

CHRONOMETRY USING DIFFUSION IN PRESOLAR SILICATE GRAINS M. Bose^{1*}, C. Till¹, and C. Floss². ¹School of Earth and Space Exploration, Arizona State University, Tempe, AZ 85287-6004. ²Laboratory of Space Sciences, Physics Department, CB 1105, Washington University, 1 Brookings Drive, St. Louis, MO 63130-4899. (*Maitrayee.Bose@asu.edu; Center for Isotope Analysis)

Introduction: Presolar silicate grains are the most abundant of the presolar phases. Typically submicrometer in size, their myriad chemistries have informed us about complex conditions [e.g., 1, 2, 3, 4] in circumstellar environments and supernova ejecta. [2] reported on the ungrouped carbonaceous chondrite Adelaide, which shows a reduced abundance of O-anomalous grains, relative to other primitive carbonaceous chondrites. Many of the identified presolar silicate grains in Adelaide exhibit enhanced Fe contents, and Fe-rich rims. These features provide evidence towards large scale thermal annealing of the meteorites' fine-grained matrix, an event that was argued to have occurred in the solar nebula in regions with high dust/gas ratios [2].

The presolar silicate grains in Adelaide partially preserve the original O isotopic compositions of the stellar environments where they condensed, allowing us to identify them. Although silicate grains with Fe-rich compositions have been identified in other meteorites, such as the ungrouped carbonaceous chondrite Acfer 094 [e.g., 1], the Fe-rich rims observed in the silicate grains in Adelaide most likely formed by diffusion of Fe from the surrounding fine-grained matrix material into the presolar grain. This is viable because bulk analyses of the Adelaide matrix show that it is Fe-rich and crystalline in nature. Assuming that Mg and Fe were diffusing in a closed system, we did diffusion modeling to quantify the time-scales and temperatures at which the thermal event occurred. Here we report the results on two presolar silicate grains A5a-18o1 and A4b-7o1 from Adelaide. The results could provide a glimpse to the conditions that existed in the solar nebula, before the asteroids formed.

Samples & Analytical Methods: The presolar grains were identified by [2] using established NanoSIMS imaging protocols. Grain A5a-18o1 shows a $^{17}\text{O}/^{16}\text{O}$ ratio of $(6.8 \pm 0.2) \times 10^{-4}$ and an $^{18}\text{O}/^{16}\text{O}$ ratio of $(1.71 \pm 0.03) \times 10^{-3}$. Grain A4b-7o1 shows a $^{17}\text{O}/^{16}\text{O}$ ratio of $(4.8 \pm 0.2) \times 10^{-4}$ and an $^{18}\text{O}/^{16}\text{O}$ ratio of $(1.59 \pm 0.04) \times 10^{-3}$. Both A5a-18o1 and A4b-7o1 are Group 1 grains and most likely formed in the circumstellar disks of low-mass Red Giant stars. Elemental data using the Auger Nanoprobe show that grain A5a-18o1 is a silicate with a (Fe+Mg)/Si ratio of 3.1 ± 0.4 , a cation/O ratio of 1.3 ± 0.1 , and Mg# of 34. Grain A4b-7o1 is a Fe- and Al-bearing oxide grain with a cation/O ratio of 0.76 ± 0.1 , indicating that it may be a spinel-like grain. Figure 1 shows the two grains that were studied.

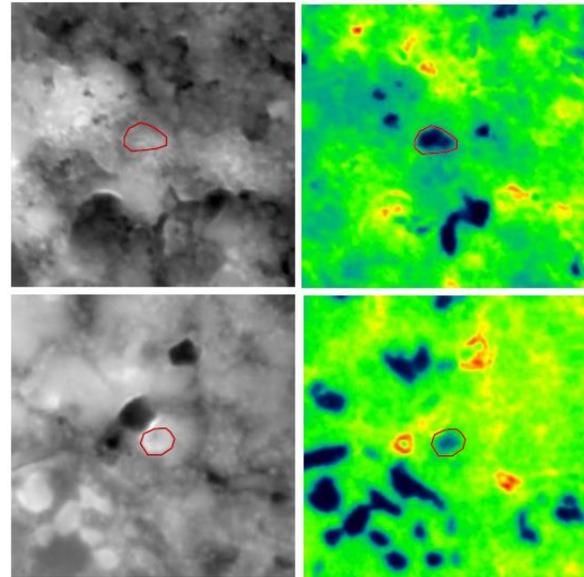


Figure 1: The secondary electron image and false color Fe map of the presolar silicate grains A5a-18o1 (205 nm in diameter) and A4b-7o1 (230 nm in diameter) from Adelaide [1]. The area of the O isotope anomaly is outlined in red.

Image J tool was used to retrieve the gradient in the Fe content from the meteorite matrix to the interior of the grain, along the long-axis of the grain in the Auger Nanoprobe maps. Diffusion of Fe in pyroxenes has been shown to be anisotropic, and is fastest along the long axis [5]. The Fe concentration profiles were modeled using an analytical solution to the diffusion equation with a Monte Carlo approach, to find the temperature and time interval that produce the lowest misfit (or 'best' solution) between the modeled and measured Fe concentration profile, using a range of possible temperatures from 0-600°C and a range of possible time-scales from 0 to 10 million years. The best solution is achieved by calculating the sum of squares of the residuals between the measured and modeled concentration profiles. We used the diffusion equation for Fe-Mg diffusivity in orthopyroxene from [5] namely $D = 1.66 \times 10^{-4} \exp(-377\text{KJ/mol})/RT$, for $X_{\text{Fe}} = 0.01$, where R is the gas constant and T is the temperature in Kelvin. The results of the modeling include a temperature-time pair that are inextricably linked in this approach to derive the best fit to the observed profile.

The starting geometry for the interface was assumed to be a step-function, which progressed to the measured

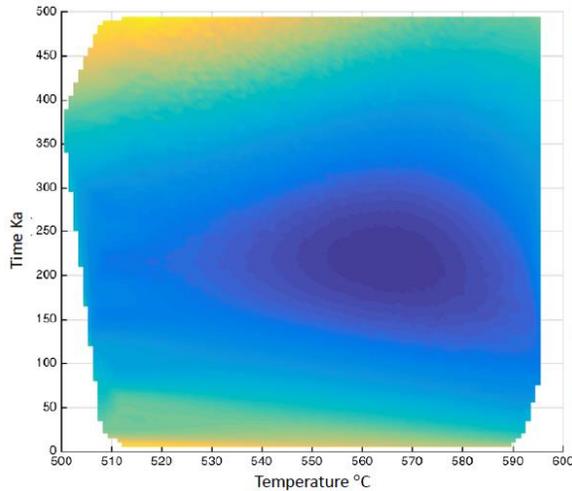


Figure 2: The distribution for grain A5a-18o1 indicates the regions of the “best fit” (deep blue region) are for the 530-590°C temperature range.

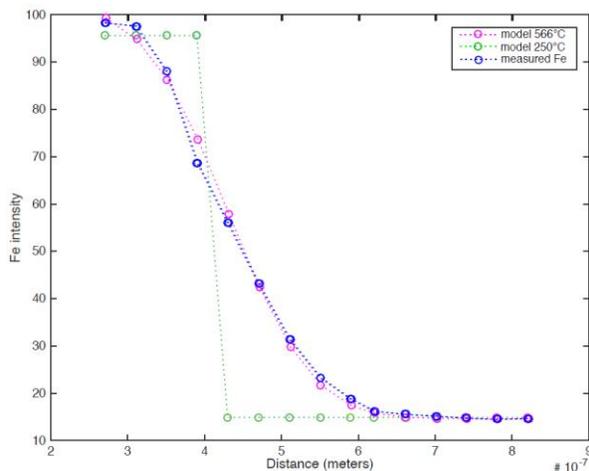


Figure 3: The measured profiles for the grain A5a-18o1, and the modeled profiles at 250°C and 566°C.

shape over time. The modeling assumes that the entire concentration profile extracted from the Fe map is within a presolar grain that has an orthopyroxene crystal structure. It is also assumed that the temperature was constant over the time that the diffusion occurred. If the temperature was not be constant for this process and instead cooled down during diffusion, the derived time-scales are lower limits.

Results: The best fits between the measured Fe concentration profile and the models indicate that the diffusion time-scale for grain A5a-18o1 is 214,000 years at 566°C (Figures 2, 3). The diffusion time-scales in case of the grain A4b-7o1 is 86,670 years at 564°C. Note here that neither of the grains show orthopyroxene compositions and may even be amorphous (we do not have structural information of these grains), which would only shorten the reported time-scales.

Discussion: O-anomalous grains are moderately abundant in Adelaide (70 ppm) [2], but are quite heterogeneously distributed within the meteorite matrix [2, 6]. In fact, coarse grained regions in the meteorite thin-section were found to contain low abundances of presolar grains, owing to heating and recrystallization of the matrix material and resulting in destruction of the presolar grains or reequilibration of their isotopic compositions [2]. A low (8 ppm) abundance of presolar SiC grains in this work also suggested significant thermal processing. The results of our diffusion modeling suggests that this thermal event occurred at temperatures of 500-600°C in <214k years. Iron diffusing into the presolar grains from the surrounding matrix necessitates that mm- to cm-sized clumps of material accreted with the presolar grains in the early solar nebula rapidly. For example, dust grains can grow from micrometer to millimeter size through surface sticking in a few 10-100 years at 1 AU [7, 8].

Clumps of dust rich in presolar grains probably formed contemporaneously with the Calcium Aluminum Inclusions (CAIs), which happened during a short time interval of ≤ 10 ka in the early Solar System. In this scenario, these clumps could encounter regions with high dust/gas ratios in the solar nebula (possibly at distances >2 A.U. to experience ~ 500 -600°C temperatures), where the diffusion event occurred in <214k years. Heating and diffusion most likely stopped abruptly, when large scale movement of these clumps occurred during the formation and migration of the giant planets. Numerical simulations can be explored to understand the properties of the clumps including coagulation & thermal metamorphism time-scales and temperatures achieved.

The temperatures experienced by Adelaide’s organic matter are suggested to be <240 °C [9], which is much lower than the modeled temperatures in the 500-600°C range. However, the measured profiles on the two presolar silicates could not be reproduced by models at lower temperatures (e.g., Figure 3) or resulted in unreasonably long time-scales. This implies that the thermal event that heated portions of the Adelaide matrix is not the same as that experienced by the organic materials in this meteorite, which were accreted at a later time.

References: [1] Bose M. et al. (2010) *ApJ*, 714, 1624–1636. [2] Floss C. and Stadermann F. J. (2012) *Meteorit. & Planet. Sci.*, 47, 992–1009. [3] Vollmer C. et al. (2007) *ApJ*, 666, L49–L52. [4] Haenecour P. et al. (2017) *GCA*, 221, 379–405. [5] Dohmen et al. (2016) *American Mineralogist*, 101, 2210–2221. [6] Davidson J. et al. (2010) *41st Lunar and Planetary Science Conference*, Abstract #2230. [7] Brauer F. et al. (2008) *A&A*, 480, 859–877. [8] Charnoz S. and Tailifet E. (2012) *ApJ*, 753, 119–131. [9] Busemann H. et al. (2007) *Meteorit. & Planet. Sci.*, 42, 1387–1416.