Formation of the first solids at the birth of our Solar System. T. Haugbølle[1], T. Grassi[1], T. Frostholm Mogensen[1], D. Wielandt[1], K. K. Larsen[1], N. M. Vaytet[1], J. Connelly[1] and M. Bizzarro[1], [1]Centre for Star and Planet Formation, University of Copenhagen, Øster Voldgade 5, Copenhagen, DK-1350, Denmark. (haugboel@nbi.ku.dk)

Introduction: Calcium-aluminum-rich inclusions (CAIs) are highly refractory, and believed to have condensed from a hot metal-rich gas close to the protosun, but no coherent formation theory exists. Absolute[1] and relative[2] isotopic dating indicates CAIs represent the oldest solids in our Solar System produced in a brief time interval of up to ten thousand years. We present a novel detailed microphysical description of CAI condensation embedded in a state-of-the-art numerical model of star formation. Our model can explain the meteoritic evidence, with CAIs forming in a few thousand years just after the birth of the Sun under very special conditions, which were not repeated at later times. It is a strong constraint for future global simulations of the formation of our and other Solar Systems, and can be used to make definite meteoritic predictions.

CAI Forming Environment: A protostar is formed through the gravitational collapse of a molecular cloud core, and accretes mass from the surrounding environment[3]. In a simple picture of low-mass star formation from a single isolated core, the mass accretion and density in the immediate environment is highest in the earliest phases, while both smoothly decreases with time. State-of-the-art numerical models[4,5] indicate that simultaneously with the birth of the star a protoplanetary disk with a size of up to a few AU is formed, which grows with time. This is supported by recent observations of well developed ~100 AU sized disks around highly embedded low-mass protostars[6,7].

Measurements show that CAIs condensed from a gas with temperatures >1,500 K and pressures of 10^{-4} – 10^{-3} bar[8]. They are either molten or irregular condensates. In general, they contain an aluminum dominated core surrounded by a calcium layer and a magnesium dominated outer layer, reflecting the thermal history of the condensate. Some CAIs have signs of multiple partial evaporation and condensation events. The varied thermal histories, types, and textures indicate a complex formation process in the hot inner region of the protosolar disk. Additionally CAIs present a wide distribution in petrographic types and sizes spanning several orders of magnitude from tens of micrometers to cm[9]. CAIs are aggregates of smaller nodules of varying composition and must have been formed through a two stage process: first the nodules condensed from the gas, and then they aggregated to form the CAIs. Lower temperature refractory solids, AOAs, are then the result of only lower temperature refractory material aggregating.

Model: To investigate the CAI forming process we focus on the inner aluminium dominated core using the first compund to condensate from the gas-phase, corundum (Al_2O_3), as a proxy. We have developed an *ab initio* microphysical model that addresses key stages including a full non-equilibrium chemical network for the formation of gas-phase Al_2O_3 and a detailed nucleation model for the condensation, growth and coagulation from monomers to macrophysical refractory solids. The microphysics is run on top of passive tracer particles embedded in a state-of-the-art 3D adaptive mesh refinement simulation of a collapsing molecular cloud core that includes radiative transfer, non-ideal MHD, dust sublimation and a realistic equation of state[10].

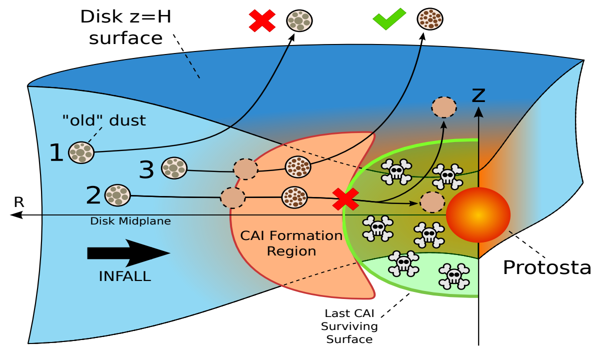

Figure: Sketch of the CAI forming process. Infalling dust sublimates at 0.08 AU from the protosun. Until 0.02 AU the conditions are right for condensing CAIs. If the CAI reaches the upper layers we assume it is carried away by an outflow.

Results: Running our microphysics on top of the simulation we find that at very early times there exists a region from 0.02 to 0.08 AU from the protosun where the temperature and pressure were right to facilitate the formation and growth of CAIs. In the first thousands of years the protosun was still heavily accreting with rates of 10^{-5} – 10^{-4} $M_\odot$ yr^{-1}, and the stellar mass was only ~0.01 $M_\odot$. This is crucial to have the right orbital timescale to form nodules directly from the gas phase, and we successfully are able to reproduce laboratory measurements of the size distribution of corundum nodules in CAIs from first principles. We assume solids that reach one scale height in the disk are carried away by the outflow, giving us the final distribution of CAI components in our model. The combination of time-scales, densities, and temperatures are only present at the very beginning of the solar system, suggesting that this was the only time where the process was able to operate. The turbulent conditions in the inner disk naturally gives a varied thermal history. The necessity of an outflow to avoid destroying the CAIs, explains how they were distributed early on throughout the envelope, resulting in an overabundance today in outer solar system material.

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