

Delivery of Supernova Material to the Interstellar Medium Through Ejecta Knots

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1. Introduction

Observations of the remnants of core-collapse supernovae show a lot of structure and inhomogeneities. Among the features observed are non-uniform distribution of matter and nucleosynthesis products, and fast moving ejecta knots [3, 5, 8, 11]. As these features are seen in the ejecta material, they are typically taken as evidence for the turbulent nature of the explosion of a massive star. This turbulence has been predicted on theoretical grounds and investigated with numerical methods. Our specific interest is it to investigate the formation of such structures in computer simulations of supernova explosions, and to follow their further evolution into the remnant phase of the explosion.

2. Calculations

The simulations were carried out with SNSPH, which is a 3-dimensional, smoothed particle radiation–hydrodynamics code with adaptive time stepping [4]. The code was augmented by adding abundance tracking capabilities and a 20 isotope (mostly alpha-chain) nuclear reaction network for tracking energy generation from nuclear burning. Accurate abundances will be determined in a post-processing step with a much larger (up to 3304 isotope) reaction network. Furthermore, a radiative cooling routine was added, based on the CHIANTI database for arbitrary compositions of optically thin plasmas. This cooling routine calculates the cooling in the ejecta due to electronic transitions and recombinations once the ejecta has expanded enough that radiation can escape from the matter. The purpose of the radiative cooling routine is to facilitate a more accurate evolution of the remnants post- explosion.

The progenitor used is a $15M_{\odot}$ star of solar metallicity, that was evolved with the stellar evolution code TYCHO [14] from the pre-main sequence to the onset of core-collapse. The collapse of the core and bounce was treated as a 1-dimensional problem and calculated in a 1D Lagrangian code developed by [6]. Once the shock reached the edge of the neutrino sphere, the 1D explosion was mapped into 3D with 1 million SPH particles, and the explosion was continued in 3D with SNSPH.

The SPH calculation was repeated from the same progenitor model for several different scenarios. A control run was performed with both the nuclear reaction network and the radiative cooling turned off for the entire run. This control run serves as a baseline for comparison to other runs. A 'burning run' was performed with the reaction network turned on to investigate the the effect of the added energy from the nuclear burning on the hydrodynamics.

A 'cooling run' was also performed where the radiative cooling routine was turned on. Since radiative cooling is not important until the ejecta expands enough to become optically thin, this cooling run was started from an intermediate output of the control run. The cooling run was started after about 0.3 yrs after the explosion, and a check was added to SNSPH to allow for cooling only in the sufficiently optically thin regions. Sufficiently optically thin was taken to mean that mean free path is comparable to the size of the respective SPH particle.

The control run was evolved out to 20 yrs, at which time the edge of the star had expanded to a radius of $\sim 0.3pc$. The burning run was stopped shortly after temperatures had dropped below $1 \times 10^7 K$, and the cooling run was evolved out to $\sim 1yr$. In all runs conducted so far the ejecta expands into vacuum. As the density of the H envelope of the star is about a factor of 1000 greater

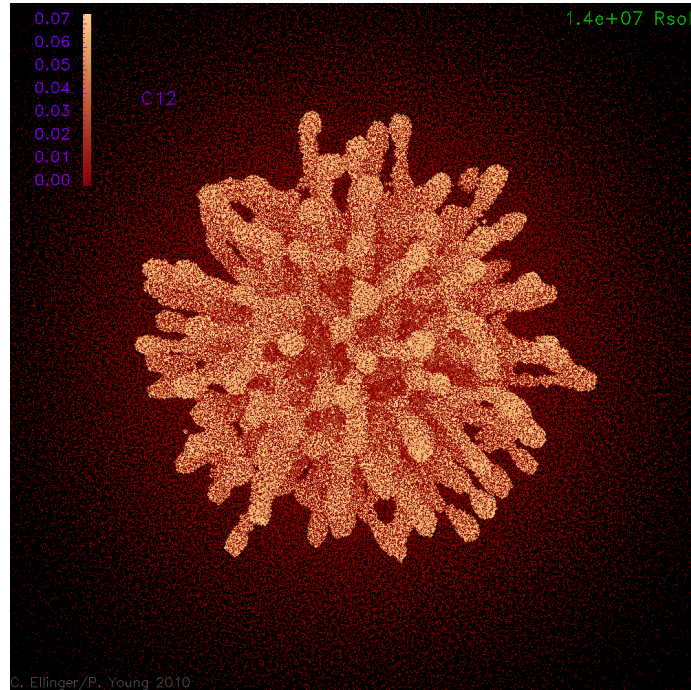


Figure 1: Shown is a snapshot from the control run at 20yrs after the explosion. The image is about 0.6 pc across. The color gradient indicates mass fraction of unprocessed ^{12}C per particle, with high abundance shown in yellow and low abundance in dark red. Apparent are fingerlike structures of higher density that have formed out of hydrodynamic instabilities during the explosion. The density in the structures reaches $\sim 10^{-18}\text{g/cm}^{-3}$.

than the density of the surrounding medium, for the initial expansion of the supernova this in an appropriate approximation. However, once the expanding ejecta sweeps up a mass of interstellar material equal to its own mass, interaction of the ejecta with the surrounding medium will become important. Thus, for the further evolution into the remnant phase, and ISM will be added to the simulations.

3. Results

Our calculations so far indicate that structure forms early during the explosion, and that its formation is dominated by the hydrodynamics. The finger-like filaments that can be seen in Fig. 1 develop early in explosion, approximately at the inner edge of the pre-supernova oxygen-rich layer. The filaments develop behind the blast wave, shortly after the shock had moved through that material, and remain behind the shock for the rest of the simulation. Preliminary calculations at a higher resolution suggest that the extend of the filaments is resolution– dependent; at higher resolutions the filaments extend out much further into the envelope. The size of the clumps at the ends of the filaments was independent of resolution, however.

The development of the filaments is likely due to Richtmyer- Meshkov instabilities. There is a steep gradient in composition between the O- rich layer and the layers below it in the star, as the average atomic number \bar{A} nearly doubles (from $\bar{A} \sim 16$ for the O- rich layer to $\bar{A} \sim 30$ for the Si/S

rich layer). A supersonic shock wave accelerated into such a gradient would result in Richtmyer-Meshkov instabilities. It is also possible that convective cells developed in the 3D calculation, and at the nodes finger-like structures formed. As a note, these clumps are still much bigger, and fewer in number than the ejecta knots as seen for example in the Cassiopeia A supernova remnant, but we expect that the radiative cooling will further fragment them into smaller clumps.

The chemical make-up of these filaments and clumps is that of the O- and C- rich layers of the star. Elements heavier than that (e.g. Fe, Ti) remain inside of these structures, and no significant mixing of those into the filaments is observed. This may be an artifact of the timing at which the 3D calculation was started. The 3-dimensional calculation was started when the blast wave had already progressed to the inner edge of the O-rich layer, and the explosion was constrained to 1D before that.

The burning run indicates that the energy released from nuclear burning during the explosion does not influence significantly the development of hydrodynamic instabilities. This is expected as the explosion of the supernova is dominated by the hydrodynamics. The effect of the decay energy of the Ni-Co-Fe decay chain on the morphology of the remnant has not yet been investigated in detail. However, a preliminary further evolution of the burning run out to several years suggests that a structure of smaller bubbles develops in the regions rich Fe-group elements, i.e. inside of the fingers and clumps seen in Fig. 1.

Radiative cooling will not be important until the matter has expanded enough to become optically thin, and a reverse shock travels through the ejecta heating it to ionizing temperatures. Once that point is reached, radiative cooling is expected to further fragment the formed clumps. As our supernovae expanded into vacuum (and also because the calculations were not evolved far enough yet), no reverse shock was observed in the simulations. Evolving the calculations further, and adding an interstellar medium to the calculations, will be necessary to investigate this.

4. Discussion

The delivery of supernova material to the interstellar medium has applications in a range of situations. Of particular interest to us is the application to the formation history of the solar system. There is evidence that our solar system was contaminated with supernova material during its formation [1, 12]. A couple of different radioactive isotopes with half lives on the order of a million years have been found in primitive solar system material that point to a supernova origin [13]. Furthermore, proto- planetary systems are often found around low- mass stars in OB associations [7], providing a natural environment and a high probability of core-collapse supernovae occurring in the vicinity of forming planetary systems. Calculations of the interaction of ejecta gas incident on a protoplanetary disk have shown that an injection of material into the latter can only occur for high density clumps or dust grains in the ejecta [9, 10]. If one assumes clumps with properties like the ejecta knots in Cas A, and an average distance between massive stars and proto- planetary disks like in the Orion nebula, one finds that the probability of contamination is about 1, that is a forming solar system intercepts on the order of one clump of supernova material when it forms. First estimates from our SPH calculations also indicate that the material in such a clump could have the appropriate composition to be considered in a supernova enrichment scenario of our nascent solar system [2].

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