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Physical, Chemical, and Mineralogical Properties of Comet 81P/Wild 2 Particles Collected by Stardust

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Abstract NASA's Stardust spacecraft collected dust from the coma of Comet 81P/Wild 2 by impact into aerogel capture cells or into Al-foils. The first direct, laboratory measurement of the physical, chemical, and mineralogical properties of cometary dust grains ranging from $<10^{-15}$ to $\sim 10^{-4}$ g were made on this dust. Deposition of material along the entry tracks in aerogel and the presence of compound craters in the Al-foils both indicate that many of the Wild 2 particles in the size range sampled by Stardust are weakly bound aggregates of a diverse range of minerals. Mineralogical characterization of fragments extracted from tracks indicates that most tracks were dominated by olivine, low-Ca pyroxene, or Fe-sulfides, although one track was dominated by refractory minerals similar to Ca–Al inclusions in primitive meteorites. Minor mineral phases, including Cu–Fe-sulfide, Fe–Zn-sulfide, carbonate and metal oxides, were found along some tracks. The high degree of variability of the element/Fe ratios for S, Ca, Ti, Cr, Mn, Ni, Cu, Zn, and Ga among the 23 tracks from aerogel capture cells analyzed during Stardust Preliminary Examination is consistent with the mineralogical variability. This indicates Wild 2 particles have widely varying compositions at the largest size analyzed (>10 µm). Because Stardust collected particles from several jets, sampling material from different regions of the interior of Wild 2, these particles are expected to be representative of the non-volatile component of the comet over the size range sampled. Thus, the stream of particles associated with Comet Wild 2 contains individual grains of diverse elemental and mineralogical compositions, some rich in Fe and S, some in Mg, and others in Ca and Al. The mean refractory element abundance pattern in the Wild 2 particles that were examined is consistent with the CI meteorite pattern for Mg, Si, Cr, Fe, and Ni to 35%, and for Ca, Ti and Mn to 60%, but S/Si and Fe/Si both show a statistically significant depletion from the CI values and the moderately volatile elements Cu, Zn, Ga are enriched relative to CI. This elemental abundance pattern is similar to that in anhydrous, porous interplanetary dust particles (IDPs), suggesting that, if Wild 2 dust preserves the original composition of the Solar Nebula, the anhydrous, porous IDPs, not the CI meteorites, may best reflect the Solar

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Nebula abundances. This might be tested by elemental composition measurements on cometary meteors.

Keywords CI meteorites · Wild 2 · Comets · Interplanetary dust particles · IDPs · Solar Nebula · Meteor streams

1 Introduction

Particles emitted by comets are believed to be the same dust that accreted, along with ices, as the Solar System was forming, ~4.57 billion years ago. This dust has been held in "cold storage," experiencing minimal thermal or aqueous processing, in the comets since their formation. Thus, comets are generally thought to have preserved a record of the processes and conditions in the Solar Nebula at the time of Solar System formation. This record is not available in bodies such as meteorites that experienced significant aqueous or thermal metamorphism since their formation. Thus the detailed characterization of cometary dust can contribute to the understanding of the processes and conditions in the Solar Nebula at the time of dust formation (Rietmeijer 2005).

In 1986 two VEGA spacecraft and the Giotto spacecraft flew through the dust coma of Comet 1P/Halley. Instruments on these spacecraft provided information on the size-frequency distribution and elemental composition of small particles, generally from 5×10^{-12} to 5×10^{-17} g. The elemental composition of an estimated 0.5 ng of material was determined by the VEGA instruments (Fomenkova et al. 1992). The properties of the grains analyzed at comet Halley are summarized by Jessberger et al. (1988), Mukhin et al. (1991), and Schulze et al. (1997).

NASA's Stardust spacecraft flew through the dust coma of Comet 81P/Wild 2 on January 2, 2004, collecting samples of Wild 2 dust by impact at ~6.1 km/s into low-density silica aerogel that was specially fabricated for the mission and into Al-foil (Tsou et al. 2004; Brownlee et al. 2006). About 3×10^{-4} g of Wild 2 material is estimated to have impacted the Stardust collector during the encounter (Hörz et al. 2006). These Wild 2 samples were delivered to Earth on January 15, 2006.

A small fraction of the Wild 2 samples collected by Stardust were studied during the Preliminary Examination. Results were reported by six teams of investigators who focused on craters (Hörz et al. 2006), organics (Sandford et al. 2006), isotopes (McKeegan et al. 2006), infrared spectroscopy (Keller et al. 2006), elemental composition (Flynn et al. 2006), and mineralogy/petrology (Zolensky et al. 2006). Rietmeijer (2008) has compared results obtained on the Wild 2 particles with the results obtained on meteors.

The dust trail from Wild 2 does not intercept the Earth, so Wild 2 does not produce a meteor stream in the Earth's atmosphere. Nonetheless, the physical, mineralogical, and chemical properties of the Wild 2 particles collected by the Stardust spacecraft should provide indications of the properties of the particles in meteor streams from other comets. Conversely, the analysis of cometary meteors can indicate if the properties of Wild 2 particles are typical for cometary material, and can resolve some of the questions raised by the Wild 2 analyses.

2 Wild 2 Particles Collected by Stardust

Long-exposure images taken by the Stardust spacecraft during the encounter (Fig. 1) show that Wild 2 is an active comet, with at least 20 areas on the surface emitting highly

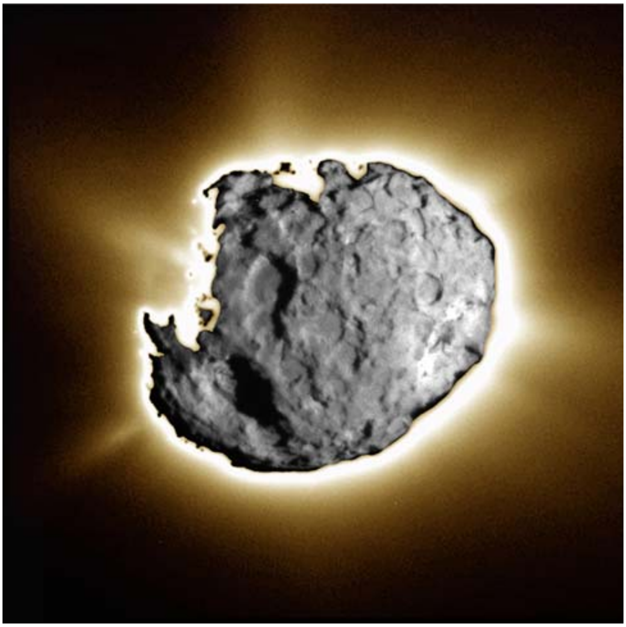

Fig. 1 Composite image of Wild 2, with a short exposure showing the surface detail overlain on a long exposure taken just 10 s later showing the jets taken during the close-approach phase of Stardust's January 2, 2004 flyby (NASA photo)

collimated jets of gas and dust (Brownlee et al. 2004). These jets are believed to originate in pockets of gas and dust in the interior of the comet. The Dust Flux Monitor Instrument, an active dust counter carried on Stardust, indicated that the spacecraft passed through several intense swarms of particles (Tuzzolino et al. 2004), some of which Sekanina et al. (2004) associated with specific jets seen in the images. These results indicate that Wild 2 particles collected in the aerogel and Al-foil flown on Stardust spacecraft sample several different source regions in the interior of the comet. Thus, the collected particles are believed to be representative of the non-volatile component of Wild 2 over the size range that was sampled during the encounter.

During the Preliminary Examination, the Elemental Composition team mapped the distributions of several major and minor elements, including S, Ca, Ti, Cr, Mn, Fe, Ni, Cu, Zn, and Ga along 23 tracks from the Stardust aerogel capture cells using Synchrotron X-Ray Microprobes (SXRMs) and determined the elemental compositions of residues deposited in 7 craters in Stardust Al-foils using Energy Dispersive X-ray Analysis in Scanning Electron Microscopes and Time of Flight-Secondary Ion Mass Spectrometry. The procedures and results are described in detail by Flynn et al. (2006). The Mineralogy/Petrology team determined the mineralogies of fragments extracted from 52 tracks from the Stardust aerogel capture cells using Synchrotron X-Ray Diffraction, Transmission Electron Microscopy, and X-Ray Absorption Near-Edge Structure spectroscopy, described by Zolensky et al. (2006). The Cratering team inferred the mineralogies of particles in craters based on residue compositions, described by Hörz et al. (2006). Although only a small fraction of the total collected mass of Wild 2 material was characterized during the Preliminary Examination, important insights into the physical, chemical, and mineralogical properties of Wild 2 particles were obtained.

3 Particle Sizes

The Stardust aerogel capture cells have a total collection area of 1,039 cm^2 and the Al-foils have a total collection area of 152 cm^2 (Hörz et al. 2006). Particles striking the foils produced elongated cavities called "tracks" as they decelerated in the aerogel. Particles impacting onto the Al-foil produced craters, many of which contained residue from the impactor.

The 6.1 km/s collection velocity can be duplicated in laboratory light-gas guns. A variety of projectiles were shot into Stardust flight-spare aerogel to determine the relationship between track dimensions in the aerogel and incident particle masses and into Al-foil to determine the relationship between crater dimensions and incident particle masses. These calibration experiments indicate that the smallest craters in the Stardust Al-foils were produced by Wild 2 particles having masses less than 10^{-15} g, while the largest track observed in the Stardust aerogel corresponds to an incident particle having a mass of $\sim 10^{-4}$ g (Hörz et al. 2006).

The mass–frequency distribution of the particles that impacted the Stardust collectors, derived from the plot of the cumulative mass–frequency distribution given by Hörz et al. (2006), is shown in Fig. 2. The Wild 2 coma, as sampled by the Stardust spacecraft, is dominated by the largest particles that were collected ($>10^{-5}$ g), and most of the mass collected by Stardust at Wild 2 was in a few particles, each >100 µm in size (Hörz et al. 2006). A similar mass–frequency distribution was reported for particles impacting the Long Duration Exposure Facility (LDEF) (Love and Brownlee 1993). For LDEF impacts, the mass flux increased from the smallest mass measured (10^{-9} g) up to a particle mass of $\sim 10^{-5}$ g then decreased for the largest mass they observed, $\sim 10^{-4}$ g (Love and Brownlee 1993).

4 Physical Properties

Control experiments demonstrate that if a single crystalline grain larger than a few micrometers in size is captured in aerogel at ~6 km/s, the resulting damage track is conical, with most of the mass of the incident particle remaining as a single, relatively unaltered particle at the end of the track. The SXRM mapping of the Wild 2 tracks extracted from Stardust aerogel capture cells showed that most of the 23 tracks mapped

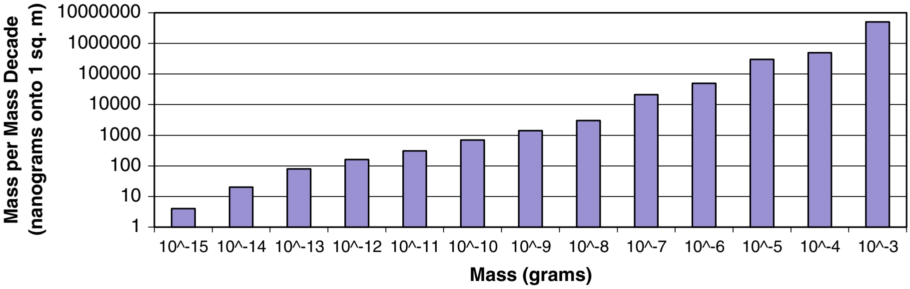

Fig. 2 The mass per mass decade incident on the Stardust collector, scaled to a 1 m^2 area, derived from Fig. 4 of Hörz et al. (2006). The sharp increase in the mass contributed by the largest particles indicates that the five particles >100 µm contain most of the mass colleted at Wild 2, and that, unless they have exceptional compositions, the smallest particles cannot significantly perturb the mean composition

during the Preliminary Examination have large amounts of material distributed along the walls of the track. Some of the tracks have large bulbs, which may result from severe fragmentation and deceleration of many tiny fragments that separated from the incident particle immediately after penetration of the aerogel (Trigo-Rodríguez 2008), with multiple tracks emerging from the bottom of the bulb.

As a result of fragmentation, a single particle incident on the aerogel frequently resulted in a multitude of fragments distributed along the damage track. The nomenclature convention established during the Stardust Preliminary Examination uses "particle" to denote the entire object that hit the collector and "fragment" to denote pieces of that object distributed along the track or in the crater. The one exception is that the phrase "terminal particle" is used to denote the fragment at the end of the longest section of the track.

Figure 3 shows one example of the Fe distribution along a conical Wild 2 track, determined by SXRM mapping. Similar measurements on other Wild 2 tracks indicate that the Fe mass of the terminal particle varies from a high of 80% of the total Fe detected in the map of the entire volume of the track to 0% of the total for two tracks that had no detectable terminal particles (Flynn et al. 2006).

The material distributed along the track walls varied dramatically in composition from one spot to the next, demonstrating that the incident particle was weak enough to break up during capture, and consisted of discrete grains of diverse composition and mineralogy. Extraction of fragments from the aerogel demonstrates that Wild 2 also contains discrete mineral grains, mainly olivine, pyroxene, and Fe-sulfide, some of which exceed 10 μm in size. One track contained fragments similar to the Ca–Al-rich inclusions found in CV carbonaceous chondrites (e.g., Allende).

Many of the craters have "compound structures," characterized by irregular outlines and overlapping depressions, which result from impactors with heterogeneous mass distributions (Hörz et al. 2006). Composition measurements on the residue in craters

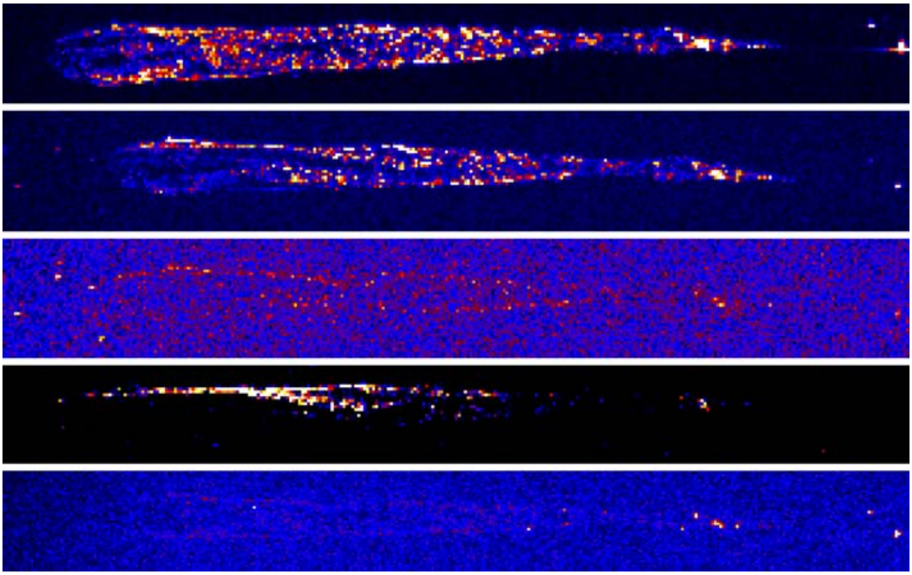

Fig. 3 X-ray fluorescence intensity maps of Fe (top), Ni, Cu, Zn, and Cr (bottom) along Wild 2 Track 19, an ~860 μm long track produced by an ~3 μm incident particle

indicates that poly-mineralic impactors dominate over mono-mineralic impactors even down to the smallest craters, less than 100 nm in size (Hörz et al. 2006). However, bowl-shaped craters, consistent with a single, homogeneous impactor are also seen on the Stardust Al-foils.

Both the crater and track morphologies indicate that many of the Wild 2 grains collected by the Stardust spacecraft are weakly bound aggregates of fine-grained, sub-micron material and larger crystalline grains, some larger than 10 µm. Because the Stardust aerogel capture cells are composed of amorphous silica, the amorphous silica content of the incident particles was not determined during the Preliminary Examination, although careful petrographic and compositional analysis may allow cometary glass to be distinguished from melted aerogel in future work.

5 Heterogeneity of the Wild 2 Samples

Because individual minerals differ significantly in elemental composition, compositional heterogeneity can be used as an indicator of the size-scale of the individual mineral grains of a sample. Maps showing the distributions several major and minor elements along tracks in the aerogel were obtained during the Preliminary Examination (Flynn et al. 2006).

One example of these analysis, for Wild 2 Track 19, a cone-shaped track having a length of 860 µm that was produced by an incident particle of ~2–3 µm in size, is shown in Fig. 3. The Fe distribution map for Track 19 indicates that Fe was deposited along the wall of the entry track as well as in the terminal particle. Nickel and Cu show a similar distribution. But, Zn was deposited along only part of the track wall, suggesting that one side of the initial particle hosted a Zn-rich phase that abraded or vaporized as the particle decelerated in the aerogel. The terminal particle has a very low Zn content. Chromium is localized in a few discrete fragments along the track.

The 20 most intense Fe spots found in the Track 19 map were analyzed individually, for longer times, to obtain high-quality X-ray fluorescence spectra. Because the elemental composition of the CI carbonaceous chondrite meteorites is believed to represent the bulk composition of the Solar System (Anders and Grevesse 1989), the Wild 2 composition results are compared to the CI composition. The CI- and Fe-normalized S, Ca, Cr, Mn, Ni, Cu, Zn, Ga and Ge abundances for these fragments, shown in Fig. 4, demonstrate that these 20 fragments from a single Wild 2 particle exhibit element/Fe ratios that differ from one another by 2 orders-of-magnitude or more. This indicates that the incident particle deposited material of diverse compositions, presumably representing a diversity of minerals, along the track.

The Mineralogy/Petrology team extracted Wild 2 material, sometimes consisting of mixtures of grains and compacted or melted aerogel, from 52 tracks, some of which were tracks previously mapped by the Elemental Composition team. They studied in detail 26 tracks that were chosen at random from those of average length. Eight of these tracks were dominated by olivine, 7 by low-Ca pyroxene, 3 by roughly equal amounts of olivine and pyroxene, 5 by Fe-sulfides, one by Na-silicate minerals, and one by refractory minerals similar to Ca–Al inclusions in primitive meteorites like the Allende CV3 carbonaceous chondrite (Zolensky et al. 2006). They found crystalline grains distributed along the length of the track, not just in the terminal particles. Many tracks contained minor mineral phases as well, including Cu–Fe-sulfide, Fe–Zn-sulfide, and possible K-feldspars (Zolensky et al. 2006), consistent with the high degree of elemental heterogeneity mapped along some tracks.

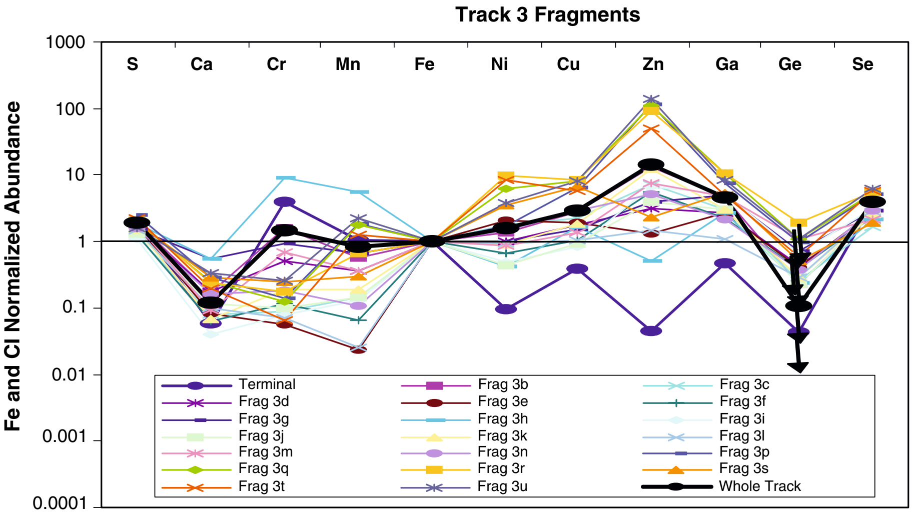

Fig. 4 CI normalized element/Fe ratios for 20 spots along Wild 2 Track 19, an 860 μm long, probably the result of capture of an initial ~2–3 μm particle. The element distribution along this track is extremely heterogeneous, with the 20 spot analyses showing variations of 2 orders-of-magnitude or more for most of the element/Fe ratios. This indicates that Wild 2 dust includes a significant fine-grained component. The elemental composition of the terminal particle (blue line) differs significantly from the average composition of this whole track (black line) with the low content of Ni and the moderately volatile elements in the terminal particle suggesting it is an anhydrous silicate

Even more striking is the difference in elemental composition from track to track, shown in Fig. 5. Only Fe or Fe and Ni were detected in two of the 23 tracks examined during the Stardust Preliminary Examination. But S, Ca, Cr, Mn, Fe, Ni, Cu, Zn, and Ga abundances were obtained on most of the remaining 21 tracks. Figure 4 shows the diversity in compositions for these elements in the 21 whole tracks examined during Preliminary Examination. Many elements show three or four order-of-magnitude variation in element/Fe ratios from one track to another. Even among the 6 largest particles, all estimated to be >10 μm in size based on their measured Fe contents, the element/Fe ratios show order-of-magnitude variations for all of the elements measured (Fig. 4). This indicates particles from Wild 2 are elementally heterogeneous at the largest size scale measured (>10 μm). Nonetheless, crater composition measurements indicate that composite particles dominate at the smallest size (~100 nm) (Horz et al. 2006). Thus, Wild 2 contains much sub-micron material along with larger mineral grains, >10 μm (Zolensky et al. 2006).

Most striking is the difference between the elemental composition of the material distributed along the whole volume of the track including the terminal particle and the composition of just the terminal particle (Fig. 4). Most of the 21 tracks that had detectable terminal particles show differences of an order-of-magnitude or more for several of the element/Fe ratios between the whole track and the terminal particle. The terminal particle frequently has a significantly lower Ni/Fe ratio than the whole track, consistent with observations by the Mineralogy/Petrology Preliminary Examination team that the terminal particles are frequently anhydrous silicates (olivine or pyroxene), which usually have low Ni/Fe. Much of the finer-grained material deposited along the track has a composition closer to the CI composition, suggesting that Wild 2 particles in the size range examined consist of large mineral grains embedded in a fine-grained matrix.

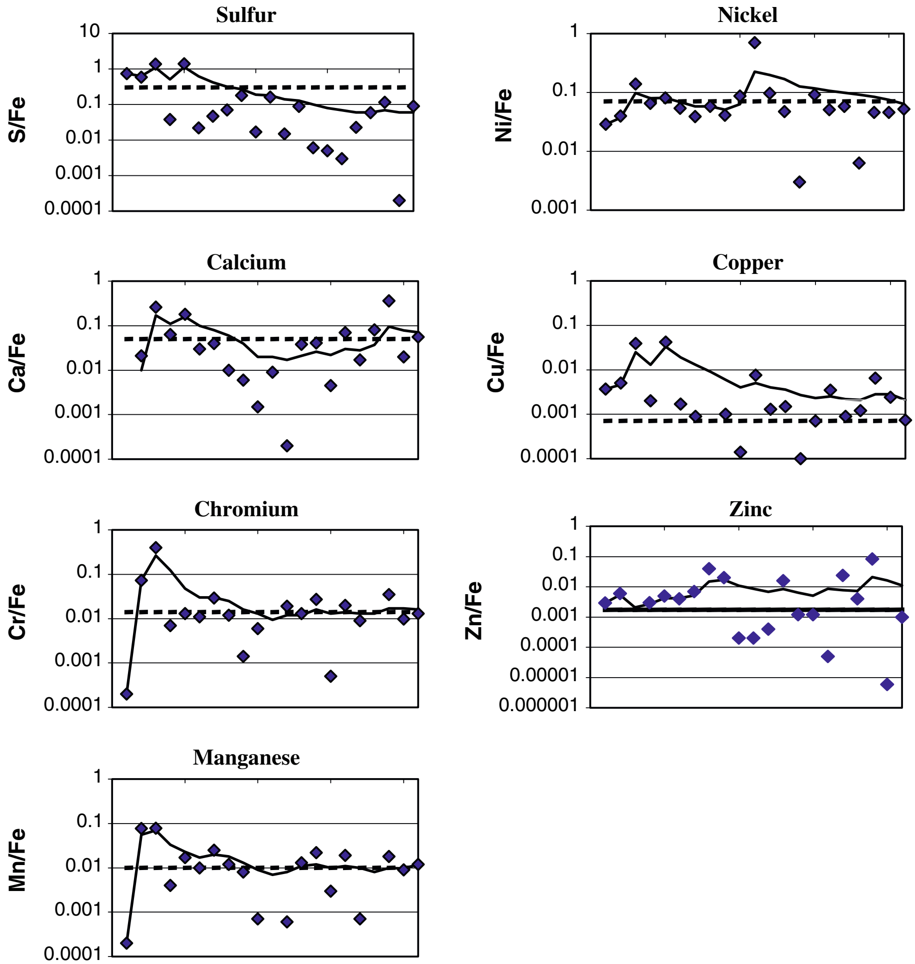

Fig. 5 Each plot shows the whole track element/Fe ratio (symbols) and the Cumulative Element/Fe ratio—the sum of the Element ratio to the Sum of the Fe for all particles up to that Fe-mass (solid line), with increasing Fe mass to the right. The CI Composition (Lodders 2003) is shown by the dashed line. Scatter in the whole track element/Fe ratios provides insight into the size of the largest minerals analyzed Good convergence in the Cumulative Element/Fe ratio suggests enough tracks were examined to provide a valid mean composition

6 Mean Elemental Composition of the Wild 2 Particles

The Si and O contained in particles that produced tracks in the aerogel could not be assessed during the Preliminary Examination because these analyses were performed on whole tracks in keystones of aerogel (described by Westphal et al. 2004) and Si and O are major elements in the aerogel. The aerogel also contains trace quantities of many other elements (Tsou et al. 2004) and these elements are frequently distributed inhomogeneously (Flynn et al. 2006), precluding quantitative background subtraction. Magnesium and Al could not be quantitatively determined for particles captured in the aerogel because the thickness and density of the overlying aerogel was not known sufficiently well to allow correction for the absorption of the low-energy fluorescence X-rays from Mg and Al. Quantitative analysis of S in tracks is difficult because the S fluorescence X-rays can experience significant attenuation by the aerogel. For elements heavier than Ca these absorption corrections are small enough that the uncertainty in thickness is only a minor effect.

The Wild 2 particles may show compositional variation with size, with FeS particles being prominent in the smaller craters (Hörz et al. 2006), but a lower fraction of the tracks were dominated by FeS (Flynn et al. 2006). Compositional variation was also seen in the particles analyzed at Comet Halley, with many of the smallest grains being Mg-rich and Si-poor, while the larger grains have a CI-like Mg/Si ratio (Mukhin et al. 1991). Because the composition varies with particle size, it is necessary to mass-weight the grains in determining the bulk composition. If all particles were given an equal weight in the average, the contribution from the smaller particles would be overestimated (Fomenkova et al. 1992). The "whole track" content of S, Ca, Ti, Cr, Mn, Fe, Ni, Cu, Zn, and Ga was determined by summing the mass of that element detected in each of the 23 Wild 2 tracks analyzed during the Preliminary Examination (see Flynn et al. 2006), a process that mass-weights the average.

Although minerals may be altered during aerogel capture, only the most volatile elements are likely to be redistributed far from the track. Track associated organic matter was detected as far as several track diameters from the track, demonstrating redistribution of a volatile organic species (Sandford et al. 2006). Thus, the whole track elemental composition is the elemental composition of the incident particle, except possibly for the most volatile elements (e.g., S).

The mean composition of the 23 tracks analyzed during the Preliminary Examination is quite well-determined. However, the large, non-normal distribution of element abundances in the 23 whole track compositions, shown in Fig. 5, made the assessment in the uncertainty of the bulk composition difficult. This dispersion in compositions dominated over the analytical uncertainties in determining the uncertainty in the mean composition of Wild 2 particles in the range of sizes that was analyzed (Flynn et al. 2006). To assess the uncertainty in the mean composition a statistical approach was adopted during the Preliminary Examination (see Flynn et al. 2006). If the 23 tracks studied by the Elemental Composition Preliminary Examination team are a random sample of Wild 2 particles in the size range studied, then the 1σ uncertainty range given for each element/Fe ratio, given in Table 1 as the mean composition + or − the modeled 1σ variation, is expected to reflect the range of mean compositions of sets of 23 other randomly selected Wild 2 particles in the same size range 68% of the time. The modeled 2σ uncertainty ranges, corresponding to the 95% confidence interval for the mean composition, are shown in Figs. 3 and 4 of Flynn et al. (2006).

Impact residue, which is abundant in all large craters in the Stardust Al-foils that were examined during Preliminary Examination, provides chemical composition data complementary to that obtained on the tracks and allows direct measurement of element to Si ratios. The elemental composition of the residue in 7 craters in the Al-foils was measured by SEM-EDX, and five of these craters were also measured by ToF-SIMS. Aluminum could not be determined for the crater residue because of the fluorescence from the underlying Al-foil, and the presence of minor quantities of other elements in the Al-foil compromised their detection in the residues. Table 1 shows the mean contents of elements detected in residue of 5 or more craters. The 1σ uncertainty was determined by the same technique as for the tracks, although the validity of this statistical technique for such a small data set is less certain.

Table 1 Mean CI-Normalized Composition of Wild 2 Particles

Element/Fe	Mean of 23 whole tracks (1σ uncertainty range)	Mean of 7 crater residues (1σ uncertainty range)	Rescaled 23 track mean (1σ uncertainty range)
Mg		1.13 (+0.22, −0.05)	
S	0.17 (+0.12, −0.06)	0.13 (+0.40, −0.06)	0.13 (+0.12, −0.06)
Ca	1.25 (+0.47, −0.43)	0.51 (+0.12, 0.05)	0.94 (+0.47, −0.43)
Ti	0.42 (+1.74, −0.23)		0.32 (+1.74, −0.23)
Cr	1.30 (+0.24, −0.31)	0.31 (+0.33, −0.04)	0.98 (+0.24, −0.31)
Mn	1.32 (+0.32, −0.37)		0.99 (+0.32, −0.37)
Fe	1[a]	0.75 (+0.05, −0.40)	0.75[b]
Ni	0.82 (+0.37, −0.24)		0.62 (+0.37, −0.24)
Cu	2.06 (+1.14, −0.89)		1.55 (+1.14, −0.89)
Zn	4.60 (+6.30, −3.10)		3.45 (+6.30, −3.10)
Ga	10.0 (+8.9, −7.5)		7.5 (+8.9, −7.5)

[a] Fe fixed at 1 × CI

[b] Fe adjusted to the value 0.75 × CI determined from crater analysis

Since Fe is the only major element easily quantifiable in the SXRM analysis of whole tracks in aerogel keystones, the 23 track mean composition was CI- and Fe-normalized in Table 1. However, Si was easily detected in the craters, and the Fe/Si ratio was measured to be ~0.75, although one large crater dominated the element abundance determination in crater residues (Flynn et al. 2006). To permit direct comparison of the mean compositions of the craters and the tracks, Table 1 also shows the track data rescaled to a CI-normalized Fe abundance of 0.75. With this rescaling, two of the three elements determined in both tracks and craters, S and Ca, have overlapping 1σ confidence ranges, but a discrepancy remains for Cr.

The similarity of the CI meteorite composition to the composition of the Solar photosphere for elements that are well-determined in the Solar photosphere led to the suggestion that the CI meteorite composition is the mean composition of the Solar System (Anders and Grevese 1989). The mean composition of the Wild 2 particles is consistent with the CI meteorite composition for the refractory elements Mg, Si, Cr, Ni, Ca, Ti and Mn, but both S and Fe appear to be depleted (at the 2σ confidence limit) compared to the CI composition and the moderately volatile elements, Cu, Zn, and Ga, are enriched relative to the CI composition. The ~10 μm size anhydrous, porous interplanetary dust particles (IDPs) (described in Bradley et al. (1988) and Rietmeijer (1998)) collected from the Earth's stratosphere, some of which have been suggested to be derived from comets based on atmospheric entry speeds inferred from heating during atmospheric deceleration (Brownlee et al. 1993), show an element abundance pattern similar to these Wild 2 grains. These anhydrous IDPs are generally chondritic, but both S (0.8 × CI) and Fe (0.78 × CI) are depleted from CI (Schramm et al. 1989) and the moderately volatile elements Cu, Zn, and Ga are enriched by factors of 2 or 3 compared to CI (Flynn et al. 1996).

7 Conclusions

The slope of the cumulative size frequency distribution of the particles in the Wild 2 coma is similar to that measured in the Halley coma, but the smallest particles (~10^{-15} g) seem to be less abundant in Wild 2 than in Halley (Hörz et al. 2006). The Wild 2 particles collected by the Stardust spacecraft were generally weakly bound aggregates of sub-micron grains and, frequently, larger individual mineral grains. The Preliminary Examination results demonstrate, for the first time by the direct sampling of a comet, that Wild 2 contains some mineral grains (olivine, pyroxene, and Fe-sulfide) >10 μm in size as well as assemblages of refractory minerals similar to the Ca–Al inclusions found in some primitive chondrites. Some of the anhydrous silicates are Mg-rich, Fe-poor minerals, while most of the sulfides are Fe-rich, and the Ca–Al material is Ca-rich but poor in Fe. Thus the stream of particles associated with Comet Wild 2 contains individual grains of diverse compositions, some that are rich in Fe and S, some rich in Mg, and others rich in Ca.

The Stardust Preliminary examination did not establish an upper limit on the grain size of individual minerals in Wild 2, since significant compositional heterogeneity was observed from one track to the next, up to the largest size studied (>10 μm). Examination of the largest Wild 2 particles collected by Stardust may establish this limit for Wild 2. The measurement of compositional heterogeneity as a function of size for the objects in the meteor streams associated with other comets could establish maximum grain size limits for the parent bodies of these meteor streams. Determining the maximum grain size in cometary bodies is critical in establishing the minimum sample size that it is desirable to collect on future comet sample-return missions.

The 23 tracks and 7 craters analyzed during the Preliminary Examination are estimated to have been produced by Wild 2 particles that had a total mass of about ~300 ng, about one-thousandth of the total mass collected by the Stardust spacecraft. The bulk refractory element abundance pattern in the Wild 2 particles is consistent with the CI meteorite pattern for Mg, Si, Cr, Fe, and Ni to 35%, and for Ca, Ti and Mn to 60%, but the Fe/Si shows a statistically significant depletion from the CI value (Flynn et al. 2006). The moderately volatile elements Cu, Zn, Ga, are enriched compared to CI, while S appears to be depleted from CI, although the effects of S mobilization during capture and the fluorescence absorption correction due to overlying aerogel are still being assessed (Flynn et al. 2006). Both the enrichment in moderately volatile elements and the depletion in S and Fe have previously been reported in the fine-grained, anhydrous IDPs (Flynn et al. 1996; Schramm et al. 1989), and an Fe depletion was reported from the Giotto analysis of dust from comet Halley (Jessberger et al. 1988). Elemental analysis of the larger particles that Stardust collected from the Wild 2 coma, which contain most of the collected mass, should significantly reduce the uncertainty in the mean composition.

The elemental composition determined from the Wild 2 samples is consistent with that obtained for Halley dust, but about two orders-of-magnitude more mass was analyzed during the Stardust Preliminary Examination than by the impact ionization mass spectrometers on the Giotto and VEGA spacecraft. The Stardust results extend the measurement of comet composition to include several moderately volatile minor elements. The major differences between the Wild 2 results and the CI meteorite composition are for elements whose abundances are not well-determined in the Solar photosphere (Anders and Grevesse 1989), suggesting that CI may not represent the mean Solar System composition (Flynn et al. 2006). Precise measurement of the abundances of elements that show differences between the CI meteorite composition and the Wild 2 or anhydrous IDP compositions, particularly S, Ca, Fe and moderately volatile minor elements, for other comets or for the particles in their meteor streams will aid in determining if the CI meteorite composition best represents the bulk composition of the Solar Nebula.

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