INSIGHTS ON CAI THERMAL HISTORY FROM TURBULENT TRANSPORT SIMULATIONS OF MICRON-SIZED PRECURSORS IN THE EARLY SOLAR NEBULA. E. Taillifet[1], 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 *(i.e.* Calcium Aluminum-rich Inclusions - CAIs and Amoeboid Olivine Aggregates - AOAs) are an important component of primitive chondritic meteorites. CAIs are the oldest objects known to be formed in our solar system (~ 4.5673 billion years ago [1]). Understanding their formation is thus essential to study the very first instants of planet formation. They show a large diversity of sizes, textures, mineralogy and mineral chemistry that attest of fairly different thermal histories. For instance, large igneous CAIs probably underwent several heating episodes whereas 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 testify that they all formed during a short time interval in the same inner region of the solar nebula where the temperature was high enough for them to condense from the gas (*e.g.* [2] [3]). Despite several attempts (*e.g.* [4]), the origin and astrophysical setting of the CAI diversity remain poorly understood.

In order to address this problem, we studied the effect of turbulent transport in the inner region of a thermally zoned solar nebula. We numerically calculated the trajectories of the refractory dust particles in a self-consistent protoplanetary disk model. We report here the first results obtained for micrometer-sized condensates. We show that their turbulence-driven transport is responsible for a complex and variable thermal history.

Numerical methods: We developed a new thermodynamical disk model that couples both viscous and radiative heating in a turbulent gas disk based on previous works (*e.g.* [5] [6]). Notably our model includes viscous spreading of the disk with time and self-consistent opacity calculations taking into account dust sublimation at the inner edge. Using this disk model we simulated the turbulent transport of new condensed grains with the Lagrangian Implicit Dust Transport 3D code (LIDT3D - [7]). 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 with their pressure and thermal histories.

Initial conditions: To simulate our system we used 1000 tracers that start from the condensation zone spatially defined using the temperatures and pressures from equilibrium condensation calculations (e.g. [3]). In a first set of experiments, we followed the evolution of these tracers in the nebula during 10^5 years with a time step of 1 year (fig 1).

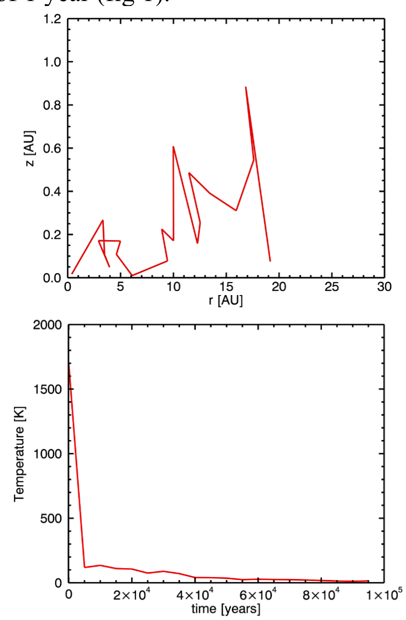

Figure 1: Example of trajectory (top) and thermal history (bottom) obtained for a micron-sized tracer.

This preliminary approach shows that (1) the particles were transported throughout the disk up to cometary distances as previously evidenced (*e.g.* [8] [9]) and (2) that their high temperature history is restricted to the first few 100s years. Subsequently, we simulated the evolution of ~8000 tracers in the nebula during 1000 years with a time step of 0.01 years and stopped the simulation when the tracer is significantly away from the hot inner region (~1.5 AU). In such a short time interval, the evolution of the disk is limited and we used a static disk corresponding to the initial compact disk.

Results: Very different trajectories and thermal histories were obtained for various tracers. Two examples are shown in fig 2. We show that some particles could have experienced a complex thermal history with multiple heating events (fig 2 (a) (b)) in the temperature and pressure range corresponding to that expected for refractory inclusions (over 1500K, 10^{-2}-100 Pa) while others quickly escaped from the high temperature region (fig 2 (c) (d)) and experienced little heating above the condensation temperature.

We thus show that the turbulent transport in the hot inner region of a thermally zoned protoplanetary disk induces very different thermal histories that are qualitatively consistent with those expected for refractory inclusions. All the high temperature history due to turbulence occurred in the first 500 years of the history of an individual condensate.

Discussion and perspectives: The production of CAIs by condensation of precursors in the innermost protoplanetary disk is expected to result in CAI formation during the entire disk lifetime (few 10^6 years), whereas the dating of meteoritic CAIs indicates that their production is limited to at most 10^5 years [e.g. 1]. However, previous works have shown that the efficiency of CAI preservation in the disk favors the presence of the oldest inclusions [10].

The calculations reported here were done using a value of the turbulence parameter $\alpha=10^{-2}$ in a Minimum Mass Solar Nebula disk. To which extent our results are sensitive to the variation of such astrophysical parameters of the model remains to be determined.

In the present state, we explored the dynamics of micrometer sized particles which could correspond to individual mineral condensates such as those found in meteorite matrices or in cometary dust. Larger size ranges (mm to cm) are now investigated to determine if these results can be extended to particles corresponding to igneous CAIs. To determine if the transport of cm-sized particles in the innermost disk is astrophysically realistic, it is also important to investigate the mechanism of CAI growth during the first 500 years after condensation.

References: [1] Connelly J. N., Bizzarro M., Krot A. N., Nordlund A., Wielandt D., Ivanova N. A. (2012) Science, 338, 651. [2] Grossman L. (1972) Geochim. Cosmochim. Acta, 36, 597. [3] Yoneda S., & Grossman L. (1995) Geochim. Cosmochim. Acta, 59, 3413. [4] Boss A. P., Conel M. O'D. A., & Morris P. (2012), E&PSL 345, 18B. [5] Calvet N., Patino A., Magris G. C., D'Alessio P. (1991) APJ, 380, 617-630. [6] Hueso R. & Guillot T. (2005), A&A, 442, 703-725. [7] Charnoz S., Fouchet L., Aléon J., & Moreira M. (2011) APJ, 737:33 (17pp). [8] Jacquet E., Fromang S., & Gounelle M. (2011) A&A, 526, L8. [9] Ciesla F. (2011) APJ, 740:9 (12pp). [10] Ciesla F. (2010) Icarus, 208, 455-467.

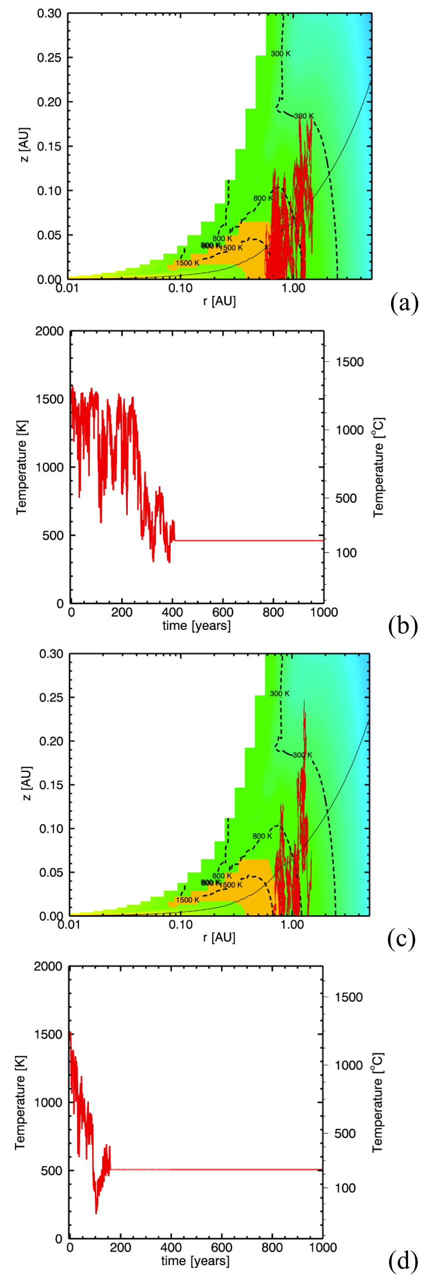

Figure 2: (a) and (c) show in red two examples of micron-sized CAIs precursor spatial trajectories in a disk, starting from the condensation zone (in yellow). The colored background corresponds to the temperature and the plain line to the pressure scale height. (b) and (d) give the corresponding thermal histories for the two examples.