Planetary and Space Science 108 (2015) 31–40

Contents lists available at ScienceDirect

Planetary and Space Science

journal homepage: www.elsevier.com/locate/pss

Cellinoid shape model for multiple light curves

Xiao-Ping Lu [a,*], Wing-Huen Ip [a,b]

[a] Macau University of Science and Technology, Avenida Wai Long, Taipa, Macau, China
[b] Institute of Astronomy, National Central University, Taiwan

ARTICLE INFO

Article history:
Received 30 July 2014
Received in revised form
20 November 2014
Accepted 17 December 2014
Available online 30 December 2014

Keywords:
Cellinoid
Light curves
Asteroids
Shape

ABSTRACT

Extended from the ellipsoid shape, cellinoid shape model consists of eight octants from eight different ellipsoids with the constraint that the adjacent octants have the same semi-axes in common. With the asymmetric shape, cellinoid shape model could be adopted in simulating the irregular shapes of asteroids. In this article, we attempt to apply cellinoid shape model to multiple light curves observed in various geometries and present some techniques to make the whole inverse process more efficient. Finally numerical experiments confirm that cellinoid shape model could derive the physical parameters of asteroids from both of synthetic and real light curves.

1. Introduction

The research about the asteroid, including its physical characteristics and its composition, plays more and more important role in the research of solar system. Especially there have been many large projects to discover much more unknown information about the asteroid. For example, the Japanese Hayabusa spacecraft visited the asteroid (25143)Itokawa in 2005 and took back regoliths from an asteroid for the first time. The Chinese Chang'e2 spacecraft firstly took the photography for the asteroid (4179) Toutatis at the end of 2012. Furthermore, the European GAIA project has been launched to establish the three-dimensional map of the galaxy, including tremendous asteroids. Nevertheless, the primary research data about asteroids are the light curves, collected by the ground-based observatories. Although there are more than 600,000 asteroids found, there are few to know their physical parameters, such as rotational periods, shape models and the orientations of their spin axes.

There have been many research focusing on deriving the physical parameters of asteroids from light curves since 1906, when Russell (1906) firstly attempted to derive the albedo map from the light curves observed on the opposition and he found that it was impossible to dispart between the surface curvature and the spot distribution for a spotted convex surface. Surdej and Surdej simulated the light curves of asteroids with the assumption that their shape is an ellipsoid (Surdej and Surdej, 1978). And with the definition of scattering law by Lumme and Bowell (1981a,b), many analogous methods based on the ellipsoid shape were presented, such as the model introduced by Karttunen (1989) and Karttunen and Bowell (1989). Furthermore, Kaasalainen et al. presented an effective method to reconstruct the shape model by an arbitrary convex surface from many light curves observed in various geometries (Kaasalainen and Lamberg, 1992a,b). Moreover they also numerically improved the performance of the algorithm by employing the efficient Lebedev quadrature (Kaasalainen et al., 2012). Based on Kaasalainen's method, Ďurech built a database to present the shape models and other physical parameters for less than 400 asteroids (Ďurech et al., 2010).

Because the observed brightness of asteroids from the ground-based telescopes is often influenced by the atmosphere and accuracy of telescopes, and it is very hard to collect enough light curves to reconstruct a sophisticated shape model for so many asteroids, the ellipsoid shape is also employed frequently in simulating the shape of an asteroid until now. Cellino et al. applied an ellipsoid shape to derive the physical parameters of several asteroids by genetic algorithm (Cellino et al., 2009). Carbognani et al. presented a method to represent the shape of an asteroid by the ellipsoid (Carbognani et al., 2012). Lu et al. illustrated a fast ellipsoid method to search the physical parameters of asteroids (Lu et al., 2013). Although the ellipsoid shape is very simple to represent the shape of a symmetric asteroid, it is not appropriate to illustrate the asymmetric shape of real asteroids. Cellino et al. presented a special shape model, consisting of eight octants from eight ellipsoids with its adjacent octants having the same semi-axes in common (Cellino et al., 1989). This shape model can be applied to simulate the asymmetric shape of real asteroids only with 3 more parameters than ellipsoid shape. Lu et al. analyzed its physical characteristics and called it 'Cellinoid' for the first time

* Corresponding author.
E-mail address: xplu@must.edu.mo (X.-P. Lu).

http://dx.doi.org/10.1016/j.pss.2014.12.019
0032-0633/

(Lu et al., 2014). The centre of mass and moment of inertial of cellinoid shape model were deduced and its stable spin axis could be calculated by the diagonalization of the tensor matrix of inertia. Besides, they also compared the derived solutions for pole orientation and rotational period, based on the ellipsoid shape and cellinoid shape respectively. The asymmetric shape of cellinoid model could fit the light curves with the asymmetric morphology better than the ellipsoid model.

Furthermore, they also attempted to derive the physical parameters only from three light curves in one apparition for the asteroid (3)Juno and (21)Lutetia. Unfortunately, the insufficient data could only derive the accurate rotational period with the rough estimate for the spin axis and shape. In this paper we attempt to apply the cellinoid shape model to more light curves observed in various geometries and show that the parameters could be refined by applying more light curves. Additionally, a preprocessing algorithm is presented to reduce the huge computational cost in searching the best-fit solutions by cellinoid shape model.

The paper will be arranged as follows. First of all, in Section 2 the cellinoid shape model will be concisely presented with its physical characteristics and the inverse process is illustrated in detail. Following the theoretical description, the numerical experiments will be shown to examine the performance of cellinoid shape in Section 3. That will be described in three parts. In Section 3.1 a method to reduce the light curves by polynomial fit is presented and the fitted solutions from original and reduced light curves are compared. Then an ideal asteroid with the standard cellinoid shape is applied to generate 10 synthetic light curves in various geometries and the derived parameters by the inverse process are consistent with the pre-setting ones, which make the whole process more reliable. Finally, by applying the cellinoid to light curves of real asteroid (3)Juno, the results show that cellinoid shape model could be employed not only to derive a rough estimate from several light curves of one apparition, but also to refine the estimate with more light curves observed in various geometries. At the end of this paper, we sum up the primary work of this paper in Section 4.

2. Cellinoid shape and inverse process

2.1. Cellinoid shape

The cellinoid shape model is shown in Fig. 1, which consists of eight octants from eight ellipsoids, such as the octant O_1 with the definition of

$$O_1: \quad \frac{x^2}{a_1^2}+\frac{y^2}{b_1^2}+\frac{z^2}{c_1^2}=1, \quad (0 \le x \le a_1,\ 0 \le y \le b_1,\ 0 \le z \le c_1). \tag{1}$$

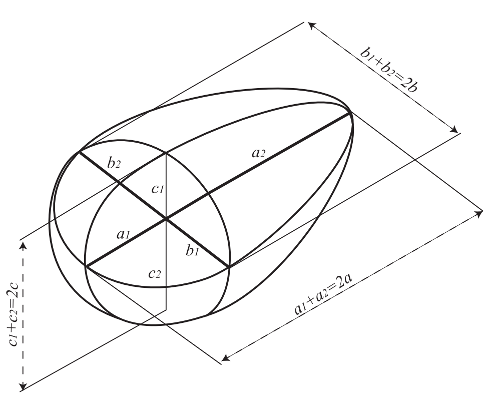

Fig. 1. Cellinoid shape model.

The cellinoid shape is totally controlled by six parameters, a_1, a_2, b_1, b_2, c_1, and c_2. Although the cellinoid shape model is continuous but not smooth in the adjacency lines of adjacent octants, it could simulate the asymmetric shape of real asteroids well, with only 3 more parameters than the ellipsoid shape model. In addition, its total volume V will be

$$V=\frac{\pi}{6}(a_1+a_2)(b_1+b_2)(c_1+c_2), \tag{2}$$

and its centre of mass $G(x,y,z)$ has the following form:

$$G(x,y,z): x=\tfrac{3}{8}(a_1-a_2), \quad y=\tfrac{3}{8}(b_1-b_2), \quad z=\tfrac{3}{8}(c_1-c_2). \tag{3}$$

Furthermore, Lu et al. calculated the moment of inertia of cellinoid shape and presented its stable rotational axis by diagonalizing the tensor of inertia (Lu et al., 2014).

2.2. Inverse process

As we have known the physical characteristics of the cellinoid shape model, the inverse process to derive related parameters of an asteroid from its light curves could be realized with the following steps.

2.2.1. Scattering law

A suitable scattering law will be very important in the inverse process. As previously introduced, there are many studies about this topic (Lumme and Bowell, 1981a,b; Hapke, 1984). As the observation accuracy of ground-based telescopes is not very high and the surface albedo of the asteroid is hard to describe, the scattering law to simulate the reflection behaviour of the light from the sun cannot be fitted very accurately. For simplicity, it is better to choose a mathematically fitted function to illustrate the scattering law. Combining Lommel–Seeliger term and Lambert term with a weight factor c, Kaasalainen et al. presented a simple function

$$S(\mu,\mu_0,\alpha)=f(\alpha)\left(\frac{\mu\mu_0}{\mu+\mu_0}+c\mu\mu_0\right), \tag{4}$$

to make the inversion more convenient (Kaasalainen et al., 2001). And in Eq. (4), $f(\alpha)$ presented by Muinonen et al.,

$$f(\alpha)=a\ \exp\left(-\frac{\alpha}{d}\right)+b+k\alpha, \tag{5}$$

is a four-parameter empirical linear exponential model for the light curves close to the opposition, where α is the phase angle, a, b, and k are the three linear parameters, and d is the single nonlinear parameter (Muinonen et al., 2002). Nevertheless, it should be noted that in this paper the light curves we adopted are relative, which means only the morphology of the curves could be valuable for the inverse process. Additionally, for most main belt asteroids the phase angle α during one observation would not vary too much, i.e. the $f(\alpha)$ in Eq. (4) will change the total amplitude of the whole light curve as an identical factor. Therefore, $f(\alpha)$ can be ignored in the inverse process for light curves with relative brightness.

2.2.2. Integrated brightness

With the scattering law in Eq. (4), the observed brightness of the asteroid under some specific observation condition, such as the observed time(JD_t), and unit position vectors (E_0, E) of the Sun and the Earth at the asteroid-centric ecliptic coordinate system, can be simulated as the following surface integration:

$$B(JD_t, E_0, E)=\iint_{C^+} S(\mu,\mu_0,\alpha)\, ds, \tag{6}$$

where

$$\mu=\eta\cdot E, \quad \mu_0=\eta\cdot E_0,$$