Research Article

Mikhail G. Shevchenko, Evgenii O. Vasiliev*, and Yuri A. Shchekinov

Transport of gas from disk to halo in starforming galaxies

https://doi.org/10.1515/astro-2017-0025
Received Sep 16, 2017; accepted Nov 16, 2017

Abstract: Using 3-D gas dynamic simulations, we study the supernova (SNe) driven transport of gas from the galactic disk. We assume that SNe are distributed randomly and uniformly in the galactic plane and we consider sufficiently high volume SNe rates that are typical for starforming galaxies: \( v_{SN} = (0.3 - 3) \times 10^{-11} \text{ pc}^{-3} \text{ yr}^{-1} \). We found that under such conditions, a major part of gas locked initially in the galactic disk is transported up to \( \sim 1 - 5 \) stellar scale heights within several millions years. As expected gas transport is more efficient in the case of a thinner stellar disk. An decrease/increase of SN rate in the galactic disk with the same stellar scale height leads to an enlarging/shortening of time scale for gas transport. Independent of SN rate, the major fraction of the swept up gas is in the cold phase \( (T < 10^3 \text{ K}) \), though its volume filling factor is rather small, \( \sim 1-3\% \). Hot gas with \( T > 10^6 \text{ K} \) is elevated to larger heights than cold gas.

Keywords: galaxies: ISM – ISM: bubbles – shock waves – supernova remnants

1 Introduction

Supernovae (SNe) explosions regulate the dynamics of the multiphase interstellar medium (e.g., McKee & Ostriker 1977) and drive circulation of gas between the galactic disk and halo. Several models have been proposed for the description of such circulation. Two major descriptions involve the formation of fountains (Shapiro & Field 1976; Bregman 1980; Kahn 1981) and chimneys (Tomisaka & Ikeuchi 1986; Norman & Ikeuchi 1989). Both mechanisms are related to hot gas production by SNe activity. It is well known that SNe heat the interstellar medium (ISM) up to millions of Kelvins (e.g., Melioli & de Gouveia Dal Pino 2004; Vasiliev et al. 2015). Such hot gas occupies a large volume fraction of the galactic disk and halo, and this gas is transported from the disk to the halo. For sufficiently high SNe rates, gas can be blown away to the outer halo (Kovalenko & Shchekinov 1985; McCray & Kafatos 1987; Mac Low & McCray 1988; Igumenshchev et al. 1990), which is identified as outflows (see for review, e.g. Veilleux et al. 2005). For smaller SNe rates, gas is lifted up to heights of several hundred parsecs over the disk, that can be observed in many edge-on galaxies as extraplanar gas (e.g., Rossa & Dettmar 2000).

During the last two decades the dynamics and structure of the ISM has been intensively studied for parameters close to those in the solar vicinity (de Avillez 2000; de Avillez & Breitschwerdt 2005a,b; Joung et al. 2009; Hill et al. 2012). This interest is obviously determined by a large amount of observational data (e.g., Oegerle et al. 2005; Moos et al. 2002; Lallement et al. 2003). However, during the same time numerous observations of the ISM in external galaxies have been made (Rossa & Dettmar 2003; Dettmar 2012; Ho et al. 2016), which led to a necessity in studying the initial phases of galactic outflows in detail (Nath & Shchekinov 2013; Creasey et al. 2013; Sharma et al. 2014; Korolev et al. 2015; Li et al. 2015; Yadav et al. 2017; Vasiliev et al. 2017). Recently, the vertical structure of the ISM is numerically investigated for a range of starforming rates (Walch et al. 2015; Li et al. 2017), however, the question of how the gas is transported from disk to halo has not been yet clearly understood. This especially concerns initial phases of gas transfer from disk to halo. Usually the transport of gas from disk to halo is supposed to be maintained by both clustered and distributed SNe (e.g., de Avillez 2000; Hill et al. 2012), the former arises from stellar clusters and is responsible for forming superbub-
bles, whereas the latter corresponds to almost uniformly distributed OB stars, which exist as background and is present in every model (e.g., de Avillez 2000; Hill et al. 2012). Such distributed star formation components may originate from the fast (less then several Myr) disruption of numerous small OB groups and remarkably high velocities of OB stars, that may lead to a mix of OB stars from different clusters and may form an almost uniform background of these SNe progenitors in the disk plane. So that possible influence of distributed SNe on the structure of gas in galactic disks is needed to be studied and has only been previously considered once before (Walch et al. 2015), however the initial dynamics of the gas transfer from disk to halo was not investigated. Here we focus on the initial phases of gas transfer driven by SNe, which are almost uniformly distributed around the mid-plane of the galactic disk. This process is inevitably accompanied by numerous observational manifestations, which will be considered elsewhere.

In this paper we investigate how gas is transported by SNe, which are uniformly distributed in the disk plane, to heights of several hundred parsecs over the disk. Section 2 describes our model. Section 3 presents the results and Section 4 summarizes our conclusions.

## 2 Description of the model

We carry out 3-D hydrodynamic simulations (Cartesian geometry) of multiple SNe explosions in the galactic disk. We set up a gaseous disk to be initially in the hydrostatic equilibrium in gravitational potential, for which we use a modified version of the Kuijken & Gilmore (1989) potential. This consists of contributions from a stellar disk and a spherical dark halo (Hill et al. 2012):

$$ g(z) = -\frac{a_1 z}{\sqrt{z^2 + z_0^2}} - a_2 z + a_3 z^2 $$

where $a_1 = 1.42 \times 10^{-3}$ kpc Myr$^{-2}$, $a_2 = 5.49 \times 10^{-5}$ Myr$^{-1}$, $a_3 = 5 \times 10^{-5}$ kpc$^{-1}$ Myr$^{-2}$, $z_0$ is stellar scale height, which varies from 50 to 200 pc in our runs. Note that because we consider small heights above the plane, the last term is negligible. Initially the gas temperature is $10^4$ K; the gas metallicity is kept constant equal to the solar value within the whole computational domain.

SNe are distributed randomly and uniformly in the galactic plane and exponentially in the vertical direction. The scale height is half of the stellar one. SN events follow one-by-one uniformly in time; we ran models with the averaged time delay $\Delta t$ from $10^6$ to $10^8$ yrs. Using the sizes of the computational domain and SN scale height, one can easily find the volume ($v_{SN}$) and surface ($\Sigma_{SN}$) SNe rates. Thus, the SNe rate can be varied by changing the time delay and scale height values. Locations of SNe do not correlate to the gas density. In all models supernova rate does not change in time; this is equivalent to a constant star formation rate. The random times and locations of supernovae are chosen at initialization, such that for all runs with a given configuration, supernovae explode in the same locations. Note that for very low SNe rates remnants of individual SNe can cool down separately before they merge into a collective bubble. However, for the models considered here, SNe rates are sufficiently frequent in order to sweep gas from the disk within a timescale of a single starburst $\lesssim 30$ Myr. We stop our simulations shortly after the shock fronts of a collective bubble leave the computational domain in the vertical direction. For the rates considered here, this occurs within several million years, i.e. long before 30 Myr.

We inject the mass and energy of each SN in a region of radius $r_0 = 3$ pc, with the energy, $10^{51}$ erg, injected as thermal energy. Note that here we use a conservative value for a single SN, but SN energy determined from the recent observations (Leahy 1017) demonstrates a scatter around a value of $10^{51}$ erg. However, we consider an ensemble of SNe, so that any possible variation in the explosion energy of the SN is averaged over the ensemble and probably will not affect the vertical dynamics of the ISM. This issue will be studied elsewhere. Standard simulations are performed with a physical cell size of 1 pc in the computational domain with $256 \times 256 \times 768$ cells.

The code is based on the unsplit total variation diminishing (TVD) approach that provides high-resolution capturing of shocks and prevents unphysical oscillations. We have implemented the Monotonic Upstream-Centered Scheme for Conservation Laws (MUSCL)-Hancock scheme and the Haarten-Lax-van Leer-Contact (HLLC) method (see e.g. Toro 1999) as an approximate Riemann solver. This code has successfully passed the whole set of tests proposed in (Klingenberg et al. 2007).

Simulations are run with radiative cooling processes with a tabulated non-equilibrium cooling function fitting the calculated one (Vasiliev 2011, 2013). The fitted function is obtained for gas cooling isochronally from $10^8$ K down to 10 K. The non-equilibrium calculation (Vasiliev 2011, 2013) includes kinetics of all ionization states of H, He, C, N, O, Ne, Mg, Si, Fe, as well as kinetics of molecular hydrogen at $T < 10^4$ K.

We apply a diffuse heating term representing the photoelectric heating of dust grains (Bakes & Tielens 1994), which is thought to be the dominant heating mechanism.
in the interstellar medium. In our simulations, the heating rate is assumed to be time-independent and uniform across the box, that assumption is able to stabilize radiative cooling of ambient gas at \( T = 9 \times 10^3 \) K. Note that any variation of heating rate in the unperturbed gas leads to an imbalance between cooling and heating. This leads to a gas located above the disk to cool and move ballistically to the mid-plane (see similar picture, e.g. in de Avillez 2000; Hill et al. 2012). Certainly, this break of the initial equilibrium, which is dependent on the heating rate, is expressed in the redistribution of mass. Because we are interested here in gas transport this effect prevents studying gaseous flows driven by SNe, so we follow Li et al. (2017) and assume that the heating rate is constant across the computational domain.

### 3 Results

#### 3.1 Dynamics

Figure 1 presents the vertical (through the center of the box, \( y = 128 \) pc) slices of density (upper row) and temperature (lower row) at 1 Myr (left panels), 2 Myr (middle panels) and 2.8 Myr (right panels) for SNe explosions with an average time delay of \( 10^5 \) yr in the disk with stellar scale height of 100 pc, which corresponds to surface and volume SN rates \( \Sigma_{SN} = 1.5 \times 10^{-9} \text{ pc}^{-2} \text{ yr}^{-1} \) and \( \nu_{SN} = 1.5 \times 10^{-11} \text{ pc}^{-3} \text{ yr}^{-1} \), respectively. Although SNe are distributed uniformly in the disk plane, several collective bubbles are formed and interact with each other. In the left panel the whole disk is spanned by such bubbles, such that the major volume of the disk is occupied by hot gas with \( T \gtrsim 10^6 \) K. Their interaction leads to the formation of thin cold gaseous walls, which can fragment on to clumps. One can distinguish several chains of these clumps, which are more clearly seen at \( t = 2 \) Myr (middle panel). Number density inside the clumps is higher than \( \sim 10 \text{ cm}^{-3} \) and the temperature is as low as several hundred Kelvins, and in the densest central parts it reaches \( \sim 100 \) K. At \( t = 2 \) Myr, the global shock wave reaches heights of around 100-150 pc. At \( t = 2.8 \) Myr (right panel), one can observe the beginning of the formation of blow-out bubbles: the shell becomes thicker on their heads. Shortly after this time, the collective shock fronts leave the computational domain. The gaseous disk within more than one scale height is entirely destroyed by SNe explosions and becomes filled by hot gas. The volume filling factor of hot \( (T > 10^6 \) K) gas is close to unity, whereas the volume factor for cold \( (T < 10^3 \) K) gas is only 13%, though the mass fractions of these phases are in an opposite relation.

Figure 2 shows the vertical profiles of horizontally averaged density as a function of height at the same time moments and SN rate as in Figure 1. Also we plot the profiles for hot \( (T > 10^6 \) K) and cold \( (T < 10^3 \) K) gas (red and blue lines, respectively), and for comparison we add the line corresponded to the initial gas density distribution (thick grey line). One can note that during evolution the gas is swept out of the disk: the gas density peaks around \( |z| \sim 50 \) pc at \( t = 1 \) Myr and reaches \( |z| \sim 150 \) pc at 2.8 Myr, whereas the gas density around the disk plane, \( z \sim 0 \), decreases correspondingly, e.g. at \( t = 2.8 \) Myr it falls down about an order of magnitude in comparison to the initial value. In the disk filled by SNe a cold \( (T < 10^3 \) K) gas dominates in mass with the contribution of hot gas always less than 10%. It is worth noting that at \( t \lesssim 2 \) Myr, both cold and hot phases are enclosed within the same height scales (see left and middle panels in Figure 2), whereas later hot gas reaches larger heights due to starting the blown-out process (see right panel in Figure 2). Note that the non-zero number density of hot gas at the bottom border of the computational domain, \( z = -384 \text{ pc} \) is evidence that a part of the gas has left the computational domain and this gas is in hot phase. The density profiles demonstrate a significant re-distribution of mass in the galactic disk, i.e. its transport to larger heights.

#### 3.2 Mass transfer

Here we are interested in the re-distribution of gas by SNe, for this purpose we study how the mass of gas is transferred from the disk to larger heights and compare the mass distribution as it evolves in time to the initial one. The computational domain is divided into several gas layers starting from the mid-plane in both directions of the vertical \( (z) \) axis. In each layer we calculate the mass enclosed within it at time \( t \) and compare this mass to that locked in the layer at the initial moment. Note that using this procedure we obtain an absolute value of mass locked in the layer, but not differential mass per unit height. This allows us to trace mass transfer across time and estimate the gaseous mass located at height \( z \). Certainly, this mass depends on both the size of the layer and the size of the computational box. However, one can find the ratio of mass locked in a layer at height \( z \) and time \( t \) to that at \( t = 0 \) and estimate how many times gaseous mass is changed under certain conditions (SNe rate, scale height etc) with this ratio independent of the sizes of both the box and the lay-
Figure 1. The vertical (through the center of the box, $y = 128$ pc) slices of density (upper panels) and temperature (lower panels) at 1 Myr (left), 2 Myr (middle) and 2.8 Myr (right) for SNe explosions with an average time delay of $10^4$ yr in the disk with a stellar scale height of 100 pc, that corresponds to surface and volume SN rates $\Sigma_{\text{SN}} \approx 1.5 \times 10^{-9}$ pc$^{-2}$ yr$^{-1}$ and $\nu_{\text{SN}} \approx 1.5 \times 10^{-11}$ pc$^{-3}$ yr$^{-1}$, respectively.
ers. Below we present the gaseous mass located at height $z$ above the disk plane at time $t$.

Figure 3 shows the gaseous mass located in the layer at height $z$ above the disk plane at time $t$ for models with an average time delay between SNe explosions of $\Delta t = 10^4$ yr in the disk with a stellar scale height of 50 pc (left panel), 100 pc (middle panel) and 200 pc (right panel), that corresponds to volume SN rates $\nu_{SN} = 3 \times 10^{-11}, 1.5 \times 10^{-11}$ and $7.5 \times 10^{-12}$ pc$^{-3}$ yr$^{-1}$, respectively. Note that the surface SN rates are equal to $\Sigma_{SN} = 1.5 \times 10^{-9}$ pc$^{-2}$ yr$^{-1}$ for all depicted models.

This data can be represented in another way. One can be interested in not only how much gas is transported, but also how many times the mass of transported gas is greater than that initially located in the layer at this height. Figure 4 presents the ratio of gaseous mass transported to the height $z$ at time $t$ to that initially located in the layer at this height for the same models as in Figure 3. Here one...
can clearly see that the transport is more efficient in the case of a thinner stellar disk: the mass is increased more than ten times at $z \sim 200 - 300$ pc and three times at heights $\sim 300 - 350$ pc for $z_0 = 50$ pc (left panel in Figure 4). For a thicker stellar disk, the gaseous scale height becomes greater, so that although the amount of transported mass is significant (see right panel in Figure 3) this mass is only two times greater than that initially located at $z \sim 200 - 300$ pc.

Figure 5 presents the mass of hot gas with $T > 10^6$ K (upper row) and cold gas with $T < 10^3$ K (bottom row) located in the layer at height $z$ above the disk plane at time $t$ for the same models as in Figure 3. One can clearly see that, at first, hot gas reaches larger heights than cold gas for the same time and, at second, the mass of the cold phase is dominant. For SNe rate higher than $1.5 \times 10^{-11}$ pc$^{-3}$ yr$^{-1}$, hot gas is systematically 'shifted' on to larger heights com-
Figure 6. The ratio of gaseous mass with \( T > 10^6 \) K (upper row) and \( T < 10^3 \) K (bottom row) transported to the height \( z \) at time \( t \) to that initially located in the layer at this height for the same models as in Figure 3. The color bar depicts the ratio in logarithmic scale.

These features can be clearly seen in Figure 6, where the ratio of gaseous mass with \( T > 10^6 \) K (upper row) and \( T < 10^3 \) K (bottom row) transported to the height \( z \) at time \( t \) to that initially located in the layer at this height is depicted for the same models as in Figure 3. For a volume SNe rate \( 3 \times 10^{-11} \) pc\(^{-3} \) yr\(^{-1} \) (left panel), hot gas at \( z \gtrsim 300 \) pc and \( t \sim 2 - 3 \) Myr becomes a major part of gas by mass (the cold phase is less than 1% by mass, compared to the bottom left panel), moreover, the mass of the hot component is double the mass of that locked at this height initially. Cold gas is locked at lower layers, e.g. for the same SNe rate and time period it can be found at \( z \gtrsim 300 \) pc. Such gas dominates by mass at intermediate heights \( z \sim 100 - 200 \) pc and its mass is more than 10 times greater than that locked at this height at \( t = 0 \). At smaller heights, the major part of gas is in the warm diffuse phase with \( T \sim 10^3 - 10^6 \) K. The decrease of the volume SNe rate leads to a less clear difference in the spatial distribution of hot/cold gaseous phases and a smaller fraction of mass transported to larger heights. For example, the ratios of mass with \( T > 10^6 \) K and \( T < 10^3 \) K reach only about \( \sim 0.1 \) and \( \sim 1.5 - 2 \), respectively, at \( t \sim 3 \) Myr for a volume SNe rate of \( 7.5 \times 10^{-12} \) pc\(^{-3} \) yr\(^{-1} \) (see right column of panels in Figure 6).

Figure 7 presents the dependence of gaseous mass located at height \( z \) above the disk plane (upper panel), and the ratio of gaseous mass transported to the height \( z \) to that initially located at this height (lower panel) at a given time \( t \), for the model with average time delay between SNe explosions \( \Delta t = 10^5 \) yr and with the stellar scale height equal to 50 pc (the equivalent volume and surface SN rates are \( v_{SN} = 3 \times 10^{-12} \) pc\(^{-3} \) yr\(^{-1} \), \( \Sigma_{SN} = 1.5 \times 10^{-10} \) pc\(^{-2} \) yr\(^{-1} \), respectively). One can see that gas expelled from the disk reaches the border of the computational domain at \( \sim 8 \) Myr, which is three times longer than the time scale \( t \sim 2.5 \) Myr needed for the same in the model with time delay \( \Delta t = 10^4 \) yr between SNe exploded in the disk with the same stellar height (left panels in Figures 3–4). The mass fraction transported to several scale heights \( z \sim 150 - 200 \) pc is greater for a shorter time delay: for \( \Delta t = 10^4 \) yr the mass at \( t \sim 2.5 \) Myr exceeds more than 10 times in comparison with the initial value at \( t = 0 \), whereas for \( \Delta t = 10^5 \) yr the mass at \( t \sim 8 \) Myr is increased by a factor of \( \sim 2 - 3 \) (see left panel in Figure 4 and bottom panel in Figure 7). Note that this gaseous mass is predominately confined in cold clumps formed under
the fragmentation of SNe shells. The velocity of shells just before fragmentation is lower for a lower SN rate, resulting in the cold clumps having lower velocities and being lifted to lower heights. Finally, one can conclude that an increase/decrease of time delay between SNe explosions in the galactic disk with the same stellar scale height leads to a larger/smaller time scale for the transport of gas.

4 Conclusion

In this paper, we study the transport of gas from the galactic plane to its halo driven by SNe explosions. We assume SNe to be distributed randomly and uniformly in the galactic plane, and we consider high SNe rates typical for star-forming galaxies: the averaged time delay between subsequent SN events in the part of galactic disk with size $0.25 \times 0.25$ kpc$^2$ ranges from $10^4$ to $10^5$ yrs. In our runs, the stellar scale height is varied from 50 to 200 pc. As the SNe scale height is assumed to be equal to half of the stellar one, the mean volume SNe rates are within $v_{SN} = (0.3 - 3) \times 10^{-11}$ pc$^{-3}$ yr$^{-1}$. We found that for such SNe rate, gas is transported up to $\sim 1 - 5$ stellar scale heights within several Myr. As expected the gas transport is more efficient in the case of a thinner stellar disk. An increase/decrease of time delay between SNe explosions in the galactic disk with the same stellar scale height leads to a larger/smaller time scale for the transport of gas. In the swept out gas of the galactic disk the cold ($T < 10^3$ K) phase dominates by mass, while the volume filling factor of this phase remains small, $\sim 1-3\%$ independent on SN rate. The hot phase with $T > 10^6$ K is transported to larger heights than the cold one and its volume filling factor is close to 1.

Acknowledgment: The numerical simulations were performed under support from the Russian Scientific Foundation (grant 14-50-00043). MS is grateful to the Ministry for Education and Science of the Russian Federation (grant 3.858.2017/4.6). YS is partially supported by the RFBR (grants 15-02-08293, 17-52-45053).

References