FAST AUTOMATED IDENTIFICATION OF DUST IMPACT CRATERS IN ALUMINUM FOILS FROM THE STARDUST COLLECTION.
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Introduction: The NASA Stardust spacecraft flew two dust collector trays for trapping particles from either comet Wild 2 or the contemporary local interstellar dust stream. Al foils, lining the ribs of the collector trays, provided a medium for study of small particles (< 1 µm). Analysis of small impact craters on the cometary foils can provide unique insight into the finest dust fraction of Wild 2 [1], including possible GEMS [2] and presolar grains [3]. Analysis of the similarly-sized impacts on the interstellar foils provides the opportunity to detect and directly analyze contemporary interstellar dust [4].

To identify impact craters, many thousands of scanning electron microscope (SEM) images are acquired from each foil and then searched. Crater density on the foils varies significantly. During the Interstellar Preliminary Examination (ISPE), searches of over 100,000 images from 13 different foils resulted in the identification of only four possible impact features that were determined to contain residue consistent with a cosmic, likely interstellar, origin [5]. These searches were performed with a combination of manual and MATLAB-based computer methods [5-7]. More recently, a massively-distributed, citizen scientist approach, Foils@Home, adapted from the highly successful Stardust@Home effort, was implemented [8].

Each of these crater identification methods has strengths and weaknesses. A manual search of all SEM images by expert scientists allows for highly accurate identification of craters, but would require an infeasible and expensive number of labor hours. The MATLAB-based crater searching software uses image cross-correlation with template images derived from known foil craters to reduce the required manual labor hours [6].

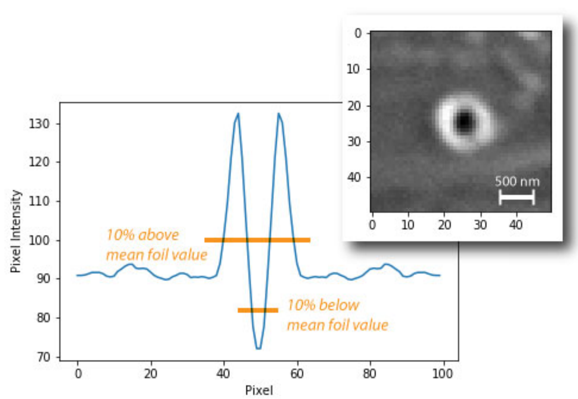

Figure 1: Grayscale intensity radial profile of an impact crater in interstellar Stardust foil I1126N.

However, this approach was comparatively slow, requiring more than a week of dedicated computer time for a single foil dataset, and often returning too many false positive matches. The Foils@Home effort successfully identified new impact features with relatively few false positive matches, but has not attracted the level of participation that the Stardust@Home effort did, in part because of the low abundance of interesting features, and little user interaction with foil images. Thus, there remains a need for fast, accurate, automated search methods for continued research on the Stardust foil collections.

Here we describe a method for fast automated detection of impact craters in SEM images of Stardust Al foils, which uses multi-core Python code to recognize the same characteristic features that humans use to identify craters—an elliptical or circular shape with a dark center and a bright rim [*Figure 1*].

Interstellar Foil Image Acquisition: SEM images of Stardust spacecraft foils I1009N, I1020W, I1021N, and I1126N were acquired with either a FEI Nova NanoLab or a FEI Helios G3 UC focused ion beam (FIB) SEM at the U.S. Naval Research Laboratory. Image resolution was 55 nm/pixel or less.

Automated Crater Searching Algorithm: Circular features can be robustly identified within each foil image using a four step algorithm [*Figure 2*]:

1. Canny edge detection to find edges in the image, including crater rims.
2. Circular Hough transform to locate circular features within the edge map. This step is performed for a range a radii to encompass all possible crater sizes. For this study, craters with diameters between 200-2000 nm were sought, matching the range of crater sizes observed during ISPE [5].
3. Local maximum filter to coarsen each Hough transform image to account for any center offsets from irregularly-shaped crater rims.
4. Combine all coarsened Hough transform images. Because a crater rim has two circular edges, inner and outer, centered at roughly the same position in the image, the Hough transform value for each crater rim edge will sum to generate a local maximum value in the final summed Hough transform image that deviates from the mean value at the 4σ-6σ threshold.

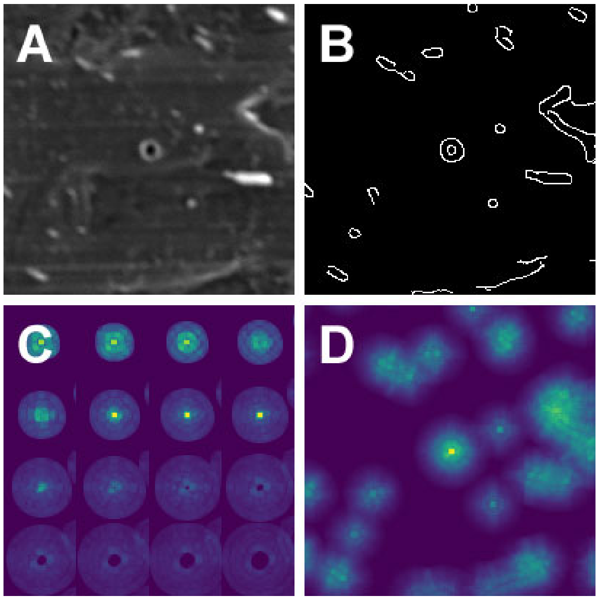

Figure 2: (A) SEM image of the I1126N crater shown in *Figure 1*. (B) Edge detection. (C) Series of Hough transform images of the crater from r = 110 nm to r = 935 nm. (D) final summed Hough transform image.

This basic algorithm, implemented in the Python programming language, returns one or more potential crater features in about 10% of the foil images, which includes real craters, but also bright-rimmed foil defects, surface contaminants with high edge density, and small aerogel pieces. Many of these false positives can be eliminated by calculating a radial profile of the final Hough transform image, rejecting features with a broad radial profile peak. Additional false positives are eliminated by requiring at least 33% of the pixels in the center of the feature to be 10% darker than the local foil mean ("black center"), and that at least 50% of the pixels in the feature are 10% brighter than the local foil mean ("bright rim") [*Figure 1*]. These criteria result in a return of a potential crater feature in <1.5% of the foil images, about 100 potential craters to evaluate manually.

Algorithm Benchmarks and Speed: The complete crater searching code was tested on images from foil I1020W, for which a complete set of craters had been previously identified by Foils@Home users [7,9], and a set of artificially-generated crater images. All real and artificial craters were identified by the algorithm, except for one real crater with a thin rim, which the edge detection routine interpreted as a single edge rather than a bright ring with an inner and outer edge.

The full crater searching program also utilizes the Python `multiprocessing` module in order to run the algorithm in parallel on 10 CPU cores. This results in a 5x enhancement in speed, such that a complete foil dataset can be searched in 2-5 hours [*Table 1*].

Table 1: Results of Crater Searching Software

Foil	I1009N	I1020W	I1021N	I1126N
Resolution (nm/pixel)	40.5	31.25	40.5	40.5
Images	21,063	7,076	16,605	17,319
Candidates	151	118	58	133
Likely Craters	9	6	9	11
Time (hrs)	5.1	1.8	4.3	4.3

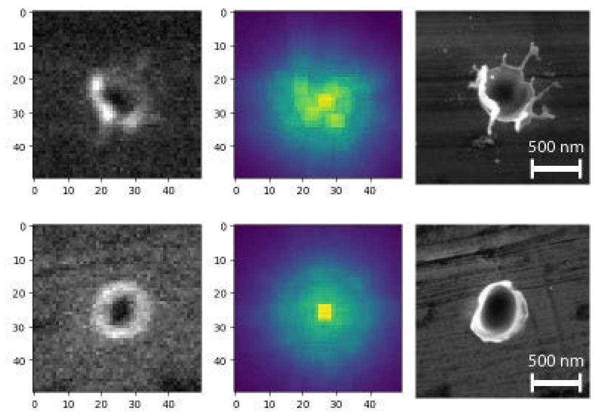

Figure 3: Two examples of real foil craters identified by the algorithm in the I1009N dataset, along with the summed Hough transform and a higher-magnification SEM image of the crater.

Results and Discussion: *Table 1* lists potential impact features identified by the algorithm, as well as those that appear to be real craters after manual inspection. Examples of hitherto unknown craters discovered by the algorithm are shown in *Figure 3*. The crater searching algorithm provides a number of benefits aside from automation and speed, as it successfully identifies craters in poor quality SEM images, such as those with low dynamic range (i.e. poor contrast) and improper focus conditions, which can stymie manual investigation of the images. It also successfully identifies elliptical craters from oblique impacts. This type of automated crater searching algorithm could be a powerful tool for "high-grading" the tens of thousands of foil SEM images in order to make more efficient and cost-effective use of the expert scientist's labor.

References: [1] Leroux H. et al. (2008) *M&PS*, 43, 143-160. [2] Stroud R. M. et al. (2010) *LPSCXLI*, 1792. [3] Leitner J. et al. (2010) *LPSCXLI*, 1607. [4] Westphal A. J. et al. (2014) *Science*, 345, 786-791. [5] Stroud R. M. et al. (2014) *M&PS*, 49, 1698-1719. [6] Ogliore R. C. et al. (2012) *M&PS*, 47, 729-736. [7] Floss C. (2015) *LPSCXLVI*, 1005. [8] Westphal A. J. et al. (2016) *LPSCXLVII*, 2275. [9] Stroud R. M. et al. (2016) LPSCXLVII, 2989.