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AIMING FOR APOPHIS: HOW WE USED COVID-19 SCHOOL LOCKDOWN AS AN OPPORTUNITY TO DO ASTEROID ASTROMETRY AND TEACH OTHERS

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On 11 March 2020, the World Health Organization declared COVID-19 a global pandemic. It had an immediate effect - as countries around the world declared public health emergencies and raced to enforce lockdowns. Canada was no different. By 21 March 2020, all Canadian provinces had declared some forms of lockdowns, closed the Canada-US border, and shut down non-essential services including schools, universities, playgrounds, and offices. The familiar world around us changed. Education turned online, social interactions became virtual, time spent outside our houses became shorter, and conversations turned to when schools will reopen, and life will return to normal.

The pandemic closed the doors of our school, but it opened windows to joys of observing the night sky and do astronomy from home. We did not have to wake up early to take the school bus, so we could stay up late observing the night sky with our telescope. We tracked the path of Mars, Jupiter and Saturn across the sky and hunted for brighter Messier objects we could observe from downtown Toronto. It was during this time, Arushi completed her “Exploring the Universe” observational astronomy certificate of the Royal Astronomical Society of Canada. She became the youngest person to do so and published her experiences in the November-December 2020 print issue of the SkyNews magazine (http://www.SkyNews.ca).

While observing the night skies from our telescope was fun, there were limitations to what we could observe from a light polluted city (Bortle Scale 9). COVID-19 confined us to our home but our imagination and curiosity remained free. In an unusual move from sibling rivalry to sibling cooperation, we decided to take up a collaborative project where we could merge our expertise and interests in astronomy. Artash loves space and machine learning. He recently obtained his “Certificate on Artificial Intelligence” after completing a year-long set of courses on Python and machine learning from the School of Continuing Studies, University of Toronto. Arushi enjoys animation, mathematics, and building robots. Both of us became the 2020 Global Winners of the NASA SpaceApps COVID-19 Challenge from 1600 teams from 150 countries (https://www.nasa.gov/feature/nasa-space-apps-covid-19-challenge-winners-share-stories-of-innovation). We have been invited by the NASA to witness a spacecraft launch when travel is deemed safe. Could we agree on a project that combines our interests and passion?

Yes, we could! And this was the start of our home-based, do it yourself project on asteroid astrometry.

Asteroid Astrometry: Drawing Inspiration from the 6th IAA Planetary Defense Conference 2019

Artash had participated in the 6th IAA Planetary Defense Conference (PDC 2019) held at Maryland, USA. He gave a poster presentation on apply machine learning algorithms to predict risk index (Palermo Technical Impact Hazard Scale) of an asteroid colliding with earth. It won him the honorable mention award during the Award ceremony. Since then, he has been actively pursuing space projects where he could apply his machine learning skills. The learnings from the PDC 2019 conference - on tracking near-earth asteroids, of the 2029 close flyby to Earth of asteroid Apophis, simulations on imaginary impact scenarios and posters on asteroid astrometry were still fresh as Artash had documented them on his website. (https://hotpoprobot.com/2019/05/03/learnings-from-the-2019-planetary-defense-conference-poster-presentation-and-simulation-exercise/). Planetary defense and asteroid deflections are inter-generational challenges, so how can school-going youths from diverse backgrounds participate in the exciting work being done?

Measuring the position of an asteroid is essential to determining and improving accuracy of its orbit. Could we take our space, robotics, and programming knowledge to the next level by applying it on a real dataset? Could we create algorithms which would search for asteroids in astrophotography images, determine their celestial coordinates, calculate their motion velocity, and perhaps even predict their trajectory and how close they will pass to Earth? The idea itself was exciting and the 3D model of the asteroid Apophis from the 6th IAA Planetary Defense Conference 2019 at our home was a constant reminder of the importance of planetary defense. We decided to proceed with the idea and see how far we could go.

Roadmap for Do-It-Yourself Asteroid Astrometry

We started with listing down what we wanted to achieve with asteroid astrometry, namely identify near-Earth asteroids in astrophotography images, determine their coordinates, track their motion over time, calculate their velocity, and eventually determine their orbital parameters, and how close they could come to Earth.

On one sheet we wrote what knowledge, resources, and tools we thought would be required to achieve our project objectives. On the other sheet we wrote what knowledge, resources, and tools we had access to, and knew how to use. The gap between the two lists was large enough to make the project incredibly challenging but not impossible. We had a lot of time on our hands and we were willing to learn new things. We then proceeded with the most important task that determines success of any project: the division of labor.

We both have different skills, interests, work habits. We work together best as a team when we do our tasks independently! Arushi loves robotics and animation, so she took up the responsibility of searching for robotic telescopes we could use and learning how to compare them based on their location, aperture, and CCD cameras. She also would have to learn how to control those telescopes, the best times to use them, testing out software that would help us in creating our observation plans, and how to download and process the images taken from robotic telescopes. If she delivered on these initial tasks, she would be the one creating our observation plans for several nights, operating the robotic telescopes, and doing initial processing of the images.

Artash is an expert in handing big datasets, in advanced programming in Python, troubleshooting, and seeking interest-based communities on astronomy. He took up the responsibility of developing algorithms to analyze the images obtained from the robotic telescopes. He would write Python functions to mark the celestial objects in the photographs, identify those objects by querying star catalogues, and match position of objects in the star catalogues to their pixel coordinates in the CCD images. This will help in distinguishing the stars from possible asteroids in the images, calculating their coordinates and performing calculations that would help us learn more about these asteroids such as their motion, and their orbital parameters

Robotic Telescopes and Software

We had experiences of handling robotic telescopes by connecting telescope in our home to the internet. In addition, during our previous visits to the Carr Astronomical Observatory (CAO) in Collingwood, Ontario run by the Royal Astronomical Society of Canada – Toronto, we had opportunities to handle their telescope digitally. We knew about the software behind these telescopes and the settings we need to input (Right Ascension and Declination) to slew the telescope to the desired objects. We had learned how to determine if the object would be visible from the observatory location, at what time it would appear above the horizon, when would be the best time to view it, and if the object was bright enough to be seen from telescope of that aperture. We had also learned about assessing weather and sky conditions to determine the best seeing window. One of our biggest challenge was to learn about CCD cameras, exposure times, limiting magnitudes and the formats in which CCD images would become available.

Searching for robotics telescopes took us on a trip around the world – virtually. We checked websites of robotic observatories in Australia to those in Canary Islands (Spain), New Mexico and Hawaii (USA), Canada and Chile. We had new respect for infrastructure built around the world by the astronomy community to pursue photons from celestial objects that help us improve our understanding of the universe.

We tried out many robotic telescopes including iTelescope.net, Slooh, Telescope.org, MicroObservatory Robotic Telescope Network, Abbey Ridge Observatory, Burke-Gaffney Observatory, and the Faulkes Telescope Project (Les Cumbres Observatory). We did so by writing to them with our proposals and doing follow ups or signing up for their trial memberships. In some cases, we made use of their heaving discounted prices available for telescope use on nights when the Moon was between three-quarters and full. During this time, these telescopes were more likely to be used by amateur astronomers.

Overall, the search for robotic telescopes was a rewarding experience. We learned new things about remote observatories, telescope types (fast or slow), resolution of charge couple device (CCD) camera, pixel scales, binning ratios, field of view, filter types, and errors. Telescopes had to be in locations where asteroids we were interested in, would appear high in the sky between sunset and sun rise. The telescopes should be available for use during that time, and the seeing conditions had to be good.

We ended up using a mix of telescopes for our project. These telescopes ranged from aperture sizes of 40cms to 2 meters. It allowed us to become more ambitious with our plans and the asteroids we wanted to image. A big thanks to all the observatories who gave us time on their telescopes and answered our questions.

Getting access to telescopes is of little use if there are no observing plans. Observations plans need to be queued in advance for these remote telescopes. Creating an observing plan requires knowledge of several supporting software. We used online version of the Stellarium software to see the position of the Moon in the star field to ensure that objects we image are not too close to the Moon. We used the Telescopius website to get the transit time of the asteroids (time at which the asteroid would appear at highest point in the sky for that location), and their Right Ascension (RA) and Declination (DEC) positions. We also got data from the NASA HORIZONS Web-Interface. One of things we had the most trouble learning was the celestial coordinates systems which were sometime in degrees, other times in hours, minutes, and seconds, and sometimes as a combination of two.

We turned to popular weather websites and learned to read the detailed weather, clouds, precipitation, and seeing conditions predictions provided by the observatories to determine whether it would be a Go or No Go for taking observations that night.

Aiming for Apophis: Asteroids Imaged for the Project

Having mastered the use of robotic telescopes and observation planning software, we created a list of asteroids we wanted to observe. We had to assign different asteroids to appropriate telescopes based on magnitudes of asteroids and their transit times, and observation time on the telescopes available to us.

We wrote our observation plans, testing out different exposure times, binning, and filters. We then uploaded these plans to robotic telescopes. In most cases, these plans had to be queued in advance. In some cases, we could watch online the view from the telescope when our observation plan came up in the queue, but those instances were rare.

We captured CCD images of several asteroids: Amphitrite, Fortuna, Ganymed, Melpomene, Parthenope, Psyche, and Vesta at different intervals. We made mistakes, we learned and became better. Some of the mistakes we made were trying to take images of asteroids too close to the full Moon which led to images becoming overexposed or underexposing the images that meant the fainter objects did not show up. In some cases, the seeing conditions were less than optimal at the time of imaging.

Having obtained observation time on a 2 meters telescope at the Siding Springs in Australia, courtesy of the Faulkes Telescope Project, our ambitions soared to include fainter asteroids (magnitude 18 or more) to our list. So, we aimed for asteroid 99942 Apophis!

Upon its discovery in 2004, Apophis was briefly estimated to have a 2.7% chance of impacting the Earth in 2029. Additional measurements later however showed there was no impact risk at that time. The fainter magnitude of the asteroid proved to be just beyond the limiting magnitudes of most telescopes we had access to. However, in just a couple of attempts with the 2 meters Faulkes Telescope in Australia we captured it on the CCD and were able to make repeated observations of Apophis as it traversed the night skies.

Python Algorithms for Astrometry

We had previous experience of using Astrometrica software and working with the International Astronomical Search Collaboration (IASC) for asteroids detection using data from their Pan-STARRS1 telescope. This meant we knew about the movements of asteroids, and how they would appear in a series of photographs taken over a time interval in the same field of view. Asteroids would appear moving in a straight line while the distant background stars would remain fixed. The process however would be different if the field of view changed.

We became aware of the various formats associated with CCD images such as FITS or the compressed FZ format. We become importance of meta data associated with astrophotography images. The header files in the FITS images contained important information about the images taken as well as telescopes and CCD cameras that imaged them. The header files usually included focal length of the telescope, dimensions of the CCD camera, pixel sizes, filters used, exposure times, time of observation (in UTC) and celestial coordinates to which the telescope was pointed.

Our first task was to import the CCD images in FITS format into Python so that we could analyze using the information captured in the meta data. Raw images when imported into Python do not show many details. The images need to be scaled properly between minimum brightness and maximum brightness values so that the faintest and the brightest images showed up. We wrote a Python function to mark all the celestial objects in the images. To do so, we wrote a pixel clustering argument. As each pixel has brightness value ranging from 0 to 255, our algorithm detected pixels of values above a certain threshold that were clustered together. This allowed us to mark all the bright spots on our image. These could be background stars or asteroids. As some of these bright spots were big (due to brighter stars in the image) while others were very faint, we wrote a centroiding algorithm to accurately find the center of these spots. The centroiding algorithm was based on taking weighted averages of pixel values. We assumed that closer we got to the center of the star, the brighter it would be and gave greater weights to brighter pixels in the CCD images.

Once the centroids of the objects on the CCD image were detected, we had to compare them with sky surveys in the same field of view. Overlaying the star coordinates from these catalogues in the same field of view as CCD image would us identify the stars in our images. The positions of stars would not have changed when comparing the CCD image with the catalogue image. While newer objects in our image that were not present in the sky surveys are likely to be asteroids as asteroids move fast. To make this happen we searched for various star surveys and their catalogue of stars such as GAIA EDR3 and USNO-B1 survey. We turned to Python routines written for different star surveys to query the coordinates of the stars present in the field of view of our CCD image. We wrote a Python function to transform the celestial coordinates of these stars to pixel coordinates and overlay them on our CCD images. The function had a step function built into it to rotate the field of view so that there is a good overlap between the catalogue stars and centroids of stars in the CCD image. Small manual rotations were then applied to get a more accurate match and reduce the errors.

Appling these functions brought us closer to identifying asteroids in the CCD images and their celestial coordinates. We were able to identify the asteroids in the CCD images we took, including asteroid Apophis! We could now take multiple images of asteroids over a time interval, apply our algorithm, and identify the asteroids in our images, calculate their celestial coordinates, and determine how much they had moved. This helped us determine their motion as viewed from Earth. Our schools are still being held virtually so we continue to devote time to this project. We are working on improving our algorithm and building our knowledge on astrometry so that we can extract more information about the asteroids from our data. But we were still happy to have reached this stage of asteroid astrometry starting with just an idea to undertake an interesting project during the COVID-19 school lockdown.

Astrometry Education and Outreach to Youths and Citizen Scientists

We believe the best way to learn new things is to think about a challenging project that would require a big learning curve, work on it for a few months to do it well, document what we did and turn it into a training module, and then teach others. The entire project took us almost four months to reach this stage. We did it while attending to our daily online school and other activities.

Making science, data, and technologies accessible to all is essential to encourage participation from youths and let them dream big. Astronomy and planetary defense are no different. Participation of the next generation is imperative as protecting the earth from probable collisions with near Earth objects and its impacts would require inter-generational collaboration. Youths can participate in planetary defense missions in several ways using knowledge they have - ranging from machine learning, animations, simulations, working on big datasets, or willingness to stay curious and ask questions. Internet, You Tube videos, Stack Overflow and GitHub have emerged as avenues to flatten the learning curve and make learning curiosity driven. Motivation and opportunities are still needed so youths, irrespective of their ages and backgrounds are supported.

As with all our projects we have created an online tutorial using Jupyter Notebook. The tutorial is available on our GitHub account (http://www.github.com/Artash-N) and is work in progress. It has allowed other youths to learn from our project and access our code. We have reached out to other youths and citizen scientists by delivering presentations at the monthly meeting of the Royal Astronomical Society of Canada-Toronto and answering questions. We have also presented this project in the Global Innovation Field Trip (GIFT) and even in our respective schools. We will continue in our quest to keep learning more about the universe, about asteroids and planetary defense, and sharing our joys and discoveries with other youths through our website, blogs, social media, and videos. It would allow youths, and families to get inspired by astronomy, math, and programming, and carry out their own astrometry calculations on asteroids of their choice. These citizen scientists have an important contribution to make in planetary defense. They will be a part of a more aware and motivated generation which understands the risks of asteroids collision and supports efforts directed at planetary defense.