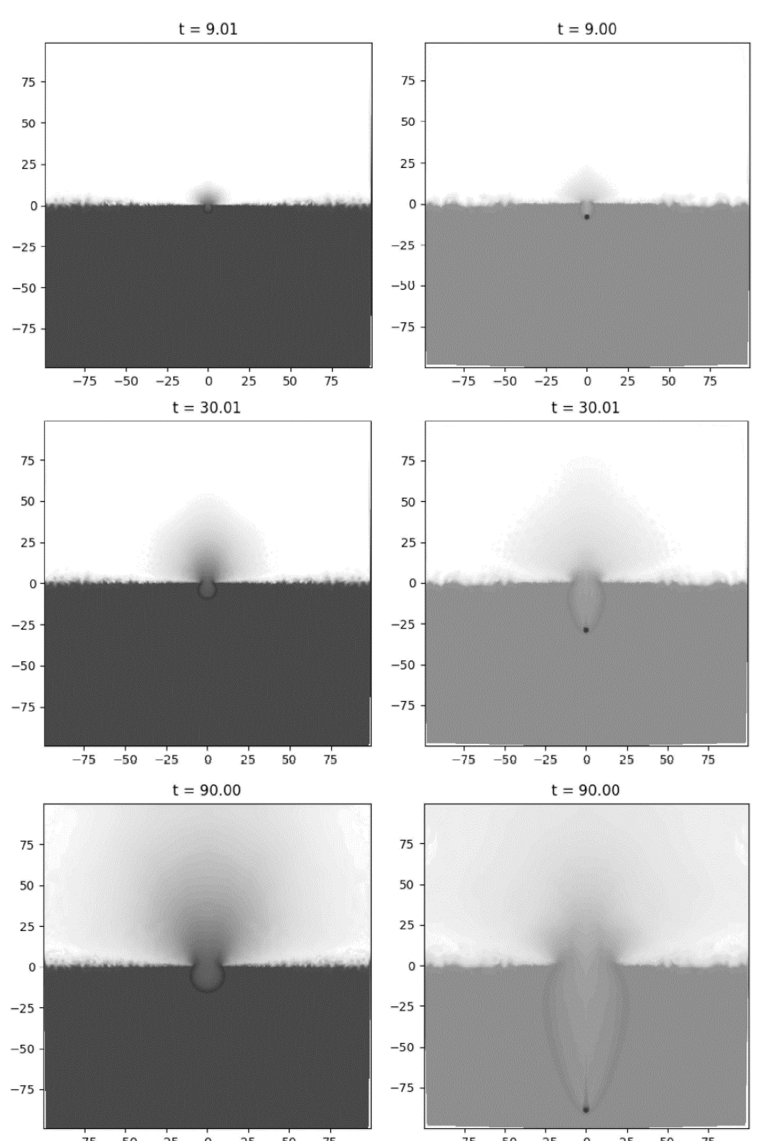
Classifying and Categorizing Lunar Craters using Convolutional Neural Networks

Jamie Johnston*, Matt Caplan†
Illinois State University, Normal IL 61790
*jjohn42@ilstu.edu †mecapl1@ilstu.edu

Abstract

Traditionally, lunar crater counting has been done by visual inspection of images of the moon's surface. This method is time consuming and has poor inter-rater reliability for smaller craters. Automating this process using a Convolutional Neural Network (CNN) greatly improves the speed and reliability at which surface features can be detected and classified. Using available high resolution Digital Elevation Model (DEM) images from the Lunar Reconnaissance Orbiter (LRO), we train a CNN to identify craters and classify them based on the slope of their ejecta blanket. Presently the population of small impactors is not well understood but improved detection of the smallest craters can constrain the size distribution of asteroids in the solar system. Additionally, we intend to search for small craters with novel features that are inconsistent with traditional asteroid impacts to potentially constrain the moon's interaction history with MACHO dark matter from the Galactic halo.

Lunar Cratering Dynamics



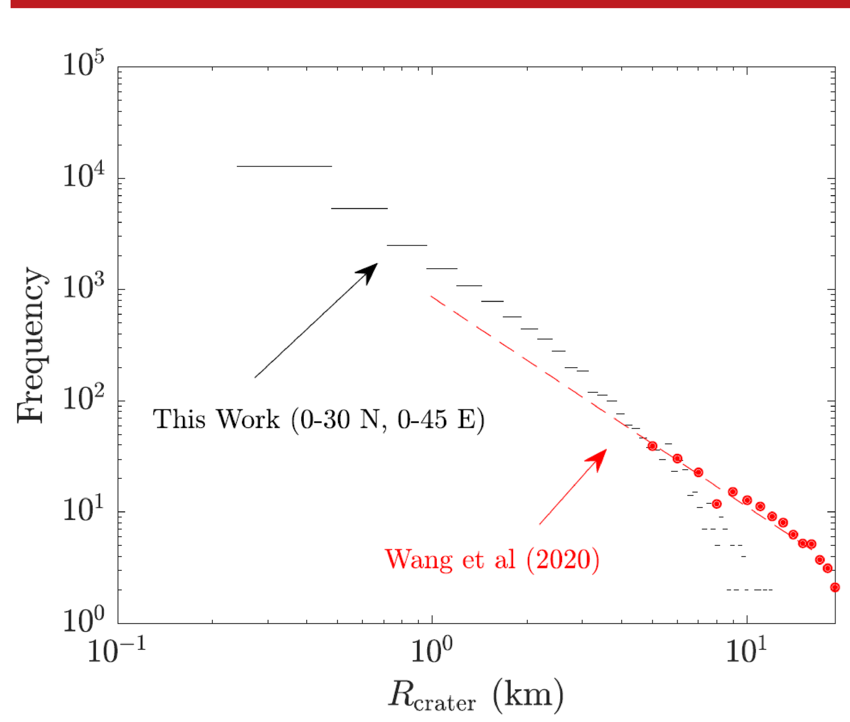
Traditional Impactor

Relativistic Compact Impactor

As much as 10^{18} g of dark matter (DM) may have transited the moon in the history of the solar system, motivating us to consider ways to use the moon as a DM detector. Craters on the lunar surface hold a record of billions of years of impacts, some of which may be due to interactions with MACHO dark matter such as primordial black holes (PBHs) or strangelets. While traditional asteroids create a point explosion at the surface which destroys the impactor on contact, relativistic compact DM fully penetrates due to its high relative density. Accretion onto a PBH during this transit drives an outward shock producing a 'line explosion' with markedly different cratering dynamics (Caplan & Yalinewich 2020).

Ejecta from a collision with a PBH results in more vertical ejecta and less radial ejecta due to the explosion dynamics, producing a steeper ejecta blanket which may be detectable in high resolution lunar surface maps now available. We seek to identify candidate craters with anomalous ejecta profiles in Digital Elevation Models taken from the Lunar Reconnaissance Orbiter (LRO). Prior work conducted using CNNs to identify surface features on the Moon have provided promising results, including those from A. Silburt & C Zhu in the DeepMoon project and a group of researchers at East China Jiaotong University (ECJU) both achieving high levels of detection and prediction accuracy.

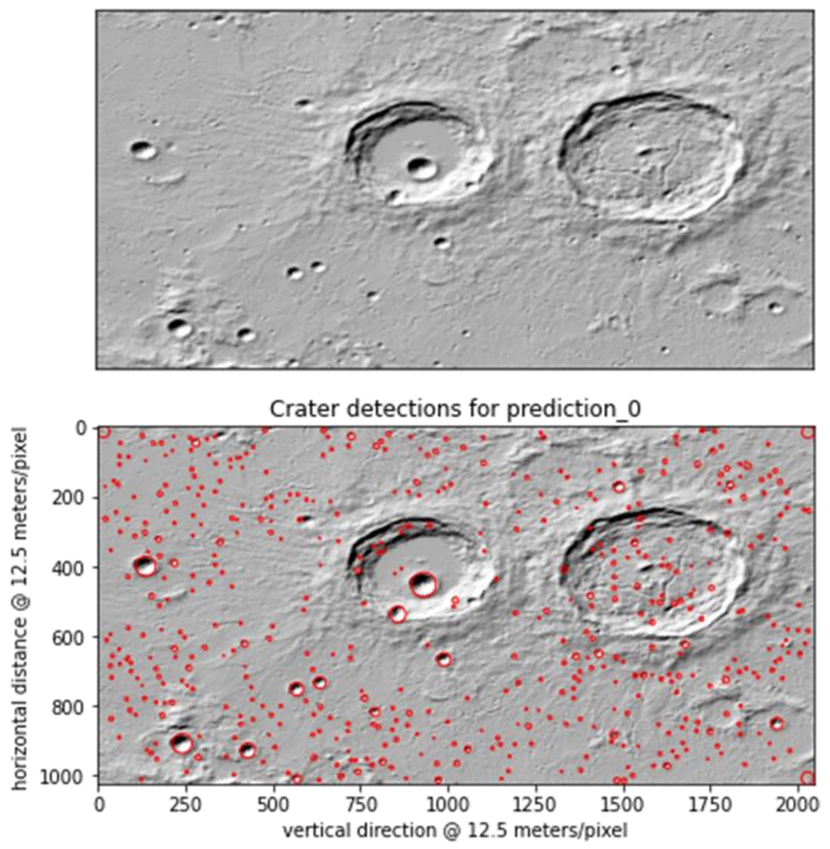
Detections



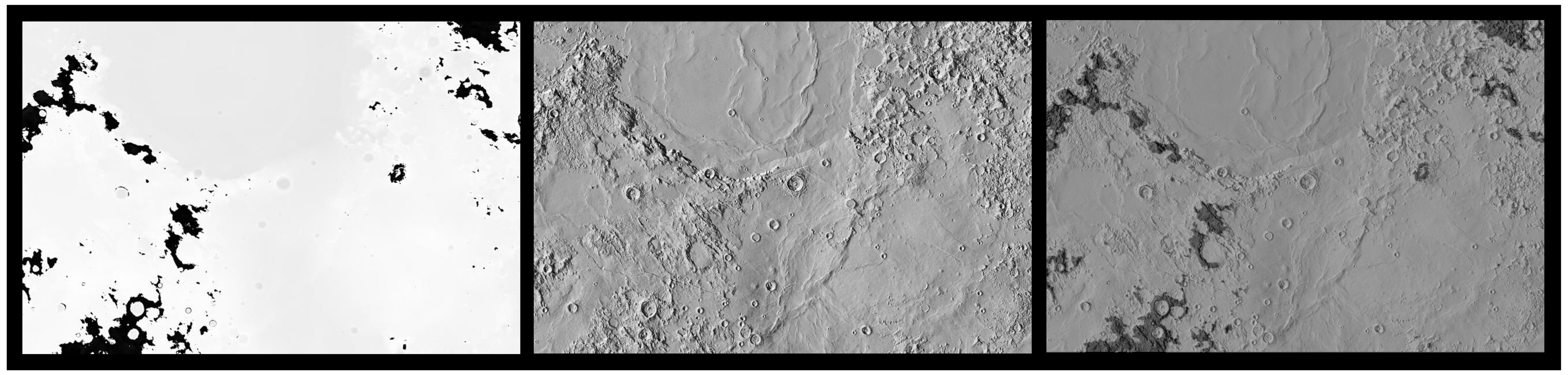
We report 35,346 crater radii detected in this work using PyCDA between N 0-30° and E 0-45° (approximately 1.8×10^6 km^2), and compare with the 19,337 craters with $R_{crater} \geq 5$ km reported in Wang et al. (2020). The distribution of crater sizes is roughly a power-law as expected and shows fair agreement for crater sizes between 5 and 10 km. While Wang et al. successfully identify craters of 5-20km in size, PyCDA was trained to detect and performs best on small craters, with detections as small as 0.25 km radius (diameters of 8 pixels). While many of the smallest identified craters may be spurious, the use of DEMs to detect ejecta blankets around the crater will aid in classifying the successful detections.

Convolutional Neural Networks

PyCDA is a Crater Detection Algorithm (CDA) utilizing a trained Convolutional Neural Network (CNN) to both identify and classify craters on celestial bodies. This model was trained to detect craters with a diameter of 80 pixels or less, and the dataset used for analysis was obtained from the Lunar Orbiter Laser Altimeter (LOLA), an instrument onboard the LRO. These images taken in 2015 each cover 30 degrees of latitude, and 45 degrees of longitude, at 512 pixels per degree (59.2 m/pixel) meaning the trained model can identify sub kilometer craters with significantly higher accuracy than can be achieved by human inspection. Analyzing these images requires us to divide each image into smaller tiles, of 1024x1024 px, and processing those images individually on the ISU High Performance Computing Cluster. Once the detection stage is complete, craters can be correlated with Digital Elevation Model (DEM) images to study crater profiles, extracting elevation data from these images will allow us to analyze the ejecta blanket for PBH collision candidates.

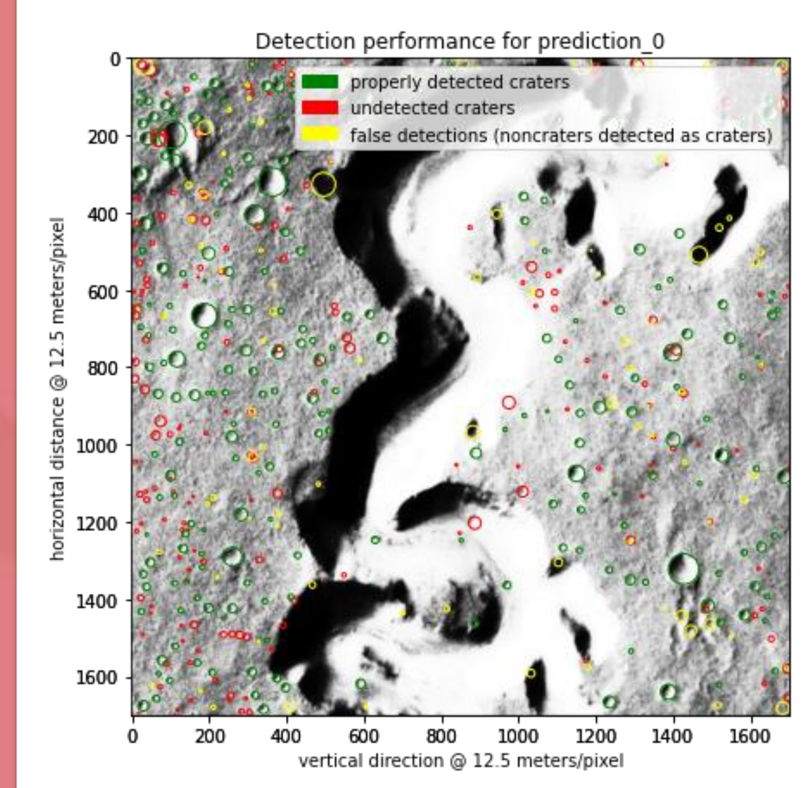


The images below show the DEM (left), topography of the Lunar surface (center), and the DEM is shown as an overlay on the topographical image to demonstrate how ejecta blanket analysis will work (right).



SLDEM 2015 00N 30N 000 045 DEM | SLDEM 2015 00N 30N 000 045 TOPOGRAPHY | SLDEM 2015 00N 30N 000 045 OVERLAY

Future Work



Past work comparing PyCDA detections to the ground truth data (*i.e.* human classified) finds that our method identifies small craters with upwards of 60% accuracy (Klear, PyCDA Project), so many of the smaller features are likely false detections. Human classification of small sub-km craters is tedious and likely unreliable, and since we detect many sub-kilometer craters in our test region, we need an alternative to a ground truth set. A radial elevation gradient surrounding the crater rim due to the ejecta blanket may be detectable, as ejecta blankets can extend 1.5-2.5× greater radii than crater rims. Our future work will attempt to validate candidate sub-km craters using the surrounding elevation in the DEM. The slopes of ejecta profiles will also allow us to search for anomalous blankets steeper than would be expected from traditional impactors. These atypical crater formations will then be catalogued as potential candidates for DM collisions.

References

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Acknowledgements

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