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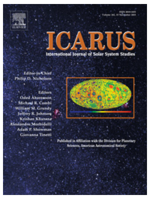

A revised shape model of asteroid (216) Kleopatra

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ABSTRACT

We used three different sets of Arecibo delay-Doppler radar images and five well-covered occultations to generate a revised three-dimensional shape model of asteroid (216) Kleopatra with a spatial resolution of ~10 km. We find Kleopatra to be a bi-lobate contact binary of overall dimensions $276 \times 94 \times 78$ km ± 15% and equivalent diameter $D_{eq} = 122 \pm 30$ km; our uncertainties are upper and lower bounds. Separated binary models are ruled out by multi-chord occultations. Our model is 27% longer than the "dog-bone" model originally published by Ostro et al. (2000) but is similar to their model in the minor and intermediate axes extents. Our model's dimensions are also consistent with more recent ones based on lightcurves, adaptive-optics, and interferometric imaging. We confirm a rotational period of $P = 5.385280\,h \pm 0.000001$ h and a rotation pole at ecliptic longitude and latitude $(\lambda, \beta) = (74°, +20°) \pm 5°$. Over its southern hemisphere (the one most frequently observed on Earth), Kleopatra's radar albedo is 0.43 ± 0.10, consistent with a high near-surface bulk density and, by inference, the high metal content expected for M-class asteroids. However, the radar albedo for equatorial observations is considerably lower and more typical of a dominantly silicate composition. This observation could readily be explained by a relatively thin (1–2 m) silicate mantle over equatorial latitudes. Kleopatra's surface is relatively smooth with a mean slope of 12° at the ~10 km baseline scale. Analysis of its geopotential surface suggests loose material will preferentially migrate to the neck, and this is supported by our radar observations.

1. Introduction

Asteroid (216) Kleopatra is the second largest Tholen M-class asteroid in the solar system. Lightcurve and early radar observations (Mitchell et al., 1995 and references therein) suggested it to be a highly elongated object and possibly a close or contact binary. Adaptive-optics (AO) observations at the European Southern Observatory in 1999 suggested a close binary object (Marchis et al., 1999; Hestroffer et al., 2002a). Subsequent radar imaging observations by Ostro et al. (2000) indicated it was a contact binary and their shape model presented the community with the now iconic "dog-bone" shape. Since then, Kleopatra has been the subject of a number of investigations.

Additional Arecibo radar imaging observations of Kleopatra were acquired in 2008 and 2013. It was observed to occult stars on seven different occasions between 1980 and 2016; five were well covered with multiple chords. It has been resolved with adaptive-optics at the Canada–France–Hawaii-Telescope (CFHT) (Merline et al., 2000) and Keck (Descamps et al., 2011, 2015; Hanus et al., 2017), and observed using interferometry with the Hubble Space Telescope Fine Guidance Sensor (HST-FGS) (Tanga et al., 2001). These observations suggest that Kleopatra may be more elongated than the Ostro et al. (2000) shape model. There is still some uncertainty over whether Kleopatra is a close or contact binary.

In this paper, we use Arecibo S-band radar (2380 MHz, 12.6 cm) radar observations from 1999, 2008, and 2013, and five multi-chord stellar occultations to refine the Kleopatra shape model. In Section 2, we briefly discuss what was previously known of Kleopatra. In Section 3, we describe our methods of radar analy-

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sis and the inversion process. In Section 4, we present our results, and in Section 5 we list opportunities for future radar observations and occultations.

2. What is known of Kleopatra

2.1. Size and shape

The size most often quoted for Kleopatra is 217 × 94 × 81 km ± 25% (Ostro et al., 2000) which gives an equivalent diameter (diameter of sphere with the same volume) of $D_{eq} = 109$ km. The shape of this model is often described as a “dog bone” and consists of a long cylinder capped by two larger knobs. However, there is considerable uncertainty in both the size and shape.

Thermal infrared observations, when combined with optical photometry, allow for an estimate of optical albedo and from this, effective diameter (diameter of sphere with the same apparent cross-sectional area at some aspect). Estimates of optical albedo and diameter are $p_v = 0.11$ and $D_{eff} = 135 \pm 2$ km from IRAS (Tedesco et al., 2002), $p_v = 0.11$ and $D_{eff} = 138 \pm 19$ km from WISE (Mainzer et al., 2011), and $p_v = 0.149$ and $D_{eff} = 122 \pm 2$ km from the AKARI mission (Usai et al., 2011). Spitzer data in 2008 (Descamps et al., 2011) are consistent with the IRAS and WISE effective diameters. In summary, most of these data sets suggest the Ostro et al. radar-estimated size is perhaps 20% too small, although still within their 25% quoted uncertainty.

There have also been suggested refinements to the radar-derived shape model. Using AO observations from Keck, Descamps et al. (2011) describe an object 271 × 65 km, with “two equal-sized misshapen lobes, each 80 km across… joined by a thin and long bridge of matter about 50 to 65 km across and 90 km long.” Similarly, interferometric observations with the HST-FGS (Tanga et al., 2001) were best modeled by two ellipsoids in contact with overall dimensions of 273 × 75 × 51 km. A summary analysis of these datasets and models by Hestroffer et al. (2002b) concluded that Kleopatra was more elongate than the radar derived shape model and specifically that the principal axis should be some 43 km longer than the Ostro et al. (2000) value (or 260 km).

Kaasalainen and Viikinkoski (2012) derive a Kleopatra shape model using 46 lightcurves, adaptive optics profiles from Descamps et al. (2011), and the HST/FGS interferometric observations of Tanga et al. (2001). Their model has similarities to those previously discussed, but they note that it was difficult to find a model that fit all the data well. They do not provide a size estimate.

Descamps (2015) used an adaptive optics image, an occultation, several lightcurves, and principles of equilibrium fluid dynamics to argue that Kleopatra’s shape is best described as a “dumb-bell,” essentially two ellipsoidal lobes connected by a thin neck with dimensions 250 × 70 km when observed in an equatorial profile.

Hanus et al. (2017) provide the most recent size and shape estimate for Kleopatra from an analysis of 55 lightcurves, 14 AO observations and 3 occultations. Their model has dimensions of 269 × 101 × 79 km giving an equivalent diameter of 121 ± 5 km, and they find a pole solution of ∼(74°, 20°). Their model is essentially identical in dimensions to the solution we present here and can be found on the web-based Database of Asteroid Models from Inversion Techniques (DAMIT, astro.troja.mff.cuni.cz, Durech et al., 2010). We show their model alongside ours later in the paper.

2.2. Composition

The red-slope and generally featureless visible/near-infrared (VNIR) spectra of the M-class asteroids are similar to that of meteoritic iron-nickel (Fe-Ni) observed in the laboratory. One interpretation of their origin is that they are the remnant cores of ancient planetesimals exposed by cataclysmic collisions (Chapman and Salisbury, 1973; Bell et al., 1989). Additional laboratory work suggests that enstatite chondrites are also a possible analog (Gaffey, 1976; Gaffey and McCord, 1979). The recent Rosetta flyby of the M-class asteroid 21 Lutetia (Vernazza et al., 2011) supports this interpretation for at least some of the M-class.

Shepard et al. (2015) used the Arecibo radar to investigate 29 M-class asteroids because radar is a more discriminating tool than spectroscopy for the presence of metal. They found that 60% of observed M-class asteroids have radar albedos consistent with the moderate metal content of enstatite chondrite analogs, while 40% have the higher radar albedos consistent with dominantly metallic objects. The radar studies of Kleopatra to date (Mitchell et al., 1995; Magri et al., 2007a; Ostro et al., 2000) suggest it belongs to this latter group.

2.3. Mass and density

The discovery of two satellites of Kleopatra (Marchis et al., 2008, 2010; Descamps et al., 2011), subsequently named Alexhelios and Cleoselena, provide a mass estimate of $4.64 \pm 0.02 \times 10^{18}$ kg and bulk density estimates ranging from 3.6 ± 0.4 g cm^{-3}, assuming $D_{eq} = 135$ km, to 5.4 ± 0.4 g cm^{-3}, assuming $D_{eq} = 109$ km. These bulk densities are consistent with a heavily fractured or rubble pile object composed chiefly of metal (Britt and Consolmagno, 2001; Carry, 2012).

2.4. Rotation pole and period

A number of pole estimates have been published from lightcurve analysis and AO observations; ecliptic longitude solutions cluster in the range $\lambda = 69°–76°$ and latitudes from $\beta = 10°–25°$. Mirror poles have been eliminated with the analysis of AO observations (Hestroffer et al., 2002b). The most recent pole solution by Hanus et al. (2017) is $(74°, +20°) \pm 5°$, while Kaasalainen and Viikinkoski (2012) report $(73°, +21°) \pm 8°$. The Ostro et al. (2000) radar-derived shape model uses a spin pole of (λ, β) $(72°, +27°)$.

Rotation periods derived from lightcurve analysis range from P = 5.38326 h to 5.38529 h, with the most recent (Kaasalainen and Viikinkoski, 2012; Hanus et al., 2017) estimate at 5.385280 h. We initially adopted this period, but also ran numerous models allowing it to float to determine if other periods were also reasonable. Our tests confirmed that P = 5.385280 h is the best period for our data with an uncertainty only in the last significant digit.

3. Observations

3.1. Radar background

We use the Arecibo S-band in two modes: continuous wave (or CW) and delay-Doppler. Continuous wave observations produce echo power spectra that are used to calibrate the radar reflectance properties of the target and can be used to place constraints on an object’s size, rotation period, and spin pole. Delay-Doppler observations are used to generate a two-dimensional radar “image” of the target that can be used to place strong constraints on an object’s shape.

For continuous wave radar observations, each observing cycle or “run” consists of transmission of a circularly polarized 2380 MHz (12.6 cm) signal for the round-trip light travel time to the target, followed by the reception of echoes for a similar duration in the opposite (OC) and same (SC) senses of circular polarization as transmitted. We integrate the received echo power spectra to measure the radar cross-sections of Kleopatra (in km^2) for each sense of polarization, σ_{OC} and σ_{SC}. The radar cross-section