Modelling injection with structured clouds

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Short-lived radioisotopes, such as Aluminum-26 ($\tau_{1/2} \approx 0.7$ Myr), were present and active in the early Solar System[1]. The origin and incorporation mechanism of the SLRs is still debated[2,3].

External enrichment scenarios via supernovae or stellar winds encounter a common bottleneck: **failure to inject enough material into our natal molecular cloud**[3]. There is an inevitable impedance mismatch between the hot diffuse ejecta and the cold dense cloud.

Most simulations assume a spherical cloud geometry. However, observations reveal that molecular clouds are structured on all scales. Further, a smooth surface deflects incident ejecta and inhibits mixing. **We suggest that sub-structure in the target cloud will increase injection efficiencies.**

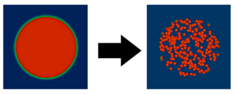

Figure 1. A clumpy geometry is more realistic and could capture more impinging material.

We use the **Athena code**[4] to solve the ideal hydrodynamics equations on a fixed grid in 2-D. We employ a weak ($\gamma = 1.1$) adiabatic equation of state, and self-gravity is included via an open-boundary FFT solver.

A shocked wind of hot gas propagates from the left boundary and impacts a dense molecular cloud. We model **structured clouds with random clumps**. We trace the ejecta with a passive scalar field.

After 1 crossing time, we measure **the fraction of ejecta that has been incorporated** into collapsing cloud regions, i.e. regions of enhanced density and converging flow. Various cloud masses, "filling factors", and shock Mach numbers are explored.

Our test case is a 25,000 $M_\odot$ cloud of radius ~9 pc, in thermal equilibrium with an ambient medium of 7500 K and 1 cm^{-3} (C_S ~ 8.3 km s^{-1}).

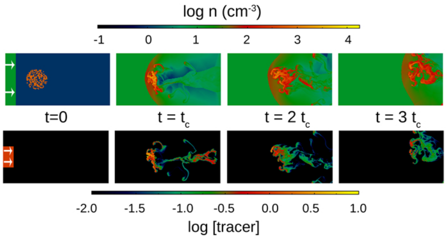

Figure 2. Snapshots of number density (top) and passive tracer (bottom) in our fiducial 2-D simulation: Mach 5 shock, 50% full cloud, 1024^2 resolution. The shock propagates from the left. t_c is the shock crossing time (2.5 Myr in this instance).

Sub-structure increases the injection efficiency in most cases.

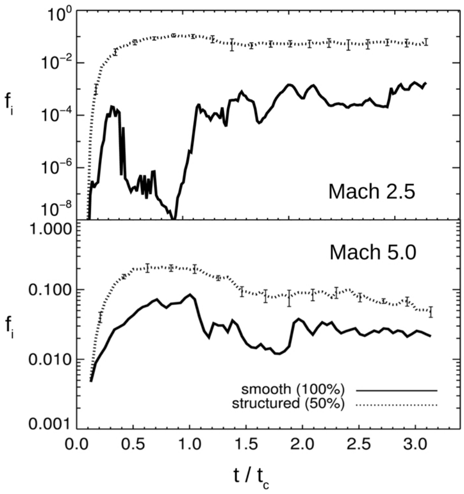

Figure 3. Injection efficiencies (f_i) for smooth and structured clouds in 2-D, as a function of crossing time (t_c). 5 random structured distributions are sampled. We report the median and standard deviation. The resolution is 1024^2.

Mach #	Filling Factor	$f_i(t=t_c)$	$f_i/f_{i,100}$
2.5	25%	0.09	3.2×10^5
	50%	0.08	2.9×10^5
	75%	0.03	1.1×10^5
	100%	2.80×10^{-7}	1.0
5.0	25%	0.17	2.1
	50%	0.21	2.6
	75%	0.22	2.8
	100%	0.08	1.0
7.5	25%	0.17	2.1
	50%	0.19	2.4
	75%	0.23	2.9
	100%	0.08	1.0
10.0	25%	0.14	1.4
	50%	0.17	1.7
	75%	0.21	2.1
	100%	0.1	1.0

Table 1. Results for our standard test case in 2-D, at a resolution of 1024^2. f_i is evaluated after one shock crossing time.

Sub-structure has the largest effect at low Mach numbers.

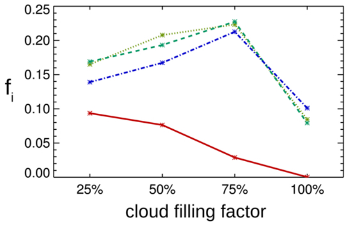

Figure 4. Injection efficiency vs. cloud filling factor, evaluated at $t = t_c$. Resolution is 1024^2.

Resolution controls our turbulent mixing.

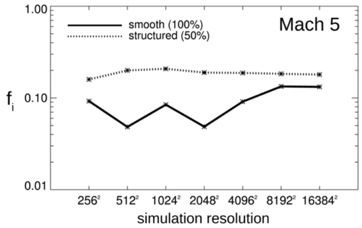

Figure 5. Resolution convergence test. f_i evaluated at $t = t_c$. We do not use mesh refinement.

Clumpy sub-structure is not only more realistic -- it may help resolve the SLR injection problem. The increase in injection efficiency is usually a factor of 2-3, but at slightly supersonic ejecta speeds **the increase can be several orders of magnitude**. A clumpy cloud surface allows incident material to **penetrate to greater depths** rather than being deflected on impact. The **increased surface area** also produces more turbulent mixing, which incorporates the SLRs into dense regions.

However, **our turbulence is resolution-dependent**. We will need mesh refinement to better resolve the mixing scales, as well as sub-grid turbulence models to control resolution effects. Future simulations will also include improved thermal physics, magnetic fields, and star formation via sink particles.

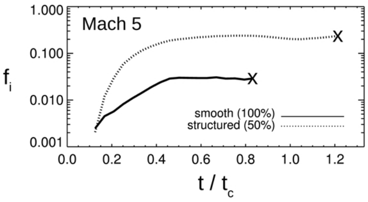

Figure 6. Preliminary results in 3-D show similar results to 2-D. Resolution is 1024^3. Gravitational collapse terminates the simulations. Further time evolution will require mesh refinement and sink particles.

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