NANOMETRE SCALE DUST DETECTION ON THE ISS USING THIN ALUMINIUM FILM

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ABSTRACT

The LOBSTER-ISS all sky monitor is an imaging X-ray telescope, which uses microchannel plate (MCP) X-ray optics to achieve a large field of view in a compact, low mass package and is designed as an external payload for the International Space Station. The LOBSTER-ISS MCP optics are coated with a thin Al film for thermal control and in preparation for this mission MCP samples, whose circular microchannel array structure supports a 60nm thick Al film, were exposed to the external ISS environment for 756 days. Post retrieval the MCPs have been examined to evaluate particle impact damage and the extent of any contamination acquired during exposure. The results indicate a high flux of nanometre-scale particles impacting at hypervelocity and with diameters at least an order of magnitude smaller than has previously been observable with microscopic and macroscopic foils.

We present data on the detected impactor fluxes, the sizes of impact holes and probable size of the impactors. Also presented are recently obtained high resolution field electron gun scanning electron microscope secondary electron and backscattered electron images of the film, revealing the impact morphologies.

1. INTRODUCTION

Microchannel plates (MCPs) are arrays of millions of holes, or microchannels, in a glass matrix. In the current work MCP samples with 12.5μm diameter microchannels on a 15μm pitch and with a length:diameter ratio (L/D) of 40:1 bear a 60nm thick Al film. These MCPs have been exposed to the external ISS environment for 756 days, between 2002 and 2004. Exposure took place on the Russian "Pirs" docking module shown in Fig. 1 as part of the X-Ray Mirror Expose Experiment (Hofer, 2004).

This experiment was designed to evaluate the extent of damage and contamination to filmed MCP optics in the ISS environment and to provide insight into the suitability of the ISS as a platform for the LOBSTER-ISS all sky X-ray monitor (Fraser, 2001). LOBSTER-ISS employs MCP optics bearing a thin Al film as a means of thermal control of the optical surfaces.

After retrieval the filmed MCPs were returned to the University of Leicester for analysis. A combination of scanning electron microscope (SEM) imaging, energy dispersive X-ray fluorescence spectroscopy (EDXRFS) and Fourier transform infra red (FTIR) spectroscopy were used to analyse the samples and determine the extent of particle impact damage and contamination. A large concentration of holes with diameters less than the 12.5μm channel diameter was observed in the film. These holes are believed to have been generated by small particles, with diameters of tens of nanometres, impacting the film at hypervelocity. Particle impact fluxes have been deduced from analysis of these holes. These flux measurements are compared with previous measurements of impact fluxes made through perforation studies of foils exposed to similar space environments. The probable size of impactors is discussed and we present examples of impact morphologies observed using field electron gun scanning electron microscopy (FEGSEM).

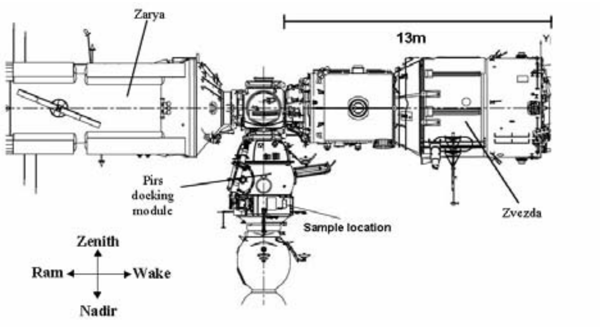

Figure 1. Mounting location of the samples on the outer surface of the Docking Compartment No. 1 ("Pirs") (image courtesy of Kayser-Threde GMBH and RKK Energia, Moscow).

2. IMPACTOR FLUX AND SIZES

Multiple SEM images were taken of the film following retrieval from the ISS and return to the University of

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Leicester. Holes in the film were identified in the images and allocated a diameter D_h equal to that of a circle with the same area as the hole. The data were then binned according to hole diameter. A circularity discriminator was applied to remove irregularly shaped holes not produced by hypervelocity impacts. The flux vs. hole size distribution was then determined taking the period of exposure to be 6.5×10^7s; this size distribution is shown in Fig. 2. The flux given for the smallest bin is likely to be smaller than the true flux as holes in this size regime approach the resolution limit of the SEM and it is likely that many holes will not have been identified. As the hole image size approaches that of a single image pixel the circularity filter becomes increasingly inaccurate, resulting in an increase in the fraction of holes with a determined circularity < 0.8.

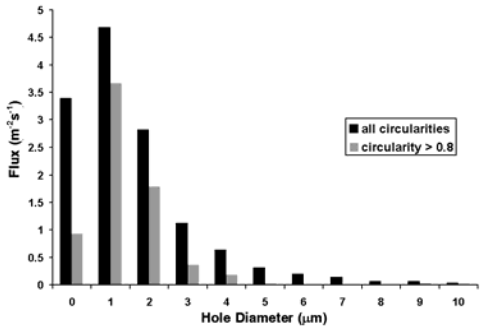

Figure 2. Hole diameter D_h and flux distribution for the MCP nanofilm hole population with circularity > 0.8 and for all circularities (after Carpenter et al., 2005).

The cumulative flux of holes in the exposed Al film, due to hypervelocity impacts, was found to be $6 m^{-2}s^{-1}$ (Carpenter et al., 2005). This flux is much higher than that experienced by previously flown foils but consistent with the increase in sensitivity provided by the thin Al films (Fig. 3) (Carpenter et al, 2005).

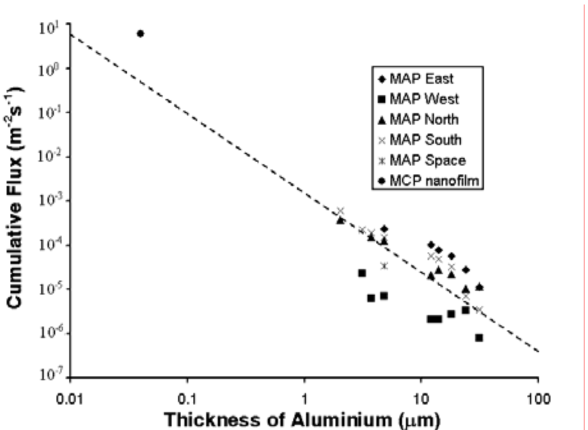

Figure 3. Comparison of cumulative hole flux data from MAP (McDonnell et al., 1993) and the presented filmed MCP (after Carpenter et al., 2005).

Assuming impact velocities of 10s of kms^{-1} the smallest particles able to penetrate the film were calculated to have diameters of ~10nm using the ballistic limit formula of McDonnell et al. (1992) and assuming a particle density of $1gcm^{-3}$. The detected fluxes are in agreement with extrapolations of previously observed trends in impact flux vs. foil thickness (Carpenter et al., 2005).

The smallest holes resolvable with the SEM were ~418 nm in diameter. Application of the Carey-Dixon-McDonnell formula (Carey et al., 1985) predicts that a 418 nm hole can be generated by a 14.4 nm diameter particle with a density of $1gcm^{-3}$ normally incident on the film at $20kms^{-1}$. Such particle size calculations assume that the impact mechanics of macroscopic and microscopic foils can be extrapolated to nanoscale evaporated films. The resultant calculated particle diameters can be applied to the observed hole size distribution to yield an estimate of the flux of particles of a given diameter. These calculated fluxes are agreement with extrapolations of previously observed flux vs. particle diameter data trends (Carpenter et al., 2005).

The results imply that there is a substantial particle population with nanometer scale diameters, impacting with a high frequency on the ISS and which have been previously undetectable. It is unclear whether this population is natural or artificial and whether or not it is local to the ISS. Thin Al films supported by MCPs represent an order of magnitude increase in the sensitivity of witness plate experiments.

3. PARTICLES AND IMPACT MORPHOLOGY

We have obtained high resolution images of the exposed film using FEGSEM. These images of the film reveal detailed impact morphology. The smallest impact hole observed with this imaging technique is just 77 nm in diameter, placing an upper limit on the minimum size of impactors. The presence of smaller holes cannot be ruled out. Some of the observed impact features in the Al film are shown in Figs. 4-6. The shapes of the holes can give insight into the incident angle of the impactor. Spherical holes will result from impactors at normal incidence. For micron scale foil thicknesses the aspect ratio (length/width) increases with increased angle of incidence. Irregularly shaped holes can result from particles with diameters >> film thickness, which punch through the film (McDonnell et al., 1998).

The impact features observed in the exposed films resemble those observed in thicker foils but can occur on much smaller scales. Impact hole shape is usually slightly elliptical, indicating a non-normal incidence angle for the impactor (Fig. 4). Approximately circular holes are also observed indicating a near-normal incidence angle. The variation in hole shape results from a variation in incidence angle. It is unlikely therefore that that the holes arise due to a single event.

Some holes have cracks surrounding them, indicating impacts at less than hypervelocity (Fig. 4). What velocities this corresponds to in such thin Al films is however unclear. The behaviour of thin films when impacted is poorly understood and it cannot be assumed that the impact mechanics is the same as that of thicker foils.

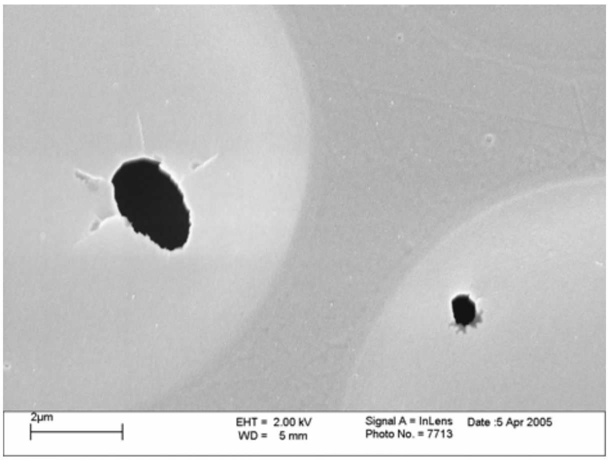

Figure 4. Impact holes on the Al film. The larger elongated impact hole on the left shows cracking.

Other features observed on the film using secondary electron imaging include structures surrounding some holes with $D_h > 1\mu m$. Often these holes are highly irregular. Similar structure is seen in many microchannels using backscattered electron imaging, which is sensitive to changes in atomic number (Fig. 5).

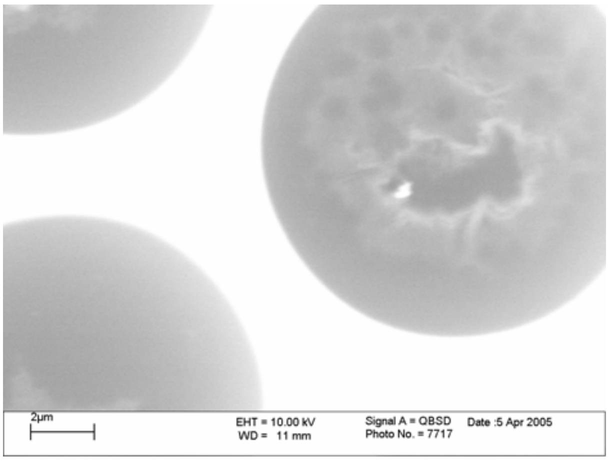

Figure 5. Backscattered electron image of structure within a single microchannel film image.

EDXRFS spectra of the bright spot visible in the microchannel on the right in Fig. 5 exhibit the K and L line peaks of fluorine and titanium. EDXRFS of contaminants on MCPs is problematic owing to the complex chemical composition of MCP glass. Elements expected in EDXRFS spectra of MCP glass include O, Na, Pb, Bi, Be, Na, K, Al, Ca, C, Si. As a result only the detection of elements not expected in MCP glass can be used to classify contaminants and impactors.

Larger and irregular holes with sizes comparable to the microchannel diameter are observed, often with associated melting features or evidence for the one time presence of fluids. In these cases the extent of damage and the size of the holes is limited by the presence of the microchannel wall. It is unclear whether this damage is due to particles similar to those generating the circular holes. This seems unlikely given the gross differences in hole shape.

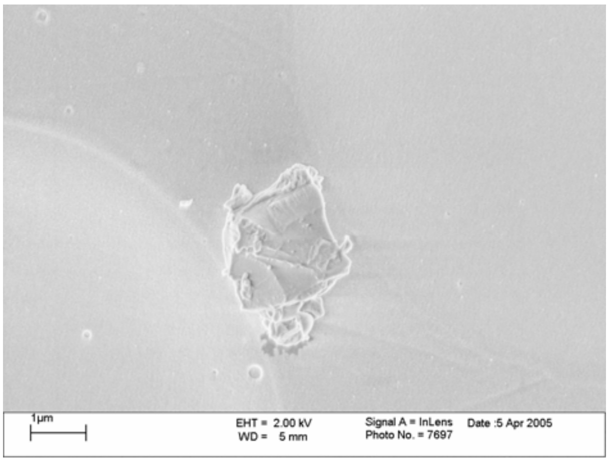

Figure 6. A single intact particle observed on the Al film.

Several intact particles have also been observed with FEGSEM secondary electron imaging, one of which is shown in Fig. 6. EDXRFS has not been possible owing to the small working distance (5mm) in the FEGSEM and the low electron accelerating voltage (2.0 kV) required to observe the film. As a result the precise nature of these particles, which can vary considerably in appearance, has not yet been determined. It is unlikely however that these particles are representative of the hole generating impactors as they have been incident at considerably reduced velocities.

4. CONCLUSIONS AND FURTHER WORK

Impact features in the thin Al films indicate the presence of a high density of particles, either natural dust or man made debris, in the ISS environment. These particles have diameters as small as tens of nanometres. These particles could not have been detected by the much thicker and less sensitive foils exposed and retrieved in the past.

The impact morphologies on the film are varied and complex. Decoding these morphologies to determine impactor characteristics is not straightforward as knowledge of thin film impact mechanics is poor. Further imaging and image analysis is required to determine more on the impact characteristics of a statistically significant sample of impact sites.

An experimental campaign is planned to investigate hypervelocity impacts by spherical Al particles with diameters of 80 – 100 nm on thin Al films. These particles have been provided by Qinetiq Nanomaterials Ltd., Farnborough, UK. The work will be carried out using the microparticle accelerator at the Open University, Milton Keynes, UK.

Intact particles have been observed on the film and further analysis of these particles may reveal their origins. The most probable origin of these particles is the ISS its self. Such particles cannot have impacted at hypervelocity, however, and are therefore unlikely to be representative of the particles producing impact holes.

We intend to begin the development of an active dust detector based on the filmed MCP technology, which will offer unprecedented sensitivity. Such a detector may use the transmissive nature of holes in the film as a means of hole detection or direct observation of the light flash associated with hypervelocity impacts. The device will be small, low in mass and require little in terms of power or telemetry. As such it will be suitable for flight on any spacecraft and could provide observations of the nanometre particle distribution in the near Earth environment and throughout the solar system.

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