection of encounters involving faint deflection effects (greater than 1 mas), observable only from space at the sub-milliarcsecond level and occurring from 2010 to 2022.

4.1. Results

With single or multiple encounters, the mass determination accuracy is very sensitive to the number of different close encounters used to compute the mass of the perturber (Michałak 2001). The best candidates for accurate mass determination are then perturbers involved in several encounters with the same or different target asteroids. In the case of GAIA observations, this statement could be slightly modified. Thanks to the high accuracy of the GAIA astrometry, we would also consider as good candidates for mass determination asteroids that only have one encounter but inducing important modifications of the orbit of the target object.

In Table A.7, one finds 51 perturbers (except 1 Ceres and 4 Vesta) involving 224 multiple MGE inducing perturbations on the orbit of the target object greater than 1 mas but smaller than 50 mas. A list of these 51 perturbers is given in Table 2. One can notice 15 new very good candidates for mass determination that have at least 2 different multiple MGE: 7 Iris, 15 Eunomia, 24 Themis, 39 Laetitia, 45 Eugenia, 46 Hestia, 76 Freia, 94 Aurora, 120 Lachesis, 121 Hermione, 128 Nemesis, 209 Dido, 375 Ursula, 451 Patientia, 566 Stereoskopia. Thanks to their multiple MGE, it will be possible to remove from mass determination uncertainties induced by observational and dynamical errors: on the one hand, fewer observational errors would be induced by the recursive observations, and on the other hand, the MGE with different asteroids would remove uncertainties induced by possible mismodelling of the target object dynamics.

Table 2. List of the asteroids (except 1 Ceres and 4 Vesta) inducing multiple MGE detectable by GAIA.The diameters and taxonomic classes are extracted from ASTORB database.

Name	Diameter km	Number of different multiple MGE	Name	Diameter km	Number of different multiple MGE
3 Juno	233.9	1	107 Camilla	222.6	1
7 Iris	199.8	5	120 Lachesis	174.1	2
9 Metis		1	121 Hermione	209.0	2
10 Hygiea	407.1	32	128 Nemesis	188.2	5
11 Parthenope	153.3	1	130 Elektra	182.3	1
13 Egeria	207.6	1	146 Lucina	132.2	1
14 Irene		1	147 Protogeneia	132.9	1
15 Eunomia	255.3	3	159 Aemilia	125.0	1
16 Psyche	253.2	36	165 Loreley	155.2	1
18 Melpomene	140.6	1	168 Sibylla	148.4	1
19 Fortuna		7	200 Dynamene	128.4	1
22 Kalliope	181.0	1	209 Dido	159.9	4
24 Themis		6	238 Hypathia	148.5	1
29 Amphitrite	212.2	3	241 Germania	168.9	1
39 Laetitia	149.5	2	308 Polyxo	140.7	1
45 Eugenia	214.6	4	334 Chicago	155.8	1
46 Hestia	124.1	2	349 Dembowska	139.8	1
48 Doris	221.8	3	375 Ursula		3
52 Europa	302.5	22	420 Bertholda	141.2	1
65 Cybele	237.3	15	423 Diotima	208.8	1
76 Freia	183.7	7	451 Patientia	225.0	2
87 Sylvia	260.9	19	511 Davida	326.1	5
88 Thisbe	200.6	1	566 Stereoskopia	168.2	2
94 Aurora	204.9	4	624 Hektor		1
106 Dione	146.6	1	704 Interamnia	316.6	1
			804 Hispania	157.2	3

In Table A.5, we have compiled the 95 candidates (without 1 Ceres and 4 Vesta) involving 609 single MGE to produce perturbations of the orbit of the target objects detectable by the GAIA mission. Among these 95 candidates, 8 have more than 20 different single MGE. One can find again the same asteroids as those detected with ground-based selection: 10 Hygiea, 16 Psyche, 19 Fortuna, 29 Amphitrite, 52 Europa, 65 Cybele, 87 Sylvia, and 511 Davida. These 8 asteroids are the best candidates for mass determination because they have at least 20 different MGE with different perturbed objects and because, thanks to the ground-based survey, we will combine different types of observations and different types of dynamical information. One can also notice that asteroids inducing multiple MGE detectable by GAIA induce also single MGE with more than 4 different target objects. This is the case for these 8 asteroids but also for 3 Juno, 7 Iris, 9 Metis, 11 Parthenope, 13 Egeria, 14 Irene, 15 Eunomia, 22 Kalliope, 24 Themis, 45 Eugenia, 46 Hestia, 48 Doris, 76 Freia, 88 Thisbe, 94 Aurora, 106 Dione, 107 Camilla, 121 Hermione, 128 Nemesis, 146 Lucina, 238 Hypathia, 349 Dewbowska, 420 Bertholda, 423 Diotima, 451 Patientia, 566 Stereoskopia, 704 Interamnia, 804 Hispania. With these 36 asteroids, one can make mass determinations by combining different types of data induced by multiple MGE and by single MGE. These mass determinations would be without systematic effects induced by the geometry of the MGE.

Asteroids producing only single MGE can also be very good candidates thanks to the important number of different MGE (greater than 4) they will induce: 6 Hebe, 20 Massalia, 59 Elpis, 145 Adeona, 259 Aletheia, 283 Emma, 324 Bamberga. 45% of the 95 candidates counts more than 4 encounters.

Thanks to the astrometry provided by the GAIA mission, it will be also possible to improve the mass determination accuracy in reducing the effects induced by the uncertainties in orbit determinations of the target objects. As it was introduced previously, another type of good candidate can be extracted from this study. It is also possible to notice quite important perturbations (perturbations in right ascension or in declination bigger than 5 mas) induced by 19 asteroids which were not yet considered as very good candidates because of the small numbers of different MGE (less than 4) they produce.

Table 3. List of the most interesting candidates for mass determinations (except 1 Ceres and 4 Vesta). These objects were selected because they induce multiple MGE (Cols. 4 and 6), or they produce perturbations detectable with ground-based observations (Cols. 4 and 5) or very high perturbations (greater than 5 mas) for the GAIA mission (Col. 7) or they have several (more than 4) single MGE with different target asteroids (Cols. 5 and 7). The diameters and taxonomic classes are extracted from ASTORB database.

Name	Diameter km	Taxonomy	Multiple MGE ground	Single MGE ground	Multiple MGE GAIA	Single MGE GAIA
2 Pallas	498.1	m		√		√
3 Juno	233.9	S			√	√
6 Hebe	182.2	S				√
7 Iris	199.8	S			√	√
9 Metis					√	√
10 Hygiea	407.1	C	√	√	√	√
11 Parthenope	153.3	S			√	√
13 Egeria	207.6	G			√	√
14 Irene					√	√
15 Eunomia	255.3	S			√	√
16 Psyche	253.2	M	√	√	√	√
18 Melpomene	140.6	S			√	
19 Fortuna				√	√	√
20 Massalia	145.5	S				√
22 Kalliope	181.0	M	√		√	√
24 Themis					√	√
29 Amphitrite	212.2	S	√		√	√
31 Euphrosyne	255.9		√			
39 Laetitia	149.5	S			√	√
45 Eugenia	214.6	C			√	√
46 Hestia	124.1	C			√	√
48 Doris	221.8	C		√	√	√
49 Pales	149.8	C				√
52 Europa	302.5	C	√	√	√	√
59 Elpis	164.8	C				√
65 Cybele	237.3	C	√		√	√
68 Leto	122.6	S				√
76 Freia	183.7	CP			√	√
85 Io	154.8	C				√
87 Sylvia	260.9	PC		√	√	√
88 Thisbe	200.6				√	√
89 Julia	151.5	S				√
94 Aurora	204.9	C			√	√
95 Arethusa	136.0	C				√
106 Dione	146.6	G			√	√
107 Camilla	222.6	C			√	√
111 Ate	134.6	C				√
120 Lachesis	174.1	C			√	√
121 Hermione	209.0	C			√	√
128 Nemesis	188.2	C			√	√
130 Elektra	182.3	G			√	√
145 Adeona	151.1	C				√
146 Lucina	132.2	C			√	√
147 Protogeneia	132.9	C			√	
159 Aemilia	125.0	C			√	√
165 Loreley	155.2				√	
168 Sibylla	148.4	C			√	
194 Prokne	168.4	C				√
196 Philomela	136.3	S				√
200 Dynamene	128.4	C			√	√
209 Dido	159.9	C			√	√
216 Kleopatra	135.1	M				√
238 Hypathia	148.5	C			√	√

Table 3. continued.

Name	Diameter km	Taxonomy	Multiple MGE ground	Single MGE ground	Multiple MGE GAIA	Single MGE GAIA
241 Germania	168.9	C			√	√
259 Aletheia	178.6					√
268 Adorea	139.9	FC				√
283 Emma	148.1					√
308 Polyxo	140.7				√	√
324 Bamberga	229.4					√
328 Gudrun	122.9					√
334 Chicago	155.8	C			√	
349 Dembowska	139.8				√	√
356 Liguria	131.3					√
375 Ursula					√	√
420 Bertholda	141.2	P			√	√
423 Diotima	208.8	C			√	√
451 Patientia	225.0	C			√	√
511 Davida	326.1	C	√	√	√	√
532 Herculina	222.2	S				√
566 Stereoskopia	168.2	C			√	√
624 Hektor					√	
704 Interamnia	316.6	F		√	√	√
790 Pretoria	170.4	PC				√
804 Hispania	157.2	C		√	√	√

This is the case for 39 Laetitia, 49 Pales, 68 Leto, 85 Io, 89 Julia, 95 Arethusa, 111 Ate, 120 Lachesis, 130 Elektra, 194 Prokne, 196 Philomela, 209 Dido, 216 Kleopatra, 241 Germania, 268 Adorea, 328 Gudrun, 356 Liguria, 532 Herculina and 790 Pretoria.

5. Discussion

In Table 3, one finds the list of the most promising candidates (in terms of induced multiple encounters, high number of single encounters or high perturbations on the target orbit) for mass determination for the period 2003–2022.

As was stressed in Sects. 3 and 4, ground-based observations will allow mass determination for a very few asteroids. 1 Ceres and 4 Vesta will be good candidates for such determination, but space astrometry will give also good opportunities to improve such mass computation. On the other hand, asteroids like 10 Hygiea, 87 Sylvia, 511 Davida and 704 Interamnia are also good candidates for mass computation on the basis of ground-based observations analysis. Furthermore, as it was demonstrated by Viateau & Rapaport (1998), it is possible to combine space astrometry with ground-based observations. For mass determination based on ground-based observations, a small arc of a very accurate orbit could be obtained thanks to space astrometry. Such accuracy obtained for a small arc of the orbit should improve the mass determination significantly. This strategy will be fruitful especially for 2 Pallas, 19 Fortuna and 511 Davida.

For mass determinations based on space astrometry, one can ask if an extension of the observed arc of orbit by ground-based observations is interesting. In the only other case of space-based astrometric observations, the observational geometry of the Hipparcos mission was such that accurate orbit determinations based only on Hipparcos observations were difficult (Hestroffer et al. 1998). It was then necessary to make the set of observations denser with accurate ground-based observations in order to obtain an accurate mass determination. One can note that in some cases (sets of Hipparcos observations well spread in time and space), mass determinations were possible only with Hipparcos observations, as demonstrated by Bange (1998) in his determination of the mass of 20 Massalia. With the GAIA mission, the geometry of observations will be simplier and would introduce less bias than in Hipparcos observations. Then, the remaining problem is the distribution in time and space of the observations. If GAIA observations are well spread in time and in space in order to perform accurate orbit determination, then ground-based observations would not be necessary. However, if the time and space cover of observations is not sufficient, then sets of ground-based observations would be needed for mass determinations.

Furthermore, one can stress that, as was described in Sect. 2, only asteroids with diameters greater than 40 km have been chosen for this work. In future work, it would be possible to expand the set of perturbed asteroids to smaller objects and then to increase the number of possible MGE.

In the end, one can consider that thanks to the spectroscopic observations realized by the GAIA mission simultaneously with the astrometric observations, it will be possible to have also information about spectroscopic characteristics of the observed asteroids. With the combination of accurate mass determination and spectroscopy, we will then be able to give a quite complete portrait of physical internal and external properties of these objects. A big step will be made in the understanding of the process of formation of our solar system main belt.

6. Conclusion

We have shown in this paper that valuable opportunities exist for direct mass determination of asteroid masses . Some are observable from ground-based observations by means of using accurate CCD astrometry. Others are only observable from space during the planned ESA GAIA mission. By studying close encounters of minor planets, it will be possible to improve the accuracy of the determination of the masses of the largest asteroids (Ceres, Pallas, Vesta and Hygiea). The GAIA data will also allow the first determination of the masses of about 70 asteroids with a very good accuracy and probably more asteroids with less precision. Combined with angular diameter data, they will provide a large amount of information about the values of the densities of the main belt asteroids and consequently about their composition and origin.

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