Shape modeling of potentially hazardous asteroid 2015 DP155 from radar and lightcurve observations.
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Introduction: We created three-dimensional models of potentially hazardous near-Earth asteroid 2015 DP155 using the SHAPE modeling software [1]. Three-dimensional models help us better understand physical characteristics of asteroids, which provide insight into their formation and evolution. Knowing surface features also helps in planning spacecraft missions to asteroids.

2015 DP155 (henceforth DP155) is an Amor asteroid with a semi-major axis of 1.32 au, a perihelion of 1.02 au, and an absolute magnitude of 21.5. Since SHAPE utilizes radar and lightcurve data, both of which have been collected for DP155, this asteroid is an ideal shape modeling candidate.

Observations: In June 2018, DP155 had a close approach with Earth of 0.02 au, making it accessible to both radar and optical observations. The asteroid will not come close enough for observations of comparable detail again until 2080. Radar observations of DP155 were conducted at Arecibo Observatory on four consecutive days starting June 9th, 2018 and with Goldstone Solar System Radar over six days between June 4th and June 17th, 2018. Optical observations were taken at Terskol Observatory [2], the Center for Solar System Studies Palmer Divide Station [3], Northolt Branch Observatories, and the European Southern Observatory from May to July of 2018.

Model Creation: The SHAPE software used to develop our model of DP155 processes a collection of vertex coordinates connected to form triangular faces. SHAPE adjusts parameters of a starting model and computes what the resultant model would produce for radar and lightcurve data. It then compares this to the actual data and repeats the process to find a model that minimizes chi-squared. Parameters in SHAPE can be held constant or allowed to float, and they include such features as overall dimensions, radar and optical scattering coefficients, and individual vertex coordinates.

We began with simple ovoid models but found none suited to the data. Instead, we utilized the three-dimensional modeling program Blender, as first used for asteroid shape modeling by Crowell et al. [4]. We produced an elongated "capsule" template in Blender which became the starting point for subsequent models. First, we located reasonable orientations for DP155's axis of rotation using delay-Doppler images and continuous wave data. Then, we let SHAPE adjust models' shapes in more detail and added lightcurve data to better produce and select accurate models.

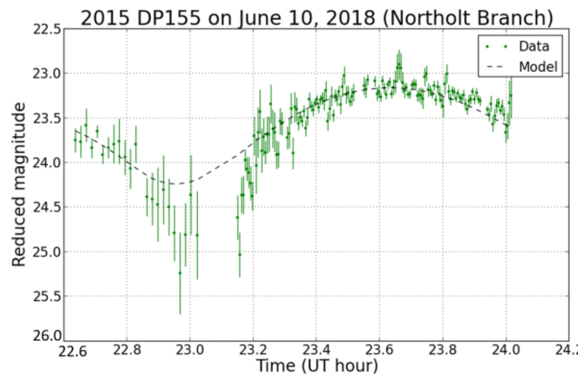

Figure 1. An example comparison between an actual lightcurve of DP155 (green points/bars) and that of a model (dashed line). Few of our models were able to match the amplitude and period of the data well, so such agreement was a helpful factor in determining which models to develop further.

On our capsule model, we performed a grid search of pole position, testing all ecliptic latitudes and longitudes at evenly spaced intervals and then "zooming in" by testing values in smaller intervals near promising positions. Often, models with the lowest chi-squared were physically unrealistic when examined visually; many were compressed along one or two dimensions. Thus, manual comparison of models and their agreement with delay-Doppler images or continuous wave spectra was crucial in selecting models to pursue.

After identifying reasonable pole positions, we allowed SHAPE to move the vertices in our capsule model. We began with one hundred vertices to make coarse shape adjustments and later increased to four hundred vertices for more detail. At this point, we also incorporated lightcurve data. Our existing models proved poor fits to the lightcurves, but by alternating between vertex adjustments and pole position searches, we were able to produce models which matched the period of the lightcurves. Since few models matched the lightcurve amplitudes, those which did became starting points for our final models. The periodic nature of lightcurves also helped us determine sidereal rotation periods for our models.

SHAPE can get stuck in local minima of the many-dimensional parameter space and accept models with physically unrealistic parameters, so frequent human guidance was necessary. For DP155, common issues included sharp spikes protruding from the model and unrealistically high radar scattering coefficients. We addressed these obstacles by holding certain hard-to-fit parameters constant during fits, manually adjusting models' shapes in Blender, and utilizing "penalty functions" that make SHAPE consider models with suspect features (in our case, spikes) mathematically worse.

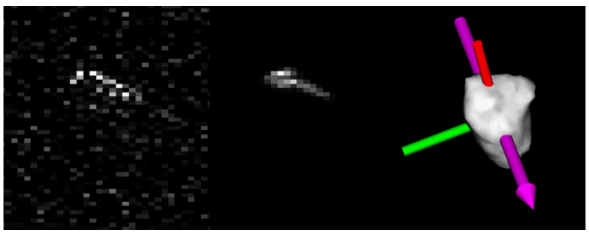

Figure 2. An example comparison between Arecibo Observatory's delay-Doppler radar data (left) and the delay-Doppler image a model would produce in radar (middle). The rightmost panel gives the plane-of-sky view for our model in the orientation at which data was collected, with principle axes shown by green and red shafts and rotation axes shown by the purple vector shaft. We rendered such images with SHAPE for each frame of radar data available in order to visually check which models were reasonable fits over time as DP155 orbits and rotates.

Results: To account for the north-south ambiguity of the delay-Doppler data, we made two final models—one with a northern and one with a southern rotational pole direction. These models have 402 vertices and share large-scale physical characteristics. They are both elongated with an extent of 200 meters along their longest axis and a volume-equivalent diameter of 140 meters. While both models feature one mostly flat side and one side with a skewed hump, the favored south pole model's hump is more pronounced.

Our "runner up" model has a northern rotation pole direction with an ecliptic latitude and longitude of 65° and 117°, respectively. This model has a sidereal rotation period of 3.095 hours. Our preferred southern pole model has ecliptic latitude -73°, ecliptic longitude 200°, and a 3.097-hour sidereal rotation period. For both radar and lightcurve data, this preferred model matches more of our collected data more closely than the northern pole model.

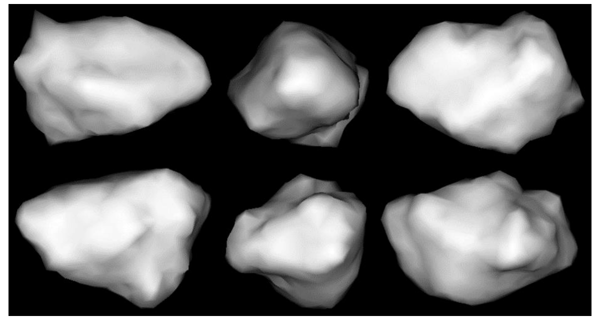

Figure 3. Views produced by SHAPE of our north pole model (top) and our south pole model (bottom) along their principle axes. The spike on the top left portion of the north pole model's first image is one feature which makes this model less preferred than our south pole model. Note that both models are elongated with a protruding hump, though the south pole model's hump is more pronounced.

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