Astron. Astrophys. 320, 652–658 (1997)

ASTRONOMY
AND
ASTROPHYSICS

The Bordeaux meridian observations of asteroids. First determination of the mass of (11) Parthenope*

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Received 14 March 1996 / Accepted 20 August 1996

Abstract. The asteroid observations made with the automatic meridian circle at Bordeaux observatory from 1985 to 1994, and which have recently become available, are presented. The residuals of these observations obtained using the orbital elements published in the "Ephemerides of Minor Planets for 1996" are analysed. An anomaly for the asteroid (17) Thetis was found, indicating a current close encounter between this asteroid and (4) Vesta. Such an encounter will allow very interesting determinations of the mass of Vesta to be made in the future. Lastly, our determination of the mass of (11) Parthenope is discussed, which was based on its perturbations on the orbit of Thetis. The result obtained, $(2.58 \pm 0.10)\ 10^{-12}\ M_\odot$, appears significant.

Key words: minor planets, asteroids – astrometry – ephemerides – planets: 11 Parthenope; 4 Vesta; 17 Thetis

1. Introduction

In the early 1980's, a preliminary list of 62 asteroids (initially 63, and finally reduced to 48 objects) was drawn up, including some of the largest asteroids among the biggest ones which were to be observed by the astrometric satellite Hipparcos. Since Hipparcos, to point these objects, needed to know their position with a precision better than 1 arcsecond (Bec-Borsenberger 1985, Calaf 1988), a campaign of ground based observations was led, mainly involving the automatic meridian circles at Bordeaux observatory since 1983 and La Palma since 1984, and also at the San Fernando observatory since 1983. With the recent automation and improvements made to the meridian circles of Bordeaux and La Palma, systematic observations of asteroids could be made dating back to 1984 with a precision noticeably better than before.

We present in the next section the observations made in Bordeaux from 1985 to 1994, before the meridian circle was equipped with a CCD camera. We have re-reduced and processed these observations, which concern the 62 Hipparcos asteroids as well as others observed during the same period. The study of these observations enabled us to obtain the results presented in Sects. 3 and 4.

2. The Bordeaux observations

2.1. Processing the observations

The observations cover the period March 1985 - February 1994. Standard procedures for precession, nutation and annual aberration were applied to convert them from apparent to (FK5, J2000.0) coordinates. The bad observations were then eliminated. For this purpose, the residuals were calculated by using a numerical integration based on the Bulirsh and Stoer method (variable-step method). The initial conditions used were the orbital elements given in the "Ephemerides of Minor Planets for 1996" (hereafter referred to as "EMP 1996"), published by the Institute of Theoretical Astronomy at S^t Petersbourg (Batrakov 1995).

We eliminated 33 erroneous observations (0.6 %) which showed very large residuals both in right ascension and declination (i.e. residuals deviating significantly from other values in the same opposition epoch). After this processing, our database contained a total of 5546 observations in right ascension and declination for 133 observed asteroids (62 asteroids first selected for the Hipparcos mission and 71 others). Table 1 (published only in electronic form) gives the number of observations for each asteroid.

After an iterative 3σ-selection procedure on the residuals of each asteroid, the mean precision of the observations was estimated, by the global standard deviation of the residuals, to be about 0.15" in right ascension and 0.25" in declination. These observations were sent to the Minor Planet Center (Viateau & Rapaport 1995). 2260 of them, published previously to lower precision in the MPCs, were simply inserted into the data archives without being republished.

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* Figs. 5, 8, 9, 11, and 12 and Tables 1, 5, 6, and 7 are only available in electronic form via anonymous ftp 130.79.128.5 or via http://cdsweb.u-strasbg.fr/Abstract.html

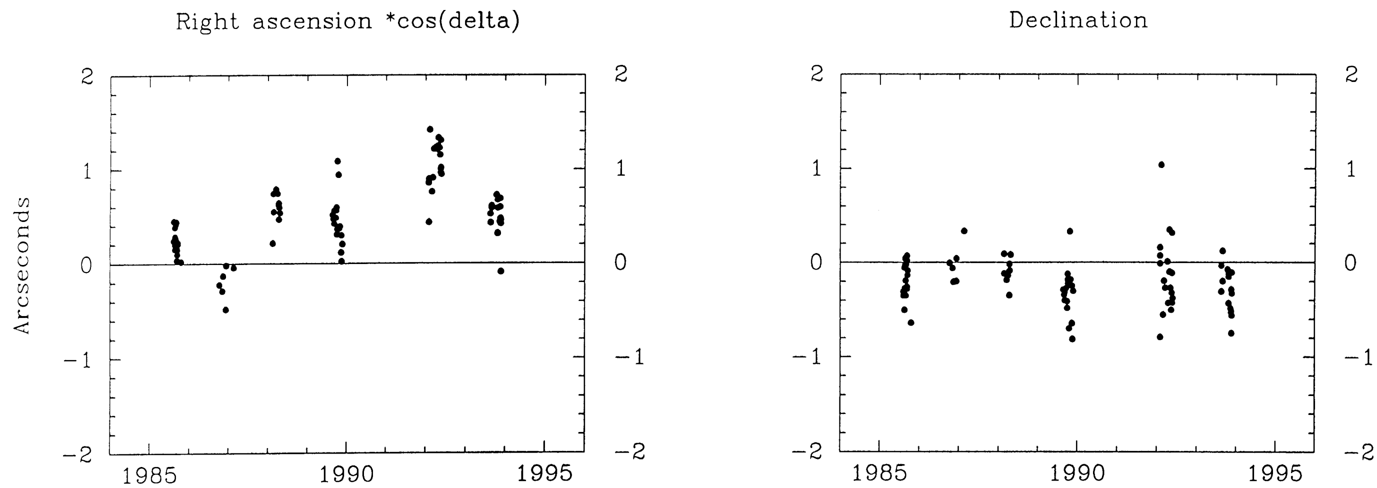

Fig. 1. a Asteroid (17) Thetis: Residuals of the meridian observations made in Bordeaux with the orbital elements published in EMP for 1995

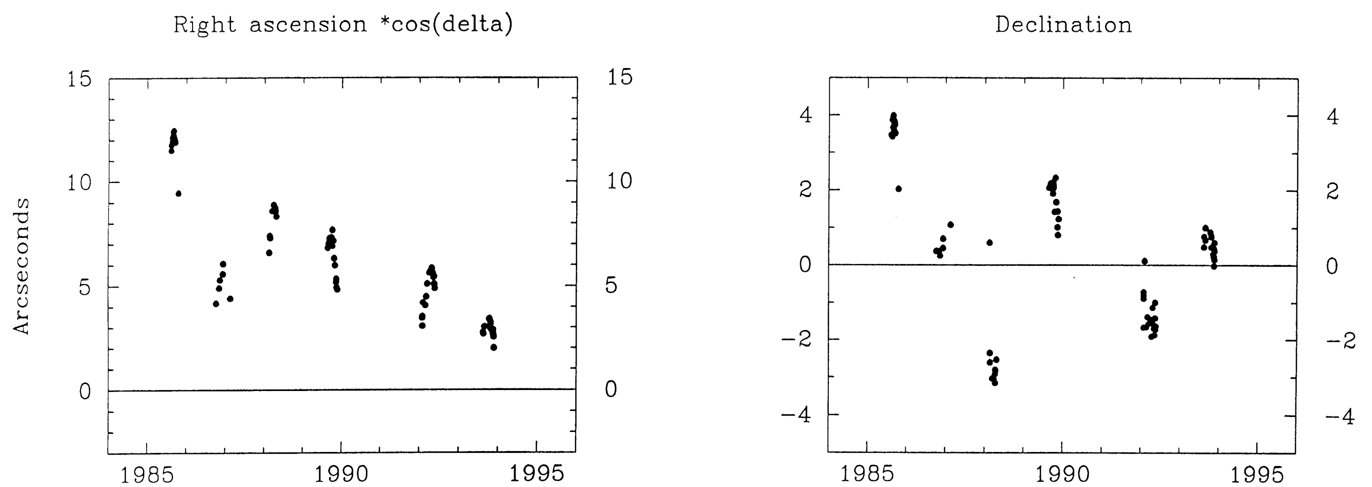

Fig. 1. b Asteroid (17) Thetis: Residuals of the meridian observations made in Bordeaux with the orbital elements published in EMP for 1996

2.2. Analysis of the residuals obtained with EMP 1996 orbital elements

We have used these observations to test the orbital elements of the observed asteroids published in EMP 1996. For most of these asteroids, the residuals calculated with these elements are well-distributed about zero, and no evidence of systematic effets can be seen.

3. Asteroid (17) Thetis and the mass of (4) Vesta

3.1. Consequences of a close encounter between Thetis and Vesta

The case of (17) Thetis is highly unusual. Although the orbital elements of Thetis published in EMP 1995 (Batrakov 1994) give residuals with a slight deviation (see Fig. 1a), the residuals calculated using the elements published in EMP 1996 show an important systematic effect, up to 12” in 10 years in right ascension (Fig. 1b).

The reason for this is that, in order to calculate the residuals, we used a standard computation model (the same model was used for all the asteroids whose orbit was studied) which takes into account the perturbations of (1) Ceres, (2) Pallas, (4) Vesta, (10) Hygiea and (704) Interamnia on the orbit of Thetis. We assumed the values 5.0 10^{-10} $M_\odot$ for the mass of Ceres (the value recommended by IAU Commission 20 at the IAU General Assembly of Buenos Aires in 1991), 1.2 10^{-10} $M_\odot$ for Pallas (which is about the mean of all mass determinations for this asteroid), 1.35 10^{-10} $M_\odot$ for Vesta (same reason as for Pallas), 4.7 10^{-11} $M_\odot$ for Hygiea (Scholl et al. 1987) and 3.5 10^{-11} $M_\odot$ for Interamnia (mean of the two values given in Landgraf 1992). These asteroids are believed to be the five most massive asteroids in the main asteroid belt.

If we neglect the perturbation of Vesta on the orbit of Thetis, approximately the same residuals are seen using the orbital elements published in EMP 1995, or those published in EMP 1996. This shows that Vesta very strongly perturbs the orbit of Thetis and is responsible for the systematic effect in the residuals shown in Fig. 1b.

The evolution with time of the distance between Thetis and Vesta is shown in Fig. 2 (a and b). It can be seen that, between

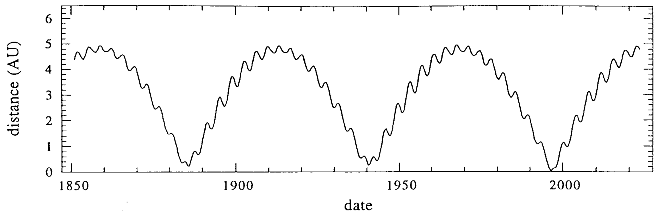

Fig. 2. a Distance between (17) Thetis and (4) Vesta from 1850 to 2023

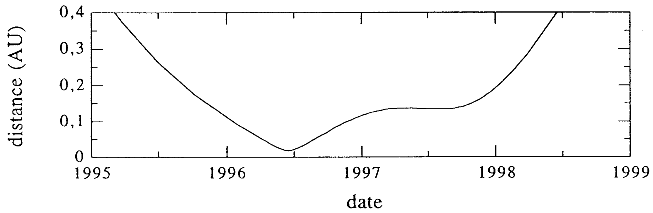

Fig. 2. b Distance between (17) Thetis and (4) Vesta from 1995 to 1999

March 1995 and June 1998, i.e. for more than 3 years, this distance is less than 0.4 AU, with a minimum of 0.0194 AU in June 1996. This very long encounter is due to the fact that the orbital elements of the two asteroids are currently close to each other. This implies that the resulting perturbation of Vesta on the orbit of Thetis is important (the deviation of the orbit of Thetis in right ascension reaches between 0.5 and 1" per year after the encounter, i.e. between 5 and 10" 10 years after the encounter, and up to 50" 50 years after it, see Fig. 3). This effect can be compared with the perturbation of Ceres on the orbit of (203) Pompeja, which is more than 80" in right ascension between 1879 and 1994 (Viateau 1995) and also on the orbit of (348) May, which is more than 100" in right ascension between 1892 and 1989 (Williams 1992).

A first consequence of this is that future determinations of the orbital elements of Thetis must take into account the perturbation caused by Vesta. On this subject, in an editorial notice on MPC 25257 (issued 1995 Aug. 10), it was noted that henceforth the standard perturbers applied to any new perturbed orbit computation at the Minor Planet Center would include (1) Ceres, (2) Pallas and (4) Vesta as a matter of course.

Moreover, such a perturbation should allow a very interesting determination of the mass of Vesta after 10 or 15 years of good post-encounter observations of Thetis, since the currently available observations of Thetis are quite abundant, with 1037 observations between 1852 and 1994. These observations were provided by the Minor Planet Center (Marsden 1995, Williams 1996). One third of them have been made since 1984, and we also noted that, since 1984, one third of the observations of Thetis have been made with the Bordeaux meridian circle. In fact, as the determination of the mass of Vesta and of the orbital elements of Thetis are closely linked, continuing observations of Thetis should begin as soon as possible, so that the orbit of Thetis and, then, the mass of Vesta, can be determined with the best precision possible.

3.2. Close encounters with Thetis in the literature

The close encounter between Thetis and Vesta was first noted by Hilton et al. (1995) and by Yoshikawa & Nakamura (1995). Yoshikawa & Nakamura found several close approaches concerning Thetis for the period 1990-2001, and announced some other very close approaches for Thetis (with a minimum distance of less than 0.01 AU) for the 21^{th} century. Apart from Vesta's approach, the most significant close approach for 1990-2001 concerning Thetis is certainly the one with the asteroid (11) Parthenope, in January 1997, for which the minimum distance will be 0.00536 AU, i.e. about 4 times closer than the one with Vesta.

We attempted to estimate the resulting perturbation of Parthenope on the orbit of Thetis, starting forward numerical integration from JED 2449600.5 = 1994 September 5.0 TT. For this purpose, we took the physical data for Parthenope (and other asteroids mentioned in this paper) from a file produced by D.K. Yeomans and provided by E.M. Standish. In this file, the asteroid radii are taken from the IRAS survey (Tedesco 1989), but some of the radii determined by occultation techniques have replaced the less certain IRAS values; the taxonomic classes come from Tholen (1989) (Yeomans 1996).

The estimated mean diameter of Parthenope is 162 km. Since its taxonomic class is S, we assumed its mean density to be 2.4 g/cm^3, taken from Standish et al. (1995), which gave an approximate mass for Parthenope of 2.7 10^{-12} M$\odot$, i.e. about 50 times smaller than the value for Vesta. Consequently, the perturbation due to Parthenope on the orbit of Thetis is not very large (up to 2.6" in $\alpha\, cos\delta$ and 0.6" in declination from 1994 to 2050, see Fig. 4) but will also have to be taken into account for future computations of the orbit of Thetis.

On the other hand, since the estimated diameter of Thetis is only 93 km, the effects of the reciprocal perturbation of Thetis on the orbits of Parthenope and Vesta are small: maximum 0.4" for Parthenope (Fig. 5, published only in electronic form) and 0.2" for Vesta in right ascension, for the period 1994-2050 (we assumed the value 5. 10^{-13} M$\odot$ for the mass of Thetis, since its taxonomic class is S).

Finally, the other close encounters detected by Yoshikawa & Nakamura for the period 1990-2001 should have only a negligible effect on the orbit of Thetis.

4. Determination of the mass of Parthenope

4.1. A very close encounter between Thetis and Parthenope

We also investigated perturbations due to Parthenope on Thetis in the past. We found that a very close encounter (0.0016 AU, i.e. about 240000 km, less than the Earth-Moon distance) occurred between the two asteroids in February 1968. The evolution with time of the distance between the two asteroids is given on Fig. 6. The resulting perturbation on the orbit of Thetis, starting backward integration from 1994, is up to 15" in $\alpha\, cos\delta$ (Fig. 7) and 4" in declination, until 1852. Such a perturbation allowed us to make, to our knowledge, the first determination of the mass of Parthenope, which will be discussed below.

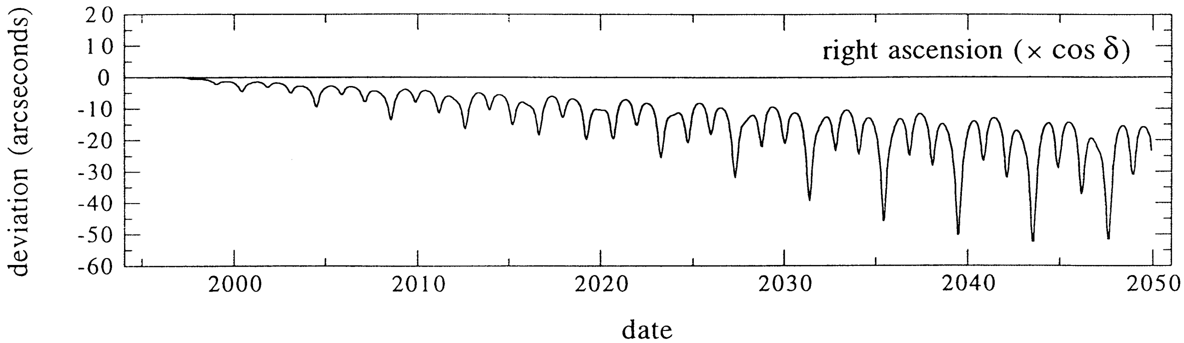

Fig. 3. Effect in right ascension ($\times cos\delta$) of the perturbation of (4) Vesta on the orbit of (17) Thetis, starting forward integration from JED 2449600.5 = 1994 Sep. 5.0 TT

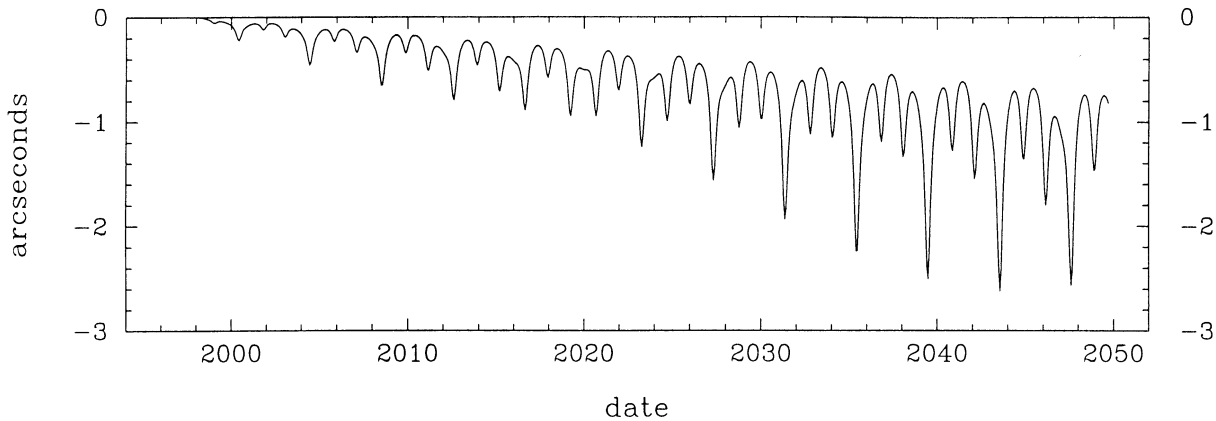

Fig. 4. Future perturbation of (11) Parthenope on the orbit of (17) Thetis in right ascension ($\times cos\delta$), starting with initial conditions in 1994 and assuming the value 2.7 10^{-12} M⊙ for the mass of Parthenope

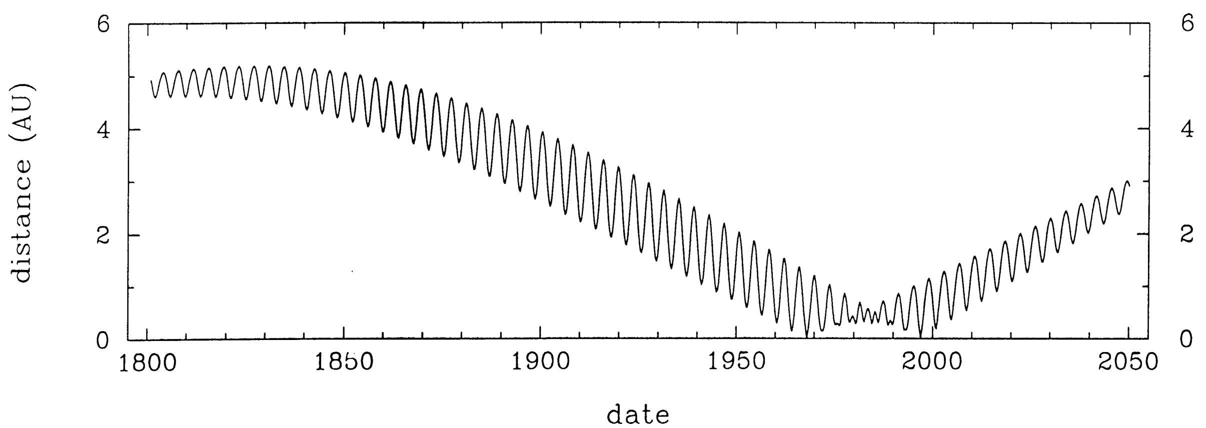

Fig. 6. Distance between the asteroids (17) Thetis and (11) Parthenope from 1800 to 2050 (minima: 0.0016 AU in 1968 and 0.0054 AU in January 1997)

4.2. A remark about the orbit of Parthenope

The perturbation of Thetis on the orbit of Parthenope for the period 1850-1994 reached a maximum of 2.8" in $\alpha\, cos\delta$ (Fig. 8a, published only in electronic form) and 0.9" in declination, as much as that of Vesta on this orbit (maximum 2.9" in $\alpha\, cos\delta$, see Fig. 8b, published only in electronic form, and 1.0" in declination). These two perturbations, which have a cumulative effect, should be taken into account for future improvements to the orbit of Parthenope.

4.3. Physical model used

In order to determine the mass of Parthenope from its perturbations upon the orbit of Thetis, we added to our physical model (described in Sect. 3.1) the perturbations of (511) Davida and

Table 2. Maximum effect of the perturbation of each asteroid upon the orbit of (17) Thetis, starting backward numerical integration at JED 2449600.5 =1994 Sep. 5.0 TT, and considering only the dates of the available observations. For all the asteroids, this maximum occurred between 1852 and 1864

Asteroid	Mass used	Maximum effect (")	
	(10^{-10} M⊙)	$\alpha \cos \delta$	δ
11	0.027	+ 15.1	- 3.9
4	1.35	+ 1.07	- 0.37
52	0.14	+ 0.78	- 0.22
2	1.2	- 0.66	+ 0.23
1	5.0	+ 0.59	- 0.24
704	0.35	- 0.15	+ 0.04
511	0.18	- 0.07	+ 0.02
10	0.47	+ 0.03	- 0.01

(52) Europa, which we believe are respectively the 6^{th} and 7^{th} most massive asteroids in the main asteroid belt. The estimated mean diameters of these asteroids are 337 and 312 km respectively, and their taxonomic classes are C and CF. Using the mean density for C-class asteroids determined by Standish et al. (1995), which is 1.8 g/cm^3, we estimated the mass to be 1.8 10^{-11} M⊙ for Davida and 1.4 10^{-11} M⊙ for Europa.

Thus, in addition to Parthenope and Vesta, our computation model takes into account the perturbations of 6 asteroids on the orbit of Thetis. We calculated their effect by computing the residuals of the observations of Thetis with and without the perturbation. For the initial conditions of Thetis we took the orbital elements published in EMP 1994 (Batrakov 1993), i.e. before the current perturbation of Vesta upon the orbit of Thetis began to take effect (Fig. 2b).

Table 2 summarizes the maximum effect of the perturbation of each asteroid on the residuals. For all the asteroids, this maximum was reached for the observations of 1864. It is apparent that the effect of the perturbation of Parthenope is strong compared with other asteroids. The effects of this perturbation for the dates of the available observations of Thetis are put in evidence in Fig. 7.

We can also note that the perturbation of (52) Europa is quite important, compared with its mass. This effect is due to several close approaches between Thetis and Europa during the 19^{th} century, with minimal distances of 0.068 AU in December 1862, 0.11 AU in June 1890 and 0.13 AU in August 1917 (Fig. 9, published only in electronic form).

Finally, since the effects of some of the perturbing asteroids on the orbit of Thetis cancel out, Fig. 10 shows the cumulative effect in $\alpha\ cos\delta$ of the perturbations of the 6 asteroids, in addition to Parthenope and Vesta, on the orbit of Thetis. We can see that this effect is always less than 0.7", but is not negligible, especially for the observations made around 1970.

4.4. Selection of Thetis observations

The residuals of the observations of Thetis using the initial conditions and the physical model described previously are shown in Fig. 11 (published only in electronic form). We made a preliminary determination of the orbital elements of Thetis and the mass of Parthenope by eliminating only those observations which gave a residual below -20" or over 10" in right ascension, or larger than $\pm 10''$ in declination ($\pm 15''$ for the 1852-1856 observations). For this first step, all the observations were given the same weight. Thus, out of 1037 observations, about 15 % were eliminated and we kept 880 observations in right ascension and 881 in declination.

Iterations were then made. For each iteration, we calculated the residuals with the solution obtained. As the precision of the observations tended to improve with time, we took this into account when calculating the standard deviation of the residuals in right ascension and in declination. Indeed, the study of these residuals showed that the observations could be separated into 5 groups, with respect to the mean precision of the observations. These 5 groups contained observations covering the periods 1852-1856, 1860-1872, 1879-1957, 1959-1983 and 1984-1994. At every iteration, a standard deviation σ was calculated for each group, and the observations giving residuals over 2.5 σ were eliminated. Finally, weights corresponding to σ were given to the observations and a new solution was computed.

In the case of photographic observations, as right ascension and declination are not independent of each other in the reduction procedure, both coordinates were rejected if one coordinate gave a residual over 2.5 σ.

Convergence was achieved in 9 iterations. The observations made between 1852 and 1856 (1^{st} group) gave very scattered residuals with a systematic trend of about 3" in right ascension and 2" in declination. Due to their very low accuracy, these observations were rejected. For the second group (1860-1872), 6 observations giving high residuals in right ascension were removed in addition. Among the observations made after 1856, a total of 141 observations were eliminated in right ascension (16.8 %) and 132 in declination (15.8 %) during the iterations. The final solution was obtained using 696 observations in right ascension and 705 in declination. Table 3 gives, for each group of observations, the number of observations used, the number of observations eliminated, the standard deviation of the residuals and the final corresponding weights given to the observations. For the last group (observations between 1984 and 1994), a distinction was made between the meridian observations from Bordeaux, the meridian observations from La Palma (Morrison 1985–94), and other observations.

For this last group, we can note that, since the 2.5 σ-selection procedure was made for all the observations at the same time, very few meridian observations were eliminated, which explains why the standard deviation in right ascension for the observations of Bordeaux is a little higher than the value determined in Sect. 2.1, while a lot of non-meridian observations were eliminated, which caused a significant drop in the standard deviation of these observations.

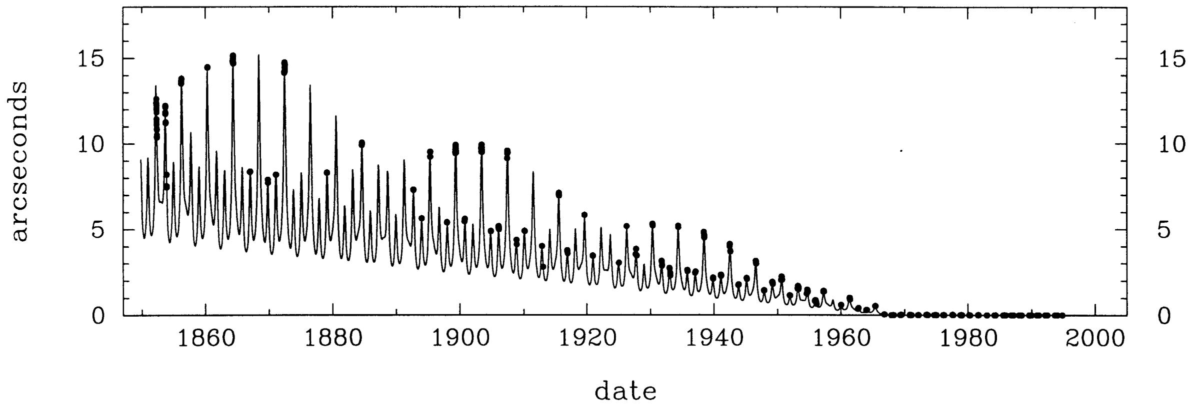

Fig. 7. Past perturbation of (11) Parthenope on the orbit of (17) Thetis in right ascension ($\times cos\delta$), starting with initial conditions in 1994 and assuming the value 2.7 10^{-12} M$\odot$ for the mass of Parthenope. Black points represent the effect for the dates of the available observations of Thetis

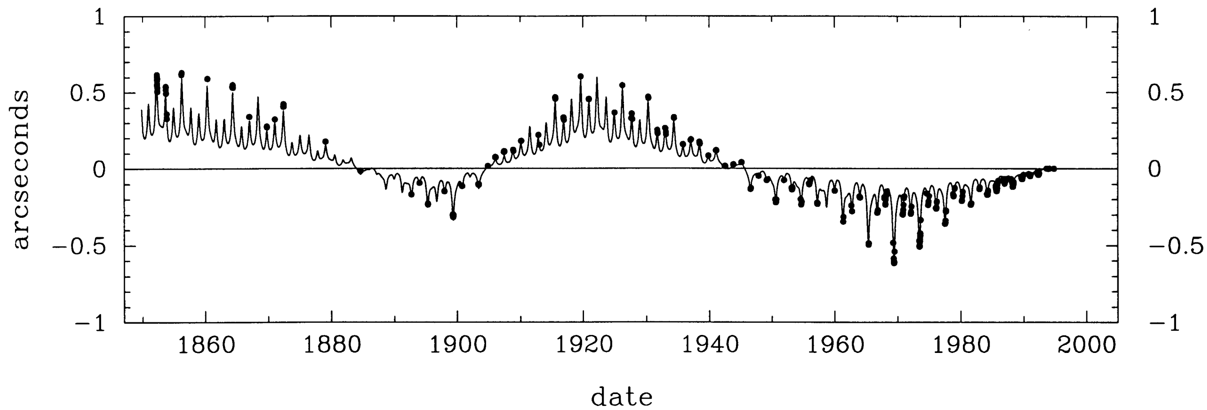

Fig. 10. Past cumulative perturbation of (1) Ceres, (2) Pallas, (10) Hygiea, (52) Europa, (511) Davida and (704) Interamnia on the orbit of (17) Thetis in right ascension ($\times cos\delta$), starting with initial conditions in 1994. Black points represent the effect for the dates of the available observations of Thetis

Table 3. Characteristics of each group of observations; "initial nb" and "final nb" are respectively the number of observations before elimination by the first iteration and after the last one; "Elim." is the difference (final nb - intial nb); "% Elim." is the ratio (elim/initial nb); "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
1860-1872		α	29	22	7	24.1	2.35	0.04
		δ	29	26	3	10.3	1.47	0.1
1879-1957		α	261	205	56	21.5	1.17	0.2
		δ	261	210	51	19.5	0.85	0.3
1959-1983		α	224	192	32	14.3	0.87	0.3
		δ	224	192	32	14.3	0.95	0.3
1984-1994 (global)		α	323	277	46	14.2	0.25	
		δ	323	277	46	14.2	0.27	
among which:	Bordeaux meridian	α	110	109	1	0.9	0.17	9
		δ	110	107	3	2.7	0.25	4
	La Palma meridian	α	136	131	5	3.7	0.26	3.5
		δ	136	133	3	2.2	0.27	3.5
	Other	α	77	37	40	51.9	0.38	1.8
		δ	77	37	40	51.9	0.33	2.3

4.5. Results

The value (2.58 $\pm$ 0.10) 10^{-12} M$\odot$ was obtained for the mass of Parthenope, which is 5 % less than the value estimated from the diameter of this asteroid. We noticed that the values obtained for the mass at each iteration lie between 2.50 and 2.80 10^{-12} M$\odot$, thus the uncertainty obtained on the final result is quite consistent.

Table 4. Orbital elements of (17) Thetis, at epoch JED 2449600.5 = 1994 September 5.0 TT; (US): our elements, obtained at the last iteration; (EMP): comparison with the elements published in EMP 1994; (σ): standard deviation on our orbital elements

	a (AU)	e	i (°)	Ω (°)	ω (°)	M (°)
US	2.469746257	0.13574206	5.585032	125.658010	136.034235	178.731494
EMP	2.4697465	0.1357423	5.58499	125.65821	136.03430	178.73109
σ	9. e-9	2. e-8	4. e-6	5. e-5	5. e-5	2. e-5

The orbital elements and their standard deviation obtained for Thetis are given in Table 4 and compared to the elements published in EMP 1994. The matrix of condition equations was well-conditioned (the value for the condition number is 197). Table 5 (published only in electronic form) gives the correlation coefficients.

As Vesta is the most perturbing asteroid on the orbit of Thetis after Parthenope, we carried out a test by calculating solutions for the mass of Parthenope and the orbital elements of Thetis assuming a range of values for the mass of Vesta within the interval 1.2-1.5 10^{-10} M$\odot$, in agreement with the existing determinations of this mass. The results are given in Table 6 (published only in electronic form). They show that the differences between these solutions and the results previously given are very small and lie within the uncertainty domain for each parameter. Residuals were calculated with each solution, and led every time to about the same result.

As mentioned in Sect. 4.3, the initial epoch was chosen to be in 1994 because the current strong perturbation of Vesta on the orbit of Thetis was not strong at that time (nor was the effect of Parthenope, which starts to act strongly around 1997). Table 7 (published only in electronic form) gives the orbital elements of Thetis for current and future dates, from 1995 to 1998, taking into account the perturbations of Vesta and Parthenope on the orbit of this asteroid.

The residuals for all the observations of Thetis obtained with our solution are plotted in Fig. 12a, while Fig. 12b shows only the residuals of the observations used (these two figures have been published only in electronic form).

5. Conclusion

In this paper, we first presented the observations of asteroids made with the automatic meridian circle at Bordeaux observatory from 1985 to 1994, and which have recently become available. The analysis of the residuals obtained using the orbital elements of the observed asteroids published in the *Ephemerides of Minor Planets for 1996* showed that, for many of the studied asteroids, the orbital elements given in EMP give residuals without important systematic effects. The anomaly found for the asteroid (17) Thetis led us to note that the orbit of Thetis is currently strongly perturbed by (4) Vesta. This discovery will allow a very interesting determination of the mass of Vesta to be made in the beginning of the next century, and for which the observations of Thetis made at Bordeaux since 1984 will provide a useful contribution.

The mass of (11) Parthenope was then determined from its perturbations on the orbit of Thetis. The result, $(2.58 \pm 0.10)\ 10^{-12}\ M_\odot$, appears significant, due to the small standard deviation compared to the value of the mass itself. To our knowledge, this is the first time that this mass has been determined and, after (1) Ceres, (2) Pallas, (4) Vesta, (10) Hygiea, (704) Interamnia and (804) Hispania, this is the seventh – and the smallest – asteroid for which the mass has been determined directly from gravitational perturbations on the orbit of another asteroid. Other masses are expected to be determined in the next years: already the asteroid (15) Eunomia, for which a mass determination has just been made (Hilton 1996), has to be added to the preceding list.

Lastly, we showed that, other than the influence of Parthenope and Vesta, non negligible perturbations on the orbit of Thetis are generated by several large asteroids. Some of these asteroids, like (52) Europa, never usually have their perturbation taken into account. This shows that this kind of investigation should certainly be conducted for other asteroids in the future. The recent improvements to observational techniques (Hipparcos observations, CCD detectors used in "Time Integration Delay") justifies work in enhancing the modelisation of the perturbations influencing on the orbit of asteroids.

Acknowledgements. The authors would like to thank E.M. Standish and D.K. Yeomans for providing helpful data and information, and the referee G. V. Williams for his constructive review of this paper.

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