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Fast, Computer-Assisted Detection of μm-Scale Dust Impact Craters on Spacecraft Materials

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The NASA Stardust spacecraft included a collector array to capture particles entering the solar system from interstellar space. While a handful of likely interstellar dust grains were identified within the aerogel collection media [1], current technology cannot reliably extract them for characterization. However, interstellar dust also impacted Al foils lining the collector, and interstellar impact residues were identified in four μm-scale craters [2]. Identification of these foil craters requires collection and manual examination of tens of thousands of high-resolution scanning electron microscopy (SEM) images, which can lead to mental fatigue and an increase in processing errors. Alternative approaches for identifying craters in these large datasets include automated image cross-correlation using images of known dust impact features [3] and crowd-sourcing [4]. Here, we implement a Python-based algorithm using a circular Hough transform to find circular features in the foil images, followed by simple filters to detect characteristic morphological features of impact craters—a dark center and a bright rim.

Between 7,000-21,000 images (depending on the area of the foil) were acquired each from 12 Al foil strips from the Stardust interstellar collector, at 20-40 nm/pixel, and at one of three image sizes (6 MP, 3.5 MP, and 1.5 MP). These images were input for crater identification code (written in Python) running over 10 2.2 GHz CPU cores. The main algorithm detects circular features in each image by (1) generating a Canny edge map, (2) calculating a Hough transform for a range of possible crater radii, (3) using a local maximum filter to coarsen each Hough transform, and (4) summing all Hough transforms. Since the bright rims of an impact crater will have two concentric circles in the Canny edge map, its location on the summed Hough transform will have a bright peak whose intensity is $> 4\sigma$ over the mean intensity across the rest of the foil. These craters, along with other highly circular features (e.g., pits, surface dust, etc.) or features with high edge density (e.g., surface dust and scratches), are evaluated by the code to ensure that candidates are selected that also are circular, contain a dark center, and contain a bright rim. The code then outputs potential crater images and metadata, resulting in a downselect of ~2-5% of the input images, significantly reducing the time and effort needed by an expert to evaluate the candidates. Potential crater sites are then reimaged with SEM for confirmation.

As validation, the crater algorithm found all crater candidates on foils I1020W and I1009N that had also been located with crowdsourcing [5]. To date, the algorithm has helped to locate 29 impact features across the 12 foils, although nearly half were found on foil I1009N. All craters extracted from these two foils contained residue consistent with secondary impacts of debris from primary dust impacts onto the spacecraft solar cells. Other foils contained 1-2 craters each, which are more likely to be due to isolated interstellar dust grains. The crater-finding algorithm also was able to successfully identify crater candidates in low quality images (e.g., images with defocus, astigmatism, or poor contrast), where they may have been missed during manual evaluation. Algorithm processing time is dependent chiefly on the total number of image pixels in the dataset. In addition, we are testing a version of the crater detection algorithm for real-time identification of candidate features using the AutoScript 4 Python interpreter for ThermoFisher DualBeam FIB-SEMs. Integrating real-time detection into image acquisition of the spacecraft foils can save valuable researcher time and storage for locating these rare impact features, as well as providing rapid location for FIB extraction.

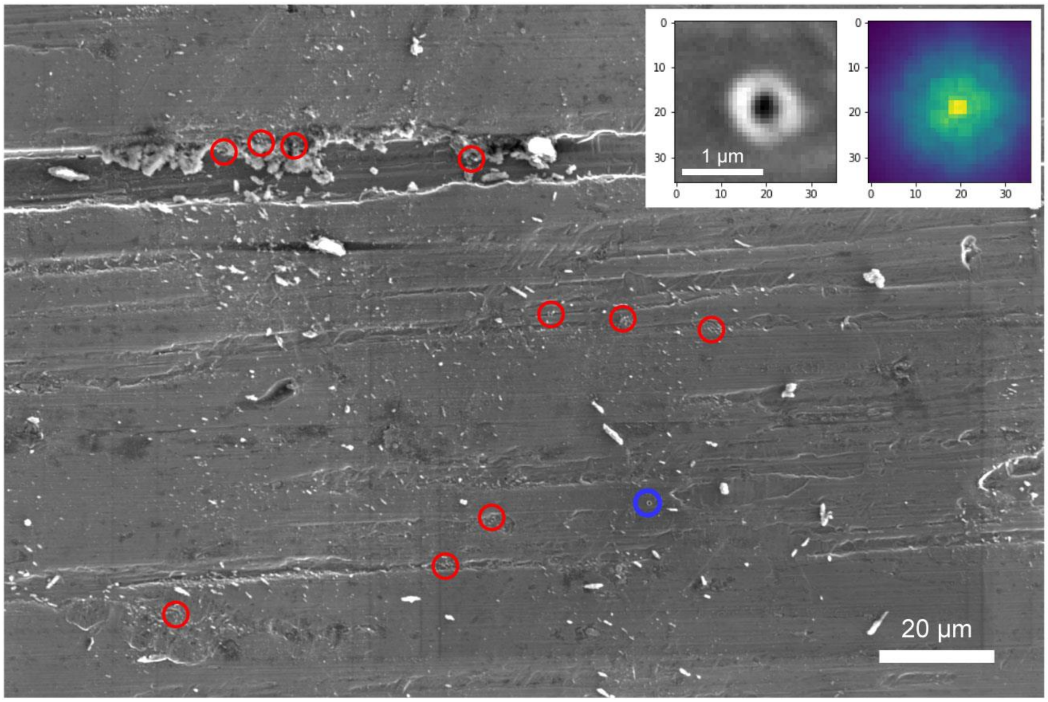

Figure 1. 6 MP SEM image from Stardust interstellar foil I1126N, with locations of circular features in the appropriate size range and Hough transform intensity for interstellar dust impacts. Only one of these features (purple circle and inset) passed all of the tests to be considered a crater candidate, which was confirmed by subsequent SEM re-imaging.

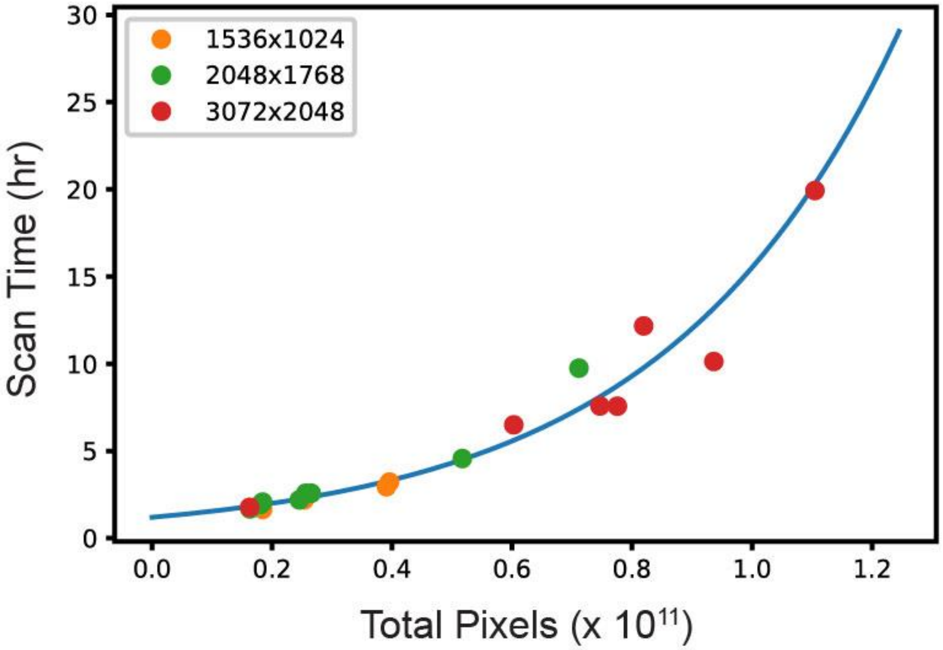

Figure 2. Running on 10 2.2 GHz CPU cores, the crater-finding code completes an foil image dataset scan in a matter of hours, up to a full day for the highest resolution datasets.

References

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