INJECTION AND HOMOGENIZATION OF SHORT-LIVED RADIONUCLIDES IN THE SOLAR SYSTEM.

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Introduction: Isotopic abundances of short-lived radionuclides (SLRN) such as ^{26}Al appear to provide precise chronometers of events in the early Solar System, assuming that they were initially homogeneously distributed. However, both ^{60}Fe and ^{26}Al were likely formed in a supernova and then injected into the solar nebula in a highly heterogeneous manner. On the other hand, the abundances in primitive meteorites of the three stable oxygen isotopes exhibit mass-independent fractionations that somehow survived homogenization in the solar nebula. The presence of refractory particles in Comet 81P/Wild 2, and the anomalously high crystallinity observed in protoplanetary disks, may both require large-scale outward radial transport from the hotter inner disk regions, even as disk gas accretes onto the central protostar. We examine here theoretical efforts to solve these seemingly disparate cosmochemical puzzles [1].

Injection: Simultaneous triggered cloud collapse and injection was proposed long ago [2] and by now has been investigated in considerable detail [3]. Supernova shock waves (Figures 1-4) have been shown to be better suited for efficient injection of SLRNs than AGB shock waves [4]. The leading alternative is injection by a supernova shock front directly into the solar nebula [5]. This mechanism is unable to inject shock front gas into the nebula, but particles with sizes of at least 0.1 micron could be injected [6]. However, most grains in supernova shocks are thought to be sputtered to much smaller sizes.

Homogenization: Viscous accretion disk models have long been proposed as agents of disk transport [7]. The leading candidate for the source of the hypothesized turbulent viscosity is magneto-rotational instability (MRI). However, MRI cannot operate in regions of low ionization, and such magnetically-dead zones are thought to occur in the nebula midplane at planet-forming distances. Viscous accretion disk models have been extended to consider disks with finite thickness [8], where it has been found that motions are radially outward in the midplane and radially inward at the disk surface [8,9]. The alternative mechanism is a phase of marginal gravitational instability (MGI), where spiral arms grow and result in rapid inward and outward transport of gas and small particles [10], as well as mixing that reduces isotopic heterogeneity to acceptable levels [11]. MGI is also consistent with the need to form both chondrules and gas giant planets [12].

Conclusions: The cosmochemical and astronomical evidence demands a multi-faceted scenario for the early Solar System: 1) injection of SLRNs into the presolar cloud (or possibly the solar nebula) by a supernova shock wave, 2) homogenization of these initially heterogeneous SLRNs to less than $\sim 10\%$ in the inner solar nebula, while 3) preserving oxygen isotope heterogeneity of order 10% throughout the entire disk, 4) transporting crystalline grains outward to distances of 3 AU or more, or annealing amorphous grains in situ, and 5) transporting refractory inclusions from well inside ~ 1 AU to the comet-forming regions in the outer disk.

Assuming the absence of MRI dead zones and the validity of assumptions about the strength of turbulent viscosity and particle diffusivity, viscous accretion disk models are quite capable of achieving goals 4) and 5). They should also lead to homogenization, though this has not yet been quantified. A better case can be made for achieving goals 2) to 5) through MGI. MGI disk models support the evidence for the relatively high degree of homogeneity observed in SLRNs as well as the finite amount of heterogeneity seen in the stable oxygen isotopes. Refractory inclusions would be expected to be transported from the inner disk to much greater distances in the solar nebula, sufficient to become incorporated there in icy planetesimals, i.e., comets. MGI disks also offer the option of thermal annealing of amorphous grains in situ, in addition to transport from the inner disk.

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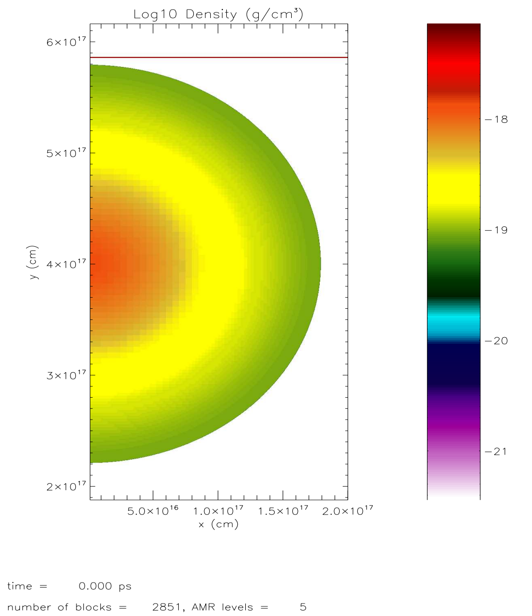

Figure 1. Supernova shock (top) about to strike the presolar cloud at 40 km/sec. Cloud radius is 12,000 AU. Symmetry about left border is assumed.

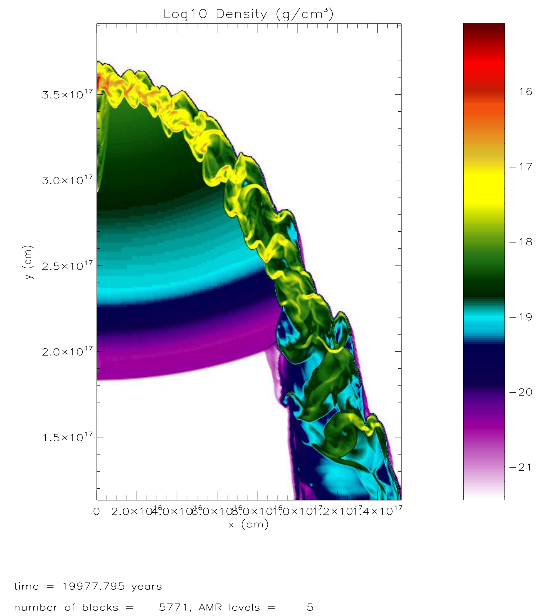

Figure 2. By 0.02 Myr, Rayleigh-Taylor fingers appear as the shock triggers the cloud into collapse while ablating some of the cloud downstream.

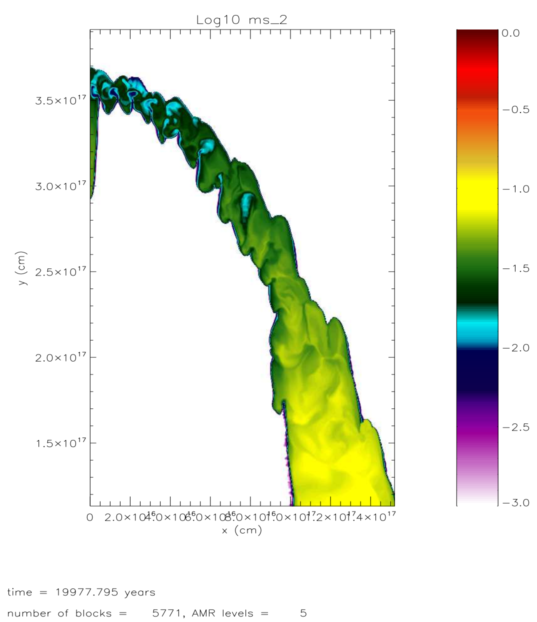

Figure 3. Shock front material only is shown at 0.02 Myr, showing injection deep into the cloud.

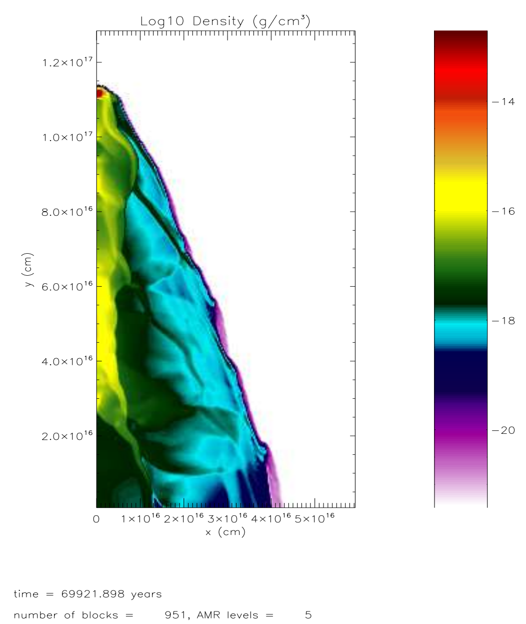

Figure 4. By 0.07 Myr, the protosun (red) has formed and begun its dynamic collapse phase.