CITIZEN SCIENCE FOR PLANETARY DEFENSE: USING REMOTE TELESCOPES, OPEN DATA, AND PYTHON TO STUDY THE DIDYMOS SYSTEM BEFORE AND AFTER THE IMPACT AND TEACH OTHERS.

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Introduction: Asteroid collision risks are real and unpredictable, and impacts could be catastrophic - making planetary defense an intergenerational challenge. But the capabilities of detecting, warning and providing advanced observations of asteroids before they impact Earth is improving. For the second time this year, humankind could detect an asteroid and issue a warning before it entered the Earth's atmosphere– bringing the total number of such detections to six. The last one was around a 1 m rock that burnt up in the skies above Toronto, Canada, as a striking fireball but caused no harm. A bigger asteroid could have had a different outcome – making planetary defense an international and intergenerational challenge.

Citizen Science For Planetary Defense: Citizen science can vastly improve planetary defense: by finding unknown asteroids, collecting information on near-earth or potentially hazardous asteroids, and supporting space missions to test methods for deflecting asteroids that may likely impact Earth one day. Many organizations engage citizen scientists in finding unknown asteroids, such as the International Asteroid Search Campaign, or to take scientific observations of known near-earth asteroids and comets, such as the Comet Chasers project that focuses on youths in classrooms.

The availability of cheap computing, open communities such as Minor Planet Mailing List, open datasets such as NASA/JPL Horizons Database, open-repositories of photometry data such as Asteroid Lightcurve Data Exchange Format (ALCDEF), and easy-to-learn programming languages such as Python have made planetary defense accessible to citizen scientists.

Citizen Science for DART Mission: To advance citizen science on planetary defense, for the past few years, I have developed algorithms using Python and its libraries which would allow any citizen scientist to undertake asteroid astrometry and photometry. I used this knowledge to support the NASA Double Asteroid Redirection Test (DART) Mission. The DART mission was aimed at testing the kinetic impactor technique of deflecting asteroids by impacting the Didymos binary asteroid system. To understand how effective the mission was, professional and amateur astronomers worldwide took observations of the Didymos system.

Methodology: My engagement as a citizen scientist for DART Mission involved five steps.

<u>Taking Time-series images of the Didymos system:</u> I submitted research proposals to the Faulkes Telescope Projects, the Burke Gaffney Observatory, the American Association of Variable Star Observers, and the Canadian Space Agency to obtain time on robotic telescopes to observe the Didymos system from both ground and space.

<u>Pre-processing of images:</u> All telescopes output the raw images as Flexible Image Transport System (FITS) files. The FITS file has two sections: the header containing metadata about the image and the image itself. The algorithm queried the FITS file and gathered essential information like the date and time of observation, celestial location of the image [right ascension (RA) and declination (Dec)], telescope focal length, image field of view (FOV), and the camera pixel size. The raw images from telescopes are primarily dark, with only a few bright pixels. As undetected asteroids are likely to be faint, my algorithm used a scaling function in Python to display the fainter pixels. The function queried the brightness value of each pixel in my image and calculated the mean pixel brightness. It then reduced the range of pixel brightness to between 1 and 2 standard deviations of the mean, successfully displaying fainter objects.

<u>Finding aperture radius:</u> To conduct photometry on comparison stars and Didymos, finding the correct aperture size was essential. My algorithm calculated a star's total brightness (after background subtraction) across all possible aperture sizes in the images. It then selected the best aperture size with the best signal-to-noise ratio. The process was repeated for all stars in my image to determine the average value of the aperture size.

<u>Finding suitable comparison stars:</u> Using the aperture size from the previous step, the algorithm calculated the total brightness of the star for each image in my dataset. It gave the plot of the change in brightness of the star over time. Four to seven comparison stars whose light curves had the smallest standard deviation were selected.

<u>Finding Didymos Magnitude:</u> Using the pre-defined aperture size and comparison stars, I calculated the brightness of Didymos across all images. Curve fitting was then used to create a light curve of Didymos, which I later used to attempt to find the orbital and rotation period of the asteroid. Using time-series observations over several nights, the algorithm achieved more accurate results.

Research Results:

From the light curves, it was possible to determine the rotation period of Didymos before and after the impact. By querying the timings of the mutual events, I attempted to measure the orbital period of the binary system. In addition, I also measured the increase in the apparent brightness of the binary system and compared it to before and without impact scenarios. To get insights into the composition of the asteroid, I measured the length of the tail caused by the ejecta from Dimorphos for four weeks post-impact.

Outreach:

To encourage youths, especially girls, to take up maths, programming, and observational astronomy, I have made my entire citizen science project open source. 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 GitHub. My time series observations were also sent to the DART mission team.

I have given several webinars and presentations on my planetary defense projects in partnership with the Royal Astronomical Society of Canada, iTelescope.net, the American Association of Variable Star Observers, and the Global Innovation Field Trip to get youths around the world excited about solving 'hard' problems that benefit humanity.

Acknowledgments:

Faulkes Telescope Project: Thanks to the Faulkes Telescope Project (FTP) for giving me time to control their 2-metre-wide telescope in Siding Spring, Australia. In addition to giving me sky images to test my algorithm, it helped me learn how to use robotic telescopes remotely.

Royal Astronomical Society of Canada: Thanks to the Royal Astronomical Society of Canada (RASC) for giving me my first exposure to astronomy after visiting their astronomical observatory in Collingwood and through their monthly meetings at the Ontario Science Centre. RASC has also taught me the basics of astronomy during their monthly virtual sessions.