**DEAD ZONES AND THEIR ROLE IN CAI PRESERVATION.** 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:** A growing body of data gathered over the past decade (e.g. [1]-[3]) seems to confirm the idea that individual chondrites consist of components that may have formed millions of years apart. In particular, Calcium-Aluminum-rich Inclusions (CAIs) seem 2 Ma older than most chondrules. However traditional disk models typically predict that free-floating millimeter-sized objects should not be preserved in the disk for more than a few hundreds of millenia and should drift into the Sun because of gas accretion to the Sun and gas-solid drag.

We have recently suggested [4] that taking into account the presence of a *dead zone* in the disk, where turbulence is reduced, could alleviate this issue. The presence of a dead zone is not an *ad hoc* solution for this problem, but actually a prediction from MHD theorists dating back to 1996 [5] and which has been actively explored since then (e.g. [6]-[12]). Chronological data on chondrite components may be viewed as a first observational confirmation of such a disk structure, pending higher resolution observations of (extrasolar) disks by ALMA in the future.

**What is a dead zone?:** Disk evolution is believed to be dictated by gas turbulence, which is measured by a turbulence parameter called α. This turbulence in turn arises because of instabilities that operate in the disk. In the current state of accretion disk theory, the most efficient instabilities should be the Gravitational Instability (GI; see e.g. [13]) and the MagnetoRotational Instability (MRI; [14]) and both are able to sustain α values of $10^{-3}$-$10^{-2}$.

However GI can only operate in a massive enough disk, which may be the case only in the early stages of disk evolution. As regards the MRI, a minimum level of ionization of the gas is required for its existence. However, beyond some heliocentric distance (0.1-1 AU) from the Sun, heat is insufficient to suitably ionize the gas, but ionizing (cosmic, X, UV) radiation cannot penetrate the disk down to the midplane because its column density is too high. Moreover, fine dust hastens recombination of electrons and ions and acts to lower the ionization fraction (e.g. [15]).

Therefore, fairly generally, there should be a range of heliocentric distances in the disk, probably between a fraction of an AU to tens of AUs typically, where turbulence is greatly reduced (say, $\alpha < 10^{-4}$). This is the *dead zone* (Fig. 1). As transport is slowed down there, mass should accumulate, yielding a relatively massive belt.

**General significance of the dead zone for solar system solids:** Given the expected extent of the dead zone, which correspond to the region of terrestrial and gaseous planets in our solar system, most of chondrite formation should take place in it. This should not be held as coincidental, because the dead zone is actually a favorable environment for accretion. A low turbulence level could allow significant settling of solids at the disk midplane and e.g. instigate streaming instabilities which can lead to planetesimal formation within a few centuries [16]. Also, the high surface density in the dead zone would allow formation of giant planets by core accretion within the disk lifetime [11].

Another important implication of a dead zone would be a significant reduction of radial drift of millimeter-sized bodies and hence a solution to the problem of their preservation over a few Ma prior to agglomeration [4]. This is because transport of the gas to the Sun is slowed down, and because the high column densities in the dead zone tighten the coupling between solids and gas, diminishing the effects of gas-solid drag.

**The case of Calcium-Aluminum-rich Inclusions:** The old age of CAIs, which may have formed in the first 0.1 Ma of the solar system, suggests that they could have formed before the formation of the dead zone. Their calculated condensation temperature is near or above the activation threshold estimated for the MRI (see Fig. 2). Moreover, at such high temperature, dust (as mentioned before, an ennemy of ionization and thus of the MRI) would be largely evaporated. Thus CAIs likely formed in an MRI-active region, and would be unique sensors of such an environment. The high temperatures would have been generated by the MRI itself, via the dissipation of turbulence it sustains. The high turbulence levels would allow efficient outward transport of CAIs, be it by diffusion ([17],[18]) or advection [4].

As the dead zone formed, CAIs would have been trapped in a low-turbulence region, thus enabling their quantitative survival until chondrite accretion. An efficient preservation seems required by the high abundance of CAIs (a few percent, see [19]) in carbonaceous chondrites, when compared to what *in situ* condensation out of a solar gas would have produced (about 6 % [20]). New CAIs produced in the inner, MRI-active zone (i.e. inside the inner boundary of the dead zone) would not have been able to diffuse in significant amounts in the dead zone because of reduced turbulence there.

**Difficulties in preserving CAIs without a dead zone:** An alternative to a dead zone would be a disk with a more or less uniform and constant turbulence parameter. How should α be tuned in such disk models to allow significant CAI preservation? If α is large, temperatures will be higher and hence the "CAI factory" will be greater in extent, and also turbulent diffusion may reach larger heliocentric distances. However the mean (inward) velocities of the gas will also be increased and *in fine* the lifetime of CAIs in the disk will be reduced. If α is small (i.e. the whole disk is a dead zone), transport will be slowed down but temperatures will be lower and CAI production limited (see [17]).

It is important to realize that turbulence is a two-edged sword, because both random motions, which contribute to outward transport, and the net transport of the gas, which is inward, scale with α. Only a dead zone scenario can combine the benefits of high and low values of α (long-range outward transport/high temperatures and slow radial drift, respectively).

Without a dead zone, the only way to account for the high abundance of CAIs in carbonaceous chondrites, despite the intrinsically low preservation, would be to assume an enhanced production, via en enrichment in condensable elements in the "CAI factory". However this may be problematic from the point of view of the redox state recorded by CAIs (e.g. $Ti^{3+}/Ti^{4+}$ ratio in pyroxene) or the total amount of condensable matter available in the disk [4].

**References:**

[1] Bouvier et al. (2007), *GCA, 71,* 1583. [2] Villeneuve et al. (2009), *Science, 325,* 985. [3] Amelin et al. (2010), *EPSL, 300*, 343. [4] Jacquet et al. (2011), *A&A, 526*, L8. [5] Gammie (1996), *ApJ, 457,* 355. [6] Bai & Goodman (2009), *ApJ, 701*, 737. [7] Fleming & Stone (2003), *ApJ, 585*, 908. [8] Fromang et al. (2002), *MNRAS, 329*, 18. [9] Ilgner & Nelson (2006), *A&A, 445*, 205. [10] Sano et al. (2000), *ApJ, 543*, 486. [11] Terquem (2008), *ApJ, 689*, 532. [12] Zhu et al. (2010), *ApJ, 713*, 1143. [13] Boss (2004), *ApJ, 616*, 1265. [14] Balbus & Hawley (1998), *RMP, 70*, 1. [15] Draine & Sutin (1987), *ApJ, 320*, 803. [16] Johansen et al. (2007), *Nature, 448*, 989. [17] Ciesla (2010), *Icarus, 208,* 455. [18] Cuzzi et al. (2003), *Icarus, 166,* 385. [19] Hezel et al. (2008), *Meteoritics & Planet. Sci., 43,* 1879. [20] Grossman (2010), *Meteoritics & Planet. Sci., 45,* 7. [21] Wooden et al. (2006), PPV.

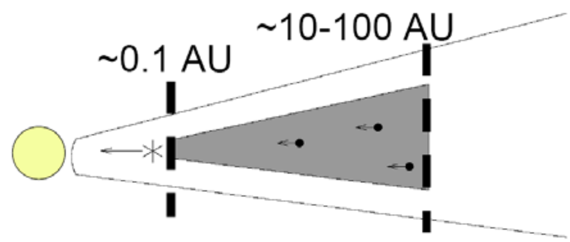


**Figure 1**: Schematic representation of a dead zone (gray) in a disk. Round objects symbolize solids.

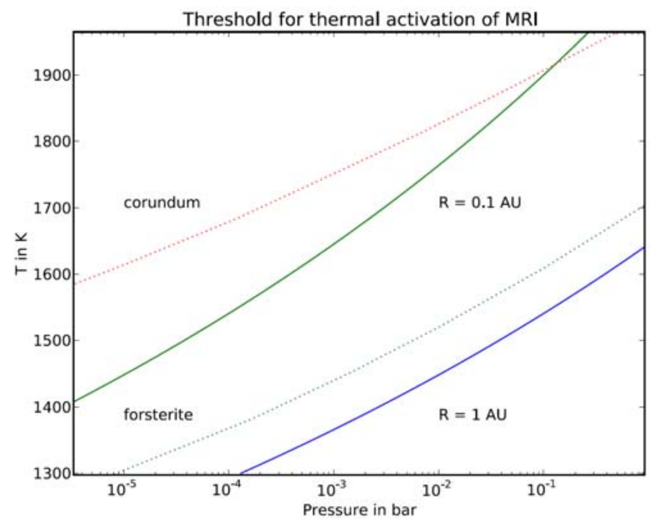


**Figure 2**: Threshold of thermal activation of the MRI as a function of pressure, assuming thermodynamic equilibrium. Overplotted are condensation temperatures of corundum and forsterite (which bracket the condensation sequence represented by CAIs) drawn from [21].