

MIXING FRACTION OF INNER SOLAR-SYSTEM MATERIAL IN COMET 81P/WILD2. A. J. Westphal¹, S. Fakra², Z. Gainsforth¹, M. A. Marcus², R. C. Oglione¹, A. L. Butterworth¹, ¹Space Sciences Laboratory, U. C. Berkeley, USA, ²Advanced Light Source, Lawrence Berkeley Laboratory, USA .

Introduction: The presence of crystalline silicates in the comae of comets, inferred through infrared astronomical observations, has been a long-standing puzzle (e.g., [1]). Crystalline silicates are unexpected if comets are composed of pristine interstellar material, since interstellar silicates are almost entirely amorphous[2]. Heating to $> 1100\text{K}$ can anneal silicates to crystallinity, but no protoplanetary heating sources have been identified that were sufficiently strong to heat materials in the outer nebula to such high temperatures. This conundrum led to the suggestion that large-scale mixing was important in the protoplanetary disk[3]. Reports of refractory CAI-like objects[4] and large concentrations of noble gases in Stardust samples[5] underscore the need to assume such mixing. However, the evidence from the Stardust samples until now has been largely anecdotal, and it has not been possible to place quantitative constraints on the mixing fraction. Here we report synchrotron-based x-ray microprobe measurements of the relative concentrations of the chemical state of iron in material from a known comet, the Jupiter-family comet 81P/Wild2. Based on measurements of the fraction of iron in sulfides and in crystalline materials, we estimate the fraction ψ of inner nebular material in 81P/Wild2. This measurement constrains models of large-scale mixing in the early solar system.

Methods: We removed eleven cometary tracks from the Stardust cometary aerogel tiles in keystones[6]. We used a microfocused tunable hard x-ray beam on beamline 10.3.2 at the Advanced Light Source at Lawrence Berkeley National Laboratory to perform micro x-ray absorption measurements. We first performed micro-XRF Fe elemental mapping of the tracks in the keystone, using an incident energy of 10keV. We then analyzed Fe particles of interest using X-ray absorption near edge structure (XANES) spectroscopy. Here the absorption spectrum is measured in the region of the Fe K-edge at $\sim 7110\text{eV}$, with high photon statistics and energy resolution $\sim 1\text{eV}$. We then used an extensive library of standards (54 standards including metals, sulfides, and Fe^{2+} - and Fe^{3+} -bearing minerals and glasses) to fit the absorption spectra and to determine the relative fraction of metal, sulfide, and oxidized Fe in each particle. Although there is degeneracy among standards within a group (e.g., sulfides), identification of the mineral group is reliable, principally because of the systematic shift in position of the K-edge as a function of oxidation state[7]. Glass standards are also highly degenerate with each other and their spectra are distinct from crystalline materials[8]. We analyzed 194 particles in the eleven tracks. We combined the measurements, weighted by the magnitude of the edge jump, to determine the bulk composition of the comet. We determined confidence limits using the Monte Carlo bootstrap method. We describe in detail these methods in Westphal et al. [8].

Results:

We presented the measurement of the relative fractions of Fe in metal, sulfide and oxidized Fe at the 39th LPSC[9].

We reported that the oxidation state of Fe in 81P/Wild2 is not consistent with that of any major meteoritic family, and that fraction of Fe in sulfides is larger in Wild2 than in any meteorite group except Kakangari.

From the same analysis, we set a statistical lower limit on the fraction of Fe in sulfides ζ . Since sulfides may be systematically lost during hypervelocity capture in aerogel, and are unlikely to be synthesized, at least in a net sense, this statistical lower limit may be taken as an actual lower limit in the original cometary material. We find that $\zeta > 0.60 \times \text{CI}$ (2σ , one-sided c.l.).

We also set a lower limit on the crystalline fraction of Fe in silicates $\eta > 0.50$ (one-sided lower limit, 2σ). η is the number of Fe atoms in crystalline silicates divided by the number of Fe atoms in all silicates. Hypervelocity capture may also convert crystalline silicates into amorphous phases. The reverse process is unexpected because of the extremely short capture timescales. This expectation is borne out in the XANES measurements on laboratory shots[10] — here we saw no evidence of crystalline silicates in tracks or residues of captured hypervelocity glass with basalt composition. We are also unaware of any reports of crystalline silicate production in the literature on hypervelocity capture in aerogel. We thus treat the measurement of the crystalline silicate fraction as a lower limit on the actual abundance in the comet.

Discussion:

Using the upper limit on the crystalline fraction η and the lower limit on the sulfide fraction ζ we place constraints on the mixing fraction of inner solar-system material in 81P/Wild2. We consider the following two-component mixing model. We assume that the comet is composed of a fraction ψ of inner solar-system material, and a fraction $1-\psi$ of unaltered material inherited from the cold molecular cloud (CMC) from which the solar system formed. These two reservoirs had distinct crystalline silicate fractions and S/Fe ratios. We assume that the solar system inherited the S/Fe ratio of the CMC, so the CMC elemental S/Fe ratio was solar. The silicates in the CMC material were interstellar and so essentially entirely amorphous [2].

In considering the inner solar-system reservoir, by “inner solar-system” we mean that part of the solar system in which conditions are favorable for producing crystalline silicates. This could either be a hot region at early times at heliocentric distance $< 4\text{AU}$ with a temperature $> 1100\text{K}$ [11], or it could be a cooler region at later times at 2-10 AU in which interplanetary shocks periodically heat and vaporize dust, and also produce chondrules [12]. In this environment, we conservatively assume that all silicates rapidly become crystalline. We have abundant samples of inner solar-system material in the form of the chondritic meteorites; they are generally depleted by factors of 3-5 with respect to CI in the moderately volatile elements (MOVEs), including S. (The major exceptions are

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CI, EH and K.) Although the physical origin and timing of the MOVE depletion is uncertain, the depletion in S in inner solar system material appears to be an observational fact.

We now consider constraints that our measurements impose on the inner nebular mixing fraction ψ . First we consider the crystalline silicate fraction. Our analytical technique is only sensitive to Fe-bearing silicates. The fraction of Fe atoms residing in silicates in the inner nebula and CMC are x_{in} and x_{cmc} , respectively. Then the crystalline fraction η is given by

$$\eta = \frac{(1 - \psi)x_{CMC}\eta_{CMC} + \psi x_{in}\eta_{in}}{(1 - \psi)x_{CMC} + \psi x_{in}} \quad (1)$$

where we assume that $\eta_{CMC} = 0$ and $\eta_{in} = 1$. Defining $f \equiv x_{cmc}/x_{in}$, the inner nebula fraction ψ is related to η by

$$\psi = \frac{f}{1/\eta - 1 + f} \quad (2)$$

We consider only the lower limit on the measured crystalline fraction η because crystalline silicates may be destroyed during capture, and because melted and compressed aerogel with dissolved Fe may be indistinguishable from any possible cometary amorphous silicates. Our lower limit on the crystalline silicate fraction is $\eta > 0.50$ (one-sided lower limit, 2σ). If we assume that the average fraction of Fe atoms in silicates in the inner nebula and the CMC are the same, that is, $f = 1$, this gives

$$\psi > 0.50 \quad (3)$$

This result depends on the assumption that the formation of the majority of crystalline silicates predated or was concurrent with strong nebular mixing. Scott and Krot [13] have reported that the matrices of primitive chondrites contain abundant amorphous ferroan silicates, and have suggested that these are formed by irradiation or vaporization and rapid cooling, probably in shocks. The presence of amorphous ferroan silicates in the inner solar system (i.e., $\eta_{in} < 1$) would require stronger mixing, i.e., a larger value of ψ , still consistent with our lower limit.

Next we consider the constraint on ψ imposed by the measured elemental S/Fe ratio ζ . We found that $\zeta > 0.31$ (2σ , one-sided c.l.). We use the lower limit here because of the possibility of S loss during capture, and the possibility of S residing in non Fe-bearing phases to which we are not sensitive. From the values for the chondritic meteorites, we take the average atomic S/Fe ratio s'_{in} in inner solar-system material to be 0.18, or approximately $0.35 \times \text{CI}$. We define $g = y_{cmc}/y_{in}$, where y_{in} and y_{cmc} are the molar fraction of Fe atoms in material in the CMC and inner nebula, respectively. It is not clear how to calculate this precisely from the meteorite groups, since the weightings are largely unknown: we took an average value of 0.8 for the Fe/Si ratio of the inner solar system, so that $g = 1.25$. The atomic S/Fe ratio in the CMC $s'_{cmc} = 0.52$ is just the solar value. Then the mixing fraction is given by

$$\psi = \frac{g(s'_{cmc} - \zeta)}{\zeta(1 - g) - s'_{in} + gs'_{cmc}} \quad (4)$$

Because ψ is a decreasing function of ζ , our lower limit on ζ gives an upper limit on ψ , so we find that

$$\psi < 0.67 \quad (5)$$

In other words, a mixing fraction $\psi > 0.67$ would violate the measured lower limit on the S/Fe ratio in the comet sample. The Fe/Si ratio that we assumed, 0.8, is a conservative choice in the sense that it gives a comparatively large upper limit.

Subject to the assumptions discussed above, we can combine these two constraints to define a range of allowed inner nebula mixing fraction $\psi = 0.6 \pm 0.1$. This fraction of inner solar-system material in Wild2 implies that mixing was surprisingly efficient over large distances in the early solar nebula.

This measurement may be used to constrain parameter space in mixing models of the solar nebula that provide quantitative predictions. For example, Ciesla [14] has developed a two-dimensional model of an evolving turbulent disk. This model exhibits a net outward flow along the mid-plane of the disk that can drive inner nebular materials to large distances. His model is also quantitative, so can be compared with the measurement presented here. For example, the models presented in Figs. 3A, 3B and 3D of [14] are inconsistent with our measurement, while that in Fig. 3C is consistent with our crystallinity fraction but probably not with our upper limit on ψ based on the observed S/Fe ratio.

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