Energy Budget in Multiple Supernova Explosions

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Standard models of large scale galactic outflows in starburst galaxies assume a high efficiency of SNe in heating the gas in central regions of starburst galaxy in order to launch outflows. We study the heating efficiency of the interstellar gas by multiple supernovae (SNe) within 3D simulations. We argue that SNe remnants have to act coherently in space and in time in order to minimize radiative losses. We show that interacting expanding shells from different SNe restrict the heating efficiency of multiple SNe even when they explode with a high rate. As a result the heating efficiency can considerably differ from a commonly assumed value (0.1–0.3).

1 Introduction

Heating of the interstellar medium by multiple supernovae (SNe) explosions is at the heart of producing galaxy-scale outflows in starburst galaxies. Standard models of outflows assume a high efficiency of SNe in heating the gas to X-ray emitting temperatures and filling the central region of starburst with hot gas, in order to launch vigorous outflows. The collective effect of clustered SNe is believed to form a superbubble (e.g., [1]) whose shell of swept up mass moves faster than the typical speed of OB associations (few km s^{-1}) and which therefore contains most of the SNe arising from the association. The study of the evolution of these superbubbles has mostly assumed continuous energy release from the center.

This problem becomes acute in the context of supernovae driven galactic winds in which it is assumed that SNe can sufficiently heat up the ISM gas, at least in the central region of disc galaxies, in order to launch a wind. This process assumes that although SNe lose most energy in radiation in isolated cases, the efficiency of heating the ISM can be large in the central region filled with hot and low density gas and that the gas in this region is thermalized [2, 3]. Numerical simulations (e.g., [4, 5, 6]) also implement the initial conditions leading to galactic winds making similar assumptions. It is believed that in a multiphase medium and in the case of multiple SNe events, the efficiency of SNe heating – the fraction of the total explosion energy transferred into thermal energy – can be larger than $\sim$0.1. These

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estimates came from the numerical and analytical studies of energy loss in *isolated* supernova remnants, which showed that the fractional energy retained in the hot interior gas of remnants was of order ~0.1. Larson [7] had first pointed out the importance of cooling with regard to galactic outflows, and derived a critical supernova rate density required to compensate for cooling.

The question of heating efficiency of SNe crucially depends on the evolution of multiple SNe which has not yet been studied in detail. Nath and Shchekinov [8] have argued that the energy input from multiple SNe in the central regions of starbursts cannot heat the gas to $T \geq 10^6$ K unless the SNe events act coherently in space and time. Here we study two aspects of the problem of multiple SNe with gas-dynamic simulations, namely, we test the importance of coherency condition and consider the time scale and conditions under which percolation of hot gas becomes possible. This allows us to study the efficiency of heating by multiple SNe events, in particular the efficiency of heating gas to high temperature.

2 Numerical method and initial conditions

We use three-dimensional unsplit TVD code based on the MUSCL-Hancock scheme and the HLLC method (e.g., [9]) as an approximate Riemann solver. In the energy equation we take into account cooling processes adopted the tabulated non-equilibrium cooling curve [10]. This cooling rate is obtained for a gas cooled isobarically from 10^8 down to 10 K. The heating rate is adopted to be constant whose value is chosen so that the background gas does not cool.

We have carried out 3-D gasdynamic simulations (Cartesian geometry) of multiple SNe explosions using periodic boundary conditions. The computational domains have size 200^3 pc^3 which consists of 300^3 cells corresponding to a physical cell size of 0.75 pc. The background number density considered ranges between 0.1–10 cm^{-3}, the background temperature is 10^4 K. The metallicity is constant within the domain, and we consider the cases with $Z = 0.1$, 1 $Z_\odot$. We inject the energy of each SN in the form of thermal energy in a region of radius $r_i = 1.5$ pc. SNe are distributed uniformly and randomly over the computational domain.

3 Results

We have performed runs with SNe exploding continuously in the computational domain of 200^3 pc^3 with resolution of 1 pc and gaps of $\Delta t = 10^3$, 10^4, 2×10^4, 3×10^4, 4×10^4 and 10^5 yr. In other words, one supernova explodes after every Δt. The positions of SNe are distributed randomly in space. Figure 1 shows the results of heating efficiencies (left) and filling factors (right) for gas with different temperatures, for all time delays (from short to long delays, from top to bottom). We denote the efficiency of heating gas to $\geq 10^{6.5}$ K by $\eta[10^{6.5}]$ and define it as the ratio of thermal energy stored in gas with $T \geq 10^{6.5}$ K at any given time to the total explosion energy deposited up to that time. It is clear that the case of more frequent SNe ($\Delta t = 10^3$ yr) shows continuous decline in the

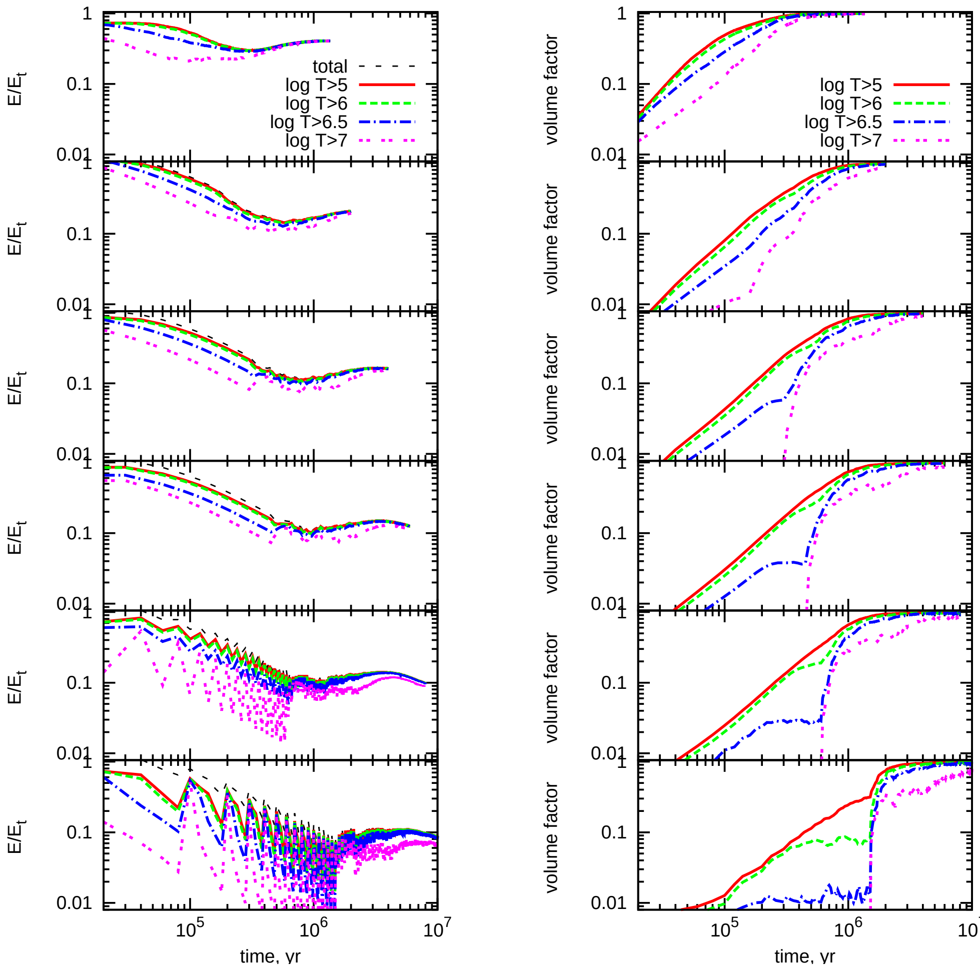

Figure 1: The evolution of the heating efficiency (left) and filling factors (right) for gas with different temperatures for a continuous series of SNe separated by time delay $\Delta = 10^3$, 10^4, 2×10^4, 3×10^4, 4×10^4, 10^5 yr (from top to bottom).

heating efficiency $\eta[10^{6.5}]$ and only after $t \simeq 10^5$ yr when the remnants practically fill the whole computational domain (60% of the volume), η increases to $\sim$0.4 because the subsequent SNe mostly expand into hot diffuse medium. Explosions with a longer delay of $\Delta t = 10^5$ yr (bottom most row) show on average similar trend on longer time scales, though as expected, with lower heating efficiency of order $\eta[10^{6.5}] \sim 0.1$. Similar to the previous model, the efficiency first declines and then increases after the remnants occupy roughly 30% of the computational zone at $t \simeq 10^6$ yr to $\eta[10^{6.5}] \sim 0.1$.

A common feature in the behavior of the heating efficiency in all models can be obviously noted: after a continuous decline down to $\eta(T) \lesssim 0.1$, it stabilizes and then grows slowly for all temperature fractions, particularly for the gas with $T \geq 3\times10^6$ K which carries a considerable amount of thermal energy. The most reasonable explanation is that the epoch of increasing η coincides with the state when the filling factor of the corresponding temperature fraction reaches a critical value $f(T) \sim 0.3$ when different bubbles percolate.

The time required for the percolation of hot gas can be found by using the result that the threshold filling factor is ∼0.3 and can be estimated as [11]

$$t_{\rm perc} \approx 10\,{\rm Myr} \left(\frac{n}{E_{51}}\right)^{4/7} \left(\frac{\nu_{\rm SN}}{10^{-10}\,{\rm pc}^{-3}\,{\rm yr}^{-1}}\right)^{-4/7}. \quad (1)$$

For a typical starburst SNe rate density of $\sim 10^{-9}$ pc^{-3} yr^{-1} and gas density of $n \sim 10$ cm^{-3} in starburst nuclei, the time scale for heating efficiency to become ≥ 0.1 is of order 10 Myr.

It is interesting to note that recent observations of 10 starburst galaxies show that there is a time lag of ∼10 Myr between the onset of star formation and the excitation of galactic winds [12]. Our simulations and the important result of percolation of hot gas when the overall filling factor crosses a threshold of ∼0.3, therefore, allow us to interpret this time lag as required for heating efficiency to become sufficiently large for an outflow to be launched.

Using our simulations for different gas densities (n = 0.3, 1, 3, 10 cm^{-3}) and keeping the SNe frequency a constant, we can infer the scaling of the heating efficiency with the SNe rate density and ambient density [11]. We find that roughly $\eta[10^{6.5}] \propto \nu_{\rm SN}^{0.2}\, n^{-0.6}$ for the heating efficiency of X-ray emitting gas.

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* The color figure is available online in the Proceedings at *http://www.astro.spbu.ru/sobolev100/*.