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Astronomy
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Photometry and models of selected main belt asteroids

V. 73 Klytia, 377 Campania, and 378 Holmia

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ABSTRACT

We present photometric observations of three asteroids: 73 Klytia, 377 Campania, and 378 Holmia, together with their spin and shape models. The models were constructed with the lightcurve inversion method, using all available lightcurves of these objects. In the case of Campania, the long persisting doubts about its rotational period have been resolved. Various authors state periods between 8.48 and 16 h, while the period we determined is 11.664401 ± 0.000010 h.

Key words. techniques: photometric – minor planets, asteroids

1. Introduction

Asteroid photometry is invariably the most abundant source of information on the physical properties of these bodies. The key is to observe one object at various longitudes and phase angles, so that one can see the changes in the amplitude, shape and the synodic period of the lightcurve. After a few apparitions there is enough data to construct a unique model of the object. In the *lightcurve inversion* method, when a unique sidereal period can be found, there is usually only one spin and 3D shape model that fits all the observed lightcurves simultaneously.

So far, about a hundred inversion models have been constructed, although there are thousands of asteroids that have been observed photometically. In the case of near–Earth asteroids, the model can sometimes be constructed on the basis of only one apparition, but main belt asteroids require repeated photometric observations at multiple apparitions. Thus there is a constant need for further photometric observations and modelling: we aim at a collection of models large enough for statistical studies of the Solar System's origin and history. Such modelling has already revealed very surprising results, such as, for example, the spatial alignment of the spin axes of the members of an asteroid family (Slivan 2002) or the directly observable effects of the Yarkovsky thermal forces (Kaasalainen et al. 2007).

This is the fifth paper in a series presenting new models of the main belt asteroids. We are trying to make the most of all observations, so we combine the available lightcurves from the literature and add a few newly observed apparitions of our own to obtain a reliable model. The complete list of the asteroids spin parameters can be found in our database at: `http://www.astro.amu.edu.pl/Science/Asteroids/` and the models from lightcurve inversion are collected at: `http://astro.troja.mff.cuni.cz/projects/asteroids3D`

2. Photometry of three main belt asteroids

Photometric observations of three asteroids: 73 Klytia, 377 Campania and 378 Holmia, all belonging to the main belt, were conducted over an eight-year span at five observatories, during 50 nights. The vast majority of the data were collected at the Borowiec Station of Poznań Astronomical Observatory in Poland. The rest of the data came from Kharkiv in Ukraine, SAAO in South Africa, ESO in La Silla (Chile), and from the network of active amateur observers from France and Switzerland.

Similar observations and models for different asteroids can be found in the four previous papers of the present series: Michałowski et al. (2004, 2005, 2006) and Marciniak et al. (2007). The photometric measurements that we perform are relative, and are usually done on small telescopes, for example in Borowiec we use 0.4-m reflector. The first paper gives a comprehensive description of our instrument and the reduction procedure.

73 Klytia was observed at four apparitions: 1999/2000, 2001, 2004/2005 and 2007; 377 Campania at five: 1999, 2001, 2004/2005, 2006 and 2007; and 378 Holmia at five apparitions as well: 1999, 2001, 2004, 2006 and 2007. The latest observations of all three asteroids were made by one of the authors (AM) in Sutherland, South Africa. In all cases those data helped to obtain a unique model and in the case of Campania they resolved long standing doubts about its period of rotation (see Sect. 2.2).

Table 1. Aspect data.

Date (UT)	r (AU)	Δ (AU)	Phase angle (°)	λ (J2000) (°)	β (°)	Obs.
73 Klytia						
1999 11 29.8	2.553	1.643	10.62	38.69	2.47	Bor
2000 01 21.8	2.552	2.194	22.33	39.78	2.26	Bor
2000 01 23.7	2.552	2.219	22.44	40.15	2.25	Bor
2001 03 06.0	2.679	1.695	3.38	156.42	1.74	Bor
2001 03 28.9	2.689	1.817	12.60	152.26	1.35	Bor
2004 12 05.1	2.590	1.879	17.82	126.72	3.21	EnO
2004 12 06.1	2.590	1.869	17.56	126.71	3.23	EnO
2004 12 07.1	2.590	1.859	17.31	126.69	3.24	EnO
2005 01 11.0	2.602	1.631	4.33	121.85	3.56	Bor
2005 02 08.8	2.613	1.685	9.12	115.47	3.28	Bor
2005 02 09.8	2.614	1.691	9.51	115.30	3.26	Bor
2007 05 25.2	2.712	2.401	21.78	326.93	–2.37	SAAO
2007 05 30.1	2.710	2.335	21.58	327.82	–2.41	SAAO
2007 06 3.4	2.708	2.266	21.24	328.63	–2.46	ESO
377 Campania						
1999 09 14.0	2.501	1.684	16.47	35.50	1.95	Bor
1999 09 16.0	2.500	1.667	15.84	35.38	1.88	Bor
1999 10 13.0	2.492	1.507	4.83	31.31	0.74	Bor
1999 10 16.0	2.491	1.500	3.39	30.65	0.59	Bor
2001 02 28.0	2.730	1.765	5.89	145.62	–8.96	Bor
2001 03 27.8	2.751	1.964	15.18	140.80	–7.60	Kha
2001 03 30.8	2.753	1.995	15.95	140.60	–7.40	Kha
2001 03 31.8	2.754	2.006	16.19	140.60	–7.30	Kha
2004 10 04.1	2.517	2.349	23.40	103.42	–5.46	Bor
2004 10 14.1	2.522	2.226	23.19	105.78	–5.99	Bor
2005 02 04.8	2.593	1.763	14.30	96.60	–9.71	Bor
2005 02 09.0	2.596	1.802	15.54	96.27	–9.54	Bor
2005 03 29.8	2.633	2.409	22.27	100.85	–7.30	Bor
2005 03 30.7	2.634	2.421	22.28	101.10	–7.30	Kha
2005 03 31.8	2.635	2.436	22.28	101.30	–7.20	Kha
2005 04 04.9	2.638	2.491	22.25	102.28	–7.06	Bor
2005 04 19.9	2.650	2.696	21.64	106.39	–6.51	Bor
2006 04 25.9	2.882	1.899	5.27	200.29	–0.86	Bor
2006 04 26.9	2.882	1.903	5.67	200.09	–0.82	Bor
2006 05 03.9	2.884	1.936	8.35	198.74	–0.58	Bor
2006 05 05.9	2.884	1.948	9.08	198.40	–0.51	Bor
2006 05 06.9	2.884	1.955	9.45	198.23	–0.47	Bor
2007 05 26.1	2.793	2.102	17.59	300.51	8.48	SAAO
2007 05 27.1	2.792	2.091	17.41	300.52	8.53	SAAO
2007 05 29.0	2.791	2.069	17.03	300.52	8.64	SAAO
2007 05 30.0	2.790	2.058	16.83	300.51	8.69	SAAO
378 Holmia						
1999 09 13.0	2.442	1.489	9.74	12.41	8.78	Bor
1999 09 15.0	2.441	1.480	8.91	12.06	8.76	Bor
2001 02 15.9	2.830	1.886	7.26	128.67	−10.46	Bor
2001 02 18.9	2.834	1.904	8.28	128.09	−10.39	Bor
2004 10 12.0	2.433	1.653	17.88	67.46	0.59	Bor
2004 10 13.1	2.433	1.644	17.58	67.43	0.54	Bor
2004 10 14.0	2.434	1.636	17.28	67.39	0.50	Bor
2006 04 05.9	3.037	2.186	11.71	158.74	–8.67	Bor
2007 05 25.0	3.072	2.062	1.77	238.20	1.29	SAAO
2007 05 26.8	3.070	2.063	2.47	237.81	1.34	SAAO

Observatory Code: Bor – Borowiec; Kha – Kharkiv; EnO – Les Engarouines Observatory; SAAO – South African Astronomical Observatory, ESO – European Southern Observatory (La Silla).

Table 2. Asteroid parameters.

Asteroid	D(km)	*albedo*	Type
73 Klytia	44	0.225	S
377 Campania	91	0.059	PD
378 Holmia	27	0.298	S

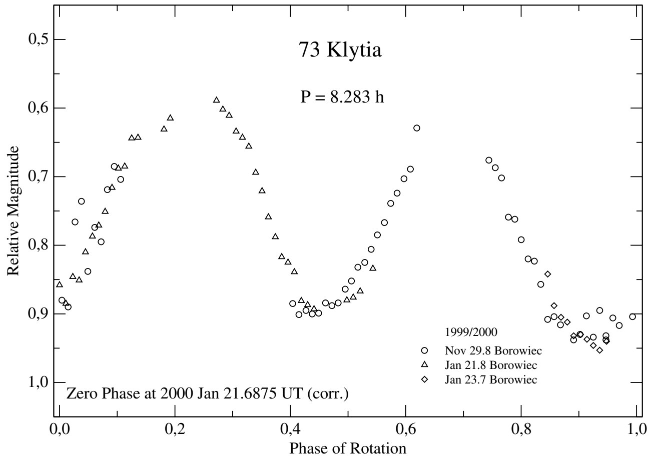

Fig. 1. Composite lightcurve of 73 Klytia in 2000.

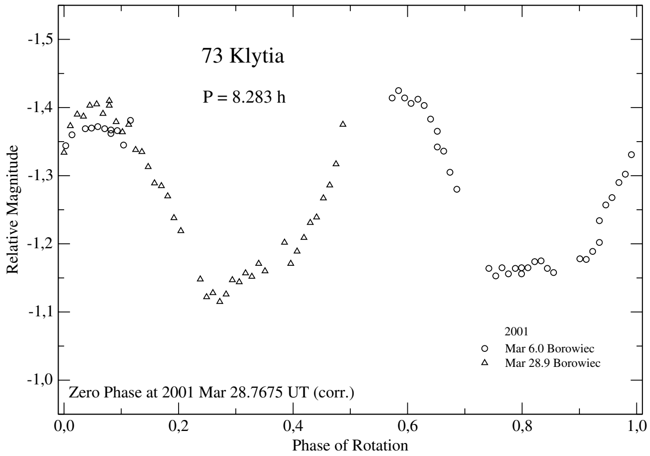

Fig. 2. Composite lightcurve of 73 Klytia in 2001.

The details of the aspect data for the observed objects are presented in Table 1. The first column shows the epoch of observation, which is the mid-time of the lightcurve. The next three columns give the distances from the asteroid to the Sun and to the Earth, and the Sun-object-Earth phase angle. In the last three columns are stated the the *J*2000.0 ecliptic coordinates of the object (λ and β) and the observatory code.

Table 2 gives the physical parameters of the objects: the *IRAS* diameter (D), albedo and the taxonomic type of the surface. These data are from *The Small Bodies Node of the NASA Planetary Data System* (`http://pdssbn.astro.umd.edu/`), where the diameters and albedos we cite came from the IRAS Minor Planet Survey (Tedesco et al. 2004) and the taxonomic classifications were taken from Tholen (1989).

We present the observations in the form of composite lightcurves, one for each apparition (Figs. 1–14). The single lightcurves from all the nights in a given apparition were composited using the procedure of Magnusson & Lagerkvist (1990). The period used for compositing is written in each frame. The different symbols represent different nights as shown in the key in each figure. Lightcurves were shifted vertically to minimize the dispersion of the data points relative to their neighbours. The vertical scale is kept the same for each asteroid and the horizontal scale is in the phase of rotation.

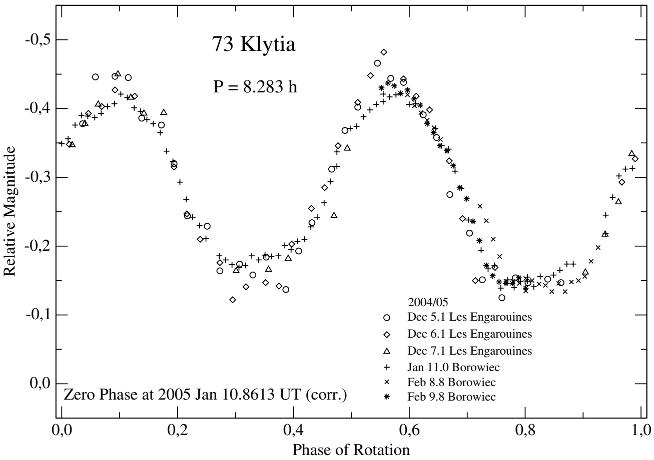

Fig. 3. Composite lightcurve of 73 Klytia in 2005.

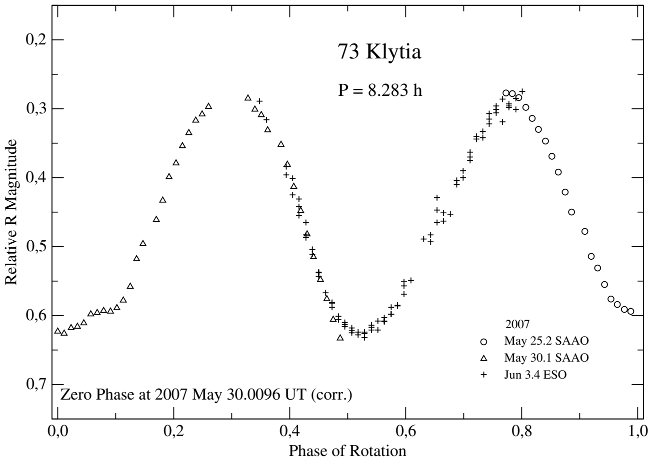

Fig. 4. Composite lightcurve of 73 Klytia in 2007.

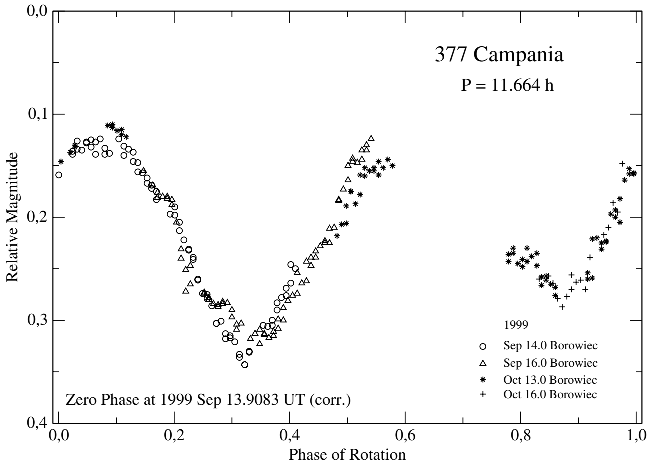

Fig. 5. Composite lightcurve of 377 Campania in 1999.

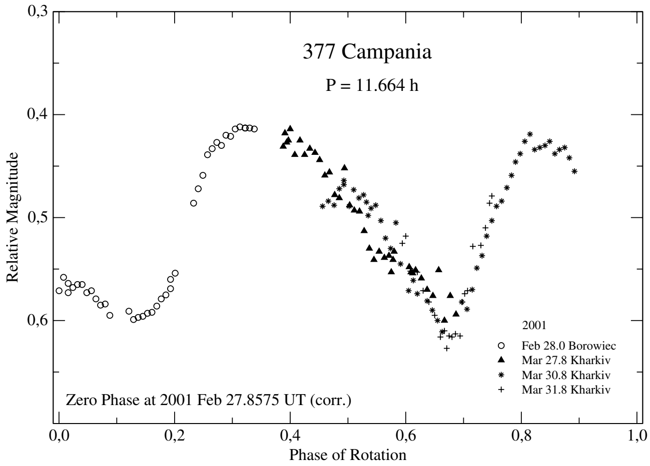

Fig. 6. Composite lightcurve of 377 Campania in 2001.

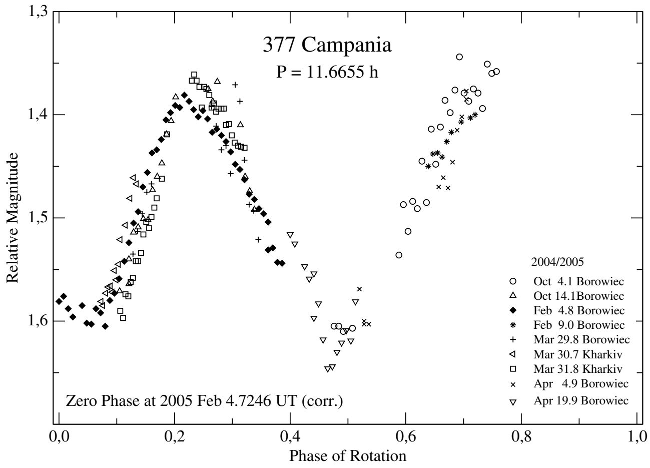

Fig. 7. Composite lightcurve of 377 Campania in 2005.

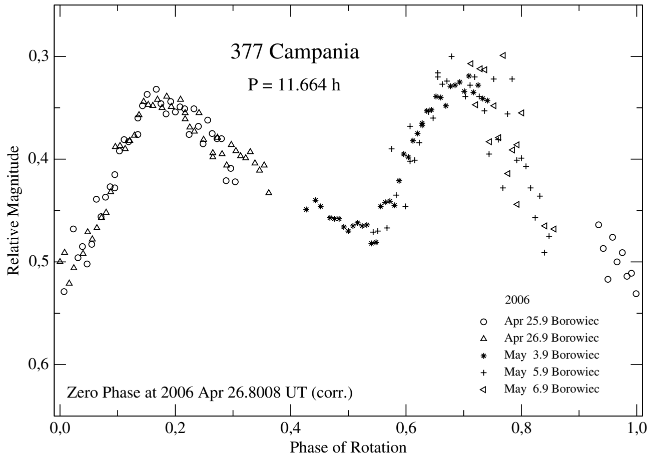

Fig. 8. Composite lightcurve of 377 Campania in 2006.

2.1. 73 Klytia

The first lightcurve of this asteroid was published by Weidenschilling et al. (1990), showing two short spans from May 1984, one with a maximum, and one with a tentative minimum. The amplitude was given as 0.82 mag, and the period was determined as approximately 13 h, with a remark that it was very uncertain. In all the later observations, Klytia's amplitude never exceeded 0.36 mag (see below), so this result must be considered erroneous, especially as it relied on one point. Next, Klytia was observed by Hainaut-Rouelle et al. (1995), on three nights in October 1990 at ESO, with a good coverage of the rotational period 8.29652 ± 0.00111 h according to the authors. The amplitude was 0.32 mag, and the minima showed a specific, flat shape. Another photometric observations of this asteroid were made by Szabó (1998). Observed on four nights in February–March 1997,

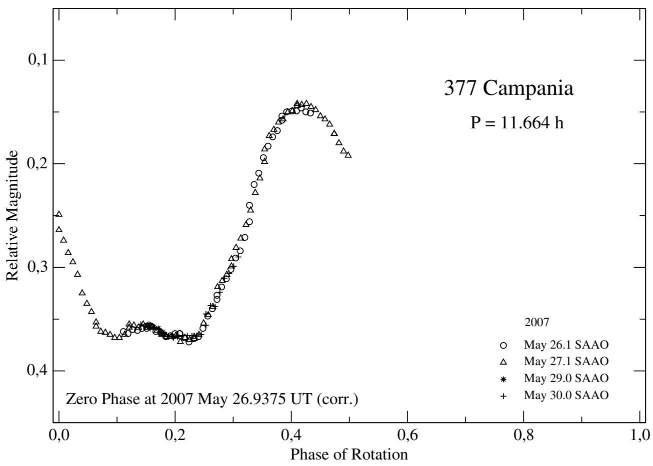

Fig. 9. Composite lightcurve of 377 Campania in 2007.

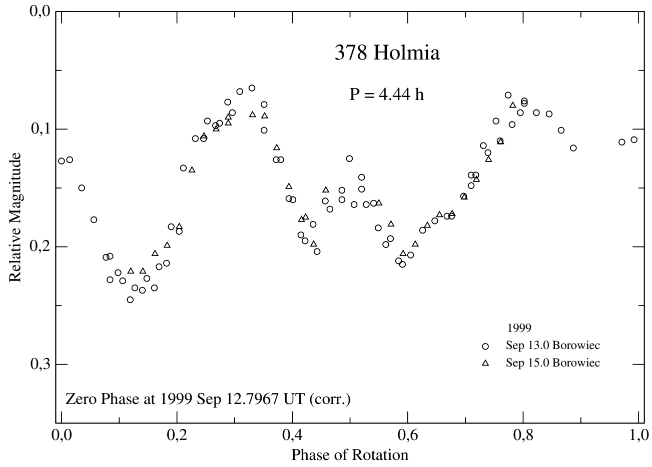

Fig. 10. Composite lightcurve of 378 Holmia in 1999.

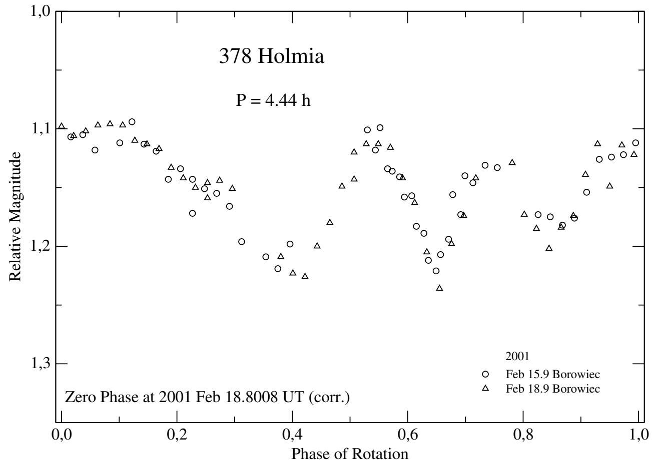

Fig. 11. Composite lightcurve of 378 Holmia in 2001.

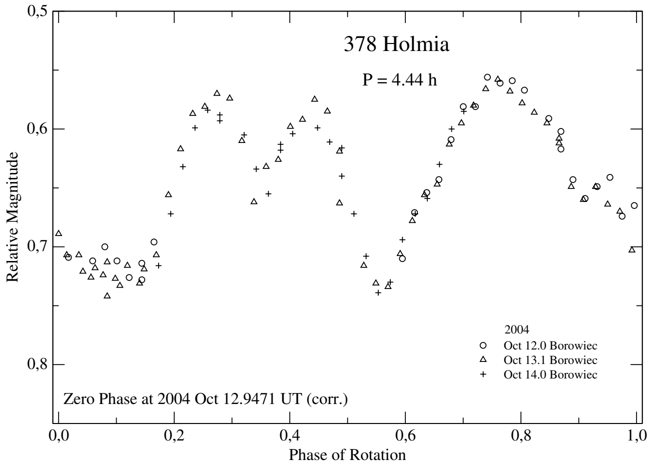

Fig. 12. Composite lightcurve of 378 Holmia in 2004.

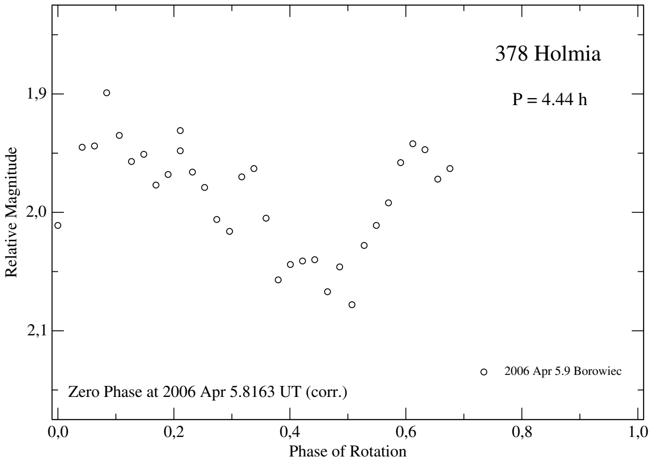

Fig. 13. Composite lightcurve of 378 Holmia in 2006.

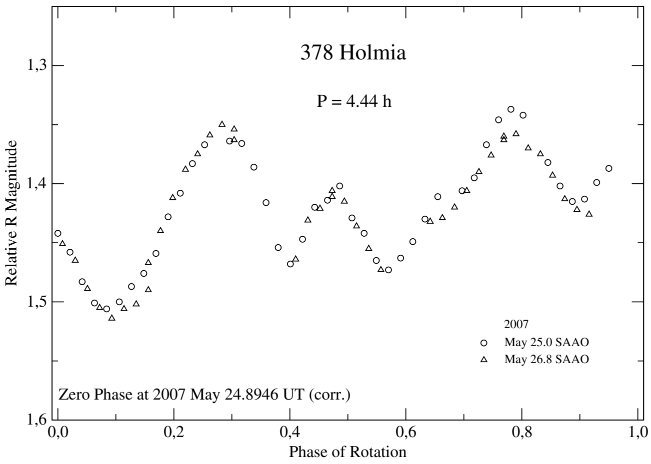

Fig. 14. Composite lightcurve of 378 Holmia in 2007.

Klytia showed a 0.28 mag amplitude lightcurve that was composited with a period of 8.275 ± 0.007 h.

Our observations of 73 Klytia spanned four apparitions. We composited all the lightcurves with the synodical period 8.283 ± 0.001 h, which is close to the values found by Hainaut-Rouelle et al. (1995) and Szabó (1998).

Below we describe the composite lightcurves from individual apparitions presented in Figs. 1–4. In the 1999/2000 apparition (Fig. 1), Klytia was observed during three nights, showing an irregularly shaped two pairs of maxima and minima. The amplitude was about 0.36 ± 0.02 mag but there was a gap in the second maximum. In the next apparition this asteroid's lightcurve became even more irregular (Fig. 2), with a peak-to-peak amplitude of 0.30 ± 0.01 mag. A flat minimum, rarely seen in asteroids, was clearly visible in these two-night observations made in March 2001. The 2004/2005 apparition lightcurve (Fig. 3) consisted of more nights, spanning over two months, which allowed a better period determination. The irregular shape with flat minima known from previous apparitions repeated itself, and the amplitude had the same value of 0.30 ± 0.01 mag. Finally, on three nights in the 2007 apparition (Fig. 4), Klytia's lightcurve became rather regular, but some asymmetry in one of the minima remained. The amplitude grew a little, to 0.34 ± 0.01 mag.

2.2. 377 Campania

Campania has long been an asteroid with an uncertain period. Almost every paper on this object gives a different value. Campania was first observed by Tedesco (1979), on one night in November 1977. Only one maximum with a strange "tail" could be seen in his 5-h piece of a lightcurve. The period was estimated as 15 h and the amplitude as more than 0.15 mag. Next observations were published by Lagerkvist et al. (1987), with just a few data points from September 1981. Schober et al. (1994) observed Campania on three nights at the beginning of the year 1983 and made an interesting remark. They noticed a maximum occurring the same time each night. From the lenght of the observing run they could rule out periods around 8 h, so their conclusion was 12 or 16 h. In September 1990 Campania was observed by Di Martino et al. (1994a) during four nights. (The paper by Schober at al. appeared later in 1994.) Their composite lightcurve showed an amplitude of 0.27 ± 0.01 and was created using a period 8.507 ± 0.003 h. One maximum was clearly brighter than the other. Another paper including observations of Campania was written by Hainaut-Rouelle et al. (1995) and contained a three-night lightcurve made in October 1990. The authors knew only about the paper by Tedesco at the time of writing their paper and they described their observations as a first complete lightcurve of this object. The period they gave was 14.557 ± 0.013 and the lightcurve amplitude was 0.18 mag. Finally, Blanco & Riccoli (1998) attempted to determine the rotational pole for this asteroid, using an A-M method. They made sparse lightcurve observations on three nights in August 1992, compositing them with a period 8.48 ± 0.01 h and an amplitude over 0.17 mag. Using also some of the data from the literature the authors found two pole solutions: $\lambda_{\rm p} = 266° \pm 7°$, $\beta_{\rm p} = 0° \pm 7°$ and $\lambda_{\rm p} = 86° \pm 4°$, $\beta_{\rm p} = 3° \pm 46°$ The axes ratios were: $a/b = 1.318, b/c = 0.898$. According to these pole solutions, there should be no light variations in, for example, the 2007 apparition when we observed a 0.230 mag amplitude (see below).

Our observations of Campania could not resolve the vagueness of the rotation period for a long time either. We observed this asteroid during five more apparitions, and it was not until the 2007 opposition that we finally found the unique period, which fitted all the previous data, including those given by other authors. Our value: 11.664401 ± 0.000010 h confirms the prediction of Schober et al. (1994) that it must be close to 12 h. In the 2007 apparition we obtained four very good quality lightcurves (Fig. 9), with exactly the same features occurring every night, almost at the same time. The problem with the previous data was too short spans of rotation phase which, composited with a long period, often created lightcurves with gaps.

We started the observational campaign of Campania in 1999 when the asteroid showed a 0.22 ± 0.01 mag amplitude brightness variation and various levels of minima (Fig. 5). Four observing nights in September–October 1999 covered 80% of the rotation phase, and composited well. In the next apparition in February–March 2001 the amplitude fell a little, to 0.20 ± 0.01 mag, and the composite lightcurve (Fig. 6) showed two separate fractions of a lightcurve that were arbitrary shifted in vertical scale to resemble other lightcurves of this asteroid. One can notice quite different shapes of minima, with sharp and blunt outlines. During the 2004/2005 apparition we observed Campania on ten nights from October till April, but still failed to find a unique period. The composite lightcurve (Fig. 7) showed differently shaped minima and a 0.28 ± 0.01 mag amplitude with an 80% coverage. All the pieces only composited well when the synodic period search was made with a smaller step, resulting in a period of 11.6655 h, while in other composites the rounded-off sidereal period 11.664 h was equally good. The next apparition in April–May 2006 again gave two not overlapping pieces, but the asymmetry in the first maximum could be noticed (Fig. 8). That five-night run showed brightness variations at the level of 0.21 ± 0.02. Finallly, in the 2007 data the period coverage was about 50% due to the short period of visibility, the amplitude was 0.230 ± 0.005 mag, and a flat minimum with a small bump could be seen (Fig. 9).

2.3. 378 Holmia

The first paper with a period determination of 4.44 ± 0.001 h for Holmia was published by Dotto et al. (1992). However, the lighturves themselves were published later by Di Martino et al. (1994b). Those observations of Holmia were made at ESO, in February 1992, during three nights. The lightcurve coverage was good and the resulting period was now 4.450 ± 0.010 h, with an amplitude of 0.13 ± 0.03 mag, and the irregularity of one maximum was already visible.

In the case of Holmia we gathered observational data during five apparitions. The synodic period 4.44 ± 0.01 that we found is identical with the value given by Dotto et al. (1992).

On two nights in September 1999 Holmia had an irregular, 0.17 ± 0.01 mag amplitude lightcurve with a sort of second peak after each of the two minima (Fig. 10). Such a shape turned out to be characteristic for this asteroid's brightness variations. During the 2001 apparition (Fig. 11), the lightcurve of this asteroid seemed to be tri-modal, with one maximum being very wide. The observations were from two nights in February 2001 and showed an amplitude of 0.13 ± 0.02 mag. On three consecutive nights in October 2004 the amplitude grew to 0.18 ± 0.01 mag, and one of the minima was a "double" (Fig. 12) one. In the 2006 apparition we managed to obtain only one noisy lightcurve that covered 70% of the previously determined period and showed an amplitude of roughly 0.12 mag (Fig. 13). In the last apparition in May 2007, Holmia was observed from the Earth'southern hemisphere and exhibited similar brightness variations as before (Fig. 14). Two double maxima could be seen in its 0.16 ± 0.01 mag amplitude lightcurve.

3. Pole and shape results

For our modelling of asteroids we apply the *lightcurve inversion* method developed in Kaasalainen & Torppa (2001), and Kaasalainen et al. (2001, 2003). This method uses all the data points from the observations at various apparitions and produces a shape model with a certain pole and period fitting the observations best, usually within the noise level. The resulting shape model is a convex representation of the asteroid shape as the signs of nonconvexity usually appear only at very large phase angles, usually unobservable for main belt asteroids (Ďurech & Kaasalainen 2003).

In Table 3 we present the results obtained for the asteroids' spins and information on the lightcurves we used. The first

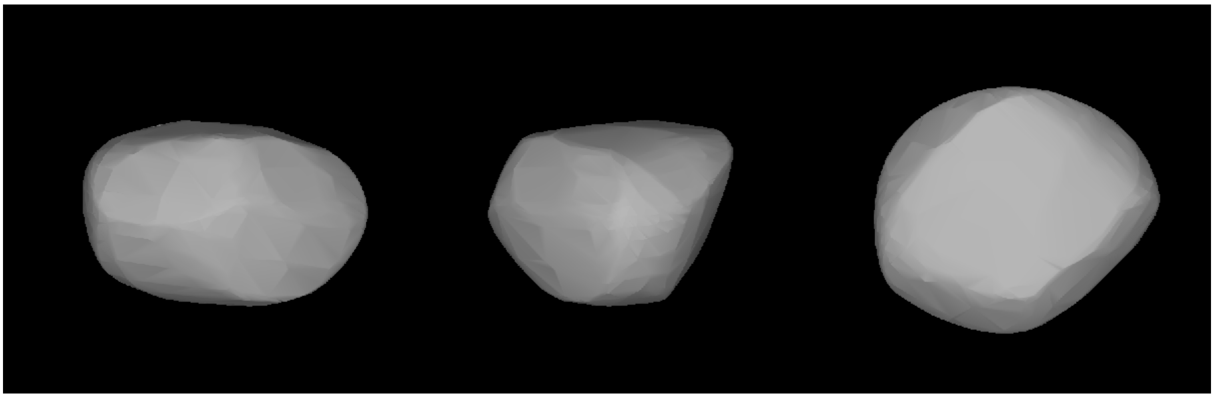

Fig. 15. Shape model of 73 Klytia, shown at equatorial viewing and illumination geometry, with rotational phases 90° apart (two pictures on the *left*) and the pole-on view on the *right*.

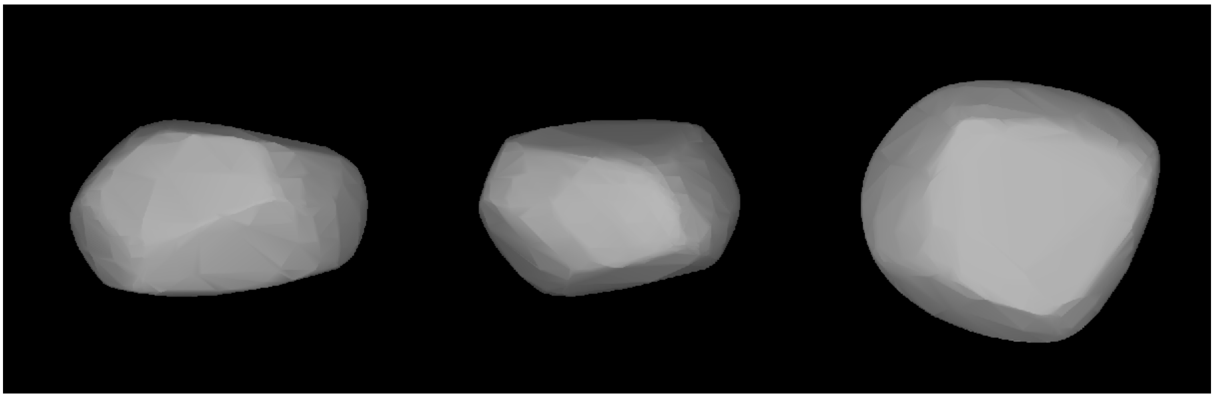

Fig. 16. Shape model of 377 Campania.

Table 3. Spin models.

Sidereal period (h)	Pole 1 λ_p	Pole 1 β_p	Pole 2 λ_p	Pole 2 β_p	Observing span (years)	N_opp	N_lc
73 Klytia							
8.283065	38°	+75°	237°	+73°	1984–2007	7	21
377 Campania							
11.664401	47°	+67°	196°	+66°	1977–2007	9	34
378 Holmia							
4.440427	130°	+60°	286°	+76°	1992–2007	6	13

column shows the sidereal period of rotation, the uncertainty of which is limited to the last digit. Then there are two pole solutions, given as the ecliptic coordinates of the asteroids' poles (for J2000), with the sign indicating the sense of rotation (positive poles for a prograde rotation). Since the orbits are close to the plane of the ecliptic, two poles with similar latitudes and longitudes some 180° apart are possible with photometric data (Kaasalainen & Ďurech 2007). The error of both λ_p and β_p is usually around ±5° on the celestial sphere. A feature of the lightcurve inversion method is that the error of the solution is much more influenced by the systematic observational errors or the uncertainty of the model than by the noise level. Thus we estimate the error by starting the inversion procedure with different parameters. As a result one usually gets poles lying within 5° error region, provided the solution is strong (see Torppa et al. 2003; Kaasalainen & Ďurech 2007, for more detailed error discussion).

Table 3 also presents the years of the observing span for a given asteroid, the number of oppositions and the number of separate lightcurves used for modelling. With the exception of 377 Campania, there are no previously published pole results for these asteroids.

The model of 73 Klytia was constructed using 21 lightcurves from 7 apparitions (in 1984, 1990, 1997, 1999/2000, 2001, 2004/2005 and 2007). Klytia appears to have an irregular shape, causing the flat minima of brightness seen at some geometries. The dimension along the axis of rotation is badly constrained as the pole is almost perpendicular to the ecliptic plane, but the pole-on silhouette is quite certain. Two solutions for the pole are given in Table 3 and the shape model is presented in Fig. 15.

After resolving the problem of the right region of the period of rotation, obtaining the final period and the pole and shape solution for 377 Campania was an easy task. We had 34 lightcurves from 9 apparitions (1977, 1981, 1983, 1990, 1999, 2001, 2004/2005, 2006 and 2007). There is an uncertainty about the value of λ_p, as we could get an almost equally good fit for a few other values besides those presented in Table 3. At such high pole latitudes this is quite understandable. For the same reason the dimension along the shortest axis can be slightly different from the one shown in Fig. 16. Our poles are completely different from those by Blanco & Riccioli. However, our model was constructed on much bigger dataset, so we believe it is more reliable. As a confirmation we tried modelling only our own data (5 apparitions), and the same result was found.

In the case of the asteroid 378 Holmia we had 13 lightcurves from 6 apparitions at our disposal (from 1992, 1999, 2001, 2004, 2006 and 2007). Holmia also appears to be an irregularly shaped

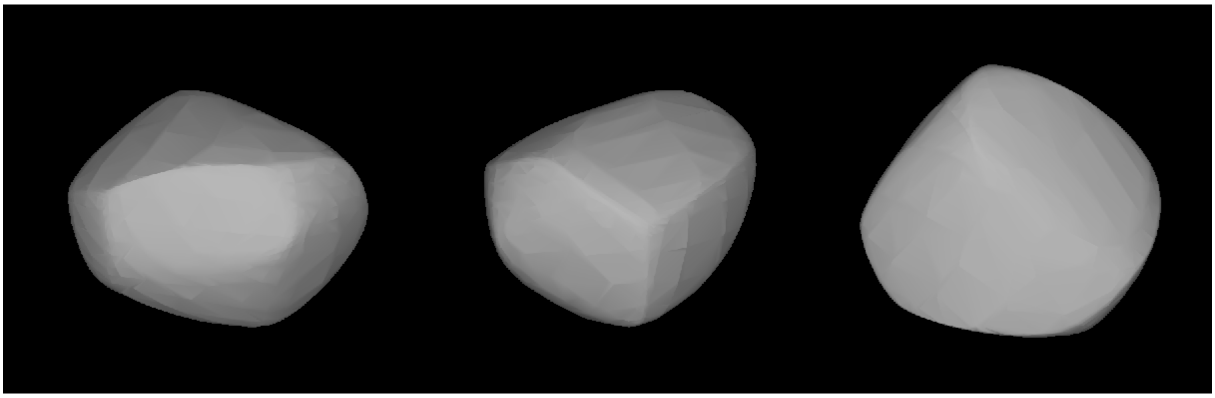

Fig. 17. Shape model of 378 Holmia.

body (Fig. 17) with flat features near the equator that probably caused the double peaks in one of the maxima. The pole solution is given in Table 3.

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