CLUMPY SUPERNOVA EJECTA INJECTION INTO FORMING PLANETARY SYSTEMS.

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Background: The first solids in the solar system include material from supernovae. The very first solids, of course, were presolar grains, a subset of which are identifiable by their stable isotope anomalies as originating in supernova ejecta. Meteoritic inclusions formed in the solar system, such as chondrules and calcium-rich, aluminum-rich inclusions (CAIs), contain isotopic evidence for the one-time presence of short-lived radionuclides (SLRs) such as ^{26}Al and ^{60}Fe [1]. The short ($\leq 1.5\,$Myr) half-lives of these isotopes argues for injection of (core-collapse) supernova material into the solar nebula [1], either as it was forming, or into the Sun's already-formed protoplanetary disk (PPD) [2-4].

Injection of supernova material into the Sun's disk has been disputed, on several grounds. [3,4] demonstrated that as supernova material sweeps past a PPD, very little gas ejecta or small grains are injected into the disk; only large grains (sizes $> 1\,\mu$m) are injected. In order to explain the initial abundance of ^{26}Al in a disk, it is necessary for a significant fraction $\eta_{\rm cond} > 10^{-1}$ of the Al to condense, and it must condense into micron-sized grains. Typically $\eta_{\rm cond} \sim 10^{-4}$ is inferred from infrared supernova observations [5,references in 4]. As well, a PPD must be situated very close (< 0.15 pc) from a supernova to receive the meteoritic abundance of SLRs [2-4,6], yet as [7,8] have pointed out, newly forming PPDs will not lie so close to a supernova. If the PPDs and the massive stars formed coevally, the disks will be > 4 Myr old by the time of the supernova; PPDs can form at ≈ 4 Myr after the birth of the massive stars, but only at distances > 2 pc, which leads to considerable geoemtric dilution.

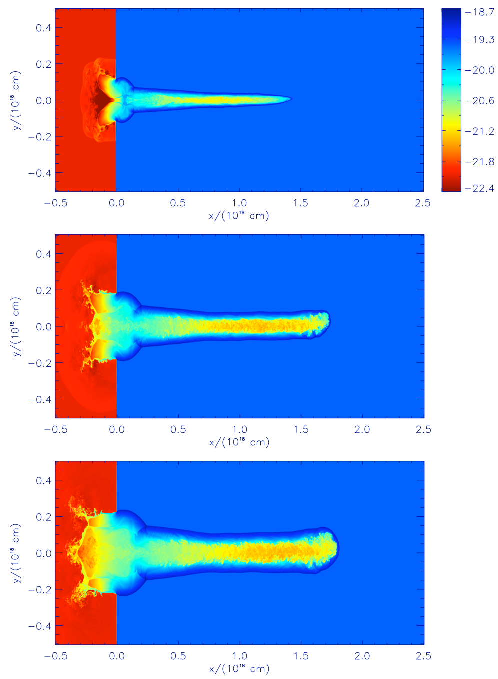
Both the low inferred condensation efficiencies and the problem of timing / geometric dilution are solved if the supernova ejecta are found preferentially in clumps. [4] argued that numerical simulations and observations of SN1987A and Cassiopeia A indicate collection of ejecta (at least inside the H-rich shell) into $N \sim 10^4$ dense, homologously expanding clumps, each with mass $\sim 10^{-4}\,M_\odot$ and radius $R \approx d/300$, where d is the distance from the explosion center. They argued that infrared observations of supernovae fail to observe significant dust, and infer $\eta_{\rm cond} \sim 10^{-4}$, because if the supernova is recent, the clumps are optically thick; while if it is older, the dust is optically thin but too cold to be detected. The geometric concentration of ejecta into clumps means that distant PPDs have a probability $f < 100\%$ of being struck: $f \approx N(R/2d)^2 \sim 1\%$. The concentration of ejecta also means that PPDs at > 1 pc will receive meteoritic abundances of SLRs if they are struck at $\sim 0.1\,$pc. Here we discuss recent evidence that further supports injection of clumpy supernova ejecta into the early solar system. We also discuss new modeling of how clumpy ejecta would enter the early solar system.

Supernova Dust: Remarkable convergence has occurred in the last two years supporting formation of dust grains in clumpy supernova ejecta, high condensation efficiencies, and injection of such grains into our PPD. Far-infrared *Herschel* observations of SN1987A [9] have dramatically revealed the presence of $0.4 - 0.7\,M_\odot$ of dust with a blackbody temperature of $\approx 20\,$K. The expected condensible mass is $0.7\,M_\odot$, yielding a condensation efficiency $\eta_{\rm cond} \approx 0.4 - 1.0$. Only four bandpasses were measured, so deviations from a blackbody curve are not detectable, but spectrally featureless emission implies grain sizes $> 1\,\mu$m. As well, the discovery and characterization of presolar graphites that condensed from supernova ejecta that contain multiple carbonaceous phases has strongly supported condensation in dense clumps [10]. These clearly indicate a condensation sequence of TiC, then Ni_2Si, Si-rich kamacite / Fe_2Si and SiC in some order, then finally graphite [10]. Modeling by [11] shows that the isotopic and elemental abundances of supernova graphites are robustly reproduced well by condensation from a mixture of supernova material from the Ni and He/N zones, but condensation of graphite after SiC and FeSi, demands pressures $> 3 \times 10^{-6}\,$bar. Pressures $\sim 10^{-4}$ bar are predited by the clumpy ejecta model of [4], but other supernova condensation models consider only pressures orders of magnitude smaller [12-14]. We expect high pressures to yield fast and highly efficiency condensation.

These supernova graphite grains may have formed at any time in Galactic history, but recent evidence has been found for injected grains. Small (size $<$ 100 nm) "nanospinel" grains have been discovered and identified as the presolar carriers of ^{54}Cr anomalies in planetary materials [15]. Isotopic analyses strongly indicate their formation in the O/Ne and C/O zones of a core-collapse supernova [15,16]. Furthermore, [16] argue that the heterogeneity of ϵ^{54}Cr among planetary materials appears to demand a late injection of these grains into the solar nebula. This would seem to strongly support injection into the Sun's PPD, as predicted by [2-4], who show that grains $\geq$ 100 nm in size may be injected efficiently into PPDs. On the other hand, [4] show that grains only 10nm in size are *not* injected efficiently into PPDs in their simulations of isotropically exploding supernovae. Simulations by [17] of the interaction of clumpy ejecta with PPDs show that denser conditions are maintained throughout the interaction, which may restrict injection to even larger grains $>$ 100 nm. At the same time, the true size of the nanospinels is not well constrained [15,16]. If nanospinels are found to be only $\sim$ 10 nm in size, this would argue against their injection into the disk.

Injection of Clumps into Molecular Clouds: Recent discoveries have strengthened the case for formation of supernova dust in clumps, at high condensation efficiency, and even late injection of supernova dust into the solar nebula. It remains unclear whether that injection was while the solar nebula was an exposed PPD. We have been strongly motivated to study injection of supernova material into the forming solar nebula at an earlier stage, while it is still embedded in and just beginning to collapse from the molecular cloud. We have used the FLASH hydrodynamics code (including realistic gas cooling) to model the injection of a clump of supernova ejecta into a molecular cloud. In the example displayed in Figure 1, we assume a spherical clump with radius 1×10^{16} cm and mass $1 \times 10^{-4}\, M_{\odot}$, and density $\rho = 4.8 \times 10^{-20}\,\mathrm{g\,cm^{-3}}$, travelling at $2000\,\mathrm{km\,s^{-1}}$ through the low-density gas of an H II region (red density) into a molecular cloud with high density $3.9 \times 10^{-20}\,\mathrm{g\,cm^{-3}}$ (blue density). The system is shown at three times spanning roughly 2000 yr, after which the clump has penetrated to a depth of ≈ 0.5 pc. The shock from the clump's penetration has opened a channel $\approx$ 0.1 pc wide. At the point of entry, some material has left the channel and entered the H II region, but our calculations show that the channel closes before all the material can leave, and the supernova ejecta is mixed inside the channel as it cools.

If the molecular cloud lay at a distance of 2 pc [4,7], the clump model of [4] predicts 1 clump would strike the molecular cloud per $(0.07\,\mathrm{pc})^2$. This is comparable to the area of the channel $(0.1\,\mathrm{pc})^2$, so essentially all of the cloud gas will see 1 supernova clump. The total mass of condensible ejecta ($\approx 2\,M_{\odot}$) is thus mixed into $4\pi(2\,\mathrm{pc})^2(0.5\,\mathrm{pc})$, or $1.4 \times 10^4\,M_{\odot}$ of molecular cloud gas. This mixing ratio of supernova ejecta to molecular cloud gas, $\sim 10^{-4}$, is exactly consistent with meteoritic ratios [6].



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