TOF-SIMS ANALYSIS OF WILD 2 COMETARY MINERAL GRAINS CAPTURED BY STARDUST.

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Introduction: Dust grains from comet 81P/Wild 2 were captured by the *Stardust* mission in 2004 and returned to Earth in January 2006 [1–3]. The primary capture medium for the cometary dust was low-density silica aerogel with 1039 cm^2 total exposed surface area. Recent analyses of *Stardust* samples reveal that a wide variety of minerals exists in Wild 2 matter, while the overall element abundances are close to the average solar system composition, represented by CI chondrites [3–7].

The present study is part of an ongoing effort to investigate individual *Stardust* cometary samples with multiple techniques, mainly time-of-flight secondary ion mass spectrometry (TOF-SIMS) and transmission electron microscopy (TEM). Here, TOF-SIMS results are presented for two terminal particles extracted from aerogel. TEM results are summarized in [8].

Samples: Microtome sections of two terminal particles from Tracks 32 and 69 from aerogel cell C2027 were selected (Fig. 1). The tracks are only ~2.5 mm apart from each other. Both are bifurcated or split tracks with several terminal particles each. After extracting the cometary particles from the aerogel, they were embedded in cyanoacrylate and ultramicrotomed. After slicing, sections were placed on Cu grids with a film of amorphous carbon. Section #20 from grid C2027,3,32,2,6 and section #25 from grid C2027,2,69,2,5 were investigated in this study.

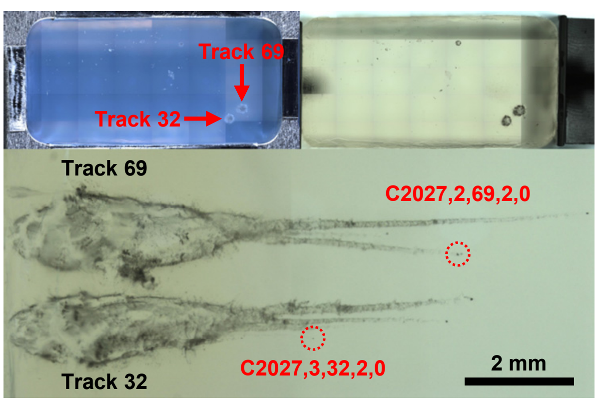

Fig. 1. Stardust cometary aerogel cell C2027 (top left: reflected light; top right and bottom: transmitted light) with two large impacts, Tracks 32 and 69. The particles investigated, C2027,3,32,2,0 and C2027,2,69,2,0, are both terminal particles.

Experimental Procedures: Each sample was sputter-cleaned by Ar^+ ion bombardment prior to the TOF-SIMS analyses. During the measurements, the particle sections were raster-scanned for ~12 hours with an intermittent Ga^+ primary ion beam with a beam diameter of ~0.3 µm, a pulse length of ~1.5 ns, and a repetition rate of 10 kHz. Both polarities were analyzed in two consecutive measurements. Further details on the TOF-SIMS technique are given in [9].

Results: Imaging TOF-SIMS results are summarized in Figs. 2 and 3. Element ratios normalized to Mg are given in Table 1. Contrary to previously analyzed Wild 2 samples that showed a rather heterogeneous chemical composition [7], both particles in this study are dominated by Mg-rich silicates. Only C2027,2,69,2,5 #25 showed a distinct region that is enriched mainly in Ca and Al. Element ratios for both regions, Mg-rich and Ca,Al-rich, are given separately in Table 1. For comparison, bulk CI chonditic element ratios are also given. CI composition is used here as an approximation for solar system abundances [10]. This does not imply that Wild 2 dust is expected to be mineralogically similar to CI chondrites. However, previous results [5–7] seem to suggest that the bulk composition of Wild 2 is similar to CI.

Table 1. Atomic element ratios relative to Mg=100[a]

Element	CI[b]	C2027,3,32,2,6 #20	C2027,2,69,2,5 #25	
			Mg-rich	Ca,Al-rich
Li	0.0053	0.0122(5)	0.0111(5)	0.009(3)
O	710	460(10)	450(10)	1400(100)
Na	5.34	0.408(2)	13.48(1)	49.5(1)
Mg	100	100.0(1)	100.0(1)	100.0(4)
Al	7.91	2.76(6)	3.17(7)	41.6(2)
Si	93.1	121.2(2)	103.4(2)	471(2)
K	0.351	0.0252(5)	0.188(1)	0.45(1)
Ca	5.69	2.07(1)	1.93(1)	20.2(1)
Sc	0.0032	0.0032(4)	0.0015(3)	0.004(3)
Ti	0.223	0.119(7)	0.103(6)	0.45(7)
V	0.0273	0.017(1)	0.0150(9)	0.022(7)
Cr	1.26	1.71(1)	1.49(1)	1.97(7)
Mn	0.889	0.792(7)	0.750(7)	1.22(5)
Fe	83.8	4.69(3)	3.57(3)	4.5(1)
Co	0.209	0.055(3)	0.017(2)	0.01(1)
Ni	4.59	0.05(2)	0.01(2)	0.04(4)

[a]Errors are 1σ, given as last significant digit in parentheses
[b]According to [10]

While previous studies show that Si dominates the Wild 2 fragments that were extracted from aerogel [7], both samples investigated in this study seem to be less affected by residual aerogel. While extremely high Si/Mg-ratios between 20 and 70 were observed previously [7], C2027,3,32,2,6 #20 and the Mg-rich region of C2027,2,69,2,5 #25 yield Si/Mg-ratios of 1.2

and 1.0, respectively. Only the Ca,Al-rich region of the second particle shows some residual aerogel, and a Si/Mg-ratio of 4.7.

C2027,3,32,2,6 #20 exhibited a rather homogeneous composition (Fig. 2) that is consistent with Mg-rich pyroxene (En_{95} and Fs_4). Some local concentrations of Na, correlated with K, and Fe were also observed (Fig. 2).

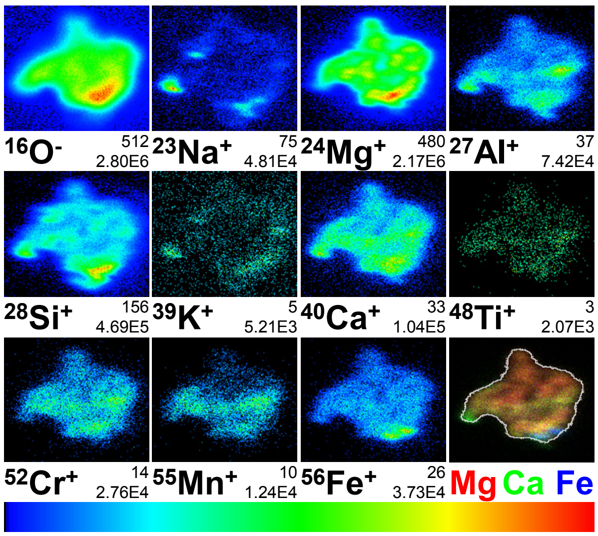

Fig. 2. TOF-SIMS secondary ion images for sample C2027,3,32,2,6 #20. The field of view is 15×13 µm^2 (179×155 pixels). All individual ion images use the linear color scale shown, where black corresponds to zero counts and red is used for the maximum intensity given below every image. The other number underneath each image is the integrated intensity of the entire field of view. A three color composite image is shown in the lower right, where red, green, and blue are assigned to the normalized intensities of Mg, Ca, and Fe, respectively. The white line marks the region of interest used to determine element ratios (Table 1).

C2027,2,69,2,0 #25 consists of two distinct regions (Fig. 3). One is clearly dominated by Mg and the element ratios observed are consistent with Mg-rich pyroxene (En_{96} and Fs_3). The Ca,Al-rich area in Fig 3, however, is different. This region, 5×3 µm^2 in size, shows a high Mg concentration (Table 1) that is consistent with approximately 22 mole-% of pyroxene of the same composition as the rest of the particle. However, the Ca and Al contents may be attributable to anorthite. This would account for 9 mole-% of that region, and the rest (69 mole-%) could represent SiO_2, most likely from the aerogel.

Discussion: Although all mineral identifications in this study are tentative since they are based only on element ratios, it is obvious that both terminal particles are much less intermingled with residual aerogel than samples analyzed previously [7]. This might in part be due to the fact that more compact, monomineralic grains have a higher tendency to survive as terminal particles while heterogeneous, more friable parts of the impacting cometary particles were already stopped along the track where they intermingled with aerogel. This, however, can only in part explain the observations, since some of the terminal particles previously studied also had high Si contents [7].

The observation of Ca,Al-rich minerals as in previous studies [4, 6] might still be surprising for cometary material overall, but seem to be consistent throughout the *Stardust* collection of Wild 2 particles.

Conclusions: The observations strongly suggest that more compact single mineral grains tend to survive the impact into aerogel as terminal particles while the more friable, fine-grained material is often stopped along the tracks. Therefore, all material that is distributed along a track needs to be analyzed to obtain a comprehensive picture of the impacting cometary particle and of Wild 2 matter in general.

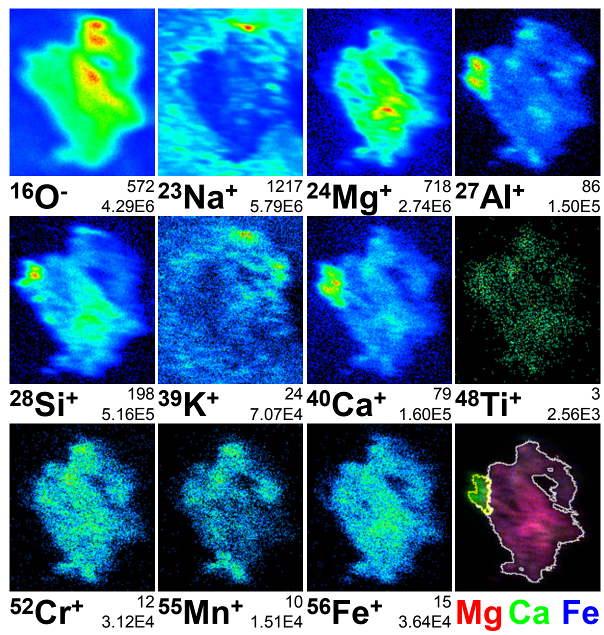

Fig. 3. TOF-SIMS secondary ion images for sample C2027,2,69,2,5 #25. The field of view is 20×23 µm^2 (164×189 pixels). The white and yellow lines in the Mg-Ca-Fe composite image mark the Mg-rich and Ca,Al-rich areas, respectively.

Acknowledgements: This work is supported through grants by NASA (NNX07AL94G) and by the *Deutsche Forschungsgemeinschaft* (STE 576/17-2).

References: [1] Brownlee D. E. et al. (2003) *JGR, 108,* E8111. [2] Tsou P. et al. (2003) *JGR, 108,* E8113. [3] Brownlee D. et al. (2006) *Science, 314,* 1711–1716. [4] Zolensky M. E. et al. (2006) *Science, 314,* 1735–1739. [5] Flynn G. J. et al. (2006) *Science, 314,* 1731–1735. [6] Stephan T. (2007) *Space Sci. Rev.,* DOI 10.1007/s11214-007-9291-2. [7] Stephan T. et al. (2008) *Meteoritics & Planet. Sci.,* in press. [8] van der Bogert C. H. and Stephan T. (2008) *LPS XXXIX,* this conference. [9] Stephan T. (2001) *Planet. Space Sci., 49,* 859–906. [10] Anders E. and Grevesse N. (1989) *GCA, 53,* 197–214.