**INTERPRETING MICROMETEOROID RESIDUES ON METALLIC SPACECRAFT SURFACES: CLUES FROM LOW EARTH ORBIT, THE LABORATORY, AND TO COME FROM STARDUST?** A. T. Kearsley[1], M. J. Burchell[2], G. A. Graham[3], M. J. Cole[2] and D. Wallis[4], [1]Department of Mineralogy, The Natural History Museum, London, SW7 5BD, UK, (antk@nhm.ac.uk), [2]Centre for Astrophysics and Planetary Sciences, School of Physical Science, University of Kent, Canterbury, CT2 7NR, UK, [3]Institute of Geophysics and Planetary Physics, Lawrence Livermore National Laboratory, 7000 East Avenue, Livermore, CA 94550-9234, USA, [4]Department of Space & Climate Physics, University College London, Gower Street, London WC1E 6BT, UK.

**Introduction:** Surfaces of spacecraft returned from low Earth orbit (LEO) preserve a record of high velocity collisions with small (<1mm) particles. Surveys of features on metal, glass and other materials have identified remains of micrometeoroids (e.g. [1] and [2] among many others). Analytical electron microscopy using energy dispersive X-ray spectrometry (EDS) has proven very successful in distinction of impacts by artificial and natural particles [3], and holds promise for interpretation of micrometeoroid residues in terms of particle origin (figure 1).

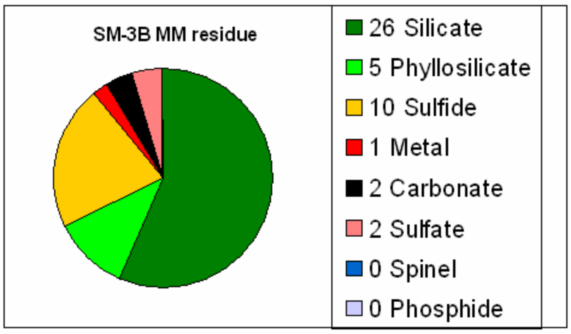


Figure 1. Relative abundance of micrometeoroid components in residues from solar cells collected from the Hubble Space Telescope by Service Mission 3B [4].

Recent work [4] has shown a paucity of alkali aluminosilicate residues, likely to be a reflection of the particle source, lacking well-defined chondrule mesostases and matrix as found in ordinary chondrite meteorites. Frothy Ni-and S-bearing mafic silicate residues may indicate impact by particles containing water, although whether structural (e.g. in phyllosilicates and hydroxyl-sulfide interlayers) or as a discrete grain component such as ice, is not known. The source of the abundant sulfur-poor mafic silicate residues has proven more difficult to determine. They may reflect impact by either glass or crystalline stoichiometric silicate minerals. Are they asteroidal or cometary?

**Experimental Analogues:** Over the last nine years we have documented residue textures and compositions from numerous light gas gun buckshot firings in the two-stage light gas gun at the University of Kent, Canterbury [5] using a wide range of meteoritic analogue minerals. The primary driver for much of this research was to aid interpretation of micrometeoroid impacts during our surveys of Hubble Space Telescope solar cells, and to assess variability in impact feature shape on metal as a function of projectile type [6]. The buckshot technique propels large numbers of grains toward the target area. Several substrates may be impacted simultaneously under identical conditions (e.g. at approximately 6 $kms^{-1}$ velocity), and with grains of several different materials. In our experiments, targets have included metal blocks of mm to cm thickness, polymer and metal foils of 10 to 100 micrometre thickness as well as solar cell glass. We now have a reference collection of hundreds of craters, of a wide range of sizes from micrometre to millimetre scale, on solar cell glass and metal alloys (figure 2).

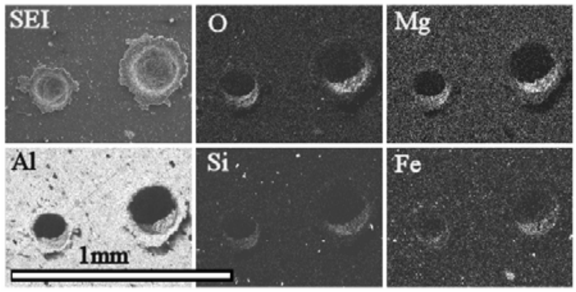


Figure 2. Secondary electron image and EDS X-ray maps of impact craters produced by impacts of grains of the CI carbonaceous chondrite meteorite Orgeuil on aluminium foil.

**Cometary versus Asteroidal origins:** Although light gas gun shots using meteorite analogue minerals have provided very valuable analogues for impacts by micrometeoroids, there remains a major problem for residue interpretation: the attainment of appropriate velocity regime for particles of asteroidal origin (20$kms^{-1}$ or more, [7]). Even greater problems attend the very high velocity of some cometary particles, never mind details of their composition and construction. Despite the success of ground based and astronomical satellite IR spectroscopy of comets e.g. [8], there is still doubt as to the characteristics of the more refractory components released as dust. Are the majority of particles loose mineral grain aggregates, or more consolidated, interlocked assemblages? Is the bulk of the silicate present as crystalline mafic minerals such as enstatite and forsterite? Is there a large quantity of silicate glass? How much iron sulfide is present? Are there discrete crystalline alkali-rich aluminosilicates? What reliable criteria could we use to distinguish residues originating from an asteroidal particle from those derived from a comet? Return of the Stardust mission [9] may help to answer these questions.

**A bonus from the Stardust mission:** The recent successful encounter between the spacecraft and comet Wild2 may yield a secondary bonus: not only collection of cometary particles in silica aerogel, but also a suite of impacts onto denser metallic substrates under velocity conditions (c. 6 $kms^{-1}$) that can be reliably simulated in the laboratory. Comparison between well-preserved cometary grains in aerogel, and residues from the impact of similar particles, under the same velocity regime, on the exposed metal components may provide a key to recognition of similar cometary particle impact residues upon spacecraft surfaces in LEO, even with the differing velocity regime.

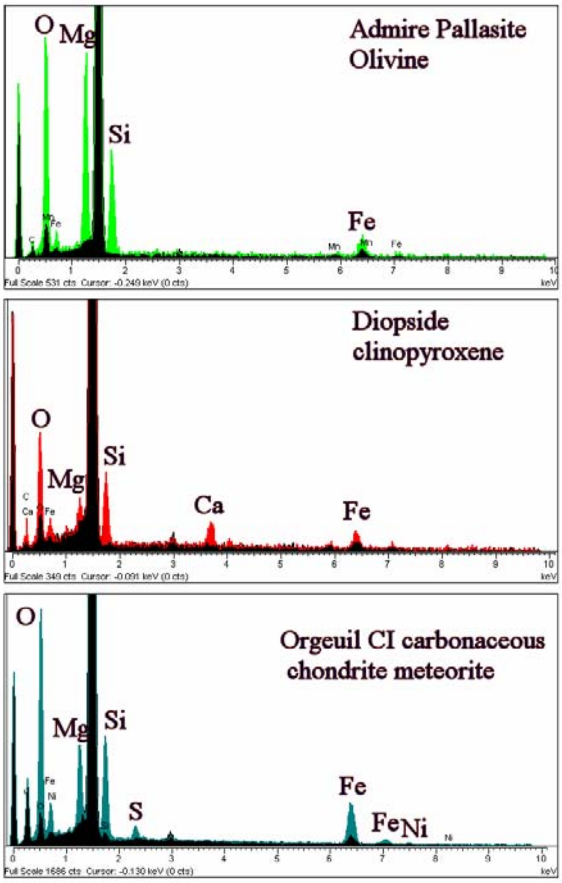


Figure 3. X-ray spectra of residues from light gas gun impacts of three different silicate materials on Al alloy. Target metal spectrum in black, residues in colour.

**Impacts on metal substrates:** Previous work has shown that density contrast between projectile and target will influence the impact feature depth/diameter ratio [6], and controls location and state of projectile residue. Aluminium alloys, widely used in aerospace applications, have a sufficiently high density that most mineral grain impacts generate a simple bowl-shape, with abundant residue in a sheet across the crater. Laboratory impact residues can retain compositions that are easily interpreted as rock-forming minerals (figure 3). Useful spectra can be obtained from a crescentic region on the steep wall, in an orientation facing toward an energy dispersive (ED) X-ray detector with a take-off angle greater than 30 degrees. Near-grazing incidence of the electron beam, generation of X-rays within a thin (micrometre-scale) residue layer and a very high takeoff angle for the X-ray detector, together reduce the magnitude of matrix effects. This is in marked contrast to solar cell residues, where mixing with borosilicate glass creates so many absorption and secondary fluorescence effects as to require correction by iterative computation, made difficult by topography of the impact crater. Only if a solar cell crater floor is broad and flat, and residue is abundant and concentrated, is it easy to perform reliable quantitative analysis of compositional contributions of target and particle, and thence calculate the primary particle mineral stoichiometry.

Aluminium alloys present some problems as a microanalysis substrate, as they may contain small quantities of Mg, Si, Mn, Fe, etc. It is very important to document the entire compositional range seen in the target material, especially as some components (e.g. Cu, Fe and Mn) may be heterogeneous in their spatial distribution, at a scale of less than 10 micrometres.

**Conclusions**: Our experiments show that there is real potential for identification of specific mineral species from hypervelocity impacts upon metal substrates where the particle size is greater than 3 micrometres diameter and the relative velocity is around 6 $kms^{-1}$.

It will be a worthwhile exercise to compare residues in impact features on metal surfaces of other spacecraft, with those upon the aluminium foils and support frames of the Stardust aerogel collectors.

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