RADIAL TRANSPORT AND SURVIVAL OF REFRACTORY INCLUSIONS IN THE PROTOPLANETARY DISK.

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Overview: Calcium, Aluminum-rich Inclusions (CAIs) or CAI-like materials, are commonly found in chondritic meteorites [e.g. 1], and have also been identified in the Stardust samples collected from Comet Wild 2 [2-4]. These objects are composed of minerals such as corundum, hibonite, perovskite, and spinel—the same minerals expected to be the first to condense from a gas of solar composition [5]. While the exact temperatures at which these minerals form is pressure dependent, they likely formed in regions of the nebula that were in excess of 1300-1500 K [5-7], temperatures which were most easily achieved near the young Sun. The isotopic similarities between the chondritic and cometary materials suggest a common origin, implying that these CAIs were formed in a single environment and were then radially redistributed to be accreted by planetesimals that formed in both the terrestrial planet region of the solar nebula and those that formed beyond the giant planets.

CAIs also provide the oldest ages of those materials found in meteorites, and thus are taken to define t=0 for Solar System chronology [8,9]. The ages of these objects can be anywhere from 1-4 Myr older than the chondrules in the same meteorites in which they were found. This has been a long-standing puzzle, not only because of the widespread distribution of the CAIs, but also because it has been recognized that the larger, millimeter to centimeter CAIs found in CV CAIs would spiral into the Sun under the influence of gas drag on timesclaes of $\leq 10^5$ years [10]; a timescale short compared to both the lifetime of protoplanetary disks and the apparent age difference between the CAIs and the chondrules with which they co-accreted.

These ages, along with the chemical and isotopic properties of the CAIs, provide constraints on the manner by which CAIs were redistributed in the solar nebula. We have begun to use these constraints to explore whether they can be explained in the context of the dynamical models for the solar nebula. It is our hope that rigorous comparisons between model predictions and cosmochemical data will allow us to better understand the dynamical histories of CAIs in the solar nebula, provide new interpretations of the collected data, or make predictions which can be further tested by the data. As an example, in studying CAI preservation, [11] found that the inward drift of large CV CAIs required that CVs should be amongst the earliest accreted chondrites. Here, we will review how data on the formation of CAIs can be understood in the context of models for their radial redistribution and survival, and what predictions these dynamical models make about the properties and evolution of CAIs.

CAI Formation Interval: High-precision measurements of ^{27}Al/^{24}Mg ratios and Mg-isotopic compositions of CV CAIs have allowed for the determination of well-defined ^{26}Al-^{26}Mg isochrons, and imply an initial value of ^{26}Al/^{27}Al in the Solar System of 5.23×10^{-5}. The uncertainties in this value suggest that all CV CAIs formed within a time period of $<10^5$ years, with $\sim10^4$ years being possible [12,13]. However, the age of one of the CAI-like particles returned from Comet Wild2 had such low initial ^{26}Al/^{27}Al, that a formation time of 1.7 Myr after the CV CAIs was inferred [14].

By tracking the radial redistribution of CAI populations that formed at different times in a viscously evolving disk, [15] demonstrated that >90% of the CAIs that survived in the solar nebula for more than 1 million years would have come from the 10^5 year time interval after the nebula was at its most massive, compact state. This was due to the ability of these objects to ride the wave of viscous expansion in the solar nebula, being carried to large distances from the Sun before drifting inwards again under the influence of mass transport and gas drag. Larger or later formed objects were not carried outwards as readily, as the viscous expansion of the disk slowed with time, and the net direction of materials in the inner disk becoming largely inwards. As such, later-formed objects were lost from the disk more readily, leaving those objects that formed in a very narrow time interval as the primary survivors of the hot regions of the hot, inner solar nebula. This implies that those CAIs which were most readily preserved formed when the nebula was most massive, corresponding to the time when infall from the parent cloud core ceased, thus marking the transition from a Class I to Class II young stellar object [16]. This would be true regardless of whether nebular evolution was controlled by a turbulent viscosity or gravitational instabilities [17].

The surviving refractory objects everywhere in the nebula were predicted to be predominately from this time period, making the late age for the cometary CAI difficult to explain. As the efficiency of outward transport decreases with time in evolving disks, three possibilities remain to explain the observed age of this object: (1) the CAI is one of the few particles able to diffuse outwards despite the inward flows associated with disk evolution—approximately 1 in 10^4 of those CAIs in the outer nebula would have been transported outward at this late time period according to [15]; (2) a separate dynamical process operated to drive the dust particles outward this late in time, such as photopheresis, which would be most efficient later in disk evolution when the population of fine dust was significantly diminished such that it could be directly irradiated by the young Sun [19]; or (3) this CAI formed at a time before ^{26}Al was injected into the nebula as has been proposed for other CAIs which exihibit low initial ^{26}Al/^{27}Al ratios [19,20].

Recently, [21] has investigated this later possibility by carrying out a similar study as [15], but tracking both the formation of the solar nebula from infall from the parent cloud core, and its evolution under the effects of turbulence and gravitational instabilities. While the refractory objects that formed right around the time when infall ceased dominate the inner regions of the solar nebula, a significant portion in the outer tens to hundreds of AU formed prior to this. If infalling material to the nebula was not uniform in its isotopic compositions, these refractory objects would record a different isotopic setting than those that formed later. As part of the infalling material to our solar system was likely enriched by a recent injection of live ^{26}Al, it is possible that these early formed objects had a different initial ^{26}Al/^{27}Al ratio than those that formed later. Thus the inferred age difference between the cometary CAI and those found in CVs would not be real, and instead due to isotopic heterogeneities in the early, nebula as it formed. Whether other isotopic variations seen in CAIs can be explained in this manner is the subject of ongoing work.

CAI Post-Formation Alteration: While the concentration of CAIs in an evolving solar nebula suggests solids are continuously carried outward from the hot, inner nebula to the cool, outer regions, individual particles are expected to take complicated paths, bouncing inward and outwards in the disk, with surviving particles experiencing net outward motions in the earliest stages of disk evolution. This bouncing would lead to the CAIs seeing complicated temperature histories: rather than monotonically cooling with time, the particles could alternate between hot and cold environments over a time period. Chemical alteration or isotopic exchange reactions would be controlled by the paths that the solids took, and thus post-formation alteration would provide key constraints on the dynamical evolution of the CAIs.

Early studies of the paths that CAIs took in a turbulent disk were discussed in [22]. These paths were used to explore the alteration of Wark-Lovering Rims in CAIs. Recently, new, improved techniques for calculating the paths that individual particles take in such a disk have been developed [23-25], which more accurately account for the diffusive motions that arise due to turbulence. We have begun using these techniques to explore the array of environments that would be seen by individual CAIs in such disks to evaluate whether such paths allow for the formation of the different levels of processing recorded by these objects. Among the key issues is whether we can explain how CAIs would have cycled in and out of ^{16}O-rich and ^{16}O-poor environments as recorded by the rims of some CAIs [26].

We have also begun to explore how such processing may occur in the context of a non-axisymmetric solar nebula, such as those expected to develop in massive, gravitationally unstable disks [e.g. 27], as has been discussed by [28].

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