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Photometric and polarimetric observations and model simulations of (216) Kleopatra

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We performed photometric and polarimetric observations, on November 8 and 9, 1999, of an M-type main belt asteroid, (216) Kleopatra by using the HBS spectropolarimeter installed at Dodaira observatory, National Astronomical Observatory of Japan (NAOJ). Photometric amplitude of lightcurve in the V band was 0.12 mag, and the averaged degree of polarization was $-1.01\pm0.1\%$. It seems that the polarimetric data might also show a slight change in the degree of polarization ($\sim$0.2%) at the second minimum of the photometric lightcurve, but we could not confirm that the feature was real because of the large errors of data. With the assumption that the surface is uniform, we have carried out lightcurve simulations based on shape models by Ostro *et al.* (2000), Tanga *et al.* (2001) and Roche binary (Cellino *et al.*, 1985). The results of simulations were compared to the configurations of lightcurves which had been obtained at different 4 geometric positions (1980, 1982, 1987 and 1999). The model by Cellino *et al.* (1985) reproduced almost all the data points without the 1987 observations within $\sim$0.05 mag., which is the best result among the 3 models. The model by Tanga *et al.* (2001) well reproduced the lightcurves, but failed in reproducing the 1982 amplitude (difference $\Delta_{\rm diff} \sim 0.2$ mag.). We also confirmed that the model by Ostro *et al.* (2000) could not explain the observed lightcurves.

Key words: (216) Kleopatra, polarimetry, photometry, Roche Binary, lightcurve simulation.

1. Introduction

The M-type main belt asteroid (216) Kleopatra has frequently been observed by ground-based photometric techniques because its drastic amplitude variations attract many observers. The amplitudes 0.09–1.2 mag., whose values depend on the geometric positions of (216) Kleopatra and the Earth, suggest that the shape of (216) Kleopatra must be elongated or binary. Recently, two shape models have been presented by radar (Ostro *et al.*, 2000) and interferometric (Tanga *et al.*, 2001) observations. Both models indicated that (216) Kleopatra had a shape with two components in contact. On the other hand, Hestroffer *et al.* (2002b) suggested that the two bodies could possibly be resolved with an adaptive optics observations in 1999.

We have performed simultaneous observations of (216) Kleopatra by both photometric and polarimetric techniques using the HBS spectro-photo-polarimeter at Dodaira Observatory (Kawabata *et al.*, 1999), Astronomical Observatory of Japan in November 1999, when the adaptive optics observations were done by Hestroffer *et al.* (2002b). It is well known that some asteroids have correlations between variations of photometric magnitude and polarization due to the changes in surface albedos (Dollfus *et al.*, 1989; Nakayama *et al.*, 2000 and others). In this paper, we present the results of observations using the HBS and simulations based on several models that were presented by several authors.

2. Observations and Reductions

2.1 Photometry

CCD images in the V band were taken using a Meade 25 cm Schmidt Cassegrainian telescope mounted on a 36-inch telescope at Dodaira Observatory of the National Astronomical Observatory of Japan (NAOJ). The dates of these observations were November 8 and 9, 1999; however the data collected on November 9 were abandoned because of instrumental trouble. A Pictor CCD camera (1024 × 1024 pixels) was used in 2 × 2 binning mode, relevant to a pixel scale of 0.16 arcsec/pixel. The exposure time was 20 seconds.

The CCD images were reduced and calibrated with a standard method, namely, dark and flatfield corrections were performed, and aperture photometries were carried out. Unfortunately, sky conditions during the observations were not photometric, so we could not determine the absolute flux of (216) Kleopatra. We only show the results of differential photometries.

2.2 Polarimetry

Polarimetric observations were performed simultaneously with the photometric observations on both Nov. 8 and 9 using a low resolution spectropolarimeter, HBS (see Kawabata *et al.*, 1999), installed on the 36-inch reflector at the Dodaira Observatory. The HBS is designed for measuring linear polarization in optical regions, covering 4000 Å $\sim$ 9000 Å with low resolution ($\lambda/\Delta\lambda$=40–200). Two-holes diaphragm mode was used during the observations, resulting

Table 1. Aspect data.

Date	λ	β	r	Δ	Phase angle	Aspect angle	Observations
1999 Nov 08	54.66	−04.34	2.1109	1.1517	9.17	147.8	Our Observations
1980 Oct 01	354.90	+13.90	2.1607	1.1900	8.80	106.9	Kennedy and Tholen (1982)
1982 Mar 23	144.08	−15.84	3.0015	2.1770	12.58	99.7	Carlsson and Lagerkvist (1983)
1987 Feb 03	181.40	−12.90	3.1486	2.4090	13.60	67.5	Weidenschilling *et al.* (1990)

Fig. 1. Model shape images of (216) Kleopatra. The left image is the elongated model by radar observations (Ostro *et al.*, 2000). Data sets are available on web pages by Scott Hudson (http://www.eecs.wsu.edu/~hudson/Research/Asteroids/index.htm). The center image is the model by HST/FGS observations (Tanga *et al.*, 2001). The right image is the Roche binary shape. All the images are pole-on views.

in a typical spectral resolution ∼150 Å.

The CCD camera used was the Site SI 502A (512 × 512 pixels). One cycle of observing procedures consisted of four successive integrations, rotating a half-wave plate at four position angles, 0°, 22.5°, 45° and 67.5°. Exposure time was set at 200 seconds.

Both the instrumental polarization and depolarization were calibrated using unpolarized standard stars with and without a Glan-Taylor prism. The zero point of the position angle was determined using strongly polarized standard stars. Data calibration and reduction were carried out by an HBSRED package developed by Kawabata *et al.* (1999). The HBSRED works mainly on IRAF. Full description of the instrument and reduction system can be found in Kawabata *et al.* (1999). The S/N of data in shorter (< 5000Å) and longer (> 6000Å) wavelengths were so low, due to the weather, that we abandoned deducing the wavelength dependence of the degree of the polarization. We took average values and 1σ deviations as error bars of the pixels, around the Solar flux maximum ranging from 5000 Å to 6000 Å where processing the data was tolerated.

3. Lightcurve Simulations

We have simulated lightcurves with several model shapes at different geometric positions (1980, 1982, 1987 and our 1999; see Table 1), considering areas illuminated by the Sun and visible from the Earth.

We adopted a pole direction of $\lambda = 72°$, $\beta = 23°$, which had been confirmed by Hestroffer *et al.* (2002b) with the adaptive optics technique. Model shapes and scattering functions are mentioned in the following sections.

3.1 Model shapes

Elongated model Several shape models of (216) Kleopatra have been presented to explain data which were obtained by several techniques (Fig. 1). The models are classified into two types: i.e. non-binary, elongated models and binary models.

Ostro *et al.* (2000) have presented the 3 dimensional shape of (216) Kleopatra, called a "dogbone" or "dumbbell", by a radar delay-Doppler imaging and inversion technique. Their high-resolution model showed (216) Kleopatra had an elongated shape.

Another shape model has also been introduced by Tanga *et al.* (2001) with an HST/FGS interferometer. Their result was almost the same as that of Ostro *et al.* (2000); that is, two almost equal-sized lobes were in contact, except that the overall shape was more elongated than the radar result.

The two observations by the radar and interferometric techniques indicated that (216) Kleopatra had a shape with two components in contact, but Hestroffer *et al.* (2002b) suggested that the two bodies could be separated by analyzing data from an adaptive optics system, ADONIS, installed on the 3.6 m ESO telescope, using the MISTRAL deconvolution technique.

Binary model—Roche Binary Equal-sized binary asteroids in the size range of 100 km could be formed by catastrophic collisions (Farinella *et al.*, 1982). Following the catastrophic events, fragments could gravitationally gather and construct rubble pile structures, making up stable shapes. In collisions, the total angular momentum played an important role in the evolution of the figure of a body. An excess of angular momentum could divide a body and result in a Roche binary system with equilibrium figures (Weidenschilling, 1980; Cellino *et al.*, 1985). (216) Kleopatra and also (90) Antiope (Michałowski *et al.*, 2002) are expected to have a quasi-Roche binary shape. Therefore, it is useful to study, in the case of (216) Kleopatra, whether hydrostatic approximation can be applied to the rubble pile structures. Equations of Roche ellipsoids have been given by Chandrasekhar (1969) and Leone *et al.* (1984).

Cellino *et al.* (1985) have studied (216) Kleopatra and estimated the Roche solution by comparing past observations.

Since their estimation was done without the light-scattering effects of asteroidal surfaces, we have simulated lightcurves with a proper scattering model. We also looked for other solutions which reproduce past observations.

3.2 Scattering function

We have tried using a simpler scattering function, that is the Lommel-Seeliger and Lambert functions are combined with a weight factor k. Reflectance r is written as follows;

$$r \sim (1-k)\cdot\frac{\mu_0}{\mu_0+\mu} + k\cdot\mu_0\,, \tag{1}$$

where μ_0 and μ are the cosines of the angles between surface normal and incidence and emission respectively. This idea was first introduced by Kaasalainen *et al.* (2001). They attributed the component of single scattering of asteroidal surfaces to the Lommel-Seeliger and that of multiple to the Lambert part. The original expression by Kaasalainen *et al.* (2001) is;

$$r \sim \frac{\mu_0}{\mu_0+\mu} + c\cdot\mu_0 \quad \left(c = \frac{k}{1-k}\right). \tag{2}$$

Equations (1) and (2) give the same results as to the simulations of lightcurves. In this paper we use Eq. (1). These formulae are empirical, but well reproduce the shapes of asteroids through lightcurve inversions (e.g. (6489) Golevka and (433) Eros in Kaasalainen *et al.*, 2001). They also reported that their scattering model had fair agreement with Hapke or Lumme-Bowell's results.

4. Results and Discussions

4.1 Photometry

A photometric lightcurve in November, 1999 is shown in Fig. 2. The figure was made with the rotational period ($P = 5^h.3853 \pm 0^h.0003$) which was obtained by Pilcher and Tholen (1982). The lightcurve appeared symmetric with equally spaced minima, although we could cover only one maximum. The amplitude was about 0.12 mag., which is one of the smallest values among past observations.

4.2 Polarimetry

It is well known that asteroids have negative values of polarization P_r when the phase angle is $\alpha < 20°$. The P_r value has a minimum around $\alpha = 10°$ ($P_{\rm min}$). An inversion angle from negative to positive is denoted as V_0, and a slope near V_0 is h. Two characteristic polarization parameters, $P_{\rm min}$ and h, have been used to deduce the albedo of an asteroidal surface by comparison with the laboratory experiments (Dollfus *et al.*, 1979; Dollfus *et al.*, 1989). The degrees of polarization can be converted into a physical (geometric) albedo by the relation between albedo and $P_{\rm min}$ as follows;

$$\log A_p = -0.98\,\log h - 1.73 \tag{3}$$

$$\log A_p = -1.22\,\log P_{\rm min} - 0.92\,. \tag{4}$$

These relations were first suggested by Zellner and Gradie (1976), and revised by Lupishko and Mohamed (1996) with IRAS data.

We display the polarimetric results of (216) Kleopatra in one rotation phase (Fig. 2). As the observations were done at almost $P_{\rm min}$ ($\alpha = 9.2°$), we regarded the averaged value -1.01 as $P_{\rm min}$ and obtained the albedo $A_p = 0.12$. This is the same value derived from IRAS ($A_p = 0.12$).

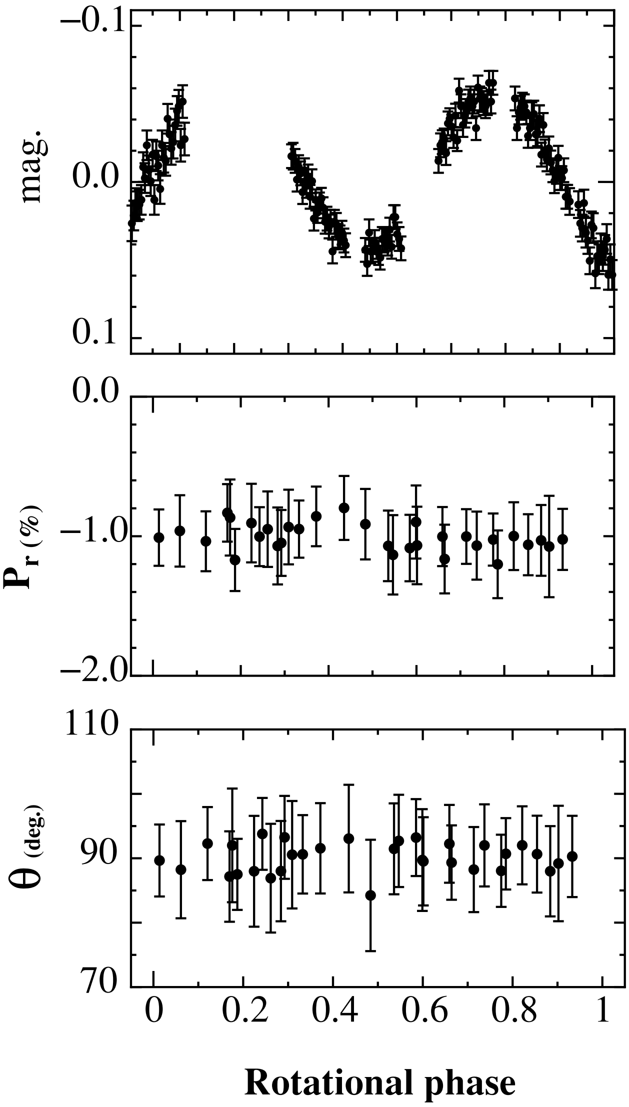

Fig. 2. Results of photometric and polarimetric observations in 1999. Top: Time variation of photometric magnitude of (216) Kleopatra in one rotation. Middle: The degree of polarization (P_r). Bottom: The angle between the surface normal of the scattering plane and the direction of linear polarization (θ).

On the other hand, small variations in polarization degree with a rotation have been reported in some studies; e.g. (4) Vesta (Dollfus *et al.*, 1989) and (9) Metis (Nakayama *et al.*, 2000). The variations are usually interpreted as the inhomogeneities of the surface.

Our data showed that one slight extremum of P_r and θ (defined as the angle between the surface normal of the scattering plane and the direction of linear polarization) might be seen around phase ~ 0.5 as expected at the second minimum.

However, we could not confirm their existence because of large error bars. Velichko (2003) reported variations in polarization degree of (216) Kleopatra from observations in February, 2000. Hestroffer *et al.* (2002a) also have pointed out that there were some possibilities of important albedo

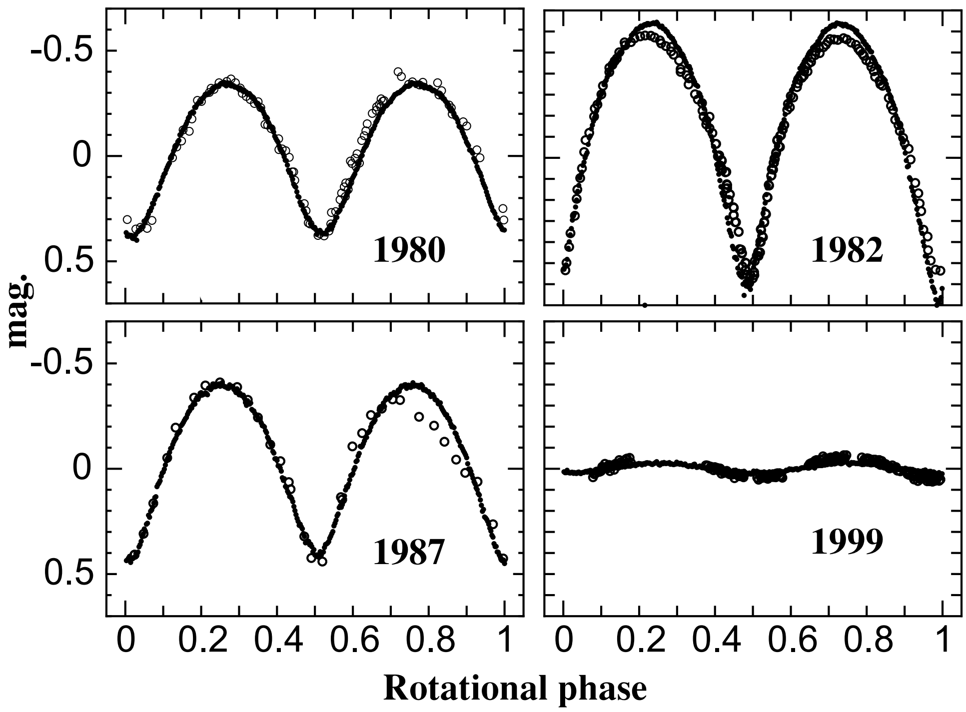

Fig. 3. Comparison with observations and simulations (Tanga *et al.*, 2001 model). Median of amplitudes are denoted as 0 mag. Weight factor is $k = 0.0$.

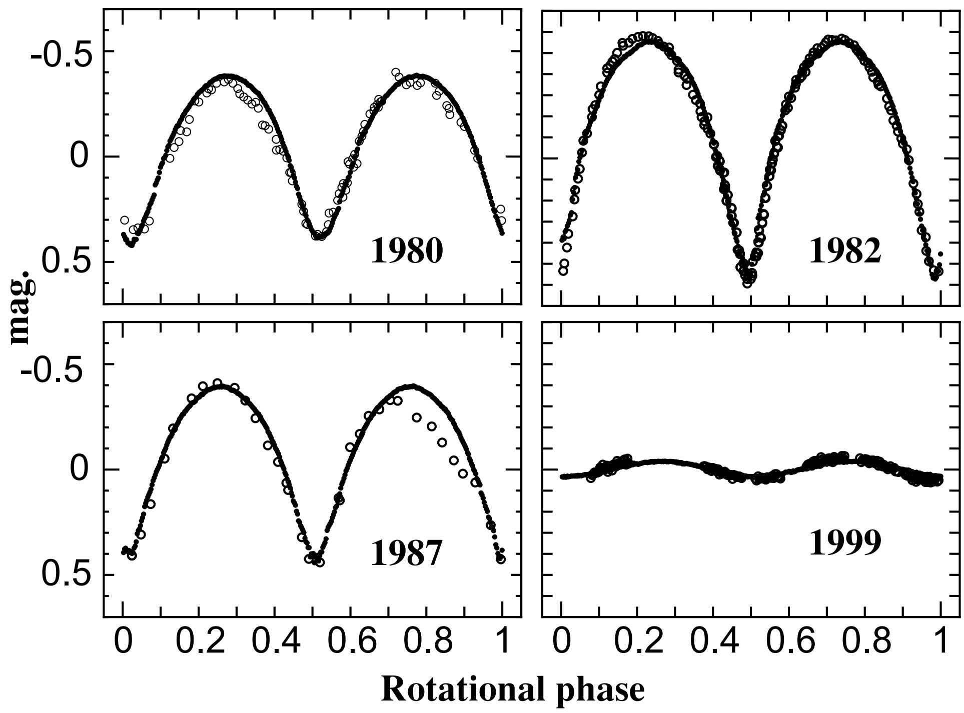

Fig. 4. Comparison with observations and simulations (A Roche binary model by Cellino *et al.*, 1985). Median of amplitudes are denoted as 0 mag. Weight factor is $k = 0.3$.

variations on (216) Kleopatra's surface if a moderate limb-darkening parameter was assumed. To verify the existence of albedo inhomogeneity, we have tested simpler cases; one circle patch is located on latitude $0°, \pm 45°, -90°$, longitude $0°, 45°, 90°, \ldots, 315°$ with different sizes and albedo values. The result was that we could not find any solutions which reproduced variations in both lightcurves and polarization. At least the expected variations in polarization ($\Delta P_r \sim 0.01\%$) were ten times smaller than those of observations ($\Delta P_r \sim 0.1\%$). Aspect angle, the angle between the spin vector and the line of sight, was 147° in the 1999 observations, which means that we saw the Southern hemi-

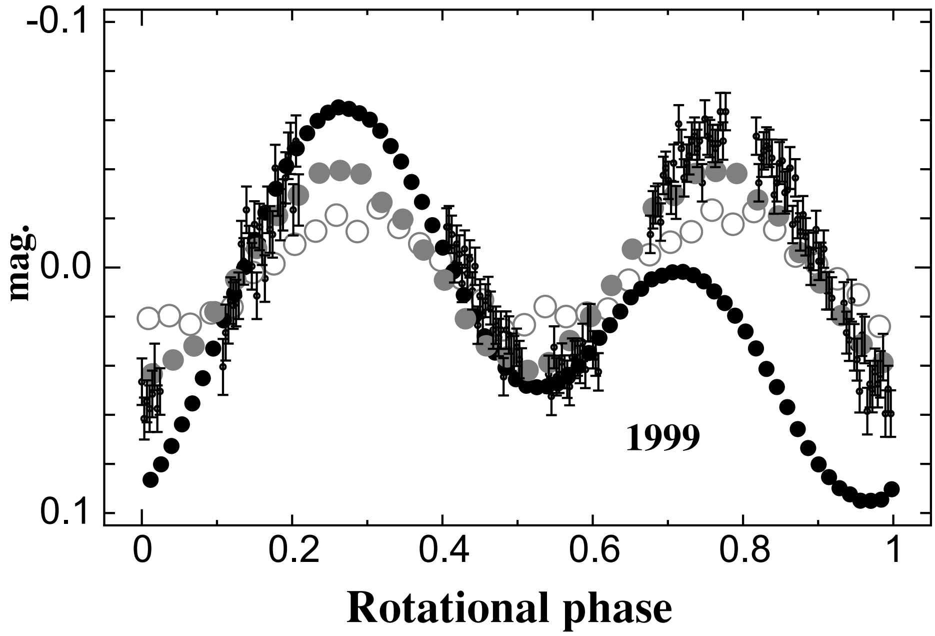

Fig. 5. Lightcurve simulations of each model for 1999 observations. Open circles show the lightcurve by Tanga *et al.* (2001), gray, by Roche binary model by Cellino *et al.* (1985) and filled, by Ostro *et al.* (2000). Although the amplitudes of the former two models are slightly lower than observations, they well reproduce the configuration of the lightcurve. The model by Ostro *et al.* (2000) has two different maxima and minima, which differs from the observations.

sphere of (216) Kleopatra. Hence we presume that there is no significant albedo inhomogeneity in the Southern area of (216) Kleopatra. We cannot discuss possible albedo inhomogeneity in the Northern hemisphere. Further simultaneous photometric and polarimetric observations at other geometric views such as equatorial and Northern ones would be needed to check the existence of albedo variegation. In this paper, we treat the surface of (216) Kleopatra as uniform in both the Northern and Southern hemispheres in the lightcurve simulations.

4.3 Lightcurve simulations

4.3.1 Elongated shape models The shape by Tanga *et al.* (2001) reproduced fairly well the 1980, 1982, 1987 and 1999 observations with the scattering parameter $k = 0.0$ (Fig. 3). But the amplitude of 1982 was slightly larger than observed amplitudes ($\Delta_{\rm diff} \sim 0.2$)mag., and the model could not simulate the differences from the second maximum to the first minimum in the 1987 observations. The observations by Tanga *et al.* (2001), as they mention in their paper, were done at nearly pole-on view, so that they could not determine the c axis precisely. If the c axis were improved, simulated lightcurves would be improved with a different weight factor.

As for the model by Ostro *et al.* (2000), we could not find any weight factors that meet the past observations. We illustrate the lightcurve of the 1999 observations with the model by Ostro *et al.* (2000) in Fig. 5. The weight factor $k = 1.0$ (Lambert law) gave the best result; however, the overall configuration was different between the observations and calculations. The observations had almost the same minima, but the calculated lightcurve had two different minima. For the other observations, we also obtained quite different results. We conclude that the real shape must be slightly different from the model by Ostro *et al.* (2000). Hestroffer *et al.* (2002a) also have tested their model by simulating lightcurves and indicated that the radar model did not match past photometric observations. They found that the real shape of (216) Kleopatra could be more elongated than the radar solution to fit the past data with proper scattering parameters. These inconsistencies between the radar model simulations and lightcurve observations would be due to the fact that S/N of (216) Kleopatra were lower than those of near-Earth asteroids, which have been presented by the same radar instruments.

4.3.2 Roche binary model The Roche binary shape by Cellino *et al.* (1985) has well reproduced the observations of 1980, 1982, 1987 and 1999 with a weight factor $k \sim 0.3$ (Fig. 4). Almost all the points of observations, except some of the 1987, were fitted within ± 0.05 mag. Among the three models, the model by Cellino *et al.* (1985) gives the best result; however, the 1987 calculations cannot simulate the differences from the second maximum to the first minimum. The situation is the same as their found in Tanga *et al.* (2001). We have also tested Roche binary solutions other than the model by Cellino *et al.* (1985). We obtained 600 randomly sampled sets of the Roche binary shapes with changing independent parameters, the primary axes b and c ($b = 0.0 \sim 1.0$, $c = 0.0 \sim 1.0$, $b > c$, see Fig. 6). For scattering parameters k, we set $k = 0.0, 0.1, 0.2, \ldots, 1.0$. A total of 6600 sets of parameters were tested and compared to the 4 observations. We selected the models that reproduced the amplitudes of 4 observations within $\Delta_{\rm diff} = \pm 0.10$ mag. for 1980, 1982, 1987 and $\Delta_{\rm diff} = \pm 0.05$ mag. for 1999 observations, and finally obtained 123 sets of parameters. The range and average values of parameters are listed in Table 2. The solutions of separation ratio d were concentrated in a small range, 0.957±0.069. This tendency indicates that two com-

Table 2. Shape parameters for each model. Nomenclature is shown in Fig. 6. Ostro *et al.* (2000) estimated the dimensions of (216) Kleopatra as 217 km × 94 km × 81 km. We take these values as L, $2b$ and $2c$, respectively. The k values of Roche binaries are modes.

Model	Ostro *et al.*	Tanga *et al.*	Cellino *et al.*	Roche binaries average
a	—	1.000	1.00	1.000
b	—	0.493	0.80	0.738±0.114
c	—	0.232	0.72	0.668±0.102
a'	—	0.942	1.11	1.011±0.036
b'	—	0.464	0.59	0.664±0.093
c'	—	0.333	0.54	0.605±0.078
L (km)	217	273	221	226 ± 13
$2b$ (km)	94	75	82	82 ± 11
$2c$ (km)	81	50.6	74	74 ± 11
L (ratio L = 1)	1.000	1.000	1.000	1.000
$2b$ (ratio L = 1)	0.433	0.274	0.371	0.359±0.051
$2c$ (ratio L = 1)	0.373	0.185	0.334	0.325±0.057
d	contacted	contacted	0.964	0.957±0.069
ρ (g/cm^3)	≥3.5	—	3.9	4.0±0.10
k	1.0	0.0	0.3 ± 0.1	0.5–0.6 (mode)

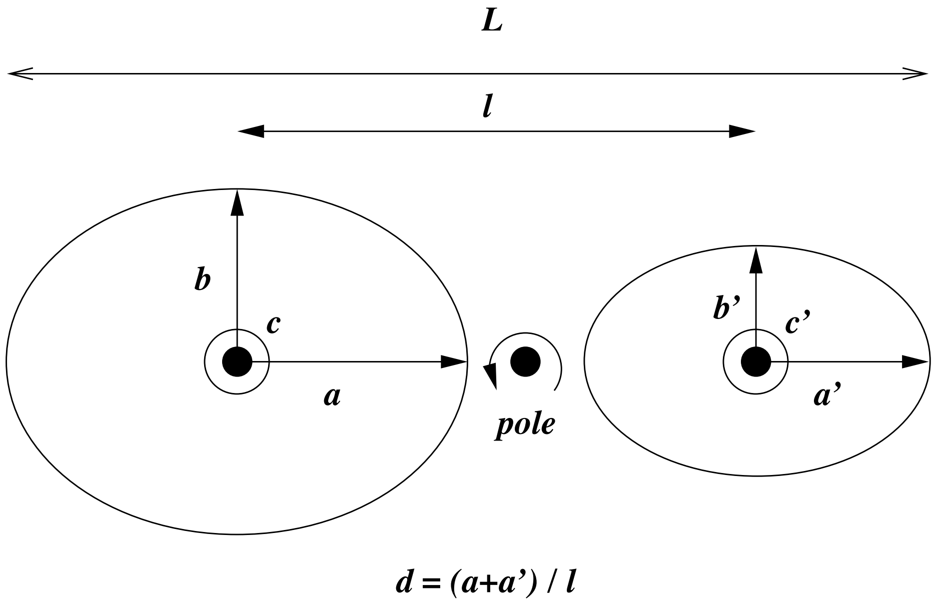

Fig. 6. Physical parameters of the shape model for (216) Kleopatra.

ponents are so close as to be in contact; that is, the binary system is almost at the Roche limit. Hestroffer *et al.* (2002b) have reported that the flux ratio of the primary to the secondary was $F = 0.81 \pm 0.03$. The flux ratio of the model by Cellino *et al.* (1985) at the time of Hestroffer *et al.* (2002b) observations varied between 0.79–0.84 during one rotation, which is consistent with the observations.

For a reference, we have converted the Roche binary average in Table 2 into real sizes using the albedo value $A_p = 0.12$ obtained through our HBS polarimetric observations. Since we could not determine the absolute magnitude in the 1999 observations, we used the past data for conversion. The result is that the average values of the shape parameters are similar to those of the model by Cellino *et al.* (1985).

4.3.3 Weight factor *k* We have a weight factor of $k = 0.0$ for the model by Tanga *et al.* (2001), $k = 0.3$ for Cellino *et al.* (1985) and $k = 0.5$, 0.6 for the Roche binaries mode values. Kaasalainen *et al.* (2001) have obtained $c = 0.1$ ($k \sim 0.09$) for S-type asteroid (433) Eros. The albedo value of (216) Kleopatra obtained through our polarimetric observations is $A_p = 0.12$, which is higher than those of the Moon, Mercury and C-type asteroids, and lower than S-type asteroids. Since a dark surface is dominated by single scattering (the Lommel-Seeliger law like), the weight factor

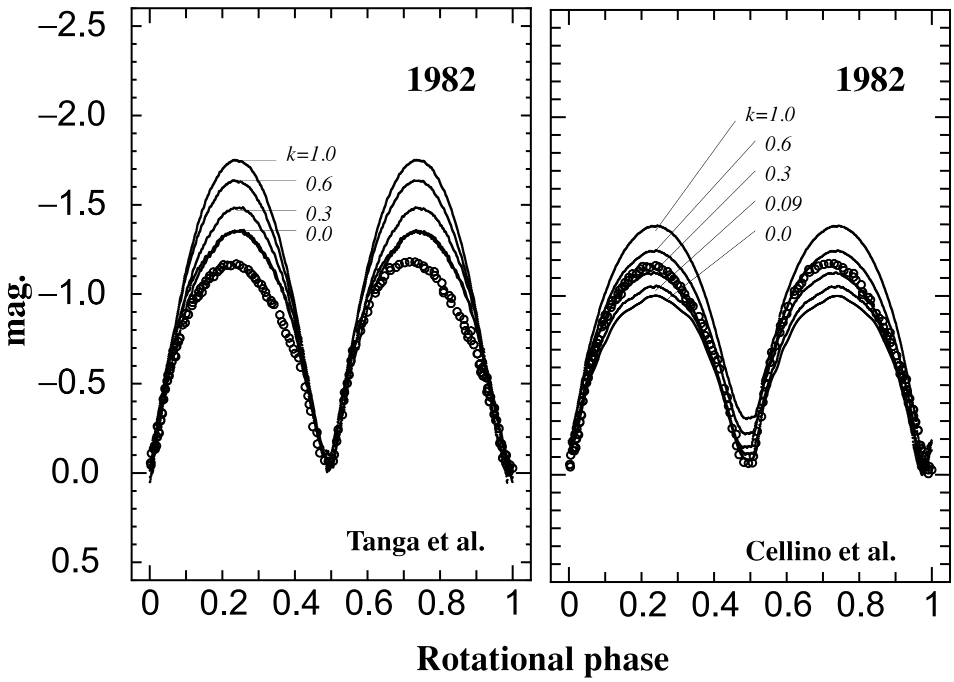

Fig. 7. Lightcurve variations changing the weight factor of k. The first minima are denoted as 0 mag. Open circles are the observations in 1982 and thick lines are the results of calculations. The best fitted values of the weight factors are $k = 0.0$ for the model by Tanga *et al.* (2001) and $k = 0.3$ for Cellino *et al.* (1985).

k of (216) Kleopatra should be smaller than that of (433) Eros. Therefore, the weight factor $k = 0.0$ of Tanga *et al.* (2001) seems valid, and $k = 0.3$ and 0.5, 0.6 of the Roche binaries invalid. In Fig. 7, we illustrate amplitude variations of the 1982 simulations by changing the weight factor k. We can see a tendency for the large k values to have large amplitudes. For the model by Cellino *et al.* (1985), we could not find a proper k value smaller than 0.1, and furthermore, with such small k values, no Roche binary models could explain all the observations.

We have simulated the lightcurve of a suspected binary EKBO 2001 QG_{298} (Sheppard and Jewitt, 2004; Takahashi and Ip, 2004). EKBOs would have dark surfaces and be expected to have smaller k values; however, we obtained larger values (about $k = 0.6 \sim 0.8$). The proper k values of M-type asteroids are quantitatively unknown, and accordingly, we cannot exclude the large k values of (216) Kleopatra. We need further k values for several taxonomic classes of asteroids in order to discuss proper values.

4.3.4 Two components and surface of (216) Kleopatra We conclude that the lightcurve simulations favor the models by Tanga *et al.* (2001) and Cellino *et al.* (1985) over that by Ostro *et al.* (2000). Among the former two models, the binary model by Cellino *et al.* (1985) gives the best results if the large scattering parameter $k = 0.3$ is proper. If so, the two components are less elongated than those of Tanga *et al.* (2001) (Table 2). Of course we cannot determine whether (216) Kleopatra is elongated or binary from ground-based photometric observations. If the two components were in contact, lightcurves would be well reproduced for all the past observations.

All models have failed in reproducing the differences from the second maximum to the first minimum in 1987 observations under the uniform albedo assumption. The 1987 observations were carried out at the Northern view (aspect angle = 67.5°). Our observations investigated the Southern area of (216) Kleopatra (aspect angle = 147.8°), and we could not see the entire Northern area. These differences between observations and simulations can be explained by both albedo inhomogeneity of the surface or deviation from the real surface. Simultaneous photo-polarimetric observations are a powerful method for investigating albedo inhomogeneity of asteroidal surfaces (Bowell *et al.* 1989). If the Northern surfaces of (216) Kleopatra have albedo patches, we can detect variations in the degree of polarization during a rotation by applying this simultaneous photo-polarimetric technique.

4.3.5 Density The expected densities of M-type asteroid (216) Kleopatra, if we assume the Roche binary, are distributed from 3.9–4.1 g/cm^3. This value is consistent with the value 3.9 g/cm^3 (Cellino *et al.*, 1985) and ≥ 3.5 g/cm^3 obtained by radar observations (Ostro *et al.*, 2000). So far, the densities of two M-type asteroids, (16) Psyche (Viateau, 2000) and (22) Kalliope (Margot and Brown, 2003) have measured 2.0±0.6 g/cm^3 and 2.37±0.4 g/cm^3, respectively. The densities of these M-type asteroids are lower than that of (216) Kleopatra. According to Rivkin *et al.* (2000), (22) Kalliope has a water absorption of 3 μm, and for that reason (22) Kalliope was classified as a W-type. On the other hand, (16) Psyche showed no water absorption feature, and it is regarded as a real M-type asteroid. If we adopt the density of a FeNi meteorite grain (7.5 g/cm^3) and assume that the bulk porosity is equal to macro porosity, the macro porosity of (16) Psyche attains 75%, the most porous object in the Solar

System, while (216) Kleopatra attains 43–48%, which might be a typical value for rubble pile asteroids (Britt *et al.*, 2003).

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