Mixing of Clumpy Supernova Ejecta into Nearby Molecular Clouds

Steven J. Desch[1], Liubin Pan[2], Evan Scannapieco[1] and F. X. Timmes[1], [1]School of Earth and Space Exploration, Arizona State University, PO Box 1404, Tempe AZ, 85287-1404, USA. [2]Harvard-Smithsonian Center for Astrophysics, 60 Garden St., MS-51, Cambridge, MA, 02138. (steve.desch@asu.edu)

Background: Many lines of evidence point to the Sun and solar system being contaminated by material from a nearby supernova, either just prior to or during its formation. Isotopic analyses of meteorites reveal evidence for the one-time presence of short-lived radionuclides (SLRs) such as ^{26}Al ($t_{1/2} = 0.71\,\mathrm{Myr}$) and ^{60}Fe ($t_{1/2} = 2.3\,\mathrm{Myr}$) [1]. Strong arguments can be raised against formation of ^{26}Al and ^{60}Fe within the solar system by solar energetic particles [2-3], so stellar contamination is argued for. The abundance of ^{60}Fe has been revised downward recently, to initial abundances $^{60}\mathrm{Fe}/^{56}\mathrm{Fe} \sim 10^{-8}$ [4-6]. Since this is near the overall average in the Galaxy, a late injection of supernova material has been questioned [6], but in fact the Sun almost certainly could not form from the hot intercloud medium within a few half-lives of ^{60}Fe, and if it did it would also contain exceeding overabundances of other SLRs, especially ^{129}I [7-8]. So a stellar source had to contaminate the forming solar system, and the only source astronomically associated with forming stars is the core-collapse supernova (or possibly the Wolf-Rayet stage preceding the supernova) [9]. Based on the homogeneity of ^{26}Al, this mixing had to occur prior to in the first < 0.3 Myr of the solar system's formation [10-11].

Contamination of a star-forming region by multiple supernovae has been considered by [12], but astrophysical objections were raised by [2], and [13] pointed out that injection from multiple supernovae will overproduce ^{53}Mn, implying a single supernova is involved. Previously, [14,15] argued that supernova material could be injected into an already-formed protoplanetary disk, but to be statistically likely the disk would have to lie < 0.2 pc from the supernova, which is inconsistent with the formation happening early in the Sun's evoluton [16,17]. Injection of supernova material into molecular clouds was considered by Boss ([18] and subsequent works), but demands low velocities ($\sim 20\,\mathrm{km\,s^{-1}}$) for supernova ejecta to penetrate into the clouds [19], demanding a distant supernova and involving dilution of isotopes. Massive stars are likely to explode still surrounded by their natal molecular gas [9], lying no more than a few pc away. Star formation appears to be triggered continuously for many Myr in the molecular gas at the periphery of the ionized H II region [9,20], so it is likely that a star can be forming in this gas as the supernova explodes after $\approx 4\,\mathrm{Myr}$. Here we investigate the interaction of this supernova ejecta with that molecular gas, to see if the ejecta can penetrate into the molecular gas and contaminate newly forming star systems.

Results: As described in [21], we have carried out a suite of numerical simulations using the FLASH 3.2 code [22], designed to investigate how clumpy supernova ejecta could interact with nearby molecular gas. Molecular gas with density $3.3 \times 10^{-20}\,\mathrm{g\,cm^{-3}}$ and temperature 40 K is separated by a plane at $z = 0$ from ionized gas with $1.7 \times 10^{-22}\,\mathrm{g\,cm^{-3}}$ and temperature 8000 K. We neglect heterogeneities within the molecular gas, but it should be considered to have been affected by a D-type shock front and to be just beginning to form stars. We assume, based on arguments advanced by [14,15] and images of the Cassiopeia A supernova remnant [23], that the ejecta are predominantly in clumps, with masses $10^{-4}\,M_{\odot}$, radii $5 \times 10^{15}\,\mathrm{cm}$, and densities $3.8 \times 10^{-19}\,\mathrm{g\,cm^{-3}}$, colliding with the molecular cloud at $2000\,\mathrm{km\,s^{-1}}$. Figure 1 shows their interaction over 10,000 years. The ejecta are seen to penetrate roughly 0.5 pc into the molecular gas. The effects of clump density, size and velocity, and of gas cooling rate and ejecta isotropy are considered in a parameter study by [21]. Penetration of supernova ejecta to depths $\sim 0.5\,\mathrm{pc}$ is robust, provided cooling is included, and that supernova ejecta really are clumpy with parameters like those assumed above; isotropically exploding supernova ejecta will *not* penetrate into a molecular cloud.

For a supernova $\approx 2\,\mathrm{pc}$ distant, clumps will be typically separated by ~ 0.07 pc, comparable to the channel width. We conclude that all stars forming at the periphery of the H II region will receive similar levels of supernova contamination (albeit from different shells of the supernova). Comparing the mass of molecular gas between the edge and a depth 0.5 pc, we infer a mixing ratio $\sim 10^{-4}$, easily consistent with the meteoritic abundances of ^{26}Al and ^{60}Fe. Statistically, a large fraction ($\sim 10\%$) of Sun-like stars can form late in the evolution of an H II region with a massive supernova, and be contaminated in this way.

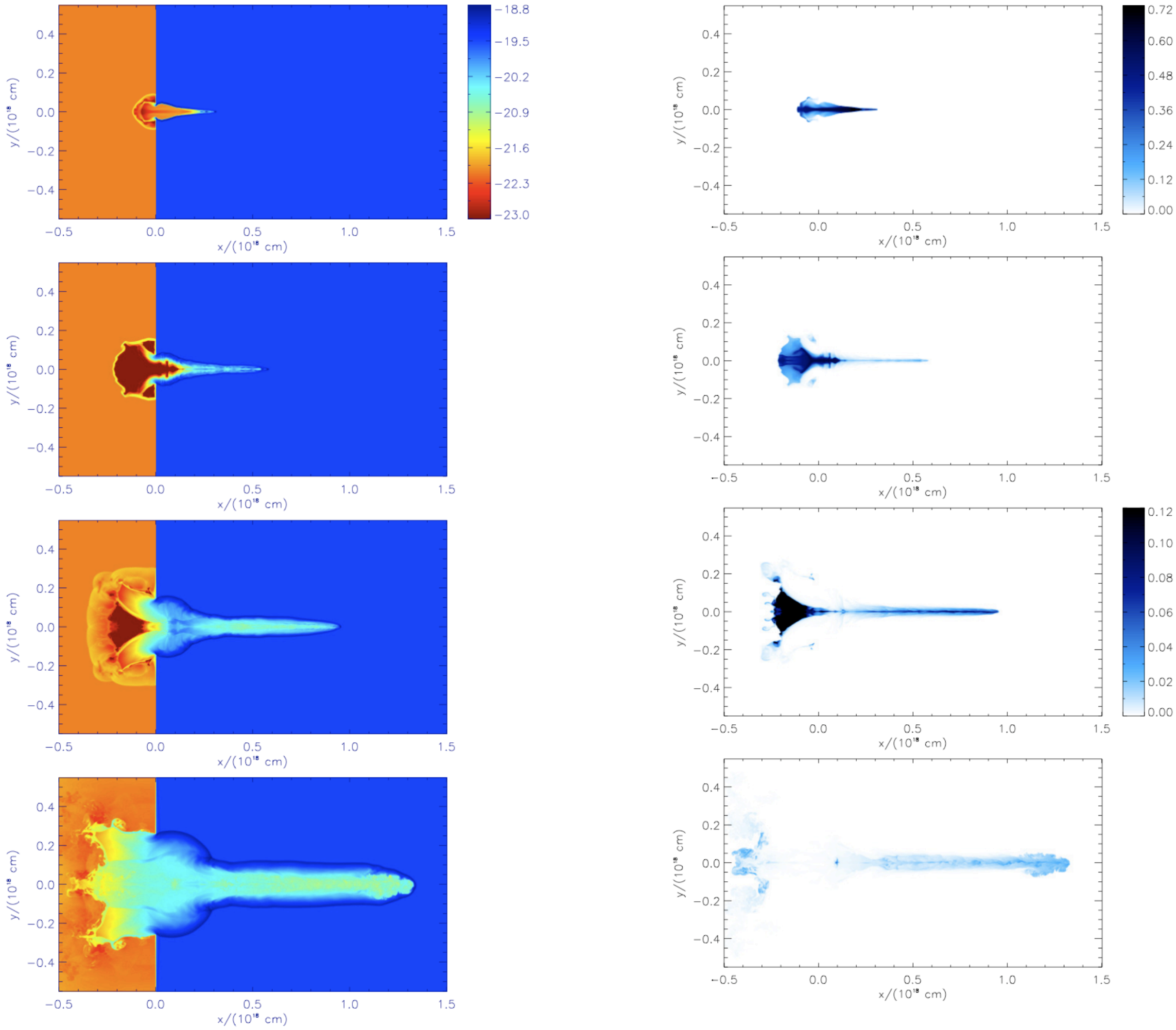

Figure: Density contours are shown using colors corresponding to the numbers on the scale bar, which are the logarithms of the density, expressed in units of $\mathrm{g\,cm^{-3}}$. Concentration contours are shown using contours ranging from zero ejecta fraction (white) to an ejecta fraction near unity (dark blue); note the different color range in the bottom two frames. From top to bottom, the four times depicted are $t = 100$, 500, 2400, and 10,000 yr following the impact of the ejecta clump, coming from the left, with the molecular gas on the right. The shock front driven by the clump carves out a channel, initially spherical and then cylindrical, as it penetrates into the cloud to a maximum depth ≈ 0.5 pc. Cooling instabilities tend to cause fragmentation of the clump so that its mass is distributed evenly along the channel it carves out.

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