Delivery Mechanism Of Supernova Produced ^{26}Al, ^{60}Fe, And Oxygen To The Forming Solar System.

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Numerous isotopes have been detected that did not originate in the material from which the Solar System formed [e.g. 10]. The elements/isotopes we focus on in this abstract/project are the unstable isotopes ^{26}Al,^{41}Ca, ^{60}Fe (half lives $\sim$1 million years), and the stable oxygen istopes ($^{16-18}$O). Some of these elements are considered essential for or conducive to the formation of live on Earth. ^{26}Al and ^{60}Fe, for example, areconsidered important for the melting and differentiation of planetesimals, and oxygen is necessary for cellular respiration for all complex life on earth and is also useful to constrain the origin(s) of those isotopes [2, 4]. ^{41}Ca has been shown to originate from the same source as ^{26}Al [9].

^{60}Fe requires a massive star as the source. Massive stars can produce all the other elements under consideration and is a viable source for those as well The most popular origin for isotopes like ^{26}Al and ^{60}Fe is through injection of supernova material into the forming solar system. Numerical calculations have shown that both a solar nebula a few parsecs away from an exploding massive star [e.g. 1] and an already formed protoplanetary disk as close as a few tenth of a parsec away [8] can survive a supernova shock wave. In the former case, the supernova shockwave has been shown to be able to trigger the collapse of the nebula under certain circumstances. As observations of star formation indicate, most stars form in a cluster with at least one massive star that will go supernova before the cluster disperses [5], giving either case a natural and probable setting. However, in the simulation of both cases (disk and nebula) the supernova material needed to be in higher density regions than the average ejecta.

Specifically, the calculations of Ouellette et al. [8] have shown that gas of density $\sim 10^2$ g/cm^3 did not get injected, but dust grains of ejecta material larger than 0.01 μm in diameter did. In their calculations a bow shock developed around the protoplanetary disk as the shock wave hit it, effectively diverting the gaseous part of the ejecta around the disk. Optical knots that have been observed in the Cassiopeia A supernova remnant have an assumed density of 10^{3-5} g/cm^3, up to three orders of magnitude greater than the average ejecta density. Such a knot may have enough momentum to overcome the bow shock and get incorporated into the disk [see 11]. In the calculation of Boss et al. [1] the injection occurred through Rayleigh-Taylor fingers that were able to penetrate the nebula due to their higher density.

This makes the case that if supernova material is to be delivered *into* the solar system, it will have to be in the form of one or more over-dense clumps of supernova ejecta, comprised of either dust, higher density gas, or both. Observations of supernova remnants (e.g. the one million second exposure of Cassiopeia A by Hwang et al. [6]) show that the ejecta is fragmented into lots of over- and underdense regions after the explosion. But fragmentation and clump formation in supernova ejecta has not been studied in detail numerically so far.

We are conducting computer simulations of supernova explosion in 3 dimensions using the parallel, 3D smooth particle hydrodynamics code of Fryer and Warren. We have run a preliminary simulation with 1 million SPH particles of a spherically symmetric (3D) explosion of a 15 M$_\odot$ star. The star was evolved from its birth to the collapse of the core and launch of the shock in 1 dimension with the TYCHO stellar evolution code. Its structure was then mapped into 3 dimensions when the

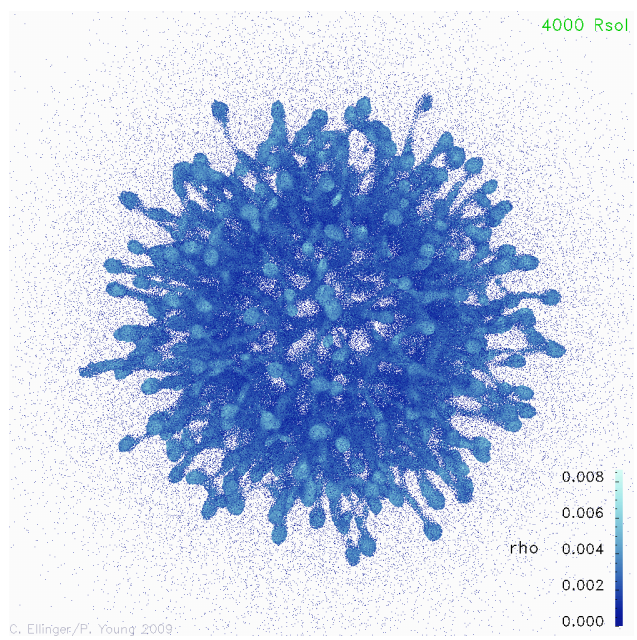

Figure 1: Density plot of a simulation of a 15 M$_\odot$ supernova explosion, showing the hydrodynamic instabilities that develop. The snapshot is at about 52 hours after the launch of the shock and measures 4000 R$_\odot$ across. The density scale bar (rho) is in 10^{-6}M$_\odot$/R$_\odot^3$

bounce shock had reached the edge of the core. Mapping it into 3-D shortly after the beginning of the explosion preserves much of turbulent behavior during the explosion while not being too computationally intensive. Hydrodynamic instabilities readily develop causing the formation of knotty structures and over-dense clumps as can be seen in figure 1). These structures persist to the end of the simulation, which was terminated at 1.5 years in the star's time. A plot of a few abundances suggests that the knots are rich in ^{16}O and devoid of ^{28}Si and ^{56}Ni. Although this simulation did not include a nuclear reaction network or an appropriate cooling routine, adding these is not expected to significantly alter the hydrodynamic behavior.

We are currently working on determining the final size and density of these structures, and their composition. For that we are working on adding a circum- stellar medium into which the remnant expands and a small nuclear reaction network to the SPH code to track energy generation as well as a cooling routine for its later evolution. We are planning to repeat the 15 $M_\odot$ explosion with this more natural setup of the code and evolve it for a longer time. We can then use a larger reaction network to post-process the simulation and determine yield of the explosion. Once that is in place we can make more accurate predictions for size, density, composition, temperature evolution of, and can start estimates for dust formation in the knots.

Although we have already achieved promising results so far from one simulation, in order to be able to make generalized predictions we will need to run simulations for a range of progenitor stars.

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