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Mass and density of asteroids (16) Psyche and (121) Hermione

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Abstract. The first determination of the mass of asteroids (16) Psyche and (121) Hermione is reported. From an encounter with asteroid (94) Aurora, the value (8.7 ± 2.6) 10^{-12} $M_\odot$ (solar mass) was derived for the mass of (16) Psyche. A mean density of (1.8 ± 0.6) g/cm^3 was deduced for this asteroid, which is much smaller than expected, since Psyche is believed to be a M-type asteroid (i.e. an asteroid of metallic composition). Some reasons that can explain this result are given, as well as some directions for further studies that could help improving the accuracy of the mass and the density of Psyche. On the other hand, the value (4.7 ± 0.8) 10^{-12} $M_\odot$ found for the mass of (121) Hermione from an encounter with (278) Paulina, and which gives a mean density of (1.8 ± 0.4) g/cm^3 for Hermione, corresponds to the expected value.

Key words: minor planets, asteroids – astrometry

1. Introduction

Asteroid mass determination is one of the important topics of the improvement of the knowledge of minor planets. On the one hand, masses of large asteroids need to be known with a good accuracy because these objects induce non negligible and, sometimes, strong perturbations on the orbits of the other asteroids and also of some planets (e.g. Standish et al. 1995, Hilton et al. 1996). On the other hand, the knowledge of the mass of an asteroid enables its mean density to be calculated, if its mean diameter is also known with a good approximation.

The first determination of the mass of an asteroid was made by Hertz in 1966 (determination of the mass of (4) Vesta). Until now, and apart from the current work, the masses of 14 asteroids among the largest ones have been determined, from their gravitational perturbations on the orbits of other solar system bodies (mainly other asteroids, but also planets and spacecraft). This number is rather few but, due to the increase of the number and the accuracy of the observations of asteroids, as well as the increase of the time spanned by these data, determinations of new masses are expected to be made in the next months or years.

In this context, we made a systematic search of close encounters involving large asteroids, and found two close encounters with favourable configuration. The first one occurred between (16) Psyche and (94) Aurora in 1937, and the second between (121) Hermione and (278) Paulina in 1944. To our knowledge, these encounters had not been previously mentioned in the literature, since systematic searches of encounters between asteroids made by other authors (Kuzmanosky & Knezevic 1993, Hilton et al. 1996) deal only with the period after 1950. Both encounters enabled us to determine for the first time the masses of Psyche and Hermione.

2. Method

This section describes the procedures of orbit computation and data treatment, which are common to both mass determinations.

2.1. Orbit computation

The theoretical positions of asteroids were calculated for a given date with the Bulirsh and Stoer numerical integration method (Bulirsh & Stoer 1966). The osculating elements given in the "Ephemerides of Minor Planets for 1995" (Batrakov 1994) were taken as initial conditions for all the asteroids (initial date JD = 2450000.5 TT). The integration of the motion of the perturbed minor planets took into account, as a standard procedure, the nine major planets but Pluto (VSOP82 theory, Bretagnon 1982) and, in addition, the perturbations of the 7 most massive asteroids (plus the asteroid of which the mass is to be determined). These asteroids are listed in Table 1 with the assumed value for their mass, and the resulting maximal perturbation on the orbits of (94) Aurora and (278) Paulina. The values of the masses were taken from the literature when possible, or, if not, were deduced from the mean diameter of the asteroids and an estimation of their mean density, as already made in our preceding mass determinations (Viateau & Rapaport 1997, Viateau & Rapaport 1998). For (1) Ceres, the assumed initial value of 4.76 10^{-10} $M_\odot$ (solar mass) was the value obtained by Viateau & Rapaport (1998). For (2) Pallas, (4) Vesta and (704) Interamnia, the values assumed are about the mean of all mass determinations for these asteroids. The value used for (10) Hygiea is the result found by Scholl et al. (1987). For (52) Europa and (511) Davida, which are respectively CF and C-class asteroids, and for which no direct mass determination has ever

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Send offprint requests to: B. Viateau (viateau@observ.u-bordeaux.fr) been made, the mass was calculated from the diameter of those asteroids given by IRAS, and an assumed mean density of 1.8 g/cm^3.

2.2. Data selection

The data used in this work were provided by the Minor Planet Center (USA), except for two observations of (94) Aurora made with the Bordeaux CCD meridian circle. As a standard procedure, all the data were expressed in the ICRF (International Celestial Reference Frame). Since all the observations do not have the same accuracy, a procedure of data selection and weighting was applied. This procedure is the same as the procedure applied in Viateau & Rapaport (1997) and Viateau & Rapaport (1998), and is described in the following.

First, all the observations provided with a precision worse than 0.1 sec of time in right ascension and 1 arcsec in declination are eliminated. Then, an iterative procedure is used. At the first iteration, the residuals of the observations are calculated using the initial conditions mentioned in Sect. 2.1. Since there are observations of very different epochs and, thus, of different accuracies among the data used, these data are separated into several groups with respect to the epoch of the observations. Each group is made up of observations showing residuals of about the same visual dispersion.

At every iteration, the standard deviation σ of the residuals is calculated for each group, and the observations giving residuals over $2.5\ \sigma$ are eliminated. Weights corresponding to σ are applied to the observations. Corrections for the mass of the perturbing asteroid and the six osculating elements of the perturbed body are calculated by a classical least-squares method, and give a new solution that is used as initial conditions for the next iteration. In the case of photographic or CCD observations, since right ascension and declination are not independent of each other in the reduction procedure, both coordinates are rejected if one of them gives a residual over $2.5\ \sigma$. Iterations are made until convergence.

3. The mass of (16) Psyche

3.1. The encounter

The close approach between (16) Psyche and (94) Aurora occurred in June 1937. During this approach, the minimal distance between both asteroids was 0.007 AU and the relative velocity of both asteroids was about 3.1 km/s. Psyche is the larger of the two asteroids. The effect of its gravitational perturbation on the orbit of Aurora was calculated by starting numerical integration from the epoch of the initial conditions (1995) back to the date of the oldest observations of this asteroid (1872), and by calculating the mass of Psyche from its diameter and an estimation of its mean density. In the different existing taxonomies of asteroids (Tholen 1989, Barucci et al. 1987, Tedesco et al. 1989), Psyche is classified as a M-type asteroid (i.e. an asteroid of dominant metallic composition). Thus, a mean density of 5 g/cm^3 was assumed for this asteroid. Previously, the same value had been adopted for M-class asteroid mean density in the computation of DE planetary ephemerides (Standish et al. 1995; Standish 1998). The mean diameter of Psyche given by IRAS is 264 km, which gave an estimated mass of 2.4 10^{-11} $M_\odot$ and a corresponding maximal perturbation on the orbit of Aurora of about 6” in right ascension and 3” in declination. The maximal effect was reached for the dates of the oldest observations of Aurora (Fig. 1). Such a perturbation enabled the mass of Psyche to be determined.

Table 1. Perturbing asteroids used with their mass, and their maximal perturbation in α cos δ on orbits of (94) Aurora and (278) Paulina. The effect in δ is about half the effect in α cos δ

Asteroid	Mass	Max. effect (”)	
	(10^{-10} $M_\odot$)	(94)	(278)
(1) Ceres	4.76	-0.52	-1.49
(2) Pallas	1.2	+0.08	-0.55
(4) Vesta	1.35	+0.04	+0.47
(10) Hygiea	0.47	-1.23	-0.02
(52) Europa	0.14	+0.03	-0.11
(511) Davida	0.18	-0.04	+0.02
(704) Interamnia	0.35	-0.14	+0.51

Reciprocally, the effect of the perturbation of (94) Aurora on the orbit of Psyche was calculated. The mean diameter of Aurora given by IRAS is 212 km. Since this asteroid belongs to a subgroup of C class, a value of 1.8 g/cm^3 was assumed for its mean density (Standish et al. 1995), which gave a value of about 4.5 10^{-12} $M_\odot$ for its mass. Thus, starting backward numerical integration from the current epoch, the effect of the perturbation of Aurora on the orbit of Psyche reached a maximum of less than 2” in R.A. for the oldest observations of Psyche, in the late 1850’s. This effect is of the same order than the precision of the observations of Psyche of the same epoch, which seems too faint to determine of the mass of Aurora (the attempts made to determine this mass remained unsuccessful).

3.2. Data

From 1872 to 1998, there are 276 available observations of (94) Aurora in the data archives of the Minor Planet Center. After elimination of 70 non astrometric observations (25%) which were provided with insufficient precision, a sample of 206 useful observations remained. Two additional observations of Aurora, made with the Bordeaux CCD meridian circle in the beginning of 1999, increased to 208 the number of observations. The O-C residuals of these data are shown in Fig. 2 in two cases, respectively without taking the perturbation of (16) Psyche on the orbit of Aurora, and with this perturbation.

In that figure, it can be seen that the observations of Aurora are not very numerous before 1925, and that the dispersion of the residuals do not decrease significantly before the 1980’s. In consequence, the observations of Aurora were separated in two groups and were selected and weighted by the iterative procedure described in Sect. 2.2. The number of selected observations for both groups and their weights after the last iteration are detailed in Table 2. It can be noted that 42% of the observations

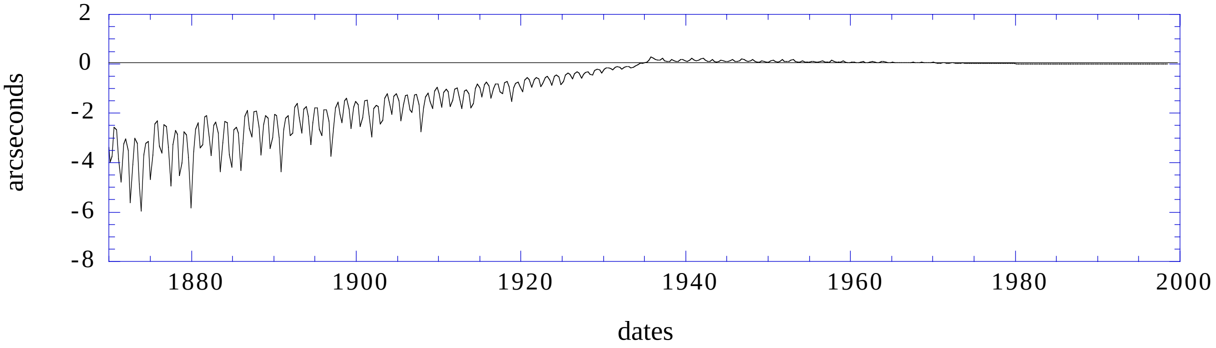

Fig. 1. Effect of the gravitational perturbation of (16) Psyche on the orbit of (94) Aurora in right ascension, starting backward numerical integration at epoch JED 2450000.5 = 1995 October 10.0 TT and assuming a mass of 2.4 10^{-11} $M_\odot$ for Psyche

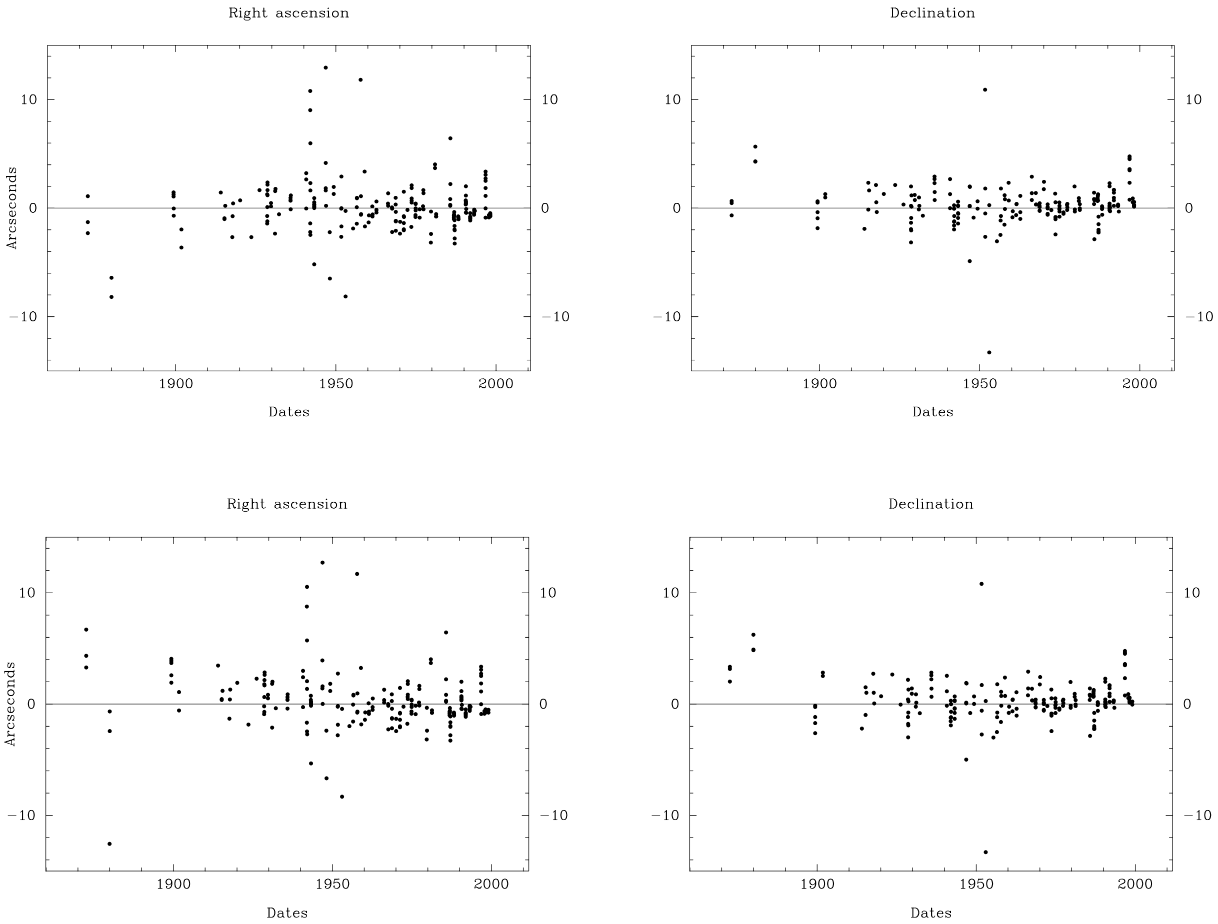

Fig. 2. Top: residuals of observations of asteroid (94) Aurora with orbital elements taken in the Ephemerides of Minor Planets for 1995 (Batrakov 1994) and neglecting the perturbation of (16) Psyche; Bottom: same, taking into account the perturbation of Psyche with an assumed mass of 2.4 10^{-11} $M_\odot$

of the second group (i.e. after 1979) have been eliminated. The reason is that this group is made up of observations of very different accuracies. This can be seen in Fig. 2 in right ascension mainly, where there are after 1985 observations of poor accuracy showing scattered residuals (up to 4”), and which were eliminated during the iterations, blended with a set of observations of better quality all giving residuals close to 0.

3.3. Results and discussion

The corrections for the mass of Psyche and for the six osculating elements of Aurora were calculated as described in Sect. 2.2. The new orbital elements of Aurora are given in Table 3, while the correlation coefficients between parameters are given in Table 4.

The value obtained for the mass of Psyche is (8.7 ± 2.6) 10^{-12} $M_\odot$. This value is three times smaller than ex-

Table 2. Characteristics of each group of observations of (94) Aurora; "initial nb" and "final nb" are respectively the number of observations before elimination by the first iteration and after the last one; "elim" and "% elim" are respectively the number and the percentage of eliminated observations; "σ" is the standard deviation of the residuals after the last iteration and "weight" is the final weight applied; unit weight corresponds to a mean precision of 0.5"

observations	coord	initial nb	final nb	elim.	% elim	σ (")	weight
1872-1977	α	139	116	23	16.5	1.30	0.15
	δ	139	116	23	16.5	1.09	0.21
1979-1998	α	69	40	29	42.0	0.28	3.2
	δ	69	40	29	42.0	0.28	3.2

Table 3. New orbital elements of (94) Aurora, and standard deviations, at epoch JED 2450000.5 = 1995 October 10.0 TT

	a (AU)	e	i ($^\circ$)	Ω ($^\circ$)	ω ($^\circ$)	M ($^\circ$)
elements	3.162289625	0.08205737	7.980755	2.895392	56.107521	244.832098
σ	25.10^{-9}	10.10^{-8}	13.10^{-6}	91.10^{-6}	134.10^{-6}	95.10^{-6}

Table 4. Correlation coefficients for initial position and velocity of (94) Aurora, and mass of (16) Psyche

	x_0	y_0	z_0	$\dot{x}_0$	$\dot{y}_0$	$\dot{z}_0$	M
x_0	1.000						
y_0	0.566	1.000					
z_0	0.305	-0.131	1.000				
$\dot{x}_0$	-0.898	-0.259	-0.130	1.000			
$\dot{y}_0$	0.776	0.549	0.451	-0.595	1.000		
$\dot{z}_0$	0.468	0.512	0.026	-0.341	-0.004	1.000	
M	-0.156	-0.069	-0.051	0.185	-0.151	-0.087	1.000

Table 5. Variation of the mass found for Psyche with respect to the value used for the mass of Hygiea

Hygiea		resulting
mass	density	mass of Psyche
10^{-11} M$_\odot$	g/cm^3	10^{-12} M$_\odot$
3.0	1.5	7.2
4.7	2.3	8.7
6.0	2.9	9.8

pected. Indeed, using the IRAS value for the mean diameter of Psyche, which is (264 ± 4) km, the mean density found for this asteroid is (1.8 ± 0.6) g/cm^3. However, Psyche is classified in the M-type asteroids, because its spectral characteristics are similar to those of metallic meteorites (McCord & Gaffey 1974, Chapman et al. 1975, Zellner & Gradie 1976, Bowell et al. 1978). Unlike asteroids belonging to other classes for which mass determinations gave in most cases a mean density about 2 g/cm^3, the mean density of M-class asteroids is expected to be much larger (Standish 1998). Thus, our value of the density of Psyche is two or three times smaller than expected.

Several reasons can explain this fact. First, the standard deviation on the value obtained for the mass is rather high, and it is known that the real uncertainty is often greater than the formal uncertainty. During the iterations, where the selection of the observations of Aurora as well as the weights applied on them varied, the result for the mass of Psyche oscillated between $7.9\ 10^{-12}$ and $1.29\ 10^{-11}$ M$_\odot$. Thus, the maximal value obtained is 15% higher than the upper bound given by the final result, but it is still half the expected value.

Additional uncertainty on the result is caused by the perturbation of (10) Hygiea on the orbit of Aurora (Table 1). The value $4.7\ 10^{-11}$ M$_\odot$ found by Scholl et al. (1987) for the mass of Hygiea was used in this work. Although the uncertainty of this mass is high, it must be noted that this value gives a mean density of 2.3 g/cm^3 for Hygiea, which seems quite normal for a C-class asteroid (Fig. 5). As an example, it is about the same density as (1) Ceres'. In order to see how the uncertainty on the mass of Hygiea influences the determination of the mass of Psyche, two computations of the latter were performed using different values for the mass of Hygiea, which correspond to quite extreme values of the mean density of this asteroid (Table 5). The result obtained for the mass of Psyche is respectively 7.2 and $9.8\ 10^{-12}$ M$_\odot$. Again, we stay in the same range of uncertainty as before, and, since the values of the mass of Hygiea were chosen as extreme, the effect of the uncertainty of this mass can be believed to be smaller than that.

For the previous reasons, the result for the mass of Psyche must be regarded as a first indication of what the actual value of this mass could be. Other close encounters between Psyche and other asteroids would be very useful for improving this result. We have made searches in this direction, but the encounters found were not close enough to enable the mass of Psyche to be determined. Further investigations should also be made about asteroids which may have induced additional gravitational perturbations on the orbit of (94) Aurora. The perturbations of the 7 largest asteroids (Table 1) are already taken into account in the standard procedure, but non negligible additional perturbations on the orbit of Aurora induced by other large asteroids could result in biases in the value found for the mass of Psyche.

The reasons evoked before give only a partial answer to the problem. Another reason that can explain why the mass of Psyche is smaller than expected is the fact that this asteroid is

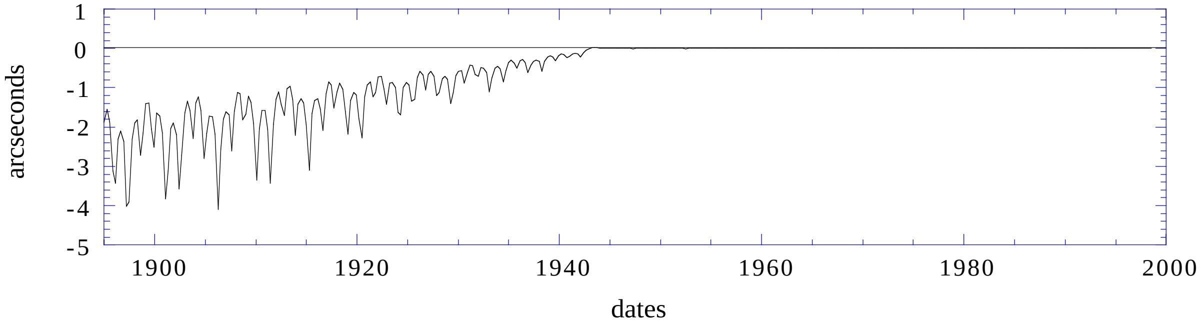

Fig. 3. Effect of the gravitational perturbation of (121) Hermione on the orbit of (278) Paulina in right ascension, starting backward numerical integration at epoch JED 2450000.5 = 1995 October 10.0 TT and assuming a mass of 5 10^{-12} $M_{\odot}$ for Hermione

not spherical but is believed to have the shape of a triaxial ellipsoid (Morando & Lindegren 1989). In such conditions, the volume of Psyche calculated from its mean diameter given by IRAS may be easily erroneous. We did not find in literature additional measurements of the dimensions of Psyche obtained from star occultations (e.g. Vasta & Manek 1998). Such measurements would be very helpful for improving the accuracy of the volume of this asteroid. Nevertheless, old determinations of the diameter of Psyche, made by radiometric or polarimetric techniques, are available and led to values about 250 km (e.g. Gaffey & McCord 1978). It must be noted that, if an uncertainty of 10% on the IRAS value of the diameter is assumed (which is not so much), a upper bound of 3.2 g/cm^3 is obtained for the mean density of this asteroid (when using the formal uncertainty on the mass). An uncertainty of 20% on the mean diameter would give a upper bound of 4.6 g/cm^3. For this reason, a better knowledge of the actual size of Psyche is essential.

The last reason which can explain a mean density smaller than expected is obviously the fact that the actual composition of Psyche may be different from what is believed.

4. The mass of (121) Hermione

4.1. The encounter

The other encounter which was considered in this work is the close approach between (121) Hermione and (278) Paulina. During this approach, the minimal distance between both asteroids was 0.0017 AU (i.e. only about 250,000 km, less than the Earth-Moon distance), and the relative velocity of both asteroids was about 2.9 km/s. The mean diameter of (121) Hermione given by IRAS is 217 km, while the diameter of (278) Paulina is only 38 km. Another determination of the diameter of Hermione was made by Stamm (1988) from a star occultation, however the value obtained was imprecise ($>$ 140 km). In consequence, the value given by IRAS was assumed.

The effect of the gravitational perturbation of Hermione on the orbit of Paulina was calculated the same way than between Psyche and Aurora. Hermione is a C-class asteroid and, as for Aurora, a mean density of 1.8 g/cm^3 was assumed for this asteroid, which gave an estimated mass of about 5 10^{-12} $M_{\odot}$. The corresponding maximal perturbation on the orbit of Paulina during the time interval covered by the observations of this asteroid is about 4” in right ascension and 2” in declination (Fig. 3). As it is described in the following, this perturbation enabled the determination of the mass of Hermione to be made.

Table 6. Characteristics of each group of observations of (278) Paulina; for explanations see Table 2

coord	initial nb	final nb	elim.	% elim	σ (“)
α	144	109	35	24.3	1.00
δ	144	110	34	23.6	0.82

4.2. Data

There are 144 observations of Paulina collected by the Minor Planet Center, and which are given with a precision better or equal than 0.1 sec of time in right ascension and 1” in declination. The residuals of these data, which cover the time interval from 1899 to 1998, are shown in Fig. 4.

In this figure, the evolution of the accuracy of the observations with time is not evident. In consequence, the observations of Paulina were taken as a whole, instead of separating them in several groups, as made for (94) Aurora. The number of selected observations are detailed in Table 6.

4.3. Results and discussion

Starting with a mass of Hermione equal to 5 10^{-12} $M_{\odot}$, the corrections for this mass and for the six osculating elements of Paulina were calculated as described in Sect. 2.2. The new orbital elements of Paulina are given in Table 7, and the correlations coefficients of the parameters are given in Table 8.

The value obtained for the mass of Hermione is (4.7 ± 0.8) 10^{-12} $M_{\odot}$. During the iterations, the value obtained always remained between 3.9 and 5.2 10^{-12} $M_{\odot}$, which indicates that the standard deviation obtained on the final result is quite consistent. This result is very close to the estimated mass of Hermione (Sect. 4.1), and gives for this asteroid a mean density of (1.8 ± 0.4) g/cm^3. This value is in agreement to the mean density of C-class asteroids found by Standish et al. (1995) in the

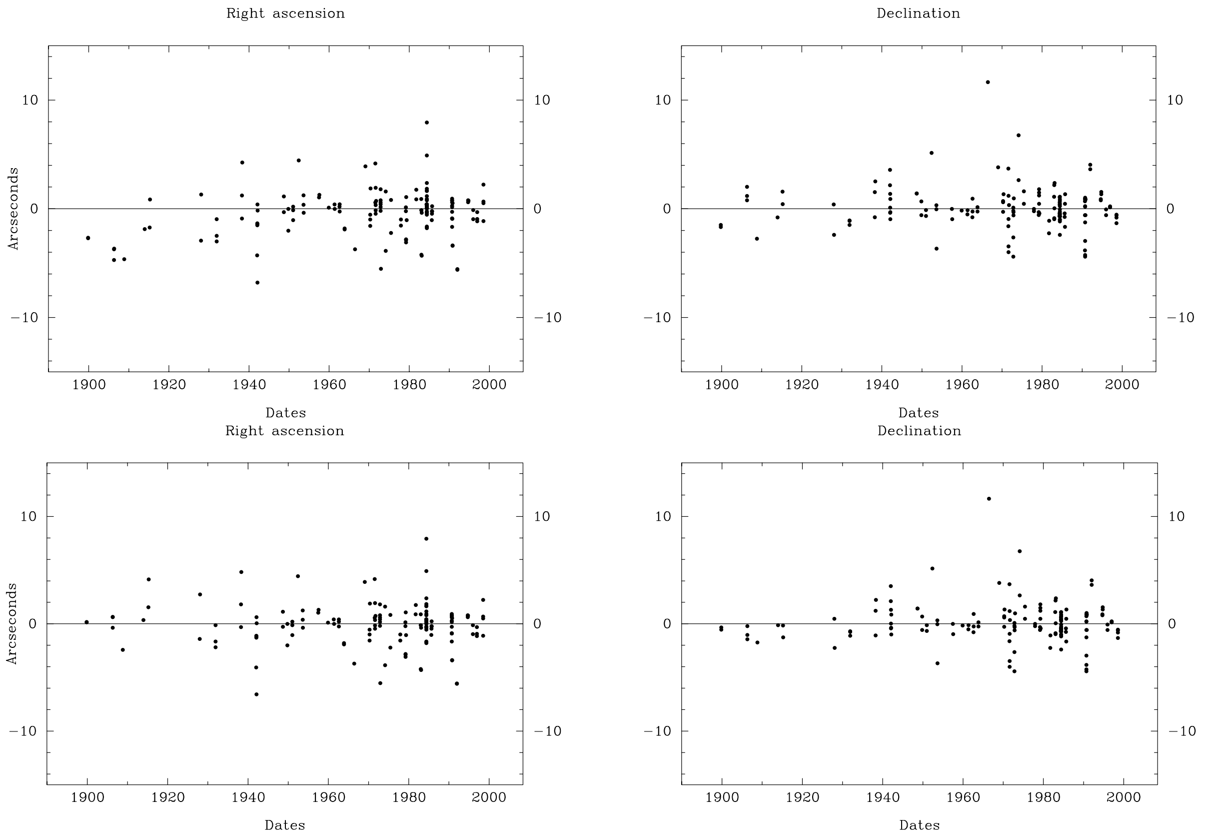

Fig. 4. Residuals of observations of asteroid (278) Paulina with orbital elements taken in the Ephemerides of Minor Planets for 1995 and neglecting the perturbation of (121) Hermione; Bottom: same, taking into account the perturbation of Hermione with an assumed mass of 5 10^{-12} $M_\odot$

Table 7. New orbital elements of (278) Paulina, and standard deviations, at epoch JED 2450000.5 = 1995 October 10.0 TT

	a (AU)	e	i (°)	Ω (°)	ω (°)	M (°)
elements	2.753974702	0.13533259	7.821750	62.254382	138.732100	208.086581
σ	27.10^{-9}	26.10^{-8}	23.10^{-6}	143.10^{-6}	165.10^{-6}	84.10^{-6}

Table 8. Correlation coefficients for initial position and velocity of (278) Paulina, and mass of (121) Hermione

	x_0	y_0	z_0	$\dot{x}_0$	$\dot{y}_0$	$\dot{z}_0$	M
x_0	1.000						
y_0	-0.728	1.000					
z_0	-0.479	0.279	1.000				
$\dot{x}_0$	0.970	-0.626	-0.493	1.000			
$\dot{y}_0$	0.645	-0.807	-0.504	0.573	1.000		
$\dot{z}_0$	0.145	-0.274	-0.198	0.227	-0.139	1.000	
M	0.407	-0.319	-0.232	0.462	0.378	0.133	1.000

DE 403 ephemerides computations. It is also consistent with the fact that most of the asteroids of which mass has already been determined have a mean density of about 2 g/cm^3 (Fig. 5).

5. Conclusion

Two new asteroid masses have been determined, which leads to 16 masses of asteroids determined until now, to our knowledge. The value obtained for the mass of Psyche, $(8.7 \pm 2.6)\ 10^{-12}$ $M_\odot$, indicates that this mass may be 2 or 3 times smaller as expected. On the other hand, the mass found for Hermione, $(4.7\pm0.8)\ 10^{-12}$ $M_\odot$, corresponds to the expected value. These determinations give a mean density of about 1.8 g/cm^3 for both asteroids, which is consistent with most of other asteroids for which mass determinations have already been made, although it is much smaller than expected in the case of Psyche. While the accuracy of the value found for the mass of Psyche needs to be improved, clarification of the situation of this asteroid could also be obtained if more accurate dimensions of this asteroid measured from star occultations were available.

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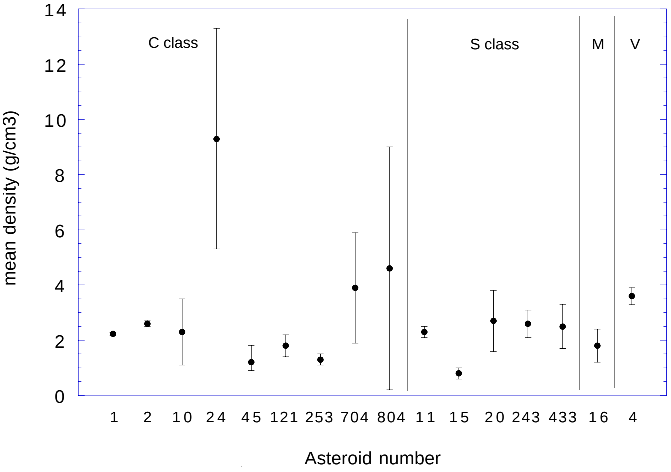

Fig. 5. Mean density of each of the 16 asteroids for which mass determinations have already been made, sorted by class; references of the masses used: (in brackets is given the asteroid number) [1] Viateau & Rapaport (1998), [2 and 4] Standish et al. (1995), [10] Scholl et al. (1987), [11] Viateau & Rapaport (1997), [15] Hilton (1997), [16] this work, [20] Bange (1998), [24] López García et al. (1997), [45] Merline et al. (1999), [121] this work, [243] Belton et al. (1995), [253] Yeomans et al. (1997), [433] Yeomans et al. (1999), [704 and 804] Landgraf (1992)

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