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Radar observations and a physical model of Asteroid 1580 Betulia

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Abstract

We report Arecibo (2380-MHz, 13-cm) observations of Asteroid 1580 Betulia in May–June 2002. We combine these continuous-wave Doppler spectra and delay-Doppler images with optical lightcurves from the 1976 and 1989 apparitions in order to estimate Betulia's shape and spin vector. We confirm the spin vector solution of Kaasalainen et al. [Kaasalainen, M., and 21 colleagues, 2004. Icarus 167, 178–196], with sidereal period $P = 6.13836$ h and ecliptic pole direction $(\lambda, \beta) = (136°, +22°)$, and obtain a model that resembles the Kaasalainen et al. convex-definite shape reconstruction but is dominated by a prominent concavity in the southern hemisphere. We find that Betulia has a maximum breadth of 6.59 ± 0.66 km and an effective diameter of 5.39 ± 0.54 km. These dimensions are in accord with reanalyzed polarimetric and radar data from the 1970s. Our effective diameter is 15% larger than the best radiometric estimate of Harris et al. [Harris, A.W., Mueller, M., Delbó, M., Bus, S.J., 2005. Icarus 179, 95–108], but this difference is much smaller than the size differences between past models. Considering orbits of test particles around Betulia, we find that this asteroid's unusual shape results in six equilibrium points close to its equatorial plane rather than the usual four points; two of these six points represent stable synchronous orbits while four are unstable. Betulia's close planetary encounters can be predicted for over four thousand years into the future.

Keywords: Asteroids; Radar observations

1. Introduction

Asteroid 1580 Betulia was discovered on May 22, 1950, by E.L. Johnson at the Union Observatory in Johannesburg, South Africa. Betulia is an Earth-crossing Amor asteroid (Shoemaker et al., 1979) and was only the fourteenth near-Earth asteroid (NEA) to be found. Its unusually high orbital inclination of 52°, along with its status as a C-class (carbonaceous) object, led to speculation that it is an extinct comet nucleus (e.g., Drummond and Wisniewski, 1990). But its most unusual feature is its triple-peaked lightcurve. Tedesco et al. (1978) used data from the favorable 1976 opposition to show that at large solar phase angles Betulia exhibits three pairs of brightness extrema per rotation, whereas almost all other asteroids have double-peaked lightcurves and a few (such as 4 Vesta) have single-peaked lightcurves produced by albedo variegation.

Although Tedesco et al. considered the possibility of albedo spots, they were able to explain their data qualitatively by means of shape alone. Their model resembles what one would get by starting with a prolate spheroid (with elongation 1.21) that spins about its shortest (z) axis, and then removing an entire quadrant in the xy plane.

Kaasalainen et al. (2004) took a different approach to estimating Betulia's shape: they inverted lightcurve data from 1976 and 1989 to estimate the spin vector while simultaneously generating a convex-definite shape model, similar to what one would obtain by "gift-wrapping" the actual asteroid. Their

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spin vector has sidereal period $P = 6.13836$ h and pole direction $(\lambda, \beta) = (136°, +22°)$ with an error radius of 5–10°. Their shape model has axis ratios $a/b = 1.1$ and $b/c = 1.4$, and is "very peculiar with a large planar area on one side." Kaasalainen and Torppa (2001) point out that the locations of concavities in an asteroid are revealed as large planar sections in the best-fit convex-definite model; hence Kaasalainen et al. (2004) note that the flat side of their Betulia model may represent a "considerable" concavity.

A separate issue is the absolute size of Betulia. Tedesco et al. used polarimetric data to derive the visual albedo and hence the mean diameter, obtaining values of 6.3 and 7 km for two possible laws relating polarimetric slope to albedo. Pettengill et al. (1979) used continuous-wave (CW) radar spectra from the 1976 apparition to obtain a zero-crossing Doppler bandwidth of 26.5 ± 1.5 Hz, which could be combined with the known rotation period to show that a lower bound on Betulia's maximum breadth is 5.8 ± 0.4 km. Lebofsky et al. (1978) combined visual photometry, 10.6-μm radiometry, and the standard thermal model to derive a mean diameter of 4.20 ± 0.20 km and geometric visual albedo $p_v = 0.108 \pm 0.012$. Since this diameter conflicts with the polarimetric and radar results, Lebofsky et al. also considered a thermal model that assumes high thermal inertia (i.e., bare bedrock or large rocks rather than fine-grained regolith) and hence significant infrared radiation from the night side; this model yielded a diameter of 7.48 ± 0.34 km and an albedo of 0.034 ± 0.004. This diameter estimate is in accord with the polarimetric and radar values.

More recently, this agreement has been called into question by Harris et al. (2005), who observed Betulia at five thermal infrared wavelengths in 2002. Harris et al. analyzed these data using the NEA thermal model (NEATM), which, unlike the two simple models considered by Lebofsky et al. (1978), treats the infrared "beaming parameter" η as an adjustable parameter, effectively adjusting the temperature distribution across the model's surface so as to be consistent with the asteroid's observed color temperature. This procedure resulted in an effective diameter estimate of 3.8 ± 0.6 km, significantly smaller than values obtained in earlier studies, and a visual albedo of 0.11 ± 0.04. Harris et al. explored this discrepancy by carrying out a second analysis, this time combining a detailed thermophysical model with the Kaasalainen et al. (2004) convex-definite shape model. The resulting effective diameter and visual albedo are 4.57 ± 0.46 km and 0.077 ± 0.015, respectively; this diameter is larger than the NEATM-based estimate but still smaller than earlier estimates. Both the Lebofsky et al. and Harris et al. p_v estimates are plausible for C-class asteroids, so we cannot use this criterion to choose between models.

Betulia's most recent favorable opposition was in 2002, when it approached to within 0.238 AU of Earth, and we took this opportunity to observe it once again with radar, this time obtaining both CW spectra and delay-Doppler images. As discussed by Ostro et al. (2002), radar data can be used to constrain the target's orbit, size, shape, and spin vector, its near-surface roughness at decimeter scales (due to surface rocks, buried rocks, and subsurface voids), and its near-surface bulk density, which can tell us about mineralogy (e.g., metal content—see Ostro et al., 1991a) or about near-surface porosity (Magri et al., 2001). Most importantly for Betulia, concavities leave a strong signature in delay-Doppler images. The primary goals of our radar experiment were to reconstruct Betulia's shape—including any possible concavities—and to determine its absolute size.

The next section describes our observations. Section 3 discusses in some detail how we use our modeling software to reconstruct the shape of a radar target. Section 4 presents the resulting shape model, and Section 5 considers the implications of our improved radar astrometry. Section 6 characterizes Betulia's gravitational environment, discussing the possible orbits in its vicinity. Finally Section 7 summarizes our results. Appendix A contains detailed information on the delay-Doppler impulse response function and on delay-Doppler image calibration, Appendix B fully describes the penalty functions used by our modeling software, and Appendix C lists Betulia's gravity coefficients.

2. Observations and data reduction

2.1. Delay-Doppler images

2.1.1. Observing scheme

The delay-Doppler images discussed here were obtained in May–June 2002 (see Table 1) at the Arecibo Observatory. For each observation (or "run") we transmitted a circularly polarized monochromatic signal at about 2380 MHz. In order to compensate for the Doppler shift due to relative motion between the telescope and the target's center of mass (COM), we generated ephemeris predictions of the COM Doppler shift, and continuously adjusted the transmission frequency so that hypothetical echoes from the COM would return at 2380.000005 MHz if our ephemeris were exactly correct. (The extra 5 Hz "transmit offset" serves to make the direction of positive Doppler clear in case of error in the instrumental setup or in the data analysis.) We used the early observations in the experiment to refine the orbit and then generated a new prediction ephemeris, so that we avoided delay and Doppler smearing produced by uncompensated changes in the COM delay and Doppler shift over a run's duration.

The transmitted signal was phase-modulated via a pseudorandom binary code, each element (bit) of which is an instruction either to invert or not to invert the transmitted sinusoid for a duration of b (for "baud length") seconds. After L elements the code repeats itself; thus the code repetition time is $p = Lb$. Such repeating "maximum-length codes" are designed to have a very low value for the autocorrelation function ($= -1/L$) for any lag other than zero, a property that was important when we decoded the echoes to produce images (see below).

We transmitted this modulated signal for a duration almost equal to the round-trip time (RTT) to the target, then switched to receive mode for an equal duration, measuring the echo signal in both the same circular polarization as was transmitted (SC) and the opposite circular polarization (OC). Echoes in each polarization were received as analog voltage signals, amplified, mixed down to baseband, and convolved with a rectangular fil-