# Physical modeling of near-Earth Asteroid (29075) 1950 DA 

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#### Abstract

Near-Earth Asteroid (29075) 1950 DA may closely encounter Earth in 2880. The probability of Earth impact may be as high as $1 / 300$, but the outcome of the encounter depends critically on the physical properties of the asteroid [Giorgini et al., 2002. Science 196, 132-136]. We have used Arecibo and Goldstone radar data and optical lightcurves to estimate the shape, spin state, and surface structure of 1950 DA. The data allow two distinct models. One rotates prograde and is roughly spheroidal with mean diameter $1.16 \pm 0.12 \mathrm{~km}$. The other rotates retrograde and is oblate and about $30 \%$ larger. Both models suggest a nickel-iron or enstatite chondritic composition. Ground-based observations should be able to determine which model is correct within the next several decades. © 2007 Elsevier Inc. All rights reserved.


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## 1. Introduction

### 1.1. Discovery and observation

Near-Earth Asteroid (NEA) (29075) 1950 DA was discovered on February 23, 1950 (Wirtanen, 1950), observed for 17 days, and then lost until December 31, 2000, when an object was discovered, given the provisional designation 2000 YK66, and then recognized as being 1950 DA (LONEOS, 2001; Bardwell, 2001). Pravec et al. (1998) at Ondřejov Observatory obtained R-band optical lightcurves on four nights be-

[^0]tween January 29 and February 28, 2001 (Table 1) as part of their photometric survey of NEAs. The lightcurves cover more than a full rotation period on three of the four nights (Fig. 1).

On March 5, 2001, 1950 DA made a 0.05 AU approach to the Earth, making it a very strong radar target. As reported in Giorgini et al. (2002), we observed it with the Goldstone ( $8560 \mathrm{MHz}, 3.5 \mathrm{~cm}$ wavelength) radar during March 3-7 and with the Arecibo ( $2380 \mathrm{MHz}, 13 \mathrm{~cm}$ wavelength) radar on March 3 and 4 (Table 1). The two datasets are complementary to each other and to the lightcurves. The Arecibo images have the highest resolution $(0.1 \mu \mathrm{~s}$, or 15 m in range), but cover only a limited amount of rotation phase and sky motion. The Arecibo Doppler-only (continuous-wave or CW) data (Fig. 2) provide the best absolute calibration of the echo power, but do

Table 1
Master Log

| Time (UTC) |  | Time (MJD) | Number of points | Rotation phase |  | Rotations | Sub-Lat |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  | Pro |  |  |  | Ret |
| Ondřejov lightcurves |  |  |  |  |  |  |  |  |
| 2001 Jan 29, | -05:29 |  | 51938.162-51938 | $29 \quad 26$ |  |  | $237^{\circ}-147^{\circ}$ | 0.75 | $-39^{\circ}$ | $37^{\circ}$ |
| 2001 Feb 15 | 2-04:55 | 51955.064-519 | 53 |  | $195^{\circ}-49^{\circ}$ | 1.59 | -47 ${ }^{\circ}$ | $47^{\circ}$ |
| 2001 Feb 15 | 2-Feb 16, 04:36 | 51955.856-519 | 2181 |  | $179^{\circ}-108^{\circ}$ | 3.80 | $-47^{\circ}$ | $48^{\circ}$ |
| 2001 Feb 28 | 1-04:50 | 51968.112-519 | 02169 |  | $52^{\circ}-56^{\circ}$ | 1.01 | $-53^{\circ}$ | $63^{\circ}$ |
| Date | Observatory | Resolution | Time (UTC) | Runs | Rotation phase | Rotations | Sub-Lat |  |
|  |  |  |  |  |  |  | Pro | Ret |
| Radar |  |  |  |  |  |  |  |  |
| 2001 Mar 3 | Arecibo | $0.10 \mu \mathrm{~s} \times 0.125 \mathrm{~Hz}$ | 11:27:51-11:59:32 | 18 | $79^{\circ}-168^{\circ}$ | 0.25 | $-43^{\circ}$ | $55^{\circ}$ |
| 2001 Mar 3 | Goldstone | $1.00 \mu \mathrm{~s} \times 6.152 \mathrm{~Hz}$ | 15:32:56-15:55:54 | 13 | $52^{\circ}-117^{\circ}$ | 0.18 | $-42^{\circ}$ | $54^{\circ}$ |
| 2001 Mar 3 | Goldstone | $0.25 \mu \mathrm{~s} \times 3.001 \mathrm{~Hz}$ | 16:04:47-18:14:45 | 61 | $142^{\circ}-149^{\circ}$ | 1.02 | $-42^{\circ}$ | $54^{\circ}$ |
| 2001 Mar 4 | Goldstone | $0.25 \mu \mathrm{~s} \times 3.001 \mathrm{~Hz}$ | 10:09:56-11:30:38 | 36 | $356^{\circ}-199^{\circ}$ | 0.63 | $-37^{\circ}$ | $49^{\circ}$ |
| 2001 Mar 4 | Arecibo | 0.500 Hz | 10:39:41-11:08:17 | 13 | $55^{\circ}-136^{\circ}$ | 0.22 | $-37^{\circ}$ | $49^{\circ}$ |
| 2001 Mar 4 | Arecibo | $0.10 \mu \mathrm{~s} \times 0.256 \mathrm{~Hz}$ | 11:10:41-12:00:04 | 28 | $143^{\circ}-282^{\circ}$ | 0.39 | $-37^{\circ}$ | $49^{\circ}$ |
| 2001 Mar 7 | Goldstone | $1.00 \mu \mathrm{~s} \times 6.152 \mathrm{~Hz}$ | 12:11:30-16:31:17 | 115 | $292{ }^{\circ}-250^{\circ}$ | 2.04 | $-16^{\circ}$ | $26^{\circ}$ |

Notes. Log of observations used in shape modeling, giving observatory, observation resolution (frequency-only denotes CW), track duration, rotation phase coverage, sub-Earth latitude at the midpoint of each set of observations for the prograde (Pro) and retrograde (Ret) models, and, for the radar observations, the number of transmit-receive cycles (runs). Rotation phase is relative to 2001 March 3, 11:00:00 UTC. Goldstone observations span more than a complete rotation on March 3 and 7.
not resolve the target in range. The Goldstone data cover multiple rotations and provide a longer sky arc, but have coarser resolution ( $0.25 \mu \mathrm{~s}$, or 37.5 m in range).

### 1.2. 2880 Earth encounter

During the course of the radar observations, the object's orbit and ephemeris were progressively updated. This radar astrometry revealed an extremely close Earth approach on March 16,2880 , with a probability of impact initially estimated as $\sim 1 / 1000$. This close approach had not been foreseen despite the fifty-year optical astrometric time base. Further analysis of the predicted close approach revealed the importance of nongravitational accelerations, particularly the Yarkovsky effect, on 1950 DA's trajectory (Giorgini et al., 2002). The Yarkovsky acceleration, due to non-isotropic thermal re-radiation, is dependent on the asteroid's shape and spin state and on the surface's thermal and optical properties. Preliminary models based on only the Arecibo images gave two possible pole directions, with uncertainties of $30^{\circ}-50^{\circ}$. Given the uncertainties in Yarkovsky perturbations, Giorgini et al. concluded "the maximum probability of impact is best expressed as being between 0 and $0.33 \%$."

Here we report estimation of the shape of 1950 DA using all of the Arecibo and Goldstone radar data and the Ondřejov lightcurves.

## 2. Observations and initial analysis

### 2.1. Elongation and rotation period

Fig. 1 shows that the lightcurves are low-amplitude, suggesting that the asteroid is not particularly elongated. The radar
echoes have a nearly constant bandwidth and a nearly constant visible range extent, supporting this conclusion. The photometric rotation period, 2.1216 h , is near the theoretical limit for a strengthless asteroid; in the NEA population, with two known exceptions (2001 OE84, $P=0.486$ h, Pravec et al., 2002, and 2001 VF2, $P=1.393 \mathrm{~h}$, Whitely et al., 2002), only objects smaller than about 200 m rotate more rapidly (Pravec, 2007; Harris and Warner, 2007).

### 2.2. Radar scattering properties

1950 DA's polarization ratio (SC/OC, echo power in the same circular polarization as transmitted to that in the opposite) is $0.14 \pm 0.03$, among the lowest out of $\sim 100$ values reported for NEAs (Benner, 2007). The mean polarization ratio and rms dispersion for NEAs are 0.36 and 0.25 , respectively. This implies that the surface of 1950 DA is very smooth at centimeter to decimeter scales.

The CW spectra have almost triangular shapes, consistent with specular scattering from a smooth, spheroidal, object. This is the first time this type of scattering has been seen on any near-Earth asteroid, out of more than 200 objects observed by radar. The images show relatively modest surface topography, with the exception of one prominent angular feature observed at both Arecibo and Goldstone (Fig. 3). In the higher-resolution Arecibo images, there are also obvious concavities and ridgelike features. The images show bright glints near zero Doppler, confirming that there is a significant specular component to 1950 DA's radar scattering law.

### 2.3. Compositional constraints from infrared spectra

Rivkin et al. (2005) reported near-IR spectra of 1950 DA, taken near perihelion. Based on a smooth, red-trending spec-


Fig. 1. Optical lightcurves and corresponding model fits. Error bars are $1-\sigma$. Magnitude is calibrated R-band, corrected to the average distance of the object during each track. Time is in MJD and UTC.
trum and the lack of any detectable thermal emission, they assigned 1950 DA a minimum optical albedo of roughly 0.2 and a taxonomic class of E or M . The M class encompasses metallic and enstatite chondritic objects and some with possibly hydrated silicate composition, whereas the E class is believed to be the progenitor of the enstatite achondrites or aubrites (Gaffey et al., 2002; Bus et al., 2002).

## 3. Modeling

### 3.1. Modeling process

To construct physical models of 1950 DA, we used our SHAPE software, which does iterative fits to delay-Doppler images, Doppler-only echo spectra, and optical lightcurves

2001 Feb 16


2001 Feb 28


Fig. 1. (continued)
using constrained least-squares (Hudson, 1993; Magri et al., 2007). Spin state, surface properties, shape and ephemeris corrections are all parameterized in our models.

We used a combination of grid searching and iterative fitting of ellipsoidal and low-order spherical harmonic models to find possible pole directions, and then switched to triangular-faceted
polyhedron models with enough vertices to match the detail in the images. The grid search covered the entire sky in pole direction with a resolution of $30^{\circ}$, which we reduced to $5^{\circ}$ near the potential poles. Because there is no evidence of non-principal axis rotation in either the lightcurves or the radar data, we only considered models with principal-axis rotation.


Fig. 2. Arecibo OC (solid lines) and SC (dashed) echoes summed over 24 min ( $68^{\circ}$ of rotation phase) on Mar 4, 2001 for solution 10 and 1 min for solution 12. The inset crosses show rotation phase coverage. Each radial line represents one transmit-receive cycle (run). Each run has 25 coherent sums. Self-noise in the echo dominates over the background in the lower panel.


Fig. 3. Selected delay-Doppler images of 1950 DA from Arecibo (range increasing from top and Doppler from left within each image). The images have a resolution of $0.10 \mu \mathrm{~s} \times 0.256 \mathrm{~Hz}$. The March 3 images were made with a relatively inaccurate ephemeris and drift in range. Note the angular feature rotating into view in the March 4 images and the features extending backward from the leading edge.

### 3.2. Pole ambiguity

We found two possible pole directions and corresponding models, as did Giorgini et al. (2002). They assigned uncertainties of $30^{\circ}-50^{\circ}$ for their estimated pole directions. Our esti-
mates include the Goldstone data and the optical lightcurves, which were not modeled by Giorgini et al., have a much longer sky arc and estimated standard errors of $5^{\circ}$ for each pole. The two models provide comparably good fits to the radar and lightcurve data (Figs. 1, 4, and 5). The two pole directions differ by $165^{\circ}$; one is prograde and one is retrograde. The prograde solution, with ecliptic longitude and latitude $(\lambda, \beta)=$ $\left(89^{\circ},+78^{\circ}\right)$, is indistinguishable from the previously reported value. The retrograde solution, $(\lambda, \beta)=\left(187^{\circ},-89^{\circ}\right)$, differs by about $50^{\circ}$ from the previously reported value.

### 3.3. Scattering parameterizations and period

We fit the optical lightcurves using the Kaasalainen et al. (2001) empirical scattering law, which is a weighted sum of Lommel-Seilger and Lambert scattering. We assume the asteroid's optical and radar scattering properties to be homogeneous and independent of surface location. Because of their monthlong time baseline, the lightcurves give the most precise measurement of the period. We used the Pravec et al. value for initial fits, and then did a grid search in period with a resolution of 0.00002 h with the final vertex models. We estimate the same period, $2.12160 \pm 0.00004 \mathrm{~h}$, for both models.

We used a radar angular scattering law containing specular (qs) and diffuse (diff) components (Magri et al., 2007), of the form

$$
\begin{align*}
\rho= & R_{\mathrm{qs}} *\left(C_{\mathrm{qs}+1}\right) * \cos (\theta)^{2 C_{\mathrm{qs}}} \\
& +R_{\mathrm{diff}} *\left(C_{\mathrm{diff}+1}\right) * \cos (\theta)^{2 C_{\mathrm{diff}}} \tag{1}
\end{align*}
$$

$\rho$ is differential radar cross-section, $\theta$ is scattering angle, and $C_{\text {qs }} \gg C_{\text {diff }}$.

The quasi-specular component accounts for specular glints at near-normal incidence, while the diffuse component captures the remainder of the echo. For both models, the two components' contributions to the echo power are roughly equal. Reflection with such a high proportion of specular glints requires not just a surface that is smooth on centimeter to decimeter scales (as indicated by the low polarization ratio), but also low meter-scale slopes within each model facet.

### 3.4. Limitations of the fits

We increased the number of vertices for each model until the match to small-scale structure was not significantly improved, giving a prograde model with 1020 vertices and a retrograde model with 510 . Even so, there are discernible deviations between the models and the observations. The most prominent is in the March 4 Arecibo images, where the prograde model does not match the structure of the echo's leading edge and the retrograde model has a slightly larger bandwidth than suggested by the observations.

The fits might be improved by using a more complicated radar scattering law, such as one that varies over the surface. We have not used a variable scattering law because doing so introduces many additional parameters that cannot be uniquely determined given the orientational coverage of our data.


Fig. 4. Individual CW spectra, one run each, and corresponding model fits. Frequency resolution is 0.5 Hz . Time increases from left to right and top to bottom. Axes are the same as in Fig. 1.

Table 2
1950 DA orbit solution 46

| Osculating element | Value | Post-fit SD $(1-\sigma)$ |
| :--- | :---: | :---: |
| Eccentricity | 0.5076354576 | $\pm 0.0000000256 \mathrm{AU}$ |
| Perihelion distance | 0.8364264895 | $\pm 0.0000000433 \mathrm{AU}$ |
| Time of perihelion (JD) | $2,453,629.8541868704$ | $\pm 0.0000037854 \mathrm{~d}$ |
| Longitude of ascending node | 356.8040204833 | $\pm 0.0000067462 \mathrm{deg}$ |
| Argument of perihelion | 224.4975866261 | $\pm 0.0000070523 \mathrm{deg}$ |
| Inclination | 12.1844736353 | $\pm 0.0000051266 \mathrm{deg}$ |
| Semimajor axis | 1.6987951355 | $\pm 0.0000000008 \mathrm{AU}$ |
| Orbital period | 808.74189246 | $\pm 0.00000055 \mathrm{~d}$ |

Notes. 1950 DA orbit solution with estimated formal uncertainties at solution epoch 1 Jan 2005 . The optical data post-fit residual root mean square (rms) is $0.600^{\prime \prime}$. For radar delay, the residual rms is $0.865 \mu \mathrm{~s}$. Doppler residual rms is 0.920 Hz . The combined normalized residual rms is 0.597 . Elements are in the ICRF93/J2000 coordinate frame of the DE-405 JPL planetary ephemeris, a quasar-based radio frame, generally within $0.01^{\prime \prime}$ of the optical FK5/J2000 frame. Angular elements are referred to the ecliptic and mean equinox of J2000.

## 4. Shape and composition

The two models have very different shapes and surface properties (Table 3; wavefront format electronic versions of the models available at http://echo.jpl.nasa.gov/~ostro/da/index. $\mathrm{html})$. The prograde model is very slightly elongated, with angular, perhaps faceted, relief and obvious indentations. The retrograde solution is quite oblate, with a prominent equatorial ridge (Figs. 6 and 7). The retrograde solution implies higher sub-radar latitude and requires a larger size to match the observed bandwidth.

### 4.1. Visible surface

The radar images provide complete rotation phase coverage, and the lightcurves sample a range of sub-Earth latitudes for each candidate pole direction, so the majority of the asteroid's surface was seen at incidence angles of less than $75^{\circ}$. The unseen (or see only at $>75^{\circ}$ incidence angle) region is somewhat larger for the retrograde model than for the prograde model, because the latitudes were uniformly higher. The shape in the unseen region is not constrained by the data, but rather by our model assumption of principal-axis rotation. The unseen re-


Fig. 5. Collage of radar images used in shape modeling, fits, and plane-of-sky projections of the models, grouped by day and observatory. Format for each row is, from left to right: retrograde model, retrograde fit, observed image at scale of retrograde fit, observed image at scale of prograde fit, prograde fit, prograde model. Delay-Doppler projections have range increasing from top and Doppler from left. Time increases downward and from left within each day.
gions constitute $15 \%$ of the surface area of the prograde model and $30 \%$ of the surface area of the retrograde model.

### 4.2. Radar albedo and surface density

Because of their different cross-sectional areas, the prograde model has a radar albedo of 0.35 while the retrograde model has an albedo of 0.23 . Both values are higher than those reported for
most other asteroids, although not as high as for (6178) 1986 DA (0.58) or 216 Kleopatra ( 0.60 ), where the radar albedo estimates force the inference of metallic composition (Ostro et al., 2000). The radar albedo of an asteroid is determined largely by the density of the top several wavelengths of the surface, which is a function of the solid (grain) density and the porosity (Magri et al., 2001).


Fig. 5. (continued)

We obtain minimum surface grain densities (assuming zero porosity) of $3.2 \mathrm{~g} \mathrm{~cm}^{-3}$ for the prograde model and $2.4 \mathrm{~g} \mathrm{~cm}^{-3}$ for the retrograde model. The asteroid's bulk density can be higher than the minimum surface grain density if the surface is relatively porous and/or if the interior is relatively compacted.

The surface grain density allows us to further constrain the composition. Based on the Rivkin et al. (2005) E or M type classification, we have three major compositional possibilities:
enstatite achondrite, enstatite chondrite, and nickel-iron. The V-band optical albedo of 1950 DA is $0.20 \pm 0.05$ for the retrograde model and $0.25 \pm 0.05$ for the prograde model, based on an estimated absolute magnitude $H=16.83$. Enstatite achondrite meteorites have optical albedos higher than about 0.3 and grain densities of $\sim 2.9 \mathrm{~g} \mathrm{~cm}^{-3}$ (Britt and Consolmagno, 2003; Smith et al., 2005). Thus the prograde model's high density and the retrograde model's low albedo rule out an enstatite achondrite composition.


Fig. 5. (continued)

If 1950 DA has a density comparable to enstatite chondrites, $\sim 3.6 \mathrm{~g} \mathrm{~cm}^{-3}$, it must have a low surface porosity ( $<30 \%$ ); that is, it must be nearly lacking in regolith. If 1950 DA is metalrich (analogous to iron meteorites), the surface porosity must be less than $\sim 60 \%$ for the prograde model and less than $\sim 70 \%$ for the retrograde model; that is, the asteroid's regolith porosity is near or within the range seen for the Moon, 30-55\% (Carrier et al., 1973).

### 4.3. Possible required tensile strength

For the retrograde model, if we assume a uniform bulk density of $2.5 \mathrm{~g} \mathrm{~cm}^{-3}$, there is a large zone around the equator where rotational acceleration is greater than gravitational attraction (Fig. 7). The extent of this zone is dependent to some degree on the distribution of mass in the unseen region. Increasing the bulk density of the retrograde model to $3.5 \mathrm{~g} \mathrm{~cm}^{-3}$ just


Fig. 5. (continued)
removes this zone. For the prograde model, with uniform density, the radar surface-density constraint $\left(>3.2 \mathrm{~g} \mathrm{~cm}^{-3}\right)$ does not permit such a zone.

A rotational acceleration greater than gravitational attraction requires that the object is strong enough to resist being pulled apart. Many asteroids are believed to be gravitationally bound agglomerates (rubble piles), but even so may have some tensile strength (Holsapple, 2004). If 1950 DA's bulk density is less than $3.5 \mathrm{~g} \mathrm{~cm}^{-3}$, then the retrograde model must have strength.

However, if 1950 DA had significant tensile strength, we might expect the topography to be more rugged, whereas the retrograde model is relatively smooth.

### 4.4. Implications of the spin state ambiguity

We currently have no basis for preferring one of our models over the other. If the rotation is prograde, then 1950 DA is composed of porous nickel-iron or solid enstatite chondrite. If the

Table 3
Model properties

|  | Prograde model | Retrograde model |
| :---: | :---: | :---: |
| Pole direction ( $\lambda, \beta$ ), $\pm 5^{\circ}$ | (88.6 ${ }^{\circ}, 77.7^{\circ}$ ) | $\left(187.4^{\circ},-89.5^{\circ}\right.$ ) |
| DEEVE dimensions ( $2 \mathrm{a}, 2 \mathrm{~b}, 2 \mathrm{c}$ ) ( $\pm 10 \%$ ) | $1.16 \times 1.17 \times 1.15 \mathrm{~km}$ | $1.39 \times 1.46 \times 1.07 \mathrm{~km}$ |
| Maximum extents along principal axes ( $\pm 10 \%$ ) | $1.19 \times 1.28 \times 1.24 \mathrm{~km}$ | $1.45 \times 1.60 \times 1.20 \mathrm{~km}$ |
| Diameter of equal-volume sphere ( $\pm 10 \%$ ) | 1.16 km | 1.30 km |
| Volume ( $\pm 30 \%$ ) | $0.82 \mathrm{~km}^{3}$ | $1.14 \mathrm{~km}^{3}$ |
| Mean OC radar cross-section $0.36 \pm 0.03 \mathrm{~km}^{2}$ Polarization ratio $0.14 \pm 0.03$ |  |  |
|  |  |  |
| Radar scattering law |  |  |
| $R_{\text {qs }}$ | $0.156 \pm 0.051$ | $0.137 \pm 0.049$ |
| $C_{\text {qs }}$ | $9.47 \pm 0.25$ | $6.70 \pm 0.25$ |
| $R_{\text {diff }}$ | $0.176 \pm 0.058$ | $0.103 \pm 0.026$ |
| $C_{\text {diff }}$ | $0.59 \pm 0.04$ | $0.77 \pm 0.05$ |
| Radar albedos |  |  |
| Equivalent quasi-specular | $0.165 \pm 0.054$ | $0.144 \pm 0.051$ |
| Equivalent diffuse | $0.160 \pm 0.052$ | $0.095 \pm 0.024$ |
| Equivalent total OC | $0.325 \pm 0.075$ | $0.249 \pm 0.055$ |
| CW total OC | $0.35 \pm 0.07$ | $0.23 \pm 0.05$ |
| V-band optical albedo | $0.25 \pm 0.05$ | $0.20 \pm 0.05$ |
| Minimum strength-less bulk density ( $\pm 10 \%$ ) | $3.0 \mathrm{~g} \mathrm{~cm}^{-3}$ | $3.5 \mathrm{~g} \mathrm{~cm}^{-3}$ |
| Minimum surface grain density ( $\pm 10 \%$ ) | $3.2 \mathrm{~g} \mathrm{~cm}^{-3}$ | $2.4 \mathrm{~g} \mathrm{~cm}^{-3}$ |

Notes. Properties of the two models. Dimensions are given for the dynamically-equivalent equal-volume ellipsoids (DEEVE). Scattering law parameters are given for both the quasi-specular and diffuse components. V-band albedo was obtained using absolute magnitude $H=16.8$, the mean of 125 absolute brightness measurements obtained during optical astrometric observations. We assume that systematic errors in these measurements are less than 0.2 mag. The minimum strength-less bulk density assumes inward acceleration at surface. The surface grain density is constrained by the radar albedo.
rotation is retrograde, then the asteroid either has a bulk density of at least $3.5 \mathrm{~g} \mathrm{~cm}^{-3}$, and the surface is again porous metal, or the bulk density is lower and the asteroid is a nearly solid rock. The latter case may be less likely, given the shape model and the relatively smooth surface.

If the rotation is retrograde, then the sum of non-gravitational forces, perturbations from other asteroids, and 15 encounters with Earth and Mars at distances less than 0.1 AU , will alter the trajectory and delay the highest-probability arrival time at the intersection with Earth's orbit in 2880 by more than two months. This would eliminate the potential impact.

Alternatively, if the prograde model is correct, then the potential impact remains possible. A more extensive statistical analysis of potential perturbations due to more than 142,000 potentially significant known asteroid encounters would be required for an improved impact probability estimate.

## 5. Future prospects

### 5.1. Radar

The next radar apparition able to yield current-Arecibo SNRs high enough for ranging is in 2032. However, the asteroid's sky position will be close to the sky arc of the 2001 radar experiment, so we will not be able to get any additional leverage on the spin state by radar imaging.

Radar ranging will eventually be able to distinguish between the models by measuring the Yarkovsky perturbation directly.

The Yarkovsky perturbation will not be detectable in 2032, but will be detectable with current radar systems during the asteroid's 2074 Earth approach

Thermal re-radiation of absorbed sunlight can cause slow changes in an asteroid's spin state via "YORP" torques (Rubincam, 2000), which depend on the rotation state and the surface's optical and thermal properties (i.e., its fine-scale structure). An approximate analysis for 1950 DA, using the method described by Scheeres (2007), implies a rate of change of the period of order $\sim 10^{-4} \mathrm{~s}^{-1} \mathrm{y}^{-1}$ for both models, comparable to that observed for the Asteroid (54509) 2000 PH5 (Taylor et al., 2007). The YORP-induced change in period of 1950 DA accumulates to roughly 0.1 s between now and 2880, and does not significantly affect calculations of impact probability. Estimates for YORP modification of the pole direction through 2880 are much smaller than the current uncertainties, so the models cannot be distinguished on the basis of thermal re-radiation effects for several decades.

### 5.2. Optical

Optical observations have the greatest ability to split the spin state ambiguity within the next few decades. Precise optical photometry while 1950 DA is near aphelion might reveal which of the two radar + optical physical models is correct, because the amplitude of the lightcurves predicted from the models are different (e.g., on October 30, 2006 the prograde model lightcurve has amplitude 0.1 mag , while the retrograde model


Fig. 6. Principal-axis projections of the prograde (top) and retrograde (bottom) models. Yellow shading marks regions that were not seen at incidence angles less than $75^{\circ}$. Renderings use a Lambertian scattering law.
lightcurve has amplitude 0.17 mag ). We obtained broad (R\&I) band lightcurves of 1950 DA with the Palomar 5.1-m telescope on October $30 \& 31$, 2006, but their systematic and statistical uncertainties are such that these lightcurves do not distinguish between the two models. The next relatively bright (apparent magnitude $<17$ ) optical apparition when the two models predict a large difference in amplitude is in 2023.

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## Prograde Pole









## Retrograde Pole



Fig. 7. Gravitational slope maps of each model, with bulk density uniform and set to $4 \mathrm{~g} \mathrm{~cm}^{-3}$ for the prograde solution (top) and $2.5 \mathrm{~g} \mathrm{~cm}^{-3}$ for the retrograde solution (bottom). The retrograde solution has regions where rotational acceleration dominates gravitational attraction (slope $>90^{\circ}$ ) around the equator for this bulk density. The slopes on the retrograde model are more uncertain than on the prograde, because the unseen region is considerably larger (Fig. 5). Slopes are in degrees from the inward surface normal.

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