Fe-bearing Mineral Groupings in Stardust Fragments.

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Introduction

NASA's Stardust mission returned genuine samples from the coma of the Jupiter-family comet Wild2 to Earth in January 2006. Particles were captured in aerogel and foil at 6 km/s. The impacting cometary particles fragmented during capture in aerogel, dispersing material along carrot- or turnip- shaped tracks. If the impacting cometary particles were completely homogenous, one would expect the mineral compositions of all fragments in a given track to be identical. If the impacting particles were heterogenous but all the impactors were drawn from the same reservoir of material, one would expect to see particles consistent with a single parent population. As shown by previous work on the Stardust samples (e.g. [3]), the fragments found along the track show a range of mineral compositions. But does each track sample the same parent material, or is each track consistent with a unique reservoir? The answer reflects the heterogeneity scale of the Wild2 comet material, which may be different than other solar system material, such as the meteorites, due to Wild2's formation conditions in the Kuiper Belt.

Methods

We acquired Fe K-edge micro x-ray absorption near-edge structure spectroscopy (μXANES) on 193 fragments in 11 Stardust tracks using beamline 10.3.2 at Lawrence Berkeley Laboratory's Advanced Light Source [2]. The fragments were selected as the richest Fe-bearing spots in the track, and varied in size from a micron to several microns in diameter. Their Fe-bearing mineral compositions were determined by fitting the Fe μXANES data to a library of 51 Fe-bearing mineral standards from 20 mineral groups. Though degeneracies exist between minerals of the same group, mineral groups are identifiable with little ambiguity in the majority of cases [4]. Therefore, for each of the 193 fragments, we calculate the fraction of each Fe-bearing mineral group in that fragment.

Self-Organizing Map

To organize and visualize the 193 fragments in terms of their mineral constituents, we employ a self-organizing map (SOM) [1]. In an SOM, a two-dimensional map is trained using input data vectors (in this case, 193 vectors that each have 20 dimensions). Each position on the SOM, or node, is a vector of the same length as a data vector (20). The initialized, random map is then trained with the input data. For each of the 193 input vectors, the best-matching node is found, then that node as well as neighboring nodes are adjusted towards the input vector. This process is iterated until the SOM changes sufficiently little between iterations.

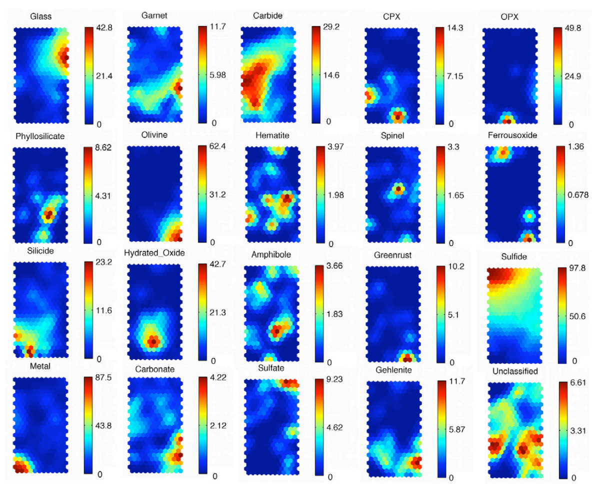

Figure 1: The 20 Fe-bearing mineral component classes of the self-organizing map of μXANES data for 194 Stardust fragments in 11 tracks.

The 20 mineral components of the self-organizing map of the Stardust μXANES data are shown in Figure 1. The SOM is separated into clusters (Figure 2) using the k-means algorithm, and the quality of the clustering is computed via the Davies-Bouldin index, which calculates the ratio of the within-cluster scatter to the between-cluster separation summed over all clusters. As shown in Figure 3, the Fe-bearing minerals cluster optimally into five groups.

The mineral group composition is calculated for each fragment and the average composition for the major components (>10%) of all the fragments for each cluster is determined, shown in Figure 4. The five clusters can be described as very metal-rich, very sulfide-rich, olivine-rich, sulfide-rich, and mixed with significant hydrated oxide (or other Fe^{3+} minerals, which our hydrated oxide standards are somewhat degenerate with) component.

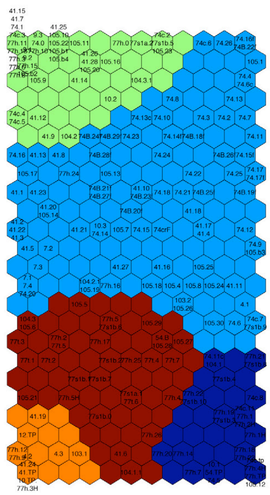

Figure 2: The five clusters of the SOM with individual fragment labels (track number (.) fragment number).

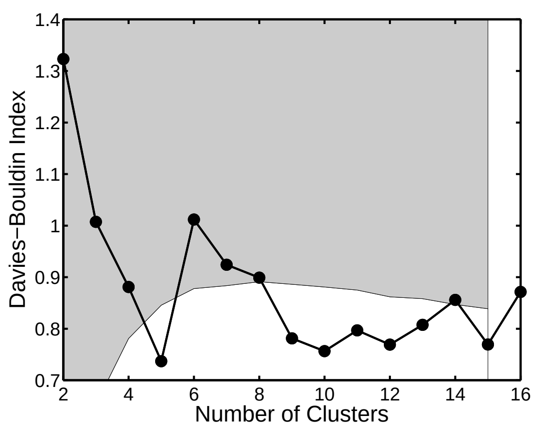

Figure 3: The Davies-Bouldin index (reflecting the quality of clustering) is plotted versus number of clusters in the SOM. The minimum (optimal clustering) occurs at five clusters. The grey area corresponds to the D-B index values from the Monte Carlo simulation (see text).

Conclusions

The 193 cometary fragments can be clustered by their Fe-bearing minerals into five populations. The 11 tracks are not distinct enough from each other to be grouped separately into 11 different populations of Fe-bearing minerals, nor are the fragments distinct enough from each other to be separated into dozens of groups.

To determine if this five-population SOM truly reflects the heterogeneity level of the comet on a few-micron level (the size of the particles we analyzed with μXANES) or if these groupings can result from a random distribution of Fe-bearing minerals, we perform a

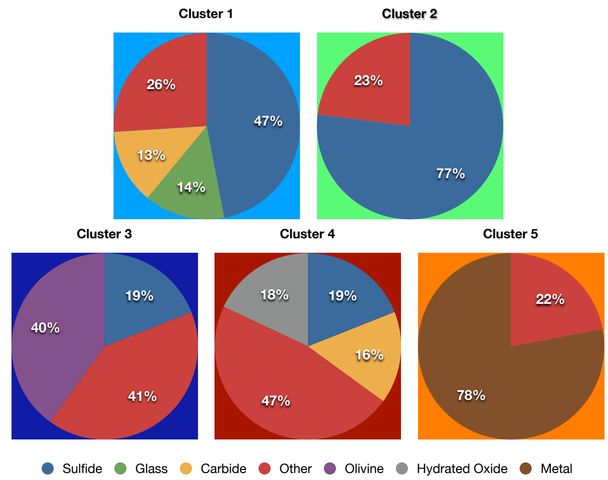

Figure 4: Pie charts of the Fe-bearing mineral composition for each cluster. The background color on each chart corresponds to the colors of the SOM clusters shown in Figure 2.

Monte Carlo simulation. We constrain the total distribution of 193 randomized fragments among the 20 mineral groups to be the same as the actual Wild2 data. For each randomized population of fragments, we calculate the SOM and Davies-Bouldin index to determine the optimal number of clusters. The D-B index values for two through fifteen clusters from 1000 simulations are shown as the grey area in Figure 3. Fewer than 1% of the simulations show nontrivial clustering (more than one group). These nontrivial randomized samples have optimally 10-15 clusters, all with a D-B index significantly higher than the optimal index at five clusters calculated from the Wild2 data. We conclude that the clustering of Fe-bearing minerals into five groups is unlikely to be the result of random chance.

Each of the 11 analyzed Stardust tracks, therefore, is not unique and completely distinct in terms of the Fe-bearing minerals (if this were true, we would see 11 clusters separated by track, instead of five). Nor are the fragments (on the few-micron scale) similar enough to each other to be thought of as drawn from the same parent reservoir. Instead, the few-micron Fe-bearing fragments seem to be of five different populations

References

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