Mixing of Supernova Ejecta into Molecular Clouds

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From isotopic studies of meteorites, it is known that the early Solar System contained over a half dozen short-lived radionuclides (SLRs) such as ^{26}Al and ^{60}Fe, with half-lives $\approx 1\,$Myr [1]. The origins of these SLRs are consistent with injection of supernova material into the Solar System, either in its molecular cloud stage or into the protoplanetary disk [1]. In fact, the origin of ^{60}Fe is only plausibly explained by a nearby supernova during the Sun's origin, within the Sun's star-forming cluster [1]. Supernovae also appear capable of contaminating forming planetary systems with stable isotopes. The oxygen isotopic abundance of the Sun, compared with field stars, suggests contamination by supernova material [2]. More important, some protostars in the Orion Ic and Id associations show overabundances of Si and O (but not C and N) compared to other stars in these associations, and especially with respect to the earlier-formed Ia and Ib associations. The pattern of overabundance strongly suggests contamination by supernova ejecta.

Motivated by these observations, we have undertaken a detailed numerical study of what happens to supernova material as it interacts with nearby molecular cloud material at the periphery of a star-forming region. Our focus is to to determine the depth to which supernova material can penetrate into the molecular gas, and whether it can be incorporated into forming stars.

The Simulations

In our initial study, we neglect complications such as the ionization front produced by the star before it dies and the density fluctuations and the supersonic MHD turbulence in the molecular cloud. Instead we adopt a simplified geometry in which a contact discontinuity separates a warm ionized region, which represents the ambient gas photoionized by the exploded star, from a cooler neutral region, which represent the edge of the molecular cloud. Both the ionized gas and the molecular cloud are assumed to be uniform in density and are taken to be static before being hit by the supernova ejecta. We then study how the ejecta, after moving through the ionized warm gas, penetrates into in the molecular cloud and mixes with the gas there.

Our simulation is carried out using FLASH version 3.2, a multidimensional adaptive mesh refinement (AMR) hydrodynamic code. To maximize mixing, we consider the ejecta to be concentrated into "clumps" such as those observed optically [6] and in X rays [7] in the Cassiopeia A supernova remnant. Motivated by these observations, we set the size of the ejecta clump to 10^{16} cm and its speed to 2000 km s^{-1}. Numerical simulations suggest the formation of $\sim 10^4$ such clumps during the explosion [8], a number consistent with the Cas A imagery. We accordingly assume a mass $\sim 10^{-4}\,M_\odot$ for each. We use the typical density of 10^4 cm^{-3} for the molecular cloud and take the temperature to be 40 K. For the ionized gas, we adopt a temperature of 8000 K. Assuming a pressure equilibrium with the molecular gas, we set the density in the ionized gas to 50 cm^{-3}.

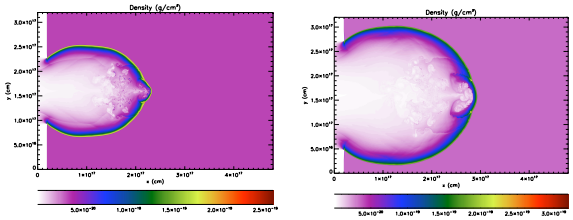

Figure 1: The density field at 90 yr (left) and 180 yr (right). The domain size is 4.8×10^{17} cm $\times$ 3.2×10^{17} cm.

Fig 1. shows the density from a 2D simulation of this interaction, which is similar to the cloud-ISM interaction studied in [9]. The high-speed clump drives a bow shock as it moves into the molecular cloud. As the molecular cloud is accelerated by the shock, the clump of gas is not able to catch up with the edge of the cloud, and remains separated throughout the simulation. Thus it appears that it is unlikely that metals in the ejecta clump can be delivered into the molecular gas unless the shock somehow stalls or breaks, e.g. by the interaction with turbulence in the molecular cloud. In our simplified simulation. Since the shock speed is initially much larger than the rms velocity in the cloud, we expect that the turbulence does not significantly affect the dynamics of the shock until very late times.

Due to the asymmetry of the bow shock, shear flows appear in the postshock region, which give rise to the Kelvin-Helmholtz instability. The vortices from the instability can transport and distribute metals in the postshock regions. In Fig. 2, we show the distribution of the ejecta at 180 yrs, which is obtained by evolving the advection equation of a passive scalar whose initial con-

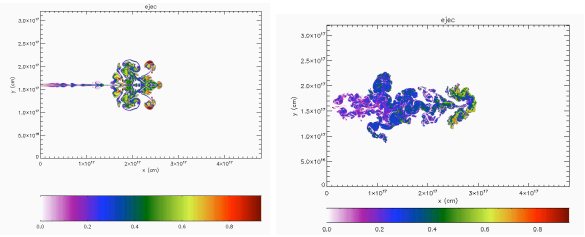

Figure 2: The distribution of the ejecta gas at time 180 yr at different numerical resolutions. The left panel is at refinement level 7 and the right at level 9. With higher resolution the ejecta material is more spread out.

figuration is set to be unity within the ejecta clump and zero otherwise. We see that the metals are spread out in the postshock region and find that the spatial range over which the ejecta material is spread depends on the simulation resolution. The right panel of Fig 2 shows the results for a higher level of AMR refinement. With higher resolution, the instability is better developed, and the metals are transported to a larger region. We point out that K-H instability can only redistribute the metals behind the shock and apparently it is incapable of delivering to the molecule gas in front of the shock. Therefore, transport by the K-H instability only provides an initial condition for the mixing later that starts when the shock stalls or breaks. This later mixing phase will be studied with a simulation including turbulent motions in the molecular cloud.

Future Work

As discussed above, turbulence in the molecular cloud may play an important role in the process of mixing the metals in the SN ejecta clump into the molecular cloud. Therefore a final answer will require us to carefully model the shock-turbulence interaction at the late evolution stage.

To address this complication we are currently simulating turbulent flows at various Mach numbers for a study addressing the general question how mixing occurs in supersonic turbulence and whether and how the mixing process depends on the Mach number. This work would provide insights on mixing of the ejecta clump after the shock breaks. The simulated supersonic turbulence with high Mach numbers corresponding to that in molecular clouds will be used to study the interactions between the shock and the turbulence of interest here. We will examine when and how the shock finally breaks and allows the metals behind the shock to be delivered to the molecular gas, as well as the mixing process after the shock breaks. As a result of this study we will modify the simulations show here to account for the impact of a a high-speed ejecta clump impinging on a much more realistic molecular cloud, whose internal velocity structure is that of fully-developed supersonic turbulence.

Another interesting question we will study w is how the density fluctuations in the cloud affect the transport of metals in the SN ejecta. It has been established by numerical simulations that the amplitude of density variations spans up to 5 orders of magnitudes in supersonic turbulence at high Mach numbers [e.g. 10]. Thus, the bow shock entering the turbulent cloud is likely to develop small-scale structures as it sweeps over the gas with significant density fluctuations. For example, when encountering lower-density regions, the bow shock could move faster and accelerate. This would give rise to Rayleigh-Taylor instability as well as the Kelvin-Helmholtz instability. This may provide a mechanism for the delivery of metals to the molecular gas: the ejecta could follow the shock penetrating to the low-density regions in the cloud and mix the the gas there with the help of the instabilities. In that case, mixing may not have to wait until the shock stalls to velocities on the order of the turbulent velocity in the cloud.

Finally, a significant fraction of the metals in the ejecta clump may be in the form of dust grains. Different for the gas-phase metals, dust grains do not directly feel the gas pressure, instead they interact with the gas through a friction force. Large grains can thus decouple from the gas motions if the friction timescale is large. Therefore these large dust grains are not restricted to the postshock regions as the gas-phase metals. If, within a friction timescale, the dust grains could reach deep into the molecular cloud, that would give another mechanism for the delivery of the newly-produced metals in the cloud. We will also preform a series simulations targeted at studying this potential transport mechanism for SN ejecta.

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