Semi-confined supernovae in Giant Molecular Clouds and their impact on the interstellar medium

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Abstract—**Massive stars formed in Giant Molecular Clouds (GMCs) often end their lives in supernova (SN) explosions. The energy and momentum injections from SNe are of fundamental importance in galactic star formation studies. Current state-of-the-art tends to employ results from low-cost 1-D fluid models to prescribe the energy coupling between SNe and their surroundings. However, 3-D GMC-scale simulations revealed that SN explosions are often largely asymmetrical. This is due to the presence of pre-SN feedback, such as ionizing radiation, that carve cavities and channels around massive stars prior to their detonation. Being partially confined, the SN energy escapes from their natal GMC preferentially through the channels, departing from the 1-D spherically symmetric blast descriptions. Using SPH, we present a novel set of simulations that investigates the semi-confinement effect on SN explosions within GMC cavities. We compare our results to analytical solutions adapted from engineering literature on vented explosions. We show that semi-confined SNe can induce a higher level of perturbation to its local environment that persists for longer timescales. A stronger kinetic input to the local ISM likely indicates a higher ability to regulate star formation.**

I. INTRODUCTION

Giant Molecular Clouds (GMCs) are the birthplace of stars. As stars evolve and reach the end phase of their lives, their cores deplete the fuel and are compressed by self-gravity. Low-mass stars may still be supported by electron degeneracy pressure, yet high-mass stars with core masses exceeding $\sim 1.44\ \mathrm{M}_\odot$ would collapse violently and in turn explode as Type II supernovae (SNe). Each explosion releases approximately 10^{44} J (10^{51} erg) of kinetic energy, forming shells of shocked gas that sweep across the surrounding interstellar medium (ISM).

SNe dominate the energy budget in the ISM. It is generally recognized that SN feedback is one of the key mechanisms for regulating star formation. SNe are also largely responsible for replenishing supersonic turbulence in the ISM [1], as well as expelling star-forming gas out of the galactic planes. It is therefore important to investigate the energy and momentum deposition from SNe on its local environment in order to understand how these ecosystems operate.

Nevertheless, galactic-scale simulations are often unable to resolve the interactions between SN remnants and the ISM. They rely on *sub-grid models*, which serve as prescriptions (or "recipes") of the SN's impact [2]. The precise injection method can introduce large uncertainties to the galactic evolutions [3]. Refining these prescriptions has thus been a priority in numerical development.

Recently there has been a growing tendency to employ 1-D (hydrodynamic) simulations [4] [5] to formulate SN sub-grid models. Their low computational costs enable large parameter grids to be scanned to account for a variety of complex ISM environments, such as different density distributions or different turbulent structures [4].

1-D models are, however, almost bound to model the SN output in a spherically symmetric manner. Previous cloud-scale studies by [6] [7] unanimously suggested that this is often not the case. Pre-SN feedback, such as ionizing radiation and stellar winds, are able to create cavities of around 10 pc (3×10^{17} m) in radius inside GMCs [5]. They also create channels along the low-density paths in the cloud that connect the embedded cavities towards the outer ISM. As SN detonates, the energy leaves preferentially through these channels [7]. This scenario largely deviates from the 1-D blast wave descriptions that we currently employ.

The situation now becomes analogous to *vented explosions* extensively studied in blast engineering, which concerns bombs detonating in room-sized chambers fitted with windows. The self-similarities in blast physics allow for applications to the astrophysical problem in hand. We aim to understand how the energy and momentum deposition would differ if the SNe were subjected to partial confinement.

This extended abstract is organized as follows. Section II describes our numerical methods, simulation setups, and the novel analytical models with which we compare to the simulations. Section III presents the key results outlining the differences in properties of the outflows between a semi-confined SN and a standard spherically symmetrical blast. Finally, we summarize in Section IV.

II. METHODS

A. Numerical methods

We use the PHANTOM SPH code [8] to simulate the GMCs. PHANTOM models astrophysical fluid as compressible flows with equal mass particles and variable smoothing lengths. Shocks are

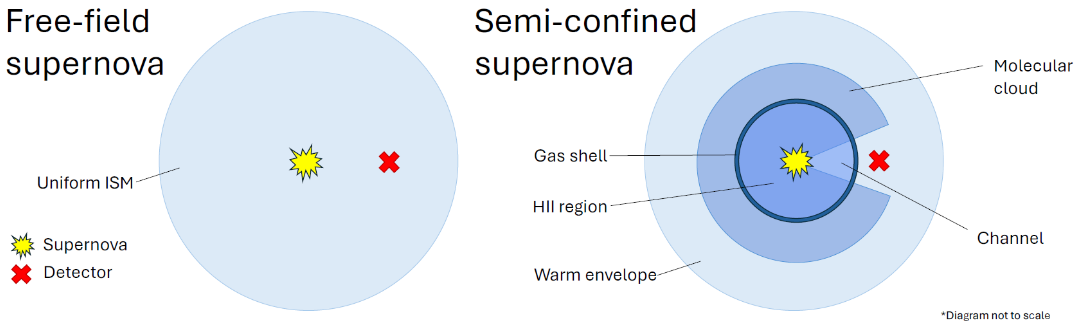

Fig. 1. *Left*: Illustration of a free-field SN. The SN detonates within a uniform medium; a detector (red cross) is placed at some distance away from the progenitor. *Right*: Illustration of a semi-confined SN. The progenitor is embedded inside an HII region (a low-density cavity), surrounded by a GMC, enveloped by warm diffuse gas. The HII region and the envelope are connected by a low-density channel. The detector is placed at the vent opening.

treated using artificial viscosity and artificial thermal conductivity. We model photoionization from massive stars using the tree-based radiation hydrodynamic scheme of [9] [10]. Radiative cooling is incorporated by employing the cooling curve in [1].

SPH methods are highly preferred in star formation studies, for they naturally follow and resolve the GMC gas fragmentation and collapse processes. SPH is also ideal for feedback simulations [7], that individual fluid parcels may be easily tracked after receiving the "kick" from SNe. Performing our tests in SPH ensures consistency with previous feedback studies.

B. Simulation initial conditions

To gauge the effect of cavities and channels on SN explosions, we consider two scenarios: a *semi-confined SN* and a *free-field SN*. The latter represents a spherically symmetrical blast as would have been modelled in 1-D simulations. The former consists of a cold (10 K) molecular cloud enveloped by a layer of warm (10^3 K) gas which represents the photodissociation region around GMCs. The SN progenitor is embedded within a bubble of ionized gas (known as HII regions; 10^4 K) created by ionizing radiation from the progenitor star. This bubble is a low-density feedback-driven cavity. A cone-shaped channel is manually carved from the inside of the HII region to the envelope. Fig. 1 illustrates the initial conditions. Turbulence and self-gravity are not included.

The use of simple-geometry GMC simulations provide a testing ground for the underlying physics. It removes the stochastic influence from turbulence, allowing for a higher degree of control over the amount of venting that the SN experiences.

C. Analytical model

Consider a detector placed at the position marked by a red cross in Fig. 1. This detector measures the interpolated fluid quantities after the shock front passes through it, providing an indication of the SN's local impact. For the free-field model, the evolution of the detected quantities may be predicted simply using the Sedov-Taylor solution with Rankine-Hugoniot relations.

Regarding the semi-confined case, we model the evolution of cavity pressure and the gas velocity at the channel after the shock has exited the cloud. Our derivation consists of two major considerations: (a) the expansion of cavity walls upon colliding with SN, and (b) the venting of gas due to pressure gradients across the channel. The latter employs the approach of [11] for modelling interior explosions. For further details on the solution, the interested reader is referred to [12].

III. RESULTS AND DISCUSSION

We present here the key results from the adiabatic runs[1]. Fig. 2 shows the evolution of gas velocity, thermal pressure and ram pressure at the detector. Scattered points plot the results obtained from SPH simulations and dashed lines indicate those computed with the analytical solutions.

Good agreement has been achieved between our theoretical and numerical models. These results demonstrate that, compared to 1-D blasts, semi-confined SNe can exert and sustain a higher dynamical impact in regions close to the progenitor. Similar results have been obtained in runs with up to four identical channels, suggesting that confinement effects remain operative as long as the vents are sufficiently small relative to the cavity.

We also examine the turbulent motions driven by the SN outflows. This is done by imposing a grid of interpolation points onto the post-shock region immediately outside the cloud to measure fluid velocities. This velocity field is then decomposed into solenoidal and compressive components, and finally converted into kinetic energy spectra via fast Fourier transforms. Fig. 3 shows the kinematic properties of the local ISM when the SN shock fronts have reached $200\ \mathrm{pc}$ $(6 \times 18\ \mathrm{m})$.

Compared to free-fields, it is clear that semi-confined SNe can locally sustain higher turbulence levels even when the remnant has expanded to large distances. In particular, its strong solenoidal component likely arises from the shear and vortices that develop as gas collides with the cavity walls. The flow is also likely subjected to Kelvin-Helmholtz instability whilst it passes through the channels, generating small-scale eddies that help regulate star formation [13].

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[1] Results for simulations that include radiative cooling can be found in [12].

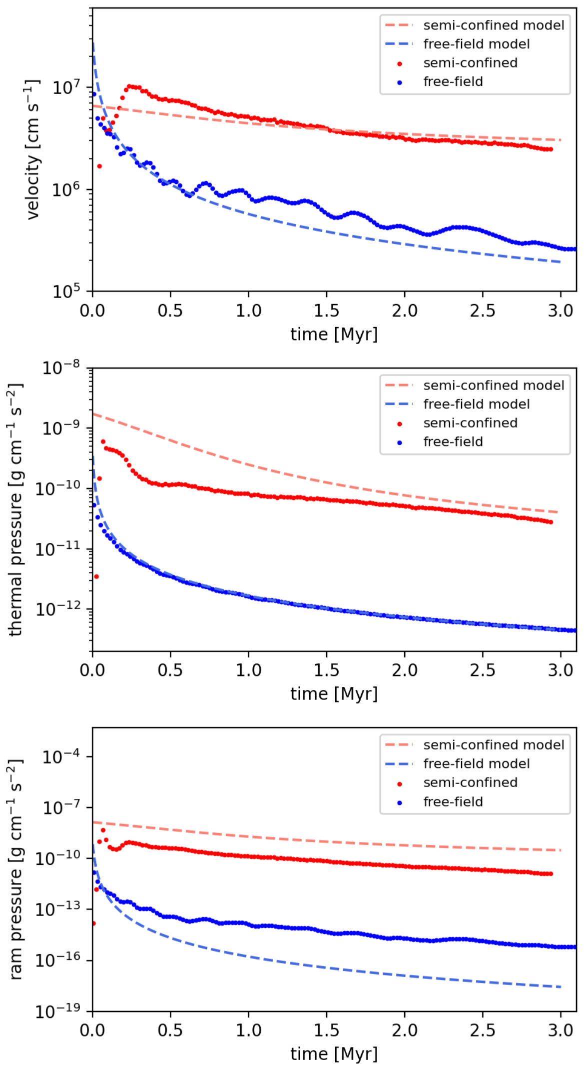

Fig. 2. Evolution of gas velocity, thermal and ram pressure at the detector, plotted for semi-confined (red) and free-field (blue), synchronized at when the shock fronts arrive. Predictions from analytical models are shown in dotted lines.

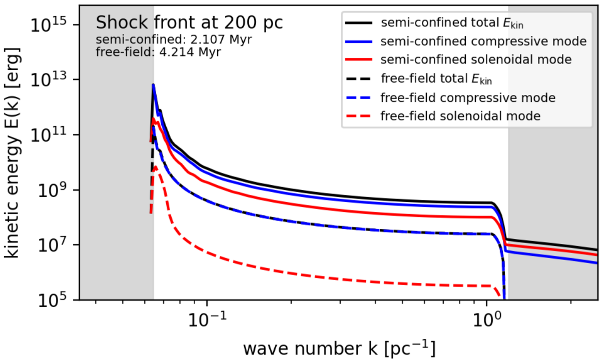

Fig. 3. Kinetic energy spectrum comparing semi-confined (solid) to free-field (dashed) when their shock fronts reach 200 pc. Total kinetic energy (black) is decomposed into solenoidal (red) and compressive (blue) components. Greyed-out regions mark the resolution limits due to grid size and separation.

IV. CONCLUSION

We presented numerical and theoretical models to illustrate how partial confinement would alter the evolution of SNe and modify their impact on the ISM. Through comparisons with free-field explosions, we showed that semi-confined SNe are more capable of sustaining perturbations to their local environments, and generate stronger helicity in their post-shock regions. We also demonstrated that SPH simulations agree well with the analytical solutions derived from vented explosion models.

Overall, our results suggest that 1-D SN models may overestimate the impact size-scale and underestimate the timescale over which the SN is dynamically coupled to the local ISM. We propose factoring the semi-confinement effect into the sub-grid models used in galactic star formation simulations.

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