REVISITING LDEF: HIGH RESOLUTION ELEMENTAL AND ISOTOPIC CHARACTERIZATION OF HYPERVELOCITY IMPACTS. F. J. Stadermann[1], C. Floss[1], D. E. Brownlee[2], and M. Rodruck[2], [1]Laboratory for Space Sciences and Physics Department, CB 1105, One Brookings Drive, Washington University, St. Louis, MO 63130 (fjs@wuphys.wustl.edu), [2]Department of Astronomy, University of Washington, Seattle, WA 98195.

Introduction: The Long Duration Exposure Facility (LDEF) satellite was flown in Low Earth Orbit (LEO) for a duration of 69 months from 1984 through 1990 [1]. Its main mission was to study the effects of the space environment on a variety of exposed surfaces, but it also carried experiments dedicated to the capture of impacting particles, which included not only cosmic dust, but also a significant fraction of man-made orbital debris. The LDEF satellite was gravity-gradient stabilized in orbit [1], resulting in different surfaces facing the same directions (e.g., leading and trailing edge, space and earth ends) during the entire time in space. This configuration made it possible to study separate regimes of particle bombardment on different sides of the satellite, with, *e.g.*, fewer impacts by man-made debris on the trailing edge [2]. Samples from LDEF were extensively studied during the early 1990s with a wide array of analytical tools available at the time [*e.g.*, 3 - 5].

The recent return of the Stardust spacecraft with hypervelocity impacts of cometary dust in Al foil targets has renewed interest in the detailed characterization of crater debris and possible inferences about the original projectile material [6]. Here we revisit impact features from the LDEF satellite using state-of-the-art analytical techniques with two major objectives in mind: (1) Prepare for the future analysis of interstellar impacts from the second collector on the Stardust spacecraft [7, 8], where the impact parameters (speed and angle) are less well defined than on the cometary side and may resemble more the conditions found in LDEF impacts. (2) Investigate whether elemental and isotopic characterization of LDEF impact features at a sub-micrometer scale can provide additional information about the nature of the LEO environment.

Experimental: We performed high resolution elemental and isotopic imaging measurements of particle impact features in Au and Al targets which were originally mounted in space-facing and trailing locations on the LDEF satellite [2, 9 - 11]. Measurements were performed by SEM-EDX, NanoSIMS and Auger spectroscopy. The latter two techniques are highly surface sensitive and offer spatial resolutions of 100 nm and 20 nm, respectively. The advantage of Auger spectroscopy is that it is non-destructive (which is important for the ISPE [7, 8]), while the NanoSIMS allows isotopic measurements combined with depth profiling. For the isotopic measurements we acquired secondary ion images of $^{12}C^-$, $^{13}C^-$, $^{16}O^-$, $^{17}O^-$, and $^{18}O^-$. The analytical conditions were similar to those used in studies of cometary craters [12] and should allow the detection of C and O isotopic signatures of presolar grain at high spatial resolution, if such particles are present among the impact debris [12, 13].

Results and Discussion: Elemental measurements of all analyzed LDEF craters (6 in Au, 2 in Al) indicates the presence of projectile residues on the crater floors, the inner walls and on the rims. High concentrations of Fe, Mg, and Si (and the absence of other elements commonly found in man-made debris in the LEO) indicate that these craters were caused by the impact of natural dust particles. Detailed images of the debris show that this material typically is highly heterogeneous on a sub-micrometer scale and that it is finely intermixed with the target materials. This observation is both consistent with earlier observations in such LDEF craters [9, 10] and is comparable to what has been observed on the cometary Stardust collector [6].

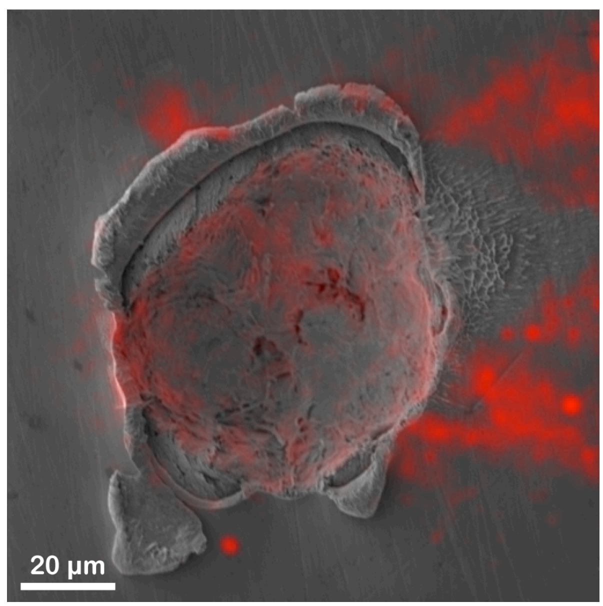

Fig. 1: Overlay of an Auger Fe elemental distribution map (red) on an SE image of a hypervelocity impact into an LDEF Au target.

A feature that has not been observed in the Stardust craters is shown in Fig. 1. It shows a thin layer of Fe-rich spray outside of the actual crater. This deposit of

Fe is too thin to be seen by EDX, but it is clearly visible by Auger elemental imaging, which detects the composition of only the top few nanometers. This feature may be a result of the possibly higher impact velocities in the case of LDEF, or it could be due to an oblique impact, which was not observed on the cometary Stardust collector where particles hit the target in normal direction. If such spray is observed in the interstellar impacts on Stardust, it may be helpful in identifying oblique angle impacts which otherwise are difficult to recognize in the Al foil targets [8].

None of the analyzed craters show C or O isotopic variations that are indicative of typical sub-micrometer sized presolar grains [12]. The O isotopic measurements of the Al target craters from the space end, however, indicate wide-spread anomalies in the topmost layers of the sample. In the analysis of a section of crater rim (Fig. 2), the entire field of view turned out to be isotopically anomalous (^{16}O-rich), with the exception of a small area highlighted in the image. The O isotopic composition of this small grain is normal within errors. This can be understood if the entire crater surface became ^{16}O-enriched during space exposure; the isotopically normal grain then represents a piece of terrestrial contamination which was added to the sample later. Such an ^{16}O enrichment of LDEF surface material has previously observed [14] and was attributed to interaction with ^{16}O-rich atomic oxygen (due to gravitational separation) in the LEO.

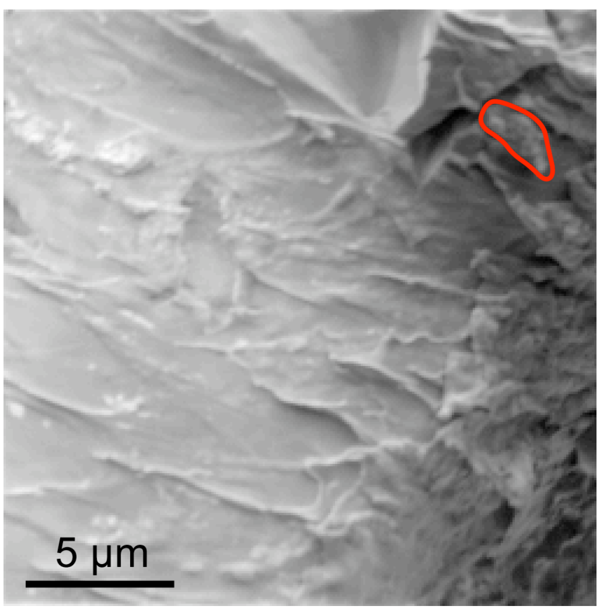

Fig. 2: Detail of the rim of an Al target impact from the space end of the LDEF satellite. The topmost material in the entire field of view is ^{16}O-enriched with the exception of the highlighted area (top right), which is isotopically normal.

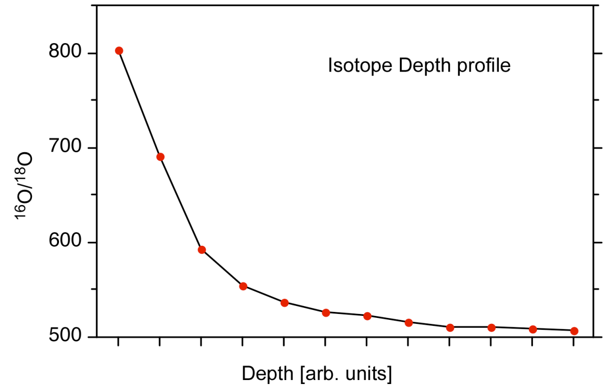

Fig. 3: Change in O isotopic composition as a function of sample depth. After the ^{16}O-enriched surface of the sample is removed (sputtered away), the isotopic composition slowly approaches the normal terrestrial ratio of $^{16}O/^{18}O \approx 500$.

A SIMS depth profile through the isotopically anomalous material is shown in Fig. 3. Consistent with [14], only the top layer of the crater residue is affected by this effect and the isotopic composition rapidly approaches a normal value during the course of the NanoSIMS imaging measurement. Since the extent of the surface anomaly likely is a function of the exposure time to LEO atomic oxygen, it may be possible to utilize such depth profile measurements for relative impact dating purposes on LDEF, since an entirely 'fresh' surface is created during the impacts.

Given that the isotopically anomalous surface material is quickly sputtered away during a measurement, it would still be possible to identify isotopically anomalous presolar grains in such craters, if they are of sufficient size and have an isotopic composition that is distinct from this ^{16}O enrichment. This is the case for most presolar silicates and oxides, but no such grains were observed in this study.

References: [1] O'Neal R. L. and Lightner E. B. (1991) Proc. 1st LDEF Post-Retrieval Symp., *NASA CP*, 3134, 3-48. [2] Amari S. et al. (1992) Proc. 2nd LDEF Post-Retrieval Symp., *NASA CP*, 3194, 513-528. [3] Levine A. S., ed. (1991) Proc. 1st LDEF Post-Retrieval Symp., *NASA CP*, 3134. [4] Levine A. S., ed. (1992) Proc. 2nd LDEF Post-Retrieval Symp., *NASA CP*, 3194. [5] Levine A. S., ed. (1993) Proc. 3rd LDEF Post-Retrieval Symp., *NASA CP*, 3275. [6] Hörz F. et al (2006) *Science* 314, 1716-1719. [7] Westphal A. J. et al. (2008) *LPS XXXIX,* Abstract # 1855. [8] Westphal A. J. et al. (2009) *this conference*. [9] Bernhard R. P. et al (1992) Proc. 2nd LDEF Post-Retrieval Symp., *NASA CP*, 3194, 551-573. [10] Brownlee D. E. et al. (1992) Proc. 2nd LDEF Post-Retrieval Symp., *NASA CP*, 3194, 577-594. [11] Stadermann F. J. et al. (1993) Proc. 3rd LDEF Post-Retrieval Symp., *NASA CP*, 3275, 461-473. [12] Stadermann F. J. et al. (2008) *Meteorit. Planet. Sci.*, 43 (1/2), 299-313. [13] Hoppe P. et al (2006) *Meteorit. Planet. Sci.*, 41, 197-209. [14] Saxton J. M. et al. (1993) Proc. 2nd LDEF Post-Retrieval Symp., *NASA CP*, 3194, 791-796.