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Study of photometric phase curve with new brightness model: refining phase function system parameters of asteroid (107) Camilla

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Abstract We characterize the morphology of the photometric phase curve model of an asteroid with a three-parameter magnitude phase function $H - G_1 - G_2$ system by considering the effect of brightness variation arising from a triaxial ellipsoid representing the asteroid's shape. Applying this new model and a Markov Chain Monte Carlo method, we refine the photometric phase curve of asteroid (107) Camilla and obtain its absolute magnitude $H = 7.026^{+0.052}_{-0.054}$ mag, and phase function parameters $G_1 = 0.489^{+0.043}_{-0.044}$ and $G_2 = 0.259^{+0.023}_{-0.023}$. Meanwhile, we also determine (107) Camilla's orientation of pole $(74.1^{\circ}{}^{+4.3^{\circ}}_{-4.5^{\circ}}, 50.2^{\circ}{}^{+5.4^{\circ}}_{-5.0^{\circ}})$ with rotational period of $4.843928^{+0.000001}_{-0.000001}$ h, and axial ratios $a/b = 1.409^{+0.020}_{-0.020}$ and $b/c = 1.249^{+0.063}_{-0.060}$. Furthermore, according to the values of phase function parameters G_1 and G_2, we infer that asteroid (107) Camilla is an X-type asteroid.

Key words: minor planets, asteroids: general: phase curve — minor planets, asteroids: individual: (107) Camilla — techniques: photometric

1 INTRODUCTION

Asteroids are thought to be the remnants of planetesimals from the early stage of the solar system. Physical studies of asteroids provide important clues on the pristine environment of the solar system and information on formation and evolution of terrestrial planets, which are crucial enigmas in modern astronomical researches. The basic physical parameters of asteroids, such as rotational period, orientation of pole and shape are important data to infer their formation and collisional evolution process. The photometric phase curve of an asteroid presents observational brightness at different phase angles. The shape of the phase curve provides us with information on surface micro-structure of an asteroid (Belskaya & Shevchenko 2000; Shevchenko et al. 2008, 2012).

In studies of photometric phase curves of asteroids and other atmosphereless solar system objects such as the Moon, interplanetary dust or rings of planets, a significant phenomenon is the so-called opposition effect. This occurs below a solar phase angle (hereafter phase angle) of 7° and leads to non-linear brightening. This phenomenon is related to the shadow and coherent backscattering mechanism (Hapke 1984, 1986, 2002; Muinonen 1994; Dlugach & Mishchenko 1999, 2013; Belskaya & Shevchenko 2000; Muinonen et al. 2002), by which surface properties such as roughness and porousness can be investigated.

In 1985, the International Astronomical Union (IAU) passed a resolution in which a semi-empirical phase function $H-G$ system was adopted as the standard phase function system of asteroids. In this system, H and G were absolute magnitude[1] of an asteroid at zero phase angle and slope factor of phase curve, respectively. In practice, the slope factor G was usually assumed to be 0.15 (Bowell et al. 1989) for most asteroids, due to the lack of data covering sufficient phase angles. Furthermore, a problem with the $H - G$ system was that it did not fit the phase curves of D- and E-type asteroids well. Muinonen et al. (2010) proposed a modified system — the three-parameter magnitude phase function $H - G_1 - G_2$ system, which was adopted as the new standard phase function system in the 28th General Assembly of the IAU. This new phase function system improved the fitting root mean square of photometric phase curves for all different type asteroids. Additionally, the phase function parameters G_1 and G_2 could be used as a way to infer the preliminary taxonomy of asteroids (Oszkiewicz et al. 2011; Shevchenko et al. 2015), especially for faint asteroids.

[1] Absolute magnitude is conventionally defined in the Johnson V band at the mean brightness of light curves.

However, to study the photometric phase curve of main-belt asteroids, photometric data covering a large range of phase angles are needed. Sometimes, sufficient data cannot be observed in an apparition due to a shortage of observational duration time. In general, the observational data obtained at different apparitions are combined. Under this situation, estimations of phase function system parameters are influenced by the non-spherical shape of the asteroid due to change of aspect angle.

Here, we develop a new brightness model to effectively estimate the phase function system parameters. The new model considers the three-parameter magnitude phase function $H - G_1 - G_2$ system and a triaxial ellipsoidal shape of an asteroid. As an application, the photometric data of asteroid (107) Camilla are analyzed with this new model. In Section 2, the brightness model used here is introduced. Section 3 includes the reduction of new observational data of (107) Camilla and the associated results of this new model. At the end of this paper, we sum up this work in Section 4.

2 BRIGHTNESS MODEL

The photometric phase curve is an important tool to determine the absolute magnitude of an asteroid and has been broadly used to study physical properties on the surface of asteroids. Previous studies of phase curves were derived by assuming the asteroid had a spherical shape. Its apparent magnitude or observed brightness V was expressed as follows,

$$V(\alpha) = 5\log_{10}(r\Delta) + f(\alpha), \tag{1}$$

where r is the heliocentric distance between the Sun and asteroid and Δ is the geocentric distance between the Earth and asteroid in AU. α is a phase angle and $f(\alpha)$ represents a certain phase function system.

In fact, most asteroids do not have spherical shapes. Therefore, the observed brightness of an asteroid can vary with its spin and with changes in viewing aspect when the geometries of observations vary. To determine the phase function system parameters accurately, a new brightness model considering the effect of brightness variation of an asteroid is introduced as follows,

$$V(\alpha,\eta) = 5\log_{10}(r\Delta) + f(\alpha) + 2.5\log_{10}(\Delta S), \tag{2}$$

$$f(\alpha) = H - 2.5\log_{10}[G_1\phi_1(\alpha) + G_2\phi_2(\alpha) + (1 - G_1 - G_2)\phi_3(\alpha)], \tag{3}$$

where η represents all the unknown parameters: rotational period P, initial rotation phase angle ϕ_0, orientation of pole (λ_p, β_p), shape $(a/b, b/c)$, absolute magnitude and phase function parameters. For the phase function system $f(\alpha)$, we adopt a three-parameter magnitude phase function $H - G_1 - G_2$ system (Muinonen et al. 2010), in which H is absolute magnitude, and G_1 and G_2 are two phase function parameters. By assuming material is distributed uniformly over the surface of an asteroid, ΔS can be normalized as follows,

$$\Delta S(\lambda_p, \beta_p, a/b, b/c, P, \phi_0) = \frac{S'}{S}, \tag{4}$$

where parameter S' represents a cross section of an equivalent spherical shape of an asteroid and S is a cross section of this asteroid illuminated by sunlight and visible by observers. In this work, a triaxial ellipsoid is used to approximately represent the shape of the asteroid. To calculate the cross sections, we use the formulae given in Pospieszalska-Surdej & Surdej (1985).

By comparing the observational brightness of an asteroid to the modeled brightness calculated by Equation (2) at different times, the unknown parameters can be estimated. To estimate these parameters, a Markov Chain Monte Carlo (MCMC) simulation procedure is adopted here. As an application of the new brightness model, the photometric data of asteroid (107) Camilla are analyzed.

3 APPLICATION

Photometric observations of asteroid (107) Camilla have been carried out by several groups (Weidenschilling et al. 1987, 1990; di Martino et al. 1987; Harris & Young 1989; Polishook 2009). The rotational parameter and orientation of pole for (107) Camilla were analyzed by Weidenschilling et al. (1987), di Martino et al. (1987), Drummond et al. (1988, 1991), Harris & Young (1989), Magnusson (1990), De Angelis (1995), Torppa et al. (2003), Ďurech et al. (2011) and Hanuš et al. (2013) with different methods. Its photometric phase curve was studied based on the $H - G$ system, and absolute magnitude $H = 7.08$ mag and slope factor $G = 0.08$ were estimated by Harris & Young (1989).

3.1 Observation and Data Reduction

To study the photometric phase curve of (107) Camilla, new photometric observations of (107) Camilla were carried out on 2015 March 2 and 3 with a 1.0-m telescope administered by Yunnan Observatories, China (Observatory Code 286). The data were gathered by using a 2k×2k pixel CCD with a field of view of $7.3' \times 7.3'$. The bias frames were sampled at the beginning and end of the observations, and the twilight flat frames in the V-band were obtained.

All the scientific images were reduced using the Image Reduction and Analysis Facility (IRAF) software. Based on the standard reduction process, the bias was subtracted and the flat was corrected to produce scientific images. Cosmic rays were identified in these images by a criterion according to four times the variation of sky background and were removed; utilizing the APPHOT task, instrumental magnitudes of reference stars and the target asteroid were measured by an optimal aperture (Wang & Wang 2012).

Before analyzing the photometric phase curve of (107) Camilla, measured magnitudes needed to be converted into

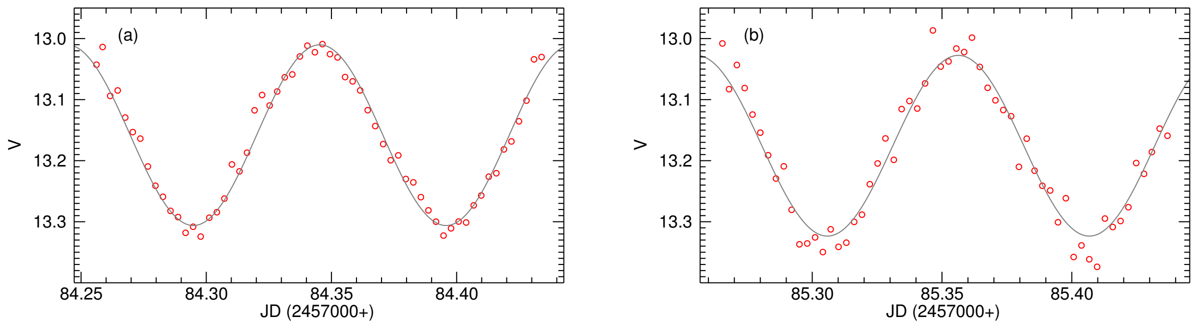

Fig. 1 Light curves of asteroid (107) Camilla shown with empty circles on Mar. 2 (a) and Mar. 3 (b) in 2015. The solid lines are modeled light curves derived by a triaxial ellipsoid.

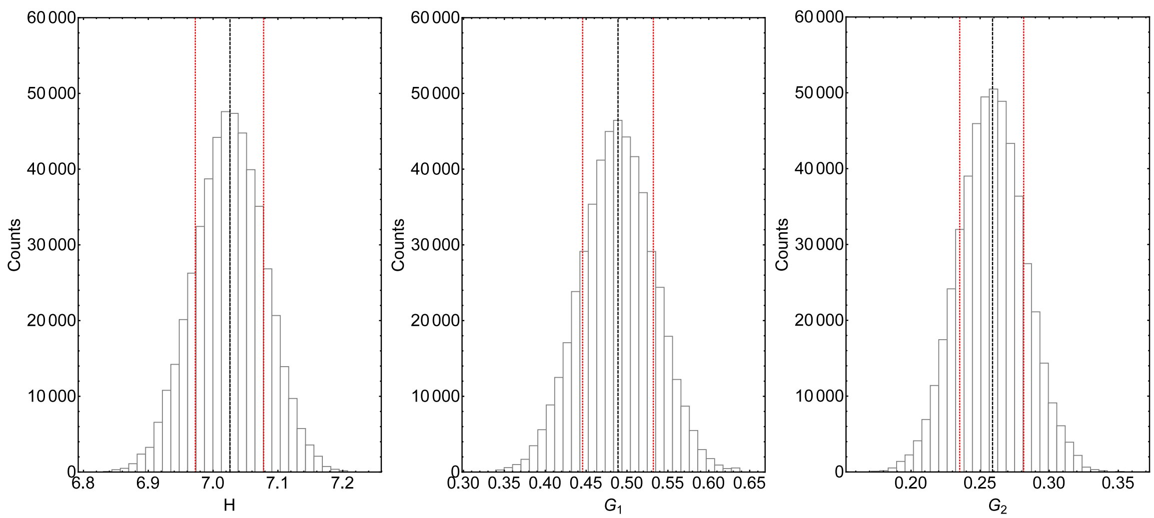

Fig. 2 The posterior probability distributions of parameters H, G_1 and G_2 of (107) Camilla. The black dashed-lines show the best values and the intervals between two dotted-lines denote the uncertainties represented by $1-\sigma$ in each panel.

a standard V-band photometry system. To calibrate the new photometric data of (107) Camilla, the zero point for magnitude of the instrument and extinction in each night were estimated by the magnitudes of reference stars and compared with those in the Carlsberg Meridian Catalogue 15 (CMC15) (Muiños & Evans 2014) in the images. Due to not having V-band data in CMC15, the relationship of Dymock & Miles (2009) was used to calculate the V-band magnitudes for reference stars from their r'-band value,

$$V = 0.6278 \times (J - K_s) + 0.9947 \times r'. \quad (5)$$

Here, the r'-band of CMC15 was the same as that in the Sloan Digital Sky Survey. J and K_s magnitudes were derived from the 2MASS catalog. Using an average of the zero point for magnitude and the extinction coefficient of reference stars, measured V-band magnitudes of (107) Camilla were calibrated and its light curves are shown in Figure 1.

Additionally, the collected photometric data of (107) Camilla were applied in our analysis. All the light curves spanned 1981 to 2015, and the phase angles of these data varied from $2.25°$ to $16.44°$. Detailed information on these photometric observations is listed in Table 1. Here, $V(1, 1, \alpha)$ denotes the mean V-band magnitude which represents a distance of 1 AU from the asteroid to both the Sun and the Earth at a phase angle α.

3.2 MCMC Simulation and Results

Applying this new brightness model introduced in Section 2, we determined phase function system parameters, rotational period, orientation of pole and shape for asteroid (107) Camilla by an MCMC simulation method based on the photometric light curves listed in Table 1. A classical Metropolis-Hastings sampling method was applied during the MCMC simulation (Collier Cameron et al. 2007; Muinonen et al. 2009); to sample a Markov Chain, and the posterior probability density p was calculated with the following equation,

$$p \propto \exp\left[-\frac{\chi^2(\lambda_p, \beta_p, a/b, b/c, P, \phi_0, H, G_1, G_2)}{2}\right]. \quad (6)$$

Table 1 Information on Photometric Observations Used in the Present Analysis of Asteroid (107) Camilla

Date	r (AU)	Δ (AU)	α (deg)	$V(1,1,\alpha)$ (mag)	Note
1981/02/01	3.250	2.275	2.99	7.41	Harris & Young (1989)
1981/02/02	3.251	2.274	2.87	7.40	Harris & Young (1989)
1981/02/04	3.251	2.274	2.74	7.39	Harris & Young (1989)
1981/02/05	3.251	2.274	2.75	7.38	Harris & Young (1989)
1981/06/15	3.308	3.727	15.14	8.02	Weidenschilling et al. (1987)
1982/01/09	3.439	3.439	16.44	8.01	Weidenschilling et al. (1987)
1982/05/20	3.531	2.693	10.56	7.75	Weidenschilling et al. (1987)
1982/06/22	3.553	3.097	15.74	8.02	Weidenschilling et al. (1987)
1983/03/27	3.711	3.465	15.50	7.84	Weidenschilling et al. (1987)
1983/05/24	3.733	2.815	7.57	7.53	Weidenschilling et al. (1987)
1983/07/03	3.745	2.788	6.07	7.46	Weidenschilling et al. (1987)
1984/06/07	3.743	3.269	14.74	8.00	Weidenschilling et al. (1987)
1984/07/05	3.734	2.926	10.69	7.87	Weidenschilling et al. (1987)
1984/08/16	3.719	2.715	2.25	7.38	di Martino et al. (1987)
1985/10/20	3.445	2.460	2.96	7.38	Weidenschilling et al. (1987)
1987/02/06	3.192	2.462	13.60	7.84	Weidenschilling et al. (1990)
1988/04/25	3.359	2.615	13.12	7.96	Weidenschilling et al. (1990)
1989/04/12	3.621	2.802	10.41	7.65	Weidenschilling et al. (1990)
2015/03/02	3.532	3.191	15.94	7.91	New observation at 1.0-m YNAO
2015/03/03	3.532	3.177	15.88	7.93	New observation at 1.0-m YNAO

Based on simulations with Markov Chain lengths of 500 000, the best values and uncertainties for the unknown parameters were obtained, which are listed in Table 2.

For the basic parameters of asteroid (107) Camilla, we obtained its rotational period of 4.843928 h, orientation of pole $(74.1°, 50.2°)$ and axial ratios of $a/b = 1.409$ and $b/c = 1.249$, which were closely consistent with the results suggested by Torppa et al. (2003), Ďurech et al. (2011) and Hanuš et al. (2013). In a previous study of the phase curve of (107) Camilla, using four light curves distributed in a small range of phase angles, Harris & Young (1989) estimated an absolute magnitude $H = 7.08$ mag by assuming a mean slope factor $G = 0.09$ for dark asteroids (Harris 1989). Here, the new observational data and the collected ones were used to fit the $H - G_1 - G_2$ phase function system parameters of (107) Camilla by utilizing our new brightness model. We obtained $H = 7.026$ mag, $G_1 = 0.489$ and $G_2 = 0.259$. The distributions of H, G_1 and G_2 are shown in Figure 2, and the phase curve of (107) Camilla is presented in Figure 3.

At present, Oszkiewicz et al. (2011) found a relationship of two phase function parameters G_1 and G_2 related to taxonomy of asteroids. Such a relationship could be utilized to roughly identify the classification of an asteroid (Shevchenko et al. 2015). According to the conclusion of Oszkiewicz et al. (2011), (107) Camilla's parameters $G_1 = 0.489$ and $G_2 = 0.259$ are suggestive of belonging to a taxonomy of X-type, which can be seen in Figure 4.

Furthermore, for asteroid (107) Camilla, three additional parameters, phase integral $q = 0.4172$, photometric phase coefficient $k = -1.4469$ and amplitude of the opposition effect $\zeta - 1 = 0.3369$, can be evaluated, based on

Table 2 The Results of Estimated Parameters and Their Uncertainties

Parameter	Value	Uncertainty	Unit
λ_p	74.1	$^{+4.3}_{-4.5}$	deg
β_p	50.2	$^{+5.4}_{-5.0}$	deg
a/b	1.409	$^{+0.020}_{-0.020}$	-
b/c	1.249	$^{+0.063}_{-0.060}$	-
P	4.843928	$^{+0.000001}_{-0.000001}$	h
ϕ_0	84.5	$^{+4.5}_{-4.6}$	deg
H	7.026	$^{+0.052}_{-0.054}$	mag
G_1	0.489	$^{+0.043}_{-0.044}$	-
G_2	0.259	$^{+0.023}_{-0.023}$	-

relationships derived by Muinonen et al. (2010),

$$q = 0.009082 + 0.4061G_1 + 0.8092G_2, \quad (7)$$

$$k = -\frac{1}{5\pi}\frac{30G_1 + 9G_2}{G_1 + G_2}, \quad (8)$$

$$\zeta - 1 = \frac{1 - G_1 - G_2}{G_1 + G_2}. \quad (9)$$

4 CONCLUSIONS

For the majority of asteroids, their photometric phase curves have been studied previously with the $H - G$ system by assuming the shape of the asteroid is a sphere. Therefore, under this condition, some errors arising from the non-spherical shape of an asteroid can be introduced into the determination of phase function system parameters. The new brightness model used here considers the variation of illuminated cross section that is visible for

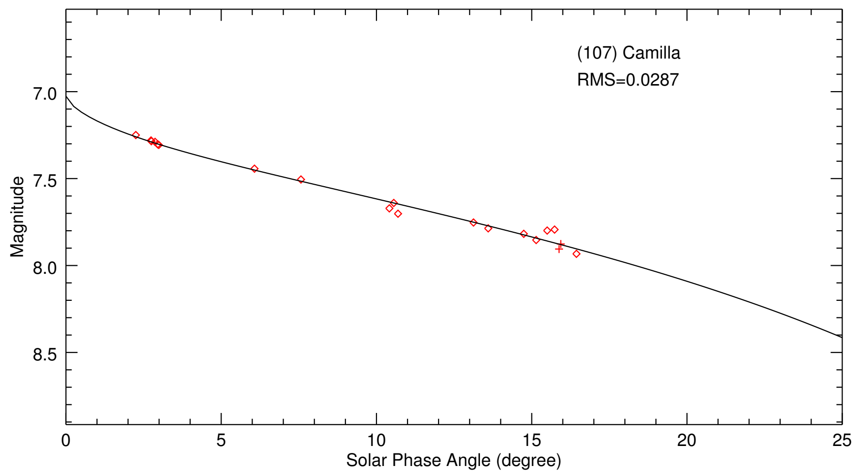

Fig. 3 The photometric phase curve of (107) Camilla based on our new brightness model. Data are shown by diamonds derived from previous researches and by two pluses derived from new observations which were carried out in March 2015 with the 1.0-m telescope administered by Yunnan Observatories.

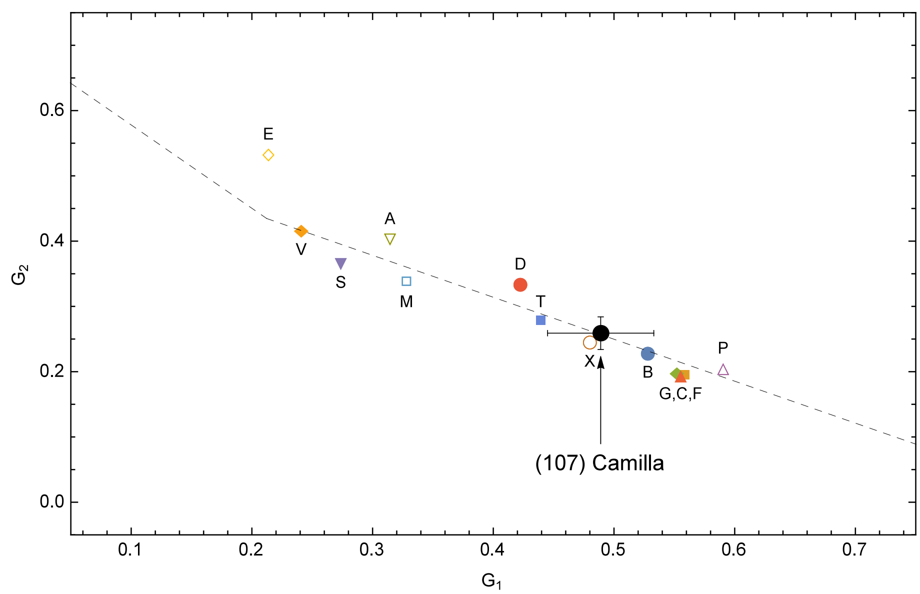

Fig. 4 The distribution of parameters G_1 and G_2 (Oszkiewicz et al. 2011). The filled circle with $1-\sigma$ error bars represents the result of (107) Camilla.

a triaxial model of an asteroid caused by changes in the viewing aspect angle. Using our model, we fit the phase function of asteroid (107) Camilla with the three-parameter magnitude phase function $H-G_1-G_2$ system and have significantly improved the model of its phase curve. We estimate its absolute magnitude $H = 7.026$ mag and two phase function parameters $G_1 = 0.489$ and $G_2 = 0.259$. Meanwhile, an orientation of pole $(74.1°, 50.2°)$ is determined with a rotational period of 4.843928 h, and an ellipsoidal shape with axial ratios $a/b = 1.409$ and $b/c = 1.249$ is obtained.

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