ORIGIN OF REFRACTORY INCLUSION DIVERSITY BY TURBULENT TRANSPORT IN THE INNER SOLAR NEBULA. E. Taillifet[1,2], K. Baillié[1], S. Charnoz[1], J. Aléon[2], [1]Laboratoire AIM / IRFU / CEA Saclay / Université Paris Diderot, l'Orme des Meurisiers, bat 709, 91191 Gif-sur-Yvette, France, esther.taillifet@cea.fr, [2]CSNSM, CNRS/IN2P3-Univ. Paris Sud, Bat 104, 91405 Orsay Campus, France.

Introduction: Refractory inclusions are the oldest objects formed in our solar system (~ 4.567 billion years ago [1]). Understanding their formation is essential to unravel the first stages of planet formation. Calculations (*e.g.* [2]) and experiments (*e.g.* [3]) show that their peculiar refractory mineralogy is well accounted for by condensation from a cooling gas of solar composition. They show a large diversity of sizes, textures, mineralogy and mineral chemistry that attest of fairly different thermal histories. For instance, the quite rare large igneous CAIs probably underwent several heating episodes whereas the common fine-grained spinel-rich inclusions (FG-CAIs) probably escaped significant melting. However, their refractory chemistry, their ancient age and the common presence of ^{16}O and ^{26}Al excesses suggest that they all formed during a short time interval in the same inner region of the solar nebula. In spite of several attempts (*e.g.* [4]), the astrophysical origin of the CAI diversity remain poorly understood.

In order to address this problem, we studied the effect of turbulence on the thermal histories of CAI precursors of various sizes evolving in the inner region of a thermally zoned solar nebula. We numerically calculated the trajectories of the dust particles in a self-consistent protoplanetary disk model. We also investigated the influence of the strength of the turbulence on dust evolution and we show that for standard values of the turbulence parameter alpha, we obtain a diversity of thermal histories in a proportion qualitatively consistent with that expected for natural refractory inclusions.

Numerical model: We developed a new 2D disk model, which couples thermal and dynamical evolution of the gas disk. It includes both viscous and radiative heating in a turbulent environment (*e.g.* [5] [6]). The viscosity is parameterized using the Shakura and Sunyaev α prescription [7]. The viscosity given by $\nu=\alpha C_s H$ (where C_s is the local sound speed and H, the pressure scale height) drives the dynamical evolution of the gas disk as well as the motion of the dust particles evolving within it. We simulated the transport of newly condensed grains using the Lagrangian Implicit Dust Transport 3D code (LIDT3D - [8]). In this stochastic model of turbulence, the dust diffusion coefficent is given by $D\approx\nu/S_c$ where S_c is the Schmidt number [9]. Because this code is Lagrangian, it allows following the dust particles individually through their journey in the nebula. They undergo star gravity, gas drag and turbulent diffusion. The pressure and temperature are recorded for a given transport step, so that in a thermally zoned disk, the simulations give the trajectories of individual dust particles as well as their pressure and temperature histories.

Results: We used 2000 tracers for 3 grain sizes: 1 µm, 500 µm and 1 cm, which are roughly the bound and the average sizes of CAIs. The tracers start from the condensation zone spatially defined using the temperatures and pressures from equilibrium condensation calculations (e.g. [2]). As a standard model, the mass of the nebula is the same as the Minimum Mass Solar Nebula but it is denser in the inner region to simulate a newly formed disk (suface density $\Sigma=1.7\times10^3\ r^{-2}$ where r is the distance from the Sun in astronomical unit - AU). In a first set of experiments, we followed the evolution of these tracers in the nebula during 10^5 years and showed that in less than 2000 years, the grains either fall into the Sun, or are transported outside the condensation zone (> 2 AU). In a second set of experiment, we followed the evolution of the newly condensed refractory dust particles during the first 2000 years of their journey into the disk with a higher temporal and spatial resolution.

For all grain sizes, the turbulent driven motion leads to thermal histories varying from simple to very complex (e.g. examples from Fig. 1). From the 2000 tracers of each size, only 5-8% of the grains survive the radial drift, the 1cm-sized grains being less likely transported outward due to their sensitivity to gas drag. While some particles quickly escaped from the hot region (Fig. 1a) and experienced little thermal reprocessing, other experience complex thermal histories with multiple heating events over 1500 K (Fig. 1c).

Among the 500 µm grains that were transported outside the hot region, about half the grains never reached the solidus, while less than 20% pass the liquidus (Fig. 2). Several tens of percent experience intermediate temperatures between 1600 K and1800 K (Fig. 2e). Thus lightly reprocessed objects (such as FG-CAIs) and objects melted to some extent (such as type-A CAIs) should be common, while extensively molten objects (such as type-B CAIs) should remain

uncommon, which is in good agreement with the meteoritic record. Panels in Fig. 2 show the proportions obtained with various α values. For low viscosity (Fig. 2A,B), all grains reach the solidus. In these models little melted or unmelted objects such as FG-CAIs are not expected to be formed in contradiction with the observations from meteorites, where they are abundant. For α greater than 0.001, the proportions obtained from the models are in good agreement with the distribution of CAIs in chondrites. We note that the agreement increases with increasing α values. Thus the CAI diversity may be used to constrain the turbulence of the solar nebula. The meteoritic record is consistent with an initial turbulence characterized by α ranging from 0.001 to 0.1, which is consistent with the astrophysical observations made on protoplanetary disks [10].

Discussion and perspectives: Our work shows that many different types of CAIs could have formed in a single environment by thermal reprocessing in the gas disk due the stochastic motion induced by the turbulence. An important consequence of this work is that the diversity of CAIs can be used to constrain the initial conditions of the solar nebula.

In this model, we made the initial assumption that the disk is well formed and took a disk denser than a MMSN in the innermost region to simulate a fairly young system. It has been suggested that CAI could have formed during the collapse of the presolar cloud before the disk is fully grown [11]. To study how this consideration may change our results, we recently developed a model that includes cloud collapse. Preliminary results show that the condensation zone exists long before the end of the disk formation and persists after the cloud entirely collapse onto the disk so that refractory objects are still produced by condensation from the gas. Turbulent transport simulations are going on and results will be presented at the meeting and compared with the results obtained without cloud collapse.

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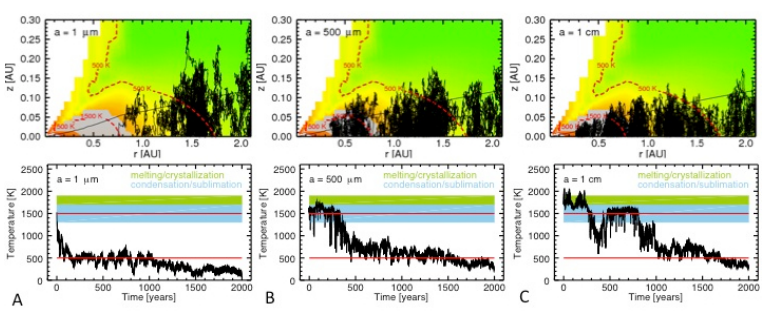

Figure 1: Examples of trajectories and thermal histories obtained for A.1 µm precursor, B. 500 µm precursor and C. 1cm precursor.

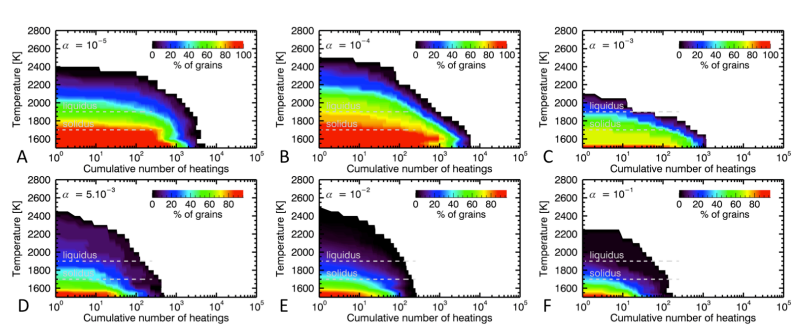

Figure 2: Percentage of 500 µm-sized grains that underwent a minimum number of heatings for various strength of turbulence from the lowest in A : $\alpha = 10^{-5}$ to the highest in F: $\alpha = 10^{-1}$