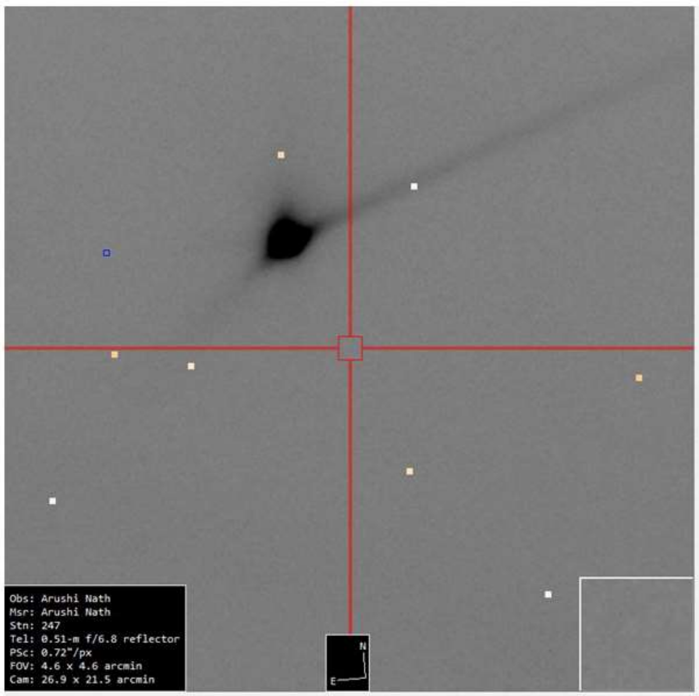
Planetary Defense by Citizen Scientists:

Measuring Impact of the NASA DART Asteroid Deflection Mission Using Open Science and Robotic Open ScienceTelescopes

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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- 2023 Young Astronomer Award
  Royal Astronomical Society of Canada
- 2020 NASA SpaceApps Global Winner

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G-HOU

Global Hands-on Universe Conference
25 August 2023

BACKGROUND

Asteroid Collision Risks are Small but Non-Zero

19 November 2022: Asteroid 2022 WJ1 (1-metre)
- Fell harmlessly in Lake Ontario
- Discovered 3 hours in advance

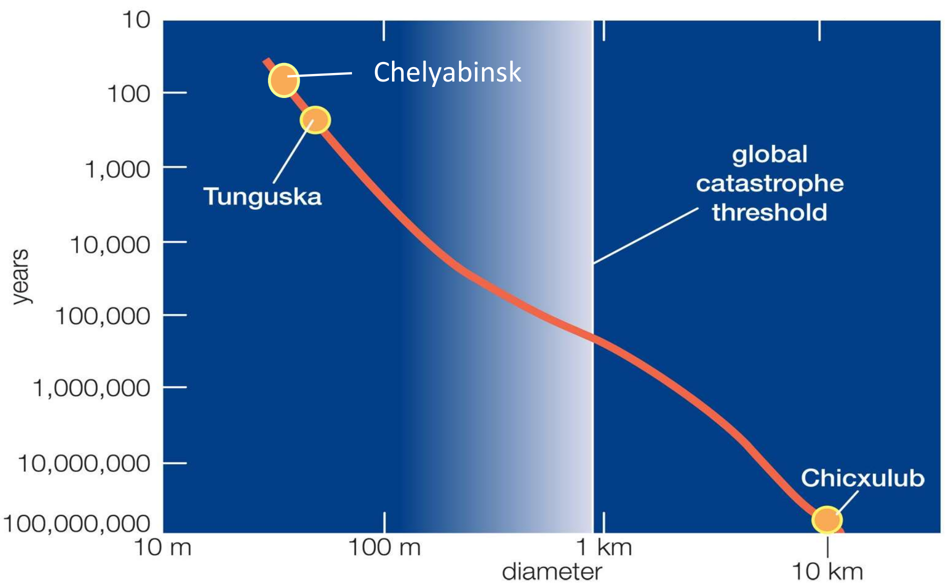
Source: EarthCam

Interval between Asteroid Impacts is Shorter for Smaller Sized Asteroids

100m Asteroids (like Tunguska):
Impact probability (every 5000 years)

20m Asteroids (like Chelyabink):
Impact probability (every 50 years)

Newly Discovered Near-Earth Asteroids (are mostly < 140m in size):
Impact probability (high)



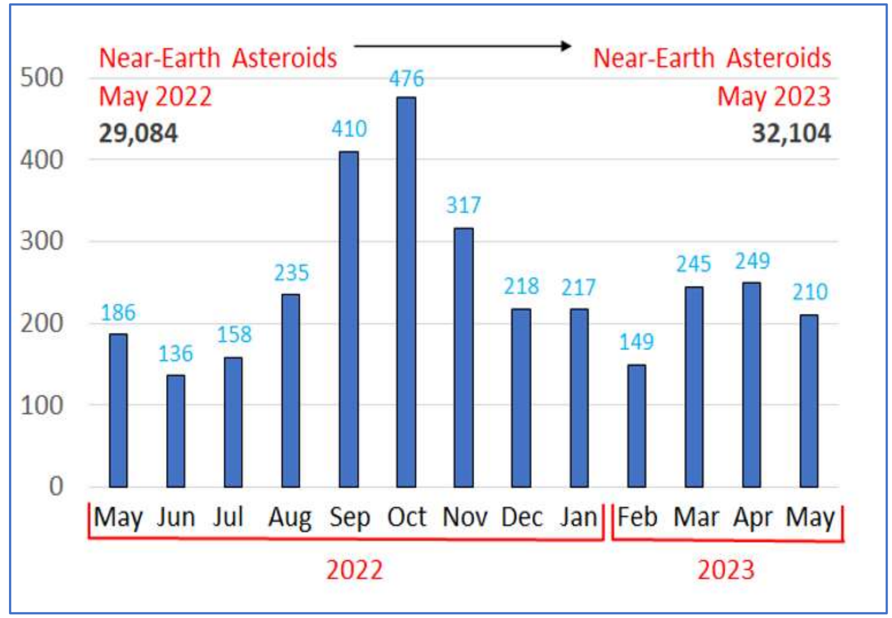
Source: Britannica

PLANETARY DEFENSE CHALLENGE

- **Pace of Discovery of Near-Earth Asteroids Outpaces their Analysis**
  3020 discoveries in the last 1 year

- **Deflecting an Asteroid Requires Knowledge of its Physical Properties**
  Eg: size and strength

Near-Earth Asteroids Discovered (May 2022 - May 2023)



Graphed using data from CNEOS

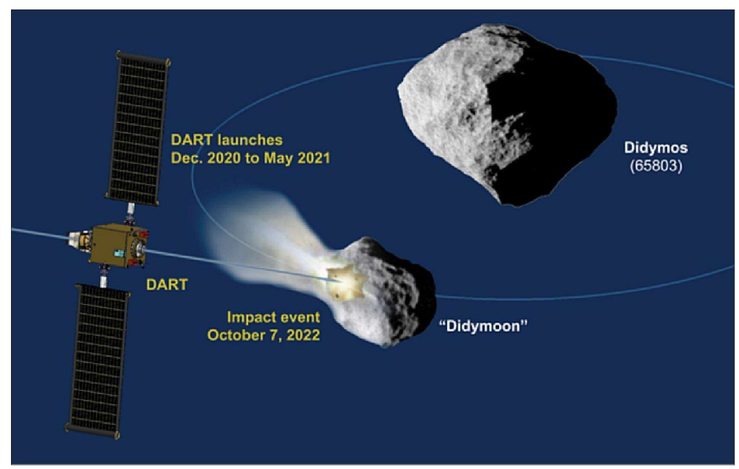
REAL-WORLD OPPORTUNITY

NASA Double Asteroid Redirection Test (DART) Mission

26 September 2022

NASA conducted its **First Planetary Defense Test** by smashing a fridge-sized spacecraft (600 kg) into Dimorphos: the moonlet of (65803) Didymos binary asteroid, to change its orbit

Didymos-Dimorphos Binary Asteroid



Source: NASA/JHAPL

Mighty NASA Projects Inspire Imagination

What if I could:

1. **Develop algorithms** to determine the physical properties of near-earth asteroids using:
   - Robotic telescopes
   - Open Science
   - Home computers

2. **Apply the algorithms** to determine the physical properties of the Didymos binary asteroid

3. **Find out if NASA DART Mission moved asteroid Dimorphos?**

OPEN SCIENCE

Makes Curiousity-driven Projects Possible

Open Knowledge:
Video Tutorials, Zoom Conferences, Webinars

Open Communities:
Minor Planet Mailing List, Cloudy Nights Forum, Astrometrica Group

Open Data:
Horizons Systems (NASA), GAIA DR3 (ESA), Photometry Lightcurve Database

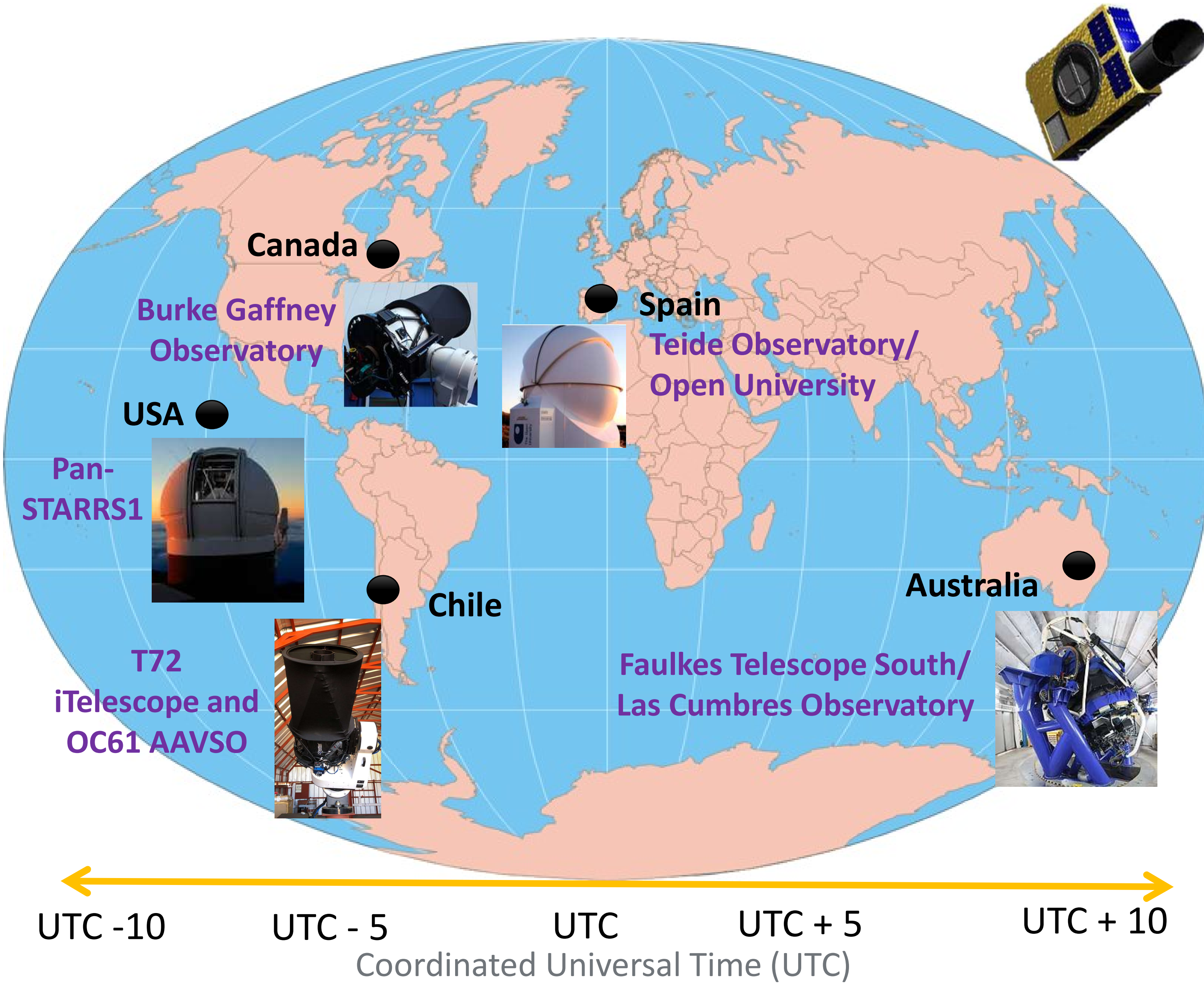
Open / Citizen Scientists Run Telescope Network:
Faulkes Telescope Project, Burke Gaffney Observatory, AAVSO

Open Programming Languages:
Python, Matplotlib, Astropy

Open science accelerated during the Covid-19 pandemic as most events turned free and virtual, making it possible for me to participate

ROBOTIC TELESCOPES USED TO OBSERVE ASTEROIDS

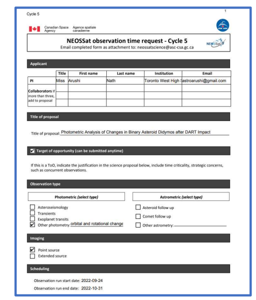
Observations from time zones across the globe allow continuous monitoring of an asteroid and result in a more accurate determination of its physical properties



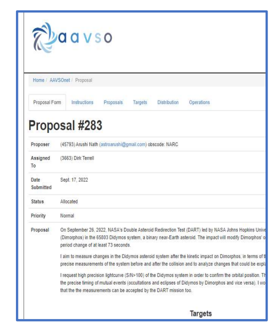
Space Telescope

NEOSSat. Canadian Space Agency

Research Proposals Written to Get Observation Time



Canadian Space Agency

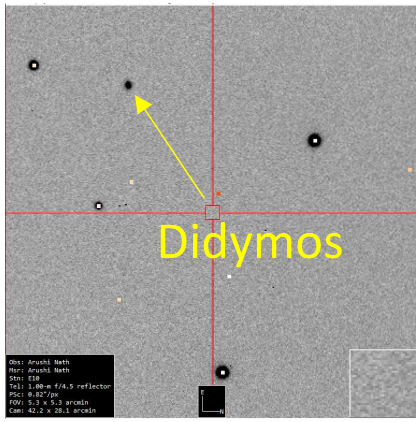


American Association of Variable Star Observers (AAVSO)

DATA: Primary Observations of Asteroid Didymos (55+ hours)

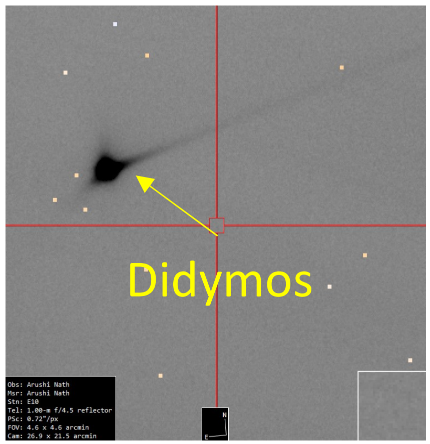
PRE-IMPACT

Date: 11 Sep 2022
Telescope: T30, Australia
Exposure: 60 sec
Apparent Magnitude: 15.0



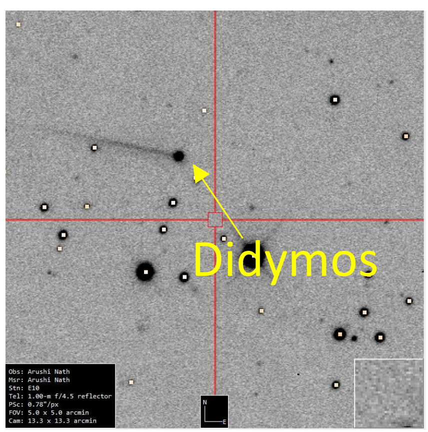
DURING IMPACT

Date: 1 Oct 2022
Telescope: T72, Chile
Exposures: 14 x 60 sec
Apparent Magnitude: 13.7



POST-IMPACT

Date: 18 Nov 2022
Telescope: FTS, Australia
Exposure: 60 sec
Apparent Magnitude: 16.4



Imaging by Arushi Nath

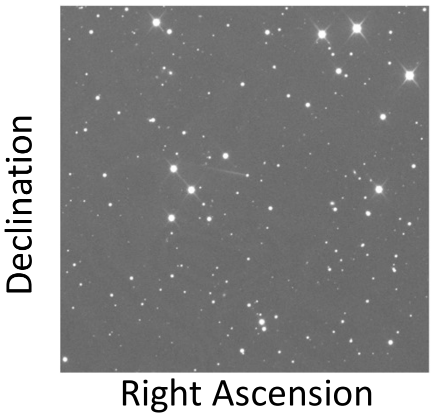
Date	Telescope	Observation (hours)	Filter
2022-09-11	T30	3.8	R
2022-09-19	T72*	2.3	R
2022-09-20	T72*	4	R
2022-09-23	T72	1.1	R
2022-09-24	T72	2	R
2022-09-27	T30	1	R
2022-09-30	T32	3.9	R
2022-10-01	OC61 AAVSO	4	SR
2022-10-01	T72	2.8	R
2022-10-02	T72	3.2	R
2022-10-02	T30*	1.2	C
2022-10-23	NEOSSat	2.2	C
2022-11-17	FTS/LCO	1.2	R
2022-11-21	FTS/LCO	1.5	R
2022-11-30	BGO	3.1	C
2022-12-02	Sugarloaf Observatory*	4	C
2022-12-21	Sugarloaf Observatory*	4	C
2022-12-25	Sugarloaf Observatory*	4	C
2022-12-26	Sugarloaf Observatory*	4	C

* In collaboration with Donald Pray, Daniel Parrott, Jean-Claude
AAVSO: American Association of Variable Star Observers
FTS/LCO: Faulkes Telescope Project / Las Cumbres Observatory
BGO: Burke Gaffney Observatory

METHODOLOGY

1. Identify and Centroid Known Stars and Asteroids in Images from Robotic Telescopes

Image from Robotic Telescope



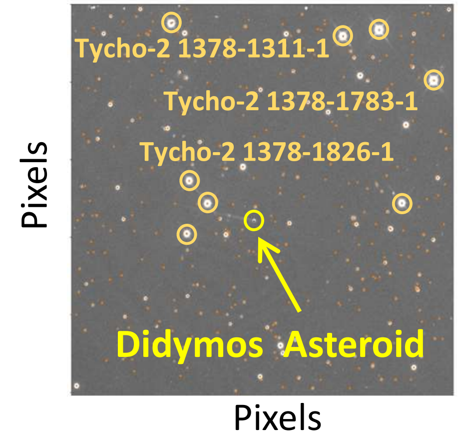
Identify Known Stars and Asteroids

Open Datasets

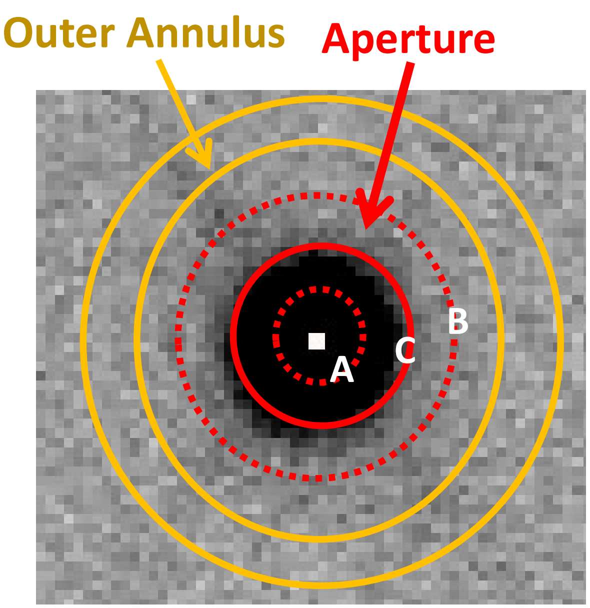
GAIA DR 3 (Star Catalog)
European Space Agency

HORIZONS (Asteroid Catalog)
NASA

Centroid Known Stars and Asteroids

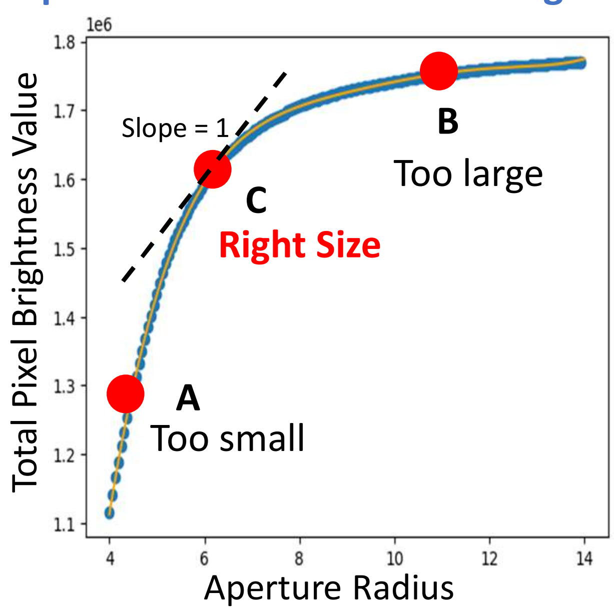


2. Find Aperture Size to Measure Total Pixel Brightness of an Asteroid (Differential Photometry)



Centroided Asteroid

Aperture Size vs Total Pixel Brightness



Small aperture size (A):
Partial brightness of asteroid is measured

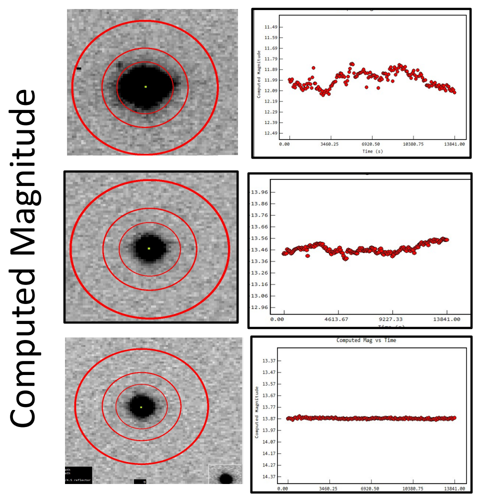
Large aperture size (B):
Too much background noise is included

Correct aperture size (C):
Asteroid brightness measured with least noise

Total Pixel Brightness of Asteroid:
Pixel brightness of Aperture – [(pixel brightness of Annulus/Annulus area) * Aperture area]

METHODOLOGY (continued)

3. Use Comparison Stars to Determine Computed Magnitude of an Asteroid



Not Suitable

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

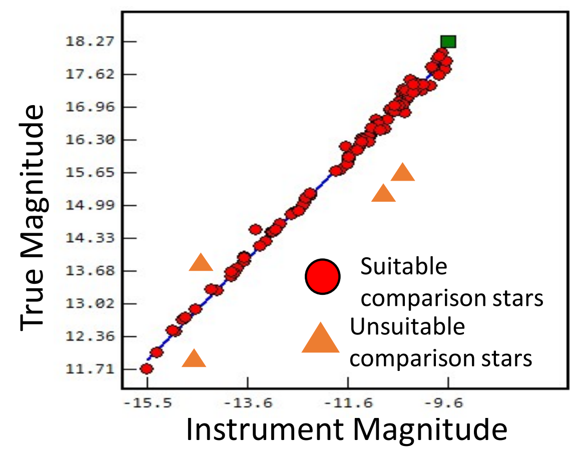
Not Suitable

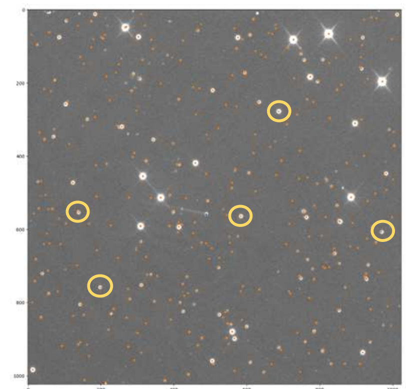
Star brightness is changing over time

Suitable Comparison Star

Star is of right size and brightness is constant over time

Selection of 4 to 7 Comparison Stars

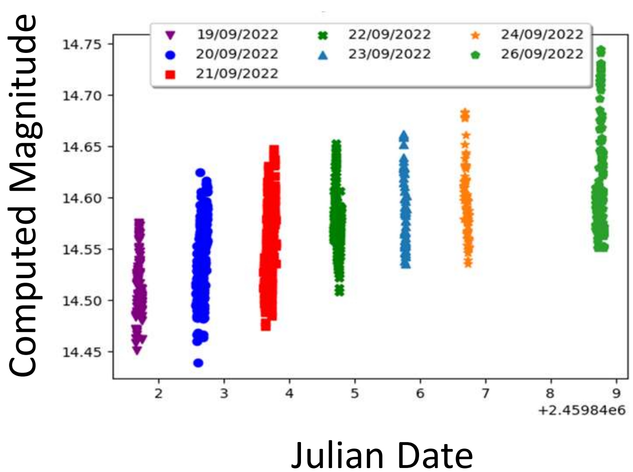




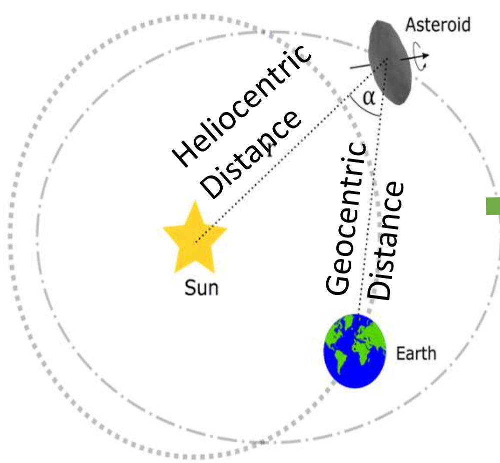
Comparison stars in the field of view

4. Apply Offsets to Time-Series Computed Magnitudes (Light Curve)

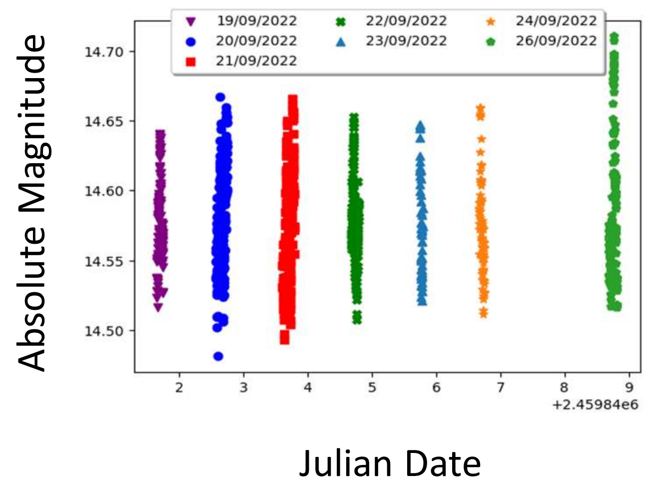
Didymos Computed Magnitude (Before Offsets)



Applying Offsets (Unity Distance, Phase Angle, Light Time Correction)



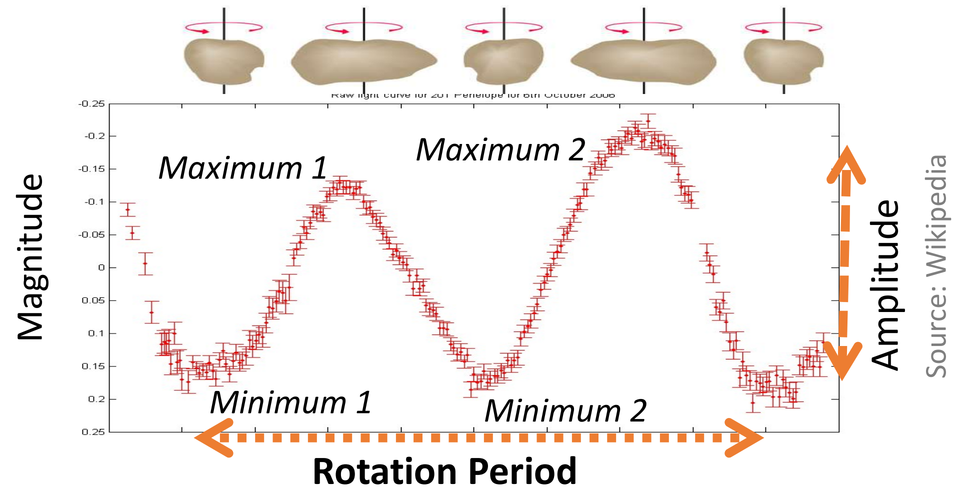
Didymos Absolute Magnitude (After Offsets)



METHODOLOGY (continued)

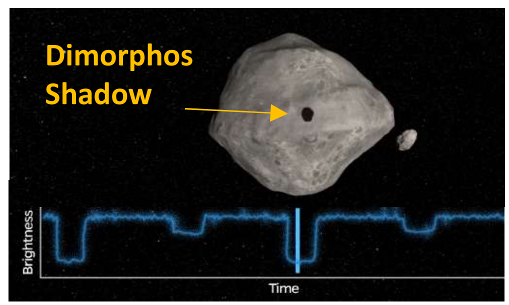
5. Finding Rotation Period

Asteroid Rotation Curve

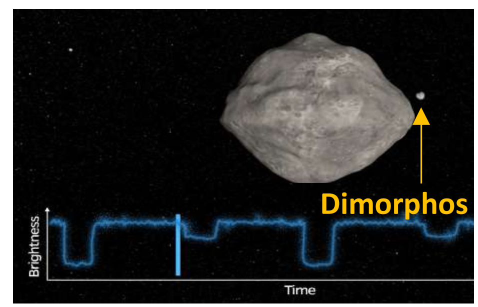


6. Finding Mutual Orbital Period of a Binary Asteroid

Primary Occultation and Eclipse

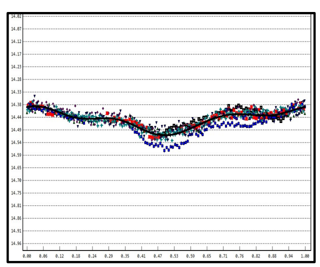


Secondary Occultation

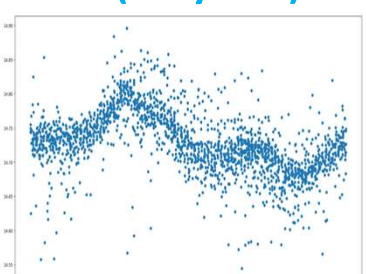


Source: NASA

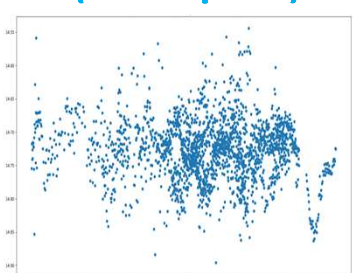
Composite Asteroid Light Curve



Primary Light Curve (Didymos)



Secondary Light Curve (Dimorphos)



RESULTS

1. Absolute Magnitude and the Size of Didymos Determined

Absolute Magnitude of Didymos (H): 18.03

Observation Dates		18 Sep 2022	23 Sep 2022	18 Nov 2022
Computed Magnitude (M)		14.53	14.50	16.15
	Earth-Asteroid Distance in AU **(R)** Sun-Asteroid Distance in AU **(r)**	0.09 1.07	0.08 1.05	0.15 1.05
	After Unity Offset $H(\alpha)$	19.61 *(+5.08)*	19.88 *(+5.38)*	20.16 *(+4.01)*
	Phase Angle in Degrees **(α)**	41.7	49.7	59.9
	Phase Offset	-1.63	-1.85	-2.15
Absolute Magnitude		17.98	18.03	18.01
Average Absolute Magnitude (H)		**18.03** *(Based on 10 Observations)*		

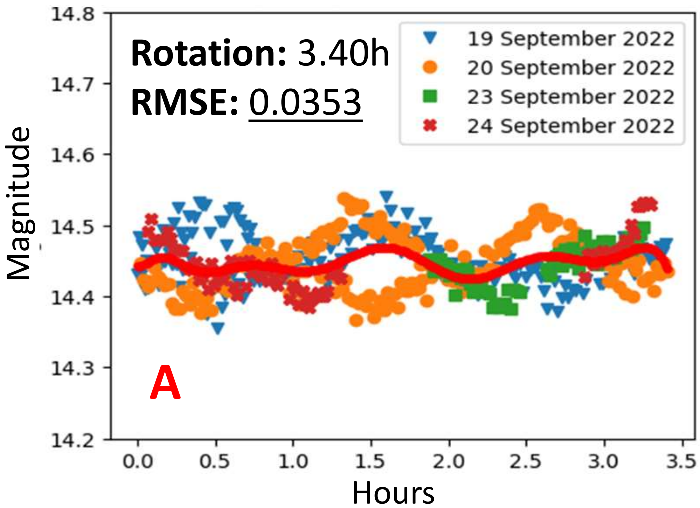
Size of Didymos (d): 820 metres

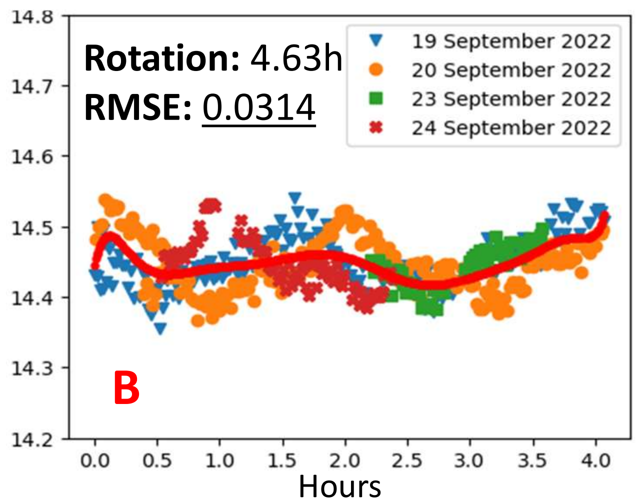
The diameter (d) of an asteroid is a function of its absolute magnitude (H) and geometric albedo (a)

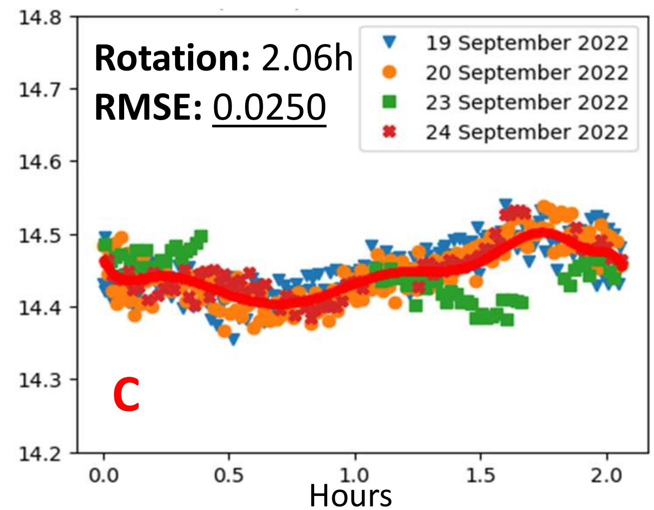
$d\ (km) = 10^{[3.1236 - 0.5\log_{10}(a) - 0.2\,(H)]}$ *(H = 18.03 from above calculations. a = 0.16)*

2. Rotation Period of Didymos Determined: Did Not Change Post-Impact

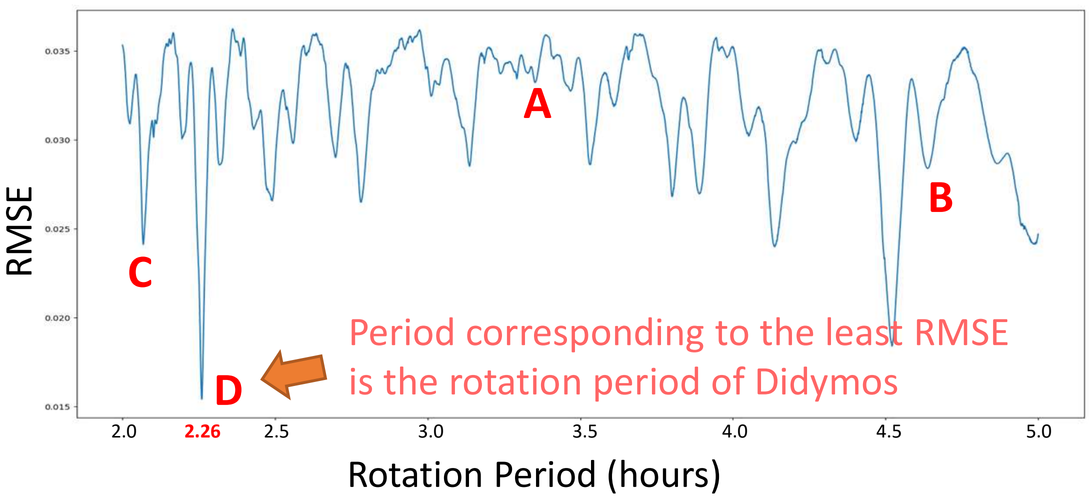
Didymos Light Curves Fitted to Different Rotation Periods Using Congruent Modulo and Root Mean Square Error (RMSE)





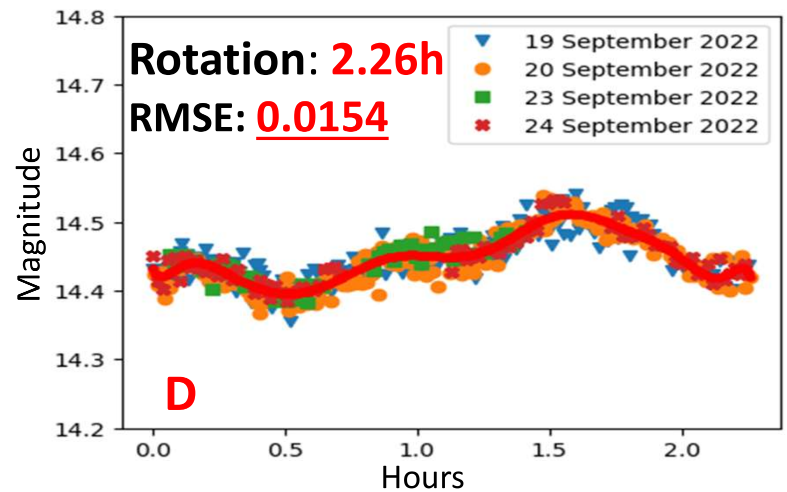


Rotation Period vs Root Mean Square Error (RMSE)



Rotation Period of Didymos

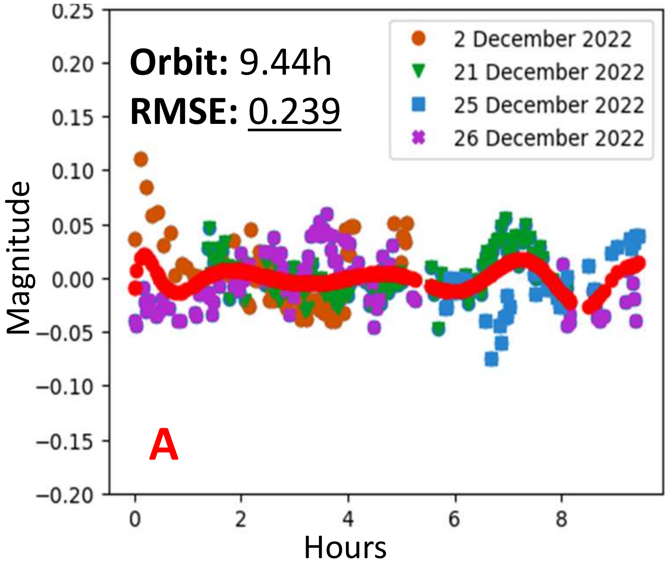
(2.26 hours)

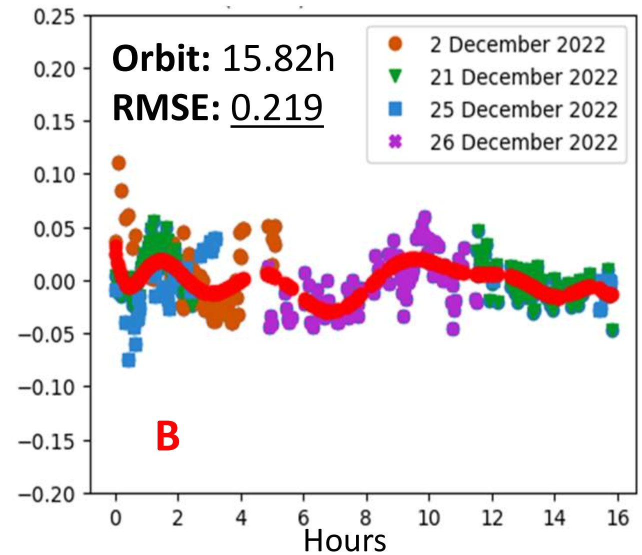


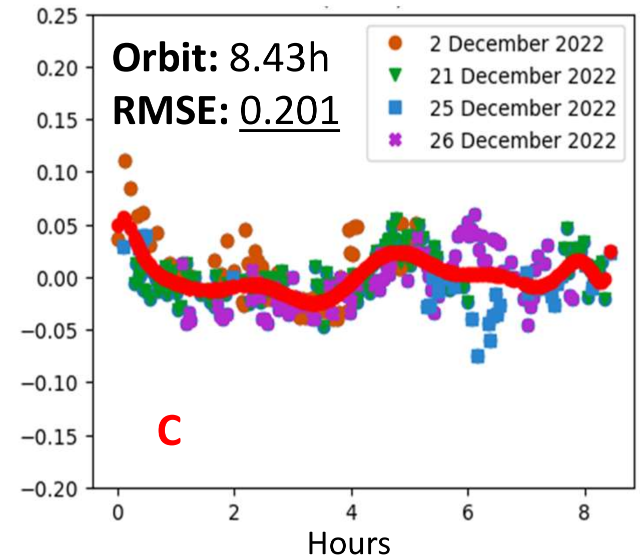
No change in the rotation period of Didymos was observed after the impact, nor any was expected

3. Mutual Orbital Period of Didymos-Dimorphos Determined: Reduced Post-Impact

Secondary Light Curves Fitted to Different Orbital Periods Using Congruent Modulo and Root Mean Square Error (RMSE)

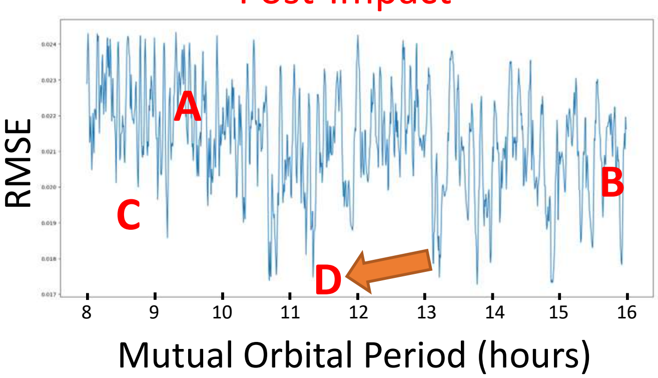






Orbital Period vs Root Mean Square Error (RMSE)

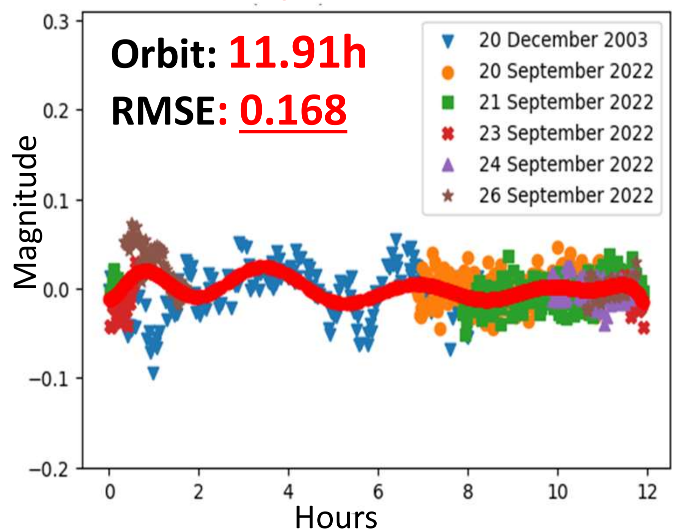
Post-Impact



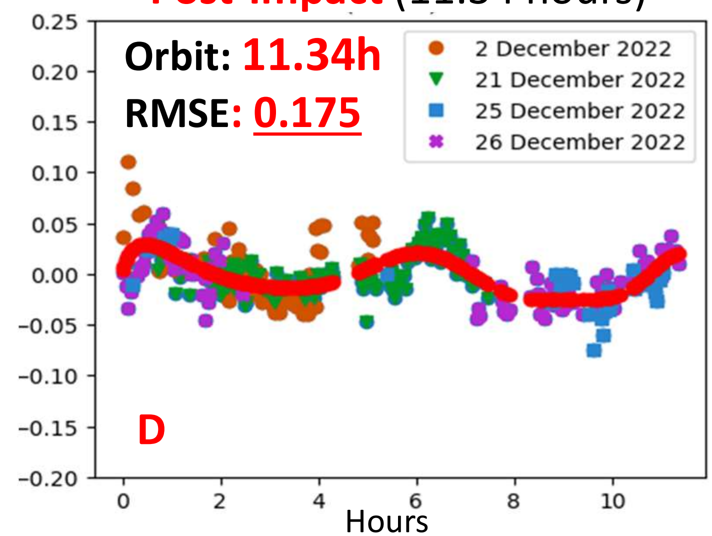
Period corresponding to the least RMSE is the mutual orbital period

Mutual Orbital Period of Didymos-Dimorphos

Pre-Impact (11.91 hours)

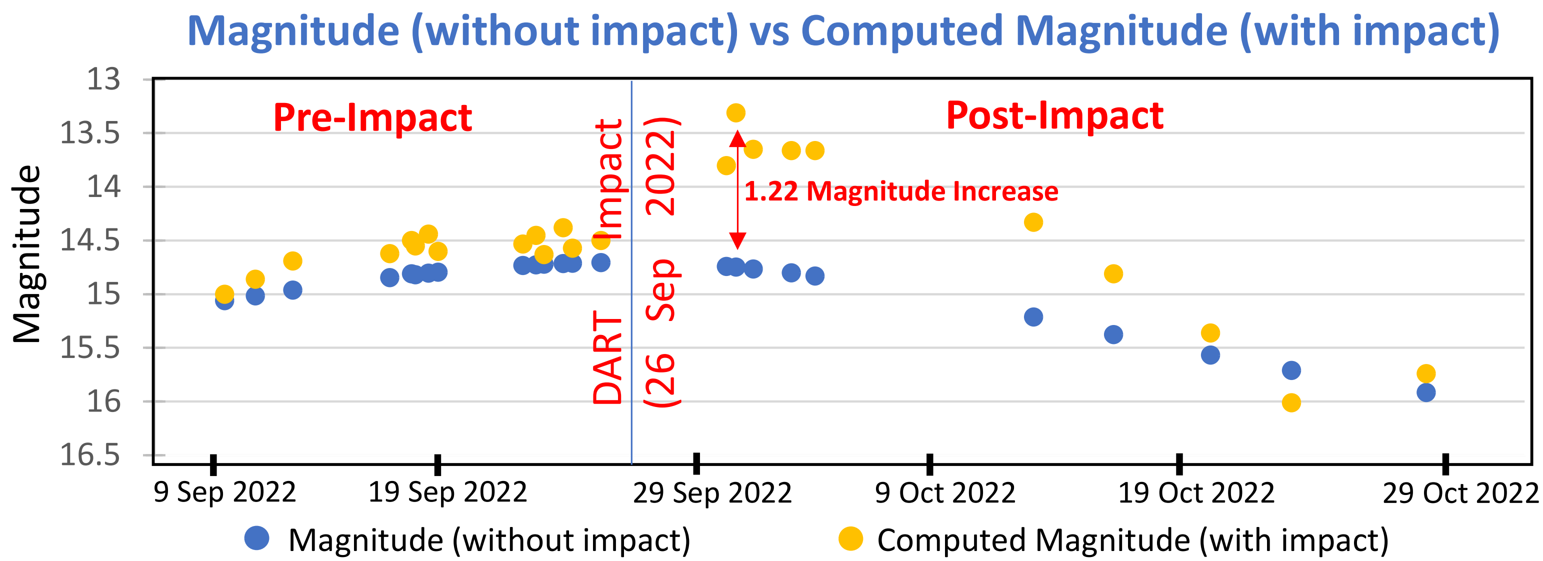


Post-Impact (11.34 hours)

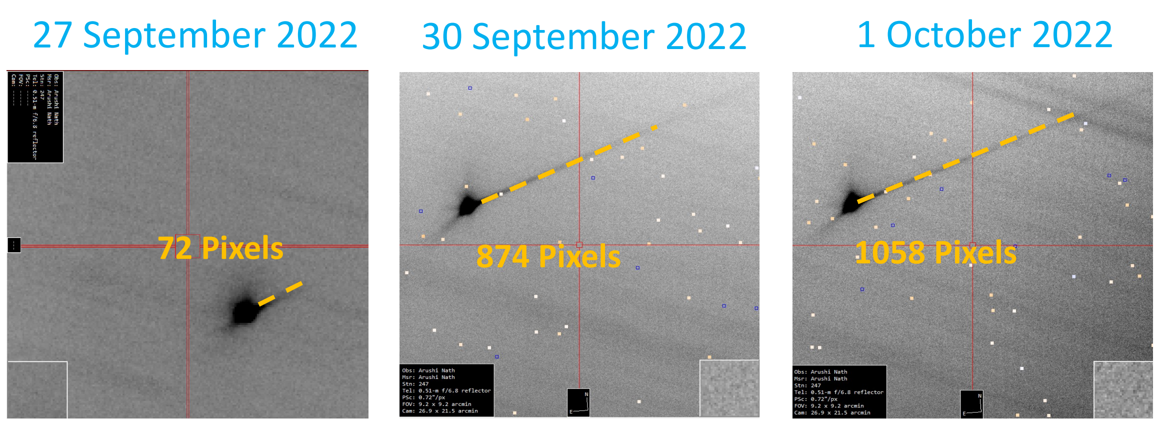


Mutual orbital period reduced by 35 minutes after the impact and was expected

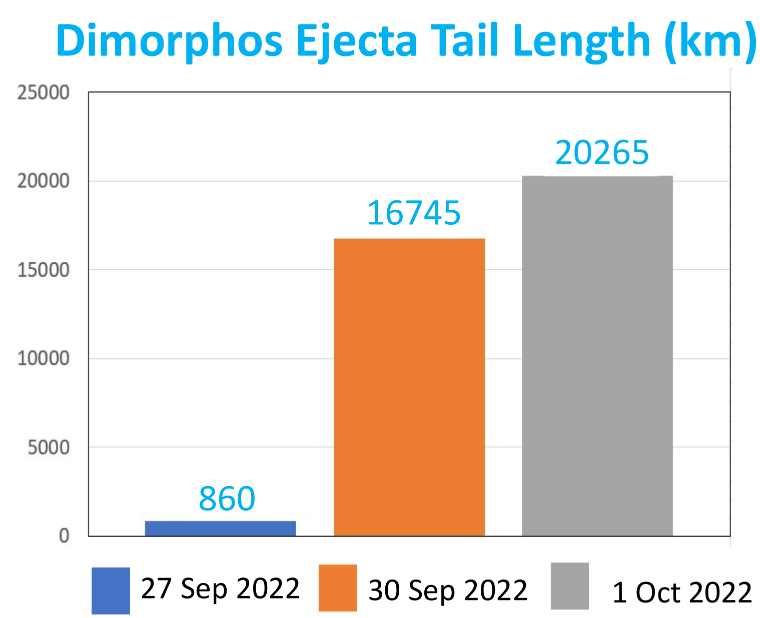
4. Post-Impact Brightness of Didymos Increased by 1.2 Magnitude



5. Ejecta Tail of Dimorphos Measured to be Over 20,000 kms



Tail Length Calculation: 1 October 2022	
Tail Length on CCD (pixels)	1058
Tail Length on CCD (arcsec) **s**	1058 * 0.36 (pixel scale)= 380
Distance from Earth (km) **R**	$11*10^6$
Tail Length (km) (2*pi*R)/360*(s/3600)	**20,265**



Ejection of material after the DART impact created the tail

6. Finding Asteroid Strength from Rotation Period

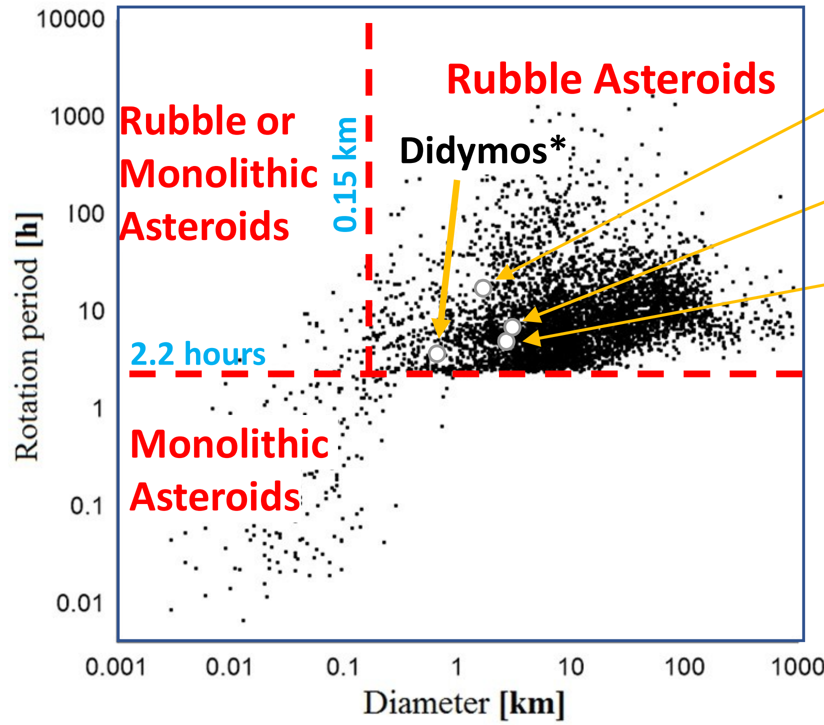
If Rotation Period < 2.2 hours

- Asteroid must be '**Strength-bound**' single rock
- Else it would fly apart

If Rotation Period > 2.2 hours and Diameter > 150 m

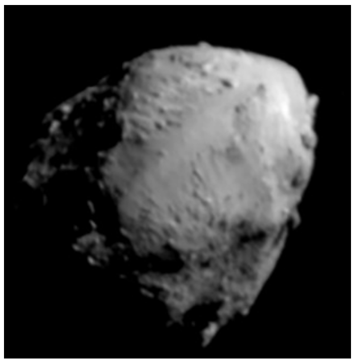
- Asteroid likely to be '**Rubble Pile**'
- Held together by mutual gravitation

Rotation Period vs Diameter (~6000 Asteroids)



*Determined by my algorithm

Adapted from rotation vs diameter plot: Lubin, P



Source: NASA DRACO Camera

Asteroid Didymos is likely a "Rubble Pile"

- Rotation Period: **2.26 hours** *(from Result 2*) is more than 2.2 hours
- Diameter: **820 metres** *(from Result 1*) is more than 150 metres

Asteroid Dimorphos is likely a "Rubble Pile"

- Dimorphos being a moonlet shares same parent material as Didymos
- The **20,000 km** debris tail *(from Result 5)* behind a 0.2 km wide Dimorphos strengthens the assumption

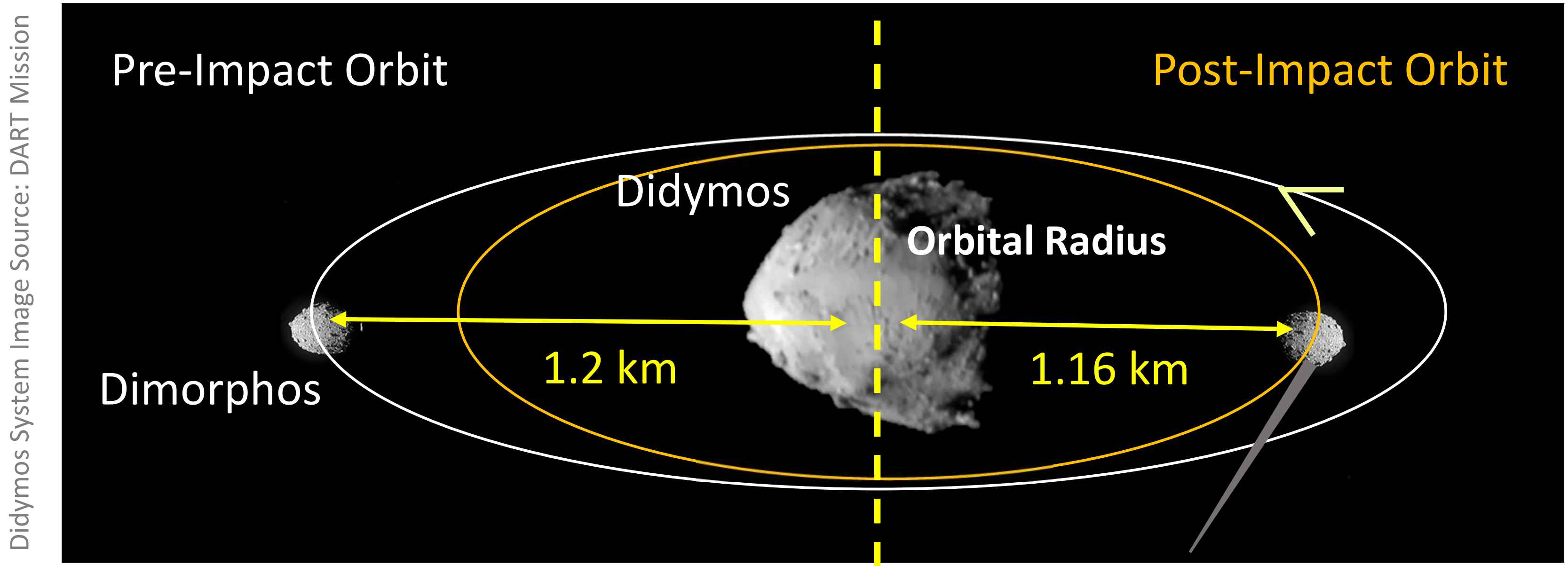
7. So Did we Move Dimorphos?

Kepler's Third Law

$$(T_1/T_2)^2 = (R_1/R_2)^3$$

Pre-Impact Orbital Period (T_1): 11.91 hours (*from Result 3*)
Post Impact Orbital Period (T_2): 11.34 hours (*from Result 3*)
Pre-Impact Didymos-Dimorphos Semi-Major Axis (R_1): 1.2 km
=> Post-Impact Didymos-Dimorphos Semi-Major Axis (R_2): 1.16 km
=> Change in Orbital Radius: 1.2 km – 1.16 km = 0.04 km (40 metres)

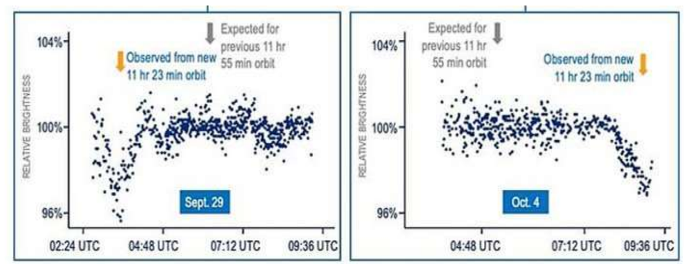
New Orbital Path of Asteroid Dimorphos After Deflection

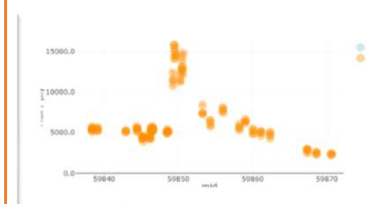
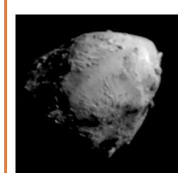


The left-hand side image is actual image from the DRACO/NASA DART Camera
The right-hand side is recreated from the left

Humanity has the capability to change the path of an asteroid
Citizen scientists can measure the success of asteroid deflection from ground

VALIDATION OF RESULTS FROM MY ALGORITHMS:

<table>
<tr><th colspan="2">Didymos Physical Properties</th><th>Calculated by My Algorithm</th><th>Measured by NASA</th><th>Accuracy</th><th colspan="2">Validation Sources</th></tr>
<tr><td colspan="2">Absolute Magnitude</td><td>18.03</td><td>18.12</td><td>99.5%</td><td colspan="2" rowspan="5">NASA Small Body Database Lookup https://ssd.jpl.nasa.gov/tools/sbdb_lookup.html#/?sstr=65803


NASA https://www.nasa.gov/feature/nasa-dart-imagery-shows-changed-orbit-of-target</td></tr>
<tr><td colspan="2">Size (metres)</td><td>820</td><td>780*</td><td>95.1%</td></tr>
<tr><td colspan="2">Rotation Period and Amplitude</td><td>2.26 hours
Amplitude = 0.1</td><td>2.26 hours
Amplitude = 0.1</td><td>100%</td></tr>
<tr><td rowspan="2">Mutual Orbital Period</td><td>Pre-Impact</td><td>11 hrs and 55 min (11.91 hrs)</td><td>11 hrs and 55 min (11.91 hrs)</td><td>100%</td></tr>
<tr><td>Post-Impact</td><td>11 hrs and 20 min (11.34 hrs)</td><td>11 hrs and 23 min (11.38 hrs)</td><td>99.6%</td></tr>
<tr><td colspan="2">Post-Impact Peak Increase in Computed Magnitude</td><td>1.2 magnitude</td><td>1.2 magnitude</td><td>100%</td><td></td><td>ATLAS Forced Photometry Server https://fallingstar-data.com/forcedphot</td></tr>
<tr><td colspan="2">Asteroid Composition</td><td>Rubble Pile</td><td>Rubble Pile</td><td>100%</td><td colspan="2"> Didymos  Dimorphos</td></tr>
</table>

**NASA measured the Didymos size from space using the Didymos Reconnaissance and Asteroid Camera (DRACO) onboard the DART Spacecraft. While my measurements were from ground-based telescopes by calculating the absolute magnitude of Didymos.*

ERRORS AND LIMITATIONS

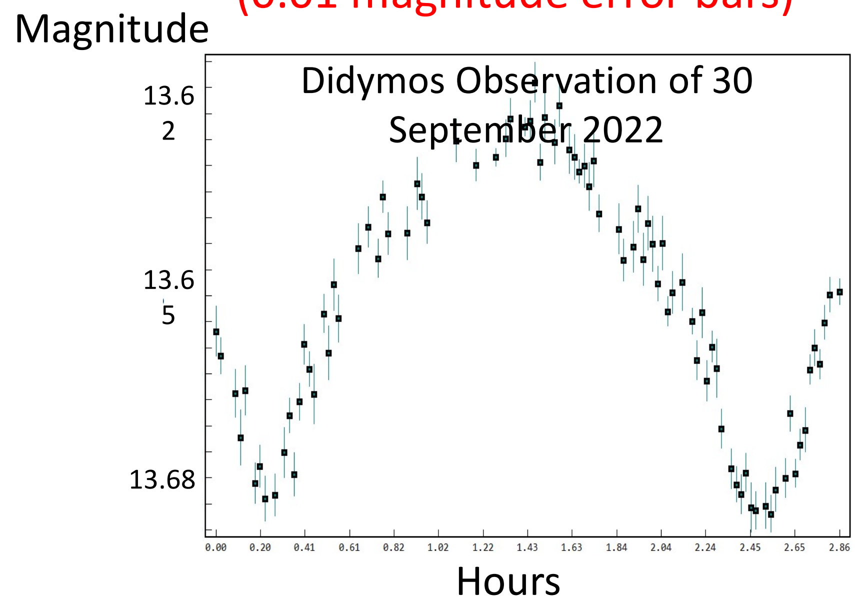
My observation plans for robotic telescopes had **Signal-to-Noise Ratio (SNR) > 100**

Uncertainty = **1 /SNR** = 0.01 = **0.01 mag** (approx)

Acceptable level of uncertainty as Didymos Rotation Period had an amplitude of 0.1 magnitude

Uncertainty in Measurements

(0.01 magnitude error bars)



Limited capability of my home computer restricted the iterations I could perform to find the best fit for rotation and mutual orbital periods to 2 significant digits

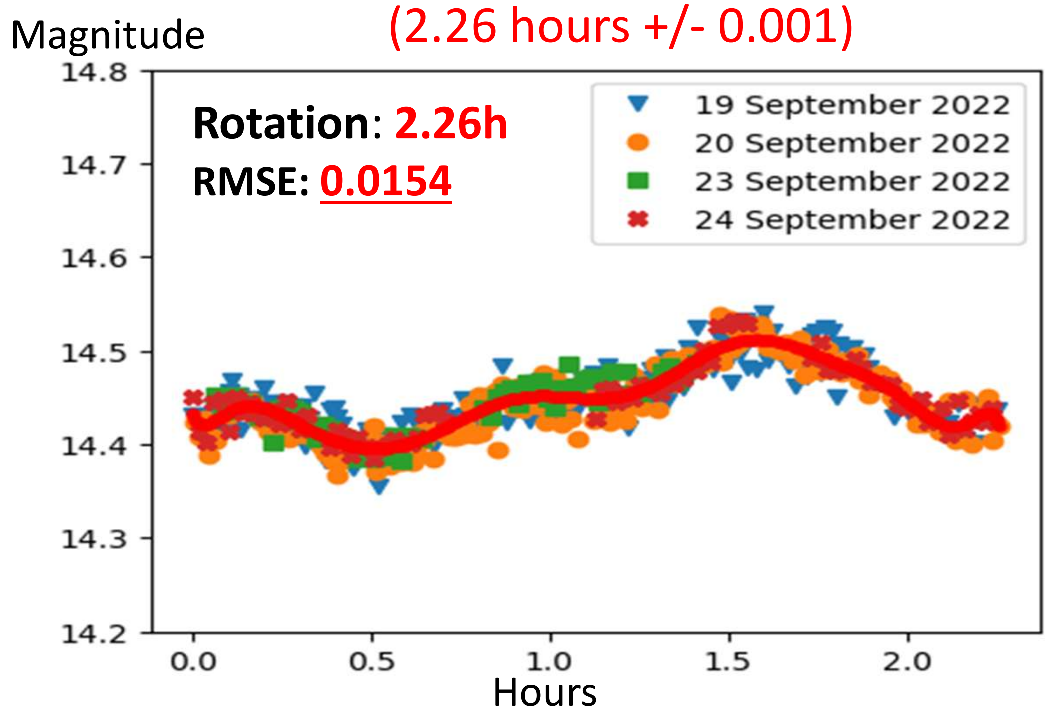
Preciseness = Time Interval (hours) / Number of Iterations

= 3/2000 = 0.0015 = +/- 0.0075

= **+/- 0.001 hours** (approx)

Rotation Period of Didymos

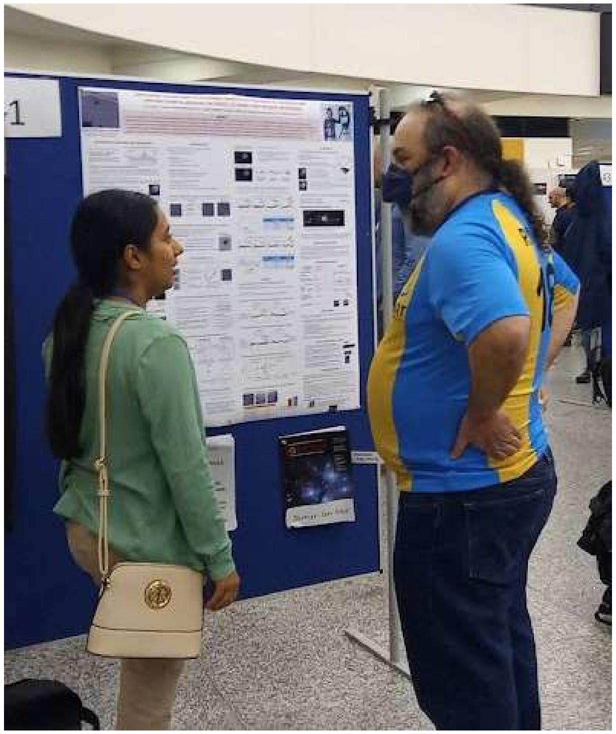
(2.26 hours +/- 0.001)



Planetary Defense Conference

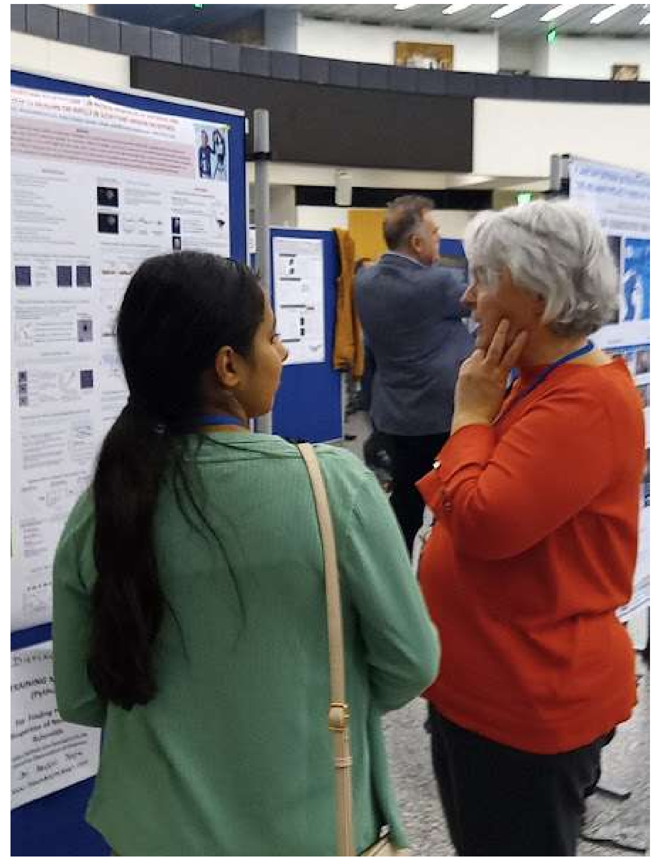
- Held once every 2 years
- Brings together experts to discuss the threats that asteroids and comets may present to the Earth
- Simulate measures that can be taken to redirect approaching objects

Sharing my Research with the DART Team Members



Andy Rivkin
DART Investigation Team Lead

Cristina Thomas
DART Observations Working Group Lead



Elizabeth
HERA Mission

<u>Breaking News:</u>

Won 2023 Best of Canada-Wide Science Fair Award

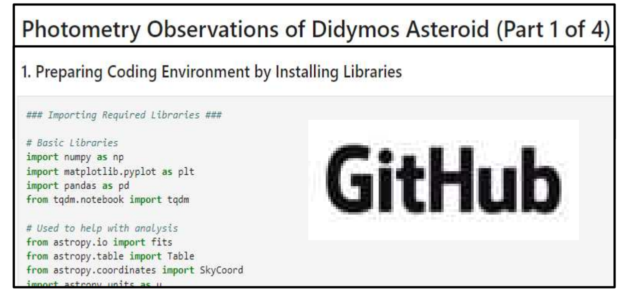
(second year in a row, breaking 33-years old record)

Will represent Team Canada at the 2023 European Union Contest for Young Scientists (EUCYS) in Brussels from 12 – 17 September

IGNITING SCIENTIFIC TEMPER IN OUR SOCIETY

Outreach

- Given 12 talks at the Royal Astronomical Society of Canada
- "Asteroid Day" talk at MacMillan Space Centre, Vancouver



Online Training to Teach Citizen Scientists

- Developed training modules using Jupyter Notebook to perform astrometry and photometry using open science
- Webinar on "Asteroid Science" with iTelescope.net

Dialogues with Policy Makers to Invest in Citizen Science

- Tech Talks with Member of Provincial Parliament, Ontario
- Deputes to Toronto City Hall on using big data and science

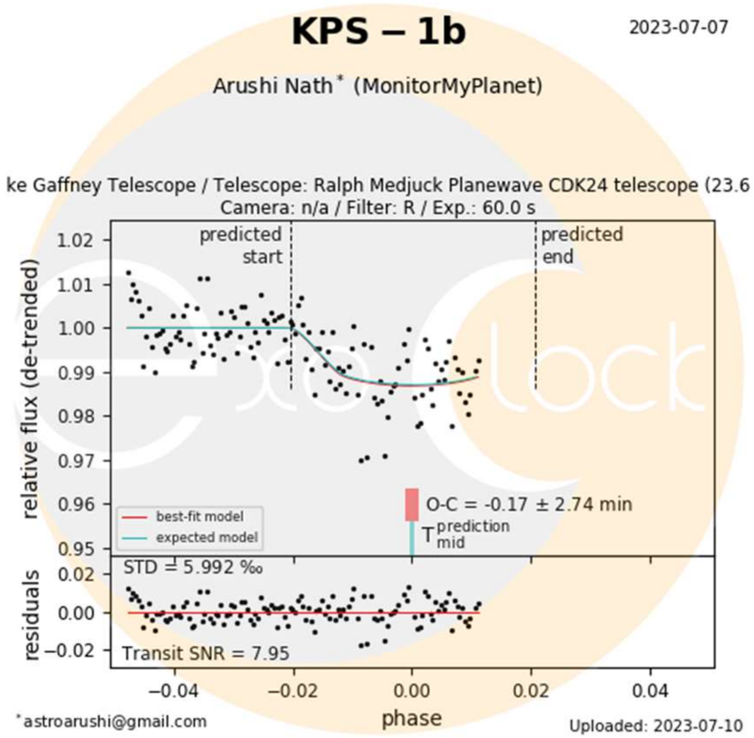
2023 Planetary Defence Conference, Vienna

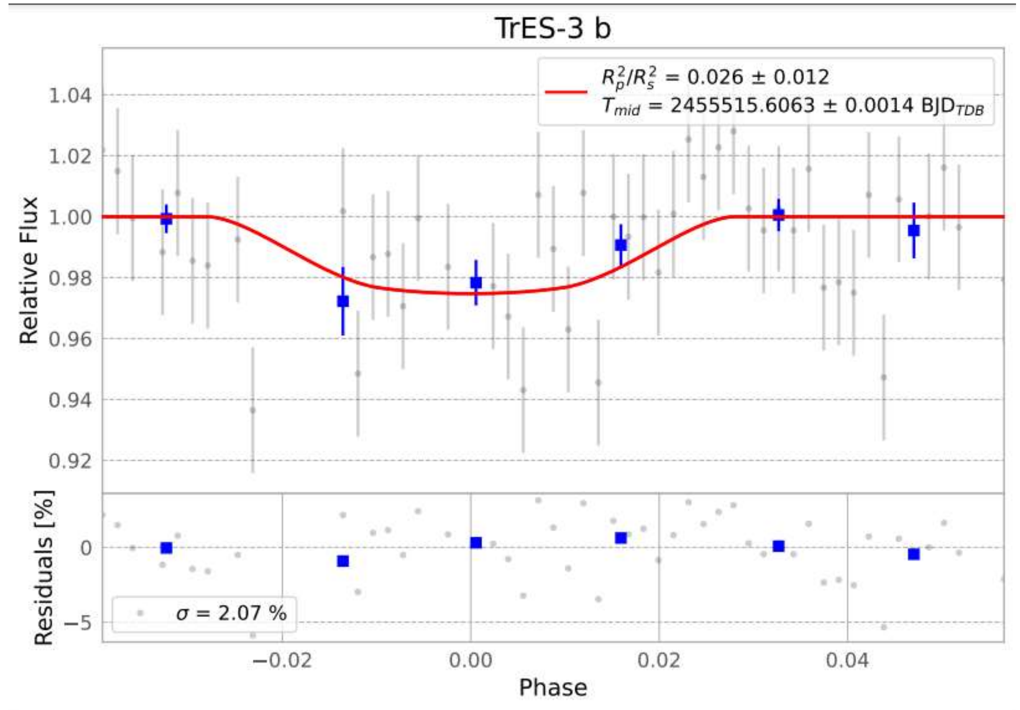
- Poster presentation about my research
- Opportunity to meet the DART Team and discuss our research

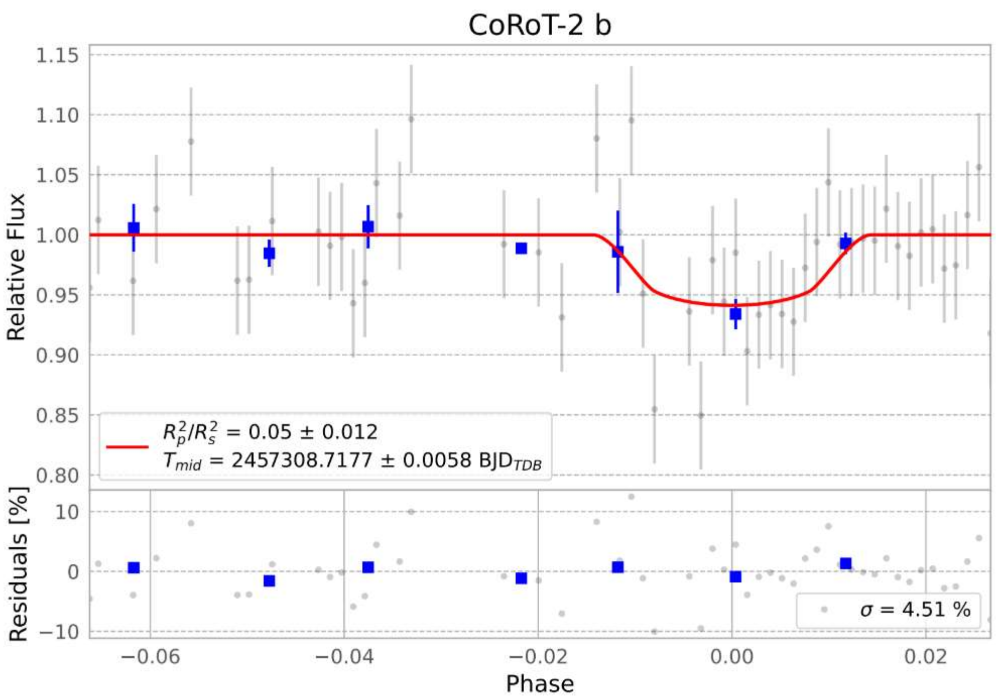
Publication

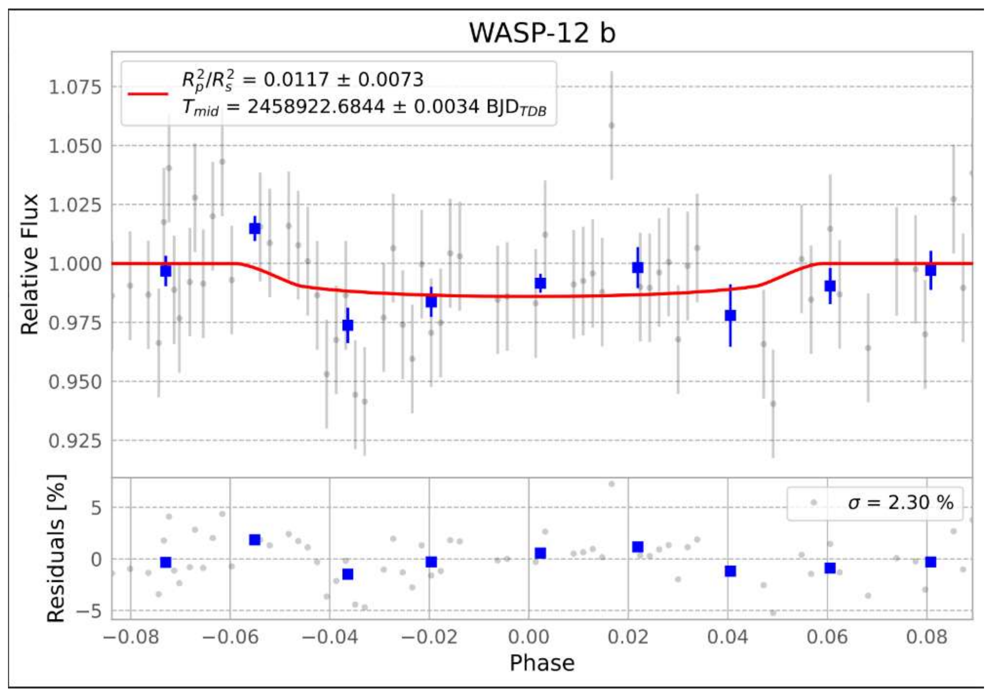
February 2023 Issue, Volume 117

Journal of the Royal Astronomical Society of Canada


KPS – 1b
2023-07-07
Arushi Nath* (MonitorMyPlanet)
ke Gaffney Telescope / Telescope: Ralph Medjuck Planewave CDK24 telescope (23.6
Camera: n/a / Filter: R / Exp.: 60.0 s
predicted start
predicted end
relative flux (de-trended)
best-fit model
expected model
O-C = -0.17 ± 2.74 min
T prediction mid
STD = 5.992 ‰
Transit SNR = 7.95
residuals
phase
*astroarushi@gmail.com
Uploaded: 2023-07-10


TrES-3 b
R_p^2/R_s^2 = 0.026 ± 0.012
T_{mid} = 2455515.6063 ± 0.0014 BJD_{TDB}
Relative Flux
Residuals [%]
σ = 2.07 %
Phase


CoRoT-2 b
R_p^2/R_s^2 = 0.05 ± 0.012
T_{mid} = 2457308.7177 ± 0.0058 BJD_{TDB}
Relative Flux
Residuals [%]
σ = 4.51 %
Phase


WASP-12 b
R_p^2/R_s^2 = 0.0117 ± 0.0073
T_{mid} = 2458922.6844 ± 0.0034 BJD_{TDB}
Relative Flux
Residuals [%]
σ = 2.30 %
Phase

CONCLUSIONS

- Algorithms successfully developed to determine the physical properties of asteroids and measure the success of the NASA DART Mission
- Open Science can be used by citizen scientists to support future space missions

FUTURE PLANS

- Learn to analyse exoplanetary atmospheres using JWST data (Eureka pipeline) and ARIEL data (ExoClock)
- Support ongoing asteroid missions (HERA, Hayabusa2/SHARP, OSIRIS-APEX)

SUPPORT MY RESEARCH!

Looking for observation time on robotic telescopes for exoplanetary research

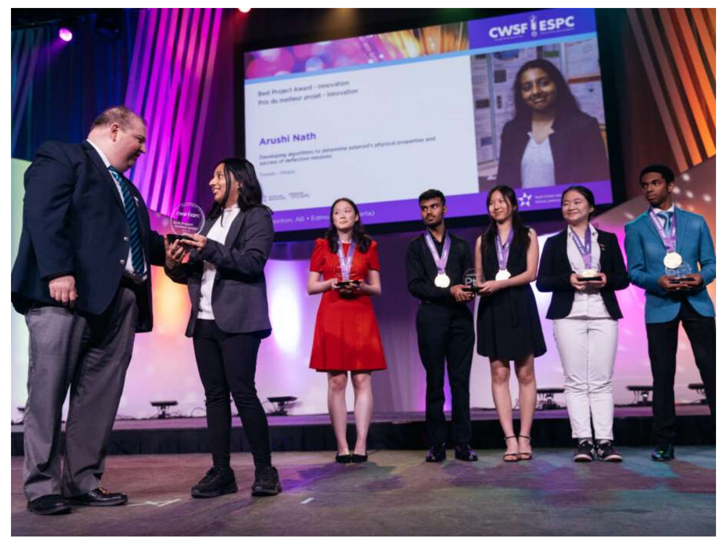
Arushi Nath

Founder, MonitorMyPlanet.com

arushi@monitormyplanet.com
Twitter @wonrobot

2023 Young Astronomer Award
Royal Astronomical Society of Canada

2020 NASA SpaceApps Global Winner



2023 and 2022 Best of Canada-Wide Science Fair Award Winner