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Fingerprints of the protosolar cloud collapse in the Solar System: Refractory inclusions distribution and isotopic anomalies in meteorites

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Abstract. Increasing evidences suggest that the building blocks of Ca-Al-rich inclusions (CAIs) could have formed with the Sun, during the collapse of the parent cloud. However, determination of the relative age of CAIs relies on the homogeneous distribution of their short-lived radionuclide ^{26}Al that is used as a chronometer. Some CAIs show evidence of ^{26}Al/^{27}Al variation that is independent of decay.

We investigate the dynamical and chemical evolution of refractories from the collapsing cloud to their transport in the protoplanetary disk focusing to the predicted isotopic anomalies resulting from ^{26}Al heterogeneities.

The interplay between the thermal properties of the dust, the isotopic zoning in the cloud and disk dynamics produce aggregates that resemble chondrites. An abrupt raise of ^{26}Al close the center of the cloud followed by a plateau throughout the cloud best matches the observations. As a consequence, the ^{26}Al-chronometer retains validity from the formation of canonical CAIs onward.

Keywords. astrochemistry, solar system: formation, meteor meteoroids

1. Introduction

Chondrites are complex aggregates made of components with wide different thermal histories, chemical and isotopic compositions (Scott & Krot 2003). The physical processes that brought this variegate mixture within the same objects are still unconstrained.

Pignatale *et al.* (2018) investigated the formation and transport of solids with different thermal properties (condensates, processed, pristine) in the forming Solar System's protoplanetary disk fed by a collapsing homogeneous parental cloud. They found that the interplay between the thermal properties of the dust, the location in which the material is injected, and the disk dynamics can produce aggregates whose petrographic and isotopic properties resemble those found in chondrites, with relatively high concentration of refractory material in the outer disk, in good agreement, for example, with the bulk composition of carbonaceous chondrites (Scott & Krot 2003). Their work supports increasing evidences that the most refractory phases, the Ca-Al-rich inclusions (CAIs), could have actually formed during the collapse of the parent cloud that resulted in our Solar System (Pignatale *et al.* 2018, and references therein).

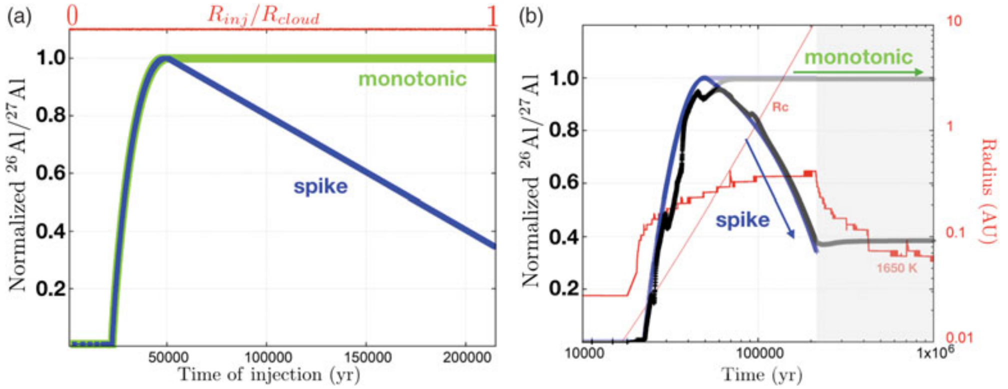

Figure 1. (a) Fiducial normalized $^{26}Al/^{27}Al$ distributions in the collapsing cloud. A monotonic distribution (green) is compared with a spike distribution (blue). (b) $^{26}Al/^{27}Al$ normalized ratios (black line) at the refractory condensation front (red line, right y-axis) for the two considered functions. After a similar initial profile, the monotonic function diverges (grey line) from the spike function. Figures adapted from Pignatale *et al.* (2019).

Subclasses of CAIs show evidences of decay-independent variation in their $^{26}Al/^{27}Al$ ratio compared with the majority of CAIs that cluster around the 5.2×10^{-5}, the canonical value (MacPherson *et al.* 1995, 2012). The short-lived radionuclide ^{26}Al is used to determine the relative ages of chondrite components (Mishra & Chaussidon 2014), but the validity of this chronometer relies on its homogeneous distribution within the disk. Given that CAIs are the oldest components in chondrites and their formation is likely contemporaneous with the cloud collapse, this suggests that the distribution of ^{26}Al in the cloud reservoir where CAIs derived was characterised by a degree of heterogeneity. This seems to be supported by discrepancies in the absolute Pb-Pb and Al-Mg ages within chondrules (Larsen *et al.* 2011).

Here we present the dynamical and chemical evolution of different refractories from the collapsing cloud to their transport in the forming protoplanetary disk with an outlook to the predicted isotopic anomalies resulting from isotopic heterogeneities in the parental cloud (Pignatale *et al.* 2019). Our 1D disk model includes several processes such as gas and dust condensation/evaporation, dust growth/fragmentation, radiative and viscous heating, dead zone (Pignatale *et al.* 2018), and a cloud infall in the form of a source term (Hueso & Guillot 2005; Yang & Ciesla 2012).

2. Results

Figure 1(a) shows the two chosen fiducial ^{26}Al distributions within the collapsing cloud in terms of the $^{26}Al/^{27}Al$ normalised ratio. The $^{26}Al/^{27}Al$ ratio abruptly raises to the maximum (canonical) and then is kept constant (monotonic) or returns to lower level (spike). These shapes reproduce the two simplest distributions dictated by the results presented in Pignatale *et al.* (2018) and the fact that most of the CAIs are canonical. Figure 1(b) shows the resulting normalised $^{26}Al/^{27}Al$ ratio at the refractory condensation front as a function of time. We see that the $^{26}Al/^{27}Al$ ratio of the condensates (black line) resembles the injection function (blue line). Earliest CAIs would be characterised by a lower amount of ^{26}Al while, after $t \sim 50$ kyr, in case of the monotonic function, CAIs will host a canonical ratio while in case of the spike, they will retain, after a peak, a lower ^{26}Al content. The CAIs produced within $t \sim 80 - 100$ kyr, are those advected more efficiently toward the outer disk (Pignatale *et al.* 2018).

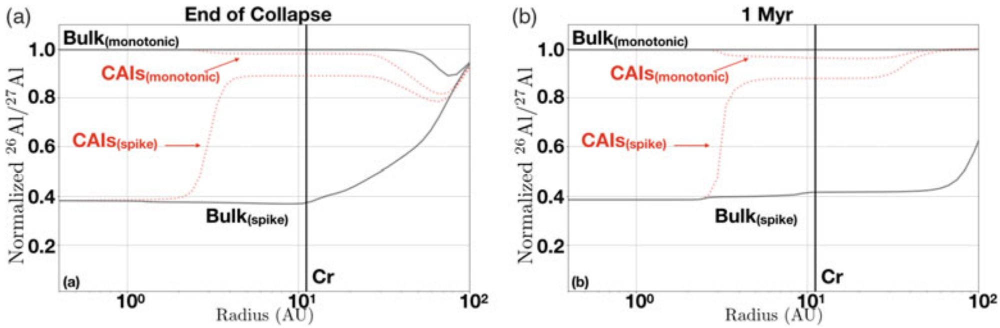

Figure 2. (a) Normalized ^{26}Al/^{27}Al ratio for the CAIs (red dotted line) and for the bulk (black continuous line) at the end of the collapse. (b) after 1 Myr. Figures adapted from Pignatale *et al.* (2019).

Figure 2 shows the radial distribution of the normalised ^{26}Al/^{27}Al ratio for the CAIs (red line) and bulk-refractory (CAIs plus processed and pristine refractories) for the two functions at the end of the collapse (a) and after 1 Myr (b). The spike produces clear differences between the CAIs in the outer and inner disk, and between CAIs and bulk (assumed to be the totality of the refractory material that would be accreted in a chondrite). The monotonic function, instead, returns similar and comparable values for the CAIs and the bulk, with differences due to the presence of the earliest ^{26}Al-poor refractory condensates.

As late CAIs would still be preferentially preserved in the disk (Makide *et al.* 2011, and Fig. 2(b)) the large heterogeneity produced by the spike in the ^{26}Al content would be clearly visible in the population of CAIs in different chondrites, but this is not the case. Experimental evidence is only compatible with a monotonic scenario. Furthermore, the ^{26}Al-poor CAIs produced by the spike would not provide the necessary ^{26}Al for planetesimal differentiation (Sanders & Taylor 2005).

3. Conclusions

We investigated the formation and transport of refractory material within a forming disk fed by a cloud that is heterogeneous in its ^{26}Al content. Our results compared with experimental evidences suggest that the distribution of ^{26}Al within the Solar System's parent cloud was likely characterised by an abrupt raise of ^{26}Al close to the center of the cloud closely followed by a monotonic constant value throughout the cloud. Since a first heterogeneity, that produced the anomalous CAIs, was in place, the ^{26}Al-chronometer retains validity from the formation of regular CAIs onward.

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