Characterization of Asteroid (163693) Atira with Arecibo Radar and Multi-Epoch Photometric Observations.

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Introduction: Asteroid (163693) Atira was discovered on February 11, 2003, by the LINEAR survey [1]. Radar observations from Arecibo Observatory in 2017 revealed Atira to be a binary system [2]. Atira was the first asteroid confirmed to orbit completely within Earth's orbit, thus becoming the namesake to the Atira subclass of asteroids interior to 1.0 au. Atira is estimated to be 4.8 km $\pm$ 0.5 km in diameter based on a preliminary assessment of the radar data and the secondary is estimated to be 1 km $\pm$ 0.5 km in diameter and assumed to be tidally locked [2]. Two different rotation periods have been reported for Atira based on analyses of photometric data: 3.3984 $\pm$ 0.0006 h [4], and 3.1532 $\pm$ 0.0001 h [5].

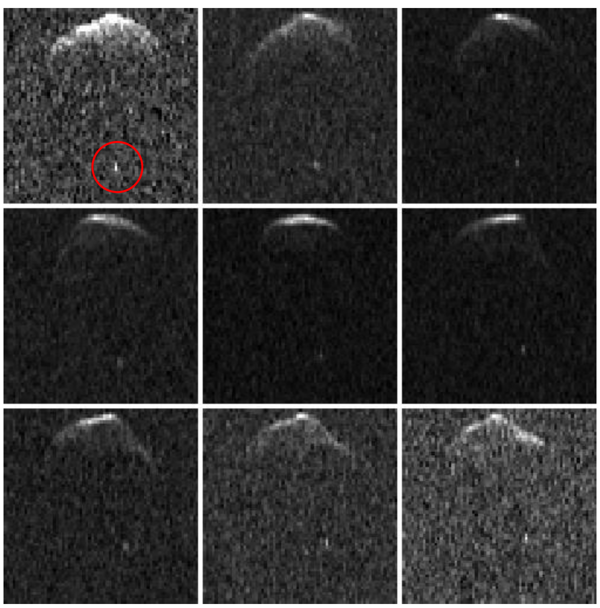

Figure 1. A mosaic of delay-Doppler images of Atira from January 20, 2017 at 2 µs resolution, time progresses to the right and down. Per panel, time delay increases downward, and the Doppler shift, frequency, decreases to the left. The radar bright object near the bottom center of each panel, circled in red in the first panel, is the secondary. Note the secondary's decrease in range as time progresses.

Aim: We characterize the shape, size, spin rate, and pole orientation of Atira by developing three-dimensional models with SHAPE software [6] using radar data from Arecibo Observatory acquired over two nights, January 20 and January 23, 2017, and photometric observations from three epochs collected over February 24 to March 2 in 2003, February, March, and April in 2017 [7], and January 30 to February 10 in 2019 [5].

Observations: Radar observations were made from Arecibo Observatory at multiple resolutions on January 20 and January 23, 2017. A total of 14 scans across 0.5 µs, 2 µs, and 4 µs resolution were done on Jan 20, and 18 scans at 2 µs resolution were done on Jan 23. The radar-bright object seen near the bottom center of each panel in Figure 1 is the secondary.

Continuous wave (CW) echo power spectra are obtained by transmitting a continuous, circularly polarized signal at 2380 MHz for approximately the duration of the round-trip time, and receiving the reflected signal for the same duration of time. With CW echo spectra, we can compare the echo power of the signal returned at an opposite circular polarization (OC), caused by one reflection of the transmitted signal, and the echo power of the signal returned with the same circular polarization (SC), caused by more than one reflection of the transmitted signal. The ratio of SC to OC echo power, μ_C, loosely describes the surface roughness and composition of the asteroid as outlined in Table 1 of [7].

CW observations from the Arecibo Observatory were made on January 20, 2017. Of the two scans performed on January 20, one echo spectrum was obtained, Figure 2. During the observation period, the reflected signal of the secondary is mingled with the primary's reflected signal seen as the large, central spike in Figure 2. We found μ_C to be 0.21, which is a typical value of the polarization ratio for S-type and C-type asteroids [7].

Our analysis also includes photometric observations from three separate groups of observers collected at three different epochs. Observations from Ondřejov Observatory were made between February 24 and March 2, 2003, and February 25 and April 30, 2017, observations from the Sierra Nevada Observatory were made between March 7 and March 12, 2017 [7], and observations from Observatório Astrônmico do Sertão de Itaparica were made between January 30 and February 10, 2019 [5].

Methods: We investigate the rotation rate discrepancy using an iterative modeling procedure. We

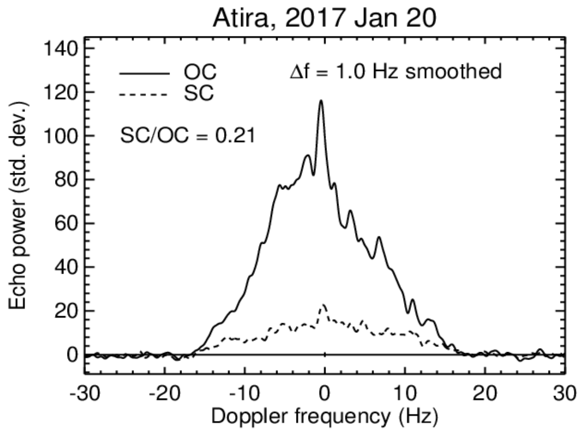

Figure 2. Continuous wave echo power spectra of asteroid (163693) Atira obtained on January 20, 2017. Opposite circularly (OC) polarized signal, solid line, is caused by a single reflection of the transmitted signal; same circularly (SC) polarized signal, dashed line, is caused by more than reflection of the transmitted signal. The ratio of these signals, SC/OC, is 0.21. The echo from the secondary is mingled with the primary's echo, seen as the large spike at 0Hz. Δf is the Doppler frequency resolution.

test models using a simple ellipsoid approximation with spin axes oriented every 10 degrees (or finer) over the celestial sphere and, after finding the best-fit northern and southern celestial hemisphere orientations, spin rates ranging from 3.1079 h – 3.4560 h. The overall best-fit ellipsoid models are used to initialize floating-vertex models containing 300 vertices to model prominent surface features. Reduced chi-squared values in conjunction with visual inspection of simulated delay-Doppler images and simulated lightcurves determine overall best-fit models.

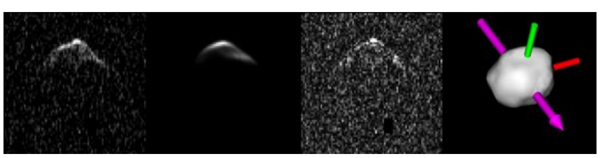

Figure 3. A collage of observation and models produced by SHAPE. From left to right: delay-Doppler image corresponding to the eighth panel of Figure 1, synthetic delay-Doppler image, residual image, and vertex model where the purple arrow indicates its orientation, ecliptic latitude -50°, longitude 192°, with respect to the celestial sphere (north is upwards). Note the surface craters and protrusion (left-side) produced in the vertex model. The black square at the bottom of the residual image is from masking the secondary in the delay-Doppler images used with SHAPE.

Results: We report preliminary results of the spin rate and pole orientation of asteroid (163693) Atira. We find a likely sidereal rotation period of 3.3984 h and a likely pole orientation of ecliptic latitude -50°, longitude 192°. SHAPE models are shown in Figure 3. We find that models with an initial spin rate closer to the other reported value of 3.1532 ± 0.0001 h [5] only produces well-fitting model lightcurves for the 2019 epoch, consistently converges to a pole latitude close to the ecliptic, and produces models that are 30-40% larger compared to the observed delay-Doppler images. Therefore, we report a more likely spin rate of 3.3984 h. This research is currently ongoing; future work includes a wider spin rate search for the primary and modeling of the secondary.

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