EFFICIENCY OF MIXING OF SUPERNOVA EJECTA INTO NEARBY PROTOPLANETARY DISKS.

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Introduction: Understanding the early evolution of the Solar System hinges on identifying the type of stellar environment in which it formed. Did the Sun form in a quiescent molecular cloud like the Taurus-Auriga complex, or did it form in a larger cluster? Most low-mass stars do in fact form in clusters with $> 10^3$ stars [1], clusters which are likely to contain at least one massive star that will go supernova [2]. Astronomical observations alone do not constrain where our Solar System formed 4.5 Gyr ago, but isotopic analyses of meteorites do. During its first few Myr of existence, the Solar System held high levels of ^{60}Fe, with $^{60}\mathrm{Fe}/^{56}\mathrm{Fe} \sim 0.3-1\times10^{-6}$ [3-5]. This ^{60}Fe existed within the first ~ 1 Myr of the Solar System's evolution. As discussed by Desch et al. (2006) [6], the only plausible source of this short-lived radionuclide (SLR) is a nearby supernova. Its half-life (1.5 Myr) is too short to have been inherited from the interstellar medium [7], and spallation reactions within the early Solar System (due to ions accelerated by solar flares) produce too little of it [8,9]. Injection from an external nucelosynthetic source is required. Asymptotic-giant-branch stars, suggested by [10,11], are not found near star-forming clouds; [12] placed a generous upper limit of 3×10^{-6} on the probability of contamination of the early Solar System by an AGB star; that is, the odds are $> 99.9997\%$ the Sun was *not* contaminated by an AGB star. A supernova is the only plausible source to explain the abundances of all the SLRs in meteorites [13,6], except for ^{10}Be which we attribute to trapped cosmic rays [14]. The only questions are *when* the supernova occurred, and *how close* was the supernova to the Solar System?

Previous investigations [15,16] have focused on the possibility that the supernova triggered the collapse of the Sun's molecular cloud core, but here we investigate the possibility that the supernova occurred after the Solar System had already formed a protoplanetary disk. This scenario is naturally suggested by astronomical observations, which show that massive stars are associated with star-forming regions and protoplanetary disks, in regions like the Orion Nebula [17] and NGC 6611 [18]. This scenario had been suggested by T. Gold in 1977 [19], who termed it the flypaper model for the way in which supernova ejecta would be plastered on the surface of the protoplanetary disk. Motivated by

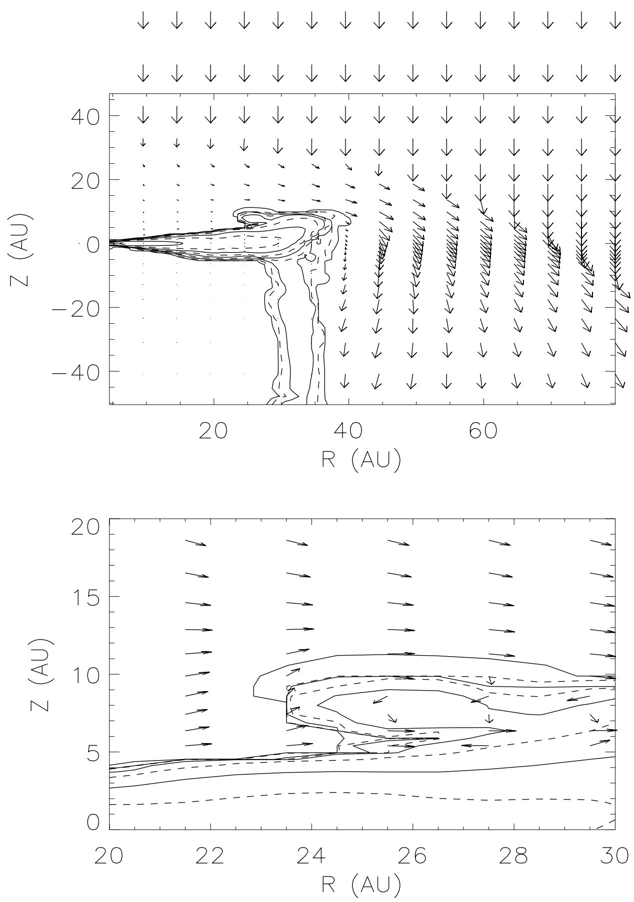

Figure 1: *top* Density contours and velocity arrows 600 years after ejecta strikes disk (top); *bottom* Close-up showing KH roll.

the *Hubble Space Telescope* images of disks near ($\sim$ 0.2 pc) the massive ($\sim 40\,M_\odot$) star θ^1 Ori C in the Orion Nebula, which will go supernova in less than ~ 1 Myr (see discussion in [6]), this scenario has been re-examined by [20] and [21]. Because we envision supernova being injected *into* the disk, in either gas or solid form, we have termed this the "aerogel" model [21]. Here we report on two-dimensional numerical simulations we have conducted to determine the efficiency with which *gaseous* supernova ejecta are injected into nearby protoplanetary disks.

Numerical Simulations: Our 2-D (cylindrical) hydroynamic simulations use a code based on the Zeus-2D algorithms [22]. The code includes gravity from a central protostar, but not self-gravity. We have included the cooling function of [23]. Our simulations use 80 radial zones from 2 AU to 80 AU and 120 zones along the axis, from 40 AU below the

Table 1 *Distance dependance*

case	injected mass	intercepted mass	% injected
0.1 pc	9.0×10^{26} g	3.8×10^{28} g	2.4
0.3 pc	3.0×10^{25} g	4.2×10^{27} g	0.7
0.5 pc	8.0×10^{24} g	1.5×10^{27} g	0.5

Table 2 *Energy dependance*

case	injected mass	intercepted mass	% injected
4.0 f.o.e.	2.4×10^{25} g	4.2×10^{27} g	0.6
1.0 f.o.e.	3.0×10^{25} g	4.2×10^{27} g	0.7
0.25 f.o.e.	3.9×10^{25} g	4.2×10^{27} g	0.9

midplane to 100 AU above. In our canonical case, we truncate a minimum-mass disk ($0.01\,M_\odot$) at 30 AU, then allow it to relax to an equilibrium state, by which time it extends to 40 AU. We then simulate a supernova explosion of 10^{51} erg ($\equiv$ 1 f.o.e.) with $20\,M_\odot$ of ejecta at a distance of 0.3 pc; the ejecta travels along the axis toward the disk at about 2000 km/s, hitting the disk face-on. The density of the ejecta decrease with time according to [24]. A color field was added to distinguish supernova ejecta from protoplanetary disk gas. The simulations run for $\sim 10^3$ years and typically take a week on a G5 workstation.

The dynamical behavior is as follows. The momentum of the ejecta strips the outer parts of the disk beyond about 30 AU. Inside 30 AU, a shock is set up when the ejecta firsts strike the disk, but stalls because its ram pressure is less than the disk gas pressure. As more disk material is shocked, a reverse shock propagates into ejecta, eventually establishing a bow shock (Figure 1). Much supernova ejecta is deflected around the disk, but some strikes it head on and is deflected laterally over the top surface of the disk. Along this boundary Kelvin-Helmholtz (KH) rolls are set up (Figure 2), which leads to mixing of supernova material into the disk. The process is inefficient, though, and only about 1% of the ejecta that is originally headed toward the disk actually is mixed into the disk gas. Eventually ($\sim 10^3$ years) the density and velocity of the ejecta become dynamically insignificant.

We have conducted a parameter study investigating the effects of supernova energy, distance to the supernova, and disk mass. Table 1 lists the "injected mass" of ejecta mixed into the disk, the "intercepted mass" of ejecta that would strike

Table 3 *Disk mass dependance*

case	injected mass	intercepted mass	% injected
$0.1\ M_\odot$	3.3×10^{25} g	4.2×10^{27} g	0.8
$0.01\ M_\odot$	3.0×10^{25} g	4.2×10^{27} g	0.7
$0.001\ M_\odot$	5.1×10^{25} g	4.2×10^{27} g	0.1

the disk, and their ratio, "% injected". Note that varying the distance from the supernova is equivalent to varying the density of the supernova ejecta. Table 2 lists the same quantities when the supernova explosion energy is varied between 0.25 f.o.e. (leading to ejecta velocities $\approx 1000\,\mathrm{km\,s^{-1}}$) to 4 f.o.e. ($\approx 4000\,\mathrm{km\,s^{-1}}$) . Table 3 shows the effect of varying disk mass from one tenth to ten times a minimum-mass disk. In all cases, the disk started with a radius of 40 AU and shrank down to 30 AU ($\pm 10\%$) due to stripping and deformation from ram pressure. After the ejecta have passed ($\sim 10^3$ years), the disks relax back to about 40 AU ($\pm 10\%$).

We are currently conducting similar studies at higher resolutions to test for numerical convergence, but we conclude that mixing of supernova gaseous ejecta into protoplanetary disks is probably very inefficient ($\sim 1\%$). We next plan to investigate the motions of dust grains entrained in the supernova ejecta. Since the radionuclides inferred from meteorites probably all condense into solid grains before striking the disk, they will probably dynamically decouple from the gas and move directly into the disk [21, 6]. We therefore view it as likely that supernova ejecta in solid form may be injected with near 100 % efficiency, which would lead to abundances of SLRs in the early Solar System consistent with those inferred from meteorites [21, 6].

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