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STRENGTHENING PLANETARY DEFENSE: DEVELOPING ALGORITHMS TO DETERMINE THE PHYSICAL PROPERTIES OF ASTEROIDS AND APPLYING THEM TO MEASURE THE IMPACT OF NASA'S DART MISSION ON DIDYMOS

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Introduction

There are over 31,300 known near-Earth asteroids as of March 2023, and thousands of new ones are discovered yearly. The pace of discovery of near-earth asteroids currently outpaces the ability to analyze them. If an asteroid were on a collision path with Earth, the deflection strategy would depend, among other factors, on its physical characteristics: its size, rotation period, whether it is monolithic or a rubble pile, and does it have a satellite.

Planetary defense is being taken seriously by space agencies and national governments. On 26 September 2022, NASA's Double Asteroid Redirection Test (DART) Mission successfully tested its first planetary defense mission by impacting asteroid Dimorphos, the moonlet of asteroid Didymos and changing its orbital period. In late December 2026, the Hera Mission of the European Space Agency (ESA) will rendezvous with the Didymos system to study the DART crater and measure the momentum transfer efficiency. In 2025 the China National Space Administration (CNSA) plans to launch a surveyor and an impactor on a Long March 5 rocket to change the trajectory of an earth-crossing Aten asteroid 2020 PN1. (https://www.space.com/china-asteroid-impact-mission-two-spacecraft)

Open science, open data and open-source algorithms could be used to determine the physical properties of asteroids and measure the effectiveness of asteroid deflection techniques; it would accelerate the analysis of near-earth asteroids. Every citizen scientist would be a planetary defender, which could mean the difference between planetary extinction and a near miss.

Project Goals and Objectives

My project had two goals. First, develop python algorithms to determine an asteroid's physical properties using robotic telescopes and open data. Second, apply my algorithm to measure changes in the Didymos system before, during and after the NASA DART impact.

The specific objectives included:

1. Developing photometry algorithms to generate composite asteroid light curves
2. Determining the rotation period of an asteroid
3. Determining the mutual orbital period of a binary asteroid system
4. Inferring the physical characteristics of the asteroid, namely its size and strength
5. Imaging Didymos before, during and after the impact to:

- Determine the physical characteristics of Didymos
- Study the ejecta tail from Dimorphos
- Determine the change in the orbital period of Dimorphos around Didymos

Imaging Didymos Using Robotic Telescopes

To gather data for my project, I imaged Didymos for over 60 hours spread over several weeks using robotic telescopes across four continents in Australia, Canada, Chile and Spain (Figure 1). Observations were also taken from a space-based telescope NEOSsat of the Canadian Space Agency.

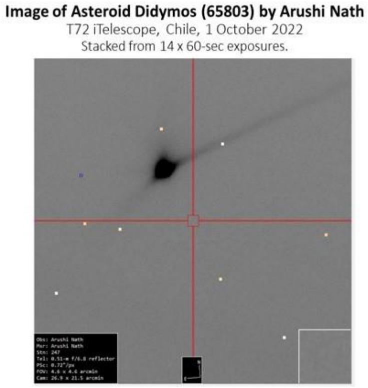
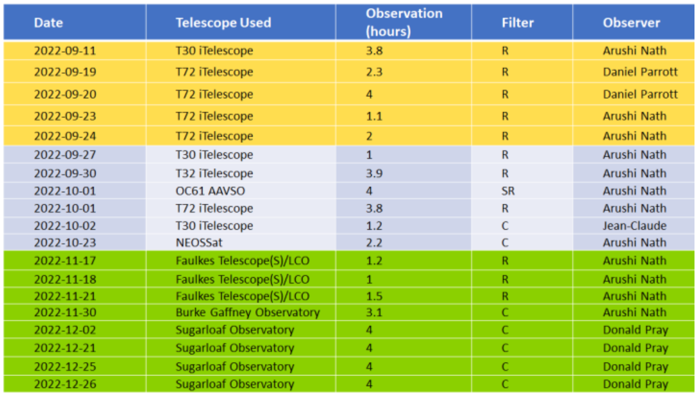


Figure 1

I wrote project proposals for the Faulkes Telescope Project, the American Association of Variable Star Observers (AAVSO), the Canadian Space Agency, and the Burke Gaffney Observatory to get imaging time on their telescopes. As there was a high demand for telescopes to image Didymos to measure the impact of the DART Mission, I collaborated with other citizen astronomers to coordinate our observations of Didymos and share data. It proved to be very useful for getting extended observations of Didymos over consecutive nights to capture the long orbital period of its moonlet Dimorphos. See Table 1 below for the list of primary observations of Didymos used for analysis.

Table 1: Primary Observations of 65803 Didymos



Date	Telescope Used	Observation (hours)	Filter	Observer
2022-09-11	T30 iTelescope	3.8	R	Arushi Nath
2022-09-19	T72 iTelescope	2.3	R	Daniel Parrott
2022-09-20	T72 iTelescope	4	R	Daniel Parrott
2022-09-23	T72 iTelescope	1.1	R	Arushi Nath
2022-09-24	T72 iTelescope	2	R	Arushi Nath
2022-09-27	T30 iTelescope	1	R	Arushi Nath
2022-09-30	T32 iTelescope	3.9	R	Arushi Nath
2022-10-01	OC61 AAVSO	4	SR	Arushi Nath
2022-10-01	T72 iTelescope	3.8	R	Arushi Nath
2022-10-02	T30 iTelescope	1.2	C	Jean-Claude
2022-10-23	NEOSSat	2.2	C	Arushi Nath
2022-11-17	Faulkes Telescope(S)/LCO	1.2	R	Arushi Nath
2022-11-18	Faulkes Telescope(S)/LCO	1	R	Arushi Nath
2022-11-21	Faulkes Telescope(S)/LCO	1.5	R	Arushi Nath
2022-11-30	Burke Gaffney Observatory	3.1	C	Arushi Nath
2022-12-02	Sugarloaf Observatory	4	C	Donald Pray
2022-12-21	Sugarloaf Observatory	4	C	Donald Pray
2022-12-25	Sugarloaf Observatory	4	C	Donald Pray
2022-12-26	Sugarloaf Observatory	4	C	Donald Pray

Methodology

I made use of photometry techniques to attain the project objectives. These included centroiding, differential photometry, applying offsets, creating composite light curves and their analysis. I developed custom algorithms using Python language and its libraries over several months to analyze the images I gathered of Didymos. Open datasets, math and open science, were used, as detailed in the ten-step methodology below:

1. Centroiding known stars and asteroids: I queried the European Space Agency's GAIA DR3 database for the positions of known stars and NASA/JPL Horizons System for the position of Didymos in the images at any given time. The centroiding algorithm used weighted means of pixel brightness values to find the center of celestial objects.

2. Determining the correct aperture size for differential photometry: Selecting the right aperture size is essential to perform differential photometry. If it is too small, it will not capture the object's total brightness value of the object, and if it is too big, it will increase background noise. My algorithm found the best aperture size for Didymos on each image and calculated the median value across all images in a single observation period to get the final size.

3. Finding comparison stars: An asteroid's brightness varies with changes in seeing conditions, such as air mass and weather. The impact of these changes can be minimized by measuring changes in the brightness of selected stars of known magnitudes in the same field of view. These selected stars, also called the comparison stars, could not be variable stars and had to be of similar brightness to Didymos. 4-7 comparison stars were selected for each image.

4. Finding the computed magnitude of an asteroid: To find the computed magnitude of Didymos, I subtracted the instrument magnitude of the comparison stars from their true magnitude (obtained from the GAIA Data Release 3 database) to get the offsets for every image. These offsets were averaged for all comparison stars and then applied to the instrument magnitude of Didymos to get its computed magnitude in every image.

5. Applying offsets to find the absolute magnitude of the asteroid: As asteroids orbit around the sun, their observed brightness varies because of changes in heliocentric distance, geocentric distance and phase angle. To account for these changes, I used open science to standardize the magnitude of Didymos as if it were one astronomical unit from the Earth and the Sun and at a zero-phase angle. Applying these offsets to the time-series computed magnitudes of Didymos yielded its absolute magnitude.

6. Combining individual light curves to create composites: Light curves from different nights must be combined to create composite light curves. To do so, I made a lower and upper estimate of the periodicity and divided them into thousands of intervals. The greater the number of intervals, the more accurate would be the periodicity value. I combined all the observations using modulus. I then found the fourth-order curve fit of the combined observations and used it to calculate the root mean square error (RMSE). The curve with the smallest RMSE was the composite light curve.

7. Finding the rotation period of asteroids: Small kilometre-sized asteroids are irregular in shape as they do not have enough gravity to make them spherical. When asteroids rotate, the light reflected from different sides causes a change in their observed brightness. The asteroid light curves reveal the difference in brightness and allow measurement of the asteroid's rotation period and the rotation amplitude. To find the rotation period of Didymos, I estimated the periodicity to be between 2 and 5 hours and subdivided these into 5000 intervals to create the most accurate composite curve.

8. Finding the orbital period of the secondary asteroid around the primary: In the case of a binary asteroid system, subtracting the primary asteroid rotation curve from the composite light curve would produce a

secondary light curve. It would contain information about the orbital period and rotation period of the secondary asteroid. Assuming that Didymos and Dimorphos are tidally locked, the orbital period of the secondary would equal one rotation of the secondary, simplifying the analysis. Estimating the orbital period to be between 8 and 16 hours, I repeated the process of dividing these into sub-intervals, finding the fourth-order curve fitting and calculations of RMSE to determine the orbital period of the secondary.

9. <u>Finding change in the apparent magnitude of the asteroid after impact:</u> The difference in the apparent magnitude of the Didymos system was measured by observing and applying photometry techniques before and after the impact. A comparison of these changes was also made with the scenario in case there was no impact to accurately measure the changes in the apparent magnitude of the asteroid because of the impact.

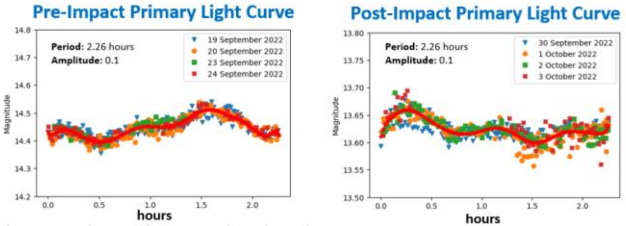
10. <u>Finding ejecta tail length:</u> I took several observations of Didymos after the impact to measure the size of the ejecta tail. I measured the length of the tail in the images in pixel counts. Using the pixel scale value of the cameras, I converted the tail length into arc minutes. I used the distance of Didymos from the Earth to calculate the ejecta length in kilometres.

Results

I was able to successfully develop my algorithm to analyze the physical characteristics of an asteroid. I applied my algorithm to images taken of the Didymos binary system, and the following results were produced:

1. <u>Absolute Magnitude and Size of Didymos:</u> The algorithm found the absolute magnitude of Didymos to be 18.03 and using a geometric albedo of 0.16, its diameter was calculated to be 820 metres.

2. <u>Rotation Period of Didymos</u>: The rotational period of Didymos was measured to be 2.26 hours with an amplitude of 0.1 before and after the DART impact (Figure 2). No change in the rotational period was expected.

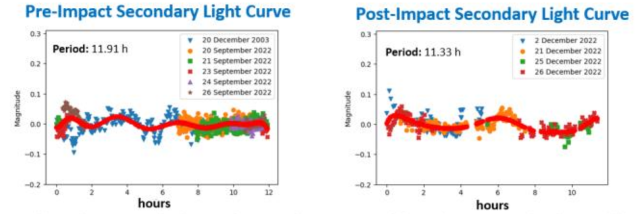


Observations by Daniel Parrott and Arushi Nath [19 Sept – 24 Sept 2022]

Observations by Arushi Nath [30 Sept – 3 Oct 2022]

Figure 2

3. <u>Orbital Period of Dimorphos</u>: The orbital period of Dimorphos before the impact was measured at 11h 55m, and after the impact, it was reduced by 35 minutes to 11h 20m (Figure 3). The change in the orbital period of Dimorphos points to the success of the DART Kinetic Impactor mission in changing the orbit of an asteroid.



Derived from observations taken by Daniel Parrot and Arushi Nath [20 December 2003, 20 – 26 September 2022]*
**As the mutual orbital period is large, to fill a missing gap in the secondary light curve, a 2003 ALCDEF observation by Petr Pravec was added to the analysis*

Derived from observations taken by Donald Pray and Arushi Nath [2 – 26 December 2022]

Figure 3

4. <u>Ejecta Analysis (Length of Visible Tail of Dimorphos):</u> After four days of the impact, I measured the ejecta tail of Dimorphos from stacked images to be over 15,000 km. Such a long debris tail from a 0.2m asteroid suggests Dimorphos is likely rubble based.

5. <u>Changes in the Apparent Magnitude of the Didymos:</u> Pre-impact, the apparent magnitude of the Didymos was observed was very similar to the predicted values for those dates. But after the impact, a maximum increase of about 1.3 in apparent magnitude was observed because of the ejecta (Figure 4). The apparent magnitude took almost a month to return to its normal value.

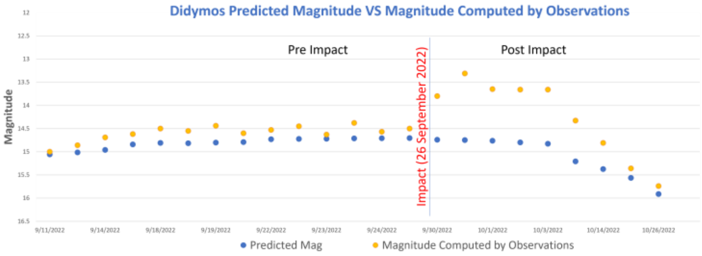


Figure 4

Project Outreach, Open-Source Code and Training Manual

I have made my entire project open source to encourage youth citizen scientists, especially girls, to take up maths, programming, and observational astronomy. I have posted my raw time series data of the Didymos system on the Asteroid Lightcurve Data Exchange Format (ALCDEF) database and published my Python algorithms and training modules as open-source code on my GitHub: *https://github.com/Spacegirl123/Photometric-Observations-of-Didymos*

I have given webinars and online training on this project in partnership with the Royal Astronomical Society of Canada, iTelescope.net, and the Global Innovation Field Trip to get youths worldwide excited about solving 'hard' problems which benefit humanity.