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Photometry and models of selected main belt asteroids

II. 173 Ino, 376 Geometria, and 451 Patientia

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ABSTRACT

Photometric observations for 173 Ino (1998, 1999, 2002), 376 Geometria (1996, 1997/98, 1999, 2000, 2004) and 451 Patientia (1998, 2002, 2003) carried out at six observatories are presented. Using all available lightcurves, the spin vectors, senses of rotation and shape models of these three asteroids were determined.

Key words. techniques: photometric – minor planets, asteroids

1. Introduction

Photometric observations of asteroids performed during 3–4 oppositions allow a determination of their sidereal rotational periods as well as pole orientations, sense of rotation and shape models. Pravec et al. (2002) showed that there was a small excess of asteroids that rotate in the prograde sense relative to those rotating in the retrograde one and the asteroid poles seemed to avoid the Ecliptic Plane.

The study of the Koronis family members made by Slivan (2002) showed that these asteroids seem to group in *spin clusters* with similar pole directions and rotation rates. The remarkability of this distribution is because families are believed to form from rapid disruption of a large parent body, after which the orientation of spin poles should be random. Another interesting result comes from the work of La Spina et al. (2004) who studied Near Earth Asteroids. Among NEAs with determined poles there exists a large excess of retrograde rotators and spatial alignment of the axes.

The above results were difficult to explain before a paper by Vokrouhlicky et al. (2003). They studied the thermal recoil force called the Yarkovsky effect, which may explain the observed effects. This force makes small, retrograde rotating bodies drift towards the Sun and those rotating in the prograde sense drift in the opposite direction. The so-called YORP effect also aligns their spin axes and periods. To be able to study such effects better a large database of asteroids with known parameters is needed.

The photometric database consists of the lightcurves of more than 1000 asteroids, but spin vectors have been determined for only about 100 of them. This paper gives the parameters for three asteroids. It is the second paper in a series devoted to the enlargement of the number of asteroids with known physical parameters and it continues the work started in Paper I (Michałowski et al. 2004). For many asteroids, their lightcurves from only one or two oppostions are known and it would be desirable to observe them at more apparitions. The new photometric observations, combined with previously published ones, will be used to determine sidereal periods, coordinates of poles and shape models for the observed asteroids. These new models will be included in the existing database of spin parameters and used for statistical investigation of the collision evolution of the asteroids (cf. Paolicchi et al. 2002). The most extensive spin and shape database is the one compiled by Per Magnusson, and recently updated at the Poznań Astronomical Observatory, which can be found at `http://www.astro.amu.edu.pl/Science/Asteroids/`

2. Observations of three Main Belt asteroids

Photometric observations of three asteroids (173 Ino, 376 Geometria, and 451 Patientia) from 47 nights in the years

1996–2004 were made at six observatories. The majority of the data (37 nights) came from the Borowiec Station of Poznań Astronomical Observatory (Poland). The other observations were carried out at European Southern Observatory, Szeged (University of Szeged, Hungary), Kharkiv (Kharkiv University, Ukraine), Rozhen (Institute of Astronomy, Bulgaria), and Quail Hollow Observatory (Zephyrhills, FL, USA)

At Borowiec Observatory a 0.4-m, $F/4.5$ Newton reflector was used, equipped with a $KAF400$ CCD camera and a set of Bessel $BVRI$ filters. An additional, clear glass filter was also used, so that unfiltered exposures could be mixed with the filtered ones without the need to refocus the optical system (see Michałowski et al. (2004) for full description of the instrument and the reduction procedure).

The asteroid 376 Geometria was also observed at four additional observatories. The ESO observations were performed with a *DLR* camera at the Bochum telescope and reduced with the software (ASTPHOT) developed by Stefano Mottola (Mottola et al. 1995; Erikson et al. 2000). Unfiltered photometry was carried out at the University of Szeged (Hungary) using a 0.28-m telescope and SBIG ST-6 CCD camera. These observations were referred to the JATE asteroid survey (see Szabò et al. 2001). A 0.70-m telescope with CCD camera and V filter were used at Kharkiv Observatory. The frames were reduced with the synthetic aperture photometry package ASTPHOT. A 0.60-m Cassegrain telescope equipped with a single-channel photometer was used at the Rhozen Observatory (Bulgaria). The transformation to the UBV standard system was carried out with standard algorithms (Denchev et al. 1998).

Additional observations of 451 Patientia were carried out at Quail Hollow Observatory on 28 January 2003. The instrument was a fully automated 0.18-m Maksutov telescope, equipped with SBIG ST-7E CCD camera. Data reduction was performed with Brian Warner's Canopus software. The observations from this observatory were also used in Torppa et al. (2003).

From all the lightcurves, only the ESO, Kharkiv and Rhozen photometry data were transformed to the standard system. The rest of the observations have not been transformed, mainly because of non-photometric weather condition and/or because the observing systems were equipped with only one standard filter.

Table 1 contains the aspect data for the asteroids observed. The first column is the date of the observation referring to the mid–time of the lightcurve observed. The next two columns are the distances (in astronomical units) from the asteroid to the Sun and the Earth, respectively. Column 4 is the solar phase angle, and Cols. 5 and 6 give the $J2000.0$ ecliptic longitude (λ) and latitude (β), respectively, referred to the time in the first column. The names of the observatories are listed in the last column of the table.

The basic parameters of the asteroids are summarized in Table 2. Their *IRAS* diameters (D), albedos and taxonomic types are taken from *The Small Bodies Node of the NASA Planetary Data System* (`http://pdssbn.astro.umd.edu/`).

Table 1. Aspect data.

Date (UT)	r (AU)	Δ (AU)	Phase angle (°)	λ (J2000) (°)	β (°)	Obs.
173 Ino						
1998 03 10.1	3.290	2.349	6.57	188.55	11.42	Bor
1998 03 11.1	3.290	2.345	6.30	188.36	11.48	Bor
1998 03 12.1	3.291	2.341	6.03	188.16	11.55	Bor
1998 03 20.0	3.295	2.318	4.04	186.23	12.05	Bor
1998 03 24.1	3.296	2.316	3.73	185.54	12.20	Bor
1999 04 30.1	3.025	2.227	13.60	260.68	19.21	Bor
1999 05 01.1	3.023	2.216	13.39	260.58	19.29	Bor
1999 05 07.0	3.013	2.158	12.05	259.90	19.70	Bor
1999 05 22.0	2.987	2.045	8.63	257.37	20.44	Bor
1999 05 29.0	2.974	2.011	7.42	255.87	20.60	Bor
2002 02 09.0	3.039	2.066	3.68	151.48	–0.22	Bor
2002 04 07.9	3.128	2.458	15.41	141.81	2.83	Bor
2002 04 27.9	3.155	2.742	17.96	142.39	3.46	Bor
2002 05 01.9	3.160	2.802	18.21	142.74	3.56	Bor
2002 05 02.9	3.161	2.817	18.26	142.85	3.59	Bor
2002 05 06.9	3.166	2.879	18.43	143.30	3.69	Bor
376 Geometria						
1996 02 08.3	2.184	1.491	22.40	196.30	–6.20	ESO
1996 02 20.3	2.160	1.356	19.30	196.90	–7.10	ESO
1997 10 29.0	2.499	1.525	5.73	24.04	8.90	Szg
1998 01 23.7	2.609	2.545	21.97	26.12	5.35	Kha
1999 03 30.9	2.409	1.903	23.20	117.91	–2.22	Bor
1999 03 31.9	2.407	1.914	23.35	118.01	–2.24	Bor
1999 04 01.8	2.405	1.923	23.47	118.11	–2.25	Bor
1999 04 09.8	2.391	2.009	24.38	119.24	–2.36	Bor
1999 04 18.9	2.375	2.107	24.98	120.95	–2.46	Bor
1999 05 02.8	2.349	2.258	25.18	124.43	–2.60	Bor
1999 05 05.9	2.343	2.289	25.12	125.29	–2.62	Bor
1999 05 06.8	2.341	2.300	25.09	125.58	–2.63	Bor
2000 08 04.0	2.031	1.020	3.57	318.61	2.43	Roz
2000 08 05.0	2.033	1.021	3.02	318.36	2.49	Roz
2000 08 06.0	2.034	1.022	2.50	318.11	2.56	Roz
2000 08 07.0	2.036	1.023	2.02	317.85	2.62	Roz
2000 08 08.0	2.038	1.025	1.62	317.60	2.69	Roz
2004 08 16.0	2.421	2.000	24.17	41.53	6.35	Bor
2004 10 06.0	2.503	1.578	10.95	40.23	8.62	Bor
451 Patientia						
1998 03 25.1	3.187	2.283	8.98	206.75	20.21	Bor
1998 03 26.1	3.187	2.279	8.77	206.58	20.24	Bor
1998 03 27.0	3.188	2.274	8.54	206.39	20.26	Bor
1998 03 30.1	3.190	2.262	7.91	205.83	20.32	Bor
2002 02 04.9	2.844	2.194	17.06	78.08	1.99	Bor
2002 02 08.9	2.845	2.243	17.79	78.17	2.23	Bor
2002 02 13.9	2.847	2.307	18.56	78.42	2.51	Bor
2002 02 14.8	2.847	2.319	18.69	78.48	2.56	Bor
2002 02 15.8	2.848	2.332	18.82	78.56	2.62	Bor
2002 02 16.8	2.848	2.346	18.94	78.64	2.67	Bor
2002 02 17.8	2.848	2.359	19.06	78.72	2.72	Bor
2003 01 28.4	3.066	2.403	15.43	181.60	19.05	Qua

Observatory Code: Bor – Borowiec; ESO; Szg – Szeged; Kha – Kharkiv; Roz – Rozhen; Qua – Quail Hollow.

The results of our observations are presented in Figs. 1–11 as composite lightcurves. They have been obtained applying a procedure described by Magnusson & Lagerkvist (1990). The lightcurves have been composited with the synodical periods shown in the graphs. Points from different nights are marked with different symbols. The vertical position of each individual lightcurve is obtained to minimize the dispersion of data points relative to their neighbours. The abscissae are the rotational phases with the zero points corrected for light-time. When the observational data are reduced to the standard system, we can present the lightcurve with $V(1, \alpha)$ magnitude reduced to the unit distances to the Earth and Sun and given phase angle α (see Figs. 4, 5, and 7). If it is necessary, the magnitude offsets for each night are also given in these figures.

2.1. 173 Ino

The first photometric observations of this asteroid were performed by Schober (1978) on three nights in August–September 1977. He obtained a lightcurve with a total amplitude of only 0.04 mag with a difference between maxima of 0.02 mag. He reported the rotational period of 5.93 h as

Table 2. Asteroid parameters.

Asteroid	*D*(km)	*albedo*	Type
173 Ino	154	0.064	C
376 Geometria	35	0.232	S
451 Patientia	225	0.076	CU

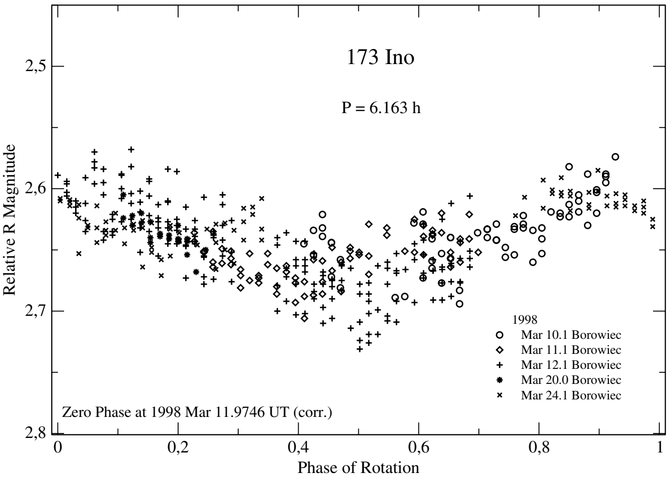

Fig. 1. Lightcurve of 173 Ino in 1998.

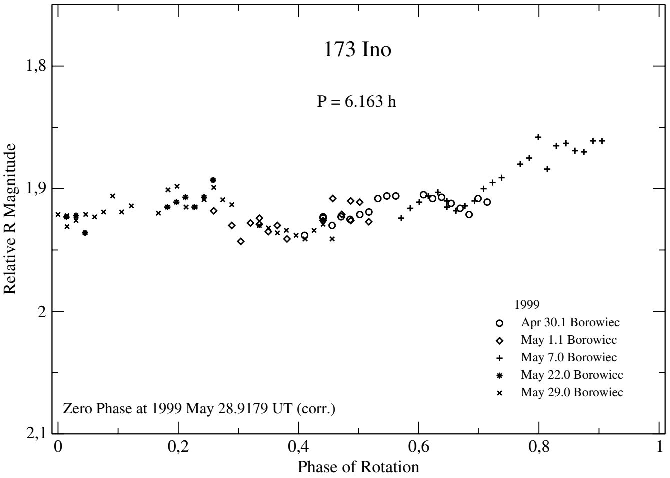

Fig. 2. Lightcurve of 173 Ino in 1999.

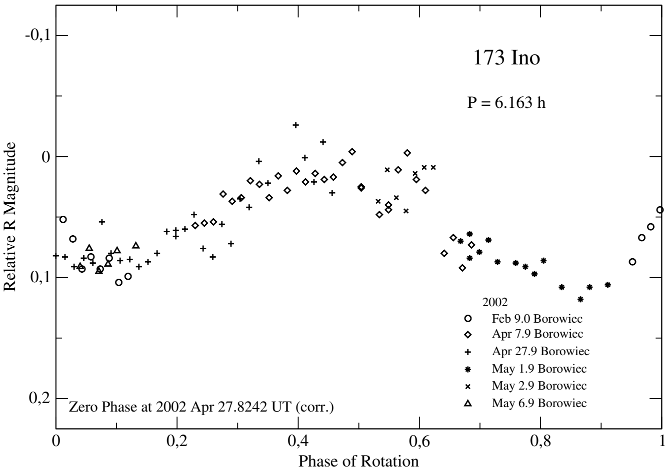

Fig. 3. Lightcurve of 173 Ino in 2002.

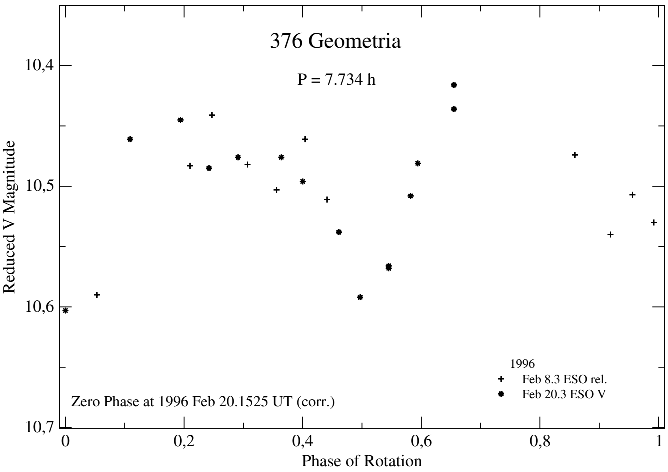

Fig. 4. Lightcurve of 376 Geometria in 1996.

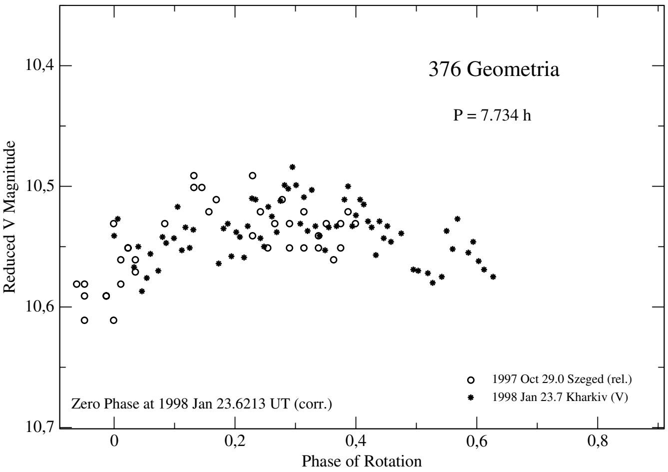

Fig. 5. Lightcurve of 376 Geometria in 1997–98.

the most probable one. Later Erikson (1990) analyzed these data again and obtained a period of 6.11 h. Di Martino & Cacciatori (1984) reported their observations carried out on 10 January 1983. The lightcurve was asymmetrical and covered only about 70% of the rotational period but they estimated an amplitude close to 0.11 mag. Debehogne et al. (1990) observed Ino on four consecutive nights in January 1988. The composite lightcurve was much more symmetrical with an amplitude of 0.15 mag. They obtained a period of 6.15 h, similar to that reported by Erikson (1990). Denchev et al. (1998) observed this asteroid on 4 April 1994. The short run of about 1 hour indicated an amplitude >0.1 mag.

We observed 173 Ino on 16 nights during three apparitions: 1998, 1999 and 2002. The composite lightcurves are constructed with the synodical period of 6.163 ± 0.005 h, which is consistent with the values given by Debehogne et al. (1990) and Erikson (1990).

The lightcurve obtained on 5 nights in March 1998 (Fig. 1) was rather noisy and showed only one maximum and one minimum per rotational cycle. An amplitude was 0.10 mag. The observations carried out on 5 nights in April–May 1999

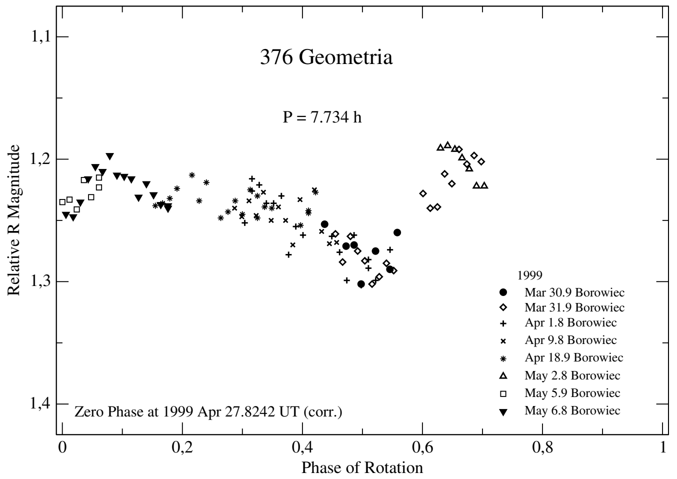

Fig. 6. Lightcurve of 376 Geometria in 1999.

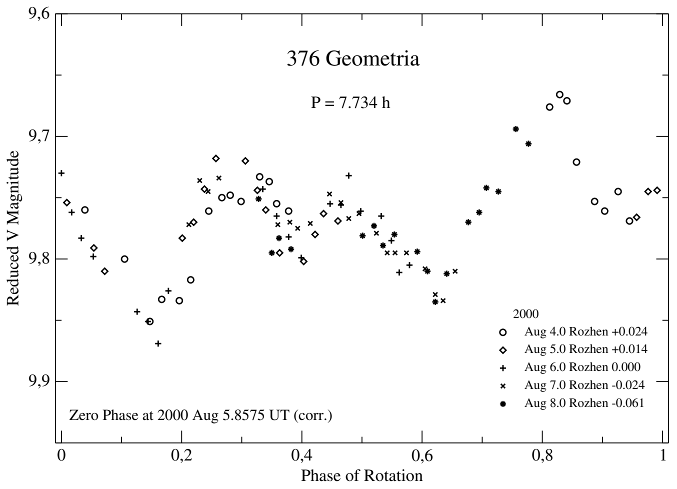

Fig. 7. Lightcurve of 376 Geometria in 2000.

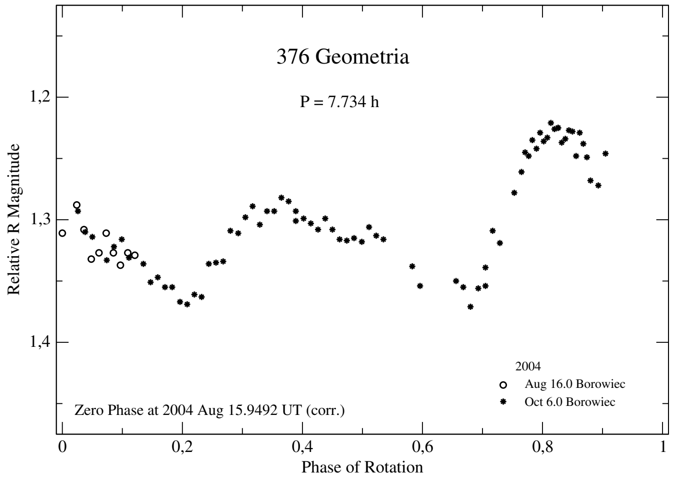

Fig. 8. Lightcurve of 376 Geometria in 2004.

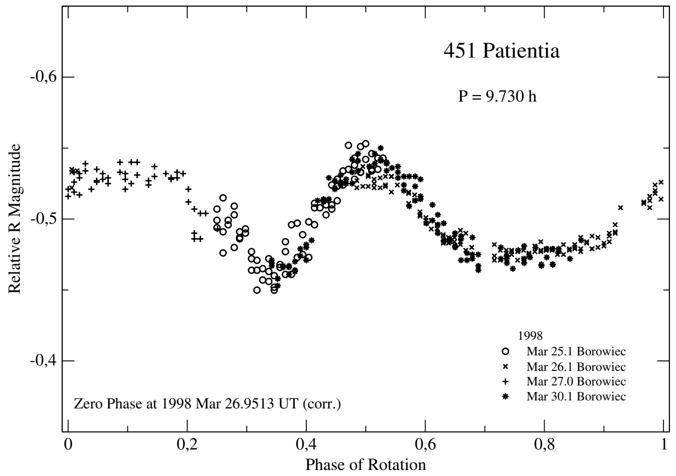

Fig. 9. Lightcurve of 451 Patientia in 1998.

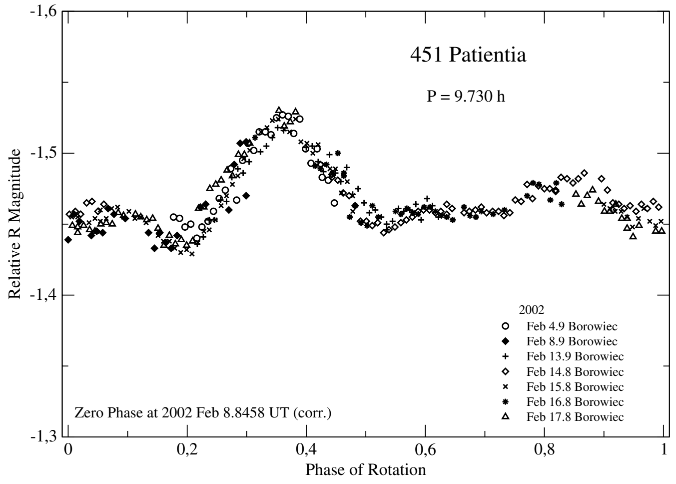

Fig. 10. Lightcurve of 451 Patientia in 2002.

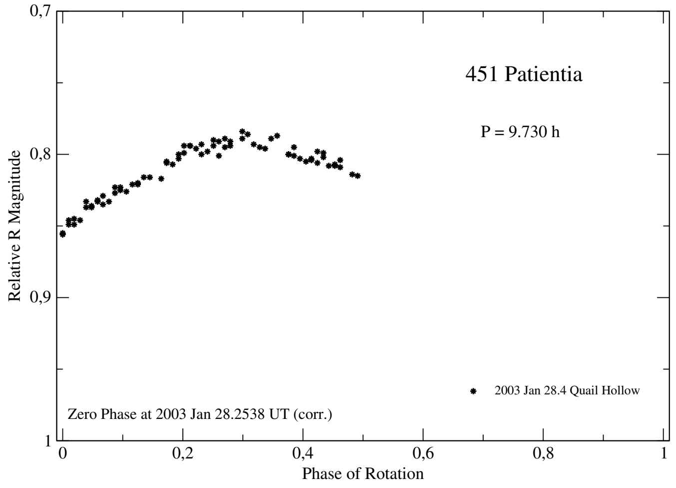

Fig. 11. Lightcurve of 451 Patientia in 2003.

(Fig. 2) covered 90% of the cycle and revealed a very irregular lightcurve with an amplitude of 0.09 mag. The lightcurve from 6 nights in February–May 2002 (Fig. 3) was also asymmertrical and the light variation was within 0.10 mag.

2.2. 376 Geometria

Barucci & Di Martino (1984) observed this asteroid on two nights in October 1983 and obtained a synodic rotational period of 7.74 h. The very asymmetrical lightcurve showed the

Table 3. Spin and shape models.

Sidereal period (days)	Sense of rotation	Pole 1		Pole 2		a/b	b/c	Method	Reference
		λ_p	β_p	λ_p	β_p				
173 Ino									
	R	198°	−21°	356°	−47°	1.23	1.6	EAM	Michałowski (1993)
		186°	−22°	365°	−21°	1.12	1.06	EA	De Angelis (1995)
0.2548546	R	178°	−14°	344°	−30°	1.1	1.1	L	Present work
±0.0000004		±5°	±5°	±5°	±5°				
376 Geometria									
		50°	36°	238°	38°	1.35	1.7	EAM	Kryszczyńska et al. (1996)
0.3219775	R	57°	−22	240°	−35°	1.0	1.0	L	Present work
±0.0000004		±5°	±5°	±5°	±5°				
451 Patientia									
		345°	25°	153°	67°	1.07	1.0	AM	Zappala & Di Martino (1986)
0.4050651	P	340°	+15°	150°	+45°	1.04	1.2	EAM	Erikson (2005)
0.4058829	P	39°	+21°	163°	+25°	1.0	1.0	L	Present work
±0.0000004		±5°	±5°	±5°	±5°				

amplitude of 0.16 mag. Next observations were performed during three nights in July 1986 (Zeigler 1987). The rotational period of 7.69 h and a lightcurve amplitude of 0.19 mag were determined. Hainaut-Rouelle et al. (1995) observed Geometria on two nights in October 1990. They obtained the rotational period of 7.715 h and the amplitude of asymmetrical lightcurves of 0.18 mag. Kryszczyńska et al. (1996) reported their two night's observations (November 1994). The asymmetrical composite lightcurve was constructed with the period of 7.734 h and the amplitude was 0.14 mag.

We obtained observational data on 19 nights during 5 apparitions: 1996, 1997-98, 1999, 2000 and 2004. The synodical period seemed to be 7.734 ± 0.002 h.

The lightcurve from two nights in February 1996 (Fig. 4) was irregular and with an amplitude of 0.18 mag. The data from two nights in October 1997 and January 1998 (Fig. 5) covered 60% of the rotational cycle. Only one maximum was clearly visible and an amplitude seemed to be a little greater than 0.1 mag. The runs from 8 nights in March–May 1999 (Fig. 6) did not cover the whole rotational cycle. The lightcurve with an amplitude of 0.10 mag was also very irregular. The observations from 5 nights in August 2000 (Fig. 7) also revealed an irregular lightcurve but the amplitude was 0.20 mag, the largest we obtained for this asteroid. The shape of the lightcurve from 2 nights in August and October 2004 (Fig. 8) was similar to that from 2000 but the amplitude was smaller (0.15 mag).

2.3. 451 Patientia

Taylor et al. (1976) observed this asteroid on three nights in December 1969–January 1970 and on two nights in December 1974. The lightcurves were very irregular and had small amplitudes, 0.1 mag for both oppositions. They were unable to determine a period but suggested that it might be of the order of 20 h. Harris & Young (1983) performed observations on three nights between October and December 1979. The amplitude was 0.09 mag and a rotational period of 9.727 h was obtained. The observations from three nights in September 1984 (Di Martino et al. 1987) confirmed the previously determined period. The composite ligtcurve was irregular and had a small amplitude of 0.05 mag. Erikson et al. (2005) observed Patientia during three apparitions: 1993 (4 nights in March), 1994 (3 nights in June) and 1995 (4 nights in September–October). All observations had small amplitudes and asymmetrically shaped lightcurves.

We present the lightcurves from 12 nights obtained during three apparitions: 1998, 2002 and 2003. Our data allowed us to determine the synodical period to be 9.730 ± 0.004 h, consistent with the previous published value.

The data from 4 nights in March 1998 (Fig. 9) showed the lightcurve with one pair of sharp extrema. The second pair presented a more shallow maximum and minimum. An amplitude was small, of 0.11 mag. Figure 10 presents data obtained on 7 nights in February 2002. Only one maximum was clearly visible while the second one almost disappeared. The amplitude of light variation was 0.10 mag. The one night's run in January 2003 (Fig. 11) covered 50% of the cycle. Only one maximum was recorded and the amplitude seemed to be greather than 0.06 mag.

3. Pole and shape of the observed asteroids

The spin vectors, sidreal periods and shape models of the observed asteroids were determined by the so–called lightcurve inversion method described by Kaasalainen & Torppa (2001) and Kaasalainen et al. (2001, 2003). This method uses all data points (both relative and absolute photometry) and finds a physical model with a large number of parameters that accurately reproduces the photometric data down to noise level.

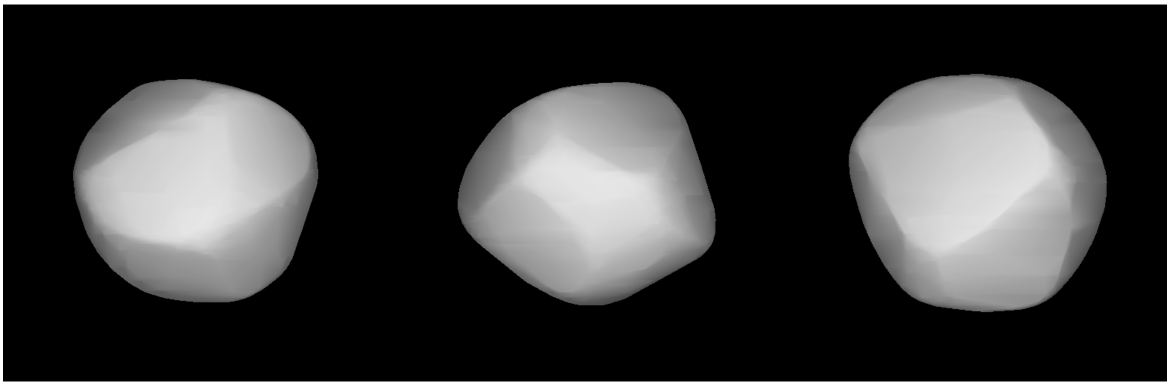

Fig. 12. Shape model of 173 Ino, shown at equatorial viewing illumination geometry, with rotational phases 90° apart (two pictures on the left) and the pole-on view in the right.

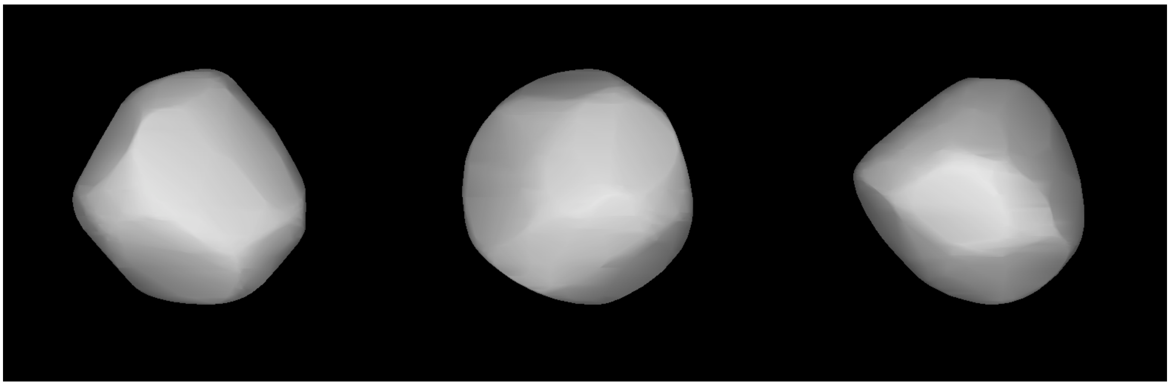

Fig. 13. Shape model of 376 Geometria.

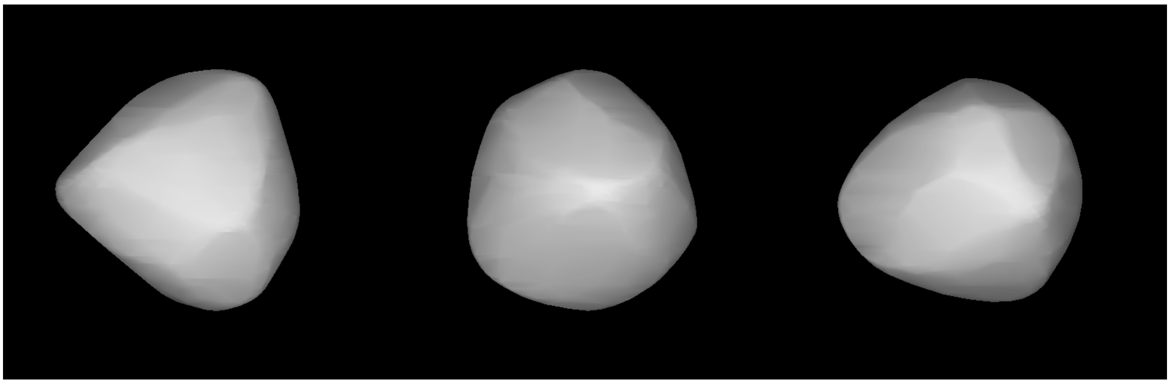

Fig. 14. Shape model of 451 Patientia.

As for other methods, $\lambda_{\rm p} \pm 180°$ ambiguity for the pole solution is always physically inevitable for asteroids moving close to the ecliptic plane. This method was also used in Paper I (Michałowski et al. 2004).

Table 3 contains the spin and shape models for the asteroids studied in the present paper. This table shows the sidereal periods, the senses of rotation (*P* – prograde, *R* – retrograde), the ecliptic coordinates (equinox 2000) of the north poles, and the ratios a/b, b/c of triaxial ellipsoid models. The results obtained by other authors are given for comparison. The methods used for calculation are also given: *E* – Epochs; *A* – Amplitude; *M* – Magnitude; *L* – lightcurve inversion.

3.1. 173 Ino

Michałowski (1993) using the lightcurves from three oppositions (1977, 1983 and 1988) obtained the physical parameters of 173 Ino (see Table 3). He suggested a retrograde sense of rotation for this asteroid. De Angelis (1995) with the *EA* method and the same observational data derived similar results (Table 3).

At present the lightcurves from seven apparitions (1977, 1983, 1988, 1994, 1998, 1999 and 2002) are available. We have confirmed that Ino is a retrograde rotator and the previous pole coordinates are within 20° of the present ones (see Table 3). The shape model of this asteroid is shown in Fig. 12.

3.2. 376 Geometria

The results presented by Kryszczyńska al. (1996) – see Table 3 – had been obtained with the data from three oppositions: 1983, 1986 and 1994. The authors were not able to determine the sense of rotation of this asteroid.

In the present work we can use the lightcurves from nine apparitions: 1983, 1986, 1990, 1994, 1996, 1997-98, 1999, 2000 and 2004. The results are given in Table 3. The pole solutions by Kryszczyńska al. (1996) are quite close to the present ones. Our solution for the shape indicates an almost spherical body and the model is shown in Fig. 13.

3.3. 451 Patientia

Zappala & Di Martino (1986) using the *AM* method and lightcurves from four apparitions (1969, 1974, 1979 and 1984) showed that this asteroid is almost spherical (Table 3). Erikson (2005) confirmed this shape on the analysis of lightcurves from seven apparitions (1969, 1974, 1979, 1984, 1993, 1994 and 1995). He obtained a sidereal period and prograde sens of rotation for this asteroid (Table 3). The ecliptic longitude of the pole solutions presented in these two papers are also very similar.

We can use data from ten oppositions, adding 1998, 2002 and 2003 to those available to Erikson (2005). Only the shape model (Fig. 14) and prograde sense of rotation (Table 3) have been confirmed. The sidereal period and pole coordinates differ from those presented in two previous papers. This is probably due to very flat lightcurves and their small light variations and difficulties in determing epochs of extrema and the amplitudes of such lightcurves.

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