Asteroids: New Observations, New Models
Proceedings IAU Symposium No. 318, 2015
S. R. Chesley, A. Morbidelli, R. Jedicke & D. Farnocchia, eds.

doi:10.1017/S1743921315008777

Studies for slowly rotating asteroids (168) Sibylla and (346) Hermentaria

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Abstract. Studies for spin parameters and shapes of asteroids provide us with important information about the interior structure of asteroids and the physical processes they have undergone. A large sample of basic physical parameters can help us also understand the evolution of asteroids. There is scarce information for slowly-rotating larger asteroids because more effort is required for observing them. Because of this, we have established an international collaboration to study slowly-rotating asteroids. As the first step of this project, we have observed asteroids (168) Sibylla and (346) Hermentaria in 2014 and 2015 using several telescopes located in China, Chile, and U.S.A. Combining previous photometric data with our new data, we have performed preliminary analyses and obtained spin parameters and shapes with their uncertainties for these two slowly-rotating asteroids for the first time, using the convex inversion method and the virtual photometry Monte Carlo method. A pair of pole solutions for (168) Sibylla are found around $(4.3°, 53.5°)$ and $(183.5°, 52.6°)$ with a period of 47.0000 h. We have found that the shape of Sibylla resembles an oblate spheroid. For (346) Hermentaria, we have also found a pair of pole solutions around $(134.5°, 16.7°)$ and $(321.5°, 14.5°)$ with comparable rms-values with a spin period of about 17.79000 h, and a shape resembling a prolate spheroid.

Keywords. Minor planets, asteroids, solar system: general, radiative transfer, scattering, methods: data analysis, methods: numerical, methods: statistical, techniques: photometric

1. Introduction

More than 690,000 asteroids have been discovered, but only a tiny fraction of them have been studied sufficiently to characterize their basic physical properties (or parameters), such as shape, pole, and spin period. A large sample of such parameters has been used to understand the origin and evolution of the Solar System and the asteroids themselves. In the last decade, knowledge on asteroid shapes and spins has accumulated rapidly. Based

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on the knowledge, interior structures of asteroids and fundamental physical processes that they have experienced have been inferred at an increasing rate.

For example, the Maxwellian distribution of spin rates for the large asteroids with diameters larger than 40 km reflects a collision-dominated evolution, whereas the non-Maxwellian distribution for the smaller asteroids in the main belt is due to the combination of the YORP effect and the collisions (Marzari *et al.* (2011), Pravec & Harris (2000), and Rubincam (2000)). The cut-off value of the spin rate at $f \sim 10$ revolutions per day (rev/d) implies that most of the small asteroids probably have ´rubble pile´ structures. The super-fast rotators are probably monolithic bodies. Some special subsets of asteroids, such as the slow rotators, which probably represent a different physical process for asteroids (Harris (2002)), can open other ways for understanding asteroids, if we learn about their basic physical parameters. Fedorets & Granvik (2015) and Marciniak *et al.* (2015) have recently published the first results from similar projects that aim to better constrain the spin and shape properties of slowly-rotating asteroids.

In order to determine the parameters of some selected slowly-rotating asteroids, especially those targets which rotate at rates about 1 rev/d or 0.5 rev/d, we have established an international collaboration in 2014. In this collaboration, the coordinated observations for the slowly-rotating asteroids are going to be carried out with telescopes distributed at different geographic longitudes. At present, two telescopes located in China, one telescope located at Kitt Peak, Arizona, U.S.A., and one telescope at Cerro Tololo, Chile are available for photometric observations.

Asteroid (168) Sibylla, a C-type asteroid with a diameter of 148 km, have been earlier observed by DiMartino *et al.* (1994), Wang & Gu (2004), and Pilcher *et al.* (2008). The first two groups reported a spin period of 23.82 h and 24.41 h, respectively, while the third group reported a period of 47.009 h. Asteroid (346) Hermentaria is an S-type main-belt asteroid with a diameter of 111 km. Several groups have made photometric observations of Hermentaria and reported diverging values for its spin period. Harris & Young (1989) and Bembrick *et al.* (2004) have reported a spin period of 28.33 h, whereas Wang & Shi (2002) and Robinson (2011) have reported a spin period of 19.4 h and 9.7 h, respectively. No pole and shape information about the two asteroids has been obtained previously. Therefore, we have selected asteroids (168) Sibylla and (346) Hermentaria as the first two targets for our study.

In Section 2, we introduce the coordinated observation for the two asteroids. In Section 3, we present our preliminary analysis results with the convex inversion method (Kaasalainen & Torppa 2001, Kaasalainen *et al.* 2001) and the virtual photometry Monte Carlo method (Wang *et al.* 2015). Finally, the discussion for the present study is given in Section 4.

2. Observations and data reduction

Based on the published results, the spin period of (168) Sibylla may be 23.5 h or 47.0 h, and the period of (346) Hermentaria may be 9.7 h, or twice or three times larger. In order to converge on the spin periods for these two asteroids and obtain their poles and shapes, we have carried out coordinated photometric observations in the apparitions of 2014 and 2015 with four telescopes located in China, U.S.A., and Chile. In total, 16 lightcurves have been obtained for the two asteroids. We give the observational details in Table 1, where the first column gives the observation date, the second and third columns give the geocentric and heliocentric distances of the asteroid, the following column gives the solar phase angle, and the last three columns give the aperture of the telescope used, the filter, and the observatory code. Actually, the photometric data for (346) Hermentaria

Table 1. New observations of (168) Sibylla and (346) Hermentaria. See text.

Date UT	Δ (au)	r (au)	α (deg)	Telescope	Filter	Obs. code
(168)						
2015/01/16.67	2.403	3.377	2.9	0.5m	Clear	Hokoon
2015/01/17.67	2.406	3.377	3.1	0.5m	Clear	Hokoon
2015/01/18.67	2.409	3.378	3.4	0.5m	Clear	Hokoon
2015/01/19.25	2.411	3.378	3.7	0.9m	V	695
(346)						
2014/12/11.67	1.790	2.697	10.0	1.0m	Clear	286
2015/01/06.25	1.741	2.723	1.6	0.9m	B,V,R	695
2015/01/19.67	1.791	2.737	7.1	0.5m	Clear	Hokoon
2015/01/20.67	1.797	2.738	7.5	0.5m	Clear	Hokoon
2015/01/21.67	1.803	2.739	7.9	0.5m	Clear	Hokoon
2015/01/22.67	1.809	2.740	8.3	0.5m	Clear	Hokoon
2015/01/23.67	1.816	2.741	8.7	0.5m	Clear	Hokoon
2015/01/23.25	1.816	2.741	8.6	0.6m	R	807
2015/03/18.67	2.438	2.796	20.5	1.0m	Clear	286

Notes: Hokoon represents the Ho Koon Nature Education Cum Astronomical Centre with a geographic position (114.1078°, 22.3838°).

from Jan. 5, 2015 are not used due to the influence of lunar light, and the data for (168) Sibylla on Jan. 3 and 12, 2015 are also omitted because of problems with the data.

While carrying out the present study, four telescopes were involved: the 1.0-m telescope at Yunnan Observatories with a 2k×2k Andor DW436 CCD camera ($0''.21$/pixel), the 0.9-m SARA telescope at KPNO and 0.6-m SARA telescope at CTIO with ARC 2k×2k CCD cameras (usually used in the 2×2 binning mode, giving a resolution of $0''.86$/pixel and $0''.72$/pixel, respectively), and the 0.5-m telescope at Hokoon with a 3k×3k CCD camera ($0''.59$/pixel). The new observational data are reduced in a standard fashion using the IRAF package. All of the scientific images are corrected for the bias, dark current, and flat-field effects. Cosmic rays in the images are identified and removed by a proper threshold. The instrumental magnitude of the objects in the images are measured with an optimal aperture using the APPHOT task of IRAF. Furthermore, the red noise in the photometric data are simulated by using the reference stars in the images, and then removed from the photometric data of the asteroids (Wang & Gu (2010)).

We have also searched the literatures for existing data of the two asteroids. For (168) Sibylla, 29 lightcurves by Pilcher *et al.* (2008) are downloaded from the MPC database and 4 lightcurves by Wang & Gu (2004) are used. 10 lightcurves of (346) Hermentaria from the APC database (Lagerkvist *et al.* (1993)) and 4 lightcurves from Wang & Shi (2002) are used. The time stamps for all the data involved are corrected for the light time and then converted into Julian Days in the TDB time system. Figures 1 and 2 show example lightcurves of (168) Sibylla and (346) Hermentaria. In the figures, α represents the solar phase angle of the asteroid, and θ and θ_0 denote angles from the line of sight and the line of incidence to the spin axis of the asteroid, respectively.

3. Results

Using the convex inversion method (Kaasalainen & Torppa (2001), Kaasalainen *et al.* (2001)) and the virtual-photometry Monte Carlo method (Muinonen *et al.* (2012), Muinonen *et al.* (2015)), the photometric data of (168) Sibylla and (346) Hermentaria are analyzed. The procedure contains two parts (for the details, see Wang *et al.* (2015)). In the first part, unknown parameters (the coefficients of the truncated spherical-harmonics series, spin parameters, and the Lambert law coefficient c) are estimated with

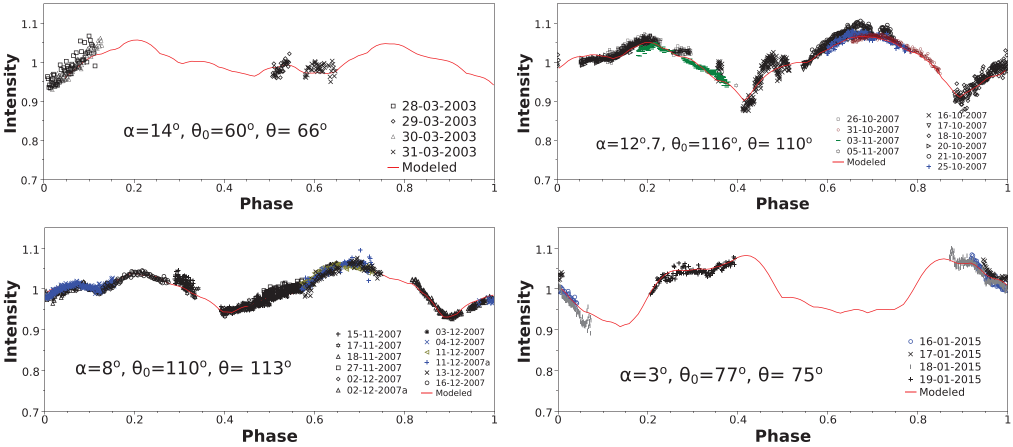

Figure 1. Lightcurves of (168) Sibylla, folded with a period of 47.00 h.

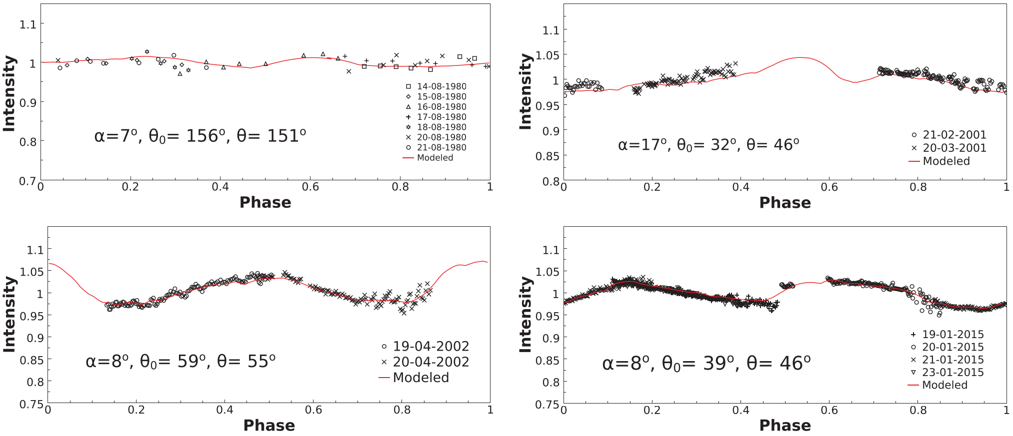

Figure 2. Lightcurves of (346) Hermentaria, folded with a period of 17.79 h.

the convex-inversion method using the Levenberg-Marquardt algorithm. A lower-resolution shape (6 rows in an octant in the triangulation) and lower-order spherical-harmonics series (up to $l = m = 6$) are adopted when searching for the best period. Then the higher-resolution shape (8 rows of triangles as per octant) represented with the higher-order spherical-harmonics series (up to $l = m = 8$) and the pole are searched with the most significant period as the initial value. In the second part, we carry out virtual-photometry Monte Carlo simulations using the convex inversion for the virtual observations. The parameter distributions composed of the virtual least-squares solutions of the convex inversion are derived. Then, the best values and the uncertainties of the spin parameters are estimated with the help of the statistics of the distributions (here we use the mode and 1σ-limits of the distributions). The best shape for a given pole solution is the one which is similar to most of the shapes based on a threshold of the Pearson's χ^2 quantity (Eq. 1 in Wang *et al.* (2015)). In what follows, we will describe the results for (168) Sibylla and (346) Hermentaria in detail.

3.1. *(168) Sibylla*

In all, 37 lightcurves of Sibylla distributed at 4 apparitions with the solar phase angle varying from 1.0° to 14.3° are used in the present analysis. Based on the previously

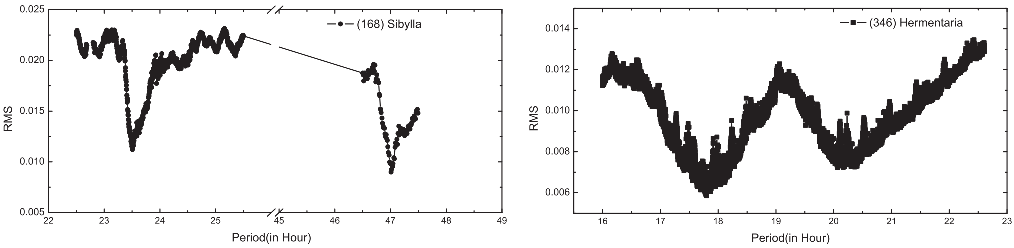

Figure 3. The rms-values of the fit vs. the spin period for (168) Sibylla (left) and (346) Hermentaria (right).

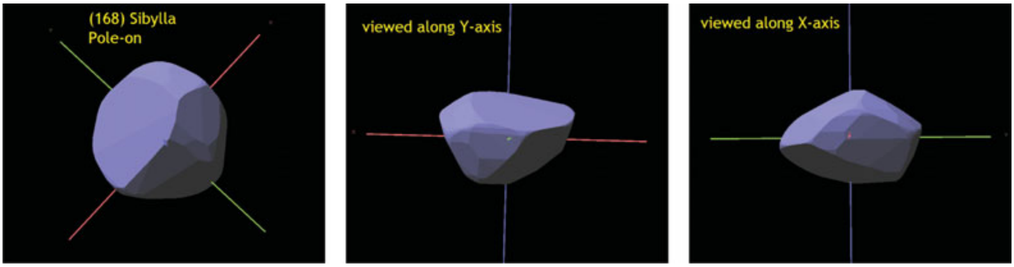

Figure 4. Convex shape of (168) Sibylla.

published results, we let the program search for the spin period at two intervals, 22h to 25h and 46h to 48h. The left panel of Fig. 3 shows the rms-value of the fit vs. the period distribution for (168) Sibylla. The most significant minimum is located at a period of 47.00 h, whereas the rms-value corresponding to the period of 23.5 h is 20% larger than that for 47.00 h. Therefore, we set an initial value of period to 47.00 h when searching for the pole solution and finding the higher-resolution shape of (168) Sibylla. Using the convex inversion method, we have found two candidate poles around $(4.3°, 53.5°)$ and $(183.5°, 52.6°)$ (in the ecliptic coordinate of the J2000.0 system) with comparable rms-values. Applying the virtual-photometry Monte Carlo method, we have obtained the best spin parameters (see Table 2) and the best shape of (168) Sibylla (see Fig. 4). Figure 5 shows the distributions of spin parameters and the coefficient c of (168) Sibylla. The coefficients of the Lambert law are 0.11 and 0.16 for the two pole solutions.

3.2. *(346) Hermentaria*

We use 23 lightcurves from 4 apparitions when searching for the spin pole and shape of (346) Hermentaria. The solar phase angle of these lightcurves varies from to 2.4° to 20.5°. The period interval between 8 h and 29 h is scanned. The most significant minimum in terms of the rms-value of the fit is located at 17.79 h (the panel on the right in Fig. 3). Then, its spin parameters and higher-resolution shape are computed with the convex-inversion method, and a pair of poles is found around $(134.5°, 16.7°)$ and $(321.5°, 14.5°)$. The shapes corresponding to the two poles are close to a prolate spheroid (see Fig. 6). With the virtual-photometry Monte Carlo procedure, the best values of the spin parameters with uncertainties (listed in Table 2) are estimated from the distributions in Fig. 7. The best values of the coefficient c are 0.05 and 0.01 for the two poles, which means a smaller weight for the Lambert law in the reflection coefficient for the surface of (346) Hermentaria.

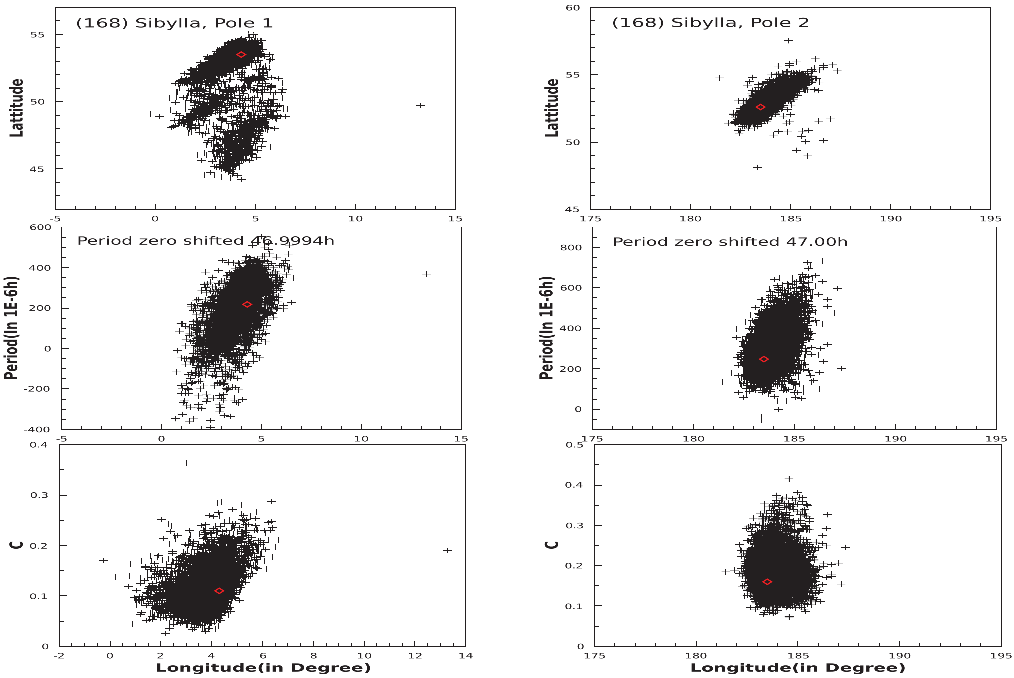

Figure 5. Distributions of spin parameters and c-coefficients for (168) Sibylla. The large empty diamond is the Mode value.

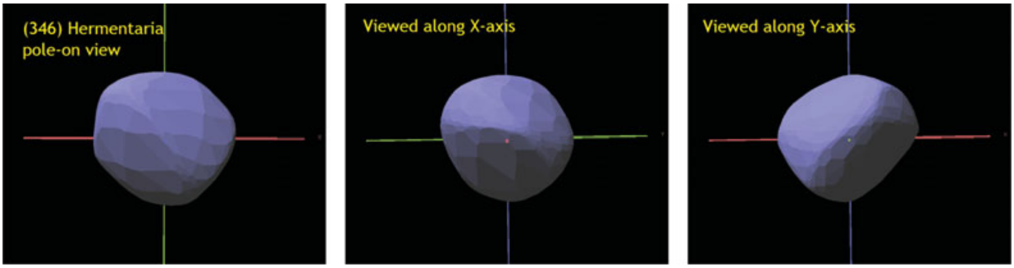

Figure 6. Convex shape of (346) Hermentaria.

4. Discussion

We have obtained the spin parameters and shapes for two slowly-rotating asteroids (168) Sibylla and (346) Hermentaria for the first time, using new data from our coordinated observations as well as existing data. We have found two possible pole solutions for (168) Sibylla at around $(4.3°, 53.5°)$ and $(183°.5, 52°.6)$. The period values corresponding to the two poles are 46.9996 h and 47.0003 h with an uncertainty of 2.5×10^{-4} h, which are close to the period by Pilcher *et al.* (2008). The corresponding convex shape of (168) Sibylla is approximately an oblate spheroid with approximate relative axial ratios $a/b = 1.0$ and $b/c = 1.4$. For the second target (346) Hermentaria, we have also found two pole solutions located at $(134°.5, 16°.7)$ and $(321°.5, 14°.5)$ with period values of 17.789993 h and 17.790038 h, respectively. This period value is different from all of the previous ones. The approximate relative triaxial dimensions (Kaasalainen *et al.* (2002)) of the derived shape of Hermentaria are $a/b = 1.1$ and $b/c = 1.0$, that is, the shape is close to a prolate spheroid.

Table 2. Spin parameters and c-coefficients for asteroids (168) Sibylla and (346) Hermentaria.

Asteroid	Period (h)	Long.	Lat.	c
(168)				
pole 1	$46.999618^{+8.9(-5)}_{-5.2(-4)}$	$4^\circ.3^{+0.1}_{-1.1}$	$+53^\circ.5^{+0.4}_{-1.5}$	$0.11^{+0.04}_{-0.03}$
pole 2	$47.000247^{+1.4(-4)}_{-3.2(-5)}$	$183^\circ.5^{+1.0}_{-0.3}$	$+52^\circ.6^{+1.0}_{-0.3}$	$0.16^{+0.05}_{-0.02}$
(346)				
pole 1	$17.789993^{+3.5(-5)}_{-2.1(-5)}$	$134^\circ.5^{+1.6}_{-1.0}$	$+16^\circ.7^{+2.3}_{-1.7}$	$0.05^{+0.07}_{-0.05}$
pole 2	$17.790038^{+1.7(-5)}_{-7.2(-6)}$	$321^\circ.5^{+1.7}_{-1.0}$	$+14^\circ.5^{+3.6}_{-0.3}$	$0.01^{+0.06}_{-0.01}$

Notes: For example, $+8.9(-5)$ stands for $+8.9 \times 10^{-5}$.

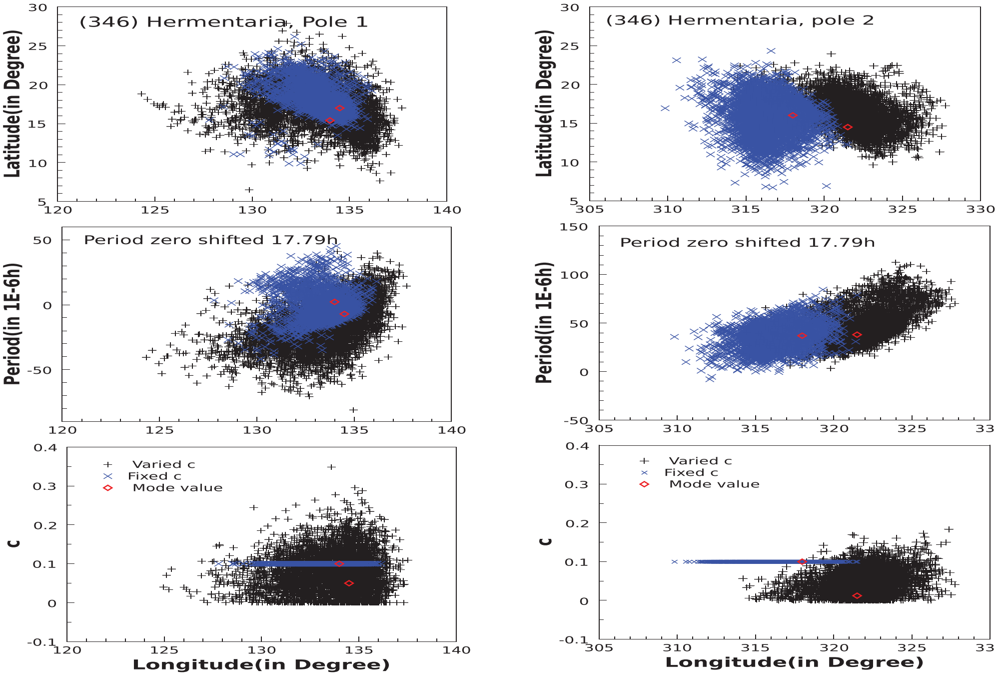

Figure 7. Distributions of spin parameters and c-coefficients for (346) Hermentaria. The large empty diamond represents the Mode value.

The uncertainties in the pole solutions for these two asteroids are quite small. This can be due to the fact that the long spin periods allow for highly detailed features to be resolved in the observational lightcurves, which, in turn, can result in highly accurate spin periods. We continue to address the spin periods in our future studies of slowly-rotating asteroids. Overall, more photometric data are needed.

On average, the Lambert coefficient c for (168) Sibylla and (346) Hermentaria are 0.14 and 0.03, respectively, which implies more weight for the Lambert law in the case of the C-type asteroid Sibylla, in comparison to the S-type asteroid Hermentaria. This result is counter-intuitive as one would expect a larger weight for the higher-albedo Hermentaria, and calls for detailed studies using, for example, the particulate-medium reflection coefficient by Wilkman *et al.* (2015).

Additionally, virtual-photometry Monte Carlo simulations with a fixed $c = 0.1$ have also been carried out for Hermentaria. The distributions of the pole for Hermentaria show slightly shifted centers as compared to the case when the coefficient c is varied. The main shift in the case of pole 1 (panel on the left in Fig. 7) is along the latitude direction, whereas the shift for pole 2 is along the longitude direction. We believe it is useful to fit the parameter c even if only relative intensities of asteroids are involved, with which we can derive the spin pole accurately.

Acknowledgements

The research has been supported by National Natural Sciences Foundations of China (contract No. 11073051) and the Academy of Finland (project No. 1257966).

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