Practice Observing a Potential Impactor:
Spacewatch was a major contributor to the lightcurve component of the IAWN campaign to study Apophis before its close approach in 2029, as if it were an unknown bright impending Earth-impactor. One of the main goals of the campaign was "exercise the observing resources and characterization capabilities that may be applied to a near-Earth object on a reasonably short timescale" (https://iawn.net/obscamp/Apophis/). Because Spacewatch is the sole user of the 1.8 and 0.9m telescopes, we can react immediately to observe a hazardous NEA such as Apophis if it had been a freshly discovered object and had a significant impact probability. In addition, we proved that we could complete our analysis and share our results within a short time span.

We participated in the International Asteroid Warning Network (IAWN, https://iawn.net/obscamp/Apophis//) to practice studying a "new" bright hazardous NEA using the well-known NEA Apophis, also known as 99942 (2004 MN4). Apophis became bright enough to be "rediscovered" serendipitously by all-sky surveys in early December 2020 and "recognized" as an NEA based on survey observations collected on December 18. We participated in the campaign in two ways. We contributed to the astrometric recovery of Apophis in order to determine how quickly the orbit could be determined to our current level of knowledge using only new observations. Most of our contribution to the campaign, however, was with lightcurve measurements.

An asteroid's lightcurve, the change in apparent brightness over time, is indicative of irregularities in its shape; and the rotation rate reveals its internal cohesion. Thus, rotation speeds of asteroids are one key element to understanding their internal structure. For cases of possible spacecraft flyby missions and rendezvous missions, the target's rotation rate needs to be known before arrival so that scientific investigations can be planned ahead of time for successful data collection to meet mission goals. For cases of possible future Earth impactors, the physical properties of the objects, including rotation rate and internal cohesion, will have to be known to plan strategies for deflection. Spacewatch contributes to worldwide investigations of asteroid rotation with the Spacewatch 1.8m telescope and the Steward Observatory 0.9m and Bok 2.3m telescopes on Kitt Peak. Using the Bok telescope allows us to observe fainter, and therefore smaller or more distant, targets than many other lightcurve groups.

Lightcurves can constrain the strength of an asteroid body, *i.e.*, how well it is held together, based on how fast it is rotating. An object with greater strength would have a higher density than a low strength object and a correspondingly larger mass than a low strength object of the same volume. NEAs are not large enough for gravity to make them round. Some asteroids are rubble piles of boulders, rocks, stones, dirt, and dust. Rubble piles like Bennu and Ryugu, which have most recently been studied *in situ* by the spacecraft OSIRIS-REx and Hayabusa 2 respectively, would shed rocks and boulders if they spun too fast. If spun extremely fast they would come apart. Large rubble piles thus can dissipate some of their angular momentum over time as they shed material. Bodies that spin very fast are usually small and must be solid bodies (monoliths), having never had or already shed loose material. Monolithic small asteroids have a much harder time dissipating rotational energy and can therefore be tumbling instead of rotating along a single axis.

As an asteroid rotates, the detected visible light is sunlight reflected off the asteroid's surface toward Earth. Because asteroids are usually irregularly shaped, as they rotate, the amount of surface area pointing toward Earth changes. More light is seen when a wide side faces Earth than when a narrow side faces Earth. To create a lightcurve, we take several series of short-exposure images of an asteroid. We then measure the brightness of the asteroid in each image compared to the brightness of the stars in that image and plot the asteroid's relative brightness over time. This creates an oscillating waveform, which we call a lightcurve. For irregularly shaped asteroids, one complete rotation involves two peaks and two troughs, also known as a double-peaked lightcurve, as we observe the 'front' side and then the 'back' side of the asteroid. The period of the undulating wave is equal to the time that it takes the asteroid to complete one rotation.

We select our lightcurve targets from four primary categories: possible future impactors, binary systems, potential targets of radar, and candidates for detecting the Yarkovsky Effect (a non-gravitation force on an asteroid that can slowly change the orbit due to the asteroid's anisotropic thermal radiation).

Possible Impactors

An impact by an asteroid or comet with the Earth is one of very few natural disasters that may be predicted in advance and that we have the possibility of preventing if the object is discovered and an orbit determined with sufficient warning time. Virtual Impactors (VIs) are NEAs and near-Earth comets with uncertainty in their heliocentric orbital parameters such that some possible orbit solutions predict a future impact with Earth within 100 years. Based on our current level of knowledge of their orbits, these objects pose a real, but very low, probability of impact. For VIs with non-negligible impact probabilities, it would be essential for VI characterization to narrow down the range of possible strengths (rubble pile to monolith) from the rotation period, and to estimate the ratio of the body's axes from the amplitude of the lightcurve. It would also be useful to determine whether the VI has a secondary rotation period or is tumbling (Reddy *et al.* 2019).

The Brinson Foundation supported our research to create new lightcurves of Apophis which were combined with those from other groups based only on new observations. The key members of the team were Prof. Jeffrey Larsen of the U.S. Naval Academy, who performed the data analysis and lightcurve fitting, and all six Spacewatch observers, Terry Bressi, Melissa Brucker, Ron Mastaler, Mike Read, Jim Scotti, and Andrew Tubbiolo, who operated the 1.8m and 0.9m telescopes to collect photometry data for Prof. Larsen to analyze. If Apophis were a completely unknown hazardous possible Earth-impactor, it would be important to determine its rotational period quickly. We began observing Apophis with the 1.8m telescope beginning on January 8, 2021 before most other lightcurve groups, while it was relatively faint (V~18). We collected 9 nights of data between 2021 January 8 and January 18, 6 of which were included in our analysis (Figure 1). Prof. Larsen quickly analyzed the January data. From the 6 nights of data, he was able to determine a rotation period of approximately 30.5 hours. We demonstrated that we could provide valuable information when time is critical for imminent threats. The 30.5 hour period told us that 'the object' has a relatively long rotation period compared to other asteroids. Because the practice target Apophis is well-known, we knew the rotation period determined with our January data agrees with its actual rotational period.

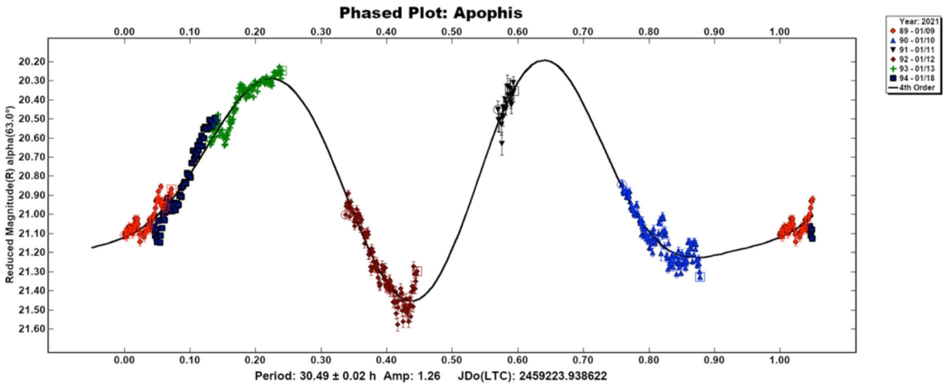

Figure 1. Spacewatch lightcurve data of Apophis with the 1.8m telescope. This plot was created by Prof. Larsen. The black line is a 4th order sinusoidal fit to the data. After a period of 30.49 hours was determined from the fit, the data from 2021 January 9 through 18 were folded to that rotation period. You can see two peaks and two troughs from the ‘front’ and ‘back’ sides of the asteroid.

Because Apophis was approaching Earth, we were able to collect lightcurve data for four months. As Apophis grew brighter, we began using the 0.9m telescope in early February 2021. In order to cover one whole rotation for analysis, Prof. Larsen calculated that 12 consecutive nights would sample all parts of the lightcurve. We were able to collect 28 nights of lightcurve data with the 0.9m telescope between 2021 February 5 and April 13, 26 of which were used in our analysis.

Prof. Larsen made an extraordinary effort, while teaching, to review and analyze all 28 nights of 0.9m telescope data and construct corresponding lightcurves within 2 weeks of the last observations being collected. See Figures 2 and 3 for a subset of the 0.9m data. With the accuracy and precision of our observations, Prof. Larsen was able to “discover” that Apophis is tumbling and thus has not yet relaxed into a state of single-axis rotation. Two indications of tumbling are seen in Figure 3 at rotational phases 0.05 and 0.9. Tumbling would be an important detail to discover quickly if Apophis were an unknown incoming hazardous asteroid.

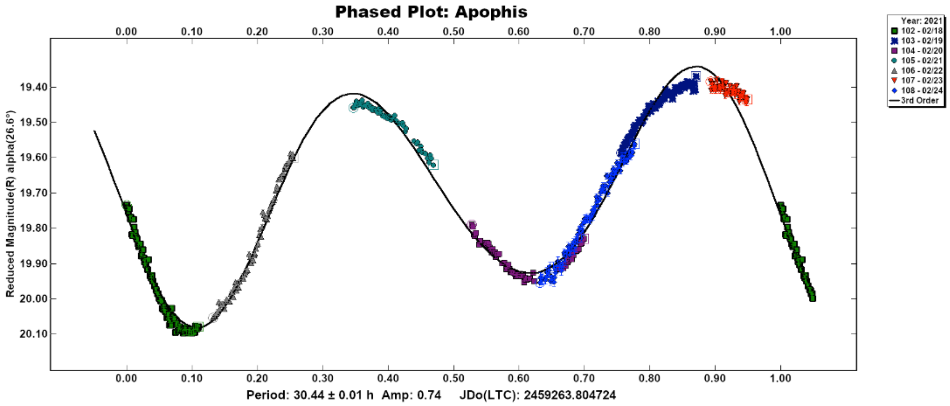

Figure 2. Spacewatch 0.9m telescope data spanning 2021 February 18 through 24, folded using a period of 30.44 hours derived from a third order sinusoidal fit to this data.

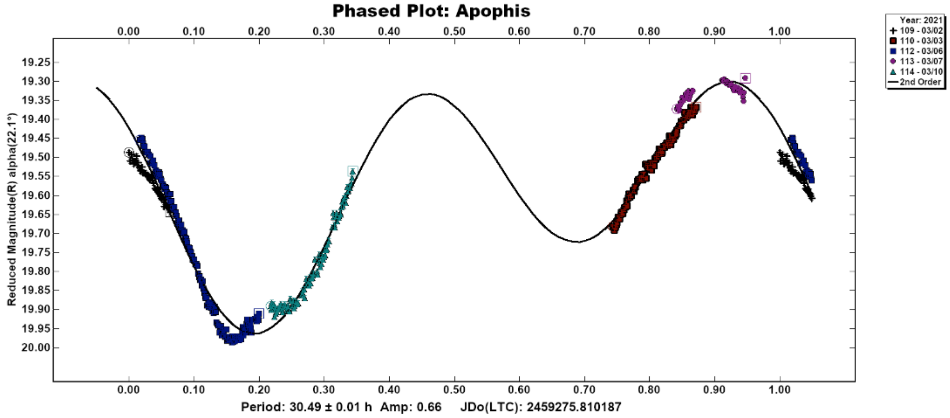

Figure 3. Spacewatch 0.9m telescope data spanning 2021 March 2 through 10 folded using a period of 30.49 hours derived from a second order sinusoidal fit to this data. The irregularities at phase 0.05 and phase 0.9 are indications of tumbling.

In order to detect a period from unevenly sampled time series data, astronomers often use a periodogram analysis (Lomb 1976, Scargle 1982). Dr. Nic Erasmus, of the South African Astronomical Observatory in Cape Town, was the lightcurve lead for the campaign. He analyzed data without and with our data. Periodic data has the potential to show aliasing, or the misidentification of the dominant period, especially if observation sets are collected in a repetitive cadence. Without the Spacewatch data, many peaks in the periodogram represented possible periods. Once the Spacewatch data were added, the resulting periodogram shows clearly that the dominant rotation period is 30.55 ± 1.47 hours.

Dr. Erasmus stated that our 0.9m data, 15% of the campaign lightcurve data, was the second largest contribution to the complete data set. He expressed appreciation at having a second large data source like ours taken at different times and longitude with different equipment than the 40% of the data set contributed by Calar Alto Observatory because it suppressed the normal 24 hour feature in the periodogram that comes from the same observatory at the same location taking data at the same time every night (personal communication, 2021 May 6).

A manuscript detailing the Apophis campaign, its results, and lessons learned for planetary defense is in preparation by the campaign lead, Prof. Vishnu Reddy, and the section leads.

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