NEOWISE Observations of the Potentially Hazardous Asteroid (99942) Apophis

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Abstract

Large potentially hazardous asteroids (PHAs) are capable of causing a global catastrophe in the event of a planetary collision. Thus, rapid assessment of such an object’s physical characteristics is crucial for determining its potential risk scale. We treated the near-Earth asteroid (99942) Apophis as a newly discovered object during its 2020–2021 close approach as part of a mock planetary defense exercise. The object was detected by the Near-Earth Object Wide-field Infrared Survey Explorer (NEOWISE), and data collected by the two active bands (3.4 and 4.6 μm) were analyzed using thermal and thermophysical modeling. Our results indicate that Apophis is an elongated object with an effective spherical diameter \( D_{el} = 340 \pm 70 \) m, a geometric visual albedo \( p_V = 0.31 \pm 0.09 \), and a thermal inertia \( \Gamma \sim 150–2850 \) J m\(^{-2}\) s\(^{-1}\) K\(^{-1}\) with a best-fit value of \( 550 \) J m\(^{-2}\) s\(^{-1}\) K\(^{-1}\) : NEOWISE “discovery” observations reveal that (99942) Apophis is a PHA that would likely cause damage to a regional level but not a global one.

Unified Astronomy Thesaurus concepts: Near-Earth objects (1092); Close encounters (255); Infrared Astronomical Satellite (785); Photometry (1234); Computational astronomy (293); Markov chain Monte Carlo (1889); Astronomy data modeling (1859)

Supporting material: animation, machine-readable table

1. Overview

Near-Earth asteroids (NEAs) are a subpopulation of asteroids that pass very close to the Earth. They are conventionally defined as small bodies with a perihelion distance less than or equal to 1.3 au, and compared to main-belt asteroids (MBAs), they tend to be smaller in size and irregularly shaped with short dynamical life spans. Due to their relative proximity to the Earth, detailed studies of their physical characteristics, such as diameter, albedo, thermal inertia, rotational period, and absolute visual magnitude, can be performed by using data obtained from either remote sensing (Ostro 1993; Werner et al. 2004; Mainzer et al. 2011a) or in situ (Lauretta et al. 2017; Watanabe et al. 2017) missions. Studying these features can help us theorize their origin and evolution in the solar system (as laid out by Binzel et al. 1992, Michel et al. 2005, Granvik & Brown 2018, and others) and take pivotal steps toward planetary defense.

The NEAs with a minimum orbit intersection distance (MOID) to the Earth of less than 0.05 au and an \( H \) magnitude less than or equal to 22 (or, correspondingly, a minimum diameter of roughly 140 m) are formally classified as potentially hazardous asteroids (PHAs), as they have the capability to cause substantial damage upon collision with the Earth. One example from recorded history is the 1908 Tunguska event, where a meteor with a diameter of ~100 m exploded over a Siberian forest, producing around 60 PJ of energy and affecting an area as large as 2150 km\(^2\) (Vasilyev 1998). A more recent and better-documented example is the 2013 Chelyabinsk event, where a small NEA about 19 m in diameter (Borovička et al. 2013) exploded over Chelyabinsk Oblast, Russia, injuring roughly 1500 people and damaging around 7200 buildings. Therefore, the discovery and categorization of such asteroids are crucial to prevent potential impacts and mitigate harm.

A particular NEA, (99942) Apophis, has been an object of great interest since its discovery in 2004 by R. A. Tucker, D. J. Tholen, and F. Bernardi. It is a well-known PHA with a catalog \( H \) magnitude of 19.7, a perihelion distance of roughly 0.746 au, and an MOID of 0.0002056 au. Thousands of optical and dozens of radar observations have allowed planetary scientists to study Apophis in great detail. Binzel et al. (2009) studied its spectral properties and composition and categorized it as an S-class asteroid (Bus 1999; DeMeo et al. 2009), and Lin et al. (2018) classified it as an S-class asteroid (Tholen 1984) after carrying out a photometric survey. Delbo et al. (2007) used polarimetric observations to estimate its size and albedo, and Müller et al. (2014b) used thermal measurements from Herschel to determine its size, albedo, and thermal inertia and also calculated its mass by using Itokawa’s density and porosity. The most recent results based on radar observations from Goldstone and Arecibo suggest that Apophis is an elongated, asymmetric, and possibly bifurcated object with a diameter of 340 ± 40 m and a visible geometric albedo of 0.35 ± 0.10 (Brozovic et al. 2018).

Postdiscovery, Apophis drew international attention when its collision probability was initially estimated to be as high as 2.7% for the year 2029. It was speculated that it might enter a so-called gravitational keyhole, which could exacerbate the possibility of an impact in 2036. Follow-up studies and analysis significantly lowered this probability, and any chance
of collision in 2029 and 2036 was ruled out. Recent radar observations from Goldstone also eliminated the slight risk of impact for 2068 and further showed that it posed no threat to the Earth for at least another hundred years. Nonetheless, Apophis remained a “virtual impactor” of special interest to the planetary defense community and was the subject of a mock planetary defense exercise during its 2020–2021 flyby.

In the exercise, Apophis was treated as a newly discovered asteroid, and the capability of research groups to identify and rapidly characterize potentially hazardous objects was tested (inspired by a similar activity performed by Reddy et al. 2019, where they tracked and characterized the NEA 2012 TC4 as a hypothetical impactor). Thermal infrared data on (99942) Apophis was collected by the Near-Earth Object Wide-field Infrared Survey Explorer (NEOWISE; Wright et al. 2010; Mainzer et al. 2014) during the object’s close approaches in 2020 December and 2021 March–April. These new observations resulted in the “discovery” of the object, and its diameter and albedo were rapidly computed following standard image processing and calibration by the NEOWISE data system (Cutri et al. 2015). While a forthcoming publication will describe the full results of the mock exercise, our study reconfirms prior results and highlights the accuracy and speed of the NEOWISE team’s analytical methods.

2. Observations

NEOWISE (Mainzer et al. 2014) is a two-band all-sky thermal infrared survey well suited to investigating the physical properties of asteroids and comets. It was initially launched as the Wide-field Infrared Survey Explorer (WISE; Wright et al. 2010) in 2009 December with the objective to map 99% of the sky using four thermal IR bands with wavelengths of 3.4, 4.6, 12, and 22 μm (named W1, W2, W3, and W4, respectively). The primary mission concluded after the solid hydrogen coolant was exhausted and the W3 and W4 channels ceased to function, and WISE was put into hibernation in 2011 February. In 2013 December, the spacecraft was reactivated and repurposed as NEOWISE with the W1 and W2 channels active, and since that time, it has detected over 40,000 different solar system small bodies.7

NEOWISE was one of the first surveys to submit “discovery” tracklets (sets of position-time measurements of candidate moving objects) for Apophis late in 2020. Thirty-one single-exposure detections were acquired during the two observing epochs (see Figure 1 for reference). First, the detections were automatically ingested by the WISE Moving Object Pipeline Subsystem (WMOPS) which associates sets of detections with apparent on-sky motions that are consistent with orbital motion. Detections were rejected if they had moon separation angles (moon_sep) of less than 15°, were saturated,8 were colocated within 6.5′ of stationary background objects such as stars or galaxies (identified from the AllWISE Atlas Image set from Cutri et al. 2013), or had poor fits to the reference point-spread functions, i.e., \( w1rch2 \geq 5 \) and \( w2rch2 \geq 5 \) (most likely due to cosmic rays).9 Lastly, the detection images were visually inspected to check for any other unflagged artifacts, and additional scan frames were extracted using the WISE Moving Object Search Tool, as a few detections were rejected by WMOPS due to the curvature of their on-sky motion or falling near a background object.10

From the first epoch in 2020 December, 17 detections were identified in the two active bands (3.4 and 4.6 μm), with an observation time spanning 32.75 hr. The signal-to-noise ratio (S/N) at 4.6 μm was approximately 5.5, and the solar elongation angle was roughly 90°. Eight additional detections were collected during the second observing epoch in 2021 April, spanning 17.25 hr with an average S/N of 32.7 at 4.6 μm and a solar elongation angle of about 110°. The S/N was noticeably higher during the second epoch because Apophis was closer to the Earth than it was during the first epoch. A summary of the observing geometry can be found in Table 1, and detailed information about the same is given in Table 2.

Lastly, visible photometry nearly simultaneous to epoch 1 was obtained using the SMARTS 1.0 m telescope from the Cerro Tololo Inter-American Observatory (CTIO) and used to provide an improved constraint on the absolute visual magnitude, i.e., \( H \) (as \( H \) magnitudes for many asteroids, particularly near-Earth objects, often have large uncertainties, which in turn reduces the accuracy of derived visible albedos). SMARTS 1.0 m is a Boller and Chivens f/10.5 telescope with a back-illuminated Finger Lakes Instruments thermoelectrically cooled camera that has 13.5 μm pixels and an array size of 2048 × 2048 pixels. Data were taken continuously on 2020 December 18 from 06:54 to 08:18 UTC with filters in the following order: clear, \( g \), \( r \), \( i \), \( z \), \( B \), and \( V \). There was an \( \sim 3 \) s delay between exposures while the filter wheel moved. In total, 112 images were taken, i.e., 16 exposures for each of the seven filters. The pixel binning size was set to 4, which produced a 1″05 pixel\(^{-1}\) image scale. The data were calibrated to Pan-STARRS, and Kostov & Bonev (2018) were referenced to convert the Pan-STARRS \( g \), \( r \), and \( i \) values to \( B \) and \( V \) (see Table 2 in that paper). These transformed \( V \) values, listed in Table 3 and plotted in Figure 2, were then used to calibrate the \( V \) filter and compute \( H = 19.1 \pm 0.5 \) using the \( HG \)-system.

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6 https://echo.jpl.nasa.gov/asteroids/Aphophis/apophis.2021.goldstone.planning.html
7 https://wise2.ipac.caltech.edu/docs/release/neowise/
8 https://wise2.ipac.caltech.edu/docs/release/neowise/exprsp/sec2_1cva.html
9 https://wise2.ipac.caltech.edu/docs/release/neowise/exprsp/sec2_1a.html
10 https://irsa.ipac.caltech.edu/applications/MOST/
delineated in Bowell et al. (1989; $G = 0.25 \pm 0.20$ from Shevchenko et al. 2019 was assumed during the conversion).

3. Thermal Models and Results

Categorizing asteroids based on diameter and albedo by modeling their thermal emission (dominant in wavelengths greater than 4 $\mu$m for most near-Earth objects and asteroids closer than $\sim$4 au heliocentric distance) has become standard practice since infrared observations of small bodies began in the 1970s. Standard thermal models (STMs) idealize asteroids as nonrotating spheres with a zero-degree solar phase angle. The asteroid model is bisected into a day- and a nightside, and it is assumed that the thermal emission on the dayside decreases from the subsolar point to the terminator, and that the nightside has zero thermal emission. Following the temperature distribution, the reflected and absorbed sunlight on the dayside of the simplified asteroid model can be considered to be in equilibrium and used to compute the effective spherical diameter and bolometric Bond albedo. Next, the V-band geometric albedo can be determined using the system laid out by Bowell et al. (1989), which uses the absolute magnitude ($H$) and phase slope coefficient ($G$) to describe the phase curve function. Additional parameters, including the so-called beaming parameter, can be used to better constrain the results by correcting for variation in thermal emission due to surface and shape irregularities, thermal inertia and rotation, spectral slope, and differing observing geometries (see Matson 1972, Morrison 1973, Jones & Morrison 1974, Morrison & Chapman 1976, Morrison & Lebofsky 1979, Lebofsky & Spencer 1989, and Harris & Lagerros 2002 for an extended discussion on the topic).

Lebofsky et al. (1986) computed an improved estimate of the beaming parameter based on observations of 1 Ceres and 2 Pallas and put forward the refined STM. While this model was demonstrated to effectively determine the size and visual albedo of several MBAs, the same estimations for NEAs had significant deviations when compared to radiometric predictions (Veeder et al. 1989). Unlike the two very large main-belt objects that were used to calibrate the parameters of the refined STM, a typical NEA is observed at higher phase angles and has distinct physical and thermal properties. These confounding factors likely decreased the fidelity of the refined STM fits for the NEAs.

Harris (1998) developed a modified version of the refined STM called the Near-Earth Asteroid Thermal Model (NEATM) and presented revised diameter and visual albedo estimates with substantially better matches to independently measured diameters for several NEAs. Two primary improvements were implemented by Harris: first, incorporating observing geometry in the calculations to account for flux variations that arise on the night- and daysides, and second, including a varying beaming parameter to figure in the assumption that the nightside had zero emission and for other uncertainties due to shape, spin pole, rotation rate, surface roughness, and thermal conductivity. The NEATM is capable of fitting the diameter, beaming, visible geometric albedo, and, under certain circumstances, albedo at shorter infrared wavelengths (3–4 $\mu$m). The precise number of parameters that can be fit depends on the number of measurements available. For asteroids detected by the reactivated NEOWISE mission, the brightnesses at 3.4 and/or 4.6 $\mu$m and (in most cases) the visible magnitude are available from archival observations. Follow-up studies such as Mainzer et al. (2011b) and Wright et al. (2018) have employed NEATM and confirmed the reliability of the thermal model.

To compute the physical characteristics of asteroids beyond the size and albedo, complex models called thermophysical models have been formulated by Lagerros (1996), Rozitis & Green (2011), Hanuš et al. (2015), and others. We used the Spherical, Cratered, Rotating, Energy-conserving Asteroid Model (simply called TPM in this paper)—developed by Wright (2007) and Koren et al. (2015) and validated by Masiero et al. (2019)—which models the asteroid as a rotating cratered sphere (or a triaxial ellipsoid) and uses thermal IR flux measurements to determine its diameter, albedo, and thermal inertia. Unlike STM or NEATM, where surface roughness is approximated by the beaming parameter, the TPM varies the fraction of the craters on the facets and calculates the thermal emission of all of the idealized craters by accounting for the incident solar flux, blackbody radiation, solar reflection, and heat conduction. Best fits for up to 10 different free parameters—the R.A. and decl. of the spin axis pole position, diameter, visual albedo, rotational period, thermal inertia, cratering fraction, $p_{\text{IR}}/p_{\text{V}}$ ratio, and $b/a$ and $c/b$ axis ratios—can be computed by employing an affine-invariant Markov Chain Monte Carlo simulation (adapted from Foreman-Mackey et al. 2013).

Priors for the different parameters mentioned above are assumed. For rotational pole position, the prior is uniform in $4\pi$. The prior for the diameter is a log-uniform distribution of values between 1 m and 1000 km, and the same for visual albedo is a mixture model of two Rayleigh distributions given by Wright et al. (2016). The rotational period prior is modeled as a log-Cauchy distribution in terms of the equatorial rotational velocity but is heavily penalized for periods <2 hr if $D \geq 200$ m (although for Apophis, the rotational period was fixed as described in the last paragraph of this section). The prior for the cratering fraction ($f_c$) is uniform in $0–1$. The surface roughness is parameterized by the cratering fraction with a slope of 75$^\circ$ and a variable fraction of flat terrain. The prior of the thermal inertia ($\Gamma$) is a log-uniform distribution for values of $2.5–2500$ J m$^{-2}$ s$^{-1/2}$ K$^{-1}$ with a width of one unit of natural log. Finally, the prior of $\ln(p_{\text{IR}}/p_{\text{V}})$ is 0.563 ± 0.340 based on Mainzer et al. (2011a).

11 Cutoffs are enforced for the triaxial ellipsoid shape model, along with the eight parameters previously listed, uniform priors are assumed for $(b/a)$ and $(c/b)$ in the range $0–1$. The distribution of $b/a$ is supplied by the light-curve amplitudes, and the diameter is computed as $D = 2(ab/c)^{1/2}$.

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|c|c|}
\hline
Epoch & MJD & WISE-centric Distance & Heliocentric Distance & Solar Elongation & Phase Angle \\
& & (au) & (au) & (deg) & (deg) \\
\hline
1 & 59,202.561219 & 0.259 & 1.018 & 90.2 & 75.1 \\
2 & 59,305.273533 & 0.137 & 1.057 & 111.2 & 61.8 \\
\hline
\end{tabular}
\caption{Observing Geometry of (99942) Apophis during the Two NEOWISE Observing Epochs}
\end{table}
Table 2
Two-epoch Observations of (99942) Apophis in the 3.4 and 4.6 μm Bands

| R.A.    | Decl.  | MJD       | Source ID | Mag  | Mag σ | Flux | Flux σ | χ² | Mag  | Mag σ | Flux | Flux σ | χ² |
|---------|--------|-----------|-----------|-------|-------|------|-------|---|-------|-------|------|-------|---|
| (1)     | (2)    | (3)       | (4)       | (5)   | (6)   | (7)  | (8)   | (9)| (10)  | (11)  | (12) | (13)  | (14)|
| 172.5647| −10.7728| 59,201.97654340| 23614r158-002887| 16.468 | 0.363 | 52.140 | 17.452 | 0.97 | 14.136 | 0.328 | 159.64 | 48.162 | 0.83 |
| 172.5647| −10.7723| 59,201.97667076| 23614r159-002689| 15.366 | ···    | 66.212 | 38.803 | 0.68 | 14.304 | 0.212 | 136.71 | 26.672 | 1.10 |
| 172.5938| −10.8056| 59,202.10731955| 23618r158-001173| 16.670 | 0.459 | 43.306 | 18.320 | 0.96 | 13.857 | 0.138 | 206.38 | 26.256 | 0.38 |
| 172.5941| −10.8058| 59,202.10744691| 23618r159-000844| 15.352 | 0.219 | 145.68 | 29.341 | 0.50 | 14.268 | 0.349 | 141.34 | 45.426 | 1.53 |
| 172.6229| −10.8388| 59,202.23809564| 23622r158-002053| 16.696 | 0.433 | 42.256 | 16.837 | 1.22 | 14.134 | 0.165 | 159.85 | 24.265 | 0.61 |
| 172.6232| −10.8387| 59,202.23822300| 23622r159-001278| 16.467 | 0.357 | 52.169 | 17.172 | 0.69 | 13.809 | 0.141 | 215.73 | 27.933 | 0.54 |
| 172.6808| −10.9049| 59,202.49926582| 23630r146-010408| 16.466 | 0.323 | 52.211 | 15.513 | 2.03 | 14.277 | 0.265 | 140.11 | 34.187 | 0.36 |
| 172.6957| −10.9209| 59,202.56099662| 23632r134-001369| 15.745 | 0.225 | 101.48 | 21.036 | 0.82 | 14.600 | 0.287 | 104.13 | 27.559 | 0.42 |
| 172.7095| −10.9375| 59,202.63042400| 23634r158-000846| 15.568 | 0.194 | 119.47 | 21.293 | 1.19 | 13.991 | 0.172 | 182.41 | 28.970 | 0.51 |
| 172.7097| −10.9370| 59,202.63055132| 23634r159-001077| 15.691 | 0.199 | 106.61 | 16.560 | 1.27 | 13.966 | 0.280 | 186.62 | 48.126 | 0.76 |
| 172.7240| −10.9540| 59,202.69587575| 23636r134-001054| 16.046 | 0.232 | 76.939 | 16.424 | 1.07 | 13.717 | 0.127 | 234.82 | 27.524 | 1.20 |
| 172.7384| −10.9703| 59,202.76120009| 23638r158-001182| 15.760 | 0.205 | 100.07 | 18.877 | 0.91 | 13.838 | 0.158 | 210.04 | 30.474 | 0.57 |
| 172.7531| −10.9868| 59,202.82665184| 23640r134-002266| 16.276 | ···    | 30.427 | 15.892 | 0.74 | 14.234 | 0.233 | 145.77 | 31.301 | 0.76 |
| 172.7674| −11.0035| 59,202.89197627| 23642r158-002419| 16.243 | 0.281 | 64.152 | 16.604 | 0.70 | 14.396 | 0.222 | 125.57 | 25.675 | 0.89 |
| 172.7817| −11.0200| 59,202.95743860| 23644r134-002555| 16.518 | 0.539 | 49.773 | 24.690 | 0.80 | 14.352 | 0.211 | 130.83 | 25.422 | 0.29 |
| 172.8100| −11.0526| 59,203.08820473| 23648r134-002554| 16.412 | 0.360 | 54.910 | 18.223 | 0.44 | 14.375 | 0.278 | 128.04 | 32.788 | 0.93 |
| 172.8671| −11.1186| 59,203.34975691| 23656r134-001623| 16.405 | 0.443 | 55.270 | 22.528 | 1.37 | 13.789 | 0.134 | 219.73 | 27.045 | 0.93 |

Note. The horizontal line near the middle row separates the first and second set of observations. The units for R.A. and decl. are degrees, and that of flux is instrumental units (DN). The source ID in column (4) is a unique ID comprising the scan ID, frame number, and source number. "Mag" in columns (5), (6), (10), and (11) refers to the instrumental profile-fit photometry magnitude of the object at the time of the observation, and σ in columns (6), (8), (11), and (13) represents the measurement uncertainty. The detailed methodology for the determination of in-band and flux calibration uncertainties can be found in Cutri et al. (2015). Columns (9) and (14) contain the χ² statistic that shows the quality of the profile-fit photometry (https://wise2.ipac.caltech.edu/docs/release/neowise/expsup/sec4_2bi.html) of the measurements.
Figure 2. The CTIO observations in $B$, $V$, $r$, and $g$, taken at nearly the same time as NEOWISE’s first epoch of observations.

Table 3
Truncated Table of CTIO Observations of (99942) Apophis in $B$, $g$, $r$, and $V$

| Filter | MJD     | R.A. (deg) | Decl. (deg) | Zero-point (mag) | Instantaneous Mag. (mag) | Calibrated Mag. (mag) |
|--------|---------|------------|-------------|------------------|--------------------------|-----------------------|
| $B$    | 59,201.290444 | 172.42233  | -10.59855   | 27.342 ± 0.048   | -7.630 ± 0.133           | 19.713 ± 0.141        |
|        | 59,201.294088 | 172.42300  | -10.59945   | 27.575 ± 0.057   | -7.995 ± 0.104           | 19.581 ± 0.118        |
|        | 59,201.297726 | 172.42366  | -10.60035   | 27.382 ± 0.061   | -7.632 ± 0.122           | 19.750 ± 0.136        |
|        | 59,201.291203 | 172.4246   | -10.59873   | 26.997 ± 0.038   | -8.319 ± 0.066           | 18.678 ± 0.077        |
|        | 59,201.294848 | 172.42313  | -10.59963   | 27.010 ± 0.053   | -8.210 ± 0.070           | 18.800 ± 0.088        |
|        | 59,201.298486 | 172.42379  | -10.60053   | 27.012 ± 0.049   | -8.223 ± 0.062           | 18.789 ± 0.079        |
|        | 59,201.302166 | 172.42459  | -10.60161   | 27.022 ± 0.037   | -8.386 ± 0.058           | 18.636 ± 0.069        |
|        | 59,201.305797 | 172.42525  | -10.60251   | 27.029 ± 0.044   | -8.435 ± 0.065           | 18.594 ± 0.078        |
|        | 59,201.309434 | 172.42590  | -10.60341   | 27.050 ± 0.053   | -8.517 ± 0.079           | 18.553 ± 0.095        |
|        | 59,201.313071 | 172.42655  | -10.60431   | 27.041 ± 0.060   | -8.616 ± 0.065           | 18.425 ± 0.089        |
|        | 59,201.316718 | 172.42733  | -10.60539   | 27.058 ± 0.036   | -8.665 ± 0.059           | 18.393 ± 0.070        |
| $V$    | 59,201.303533 | 172.42798  | -10.60629   | 27.057 ± 0.036   | -8.520 ± 0.066           | 18.538 ± 0.075        |
|        | 59,201.322838 | 172.42719  | -10.60719   | 27.075 ± 0.055   | -8.434 ± 0.056           | 18.641 ± 0.078        |
|        | 59,201.327613 | 172.42927  | -10.60809   | 27.071 ± 0.050   | -8.379 ± 0.065           | 18.692 ± 0.082        |
|        | 59,201.331241 | 172.42990  | -10.60899   | 27.045 ± 0.057   | -8.479 ± 0.054           | 18.566 ± 0.078        |
|        | 59,201.334883 | 172.43067  | -10.61006   | 27.029 ± 0.047   | -8.484 ± 0.057           | 18.545 ± 0.074        |
|        | 59,201.338529 | 172.43130  | -10.61096   | 27.056 ± 0.044   | -8.447 ± 0.053           | 18.608 ± 0.069        |
|        | 59,201.342191 | 172.43193  | -10.61185   | 27.022 ± 0.053   | -8.296 ± 0.068           | 18.726 ± 0.086        |
|        | 59,201.345835 | 172.43269  | -10.61293   | 27.045 ± 0.047   | -8.543 ± 0.052           | 18.502 ± 0.070        |

Note. The CTIO V-filter observations began on 2020 December 18 at 06:59:20 and ended on 2020 December 18 at 08:18:00 (i.e., separated from NEOWISE’s first epoch of observations by roughly 15 hr). The airmass during the first image was 1.6, and the same during the last image was 1.22. Airmass was reducing during the observing run. All observations were taken during nighttime and were 4 days past new moon (i.e., there was no moon effect). The table has been truncated for conciseness. All values below the ellipses are in $V$, and observations in the $B$, $g$, and $r$ filters can be accessed in an electronic format. Only the median $V$ magnitude ($18.60 \pm 0.11$) was used in this paper to constrain the $H$ magnitude.

(This table is available in its entirety in machine-readable form.)

period and $\Gamma$ prior by adding a penalty to the $\chi^2$ when a model is outside the allowed range. These penalties are of the form $[\ln(\text{parameter/limit})/\text{width}]^2$ but only applied if the parameter is greater than the upper limit or less than the lower limit. The walkers update their position and compute a new parameter set using the equation $p_t = p_1 + (p_2 - p_1)z$, where $z$ is in the range 0.5–2 and the square root of $z$ is uniformly distributed, and ultimately, the goodness of fit is determined by a robust $\chi^2$ test.

For (99942) Apophis, measurements at both the 3.4 and 4.6 $\mu$m bands were applied to the NEATM and TPM to derive size and visual albedo estimates. Thermal inertia ($\Gamma$), crater fraction, and axis ratios were also calculated by the TPM.
For implementing NEATM, values for the beaming parameter and the ratio of infrared to visible albedos (\(p_{IR}/p_V\)) were assumed based on prior measurements of these quantities from cases where more thermally dominated infrared bands were available. Beaming was assumed to be \(1.4 \pm 0.5\), and \(p_{W2}/p_V\) was assumed to be \(1.6 \pm 1.0\) based on Mainzer et al. (2011c) and Masiero et al. (2021a); the slope parameter \(G\) was set to \(0.25 \pm 0.2\)—a value appropriate for S-type asteroids (Delbo et al. 2007; Vereš et al. 2015)—and the \(H\) mag was set to the derived value of \(19.1 \pm 0.5\). For the first epoch, only the W2-band data were used, as observations in W1 were too faint to produce reliable results. However, the object was much brighter during the second epoch of observations, and data from both bands were used. The NEATM analysis of the first-epoch data returned a diameter of \(306 \pm 86\) m and a geometric albedo of \(0.43 \pm 0.24\), and applying the same to the second-epoch data yielded a diameter of \(406 \pm 123\) m and a visible geometric albedo of \(0.29 \pm 0.20\). The average effective spherical diameter was calculated to be \(355 \pm 75\) m, and the average visible geometric albedo was found to be \(0.36 \pm 0.16\). The results obtained were in agreement with systematic uncertainties associated with NEOWISE diameter and albedo estimates derived solely using 3.4 and 4.6 \(\mu m\) photometry (expected to be \(\sim 20\%\) and \(\sim 40\%\), respectively, as shown by Mainzer et al. 2012 and Masiero et al. 2012). Figure 3 contains the light-curve information from the two sets of observations.

For the TPM, the average flux was computed for each band at each observing epoch. First, the spherical shape model (also denoted as spherical TPM in this paper) was employed with a fixed rotational period of 30.568 hr,\(^{12}\) a \(G\) value of 0.25, an \(H\) value of \(19.1 \pm 0.5\), and an emissivity of 0.9. Two hundred priors were generated, and after 48,600 Markov chain loops, the TPM yielded an effective diameter of \(340 \pm 65\) m, an effective visible geometric albedo of \(0.31 \pm 0.09\), and thermal inertia (\(\Gamma\)) in the range of \(350–3400\) J m\(^{-2}\) s\(^{-1}\) K\(^{-1}\) with a best-fit value of \(950\) J m\(^{-2}\) s\(^{-1}\) K\(^{-1}\). The crater fraction was found to be \(0.49 \pm 0.32\). The thermophysical results were further constrained using the Asteroid Lightcurve Database (LCDB; Warner et al. 2021) pole solution for Apophis, \((\alpha, \delta) = (119^\circ, -79^\circ)\), with a search radius of 50\(^\circ\). In this case, the TPM yielded an effective diameter of \(330 \pm 50\) m, an effective visible geometric albedo of \(0.32 \pm 0.08\), \(\Gamma \sim 300–2150\) J m\(^{-2}\) s\(^{-1}\) K\(^{-1}\) with a best-fit value of \(700\) J m\(^{-2}\) s\(^{-1}\) K\(^{-1}\), and a crater fraction equal to \(0.46 \pm 0.28\).

Apophis was also modeled as a triaxial ellipsoid in the TPM (referred to as triaxial TPM in this paper) and run with the same rotational period, \(H\), \(G\), and emissivity values as the spherical model. With the triaxial implementation, the TPM yielded an effective diameter of \(330 \pm 90\) m, an effective visible geometric albedo of \(0.31 \pm 0.10\), a crater fraction of \(0.51 \pm 0.10\), a \(b/a\) axis ratio equal to \(0.63 \pm 0.10\), a \(c/b\) axis ratio equal to \(0.85 \pm 0.11\), and thermal inertia (\(\Gamma\)) in the range of \(100–2800\) J m\(^{-2}\) s\(^{-1}\) K\(^{-1}\) with a best-fit value of \(500\) J m\(^{-2}\) s\(^{-1}\) K\(^{-1}\). Similar to the spherical model, the triaxial TPM implementation was further constrained using the LCDB pole solution for Apophis. This yielded an effective diameter of \(340 \pm 70\) m, an effective visible geometric albedo of \(0.31 \pm 0.09\), a crater fraction of \(0.52 \pm 0.34\), a \(b/a\) axis ratio equal to \(0.63 \pm 0.15\), a \(c/b\) axis ratio equal to \(0.87 \pm 0.10\), and \(\Gamma \sim 150–2850\) J m\(^{-2}\) s\(^{-1}\) K\(^{-1}\) with a best-fit value of \(550\) J m\(^{-2}\) s\(^{-1}\) K\(^{-1}\). The plots in Figures 4 and 5 are associated with the TPM, and they display the flux during the two epochs, the effective spherical diameter of the object, the best-fit thermal inertia value, and the distribution of the visual albedo results.

\(^{12}\) The rotational period was computed by averaging the five different results listed in Loeza-González et al. (2021), along with the rotational period derived by Augustin & Behrend as listed on the Geneva Observatory’s Rotation curves of asteroids and comets, CDr web page: https://obswww.unige.ch/~behrend/page5cou.html.
4. Discussion

Delbo et al. (2007) were the first to present size and visible albedo estimations of (99942) Apophis using polarimetric observations from the 8.2 m VLT-Kueyen telescope of the European Southern Observatory, finding $p_V = 0.33 \pm 0.08$ and $D_{\text{eff}} = 270 \pm 60$ m. Müller et al. (2014b) used far-infrared observations from the Herschel Space Telescope PACS instrument and estimated $D_{\text{eff}} = 375^{+14}_{-10}$ m and $p_V = 0.3^{+0.05}_{-0.06}$.

Licandro et al. (2016) combined Herschel-PACS data with GTC/CanariCam data and reported an effective diameter between 380 and 393 m and a visible albedo in the range 0.24–0.33. Brozovic et al. (2018) found a best-fit diameter of $340 \pm 40$ m and a visible albedo of $0.35 \pm 0.10$ by examining (99942) Apophis using radar observations from Goldstone and Arecibo and rendering it as a 3D model using light curve–derived shape and spin states from Pravec et al. (2014). Our

Figure 4. Plots highlighting the TPM results with (99942) Apophis modeled as a sphere. Clockwise from top left: average flux density during the two epochs along with the span of the bandpasses (the average flux was 95.77 $\mu$Jy in W1 and 381.13 $\mu$Jy in W2 during the first epoch and 622.88 $\mu$Jy in W1 and 3475.26 $\mu$Jy in W2 during the second epoch), histogram of the diameter results with the 68% (dashed lines) and 95% (dotted lines) confidence interval ranges, histogram of the thermal inertia results with the 68% (dashed lines) confidence interval range (the 95% confidence interval values lie outside the x-axis range), and histogram of the visual albedo results with the 68% (dashed lines) and 95% (dotted lines) confidence interval ranges. The fainter histograms in the top right, bottom left, and bottom right panels signify the solutions without the LCDB pole solution constraint.
effective diameter and visible albedo estimate for Apophis from both NEATM and TPM are consistent with estimates put forward by Müller et al. (2014b), Licandro et al. (2016), and Brozovic et al. (2018) to within the measurement uncertainties. Our results show that Apophis most likely has a thermal inertia value of \( \sim 550 \text{ J m}^{-2} \text{s}^{1/2} \text{K}^{-1} \), and such a value suggests that the asteroid’s surface may consist of small and moderately sized boulders possibly interspersed with coarse sand. Our derived thermal inertia result overlaps with estimated ranges cited in the previous studies. The same study by Müller et al. (2014b) found a thermal inertia in the range of 250–800 J m\(^{-2}\) s\(^{-1/2}\) K\(^{-1}\) with a best fit at 600 J m\(^{-2}\) s\(^{-1/2}\) K\(^{-1}\), and Licandro et al. (2016) cited a thermal inertia in the range of 50–500 J m\(^{-2}\) s\(^{-1/2}\) K\(^{-1}\). A much lower value of \( \Gamma = 100^{+340}_{-100} \text{ J m}^{-2} \text{s}^{1/2} \text{K}^{-1} \) was also put

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**Figure 5.** Plots highlighting the TPM results with (99942) Apophis modeled as a triaxial ellipsoid. Clockwise from top left: average flux density during the two epochs along with the span of the bandpasses (the average flux was 95.37 \( \mu \text{Jy} \) in W1 and 385.73 \( \mu \text{Jy} \) in W2 during the first epoch and 621.31 \( \mu \text{Jy} \) in W1 and 3496.75 \( \mu \text{Jy} \) in W2 during the second epoch), histogram of the diameter results with the 68% (dashed lines) and 95% (dotted lines) confidence interval ranges, histogram of the thermal inertia results with the 68% (dashed lines) confidence interval range (the 95% confidence interval values lie outside the x-axis range), and histogram of the visual albedo results with the 68% (dashed lines) and 95% (dotted lines) confidence interval ranges. The fainter histograms in the top right, bottom left, and bottom right panels show the distribution without the LCDB pole solution constraint.
forward by Yu et al. (2017). For comparison, Itokawa—an asteroid very similar to Apophis in size and taxonomic class—was measured to have $\Gamma = 700 \pm 200 \, \text{J m}^{-2} \, \text{s}^{-1/2} \, \text{K}^{-1}$ by Müller et al. (2014a). However, low thermal inertia values cannot be dismissed given the case of Bennu ($\Gamma \sim 300 \, \text{J m}^{-2} \, \text{s}^{-1/2} \, \text{K}^{-1}$), where surface property predictions based on remote observations were incongruent with those based on in situ observations (Rozitis et al. 2020).

The TPM may seem preferable to the NEATM, since it can be used to compute parameters beyond diameter and albedo, such as spin axis or thermal inertia; however, both thermal models are useful depending on the type and quantity of the data and the goal of the study. The NEATM is highly computationally efficient, consuming seconds to minutes to produce results for a single object such as Apophis, whereas the TPM takes several hours to do the same. The NEATM is most appropriate for objects where only a single viewing geometry and a limited number of wavelengths are available. On the other hand, the TPM is suitable in cases where multiepoch data and a limited number of wavelengths are available. In the case of Apophis, both epochs of W2 observations are thermally dominated, as the heliocentric distance of the object was roughly 1 au.

Regardless of the thermal model used, appropriate selection of the phase curve slope parameter $G$ is necessary to accurately determine the apparent visible magnitude from the absolute magnitude ($H$) at the time of the NEOWISE IR observations. For an S- or Sq-class asteroid like Apophis, the $G$ value is typically assumed to be 0.25. We used the average phase integral value ($q = 0.47 \pm 0.15$) put forward by Shevchenko et al. (2019) to calculate $G = 0.25 \pm 0.20$. Vereš et al. (2015) and Colazo et al. (2021) computed a value of $G \sim 0.20$ for such asteroids, but this value is within the measurement uncertainty range and does not seem to have a noticeable effect on the results. For instance, taking $G = 0.2 \pm 0.1$ gives a result of $D_{\text{fit}} = 355 \pm 79 \, \text{m}$ and $p_V = 0.387 \pm 0.302$ using the NEATM and $D_{\text{fit}} = 365 \pm 63 \, \text{m}$ and $p_V = 0.33 \pm 0.10$ via the TPM; while larger variations in the slope parameter would affect the resultant visual albedo, estimates for $G = 0.20 \pm 0.10$ and 0.25 $\pm 0.10$ are virtually identical. Small changes in the absolute magnitude $H$, however, drastically affect the $V$ albedo, as shown by Masiero et al. (2021b). The Horizons catalog $H$ mag of 19.7 was thus not used in the thermal models because $H$ estimates for NEAs tend to be imprecise due to poor sampling of the phase curve over a small range of phase angles. Near-simultaneous photometry from CTIO enabled us to calculate $H = 19.1 \pm 0.5$ (for comparison, Pravec et al. 2014 reported a similar $H$ value of 19.09 $\pm 0.19$).

Considerations regarding the choice of emissivity value and pole position were also made. Studies show that meteorite samples and asteroid analogs typically have emissivities close to 0.9 in the low- and mid-IR ranges (Donaldson Hanna et al. 2019; Maturilli et al. 2016). Rozitis et al. (2018) noted that an emissivity of 0.9 is a fair assumption at all observed wavelengths, as thermophysical models have been able to reproduce 4–40 $\mu$m observations of various asteroids. We quantified the influence of emissivity by running the TPM with NEOWISE’s Apophis observations using emissivity values of 0.8, 0.9, 0.95, and 0.99. No significant differences were observed in the TPM results for the four different emissivity values (see Table 4). The mean pole positions computed in the four scenarios were also virtually identical (spin pole results for an emissivity of 0.9 can be found in Figure 6). Thus, an emissivity of 0.9 was used for the final TPM implementation.

Reflected-light contributions were also considered to ensure that the bands were thermally dominated during the observations. In our implementation of the NEATM, if more than three-quarters of the light in the first band comprises reflected light, then fitting is redone with the infrared albedo as a free parameter (the thresholds are different if three or more detections exist). In the case of NEOWISE’s (99942) Apophis observations, the reflected-light contributions were $\sim 57\%$ in W1 and $\sim 1\%$ in W2 in epoch 2. The same for the latter was $\sim 2\%$ in epoch 1 (W1 observations from epoch 1 were discarded during the NEATM fitting routine due to their low S/Ns). Therefore, W2 was thermally dominated during both of the observing epochs, indicating that there is sufficient thermal flux for thermal modeling.

In this paper, the TPM was employed using both the LCDB pole solution and the pole solution constrained using NEOWISE’s Apophis data. The use of the LCDB pole solution is intended to demonstrate how rotational state data, which could be obtained during a close-approach event, would improve the TPM results and greatly benefit planetary defense. The triaxial TPM was implemented under the assumption that if the object were to truly impact Earth, a coordinated campaign to determine the shape from light-curve inversion would have been carried out. Although not part of the exercise as it was undertaken, such data could have been acquired during a close-pass epoch if additional resources had been brought to bear. Further areas of improvement could include combining the NEOWISE data with Herschel’s and implementing the triaxial (or a more complex) shape model in the TPM to better constrain the size, albedo, and thermal inertia. The same could be achieved through multiepoch thermal observations as well, although such observations are hard to obtain from NEOWISE due to a fixed scanning pattern and limited mission time. Upcoming projects like the Near-Earth Object Surveyor (Mainzer et al. 2015) could make it possible to obtain multiepoch data in wavelengths dominated by the thermal emission of asteroids. Future studies could theorize the effect of a large thermal inertia value on the Yarkovsky drift (Bottke et al. 2002) and close-approach gravitational perturbations (Chodas 1999).

### Table 4

| Emissivity | Diameter (m) | Albedo  | Thermal Inertia (J m$^{-2}$ s$^{-1/2}$ K$^{-1}$) |
|------------|-------------|---------|---------------------------------|
| 0.80       | 320 ± 60    | 0.33 ± 0.10 | 1050$^{+250}_{-300}$ |
| 0.90       | 340 ± 65    | 0.31 ± 0.09 | 950$^{+250}_{-300}$ |
| 0.95       | 340 ± 70    | 0.31 ± 0.09 | 900$^{+250}_{-300}$ |
| 0.99       | 350 ± 70    | 0.31 ± 0.09 | 900$^{+240}_{-300}$ |
| 0.80       | 320 ± 80    | 0.31 ± 0.10 | 400$^{+250}_{-300}$ |
| 0.90       | 330 ± 90    | 0.30 ± 0.10 | 500$^{+300}_{-300}$ |
| 0.95       | 330 ± 90    | 0.31 ± 0.10 | 400$^{+150}_{-150}$ |
| 0.99       | 330 ± 90    | 0.30 ± 0.10 | 350$^{+180}_{-180}$ |

**Note.** The results shown are TPM implementations without the LCDB pole solution constraint. The top four rows are results from the spherical TPM, and the bottom four are from the triaxial TPM.
The density was assumed to be 2700 kg m\(^{-3}\) from Carry (2012), and the impact velocity was assumed to be 20 km s\(^{-1}\) from Harris & Hughes (1994) and French (1998).

13 The density was assumed to be 2700 kg m\(^{-3}\) from Carry (2012), and the impact velocity was assumed to be 20 km s\(^{-1}\) from Harris & Hughes (1994) and French (1998).
