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DART time of impact observations and long-term photometry of Didymos from the LCOGT Network

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Extended Abstract—

The LCO NEO Follow-up Network uses the telescopes of the Las Cumbres Observatory (LCO) Global Telescope (LCOGT) Network and a web-based target selection, scheduling and data reduction system to confirm Near Earth Object (NEO) candidates and characterize targets of special interest. These include radar-targeted known NEOs, close passing NEOs, potential and actual mission destinations. The goal of NASA's Double Asteroid Redirection Test (DART; [1]) was to intentionally collide the spacecraft into Dimorphos, the secondary of the binary asteroid 65803 Didymos to test planetary deflection missions. This occurred on 2022 Sep. 26 23:14 UTC [2] during the night for LCO's South Africa site. We used three of LCO's 1-meter telescopes and the fast readout guider cameras to obtain quasi-simultaneous multicolor data covering the time of DART's impact and for several hours after. The images and photometry from the time of impact allow study of the initial impact and resulting effects. In addition to the time of impact observations, lightcurve [3] and ejecta monitoring observations were carried out at all 1m telescope sites of the LCOGT network over the span of 150 days from 2022 September to 2023 February.

The LCOGT Network—

During the roughly thirty-day period after the impact, Didymos was in the Southern Hemisphere where LCO has most of its telescopes. The LCOGT Network is a global facility (see Figure 1) of remote, robotic telescopes which can be dynamically scheduled and has the ability to react to new targets within minutes. It is also able to perform long-term monitoring for extended periods of time. The LCOGT network comprises two 2-meter telescopes, twelve 1-meter telescopes, with eight located in the Southern Hemisphere at Cerro Tololo (Chile), SAAO (South Africa) and Siding Spring Observatory (Australia). In addition, there are four additional 1-meter telescopes, two at both McDonald Observatory (Texas) and Tenerife (Canary Islands), ten 0.4-meter telescopes distributed across the above sites and at Haleakala (Hawaii).

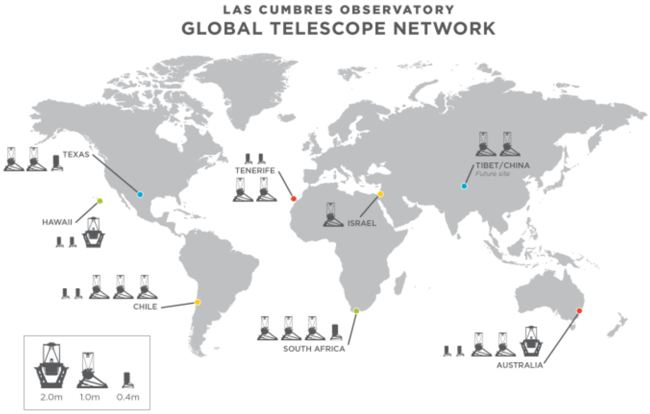

Figure 1 Map of the Las Cumbres Observatory telescope network showing the different classes/sizes of telescope at each site.

The network has been fully operational since 2014 May, and observations are executed remotely and robotically. In addition, all the observatory software to submit, schedule, execute observations and reduce the data is all cloud-based. Work is underway to deploy two 1-meter class PlaneWave telescopes to the Ali (Tibet) site in 2023. This will produce a complete Northern

Hemisphere ring for continuous coverage in addition to the existing Southern Hemisphere ring.

The twelve 1-meter telescopes each have a *Sinistro* CCD optical imager giving a 26'x26' FOV with a filterwheel containing 21 filters including the complete Bessell and Sloan/PanSTARRS sets, plus the broad PanSTARRS-*w* filter (equivalent to SDSS *g'*+*r'*+*i'*). In addition to the main imaging cameras, each 1-meter telescope has a 1024 × 1024 FLI CCD camera capable of imaging at up to 0.5 Hz rate.

Time of Impact Observations—

Although not part of the mission goals for the DART mission and despite considerable uncertainty pre-impact on what would be visible from ground-based observatories, we decided to take advantage of the multiple 1-meter telescopes and fast frame rate cameras at LCOGT's South African node. We attempted multi-telescope imaging of the evolution of the impact plume and ejecta after the DART spacecraft's impact into Dimorphos. The initial predictions were that Didymos, Dimorphos and any plume produced after impact would be unresolved from the ground and all that could be monitored was a change in total brightness. We configured quasi-simultaneous observations using the fast frame rate autoguider cameras with each camera observing in a different filter (SDSS g' and i', along with a broad bandpass (400–1200nm) clear filter) with a repeating pattern of 2x2s, 2x10s and 2x30s exposures. These were timed to start just prior to the time of impact (23:00 UTC) and continue afterwards to the end of the local night (03:00 UTC) before it became visible to larger aperture and higher resolution assets in Chile. This mode of use of the LCOGT autoguider cameras for science observations was one that is also used regularly for very similar high cadence observations for occultations e.g. [4].

Observations coming back in near real-time and visible in the monitoring and control interface at LCO HQ in Goleta, CA, showed that a large cloud of expanding fast-moving ejecta had been produced as a result of the impact of the DART spacecraft into Dimorphos contrary to and exceeding the predictions (see Figure 2).

Data were transferred back from the site in real time and processed through the normal LCOGT Banzai pipeline [5] to perform basic calibration tasks and then the NEOexchange pipeline was used to derive astrometric solutions and perform photometric zeropoint determination. Due to the small field of view and the short exposures, there was also often a lack of suitable references stars to use for calibration, particularly in the lower sensitivity g' and the 2s exposures. To combat this, we made use of linear interpolation between valid solutions in longer exposure frames before and after the affected frame to propagate a position for Didymos and the photometric zeropoint.

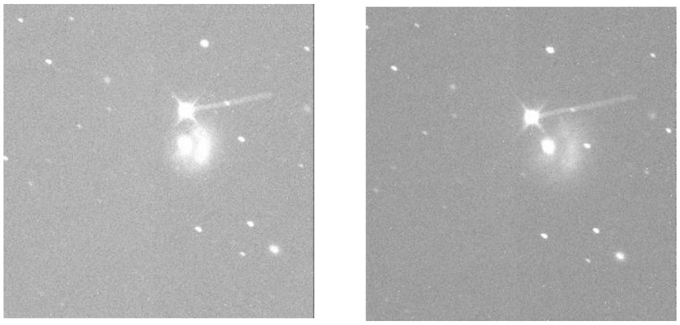

Figure 2 LCO 1m + FLI clear filter observations of the expanding fast-moving ejecta cloud following the DART spacecraft impact into Dimorphos. Frames taken at 12- and 15-minutes post-impact.

Photometric observations were performed in a range of aperture sizes corresponding to 1" – 20" radius in all three filters to measure the initial rise and decay of the ejecta. We found that there was considerable chromaticity in the ejecta with the red (SDSS-i') and clear filter showing a large brightening (~2 mags over the pre-impact baseline) and then a rapid decay. Meanwhile the bluest (g') data showed only a rapid rise to a steady ~1.5mag increase in brightness level over the original baseline. Combination and comparison of these datasets obtained at the time of impact from other facilities and analysis and interpretation is ongoing (Fitzsimmons et al. 2023 in preparation).

Long-term ejecta monitoring observations with the LCOGT Network—

The network of 1-meter telescopes was used to obtain high-precision light curves of Didymos to determine the new binary period after the DART impact ([3]; Scheirich et al., Naidu et al., Moskovitz et al. this meeting). We also used the LCOGT Network for nightly cadence observations to monitor the evolving ejecta brightness and tail development over several months. This utilized our cloud-based observing portal (NEOexchange; [6]) to schedule a nightly cadence for each telescope site. LCO's unique global network of robotic telescopes allowed regular monitoring of the evolving brightness of Didymos, and the ejecta tail every ~8 hours over a period of five months from 2022 Oct to 2023 Feb. We supplemented these single filter observations and cadence with data in other filters and with data from the 4-channel MuSCAT3 [7] imager on Faulkes Telescope North on Haleakala. These observations were made in collaboration with schools and other groups in the United Kingdom who used the educational interfaces to the LCOGT observing system to obtain additional data which is used in a combined analysis (see also Usher et al. this meeting).

Our monitoring consisted of between 4 and 7 observations with exposure times ranging from 75 – 240s, depending on both the brightness of Didymos (and ejecta initially) and the on-sky rate of motion in order to prevent trailing of the stellar or asteroid point-spread function. Observational data was also processed through the normal LCOGT Banzai pipeline [5] to perform basic calibration tasks and then the NEOexchange pipeline to perform astrometric solutions and photometric zeropoint determination in a very similar manner to what was performed for the FLI camera data discussed above. All the data has been consistently photometrically calibrated using field stars from the Gaia DR2 catalog [8]. We used the `calviacat` code [9] to perform zeropoint determination for the entire dataset as there was a period following impact when Didymos was located too far south to make use of the more accurate PanSTARRS DR1 photometric catalog.

Observations over the first 30 days following impact (Kareta et al. in preparation) showed a steady linear decline in brightness, with this reaching a turning point around 28 days after impact. It appears that the measured brightness of Didymos returned to the predicted baseline magnitude from JPL HORIZONS (and converted using the pre-impact V-r color) around 80 days following the impact (Figure 3).

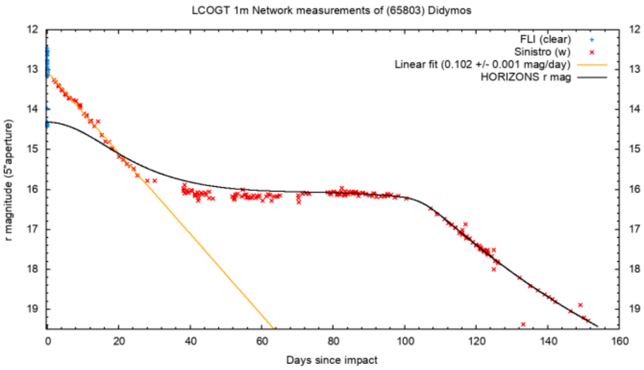

Figure 3 Calibrated r' magnitude of Didymos (red crosses) as a function of time since impact on 2022-09-26 23:14 UTC. Also shown in the plot are the predicted magnitude of Didymos from JPL HORIZONS (black line) and a linear fit (orange line) to the 1st 30 days of data.

Conclusions—

We present both immediate impact results and long-term photometric data of the evolution of the Didymos ejecta cloud and tail. These observations were obtained with the LCO NEO Follow-up Network starting at the time of impact of the DART spacecraft and continuing for hours to months after the event. This shows the power of a worldwide telescope network with flexible scheduling. In addition to ongoing NEO observational efforts, we and LCO continue to develop the software and collaboration agreements that allow networking a range of telescopes from 0.4-meter to 8-meter diameter telescopes through AEON, the Astronomical Event Observatory Network. This will allow a network of robotic and part-robotic telescopes including LCO, the SOAR 4-meter and the Gemini 8-meter telescopes to operate together and respond rapidly for NEO characterization observations on targets of interest, including new and close-passing NEOs that are the targets of future space missions and that will be discovered in increasing numbers by future sky surveys.

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