STARDUST INTERSTELLAR PRELIMINARY EXAMINATION (ISPE). A. J. Westphal[1], C. Allen[2], S. Bajt[3], R. Basset[17], R. Bastien[2], H. Bechtel[4], P. Bleuet[5], J. Borg[6], F. Brenker[7], J. Bridges[8], D. E. Brownlee[9], M. Burchell[10], M. Burghammer[5], A. L. Butterworth[1], P. Cloetens[5], G. Cody[11], T. Ferroir[17], C. Floss[12], G. J. Flynn[13], D. Frank[2], Z. Gainsforth[1], E. Grün[14], P. Hoppe[15], A. Kearsley[16], L. Lemelle[17], H. Leroux[18], R. Lettieri[1], W. Marchant[1], B. Mendez[1], L. R. Nittler[11], R. Ogliore[1], F. Postberg[27], S. A. Sandford[19], S. Schmitz[7], G. Silversmit[25], A. Simionovici[20], R. Srama[14], F. Stadermann[12], T. Stephan[21], R. M. Stroud[22], J. Susini[5], S. Sutton[23], M. Trieloff[27], P. Tsou[24] A. Tsuchiyama[25], T. Tyliczszak[4], B. Vekemans[26], L. Vincze[26] J. Warren[2], M. E. Zolensky[2], >26,000 Stardust@home dusters[26] , [1]*Space Sciences Laboratory, U. C. Berkeley, USA,* [2]*KT NASA Johnson Space Center, USA,* [3]*DESY, Hamburg, Germany,* [4]*Advanced Light Source, Lawrence Berkeley Laboratory, USA,* [5]*European Synchrotron Radiation Facility, Grenoble, France,* [6]*IAS Orsay, France,* [7]*Geoscience Institute, Universität Frankfurt am Main, Frankfurt, Germany,* [8]*Space Research Centre, University of Leicester, Leicester, UK,* [9]*Astronomy Dept., University of Washington, USA,* [10]*University of Kent, UK,* [11]*Carnegie Institution of Washington, USA,* [12]*Physics Dept., Washington University, USA,* [13]*Dept. of Physics, SUNY – Plattsburgh, USA,* [14]*Max-Planck-Institut für Kernphysik, Heidelberg, Germany,* [15]*Max-Plank-Institut für Chemie, Germany,* [16]*IARC, Dept. of Mineralogy, The Natural History Museum, UK,* [17]*ENS, Lyon, France,* [18]*Université des Sciences et Technologies de Lille, France,* [19]*Astrophysics Branch, NASA-Ames Research Center, USA,* [20]*Observatoire des Sciences de l'Univers de Grenoble, France,* [21]*University of Chicago, USA,* [22]*Naval Research Laboratory, Washington DC, USA,* [23]*Advanced Photon Source, Argonne National Laboratory, USA,* [24]*Jet Propulsion Laboratory, USA,* [25]*Osaka University, Japan,* [26]*University of Ghent, Belgium,* [27]*Institut für Geowissenschaften, University of Heidelberg, Germany,* [28] *Worldwide* .

In January 2006 the Stardust sample return capsule returned to Earth bearing the first solid samples from a primitive solar system body, Comet 81P/Wild2, and a collector dedicated to the capture and return of contemporary interstellar dust. Both collectors were $\sim$0.1 m^2 in area and were composed of aerogel tiles (85% of the collecting area) and aluminum foils. The Stardust Interstellar Dust Collector (SIDC) was exposed to the interstellar dust stream for a total exposure factor of 20 m^2·day during two periods before the cometary encounter. The Stardust Interstellar Preliminary Examination (ISPE) is a three-year effort to characterize the collection using non-destructive techniques. The goals and restrictions of the ISPE are described in Westphal et al. [1].

The ISPE consists of six interdependent projects:

- Candidate identification through automated digital microscopy and a massively distributed, calibrated search
- Candidate extraction and photodocumentation
- Characterization of candidates through synchrotron-based Fourier-Tranform Infrared Spectroscopy (FTIR), Scanning X-Ray Fluoresence Microscopy (SXRF), and Scanning Transmission X-ray Microscopy (STXM)
- Search for and analysis of craters in foils through FE-SEM scanning, Auger Spectroscopy and synchrotron-based Photoemission Electron Microscopy (PEEM)
- Modeling of interstellar dust transport in the solar system
- Laboratory simulations of hypervelocity dust impacts into the collecting media

Candidate identification in aerogel tiles

Using an automated microscope, approximately 36% of the aerogel tiles have been digitally imaged with $\sim$0.5 μm resolution. The coverage of each tile was typically $\sim$80%, because of the extreme relief and fracturing near the edge of each tile. In some cases, tiles that were unusually fractured were less well covered. The digital imagery consists of stacks of $\sim$40 images in each field of view of the microscope, spanning $\sim$200 μm in focus range. These images are distributed through the Stardust@home project to amateurs ("dusters") who search the images for candidate impacts. Dusters use a web-based virtual microscope to focus through the image stacks in each field of view. To qualify to participate, the dusters must take web-based training and must pass a test. >26,000 volunteers have qualified to participate. The detection efficiency and false positive rate ("sensitivity" and "specificity", respectively) are measured for all dusters using calibration fields of view in which images of impacts from laboratory simulations have been dubbed, or in images which have already been examined and are assessed to be blank by the Stardust@home team at Berkeley. The images of the impacts are scaled to allow a measurement of sensitivity as a function of track diameter and depth. The average individual sensitivity is >90% for tracks $> 5\,\mu$m in diameter, which corresponds to a impactor diameter of $\sim$ 500 nm assuming the empirical scaling of Burchell et al. [2]. Through Stardust@home we have identified 27 *bona fide* high-angle tracks in the collector [3]. These projectiles are consistent with secondary ejecta originating from three separate impacts on the spacecraft. The tracks are $< 3\,\mu$m in diameter, and were typically identified by > 300 dusters; these provide an independent validation of the Stardust@home approach. Approximately 100 candidates have been identified in the 247 cm^2 searched area, through duster response data plus verification by the Stardust@home team and a "Red Team" recruited from the top dusters.

Candidate extraction from aerogel

We extracted the impact candidates from the interstellar collector in so-called "picokeystones" [4] — these are wedge-shaped volumes of aerogel machined from the tiles using glass needles controlled by automated micromanipulators. The candidates are located in a thin ($50 - 70\,\mu$m) section of the picokeystone so that all synchrotron-based analytical techniques can be applied. The picokeystones are extracted on barbed polysilicon forks, then carefully transferred to a sandwich consisting of two 70 nm-thick Si_3N_4 windows. This mounting technique simultaneously protects the samples from contamination, reduces risk of loss by physically trapping the samples, and allows for all synchrotron-based analyses except tomography. Because trajectory information may be critical in distinguishing interstellar dust impacts from those of other dust sources [5], we have placed a very high priority on preserving trajectory information as much as possible. Because removal of tiles from the tray can induce distortions in the tiles and carries some risk of loss, we have chosen to extract candidate events directly from the tray itself rather than from extracted tiles as is done on the cometary collection. This approach requires extreme care and comparatively slow micromanipulator motion, so the extraction is dramatically slower than originally anticipated. We have so far extracted five blank picokeystones, seven off-normal tracks, and 14 IS candidates. Two IS candidates were damaged during handling but are still analyzable, and one was lost during transfer to the Si_3N_4 sandwich due to the propagation of a pre-existing fracture in the aerogel.

Synchrotron analysis of candidates

We have conducted analyses of extracted picokeystones using three synchrotron-based techniques on six beamlines.

FTIR (beamlines 1.4.3, ALS and X1A, NSLS): We have found no evidence for organic material in any of the IS candidates. The native organics in the aerogel picokeystones are highly variable both in concentration and in species. We have found that synchrotron x-ray analysis induces a change in the organic concentration and speciation [6]. This effect can be quantified and will be important in establishing x-ray dose limits.

XRF (ESRF ID13; ESRF ID22; APS 2-ID-D): Synchrotron X-ray fluorescence is sensitive to major, minor and trace elements with Z >= 16. Samples at the ESRF were analyzed using a submicron X-ray beam of 12.9 keV (ID13) and 17 keV (ID22), and at the APS with a 10-20 keV beam. All samples were successfully analyzed with a spatial resolution of $\leq$ 200 nm. Off-normal candidates were found to be rich in Ce, Zn, and Mg, consistent with the Ce-rich glass covers of the aft solar panels of the Stardust spacecraft. In six cases, IS candidates were identified as probable terrestrial contaminants because of elemental ratios of, e.g. Zn/Fe and Se/Fe. No detectable elements were found in a crater-like feature, raising the possibility of a purely organic impactor; however, no evidence of organic material was found by FTIR in this feature. An apparent contaminant particle, $\sim 1\,\mu$m in size, having a CI-like Ni/Fe ratio was identified, suggesting the easily measured Ni/Fe ratio may not be a good identifier of extraterrestrial material in the IS collectors. Analyses of other tracks are in progress.

STXM (ALS 11.0.2): Scanning Transmission X-ray Microscopy has very high spatial resolution ($\sim$30 nm) and is sensitive to major elements excluding H, S and Ca. Samples were successfully mounted and analyzed in Si_3N_4 window sandwiches. Using a combination of x-ray absorption mapping and XANES, we have identified alumina and silica glass among the candidates. Using the off-normal tracks of secondaries, we have been able to demonstrate that STXM can be used to image the track itself in the aerogel even in the absence of any residue along the track of the projectile. Using this approach, we have rejected three candidates based on the lack of an impact track. Analysis of one possible impact track is in progress.

Identification and analysis of craters in foils

Two foils have been extracted from the SIDC, and another 15 foils are anticipated shortly. These foils have not yet been examined. Standards have been distributed to the foils team for evaluation of carbon deposition rates in the instruments in the individual laboratories. Preliminary experiments indicate that the carbon deposition rates during large-area imaging of the foils is expected to be negligible. Except for highly oblique impacts, trajectory information is not easily interpreted from simple images of foil craters. What, then, is a suitable criterion for identification of IS dust impacts on foil? Young et al. [7] have recently reported that the solar system appears to be anomalous in ^{17}O, about 400 permil lower than the galaxy. Perhaps distinctive oxygen isotope signatures may be recognisable in Al crater residues?

IS dust trajectory modeling

Although modelling of dust transport with a focus on Stardust has been done previously [8], this effort was not focussed on predicting the distribution of particle trajectories in the Stardust collector. The ISPE modelling effort incorporates the actual heliospheric conditions during the collection periods: the interplanetary magnetic field strength was $\sim$2.5 times larger than assumed by Landgraf et al. [9]. This could have the effect of significantly depressing the flux of small particles.

Laboratory simulations

Light Gas Gun tests at Kent have confirmed that secondary ejecta from impacts on solar cells give tracks in aerogel which contain glass, confirming the identification of secondary ejecta in the off-normal tracks. In November 2008 we conducted exposures of Stardust flight spare tiles and foils to dust accelerated to 5–25 km sec^{-1} by the van de Graaf dust accelerator at Heidelberg. The projectiles consisted of monodisperse latex spheres, aluminum + PMMA, iron, and orthopyroxene. The analysis of laboratory simulations will be critical in recognizing and understanding the actual interstellar impacts. Some of these impacts have been analyzed by STXM at the ALS.

Discussion

No interstellar dust particles have been identified during the ISPE among the ten candidates for which the analysis is complete and conclusive. This result is not entirely unexpected since statistically $\sim$1 candidate might be expected to have been found among these ten, based on the fluence estimate of Landgraf et al. [8]. Analysis of three other candidates is in progress. We have shown that the analytical techniques employed by the ISPE have the sensitivity and spatial resolution required to characterize these samples. The Stardust@home project has unambiguously identified tracks that are smaller in diameter than those expected for interstellar dust based on an extrapolation from recent laboratory calibrations, thus providing independent validation of this unusual approach.

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