THE DYNAMICS AND AGES OF REFRACTORY OBJECTS IN THE SOLAR NEBULA. F. J. Ciesla[1] and L. Yang[1], [1]Department of the Geophysical Sciences, The University of Chicago, 5734 South Ellis Avenue, Chicago IL 60637 (fciesla@uchicago.edu).

Introduction: Refractory objects, those which formed in regions of the solar nebula with temperatures in excess of ~1350 K, have been found in primitive bodies throughout the solar system. Calcium, Aluminum-rich Inclusions (CAIs) and Amoeboid Olivine Aggregates (AOAs) have been identified in nearly all classes of chondritic meteorites, though the abundances and properties of these refractory materials do vary among the different meteorites [1]. More recently, CAIs have been identified in the materials collected from the Stardust spacecraft from Comet Wild 2 [2-4], with possible AOA-like materials also having been identified [5]. Along with these are Mg-rich, crystalline silicates that are thought to have formed via condensation or annealing at high temperatures [6].

Refractory objects are thought to provide very important clues about the early evolution of our solar nebula. The CAIs found in chondritic meteorites (particularly the CV chondrites) have the oldest ages of all the materials that have been dated in our meteorite collections, predating the chondrules with which they co-accreted by at least 1-2 million years [7]. The mineralogy and chemical compositions of these objects are similar to what is expected to form when a gas of solar composition begins to condense as it cools [8], with subsequent, and possibly multiple, evaporation and condensation processing occurring at high temperatures [9]. AOAs are composed of forsterite, but also contain some of the minerals found in CAIs and Fe-Ni metal and have oxygen isotope ratios very similar to CAIs, suggesting a genetic relationship exists between the two types of objects [1]. Given these properties, these refractory objects are thought to record information about the hottest, earliest stages of our solar nebula.

Recently, efforts have been made to gain further insight into the timing of the formation of these refractory objects and what they can tell us about processes and conditions that were present within the solar nebula. Rather than just look at the age differences between the CAIs and chondrules, efforts have been made to date the duration of CAI formation, with some studies suggesting a period of just 20,000 yrs [10,11].

An important aspect of the story of refractory objects, however, is that they experienced significant dynamical evolution within the solar nebula prior to their incorporation into the bodies in which they are found. Here we present results of models showing how the dynamical evolution of a protoplanetary disk and transport of solids contained within impact inferred ages and/or formation duration of the CAIs and other refractory objects.

Model: We adopt a similar approach as Cuzzi et al [12] by using the standard α-viscosity model to describe the mass and angular momentum transport in the solar nebula by attributing them to shear stresses within the differentially rotating gaseous disk. We define the formation region for refractory objects as being wherever temperatures are above 1350 K. This temperature is close to the condensation temperature of forsterite at inner nebula pressures [13], and thus represents the region where processing of CAIs and AOAs may occur, or the region from which crystalline objects may condense [6].

Refractory objects are then redistributed by the combined effects of the large-scale flows associated with disk evolution, turbulent diffusion, and inward drift from gas drag. We consider refractory objects of different radii in order to investigate any size dependence that is expected in the absolute ages or spread in ages of the refractory objects available to be incorporated into planetesimals throughout the solar system as a function of time.

Results: The results of a typical model simulation are shown in Figures 1-3. For this run we considered the dynamics of a 0.1 $M_{\odot}$ solar nebula, with the mass distributed from 0.1 to 10 AU, and a turbulence parameter of $\alpha=10^{-3}$. Figure 1 shows the initial surface density of the disk (heavy line) and the surface density at 500,000 year intervals. There is substantial dynamical evolution of the disk, as it thins and grows in radial extent due to mass and angular momentum transport.

As the disk evolves, it cools over time, as shown in Figure 2, which gives the temperature distribution of the inner disk at 500,000 year intervals. During the earliest stages of evolution, temperatures in excess of 1350 K extend out to nearly 3 AU. The plateau in the temperatue at 1350 K is due to the changes in opacity associated with the evaporation of forsteritic dust [13]. Temperatures in excess of 1350 K persist for just over 1 million years in this simulation, allowing refractory objects to be produced over this time interval.

Figure 3 shows the age distribution of the refractory objects remaining in the disk after 2 million years of evolution, with each line representing the fraction of objects that formed in 10^5 year intervals. The solid line represents those refractory objects that formed between $t=0$ and $t=10^5$ years, the dashed lines those that formed between $t=10^5$ and $t=2\text{x}10^5$ years, and so on. The particular results here are for 1 millimeter diameter objects but similar results are found for smaller and larger sizes. Those objects that formed during the very earliest stages ($t<10^5$ yrs) of disk evolution make up over 99% of the survivors.

Discussion: We have performed a series of model runs like that shown here, varying key parameters, and find that the general results are robust: the population of refractory objects that is most abundant after >1 million years of evolution are those that formed during the earliest stages (<10^5 yrs) of disk evolution. There are two main reasons for this result. The first is that the greatest number of refractory objects are produced during the earliest epoch of disk evolution. This is when the disk is most massive and when the highest temperatures are reached. As the disk evolves, it cools reducing the rate at which refractory objects produced.

Further, outward transport occurs most readily during the initial stages of disk evolution. As mass is transported inward through the disk due to its viscous evolution, the disk grows in radius due to angular momentum transport. The most rapid expansion occurs early on, with net outward velocities existing very close to the star. As the disk evolves, the location marking the division between net inward and net outward velocities of disk materials migrates outwards, meaning that objects formed at later times would be subjected to inward flows throughout much of the disk, making survival for long periods of time difficult.

Large objects will also develop increasingly larger inward velocities due to gas drag as the gas densities decrease, making survival difficult. As with previous studies [e.g. 12], these inward velocities pose a challenge to keeping the needed number of large refractory objects to explain the observed abundances of CAIs in CV chondrites. We are currently exploring possible solutions to this issue, including variations in the effecitive α of the disk as would be expected in a gravitationally unstable solar nebula [14] and investigating the dynamical evolution of the nebula as mass is added to it through infall of the parent molecular cloud [15]. Preliminary results from both possibilities continue to support our main conclusion: Refractory objects formed during t<10^5 years will dominate the population accreted into a given meteorite parent body or comet. This limits the time when short-lived nuclides could be introduced into the solar system and constrains where the t=0 in meteoritics falls in the astrophysical stages of star and disk formation.

References: [1] Scott E. R D. and Krot A. N. (2005) *Treat. Geochemistry, 1,* 143-200. [2] Brownlee et al. (2006) *Science., 314,* 1711-1716. [3] Zolensky et al. (2006) *Science,* 1735-1739. [4] McKeegan et al (2006) *Science*, *314,* 1724-1728. [5] Messenger et al. (2008) *Metorit. Plan. Sci., 43,* #5308. [6] Wooden D. H. (2008) *Space Sci. Rev., 138*, 75-108. [7] Amelin et al. (2002) *Science, 297,* 1678-1683. [8] Grossman L. (1972) *Geochim. Cosmochim. Acta, 36,* 597-619. [9] Richter et al. (2006) *Meteorit. Plan Sci., 41,* 83-93. [10] Thrane et al. (2006) *ApJ, 646,* L159-L162. [11] Jacobsen et al. (2008) *Earth Plan. Sci. Let., 272,* 353-364. [12] Cuzzi et al. (2003) *Icarus, 166,* 385-402. [13] Cassen (1994) *Icarus, 112,* 405-429. [14] Boss, A. P. (2008) *Earth Plan. Sci. Let., 268,* 102-109. [15] Yang L. and Ciesla F. J. This conference.

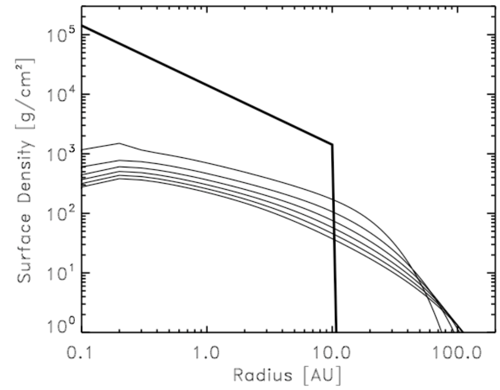

Figure 1: The surface density evolution of the disk considered here, with the heavy line indicating the initial structure and other lines indicating the structure at 500,000 year intervals.

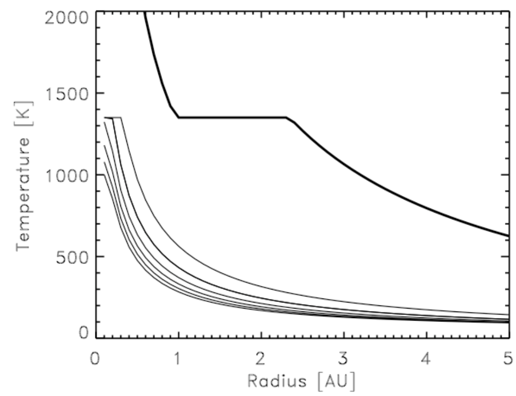

Figure 2: The thermal evolution of the inner disk at 500,000 year intervals, with the heavy line indicating the temperature at the beginning of the simulation. The plateau at 1350 K is due to the evaporation of fine dust, which lowers the opacity [13].

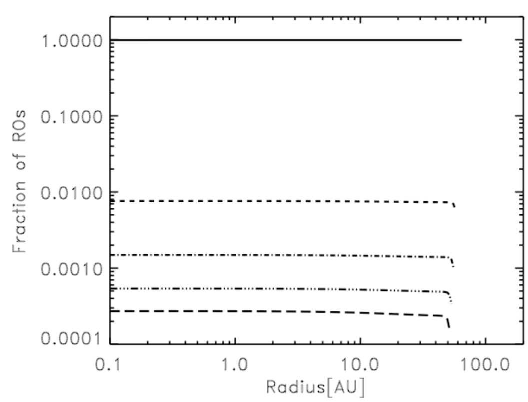

Figure 3: The distribution of ages for refractory objects surving in the disk for 10^6 years. Each line indicates the fraction of objects formed at different 10^5 year intervals, with the heavy line indicating those that formed earliest (0<t<10^5 yrs).