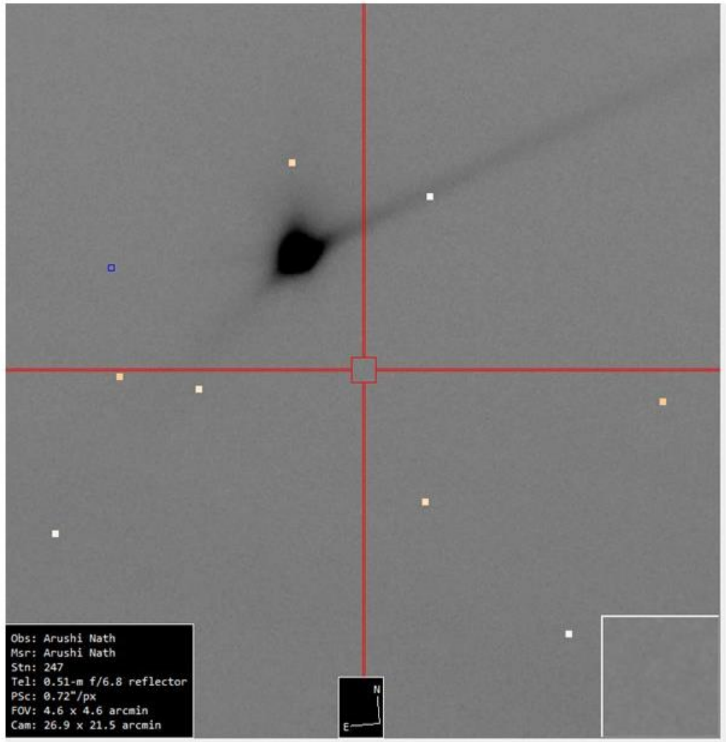
Strengthening Planetary Defense:

Developing Algorithms to Determine the Physical Properties of Asteroids and Applying them to Measure the Impact of NASA's DART Mission on Didymos

Image of Asteroid Didymos (65803) by Arushi Nath
T72 iTelescope, Chile, 1 October 2022
Stacked from 14 x 60-sec exposures.



Arushi Nath

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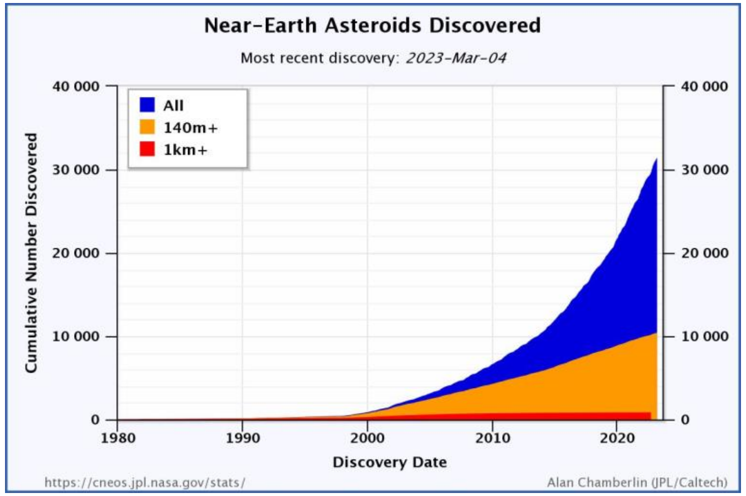
IAA Planetary Defense Conference (PDC)
3 to 7 April 2023
Vienna, Austria

Background Challenge

Pace of Discovery of near-Earth Asteroids Outpaces Analysis

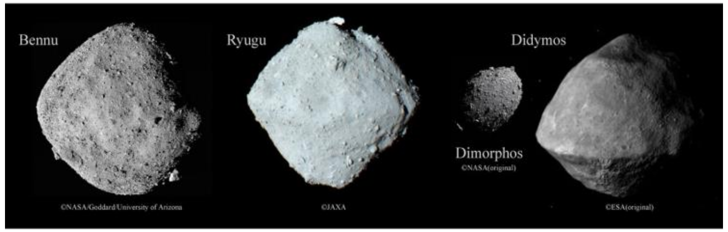
There are over 31,300 near-Earth asteroids (March 2023), and thousands of new ones are discovered yearly. The pace of discovery of near-earth asteroids currently outpaces the ability to analyze them



https://cneos.jpl.nasa.gov/stats/totals.html

Deflecting an Asteroid Requires Knowledge of its Physical Properties

Asteroid collision risks are real and unpredictable. If an asteroid were on a collision path with Earth, the deflection strategy would depend on its physical characteristics: its size, is it monolithic or a rubble pile, and if it has a moonlet. This information would determine the kinetic impact needed to bring a slight change in its orbital path that, over time, could lead the asteroid to miss Earth completely



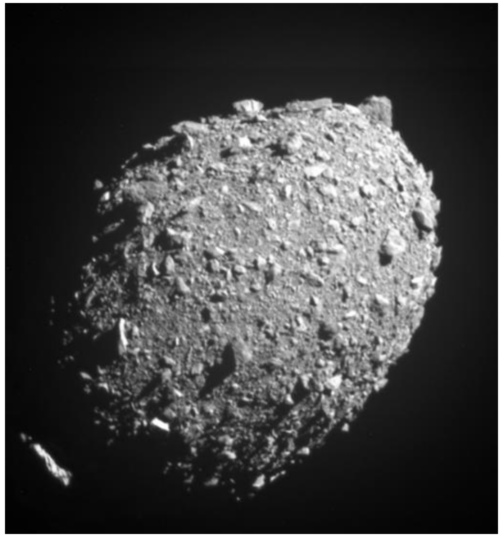
https://www.isas.jaxa.jp/home/research-portal/en/gateway/2022/1125/

Citizen Scientists Can Play a Role in Planetary Defense

If citizen scientists could determine the physical properties of asteroids and the effectiveness of asteroid deflection techniques this could mean the difference between planetary extinction or a near miss

Every asteroid (Bennu, Itokawa, Ryugu, Dimorphos and Didymos) visited by a spacecraft mission was found to be rubble pile asteroids. It is important to be prepared to deflect such asteroids.

NASA Double Asteroid Redirection Test (DART) Mission



Dimorphos
Source: NASA DART
DRACO imager

First-ever space mission to test asteroid deflection for planetary defense

Goal:

Deflect an asteroid by smashing a with a kinetic impactor (spacecraft) into an asteroid

Target:

Asteroid Dimorphos: Satellite (65803) of the Didymos Binary Asteroid System

Objectives:

- Collide a spacecraft with Dimorphos ✅
- Change the orbital path of Dimorphos by 73 seconds ✅
- Measure the momentum transfer efficiency of the impact ✅

Status: Successfully impacted Dimorphos on 26 Sep 2022, 7:14 EDT and met its objectives

Project Goal and Objectives

Project Goal:

Develop algorithms to determine the physical properties of asteroids using robotic telescopes and open data. Gather data from the Didymos Binary Asteroid System and apply the algorithms to measure changes before, during and after the impact by the NASA DART Mission

Project Objectives:

1. Develop photometry algorithms to generate asteroid light curves
2. Determine the rotation period of an asteroid
3. Determine the mutual orbital period of a binary asteroid system
4. Infer the physical characteristics of the asteroid (size and strength)
5. Use robotic telescopes to observe Didymos before, during and after the impact by the DART mission to:
   - Determine physical characteristics of Didymos
   - Study the ejecta tail of Dimorphos
   - Determine the change in the orbital period of Dimorphos around Didymos

Photometry Analysis of Asteroids and Measuring Impact of the NASA DART Planetary Defense Mission: 10 Steps

Remote Observations and Centroiding

1. Imaging the night sky and data processing
2. Plate solving and centroiding known stars and asteroids

Differential Photometry

3. Determining the correct aperture size
4. Finding comparison stars
5. Finding the apparent magnitude of the asteroid

Generating Composite Light Curves

6. Applying offsets to find the absolute magnitude of the asteroid
7. Combining individual light curves to create composites

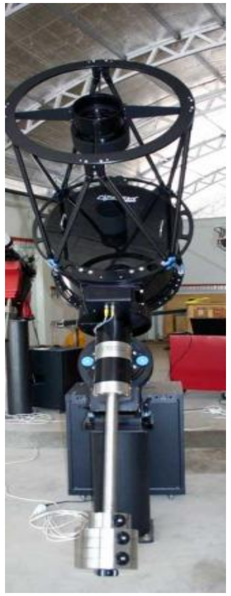
Physical Characteristics and Ejecta Analysis

8. Finding the rotation period
9. Finding changes in the binary orbital period
10. Finding the length of the ejecta tail and changes in apparent magnitude

REMOTE TELESCOPES USED TO OBSERVE ASTEROIDS

On 4 Continents and in Space

Membership-based: iTelescope



iTelescope
T-30 Australia

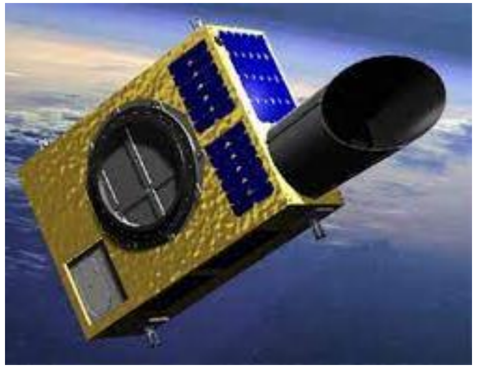
iTelescope
T-32 Australia

iTelescope
T-72 Chile

Research Proposal Submitted and Accepted

American Association of Variable Star Observers (AAVSO) OC61 Chile

Faulkes Telescope
LCO Australia



Canadian Space Agency
NEOSSat Space-based

Courses and Collaborations

Open University/COAST Telescope Spain

Burke Gaffney Observatory
Canada

IASC: Pan-STARRS1
Hawaii USA

Specifications of Remote Telescopes Used

Telescopes	Country	Aperture (metre)	Field of View (arc minutes)
Faulkes Telescope South (Las Cumbres Observatory)	Australia	1.0	26 x 26
iTelescope T30	Australia	0.5	27.8 x 41.6
iTelescope T32	Australia	0.43	43.2 x 43.2
AAVSO OC61	Australia	0.61	14 x 14
Burke Gaffney Observatory	Canada	0.61	24 x 24
iTelescope T72	Chile	0.43	26.93 x 21.53
Open University / COAST Telescope	Spain	0.43	61 x 61
Sugarloaf Mountain Observatory	USA	0.5	24 x 24
NEOSSat (Canadian Space Agency)	Space-based	0.15	51 x 51

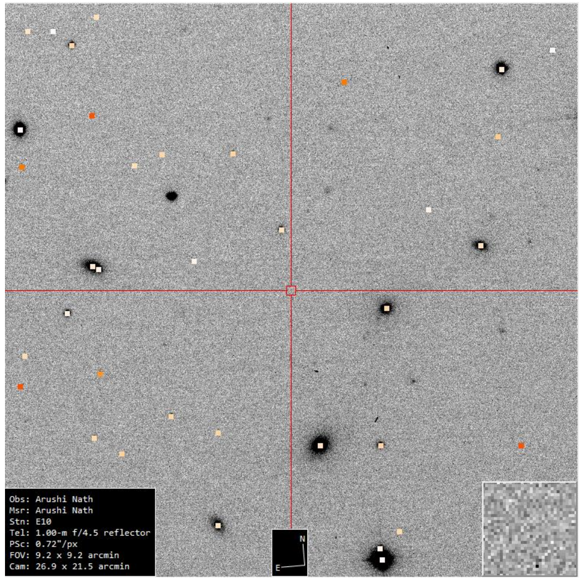
Three Stages of Imaging Didymos and Analysis

Pre-Impact

[11 Sept 2022 - 26 Sept 2022]

Baseline Data

- Measure the rotation period of Didymos and infer its size
- Measure the orbital period of Dimorphos



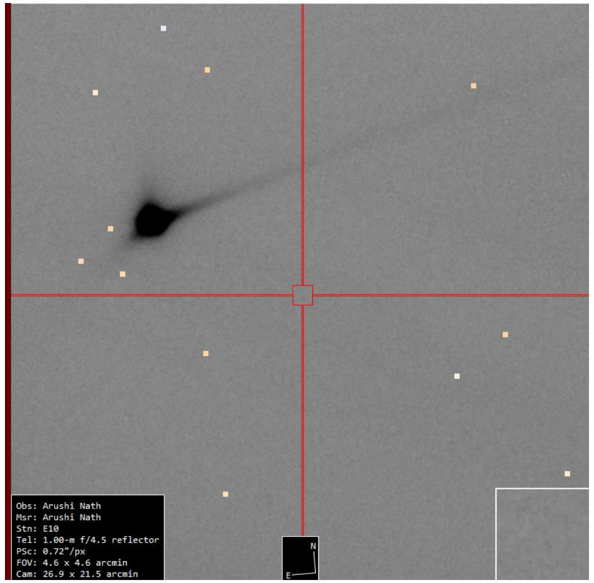
T72. 24 September 2022

During-Impact

[27 Sep 2022 – 30 Oct 2022]

Ejecta Analysis

- Measure the increase in brightness of the Didymos
  Measure the length of the ejecta tail of Dimorphos



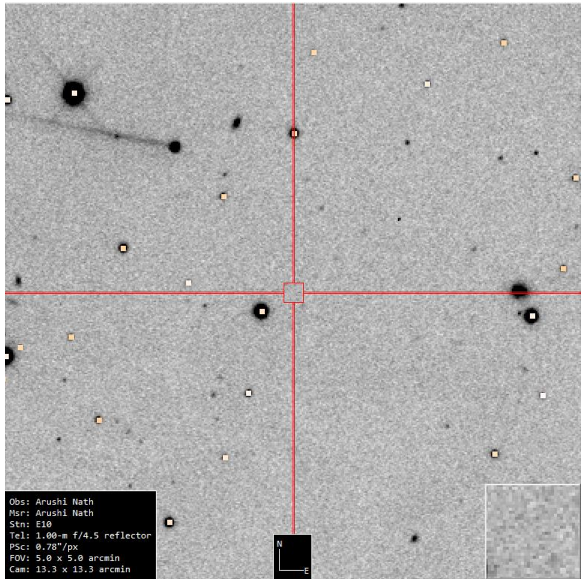
T72. 2 October 2022

Post-Impact

[1 Nov 2022 – 25 Dec 2022]

Success of Deflection

- Measure change in the orbital period of Dimorphos



FTP/LCO. 17 November 2022

Data: Primary Observations of (65803) Didymos

	Date	Telescope Used	Observation (hours)	Filter	Observer
Pre Impact	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
During Impact	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
Post Impact	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

Open Datasets, Math and Programming Languages Used

Datasets

NASA Horizons System

To create observation plans for robotic telescopes

ESA GAIA Data Release 3

Finding comparison stars

Asteroid Lightcurve Data Exchange Format (ALCDEF)

Obtain raw light curves data from other apparitions

Math Tools

Area of circle
For centroiding

Weighted Mean
For centroiding

Geometric Mean
Finding aperture size

Logs
Offset calculation

Modulus
Composite light curves

Root Mean Square Error
Rotation period

Programming Language and Libraries

python™

NumPy

matplotlib

astropy
A Community Python Library for Astronomy

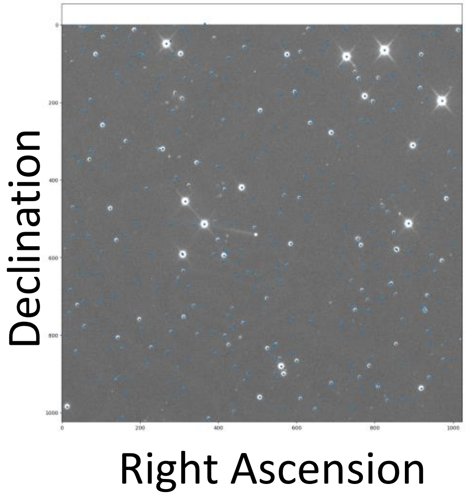
Training Modules

jupyter

GitHub

Centroiding Known Stars and Asteroid using Open Data

Image in Celestial Coordinates



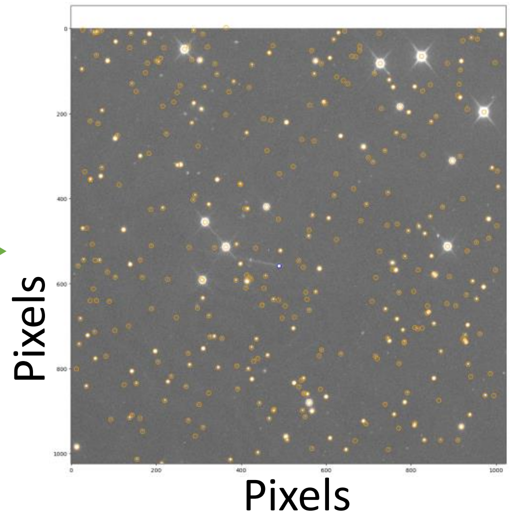
Find Known Stars and Asteroid

Open Datasets
European Space Agency GAIA Data Release 3

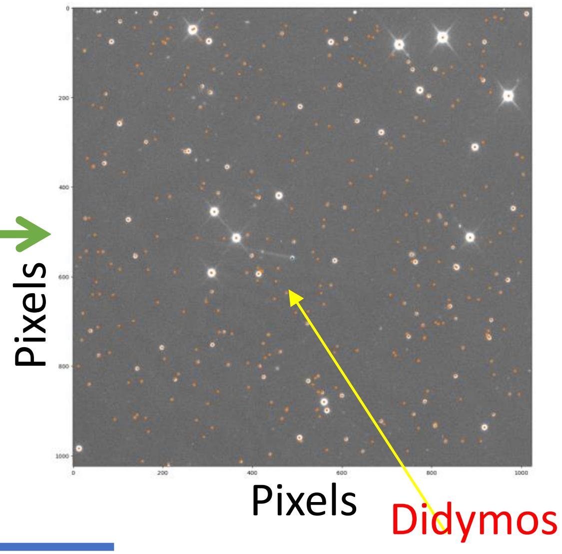
NASA JPL Horizons System

Plate Solving

Image in Pixel Coordinates

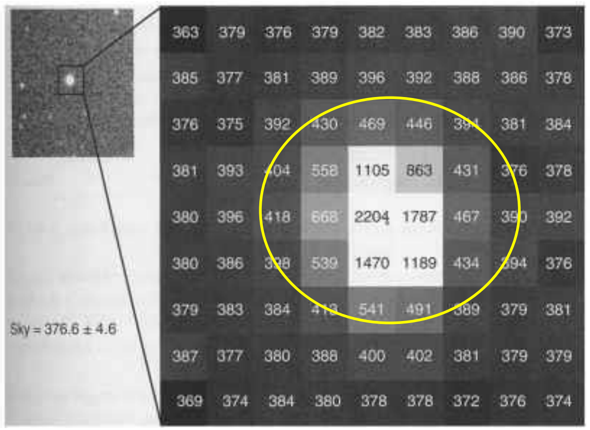


Centroiding of Stars and Didymos



Assumptions

- Starlight spread is circular and falls over several pixels
- Stars are brightest in the centre and become dimmer away from it



Centroids of stars and asteroid were calculated using the "weighted mean" of pixel brightness values

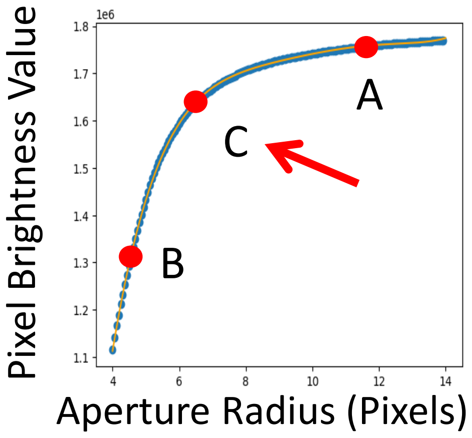
METHODOLOGY

Differential Photometry: Measuring Brightness of an Asteroid

When light falls on the camera, the pixels record the raw brightness values

- **Object Aperture:** Bounds the asteroid to measure total pixel brightness value **(S)**
- **Outer Annulus:** Measures the background noise in the image **(N)**

Finding the Right Aperture Size for an Image

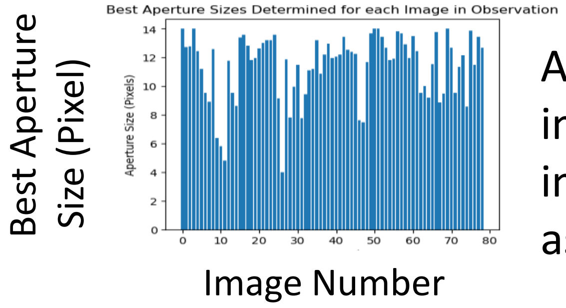


Very large (A): Too much background noise is included

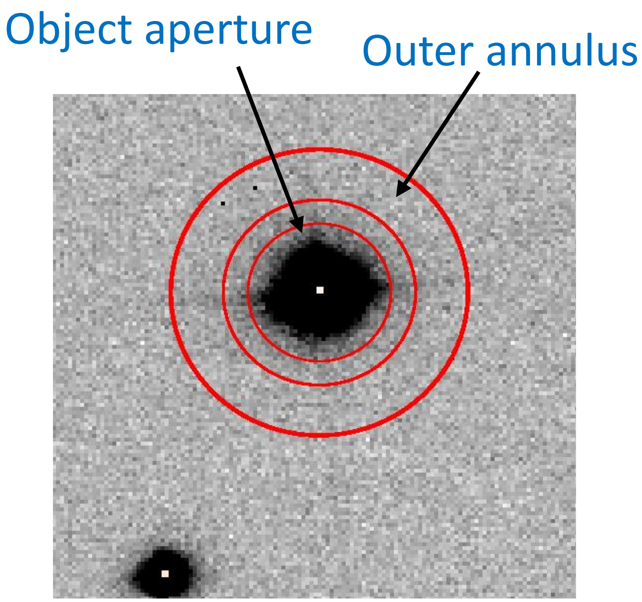
Very small (B): Partial brightness of asteroid is included

Right size (C): Includes most brightness for smallest aperture

Finding the Right Aperture Size for all Images in an Observation



As the aperture size must be the same for all the images in an observation, the best size for each image was calculated. The median value was used as the common aperture size



Raw Pixel Brightness of Asteroid
= S – [(N/Outer Annulus Area) *Object Aperture Area)]

Instrument Magnitude of Asteroid
= -2.5 * log(Raw Pixel Brightness * gain/exposure time)

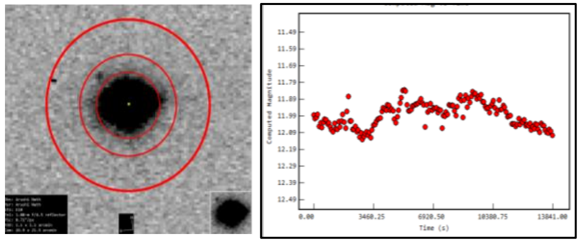
gain = e^-/ADU (dependent on camera)

METHODOLOGY

Finding Comparison Stars: To Reduce Impact of Seeing Conditions

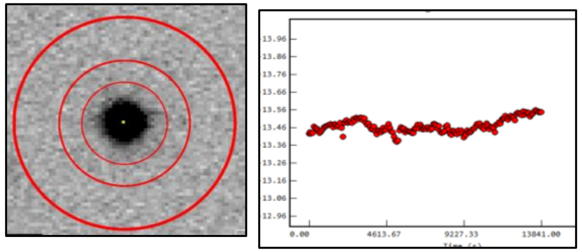
Observed brightness of an asteroid varies with changes in seeing conditions, such as air mass and weather. These can be reduced by measuring changes in the brightness of stars of known magnitudes in the same field of view (Comparison Stars)

Computed Magnitude



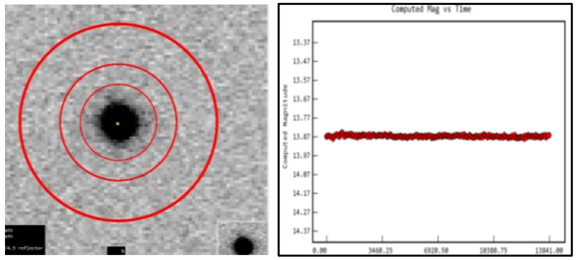
Not Suitable

Star is too big or too small for the selected aperture size



Not Suitable

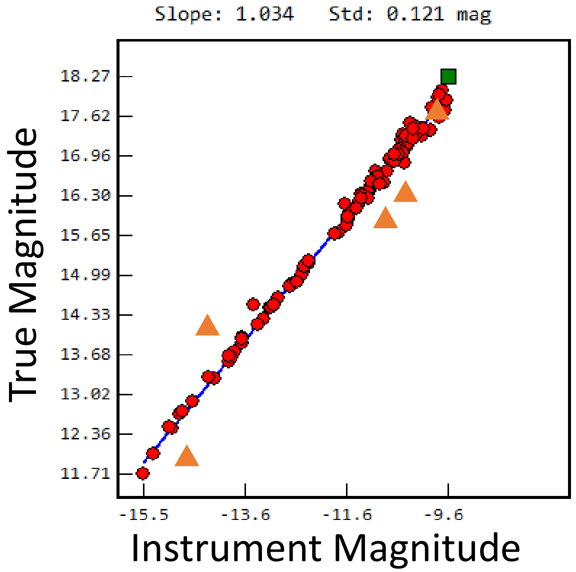
Star brightness is changing over time



Suitable

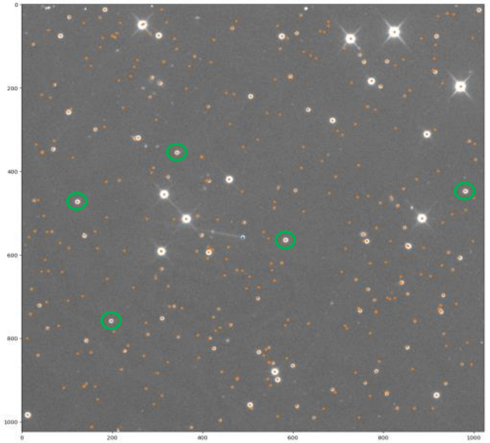
Star is of right size and the brightness remains same over time

Selection of 4 – 7 Comparison Stars



Suitable comparison stars

Unsuitable comparison stars



Comparison stars selected of brightness similar to the asteroid

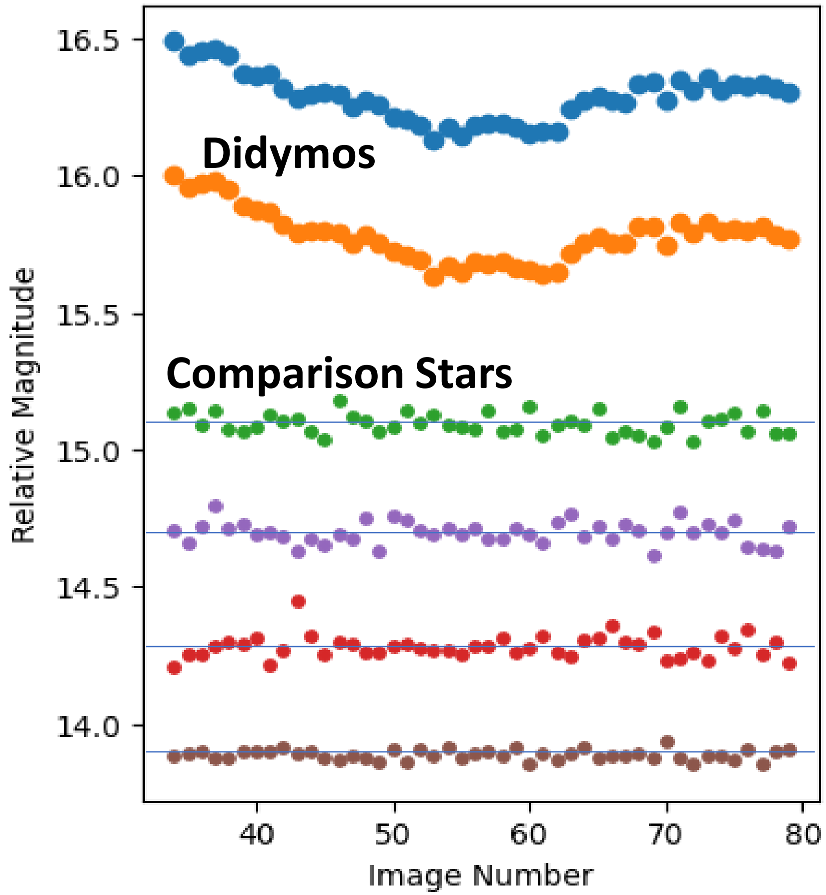
Time-Series Computed Magnitude of an Asteroid

Computed magnitude pertains to the observed magnitude of the asteroid at a given instance after minimizing changes in seeing conditions by using comparison stars

Algorithm Steps:

1. Select a few stars of similar brightness to the asteroid in the image and calculate their instrument magnitudes
2. Query the true magnitude of stars from the GAIA DR3 star catalogue. Subtract the two to get the offset
3. For each image, take the average of offsets of all the selected stars to get the final offset for that image
4. Subtract the final offset for each image from the instrument magnitude of the star to obtain the time-series computed magnitude of that star
5. Subtract it from the instrument magnitude of the asteroid to obtain the asteroids' time-series computed magnitude

Relative Computed Magnitudes (Single Night Observation)



METHODOLOGY

Offsets: Unity Distance, Light Time, Phase Angle Corrections

As asteroids orbit the Sun, their observed brightness varies because of changes in:

- **Heliocentric** (Sun-asteroid) distance (r)
- **Geocentric** (Earth-asteroid) distance (R)
- **Phase angle** (angle between the Earth and Sun as viewed from the asteroid)

Offsets are applied to time-series Computed Magnitudes of asteroids to eliminate these changes:

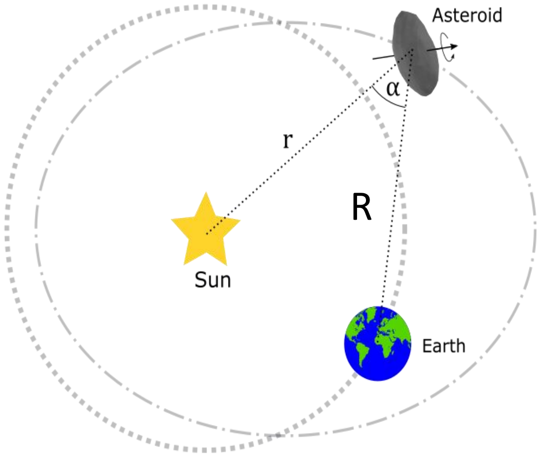
- **Unity Distances Correction (Reduced Magnitude):**
  Find the asteroid's brightness if it was at 1 AU from the Earth and the Sun
  $\Delta M = -5 * \log(rR)$

- **Light Time Correction (Referencing timings to when the light left the asteroid):**
  As light travels at a finite speed, there is a need to ensure that the timings of the observations are referenced to a fixed distance
  $\Delta t = -0.005778\, r$ $\Delta t =$ correction in days

- **Phase Offset:**
  Referencing of reduced brightness of an asteroid at a phase angle Zero.
  H is the reduced magnitude at zero phase angle.

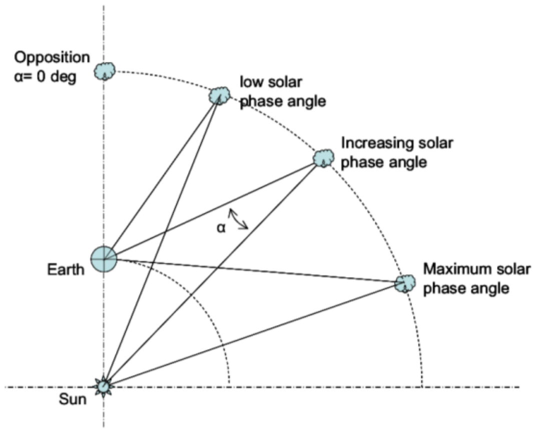
$$H(\alpha) = H - 2.5log[(1-G)\Phi_1(\alpha) + G\Phi_2(\alpha)]$$

Unity Distance Correction



https://www.open.edu/openlearn/science-maths-technology/astronomy.

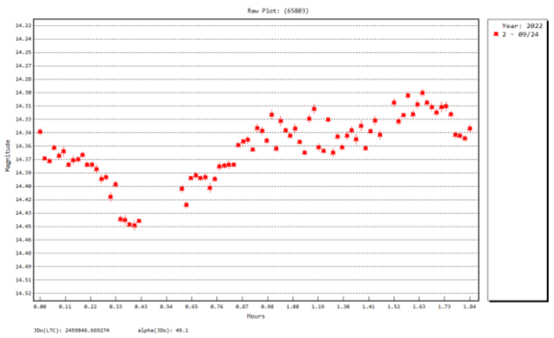
Phase Offset



METHODOLOGY

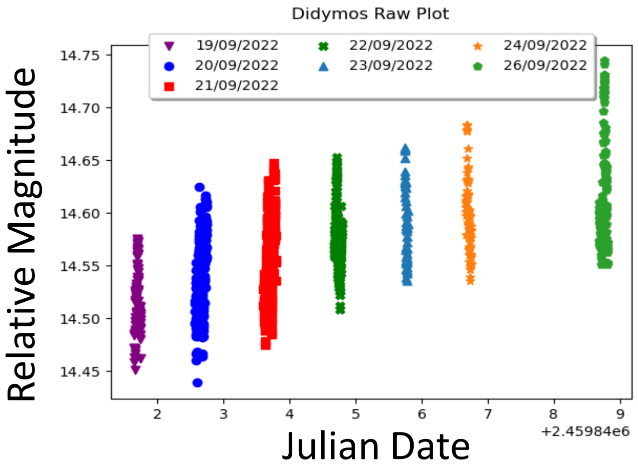
Applying Offsets to Individual Asteroid Light Curves

Didymos Light Curve
(Single Night Observation)

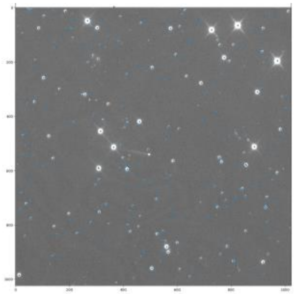


Combined

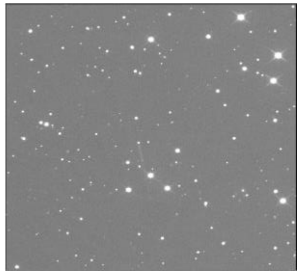
Didymos Light Curves
(Multiple Nights Observations)



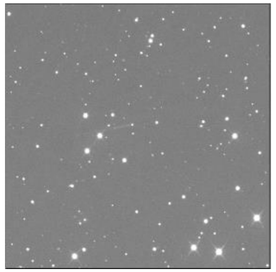
A



B

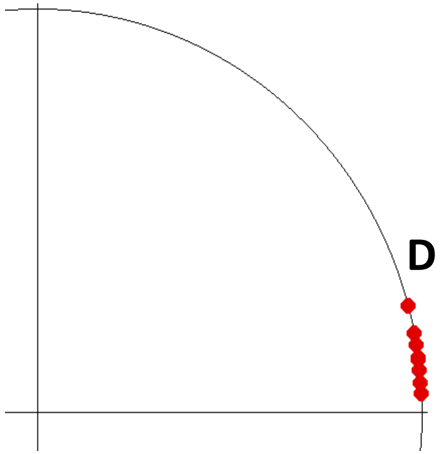


C



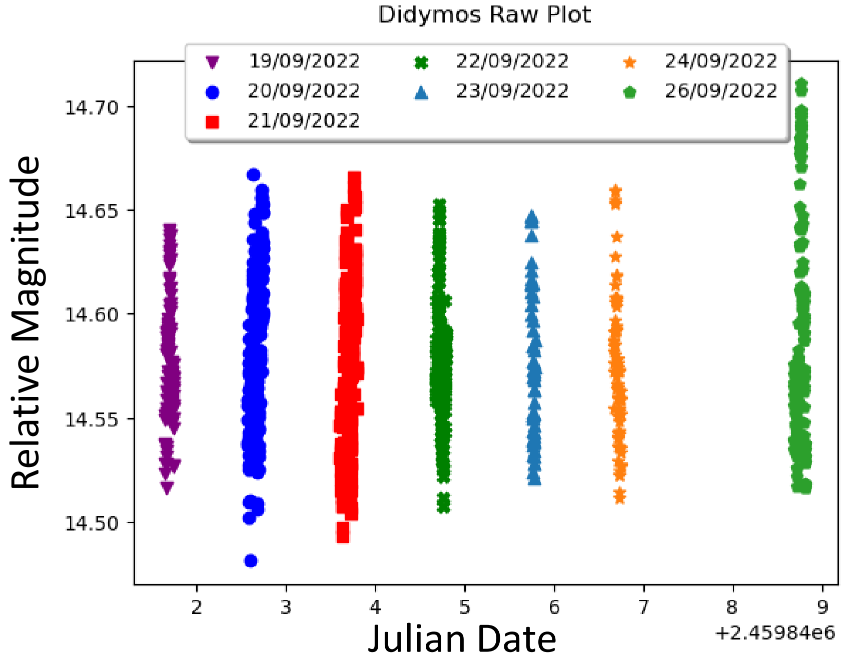
D

Change in Phase Angle of Didymos over Different Nights



Unity Distance, Light Time, Phase Angle Corrections Offsets Applied

Didymos Light Curves
(Multiple Nights Observations)



Observations by Arushi Nath and Daniel Parrott
[19 Sept – 26 Sept 2022]

METHODOLOGY

Generating Composite Asteroid Light Curves

Combining light curves from observations over multiple nights into a single composite light curve

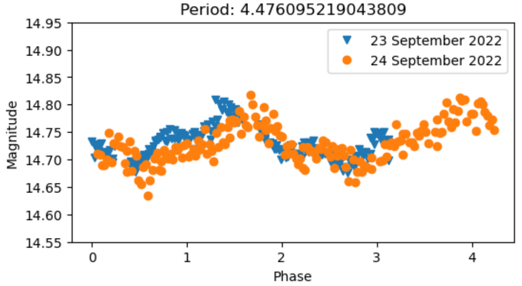
Algorithm Steps:

1. Start with an estimate of the periodicity of the composite light curve, say between **A** (2 hours) and **B** (5 hours)
2. Create **(N)** intervals between **A** and **B**, say 5000
3. Convert the time corresponding to each image from Julian Date (JD) to hours (h) with zero as the first observation
4. For each iteration step: A + i*[(B-A)/N] (i = 1 to N)
   - Find the remainder of h/{A + i*[(B-A)/N]}. This will determine the 'phase' of the image
   - Repeat the process for all the images
5. Scatter plot Phase (x-axis) and Magnitude (y-axis) for each Image. It will yield (N) scatter plots
6. Create a 4^{th} order curve fit from the scatter plot
7. Find the Root Mean Square Error (RMSE) between the observed magnitude and their corresponding magnitude on the fitted curve for all (N) images
8. The fitted light curve corresponding to the smallest RMSE will be the composite light curve for the asteroid

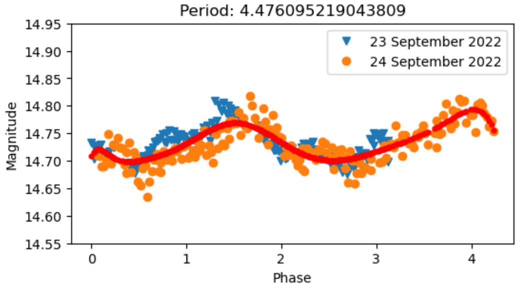
Steps 1 - 4: Iteration Step = 4.456h

Julian Date (JD)	Hours (h)	Phase
2459841.637	0	0
2459841.767	3.119	3.119
2459842.572	22.440	0.060
2459842.746	26.616	4.236

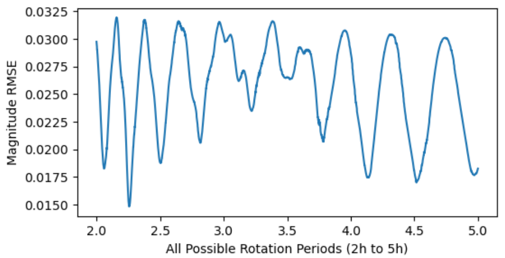
Step 5: Magnitude vs Phase Scatter Plot



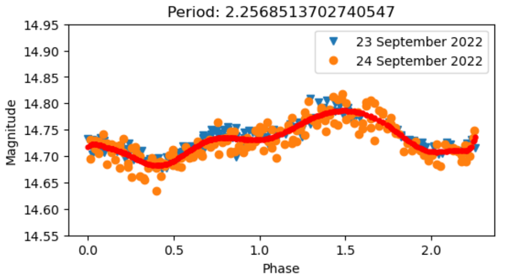
Step 6: Magnitude vs Phase Curve Fit



Step 7: RMSE for All (N) Curve Fits (between 2h and 5h)

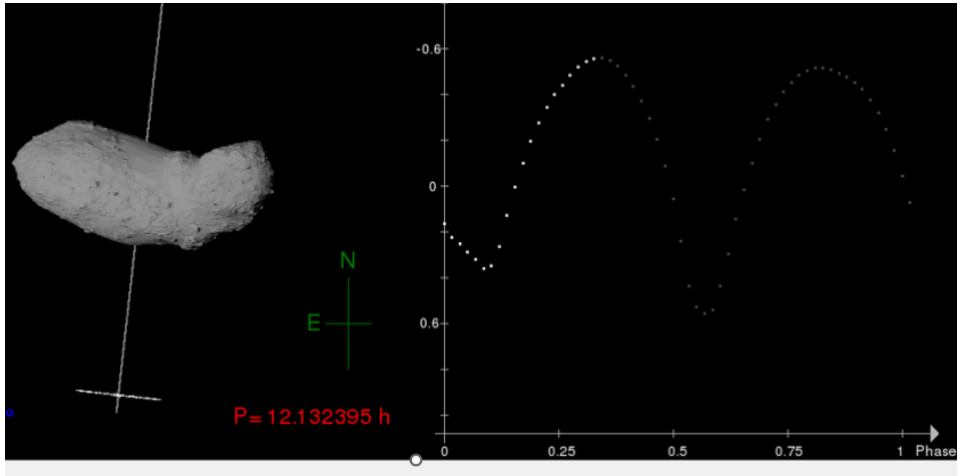


Step 8: Composite Light Curve is the Curve with the Smallest RMSE

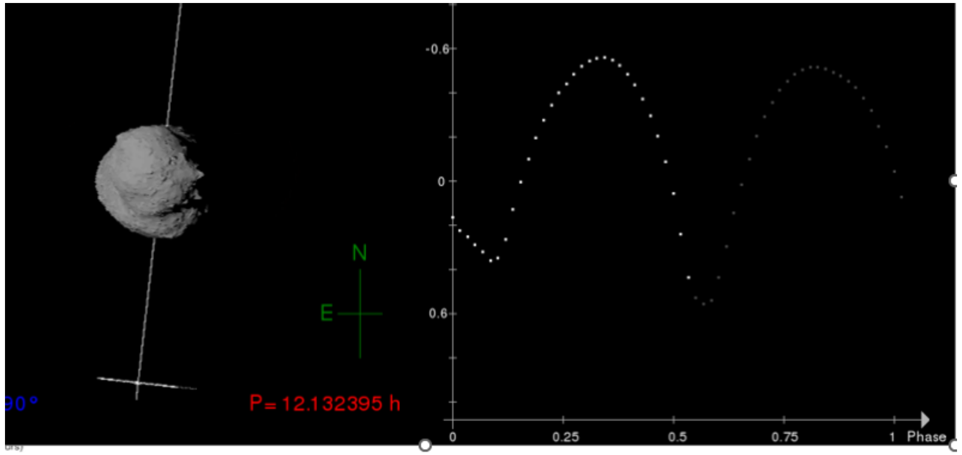


Light Curves Analysis: Finding Rotation Period of an Asteroid

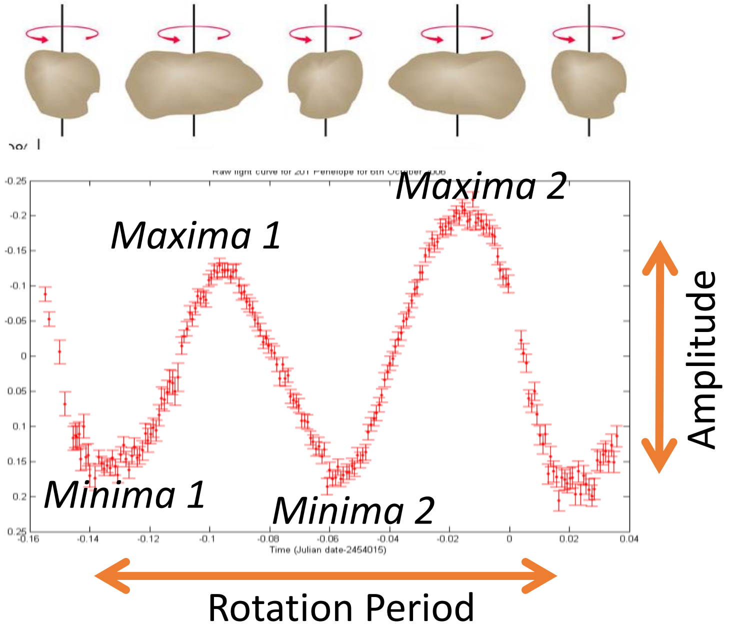
Side view



Front view



- Small asteroids (kilometer-sized) are irregular in shape as they do not have enough gravity to make them spherical
- When they rotate, light reflected from different sides causes a change in their observed brightness
- The Asteroid Light Curves reveal the change in brightness and allows measurement of the rotation period and amplitude



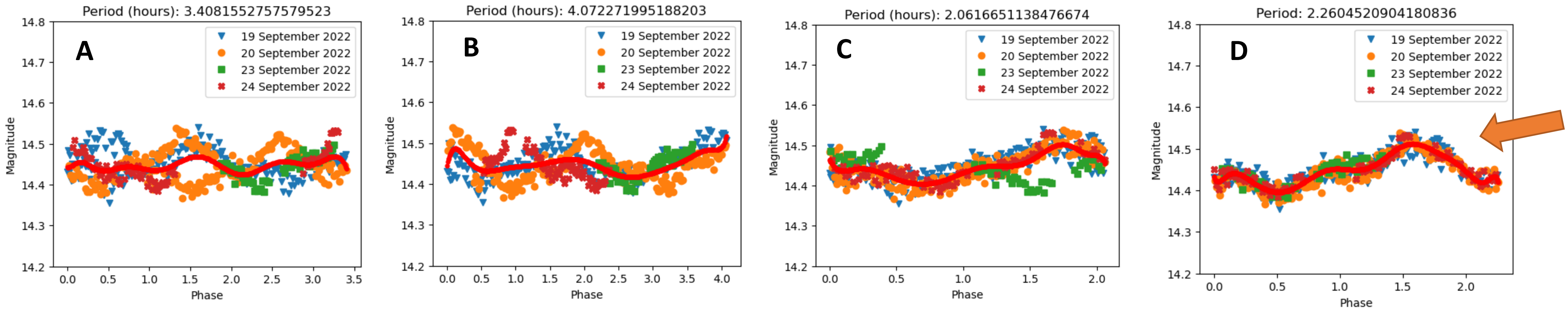
Rotation Period:
Horizontal Distance between similar maxima or minima

Amplitude:
Vertical distance between maxima and minima

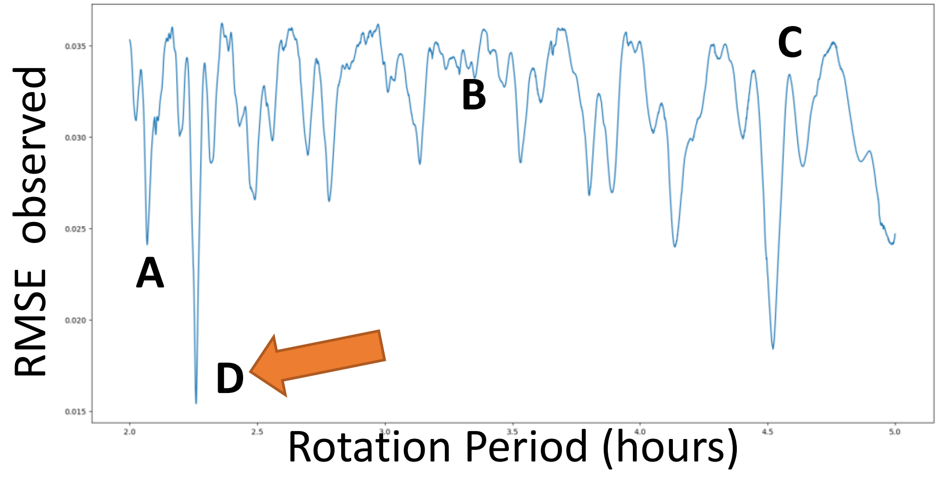
METHODOLOGY

Finding Asteroid Rotation Period: Minimizing Fitting Errors

Need to fit individual light curves data to different periods and calculate the root means square error of the fittings. The rotation period would correspond to the best fit.



Rotation Period vs Root Mean Square Error (RMSE)

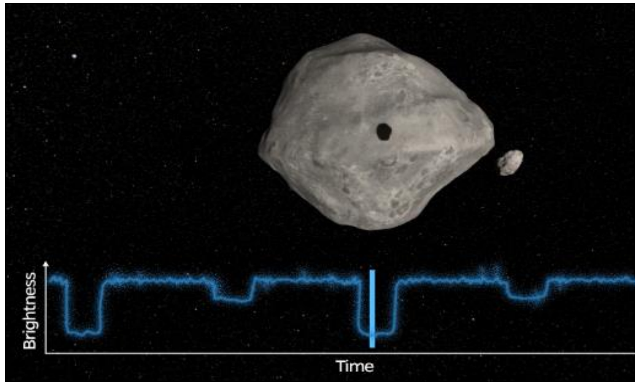


Rotation Period corresponds to Period Fitting with the Least RMSE

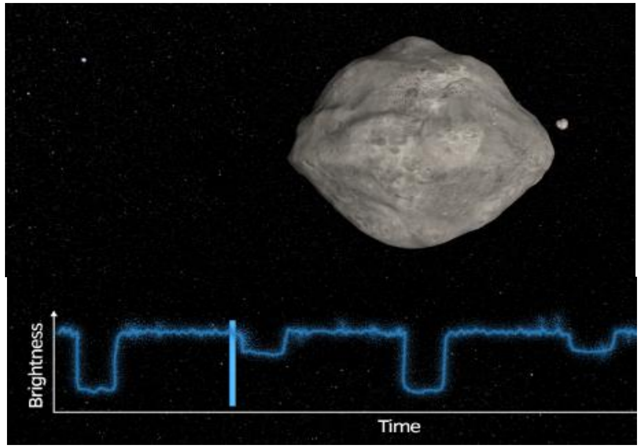
Figure	Root Mean Square Error (RMSE)	Rotation Period (hours)
A	0.0353	3.40
B	0.0314	4.63
C	0.0250	2.06
D	0.0154	**2.26**

Light Curves Analysis: Finding Orbital Period for Binary Asteroids

Primary Occultation and Eclipse:
Dimorphos and its shadow passing in front of Didymos

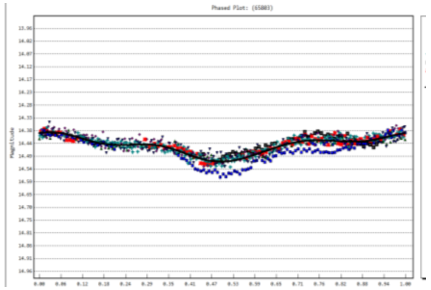


Secondary Occultation:
Didymos passing in front of moonlet Dimorphos



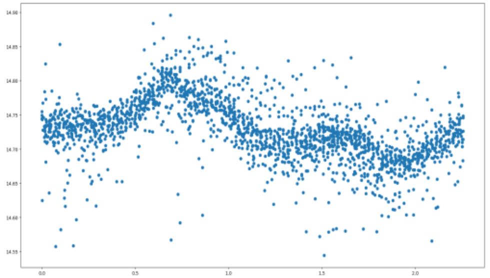
Composite Light Curves of Binaries contain information about:

- Primary Rotation Period (Didymos)
- Secondary Rotation Period (Dimorphos)
- Orbital Period (Occultations and Eclipses)



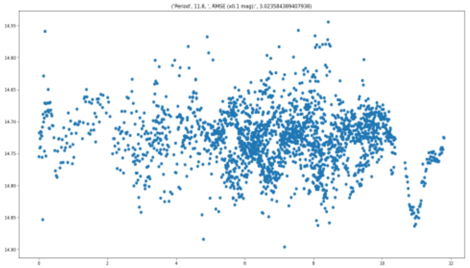
Composite Light Curve

−



Primary Light Curve

=



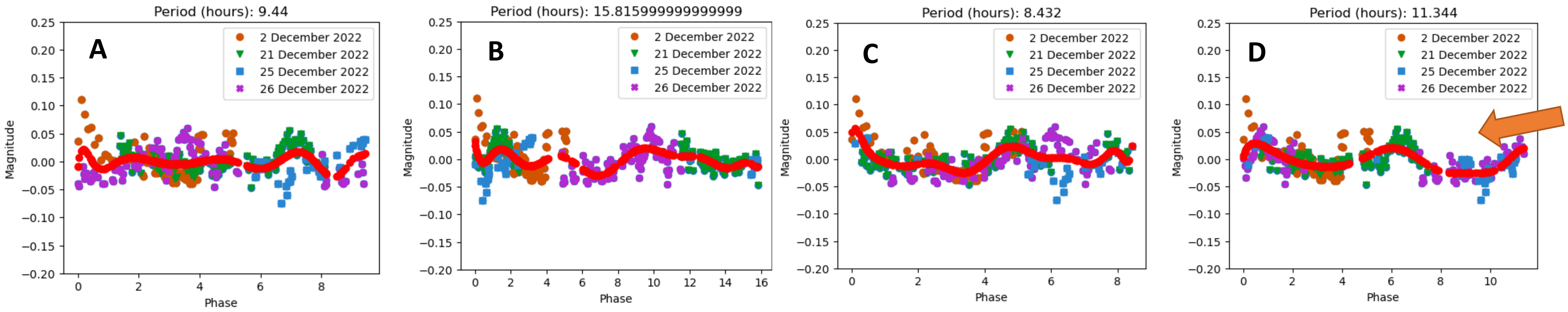
Secondary Light Curve

Subtracting the Primary light Curve from the Composite Light Curve should reveal light curves with information about the orbital period and rotation period of the secondary

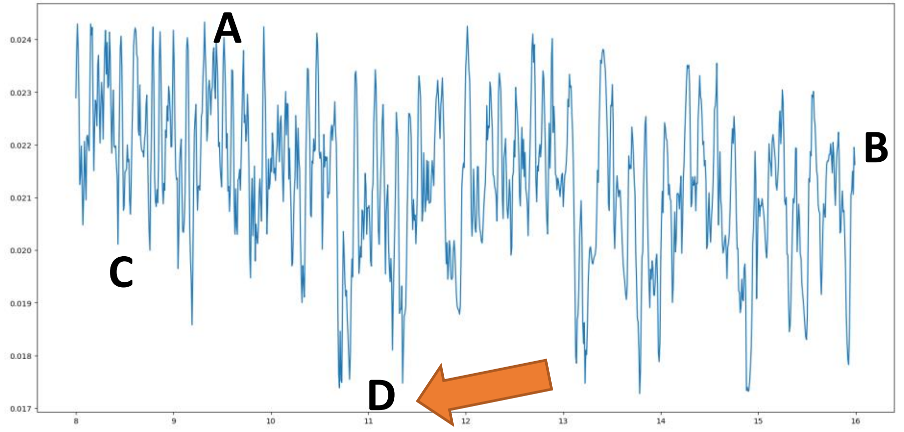
If secondary satellite is tidally locked with the primary, then the orbital period would equal one rotation of the secondary, simplifying the analysis

Finding Orbital Period: Minimizing Fitting Errors in Secondary Light Curve

Need to fit secondary light curves data to different periods and calculate the root means square error of the fittings.
The orbital period of the secondary would correspond to the best fit.



Orbital Period vs Root Mean Square Error (RMSE)



Orbital Period corresponds to Period Fitting with the Least RMSE

Legend	Root Mean Square Error (RMSE)	Orbital Period (hours)
A	0.0239	9.44
B	0.0219	15.82
C	0.0201	8.43
D	0.0175	**11.34**

Result 1: Absolute Magnitude and Size of Didymos

An asteroid's absolute magnitude is the visual magnitude an observer would record if the asteroid were placed 1 AU away from the Sun and 1 AU from the Earth and at a zero-phase angle

Absolute Magnitude of Didymos (H): 18.03

The mean value of reduced magnitude was calculated from multiple observations of Didymos. The phase angle formula was then applied to reference the reduced magnitude to phase angle Zero to get the absolute

$$H(\alpha) = H - 2.5 log[(1 - G)\Phi_1(\alpha) + G\Phi_2(\alpha)]$$

Size of Didymos: 820 metres

The diameter (d) of an asteroid is a function of its absolute magnitude (H) and its geometric albedo (a)

$$d\ (km) = 10^{[3.1236 - 0.5\log_{10}(a) - 0.2\ (H)]}$$

(assuming albedo = 0.16)

Table of Approximate Asteroid Diameters

Albedo (a)

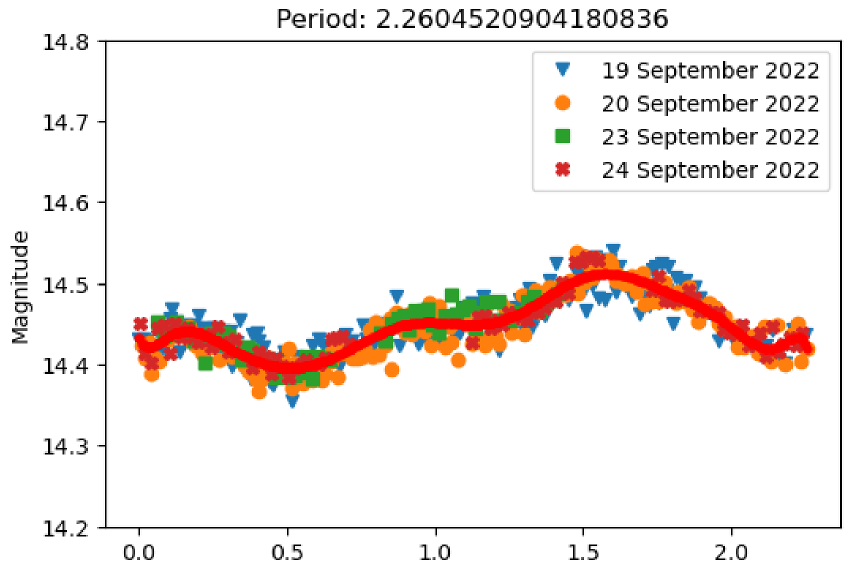
Absolute Magnitude (H)

albedo	0.30	0.25	0.20	0.15	0.10	0.05
H						
30.0	0.0025	0.0027	0.0030	0.0035	0.0043	0.0060
23.5	0.049	0.054	0.060	0.069	0.085	0.12
23.0	0.062	0.068	0.076	0.087	0.11	0.15
22.5	0.078	0.085	0.095	0.11	0.13	0.19
22.0	0.098	0.11	0.12	0.14	0.17	0.24
21.5	0.12	0.14	0.15	0.17	0.21	0.30
21.0	0.16	0.17	0.19	0.22	0.27	0.38
20.5	0.20	0.21	0.24	0.28	0.34	0.48
20.0	0.25	0.27	0.30	0.35	0.43	0.60
19.5	0.31	0.34	0.38	0.44	0.54	0.76
19.0	0.39	0.43	0.48	0.55	0.68	0.96
18.5	0.49	0.54	0.60	0.69	0.85	1.2
18.0	0.62	0.68	0.76	0.87	1.1	1.5
17.5	0.78	0.85	0.95	1.1	1.3	1.9
17.0	0.98	1.1	1.2	1.4	1.7	2.4
16.5	1.2	1.4	1.5	1.7	2.1	3.0
16.0	1.6	1.7	1.9	2.2	2.7	3.8
15.5	2.0	2.1	2.4	2.8	3.4	4.8
15.0	2.5	2.7	3.0	3.5	4.3	6.0
14.5	3.1	3.4	3.8	4.4	5.4	7.6
14.0	3.9	4.3	4.8	5.5	6.8	9.6

Center for Near Earth Object Studies (CNEOS)
https://cneos.jpl.nasa.gov/tools/ast_size_est.html

Result 2: Rotation Period of (65803) Didymos Asteroid

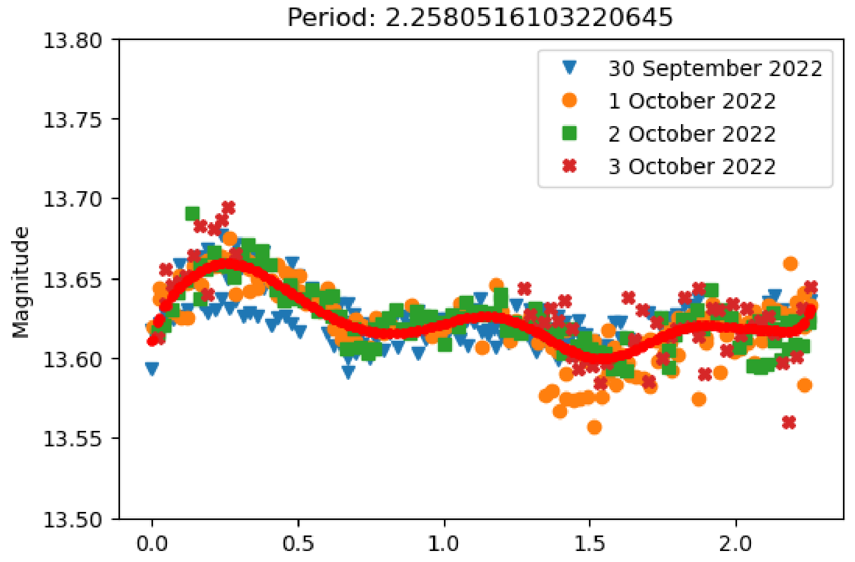
Pre-Impact Primary Light Curve



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

Rotation Period : 2.26 hours
Amplitude: 0.1

Post-Impact Primary Light Curve



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

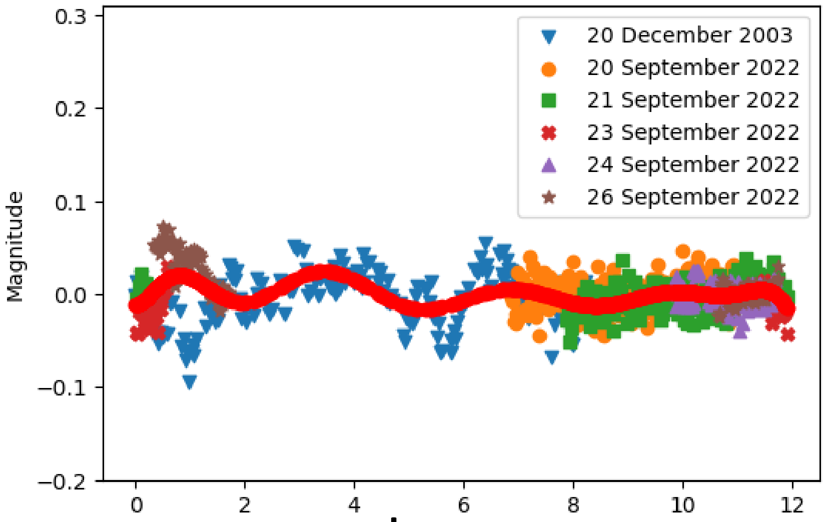
Rotation Period: 2.26 hours
Amplitude: 0.1

Inference:

No change in the rotation period of Didymos was observed after the kinetic impact, nor any was expected

Result 3: Orbital Period of Dimorphos

Pre-Impact Secondary Light Curve

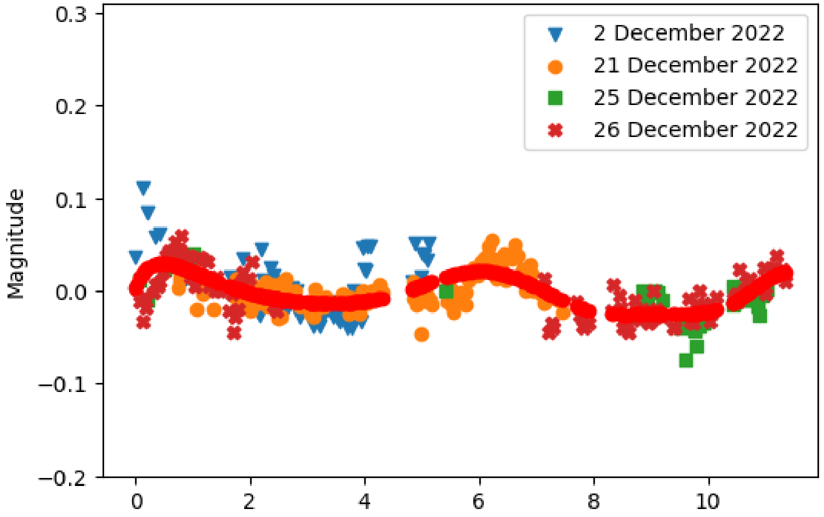


Orbital Period: 11h 55m

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*

Post-Impact Secondary Light Curve



Orbital Period: 11h 20m

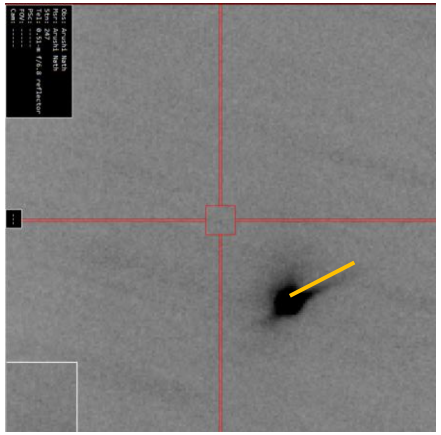
Derived from observations taken by Donald Pray and Arushi Nath [2 – 26 December 2022]

Inference:

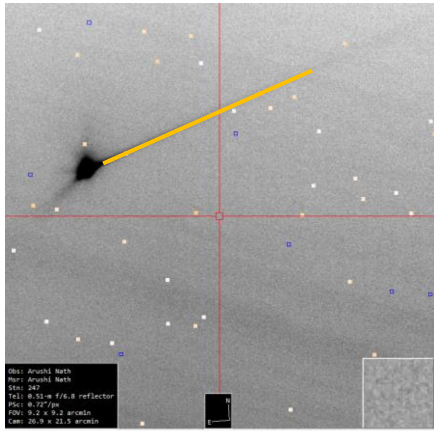
Change in the orbital period of Dimorphos points to the success of the DART Kinetic Impactor mission.
It is the first time that humanity has been able to change the trajectory of a celestial object purposely

Result 4: Ejecta Analysis (Length of Visible Tail of Dimorphos)

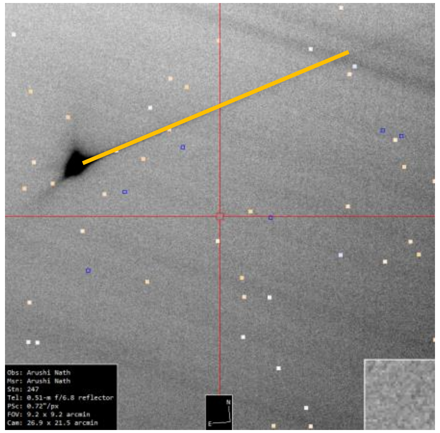
27 September 2022

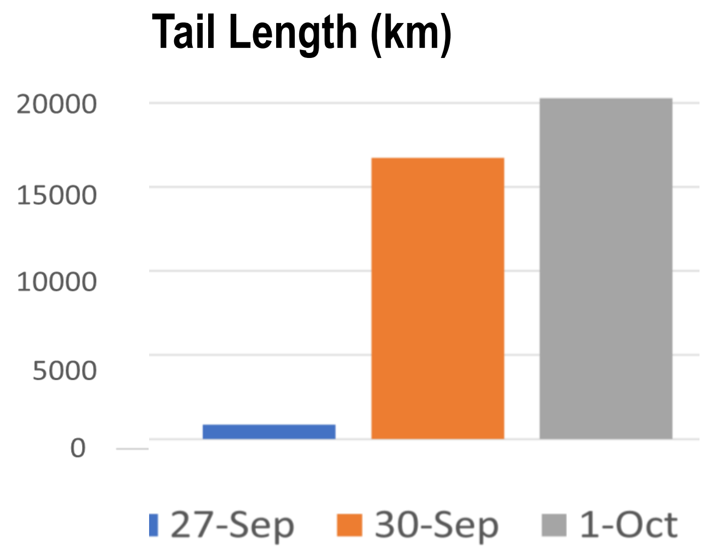


30 September 2022



1 October 2022





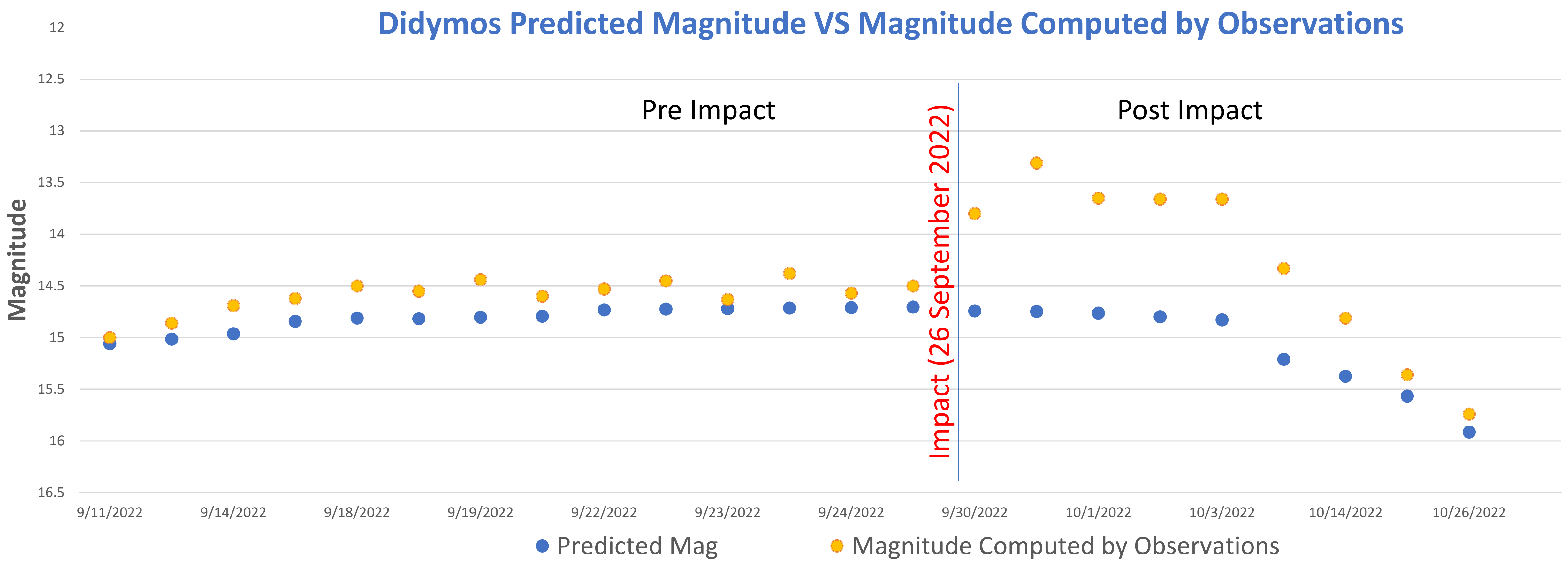
Tail Length Calculation: 30 September 2022	
Pixel Scale (arcsec/pixel)	0.359
Tail Length on CCD (arcsec) a	314
Distance from Earth (km) r	$11*10^6$
Tail Length (kms) (2*pi*r)/360 * (a/3600)	**16754 (line of sight)**

Inference:

- The 15,000 km debris trail behind a 0.2 km wide Dimorphos means it is likely a rubble pile
- The ejection of material opposite to the direction of motion of Dimorphos would have imparted even more momentum – leading to a higher change in orbital period than expected

Result 5: Changes in the Apparent Magnitude of the Didymos System

Comparing changes in the apparent magnitude of the Didymos system before and after the impact and if there was no impact



Notes:

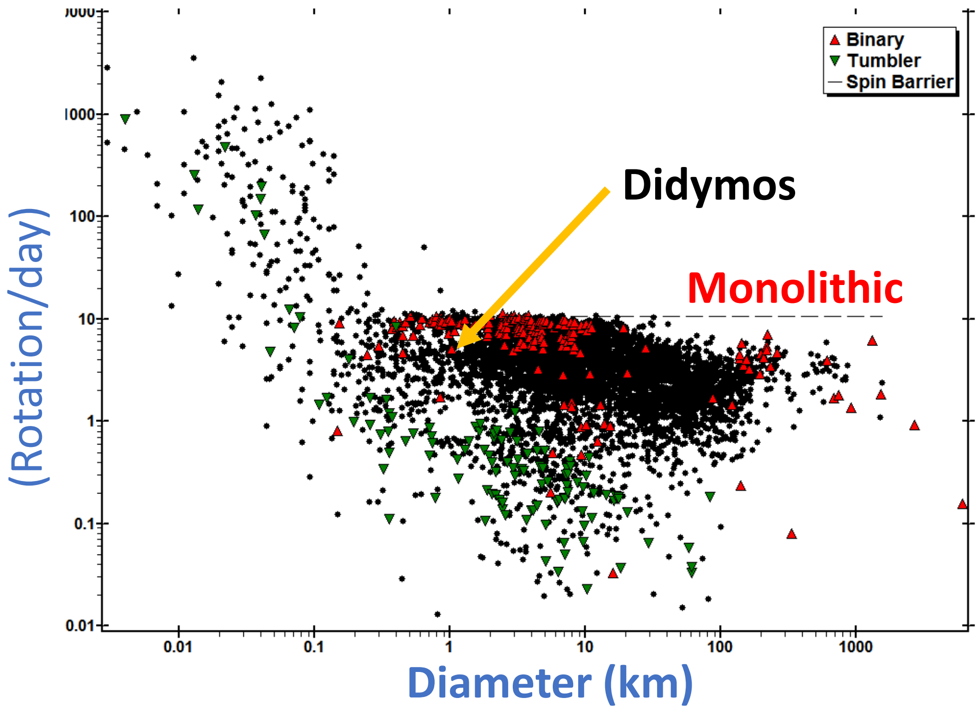
- *Dates are not evenly spread out*
- *There could be more than one observation on the same day but from different locations*

Inference:

The magnitude of the Didymos system increased by almost 1.3 magnitudes immediately after the DART spacecraft impacted moonlet Dimorphos

Discussion: Finding Asteroid Composition from Rotation Period

Minor Planets
Rotation Frequency vs Diameter Graph



Most minor planets have rotation periods of more than 2.2 hrs (or 11 rotations/ day), with a majority of them having rotation periods of 4-10 hrs (or 2-6 rotations/day)

Rotation Period and Composition

Less than 2.2 hours

- Asteroid must be a single rock (monolithic)
- Else it would fly apart

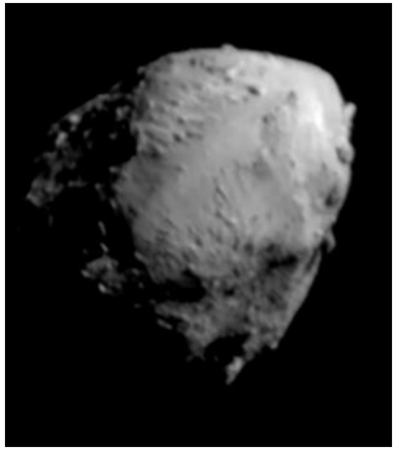
More than 2.2 hours (diameter > 150 metres)

- Rubble held loosely together by gravity
- Smaller asteroids are likely to be "rubble piles"

Inference:

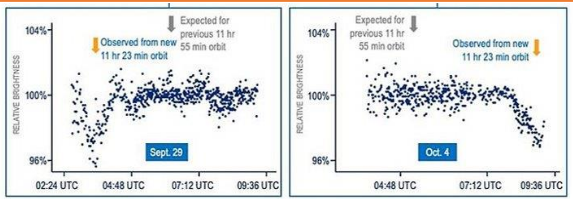
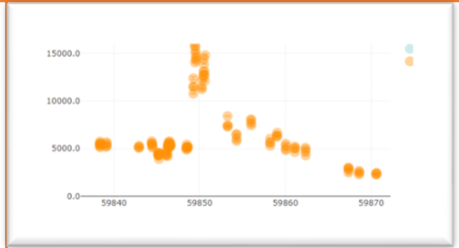
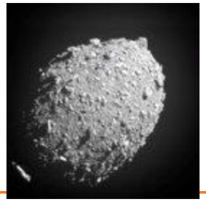
Didymos Rotation Period: 2.26 hours
Rotation Frequency: 9.23 rotations/day
Didymos Diameter > 150 metres

Didymos is likely to be a rubble pile held together by mutual gravitation



https://www.nasa.gov/feature/dart-s-final-images-prior-to-impact

Validation of Results

Characteristics		Calculated Using Citizen Science	Actual	Source
Absolute Magnitude		18.03	18.12	**NASA Small Body Database Lookup** https://ssd.jpl.nasa.gov/tools/sbdb_lookup.html#/?sstr=65803
Size (metres)		820	780	
Rotation Period of Didymos and Amplitude		2.26 hours Amplitude = 0.1	2.26 hours Amplitude = 0.1	
Orbital Period	**Pre Impact**	11 hours and 55 minutes (11.910 hours)	11 hours and 55 minutes (11.916 hours)	 **NASA** https://www.nasa.gov/feature/nasa-dart-imagery-shows-changed-orbit-of-target
	Post Impact	11 hours and 20 minutes (11.33 hours)	11 hours and 23 minutes (11.38 hours)	
Increase in Magnitude of Didymos System after Impact		1.35 magnitude	1.2 magnitude	 ATLAS Forced Photometry Server https://fallingstar-data.com/forcedphot
Asteroid Composition		Rubble Pile	Rubble Pile	 Didymos  Dimorphos

Conclusions

- Open-source algorithms were developed that can analyze observations taken from remote telescopes over multiple nights to determine the physical properties of asteroids

- The algorithms were successfully applied to data gathered of the Didymos Binary Asteroid system to learn about its physical properties and measure changes before, during and after the impact by the NASA DART Mission

- The algorithm determined the following physical properties of the Didymos system, and the values were validated from other sources:
    - Absolute Magnitude: **18.03**
    - Size: **820 meters**
    - Rotation Period: **2.26 hours**
    - Orbital Period of Dimorphos: **11.91 hours (before impact)** and **11.33 hours (after impact)**
    - Strength: **Rubble Based**

- The Algorithm was able to photometrically analyze the ejecta from the DART impact to measure changes in the magnitude of the Didymos system and calculate the length of the tail of the Dimorphos

- Any citizen will be able to support planetary defense by analyzing observations from robotic telescopes and combining them with open data to learn more about the physical properties of asteroids

Errors and Limitations

Errors

- To find the computed magnitude of the asteroid, offsets of all stars in the image were calculated. The standard deviation of the mean represented the errors in the average offset

- The asteroid size calculation assumes that the object is spherical with a uniform surface. As smaller asteroids are not spherical, an uncertainty in size calculations would occur

- In November 2022 (post-impact), Didymos moved into a crowded star field (the Milky way). During imaging, many stars came in the path of the asteroid, affecting the quality of light data

Limitations

- Limited processing capacity of the home computer limited the number of iterations that could be done to check for different rotation and orbital periods

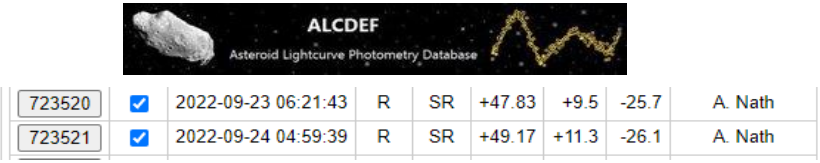
- Most remote telescopes had apertures around 0.5 metres. Long exposure times were needed to get a high Signal to Noise ratio (>100). It decreased the number of images available for photometry analysis

- This project requires the asteroid to be discovered several years in advance to allow observations to determine its composition and launch a planetary defense mission to make a small change in its orbit

Furthering Citizen Science: Open Data and Code, Outreach and Training Modules

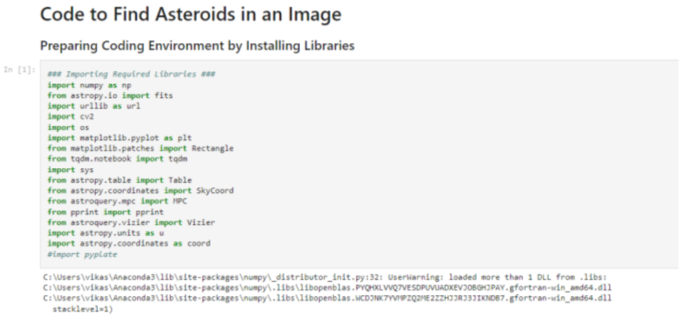
Raw Time-Series Datasets

Submitted my raw-time series photometry observations to:
Asteroid Lightcurve Data Exchange Format (ALCDEF) www.alcdef.org



Python Code and Training Module

Released my entire code under an open-source creative commons license and will be posting training modules using Jupyter Notebooks
https://github.com/Spacegirl123/Photometric-Observations-of-Didymos



Trainings Imparted

Live Online webinar **"Asteroid Science with Robotic Telescopes"** with ITelescope.net so that youths and citizen scientists can use my methodology to replicate results and improve the algorithm

Presentations

2022 Royal Astronomical Society of Canada, Toronto, Canada
2023 Lunar and Planetary Science Conference, USA
2023 Planetary Defense Conference, Vienna, Austria

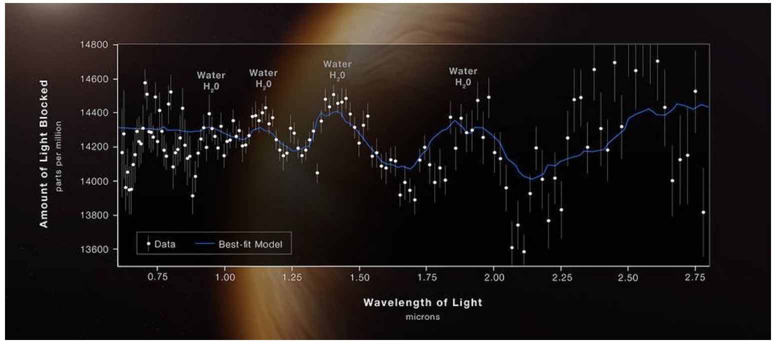
Future Goals: Radar Observations and Exoplanets

- Provide citizen science support to the European Space Agency's Hera Mission that will orbit Dimorphos and perform a detailed post-impact survey of the target asteroid in December 2026

- Use data from China's "Compound Eye" or the Fuyan project: a network of radar antennae to track asteroids and determine if they could threaten Earth. Combining radar and photometric observations would provide more information for planetary defense

https://news.cgtn.com/

- Adapt the light curves generation and analysis methodology to detecting exoplanets and studying their atmospheres using data from James Webb Space Telescope



Project Acknowledgements

- **Brian D. Warner (ALCDEF):** For providing the most recent version of the asteroid lightcurve database (LCDB)
- **Christian Sasse, Mladen Dugec, and Leigh Moore (iTelescope):** Supporting my telescope observation runs and technical assistance
- **Cristina Tomas (NASA):** Project Lead, Observations Working Group for NASA DART Mission for advice over zoom calls on the project
- **Daniel Parrot (Tycho Software):** Providing technical inputs and coordinating on Didymos observations
- **Donald Prey (Sugarloaf Mountain Observatory):** For sharing post-impact observations of Didymos
- **Jean-Claude Merlin (France):** For sharing observations of Didymos ejecta
- **Kenneth Menzies and Dirk Terrell (AAVSO):** For supporting my proposal and providing data from OC61 telescope
- **Martin Bergeron and Denis Laurin (Canadian Space Agency):** For supporting my NEOSSat observation proposal and providing data
- **Paul Roche (Cardiff University, UK):** For advice on project outreach to youths and schools
- **Sarah Roberts (Faulkes Telescope Project):** For telescope time with Faulkes Telescope South and advice

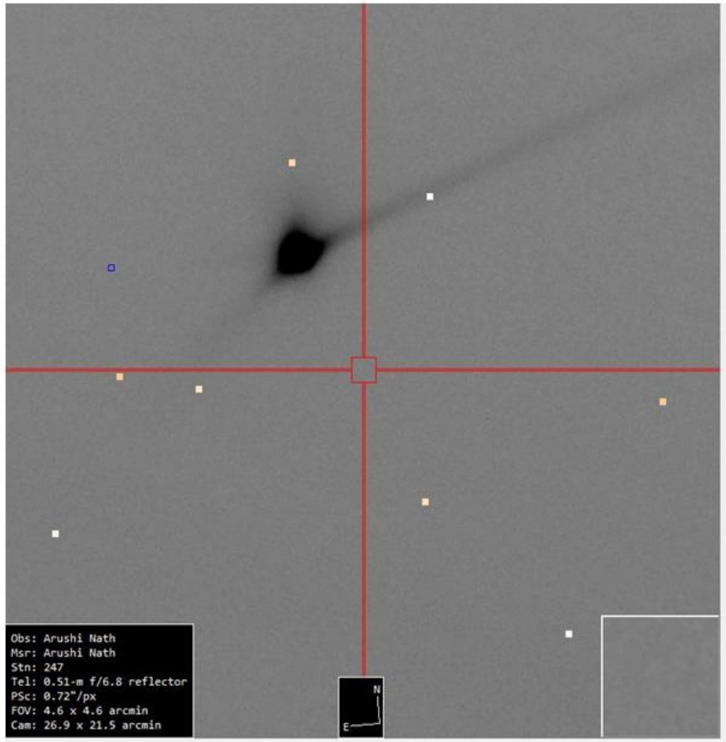
If you or your organization can provide Telescope time for my future observations, please write to me at: arushi@monitormyplanet.com

Your support would be appreciated and acknowledged.

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

Image of Asteroid Didymos (65803) by Arushi Nath
T72 iTelescope, Chile, 1 October 2022
Stacked from 14 x 60-sec exposures.



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IAA Planetary Defense Conference (PDC)
3 to 7 April 2023
Vienna, Austria