CONDITIONS FOR SUPERNOVAE-DRIVEN GALACTIC WINDS

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ABSTRACT

We point out that the commonly assumed condition for galactic outflows, that supernovae (SNe) heating is efficient in the central regions of starburst galaxies, suffers from invalid assumptions. We show that a large filling factor of hot ($\gtrsim 10^6$ K) gas is difficult to achieve through SNe heating, irrespective of the SN’s initial gas temperature and density, its uniformity, or its clumpiness. We instead suggest that correlated supernovae from OB associations in molecular clouds in the central region can drive powerful outflows if the molecular surface density is $> 10^5 M_\odot$ pc$^{-2}$.

Key words: galaxies: ISM – galaxies: starburst – ISM: bubbles – ISM: clouds – ISM: supernova remnants

1. INTRODUCTION

Standard models of supernovae (SNe)-driven galactic outflows assume a central region where the SNe energy input is thermalized (e.g., Larson 1974; Chevalier & Clegg 1985; Heckman et al. 1990; Suchkov et al. 1994; Strickland & Heckman 2009; Sharma & Nath 2013). These models posit that SNe explosions shock heat the interstellar medium (ISM) within this region (of size $\sim 200$ pc); numerical simulations for winds also implement this assumption (e.g., Suchkov et al. 1994, 1996; Cooper et al. 2009). The basic assumption is that, even with a small heating efficiency ($\sim 0.1$), SNe can heat a low density gas to $\gtrsim 10^6$ K and launch a galactic wind.

There are two assumptions here, one that involves the energetics of SNe explosions and another regarding the thermalization of this energy. While the energy budget can be met in the case of a high SN rate in starbursts, the process of thermalization assumes that SNe remnants overlap and reach a porosity larger than unity. Suchkov et al. (1996) and Strickland & Heckman (2009) have discussed this issue in the context of the observed X-ray emission from the outflowing hot gas in M82. The required SNe heating efficiency of $\epsilon$ is connected with the mass loading factor, the ratio $\beta$ between the total mass deposition rate and the mass lost through SNe and stellar winds. The temperature and brightness of the gas depend on different combinations of $\epsilon$ and $\beta$, and Strickland & Heckman (2009) suggested an optimum condition of $\beta \sim 1$–3 and $\epsilon \sim 0.1$–0.3. They suggested that $\epsilon$ could be large in the case of a low density gas ($\sim 0.1$ cm$^{-3}$). The average density of the diffuse ionized medium in starbursts is, however, $\approx 24$ cm$^{-3}$ (Armus et al. 1989).

The question at hand is whether or not SNe remnants can overlap in these regions and sufficiently heat the gas (Melioli & de Gouveia Dal Pino 2004). We argue in this Letter that it is difficult to achieve high porosity for hot ($\gtrsim 10^6$–$10^7$ K) gas irrespective of the ambient density being small or large if SNe remnants occur randomly in this region. In order to overcome this difficulty, we suggest that galaxies approaching a galactic wind stage are likely to produce super star clusters with an enhanced star formation rate (SFR). We note here in passing that other processes have also been invoked to aid galactic winds, such as radiation pressure (Nath & Silk 2009; Murray et al. 2011) and turbulence (Scannapieco 2013), and also cosmic rays (Uhlig et al. 2012), which can operate outside the central region.

2. POROSITY IN A UNIFORM ISM

Consider the estimation of the porosity of hot ($\gtrsim 10^6$ K) gas in a uniform ISM of ambient density $n_0$. In the context of the three-phase ISM model, the porosity of the coronal gas is estimated by the final volume of SN remnants when the shells decelerate to the sound speed of the ambient gas (McKee & Ostriker 1977; Cox 2005). The “hot” interior gas at this stage has a temperature $\sim 5 \times 10^5$ K, which was used to infer the three-phase model of the ISM. The same expression was, however, used by Heckman et al. (1990) in order to derive a high value of porosity of a hotter gas at $\gtrsim 10^6$ K gas (for $n_0 \sim 100$ cm$^{-3}$ and $T_0 \sim 10^5$ K; their Equation (2)), and this argument has been repeated by other authors (e.g., Suchkov et al. 1994; Strickland & Heckman 2009). The average temperature of the interior gas at this shell speed is, however, less than $10^6$ K, and cannot be used to determine the porosity of gas with $T \gtrsim 10^6$ K.

We recall that the average gas temperature inside an SNe remnant decreases rapidly after the gas cools down to a temperature $\sim 10^6$ K. Cox (1972) showed that the energy of the remnant scales as $E(t) \propto R^{-2}$, after the shell enters the radiative phase (at shell radius $R_c$). One has,

$$E(t) = 0.22 E_0 \left( \frac{R}{R_c} \right)^{-2}, \quad R_c = 22.3 \text{ pc} E_5^{5/17} n_0^{-7/17},$$

where the initial explosion energy is $E_0 = 10^{51} E_{51}$ erg, and $n_0$ is the ambient particle density (in cm$^{-3}$). The corresponding timescale is $t_c \approx 5 \times 10^4 \text{ yr} E_{51}^{4/17} n_0^{-9/17}$. Inverting this relation, we have the shell radius at a time when the internal energy has decreased to a fraction $f$ of the initial value as $R(f) = 0.47 R_c f^{-1/2}$. The corresponding timescale is $t(f) = 0.07 t_c f^{-7/4}$. Denoting the SN rate density as $\nu_{SN}$ (yr$^{-1}$ pc$^{-3}$), we can define the porosity when the energy has decreased by a fraction $f$, as,

$$P(f) \approx 1.6 \times 10^5 (f/0.5)^{-13/4} \nu_{SN} E_{51}^{19/17} n_0^{-30/17}.$$  

We have scaled the expression to $f = 0.5$, since the average interior temperature falls to $\sim 10^6$ K at this stage, according to Cox (1972; see his Figure 2(a)). This is borne out by the $^5$ We note that the Slavin & Cox (1993) prescription would have yielded a value of porosity smaller by a factor of $\sim 5$. 

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Note: The above text is a natural reading of the document, aimed at converting the scientific content into plain text while preserving its original meaning and structure as much as possible.
simulations of Shelton (1998) for \( n_0 = 0.01 \), where the interior gas temperature decreases below \( 10^6 \) K after \( t_c = 5 \times 10^5 \) yr appropriate for this density, as expected.

The condition for \( \sim 10^7 \) K gas to overlap (required to explain X-ray observations) is more stringent and therefore we can use the porosity in Equation (2) as an upper limit. Note that the shell speed in Cox (1972) at this stage \( (f = 0.5) \) drops down to \( \sim 100 \) km s\(^{-1}\). We can also use this velocity criterion to estimate the porosity for hot gas.

The typical SN rate density in starburst regions \( v_{SN} \sim 10^{-9} \) yr\(^{-1}\) pc\(^{-3}\) implies a porosity \( \approx 0.2 \) for \( n_0 = 1 \), and can be even lower for the average density in starbursts (Armus et al. 1989). For \( f = 0.1 \), as suggested by Strickland & Heckman (2009), the porosity is \( \approx 3 \times n_0^{-3.0/17} \), still less than unity. Moreover, for \( f \sim 0.1 \) the temperatures inside SN remnants decrease to \( \lesssim 3 \times 10^5 \) K, which is not enough to explain the observed X-ray emission. Furthermore, if the gas reservoir of \( 5 \times 10^7 M_\odot \) required to explain the mass loading rate in M82 (Suchkov et al. 1996), were uniformly distributed in the 200 pc central region, the density would be \( \approx 70 \) cm\(^{-3}\), precluding the possibility of a large porosity factor for hot gas.

If this gas were uniformly heated to \( 10^7 \) K, then it should emit hard X-rays with \( 10^{44} \) erg s\(^{-1}\). The requirement that \( n_0 \) \( H_\mu m H \) gas is small, of the order of \( 0.1 \), the remnants will stop expanding, this is the porosity provided by new SNe inside MCs. These sites can provide high temperature gas with a given star formation, or equivalently, SNe rate. This can be achieved by allowing SNe remnants to explode in a coherent manner so as to avoid excessive radiative cooling and act collectively. One must invoke spatial and temporal clustering of SNe events in order to increase the efficiency of SN heating, even if the heating is confined to small region we can define the porosity of SNe by requiring the four-volume at \( t_c \) to be of the order of unity (4\( \pi R_c^3 t_c/v_{SN}/3 \approx 1 \)) in a given localized region. This will ensure that new SNe will help compensate for the radiative loss in this region and keep the interior gas at \( \gtrsim 10^6 \) K.

Massive stars (the progenitors of SNe) are likely to form in OB associations in molecular clouds (MCs). These sites can provide the spatial and temporal coherency needed for this scenario. In order for these SNe to emerge from the parent MC and then heat up the intercloud medium, it is necessary for the SNe explosions to destroy the MC.

Consider an MC of mass \( M_{MC} = 10^7 M_{MC,5} M_\odot \) and a radius of \( R_{MC} = 5 R_{MC,5} \) pc. One fiducial example of such an MC is provided by G0.253+0.016 (called the “Brick”) in the central region of Milky Way, with a mass \( \sim 1.3 \times 10^5 M_\odot \) and a radius \( \sim 2.8 \) pc (Longmore et al. 2012). The density of molecular hydrogen \( (\mu = 2.3) \) is \( n = 5 \times 10^3 \) cm\(^{-3}\) \( M_{MC,5} R_{MC,5}^3 \). The corresponding free-fall timescale is \( t_{ff} \approx 2 \times 10^{10} n^{-1/2} \) s \( \approx 1 \) Myr. A high mass \( M_{MC,5} R_{MC,5}^3 \).

One can show that for a star formation rate \( \epsilon_{SFR} M_{MC}/t_{ff} \), the density \( n_0 \approx 0.02 \) is the star formation efficiency per free-fall time (Lada et al. 2010), the porosity is given by \( P = (4\pi/3) R_{SN,5}^3 t_c/v_{SN}/3 \), similar to the estimates in Section 2, since this is essentially the Silk–Elmegreen law applied on a small scale). Although the porosity is formally less than unity in this case, the effect of even a single SN can be catastrophic for a small MC, since \( R_c \gg R_{MC} \). This effect is expedited by the ionization of the MC by massive stars prior to SNe events (Monaco 2004). Walch et al. (2012) have found from simulations of a single SN in an MC that the ensuing ionization front disperses the cloud on a timescale comparable to the sound crossing time of the ionized gas, of order a Myr; moreover, radiation pressure may help in this regard (Murray et al. 2011).

## 3. COHERENCY OF supernovae

The problem boils down to maintaining a large porosity for high temperature gas with a given star formation, or equivalently, SNe rate. This can be achieved by allowing SNe remnants to overlap in a coherent manner so as to avoid excessive radiative cooling and act collectively. One must invoke spatial and temporal clustering of SNe events in order to increase the efficiency of SN heating, even if the heating is confined to small region we can define the porosity of SNe by requiring the four-volume at \( t_c \) to be of the order of unity (4\( \pi R_c^3 t_c/v_{SN}/3 \approx 1 \)) in a given localized region. This will ensure that new SNe will help compensate for the radiative loss in this region and keep the interior gas at \( \gtrsim 10^6 \) K.

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## 4. INITIATING A galactic wind

Although star formation in MCs help to concentrate the effects of SN remnants, it remains to be seen whether the energetics are sufficient for galactic wind. In the case of
correlated multiple SNe, superbubbles can be energetic enough to break out of the disk and reach a sufficient height above the disk with enough momentum so as to seed a galactic wind (Mac Low & McCray 1988; Roy et al. 2013 and references therein). The threshold mechanical luminosity for a superbubble to breakout with a Mach number of 5–10 depends on the ambient density ($\rho_0$), sound speed ($c_s$), and the scale height ($H$). Roy et al. (2013) has determined a threshold luminosity of $L_{cr} \approx 100\rho_0 H^2 c_s^3 \approx 1.5 \times 10^{33} \rho_0 H_{pc}^2$ erg s$^{-1}$, for an ambient gas at $10^4$ K and $n_0 = 1$ cm$^{-3}$. For $10^6$ K gas, the requirement is $10^7$ times larger. If we use $n_0 = 10$ cm$^{-3}$, $H_{pc} = 50$, and $T = 10^6$ K, the threshold mechanical luminosity for breakout is $L_{cr} \approx 4 \times 10^{36}$ erg s$^{-1}$.

For a Kroupa/Chabrier IMF, this translates to a threshold SFR of $0.1 M_\odot$ yr$^{-1}$ in the central region. This also implies an SNe rate of $10^{-3}$ yr$^{-1}$, which can be compared with the SNe rate $2.5 \times 10^{-3}$ yr$^{-1}$ in the nuclear (35 pc) region of M82 (Table 1 of Förster Schreiber et al. 2003). If we considered the whole region of radius 200 pc and total height 100 pc, this would imply a low SN rate density and, consequently, a small porosity, but that would neglect the effect of coherent SNe inside the small size of a OB association (few tens of parsecs). Superbubbles breaking out of a stratified disk ultimately assume an oval shape, with an extent in the plane of the disk $\approx \pi \times$ the scale height, in the Kompaneets approximation. Therefore, such a superbubble would ultimately engulf the central region, with a radial length scale $\sim 200$ pc and a scale height $\sim 50$ pc and the gas inside this region would be shock-heated.

Assuming continuous star formation for the timescale of the wind ($\sim 100$ Myr) and a typical SNe explosion energy of $10^{51}$ erg, this critical luminosity implies a total number of OB stars of $N_{OB} \approx 1.2 \times 10^2 (H_{pc}/50)^2 (n_0/10$ cm$^{-3})^{-3}$. For a Kroupa/Chabrier IMF, the corresponding stellar mass is $\approx 1.2 \times 10^7 M_\odot (H_{pc}/50)^2 (n_0/10$ cm$^{-3})^{-3}$. Matzner & McKee (2000) have estimated that a fraction $0.25-0.75$ of the MC mass is ultimately converted into stars. Using the upper limit of 0.75, one then finds a conservative estimate for the required total mass of the parent molecular cloud(s) to be $\sim 10^7 M_\odot (H_{pc}/50)^2 (n_0/10$ cm$^{-3})^{-3}$.

Another way of estimating this is to use the empirical SFR in MCs as determined by Lada et al. (2010). They found the SFR to be $4.6 \pm 2.6 \times 10^{-8} M_\odot M_\odot$ yr$^{-1}$, where $M_\odot$ is the mass of the cloud above a density threshold of $n_{th} \sim 10^2$ cm$^{-3}$. The above SFR then implies $M_{th} \approx 2 \times 10^9 M_\odot$. According to Figure 3 of Lada et al. (2010), dense clumps amount to a fraction 0.03–0.15 of the total mass of MCs. Using the upper value of 0.15 yields a conservative estimate for the total molecular mass $M_{th} \sim 10^7 M_\odot$.

For MCs in the central regions of galaxies, the requirement may be stronger than this. In the central regions of galaxies, as in our Galaxy, the turbulent speed is likely to be large. Krumholz & McKee (2005) and Padoan & Nordlund (2011) have shown that due to turbulence, the threshold gas density for star formation increases to $n_{th} \sim A_{th} c_{th} M^2 n$, where $A_{th}$ is a constant close to unity, $c_{th} \approx 1.5$ is the virial parameter for the cloud, $n$ is the ambient density, and $M$ is the Mach number. Typically $M \sim 50$, as in the case of the “Brick” cloud in the Galactic central molecular zone (Kruisjens et al. 2013). For our fiducial MC, with an average density of $n \approx 5 \times 10^3$ cm$^{-3}$, $M_{MC}=5 R_{MC}^3$, the critical density for star formation then becomes $n_{th} \sim 1.4 \times 10^5$ cm$^{-3}$. We can estimate the mass in clumps with density greater than this by using the fact the probability distribution function of density in a turbulent ISM at high density end is described as a power law, $dp/dn \propto n^{-\gamma}$, with $\gamma \approx 2.5$–2.75 (Kritsuk et al. 2011). If the cumulative mass (above a certain density) for $n_{th}$ (the threshold without turbulence, $10^4$ cm$^{-3}$) and $n_{th}$ (the threshold with turbulence) are denoted as $M_{th}$ and $M_{th}$, then one has $M_{th}/M_{th} \approx (n_{th}/n_{th})^{-\gamma}$. For $\gamma \sim 2.5$, and for the above values of two threshold densities, we then have $M_{th} \approx (1/40) M_{th}$.

Given the uncertainties, we can conclude that the total mass requirement is increased by a factor $\geq 10$, to $\sim 10^8 M_\odot$ in order to mitigate the effect of turbulence and create energetic superbubble(s). We can compare this with the observations of molecular mass in the central regions of nearby starburst galaxies. Plenisias et al. (1997) estimated a molecular mass of $10^8$–$10^9 M_\odot$ in the central regions of nuclear starburst galaxies NGC 2903, NGC 3351, and NGC 3504.

This threshold molecular mass requirement is rather less than the region of radius 200 pc implies a surface density $\geq 10^5 M_\odot$ pc$^{-2}$, which can be considered as a pre-condition for producing coherent SNe in order to initiate a galactic wind. Since the Kennicutt–Schmidt SFR is somewhat lower at sub-kiloparsec scale (e.g., Momose et al. 2013), this surface density implies an SFR of $\sim 1 M_\odot$ yr$^{-1}$ kpc$^{-2}$ in the nuclear 200 pc region.

For comparison, most of the nearby galaxies observed in the BIMA SONG survey have central CO surface densities less than this and do not show signs of wind (Helfer et al. 2003). In contrast, CO observations of ULIRGs show the existence in the central few hundred parsecs region a molecular gas of mass $(0.4–1.5) \times 10^8 M_\odot$, with a surface density of $\sim (0.5–1) \times 10^5 M_\odot$ pc$^{-2}$ (Solomon et al. 1997). We compare the observed molecular surface density of a few nearby starburst with winds in Table 1.

| Name       | Size of Central Region | $\Sigma_{\text{CO}}$ (10$^3 M_\odot$ pc$^{-2}$) |
|------------|------------------------|-----------------------------------------------|
| NGC 1377   | ...                    | 5$^{11}$                                       |
| NGC 253    | 300                    | 10$^{12}$                                      |
| Arp 299    | ...                    | 62$^{13}$                                      |
| Arp 220    | 100                    | 58$^{14}$                                      |
| NGC 3079   | 125                    | 100$^{15}$                                     |

References. (1) Aalto et al. 2012; (2) Sakamoto et al. 2011; (3) Sargent & Scoville 1991; (4) Scoville et al. 1997; (5) Sofue et al. 2001.

5. DISCUSSION

The nature of the central region of galaxies can affect the mass loading in outflows, especially the amount of cold material in the outflow. In the case of SNe remnants producing a high porosity of hot gas, MCs are likely to be destroyed, whereas in the present scenario, the amount of cold/molecular gas in the outflow could be large. This is because the timescale of superbubble(s) destroying the parent molecular cloud(s) is a few $\times 10$ Myr (lifetime of massive stars), is also the timescale of galactic outflows, and the dynamical effects of starbursts on the surrounding medium. It is therefore reasonable to expect that remnants of MCs will be advected into the outflows in this case, as has been observed in NGC 253 (Bolatto et al. 2013) with ALMA, where molecular gas is seen to envelope the X-ray emitting region and superbubbles can identified.

It is not necessary that all SNe explode within one OB association in this scenario. The initial trigger can be provided by a super star cluster ($M \sim 10^7 M_\odot$; e.g., Walcher et al.
after which the resulting superbubble can enhance star formation in the vicinity. On one hand, the shock wave from superbubble can trigger star formation in a nearby cloud, and on the other hand, the increased gas pressure can enhance the SFR (Blitz & Rosolowsky 2006). Also, the loss of mass through the superbubble creates pockets of low density gas, which can be heated with high efficiency by latter generation SN remnants and create a reservoir of hot gas.

To conclude, we have argued that it is difficult to thermalize the energy input from SNe in the central regions (∼200 pc) of starbursts and create a large filling factor for hot (>10^6 K) gas as is commonly held. We suggested that coherency of SNe is need to create superbubbles that are energetic enough to initiate a galactic wind, and determined a threshold molecular surface density ≳10^3 M⊙ pc^-2 in the central region for this scenario.

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