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Strömgren photometry of 40 Harmonia, 45 Eugenia and 52 Europa

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Abstract. The Asteroids 40 Harmonia, 45 Eugenia and 52 Europa have been studied photometrically. From their lightcurves synodic periods of $8^{\rm h}54^{\rm m}36^{\rm s}$, $5^{\rm h}42^{\rm m}00^{\rm s}$ and $5^{\rm h}37^{\rm m}46^{\rm s}$, and maximum amplitudes of $0\overset{\rm m}{.}15$, $0\overset{\rm m}{.}12$ and $0\overset{\rm m}{.}20$, have been deduced for 40 Harmonia, 45 Eugenia and 52 Europa, respectively. Improved solutions for the sense of rotation, sidereal period, pole orientation and shape properties are proposed.

Key words: minor planets, asteroids — techniques: photometric

1. Introduction

A very important part of the evolution of the solar system relates to the evolution of the minor planets. Amongst other characteristics, the fundamental attributes of an asteroid are its shape, the parameters that define its rotational motion, its taxonomic class and its possible colour and/or albedo variegation on its surface. Physical properties of asteroids such as their shapes, spin periods and spin axes can help in constructing our knowledge of their collisional evolution (Tedesco & Zappala 1980; Farinella et al. 1981; Dermott et al. 1984).

Lightcurve observations of an asteroid are planned for more than one night to improve the accuracy of the period determination, to define the phase relation and absolute brightness as function of the solar phase angle and to determine possible albedo and colour variegation on the surface. Multiple observations of lightcurves from different aspects as an asteroid orbits provide information about spin period, axis orientation and body shape.

In this paper lightcurves of 40 Harmonia, 45 Eugenia and 52 Europa taken in 1997, for two observing periods are presented, one during September and the other during October, from the observatory of Sierra Nevada, Spain (0.9 m Telescope). Our object is to increase the ecliptic longitude coverage of these asteroids to obtain a larger data base relating to their asteroidal lightcurves in order to improve future work on their rotational and shape properties.

Here, *uvby* Strömgren photometry for 40 Harmonia, 45 Eugenia and 52 Europa are obtained and used to derive phase coefficients correction, multiple scattering factors, Strömgren and Johnson zero-phase angle magnitudes and colour indices and to determine possible colour variegation of the surface of these asteroids during their rotational cycles. Results for rotational and shape parameters for these asteroids have also been obtained and compared with previous results.

2. Observations

The observations were carried out on different nights of September and October 1997 using the 90 cm telescope at Sierra Nevada Observatory, Spain. This telescope is equipped with a six channel *uvbyβ* photometer for simultaneous measurements in *uvby* or in the H_β channels, respectively (Nielsen 1983), but only *uvby* measurements were collected during this observing run.

In order to make differential photometry, different sets of comparison stars were used during September and October. The comparison stars were chosen taking into account their spectral type (close to solar) and in the neighbourhood of the asteroids for better reduction of the data avoiding extinction problems. Each set of comparison stars contains one main comparison and one check star. During September observations C1=SAO 146842 ($V = 7\overset{\rm m}{.}2$, F8) was used as the main comparison star and C2=SAO 146908 ($V = 7\overset{\rm m}{.}6$, F8) as a check star. During October observations C3=SAO 165708 ($V = 6\overset{\rm m}{.}4$, G0) was used as the main comparison star and C4=SAO 165638 ($V = 7\overset{\rm m}{.}7$, G5) as a check star. In order to make the two sets of comparison stars compatible the main and the check stars of both sets were observed simultaneously during different nights.

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Table 1. Aspect data

Date (0 UT)	Long (1950)	Lat (1950)	phase (deg)	r (AU)	Δ (AU)
40 Harmonia					
08 09 1997	352.11	−7.65	4.92	1.16620	2.16443
09 09 1997	351.86	−7.67	4.56	1.16501	2.16431
10 09 1997	351.61	−7.68	4.23	1.16406	2.16419
02 10 1997	346.36	−7.59	10.43	1.20539	2.16231
03 10 1997	346.17	−7.56	10.91	1.21001	2.16225
07 10 1997	345.47	−7.45	12.76	1.23066	2.16208
45 Eugenia					
08 09 1997	348.58	−3.53	1.89	1.78740	2.79222
09 09 1997	348.36	−3.57	1.60	1.78771	2.79301
10 09 1997	348.13	−3.60	1.40	1.78831	2.79380
02 10 1997	343.59	−4.19	8.63	1.87130	2.81091
03 10 1997	343.43	−4.21	8.99	1.87811	2.81167
07 10 1997	342.81	−4.27	10.40	1.90779	2.81470
52 Europa					
08 09 1997	352.22	−7.19	3.22	2.23452	3.23064
09 09 1997	352.03	−7.22	2.98	2.23227	3.22979
10 09 1997	351.83	−7.25	2.76	2.23030	3.22893
02 10 1997	347.54	−7.60	6.69	2.25939	3.20973
03 10 1997	347.37	−7.61	7.00	2.26392	3.20885
07 10 1997	346.71	−7.61	8.25	2.28467	3.20528

The observing and reduction procedure was standard, based on consecutive measurements of the selected main comparison star, check comparison star, asteroids and sky reading. During the observations reported here, neither of the comparison stars showed any sign of variability within $0\overset{\mathrm{m}}{.}005$.

To transform our data into the standard *uvby* system we have used the same procedure described in Rodríguez et al. (1997). After differential magnitudes in the standard system were obtained for the asteroids with respect to one main comparison star (C1=SAO 146842) we correct them to unit distance from the sun and the earth and perform light-time corrections to all the observations. Then, we transform these differential magnitudes to absolute magnitudes using the absolute values of C1, $V = 7\overset{\mathrm{m}}{.}156$, $b-y = 0\overset{\mathrm{m}}{.}310$, $m_1 = 0\overset{\mathrm{m}}{.}163$ and $c_1 = 0\overset{\mathrm{m}}{.}413$, listed in the Hauck & Mermilliod (1998) catalogue.

In addition, we obtained the following values of $V = 7\overset{\mathrm{m}}{.}656$, $6\overset{\mathrm{m}}{.}377$, $7\overset{\mathrm{m}}{.}750$, $b-y = 0\overset{\mathrm{m}}{.}290$, $0\overset{\mathrm{m}}{.}548$, $0\overset{\mathrm{m}}{.}589$, $m_1 = 0\overset{\mathrm{m}}{.}165$, $0\overset{\mathrm{m}}{.}269$, $0\overset{\mathrm{m}}{.}345$, and $c_1 = 0\overset{\mathrm{m}}{.}517$, $0\overset{\mathrm{m}}{.}427$, $0\overset{\mathrm{m}}{.}357$ for C2, C3 and C4, respectively, in good agreement with the values listed in Hauck & Mermilliod (1998).

3. Analysis

In Table 1 the aspect data for each asteroid, the longitude and latitude relative to the ecliptic, the solar phase angle, the geocentric, r, and heliocentric, Δ, distances, are listed for every day of observation.

3.1. Photometry

These observations were carried out during different nights of September and October when each asteroid had different phase angles, thus different magnitudes were observed. The mean reduced magnitudes observed for each *uvby* Strömgren filter, $\overline{uvby}(1,\alpha)$, the average phase angle of the observations, $\overline{\alpha}$, and the range of phase angle covered, during September and October observations, are presented in Table 2. The observed Strömgren colour indices, $b-y$ and $u-b$, are also listed.

We have applied a linear phase correction to transform the observed *uvby* reduced magnitudes to zero-phase angle magnitudes, *uvby* (1,0). No significative differences are found in the individual linear phase coefficients, β_{filter}, obtained using the different Strömgren filters. The slight differences found are, in all the cases, within the error bars of the determinations, but these slight differences could influence the colour indices when they are transformed to zero-phase angle. In order to preserve the colour indices measured, a mean linear phase coefficient, β_{m}, that is more suitable for the observed magnitudes at phase angles greater than 7° in all the Strömgren filters, is used to transform to zero-phase angle magnitudes. The magnitudes *uvby* (1,0) are calculated as $uvby(1,\alpha) = uvby(1,0) + \beta_{\mathrm{m}}\alpha$. This relation has been applied to the measurements taken during October when the solar phase angles were greater than 7° for all the asteroids.

Lumme & Bowell (1981a, 1981b) showed that the light observed at phase angle α relative to the luminosity at zero phase is decomposed into a single scattering part and a multiple scattering part, and the magnitudes at phase angle α can be expressed as $V(\alpha) = V(0°) - 2.5\ \mathrm{Log}((1-Q)\phi(\alpha) + Q)$. Here, $\phi(\alpha)$ is the corresponding phase function for single scattered light and Q is the multiple scattering factor. Lumme & Bowell (1981b) found that $\phi(\alpha)$ can be expressed as $\phi(\alpha) = 1 - \sin\alpha/(0.124 + 1.407\ \sin\alpha - 0.758\ \sin^2\alpha)$ in the phase range $0° \leq \alpha \leq 25°$. We have used all the data measured from September to October, for each asteroid, to find the values of Q_{filter} and $V_{\mathrm{filter}}(0)$ which produce the best fit, for each filter, to the Lumme & Bowell (1981b) relation.

The Strömgren magnitudes and colour indices obtained by linear analysis, $\overline{uvby}(1,0)$, and those obtained by following the radiative transfer theory of Lumme & Bowell (1981b), $\overline{uvby}(0)$, are shown in Table 2. These Strömgren values are transformed into the UBV Johnson system by using the transformation equations of Warren & Hesser (1977) to transform the Strömgren $b-y$ and $u-b$ colour indices to Johnson $B-V$ and $U-B$ colour indices. As the "y" standard magnitude obtained using the "y" Strömgren filter is equivalent to the "V" magnitude of the "V" Johnson filter, knowing the $B-V$ and $U-B$ colour indices, the B and U magnitudes are calculated directly. The Johnson magnitudes and colour indices obtained are

Table 2. Photometry

$\overline{uvby}(1,\alpha)$ (mag)	$\overline{uvby}(1,\alpha)$ (mag)	$\overline{uvby}(1,0)$ (mag)	$\overline{UBV}(1,0)$ (mag)	Q factors	$\overline{uvby}(0)$ (mag)	$\overline{UBV}(0)$ (mag)	$\Delta_{((0,1)-(0))}$ (mag)	TRIAD (mag)
40 Harmonia								
$\overline{\alpha} = 4.^\circ25$	$\overline{\alpha} = 12.^\circ01$	$\beta_{\rm m} = 0.029$						
$0.^\circ31$	$1.^\circ21$	0.004						
y 7.402	y 7.705	$y_{(1,0)}$7.369	$V_{(1,0)}$7.369	Q_y 0.145	$y_{(0)}$7.043	$V_{(0)}$7.043	ΔV 0.33	$V_{(0)}$7.14
0.050	0.060	0.048	0.048	0.021	0.045	0.045	0.09	
b 7.939	b 8.239	$b_{(1,0)}$7.903	$B_{(1,0)}$8.231	Q_b 0.148	$b_{(0)}$7.581	$B_{(0)}$7.910	ΔB 0.32	
0.050	0.061	0.048	0.059	0.021	0.045	0.195	0.25	
v 8.683	v 8.984	$v_{(1,0)}$8.648	$U_{(1,0)}$8.629	Q_v 0.148	$v_{(0)}$8.325	$U_{(0)}$8.292	ΔU 0.34	
0.050	0.061	0.048	0.074	0.021	0.045	0.265	0.35	
u 9.831	u 10.146	$u_{(1,0)}$9.810		Q_u 0.122	$u_{(0)}$9.460			
0.061	0.065	0.051		0.022	0.051			
$b-y$ 0.536	$b-y$ 0.535		$B-V$ 0.862		$b-y$ 0.538	$B-V$ 0.867	$\Delta_{B-V}-0.005$	$B-V$ 0.85
0.007	0.007		0.011		0.090	0.150		
$u-b$ 1.892	$u-b$ 1.902		$U-B$ 0.398	Q_m 0.141	$u-b$ 1.879	$U-B$ 0.382	Δ_{U-B}0.016	$U-B$ 0.43
0.021	0.020		0.015	0.021	0.096	0.070		
45 Eugenia								
$\overline{\alpha} = 1.^\circ46$	$\overline{\alpha} = 9.^\circ83$	$\beta_{\rm m}$ 0.030						
$0.^\circ14$	$0.^\circ92$	0.010						
y 7.661	y 8.098	$y_{(1,0)}$7.815	$V_{(1,0)}$7.815	Q_y 0.142	$y_{(0)}$7.504	$V_{(0)}$7.504	ΔV 0.31	$V_{(0)}$7.27
0.043	0.054	0.052	0.052	0.020	0.042	0.042	0.09	
b 8.086	b 8.216	$b_{(1,0)}$8.216	$B_{(1,0)}$8.455	Q_b 0.174	$b_{(0)}$7.935	$B_{(0)}$8.193	ΔB 0.26	
0.046	0.044	0.044	0.120	0.020	0.039	0.177	0.30	
v 8.688	v 9.112	$v_{(1,0)}$8.828	$U_{(1,0)}$8.665	Q_v 0.157	$v_{(0)}$8.532	$U_{(0)}$8.394	ΔU 0.27	
0.049	0.051	0.044	0.161	0.019	0.039	0.279	0.44	
u 9.721	u 10.142	$u_{(1,0)}$9.856		Q_u 0.162	$u_{(0)}$9.5650			
0.082	0.041	0.066		0.031	0.063			
$b-y$ 0.425	$b-y$ 0.401		$B-V$ 0.659		$b-y$ 0.431	$B-V$ 0.689	$\Delta B-V-0.030$	$B-V$ 0.66
0.020	0.041		0.051		0.081	0.135		
$u-b$ 1.634	$u-b$ 1.643		$U-B$ 0.207	Q_m 0.159	$u-b$ 1.630	$U-B$ 0.201	$\Delta U-B$ 0.006	$U-B$ 0.27
0.055	0.056		0.041	0.023	0.102	0.074		
52 Europa								
$\overline{\alpha} = 2.^\circ77$	$\overline{\alpha} = 7.^\circ75$	$\beta_{\rm m}$ 0.040						
$0.^\circ21$	$0.^\circ81$	0.012						
y 6.665	y 6.935	$y_{(1,0)}$6.640	$V_{(1,0)}$6.640	Q_y 0.093	$y_{(0)}$6.382	$V_{(0)}$6.382	ΔV 0.26	$V_{(0)}$6.25
0.058	0.060	0.052	0.052	0.026	0.071	0.071	0.12	
b 7.094	b 7.348	$b_{(1,0)}$7.053	$B_{(1,0)}$7.313	Q_b 0.127	$b_{(0)}$6.822	$B_{(0)}$7.086	ΔB 0.23	
0.059	0.061	0.053	0.081	0.035	0.072	0.214	0.29	
v 7.732	v 7.980	$v_{(1,0)}$7.685	$U_{(1,0)}$7.580	Q_v 0.138	$v_{(0)}$7.463	$U_{(0)}$7.359	ΔU 0.22	
0.058	0.063	0.054	0.107	0.035	0.073	0.335	0.44	
u 8.819	u 9.064	$u_{(1,0)}$8.769		Q_u 0.143	$u_{(0)}$8.551			
0.088	0.066	0.061		0.046	0.094			
$b-y$ 0.429	$b-y$ 0.413		$B-V$ 0.673		$b-y$ 0.440	$B-V$ 0.704	$\Delta B-V-0.031$	$B-V$ 0.66
0.021	0.014		0.029		0.143	0.239		
$u-b$ 1.725	$u-b$ 1.717		$U-B$ 0.267	Q_m 0.125	$u-b$ 1.729	$U-B$ 0.273	$\Delta U-B-0.006$	$U-B$ 0.33
0.062	0.036		0.036	0.036	0.166	0.121		

also shown in Table 2, together with the differences found between the Johnson magnitudes calculated using a linear phase correction, $\overline{UBV}(1,0)$, and those obtained by using the Lumme and Bowell relation $\overline{UBV}(0)$, (values $\Delta_{((0,1)-(0))}$ in Table 2).

In order to obtain the corresponding rotational synodic periods for each asteroid, analysis of frequencies were carried out on our data using the method described in Rodríguez et al. (1998). Synodic periods of $0.^{\rm d}37125$, $0.^{\rm d}23750$ and $0.^{\rm d}23456$ are obtained for 40 Harmonia, 45 Eugenia and 52 Europa, respectively.

Figures 1 to 3 show the composite lightcurves derived using these synodic periods for each asteroid. The (1,0) magnitudes derived in the different Strömgren filters and the $b-y$, $v-b$ and $u-b$ colour indices versus the rotational phase are also shown in these figures. The Strömgren

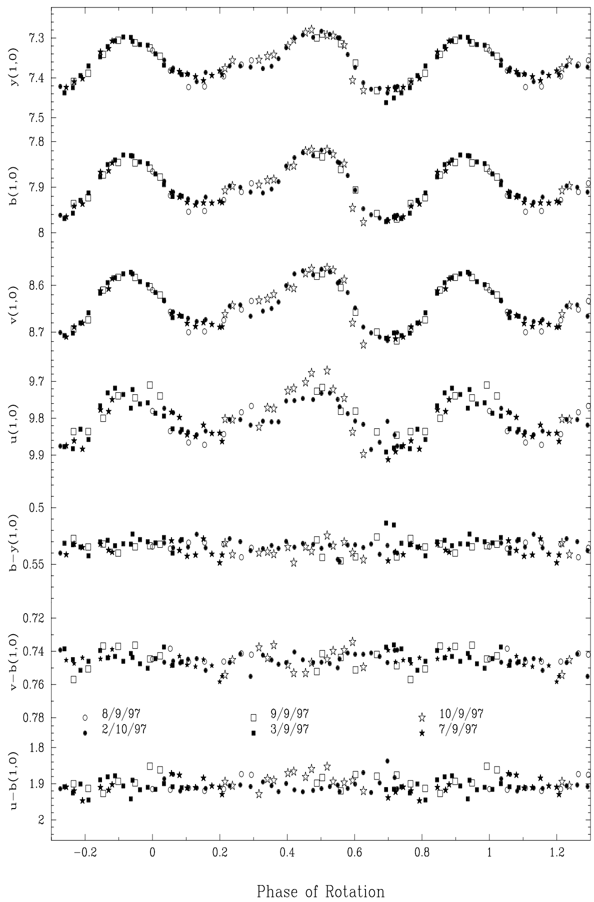

Fig. 1. Lightcurves and colour indices of 40 Harmonia in rotational phase. The 0 phase time corresponds at JD 2450700.5388 corrected for light-time

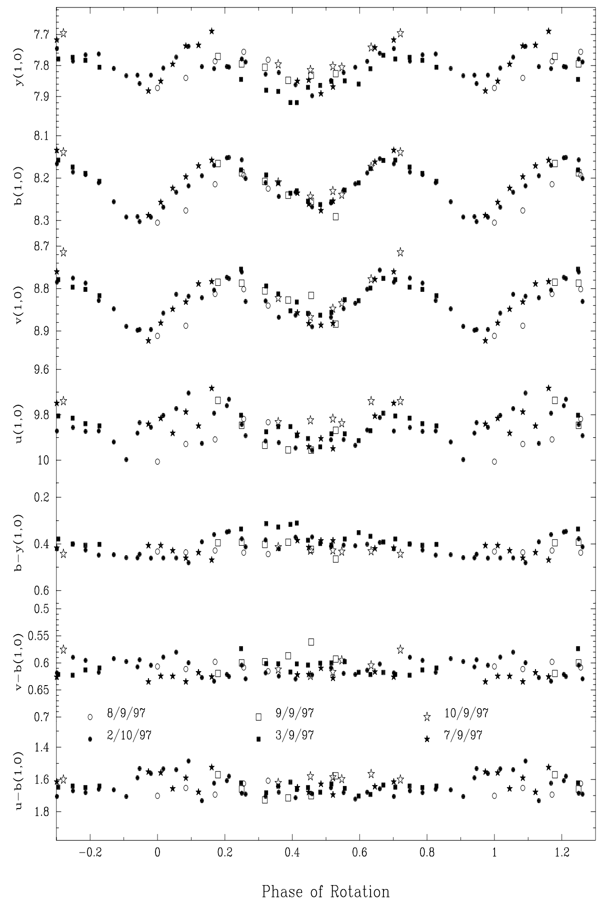

Fig. 2. Lightcurves and colour indices of 45 Eugenia in rotational phase. The 0 phase time corresponds at JD 2450700.5473 corrected for light-time

magnitudes observed during September need a greater phase angle correction than that applied to those observed during October when the phase angles are greater than 7°. Therefore September magnitudes are shifted by additional constants of $+0\overset{\mathrm{m}}{.}07$, $+0\overset{\mathrm{m}}{.}18$ and $+0\overset{\mathrm{m}}{.}05$, in all the *uvby* filters, for 40 Harmonia, 45 Eugenia and 52 Europa, respectively. The composite lightcurves obtained for each asteroid show very regular shapes with two maxima and two minima per rotation cycle.

3.2. Poles and shapes

Poles and shapes for these asteroids have been determined using the Epoch/Amplitude method (see Taylor 1979; Magnusson 1986 and Magnusson et al. 1989). Lightcurve data reported in the literature together with lightcurves obtained here for these asteroids have been used in the analysis. Most of the lightcurves used in this work can be found in the Asteroid Photometric Catalogue by Lagerkvist et al. (1987, 1988, 1992). The epochs of maximum brightness and the lightcurve amplitudes used for each asteroid together with the references for the lightcurves used are listed in Table 3.

We use the method proposed by Michalowski & Velichko (1990) that use the Epoch and Amplitude equations to build expressions, $f_{\mathrm{l}}(Tsid, \lambda_{\mathrm{p}}, \beta_{\mathrm{p}}, b/a, b/c, \beta_{\mathrm{A}}) = 0$ for $l = 1, ...(k + m)$, where k is the number of pairs of lightcurves used for the Epoch equations, m is the number of lightcurves used for the Amplitude equations, $Tsid$ is the sidereal period of rotation of the asteroid, λ_{p} and β_{p} are the pole coordinates of the asteroid, $a \geq b \geq c$ are the symmetry axes of the asteroid (considered as a triaxial ellipsoid of axis $a \geq b \geq c$ rotating about their shortest axis) and β_{A} is a phase coefficient taking into account the phase angle effects on the amplitude of the lightcurves. Following the work of De Angelis (1993), we have used the same procedure of standardization of the variables f_{l}, dividing each f_{l} by the standard deviation σ of all f_{l} of the same group of equations, and then, these

Table 3. Epochs of maximum brightness and Amplitudes observed

Date	JD	Ecliptic Long (1950)	Ecliptic Lat (1950)	Phase (deg)	Amp. (mag)	Reference
40 Harmonia						
14 1 1958	2436217.8864	146.93	4.37	13.48	—	Gehrels and Owings (1962)
29 1 1958	2436232.7303	143.89	4.99	6.65	0.23	Gehrels and Owings (1962)
29 1 1958	2436232.9298	143.84	5.00	6.55	—	Gehrels and Owings (1962)
14 2 1975	2442457.5334	127.61	4.73	7.25	0.28	Lagerkvist (1978)
6 10 1983	2445614.2994	291.30	−3.62	26.81	0.30	McCheyne et al. (1985)
7 10 1983	2445615.3196	291.56	−3.62	26.86	—	McCheyne et al. (1985)
8 10 1983	2445616.3273	291.82	−3.61	26.91	—	McCheyne et al. (1985)
8 5 1986	2446558.7162	233.41	5.12	3.59	0.15	Gallardo and Tancredi (1987)
9 9 1997	2450701.4624	351.62	−7.68	4.24	—	This work
10 9 1997	2450701.6148	351.58	−7.68	4.20	0.15	This work
11 9 1997	2450702.5703	351.34	−7.70	3.95	—	This work
2 10 1997	2450724.4850	346.17	−7.56	10.90	0.15	This work
3 10 1997	2450725.3888	346.00	−7.54	11.33	—	This work
45 Eugenia						
11 6 1969	2440383.6909	217.87	9.96	16.05	—	Taylor et al. (1988)
4 5 1978	2443632.6831	226.59	10.77	4.56	0.29	Debehogne and Zappala (1980)
1 6 1978	2443660.6991	221.04	10.50	11.95	—	Harris and Young (1979)
13 1 1982	2444982.9384	172.49	0.95	18.66	0.17	Weidenschilling et al. (1987)
13 3 1982	2445041.5846	164.76	3.62	2.97	—	Debehogne et al. (1983)
21 5 1982	2445110.6812	161.27	4.68	22.75	0.20	Weidenschilling et al. (1987)
14 7 1982		176.10	4.60	21.40	0.18	Weidenschilling et al. (1987)
21 5 1983	2445476.0576	298.15	6.82	19.90	0.14	Weidenschilling et al. (1987)
30 6 1983	2445515.9700	294.80	6.81	7.17	0.11	Weidenschilling et al. (1987)
11 10 1983	2445618.7777	290.34	1.91	22.04	0.15	Weidenschilling et al. (1987)
11 11 1983	2445649.6401	298.90	0.89	20.45	0.15	Weidenschilling et al. (1987)
29 9 1984	2445972.7803	35.09	−8.14	9.97	—	Taylor et al. (1988)
24 10 1984	2445998.1970	29.82	−8.87	3.03	—	Taylor et al. (1988)
18 11 1984		24.90	−8.80	10.2	0.36	Weidenschilling et al. (1987)
27 11 1984	2446032.1503	23.74	−8.52	13.01	—	Taylor et al. (1988)
17 1 1985	2446082.7266	26.52	−6.86	19.51	0.41	Weidenschilling et al. (1987)
20 10 1985	2446359.0875	119.07	−5.22	20.27	0.15	Weidenschilling et al. (1987)
17 1 1986	2446447.8954	116.55	−5.23	1.83	0.09	Weidenschilling et al. (1987)
16 6 1987	2446962.6469	223.69	10.06	15.59	—	Lebofsky et al. (1988)
9 9 1997	2450700.6000	348.34	−3.57	1.58	0.12	This work
2 10 1997	2450724.4542	343.44	−4.21	8.97	0.12	This work
3 10 1997	2450725.4125	343.28	−4.22	9.32	—	This work
52 Europa						
17 11 1976	2443100.3604	64.73	−10.51	4.88	—	Scaltriti and Zappala (1977)
18 11 1976	2443100.6041	64.68	−10.51	4.82	—	Scaltriti and Zappala (1977)
19 11 1976	2443102.4801	64.29	−10.50	4.35	—	Scaltriti and Zappala (1977)
11 12 1976	2443124.2884	59.81	−9.93	7.52	0.09	Scaltriti and Zappala (1977)
12 12 1976	2443124.5264	59.76	−9.92	7.60	—	Scaltriti and Zappala (1977)
24 1 1983	2445359.3366	119.91	−1.52	1.49	0.10	Zappala et al. (1983)
24 1 1983	2445359.4646	119.91	−1.52	1.49	—	Zappala et al. (1983)
25 1 1983	2445359.5729	119.86	−1.51	1.58	—	Zappala et al. (1983)
25 4 1984	2445815.5260	211.19	10.83	3.58	0.08	Barucci et al. (1986)
2 9 1986	2446675.5158	347.15	−6.32	3.26	0.23	Dotto et al. (1995)
2 9 1986	2446675.6309	347.12	−6.33	3.22	—	Dotto et al. (1995)
2 11 1992	2448928.7170	26.44	−10.90	5.53	0.10	Michalowski et al. (1995)
8 2 1994	2449391.7604	124.43	0.16	4.94	0.11	Michalowski et al. (1995)
8 2 1994	2449391.8824	124.41	0.16	4.99	—	Michalowski et al. (1995)
9 9 1997	2450700.6467	351.99	−7.22	2.95	0.20	This work
11 9 1997	2450702.5240	351.62	−7.27	2.57	—	This work
2 10 1997	2450724.3380	347.39	−7.61	6.95	0.20	This work
3 10 1997	2450725.3984	347.21	−7.61	7.29	—	This work
7 10 1997	2450729.3837	346.58	−7.61	8.52	—	This work

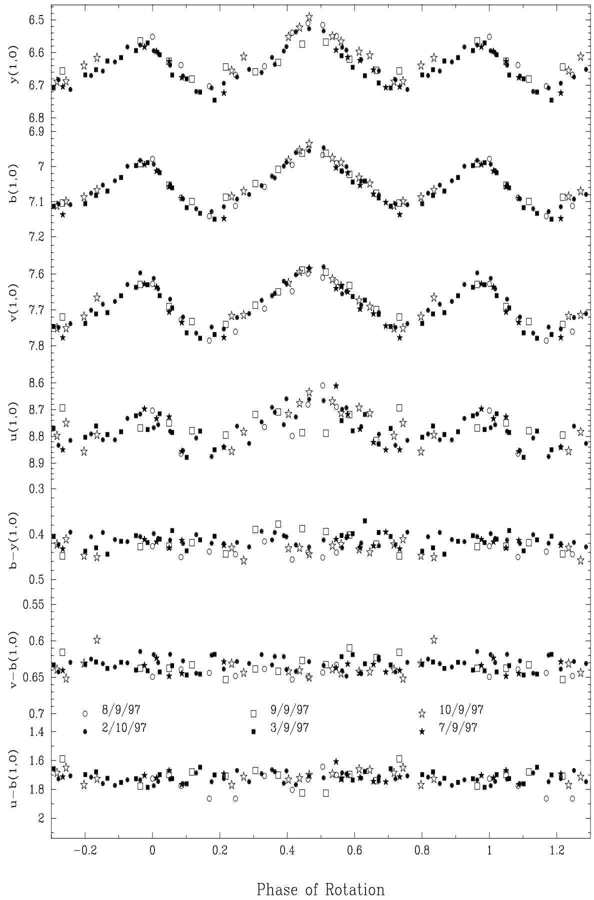

Fig. 3. Lightcurves and colour indices of 52 Europa in rotational phase. The 0 phase time corresponds at JD 2450700.5384 corrected for light-time

expressions for $f_{\rm l}$ have been used as elements of a sum of squares to be minimized by a least-square fit.

First of all we look for a mean synodic period that suits all the epochs of maximum light for each asteroid. There are cases where this mean synodic period is not well defined, as it is possible to choose between different mean synodic periods. For these cases we look for different solutions for each of the possible mean synodic periods by using a grid of $\lambda_{\rm p}$ and $\beta_{\rm p}$ as trial poles making a least-square fit for each trial pole, first for prograde and then for retrograde solutions. The solutions with least residuals are considered as the most probable solutions. In this way we obtain a more likely solution for the corresponding values of $Tsid, \lambda_{\rm p}, \beta_{\rm p}, a/b, b/c$ and $\beta_{\rm A}$ simultaneously.

In Table 4 we have listed the final solution obtained for $Tsid, \lambda_{\rm p}, \beta_{\rm p}, a/b, b/c$ and $\beta_{\rm A}$ for each asteroid, together with the mean synodic period used. Previous solutions reported by earlier authors are also shown in Table 4.

4. Results

4.1. 40 Harmonia

40 Harmonia is a S-type asteroid (Tholen 1989) with a diameter of 111 km (Tedesco 1989). From our data we find a synodic period for 40 Harmonia of $8^{\rm h}54^{\rm m}36^{\rm s}$. The composite lightcurves obtained for 40 Harmonia show a regular shape in all the *uvby* filters, with two maxima and two minima per rotational cycle. The maximum amplitude in all the *uvby* filters is of $0\overset{\rm m}{.}15$ and the amplitude averaged in the rotational cycle is of $0\overset{\rm m}{.}13$. No significative difference in the lightcurve amplitude is found in the lightcurves measured during October, $\overline{\alpha} = 12\overset{\circ}{.}001$, with respect to those measured during September, $\overline{\alpha} = 4\overset{\circ}{.}025$. The colour indices do not show any variation greater than the scatter of the data during the rotational phase of this asteroid (see Fig. 1).

Using a linear phase angle correction, a mean linear phase coefficient, $\beta_{\rm m}$, of 0.029 ± 0.004 mag/degree is obtained by averaging the linear phase coefficients obtained in each of the Strömgren filters. The mean values of $V(1,0) = 7\overset{\rm m}{.}369$, $B-V = 0\overset{\rm m}{.}862$ and $U-B = 0\overset{\rm m}{.}398$ found using a linear phase angle correction, agree with the mean values of $V(0) = 7\overset{\rm m}{.}043$, $B-V = 0\overset{\rm m}{.}867$ and $U-B = 0\overset{\rm m}{.}382$ found by using the radiative transfer theory of Lumme & Bowell (1981b) and with the values reported in the TRIAD file of Bowell et al. (1979). The difference found in the magnitudes deduced for both methods, $V(1,0) - V(0°)$, of $0\overset{\rm m}{.}33$ is as expected for all the asteroids (Bowell & Lumme 1979). The multiple scattering factor obtained from the u Strömgren filter, Q_u, is smaller than that obtained from the other Strömgren filters, that have very similar values. However the difference found for the Q_u factor is within the error bars of the determination and thus may not be significant. The average value found in all the Strömgren filters of the multiple scattering factor, Q_m, of 0.141 ± 0.021 is in agreement with the mean value of an asteroid of type S (Bowell & Lumme 1979).

Tancredi & Gallardo (1991) determined for this asteroid values of $\lambda_{\rm p}$ of $15° - 25°$ and $\beta_{\rm p}$ of $20° - 60°$ (or $\lambda_{\rm p} = 195° - 210°$, $\beta_{\rm p} = 20° - 70°$) and a value for a/b of $1.27 - 1.35$. Michalowski (1993) obtained a prograde sense of rotation with a $Tsid = 0\overset{\rm d}{.}3712522$ and values $\lambda_{\rm p} = 208°$, $\beta_{\rm p} = 21°$, $a/b = 1.27$ and $b/c = 2.07$.

Here we obtain the best fit considering 40 Harmonia as a prograde rotator obtaining $Tsid = 0\overset{\rm d}{.}3711872$ being $\lambda_{\rm p} = 22°$, $\beta_{\rm p} = 28°$ (or $\lambda_{\rm p} = 203°$, $\beta_{\rm p} = 38°$), $a/b = 1.31$, $b/c = 1$ and $\beta_{\rm A} = 1\ 10^{-5}$. A solution with a value of $Tsid = 0\overset{\rm d}{.}3712535$ is also obtained but this solution has slightly greater residuals.

The observed amplitudes together with the theoretical amplitudes, at zero-phase angle, obtained with the solution values of a/b and b/c versus the aspect angle are plotted in Fig. 4. The agreement obtained is surprisingly good, however more lightcurves of 40 Harmonia would improve

Table 4. Rotational properties

Reference	Mean Tsyn	Sense	$Tsid$	$\lambda_{\rm p}$	$\beta_{\rm p}$	$\lambda_{\rm p}$	$\beta_{\rm p}$	a/b	b/c	$\beta_{\rm A}$
40 Harmonia										
Tancredi & Gallardo (1991)				20°	40°	203°	45°	1.31	1	
Michalowski (1993)		P	$0^{\rm d}.3712522$			208°	21°	1.24	2.07	
This work	$0^{\rm d}.3712973$	P	$0^{\rm d}.3711872$	22°	28°	203°	38°	1.31	1	0.00001
This work	$0^{\rm d}.3713638$	P	$0^{\rm d}.3712535$	12°	34°	201°	41°	1.31	1	0.00001
45 Eugenia										
Taylor et al. (1988)		R	$0^{\rm d}.2374645$	106°	26°	295°	34°			
Drummond et al. (1988)		R	$0^{\rm d}.2374646$			307°	44°	1.33	1.65	
Magnusson (1990)		R	$0^{\rm d}.2374646$	116°	26°	305°	35°	1.36	1.48	
Lumme et al. (1990)		R	$0^{\rm d}.2374646$	128°	16°	313°	25°	1.3	1.4	
Drummond et al. (1991)		R	$0^{\rm d}.2374646$			307°	44°	1.33	1.65	
De Angelis (1995)		R	$0^{\rm d}.2374650$			289°	27°	1.33	1.23	0.0054
This work	$0^{\rm d}.2374297$	R	$0^{\rm d}.2374644$	106°	42°	313°	41°	1.33	1.4	0.0030
52 Europa										
Barucci et al. (1986)				0°	37°	203°	38°	1.12	1	
Dotto et al. (1995)		R	$0^{\rm d}.2346504$	70°	40°	260°	55°	1.21	1.30	
Michalowski et al. (1995)		R	$0^{\rm d}.2347019$	77°	18°	264°	32°	1.20	1.17	
This work	$0^{\rm d}.2346131$	P	$0^{\rm d}.2345855$	63°	46°	261°	60°	1.19	2.2	0.0050

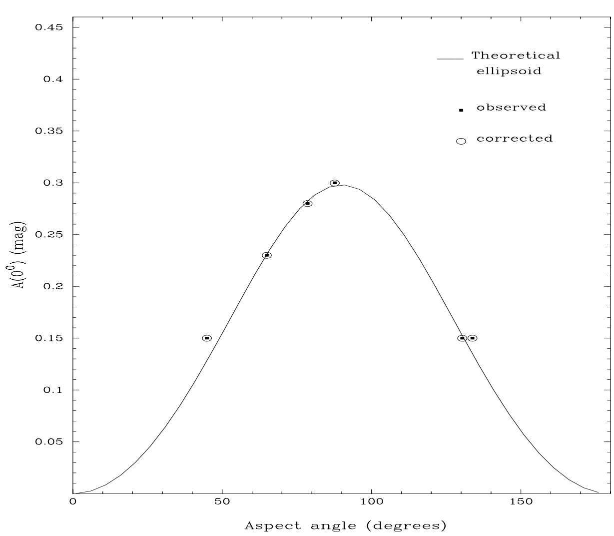

Fig. 4. Amplitude obtained considering 40 Harmonia as a triaxial ellipsoid with $a/b = 1.31$ and $b/c = 1$. Amplitudes observed and corrected by a phase factor $\beta_{\rm A} = 0.00001$

the determination of its sidereal period and rotational parameters.

4.2. 45 Eugenia

45 Eugenia is a 214 km FC-type asteroid (Tedesco 1989; Tholen 1989). This asteroid has been observed during eight oppositions between 1969 and 1988 and now in 1997. We find a synodic period of $5^{\rm h}42^{\rm m}00^{\rm s}$ from our data. The composite lightcurves obtained for 45 Eugenia show regular shapes in all the *uvby* filters, with two maxima and two minima per rotational cycle. The scatter of the data is greater in the u and y filters. The maximum amplitude in all the *uvby* filters is of $0^{\rm m}.12$ and the amplitude averaged in the rotational cycle is of $0^{\rm m}.11$. No significant differences in the amplitude can be deduced from our data for October observations, $\overline{\alpha} = 9^\circ.83$, with respect to September observations, $\overline{\alpha} = 1^\circ.046$. The colour indices during the rotational phase of this asteroid show large dispersions. The $b-y$ colour index seems to present maximum values at half of the rotational phase of this asteroid while the $u-b$ colour index seems to show a variation anticorrelated with that of the $b-y$ curve. However these variations are within the scatter of the data and may be of no significance (see Fig. 2).

Using a linear phase angle correction a mean linear phase coefficient of 0.030 ± 0.010 mag/degree is obtained from all the Strömgren filters. The mean values of $V(1,0) = 7^{\rm m}.815$, $B-V = 0^{\rm m}.659$ and $U-B = 0^{\rm m}.207$ found using a linear phase angle correction and the ones of $V(0) = 7^{\rm m}.504$, $B-V = 0^{\rm m}.689$ and $U-B = 0^{\rm m}.201$ found following Lumme & Bowell (1981b) theory are in very good agreement. However, the value of $U-B$ obtained here is smaller than the one reported by the TRIAD file. The multiple scattering factors, $Q_{\rm filters}$, obtained from the different Strömgren filters do not vary greatly. The average value found in all the Strömgren filters, Q_m, is of 0.159 ± 0.023. These values are greater than the mean

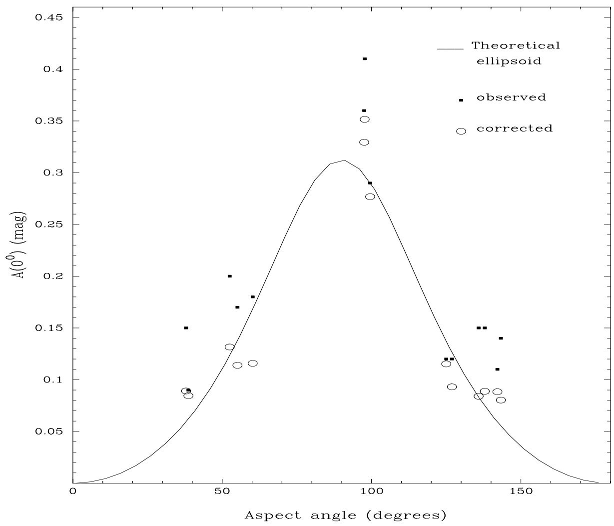

Fig. 5. Amplitude obtained considering 45 Eugenia as a triaxial ellipsoid with $a/b = 1.33$ and $b/c = 1.4$. Amplitudes observed and corrected by a phase factor $\beta_{\rm A} = 0.003$

values reported for C type asteroids, and also for U type asteroids (Bowell & Lumme 1979; Lumme & Bowell 1981b).

Previous solutions show 45 Eugenia as a retrograde rotator. Here we obtain the best fit with $Tsid = 0\overset{\rm d}{.}2374644$ and $\lambda_{\rm p} = 313°$ and $\beta_{\rm p} = 41°$ or ($\lambda_{\rm p} = 106°$ and $\beta_{\rm p} = 42°$) and values for a/b of 1.33, b/c of 1.4 and $\beta_{\rm A}$ of 3 10^{-3}. This solution is in agreement with previous determined values for $\lambda_{\rm p}$ and a/b, however the value of $\beta_{\rm p}$ seems to be greater than the average value of the previous determinations (although Drummond et al. 1988, 1991, reported values of $\beta_{\rm p} = 44°$).

In Fig. 5 the observed amplitudes together with the theoretical, at zero phase angle, obtained with these values of a/b and b/c are plotted versus the aspect angle. This figure shows very dispersed amplitude values, for aspect angles from 40° to 60°, from 120° to 150° and close to 100°. More lightcurves covering the gaps in the aspect angle would help us to discern the rotational parameters of 45 Eugenia.

4.3. 52 Europa

This object is a CF-type asteroid (Tholen 1989) with a diameter of 312 km (Tedesco 1989). Zappala et al. (1983) observed 52 Europa in January 1983 and obtained a synodic period of $5\overset{\rm h}{.}631$ and an amplitude of $0\overset{\rm m}{.}10$. From our data we find a synodic period of $5^{\rm h}37^{\rm m}46^{\rm s}$. The composite lightcurves obtained for 52 Europa show regular shapes in all the *uvby* filters, with two maxima and two minima per rotational cycle (see Fig. 3). The maximum amplitude in all the *uvby* filters is of $0\overset{\rm m}{.}20$ and the amplitude averaged in the rotational cycle is of $0\overset{\rm m}{.}14$. No significant differences in the lightcurve amplitude can be deduced from our data at $\overline{\alpha} = 7\overset{\circ}{.}75$ (October observations) with respect to those at $\overline{\alpha} = 2\overset{\circ}{.}77$ (September observations) and the colour indices seem to be constant during the rotational phase of the asteroid.

A mean linear phase coefficient, $\beta_{\rm m}$, of 0.040 ± 0.012 mag/degree is obtained from all the Strömgren filters. This coefficient is obtained for an average phase angle of $7\overset{\circ}{.}75$ when a possible greater phase correction than the one deduced at greater phase angles is to be expected. We find mean values of $V(1,0) = 6\overset{\rm m}{.}640$, $B-V = 0\overset{\rm m}{.}673$ and $U-B = 0\overset{\rm m}{.}267$ using a linear phase angle correction that agree with the mean values of $V(0) = 6\overset{\rm m}{.}382$, $B-V = 0\overset{\rm m}{.}704$ and $U-B = 0\overset{\rm m}{.}273$ obtained by using Lumme & Bowell (1981b) theory. The difference $V(1,0) - V(0) = 0\overset{\rm m}{.}26$ is slightly smaller than the expected but could be explained by considering that the magnitude, $V(1,0)$, has been obtained with a linear phase correction to values obtained at phase angles between 7° and 9° and, as was commented before, the linear phase coefficient used could be a little greater than that obtained at greater phase angles, producing a consecutive decrease in the extrapolation to the $V(1,0)$ magnitude. The values obtained here for the magnitude and the colour indices agree with the values reported in the TRIAD file.

There are slight differences in the values of the multiple scattering factors, $Q_{\rm filters}$, deduced using the different Strömgren filters. The value obtained in the y filter is the smallest one, increasing for the b, v and u filters. This value, $Q_y = 0.093 \pm 0.026$, is within the range of the mean values of Q_V reported for a C-type asteroids (Bowell & Lumme 1979).

Scaltriti & Zappala (1977), Zappala et al. (1983) and Barucci et al. (1986) observed 52 Europa in December 1976, January 1983 and April 1984 finding amplitudes in their lightcurves of $0\overset{\rm m}{.}09$, $0\overset{\rm m}{.}10$ and $0\overset{\rm m}{.}08$, respectively. Dotto et al. (1995) observed 52 Europa during August-September 1986 and obtained a lightcurve of $0\overset{\rm m}{.}23$ of amplitude. They found 52 Europa as a retrograde rotator with $Tsid = 0\overset{\rm d}{.}2346504$ and $\lambda_{\rm p} = 70°$, $\beta_{\rm p} = 40°$ (or $\lambda_{\rm p} = 260°$, $\beta_{\rm p} = 55°$) and values for a/b of 1.21 and for b/c of 1.30. Michalowski et al. (1995) observed 52 Europa in 1992 and 1994 obtaining lightcurves with $0\overset{\rm m}{.}10$ and $0\overset{\rm m}{.}11$ of amplitude, respectively. They obtained 52 Europa as a retrograde rotator with $Tsid = 0\overset{\rm d}{.}2347019$ and $\lambda_{\rm p} = 77°$, $\beta_{\rm p} = 18°$ (or $\lambda_{\rm p} = 264°$, $\beta_{\rm p} = 32°$) and values for a/b of 1.20 and for b/c of 1.17.

Here we obtain the best fit when 52 Europa is considered as a prograde rotator (when 52 Europa is considered as a retrograde rotator the residuals coming from the Epoch method increase substantially) obtaining $Tsid = 0\overset{\rm d}{.}2345855$ and $\lambda_{\rm p} = 261°$, $\beta_{\rm p} = 60°$ (or $\lambda_{\rm p} = 63°$, $\beta_{\rm p} = 46°$) and values for a/b of 1.19, for b/c of 2.2 and for $\beta_{\rm A} = 5\ 10^{-3}$. These results are in agreement with

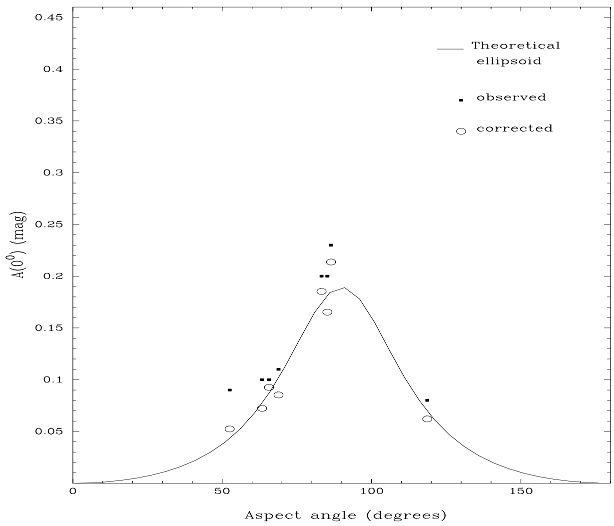

Fig. 6. Amplitude obtained considering 52 Europa as a triaxial ellipsoid with $a/b = 1.19$ and $b/c = 2.2$. Amplitudes observed and corrected by a phase factor $\beta_A = 0.005$

previous determinations for λ_p and β_p obtained by Dotto et al. (1995). However the values of β_p obtained by Michalowski et al. (1995) are smaller. The value obtained for a/b is in agreement with previous determinations while the value found for b/c is greater than previous determinations. The values of the observed amplitudes and the theoretical ones calculated with this solution at zero phase angle are plotted in Fig. 6. The agreement obtained is very good. Again new lightcurves for increasing the ecliptic longitude coverage of this asteroid would help to improve future work on the rotational properties of 52 Europa.

5. Conclusions

Lightcurves of asteroids 40 Harmonia, 45 Eugenia and 52 Europa from September to October 1997 are presented using *uvby* Strömgren photometry. The lightcurves obtained for these three asteroids show very regular shapes with two maxima and two minima per cycle. Although in all the cases the two peaks are of slightly different amplitudes. The absolute magnitudes and colour indices obtained agree well with previous measurements. No significative tendencies are found in the colour indices during their rotational phases. The values for the linear phase coefficients and for the multiple scattering factors obtained for 40 Harmonia and 52 Europa are in good agreement with the mean values expected for S-type and C-type asteroids, respectively. However, for 45 Eugenia a multiple scattering factor greater than the mean values expected for C-type asteroids (also for U-type) is obtained.

Values of sidereal periods, poles and shapes parameter are proposed. However lightcurves taken at different ecliptic longitudes and at different solar phase angles would help to obtain more accurate rotational and shape solutions.

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