TRANSPORT AND PRESERVATION OF CALCIUM-ALUMINUM-RICH INCLUSIONS: THE ROLE OF THE DEAD ZONE. E. Jacquet[1], M. Gounelle[1] and S. Fromang[2,3], [1]LMCM, UMR 7202, CNRS & MNHN, CP52, 57 rue Cuvier, 75005 Paris, France. (ejacquet@mnhn.fr) [2]CEA, Irfu, SAp, Centre de Saclay F-91191 Gif-sur-Yvette. [3]UMR AIM, CEA-CNRS-Univ. Paris VII, Centre de Saclay, F-91191, Gif-sur-Yvette, France.

Introduction: Calcium-aluminum-rich inclusions (CAIs) make up a few percent of many carbonaceous chondrites [1] and are generally believed to have formed by condensation out of a gas of solar composition at 1400-1800 K, although secondary reprocessing is common. Chronological data, mainly drawn from studies of CV chondrites, suggest that they formed at the start of the solar system, about 1-2 Ma before the onset of chondrule formation, during a short time interval perhaps spanning a few 10^4 a ([2]-[4]).

These timing constraints pose an astrophysical challenge, since millimeter-sized bodies are generally expected to drift toward the sun within a few 10^5 a because of advection by gas accreting onto the sun and gas-solid drag. One therefore needs to account for both the transport of CAIs from inner regions of the disk, where temperatures are high enough for their formation, and the preservation of these CAIs for a few Ma in the disk before chondrite accretion. Given that the mass fraction of CAIs in many carbonaceous chondrites is comparable to what *in situ* condensation out of a solar gas would have achieved [5], and that CAIs have been identified in dust returned from comet Wild 2 (e.g. [6]), it is necessary that the production and transport mechanisms envisioned be efficient.

Scenarii involving jets, such as the X-Wind [7], or meridional circulation [8], while possibly relevant, would not *per se* reproduce the narrow age range of CV CAIs. On the other hand, transport by spiral arms due to Gravitational Instabilities (GI ; [9]), or turbulent diffusion ([10]-[11]), would be efficient only in the early phases of the disk. As regards turbulent diffusion models, [11] estimated that, alone, they lead to CAI abundances 1-2 orders below the observations, and matching the latter thus required either enhancement of the condensable fraction in the "CAI factory" by inward drift of meter-sized, carbon-rich solids, or preferential settling of CAIs toward the disk midplane before chondrite accretion.

In this study [12], we propose CAI transport by advection in an initially compact disk undergoing viscous expansion. We show that the disk model *must* lead to the formation of a quiescent "dead zone" where the reduced CAI velocities allow survival for a few Ma.

Disk model: We adopt a self-similar surface density profile of the form:

$$\Sigma=M_D\exp(-R/R_D)/2\pi R R_D$$

with R the heliocentric distance, and M_D and R_D the disk mass and radius, respectively. The latter are function of time and evolve assuming a fixed "turbulent viscosity" profile.

"Turbulent viscosity" is the standard way to measure how turbulence drives accretion. The turbulence may arise either because of GI or the MagnetoRotational Instability (MRI ; [13]). It is therefore important to check whether either one of these instabilities can indeed operate ; otherwise, our assumed value for the "turbulent viscosity" cannot hold.

As an initial condition, we consider a compact and massive disk, a few AU across. The idea that disks could actually start off being this compact is bolstered by observations of class 0 objects which have still not unambiguously identified disks (e.g. [14]) and numerical simulations of prestellar cloud collapse taking the role of magnetic fields into account [15].

Outward transport: Disk evolution through "turbulent viscosity" leads to mass loss to the star and expansion of the disk. Gas velocities are outward beyond a "turnover radius" ($R_{switch} = R_D/2$ in our model) and thus solids may be transported outward.

In Fig. 1, trajectories of solids are drawn as dashed lines, and we show the 1500 K isotherm. This temperature arises not because of irradiation by the central star, but because of viscous dissipation of turbulence due to the MRI. It is seen that early in the disk history, when the disk is compact enough, high temperatures are generated even in those regions of the disk where the velocities are outward. Hence, CAIs may be transported this way up to heliocentric distances of order 10 AU, more efficiently than through turbulent diffusion alone. This outward transport will stop as soon as the disk has expanded enough, hereby accounting for the narrow age range of CV CAIs, analogously to [11].

Preservation: Due to gas drag and the "backward surge" of the gas, this outward motion cannot last more than ~10^5 a., and, if the model is extrapolated further (as is done in Fig. 1 and 2), CAIs should return to the Sun on this timescale (as in previous studies). However, this extrapolation will turn out to be unfounded. Indeed, as mentioned earlier, we need to check whether the instabilities that underly the "turbulent viscosity" are present.

In Fig. 1, we shade in yellow the maximum domain where GI can occur. It is calculated ignoring viscous heating due to MRI. Note that if MRI is present, the resulting increase of temperature and hence pressure support acts to suppress the GI. It is seen that after 40 ka, surface densities are not high enough for GI to persist anywhere in the disk.

In Fig. 1, we shade in green the domain where the MRI **cannot** occur. For the MRI to exist, it is necessary that a sufficient ionization fraction in the gas be maintained, either through high temperatures (due to the dissipation of the MRI-powered turbulence itself) or cosmic rays. Gammie [16] showed that, for most disk parameters, there should be a range of heliocentric distances where the MRI is suppressed, as is the case here: this is the *dead zone*.

While in the first tens of millenia, the failure of the MRI to operate may be compensated by GI, we see that by ~10^5 a, the dead zone must be truly dead, in the sense that the "turbulent viscosity" drops by orders of magnitude. In this case, the gas advection velocities drop accordingly, and mass accumulates in the dead zone (hereby reducing the relative drift between CAI and gas due to gas-solid drag). Thus, since the net velocity of CAI has shrunk, their survival for a few Ma is ensured.

It must be emphasized that the presence of a dead zone is a general feature of accretion disks, and thus, the CAI preservation mechanism outlined here is actually independent of the outward transport phase. It would be conceivable, for instance, that turbulent diffusion dominated the outward transport of CAI (as in [11]), if the disk started off being less compact than we have assumed, but their preservation would still be ensured by the appearance of a dead zone. Since subsequent CAI production would be essentially confined to the disk region inside the inner boundary of the dead zone, as temperatures drop significantly across it, these would not be able to reach the future chondrite-forming regions. Hence, the appearance of a dead zone would also be able to account *per se* for the narrow age distribution of CV CAIs.

References:

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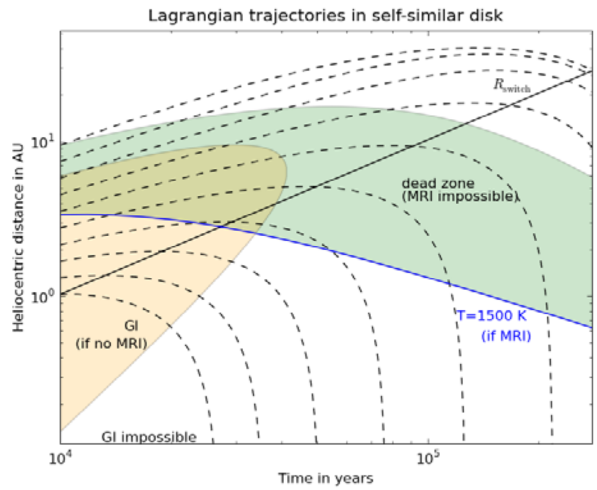

Figure 1: Space-time diagram for the self-similar model (assuming $M_D R_D^{1/2}$ = 0.4 M$_\odot$.AU$^{1/2}$, a turbulent viscosisty $\nu = 5\ 10^{10}$ m²/s (R/1 AU), and an irradiation temperature T = 280 K (R/1 AU)$^{-1/2}$). Dashed lines are trajectories of solids. Continuous black line is the locus of the turnover radius (R_{switch}). The yellow domain shows where GI may occur if one ignores heating due to MRI-driven turbulence. GI are impossible elsewhere. The green domain is the "dead zone", where MRI cannot operate.

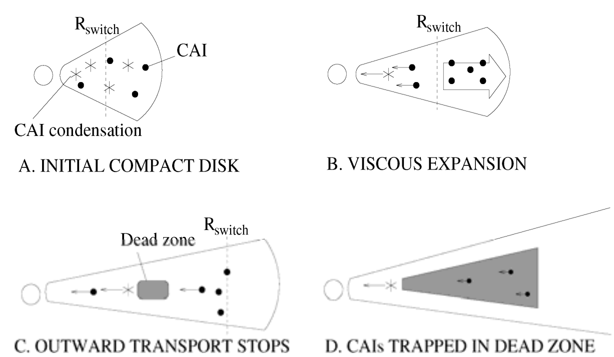

Figure 2: Cartoon of the proposed scenario. An initially compact disk (A) undergoes viscous expansion (B), entraining CAI outward. By the time this outward transport stops (C), a dead zone has developped where the CAI sunward velocity is reduced, hereby ensuring their survival until chondrite accretion.