Galactic outflows and the chemical evolution of dwarf galaxies

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Abstract.

Galactic winds in dwarf galaxies are driven by the energy released by supernova explosions and stellar winds following an intense episode of star formation, which create an over-pressured cavity of hot gas. Although the luminosity of the star formation episode and the mass of the galaxy play a key role in determining the occurrence of the galactic winds and the fate of the freshly produced metals, other parameters play an equally important role. In this contribution we address the following questions (i) What is the late evolution of superbubbles and what is the final fate of the superbubble cavities? (ii) How does the multi-phase nature of the ISM, in particular the coexistence of hot gas with embedded clouds, affect the development of galactic winds? (iii) What is the relation between the flattening of a galaxy and the development of bipolar galactic winds?

1. Introduction

After an intense episode of star formation (SF), the interstellar medium (ISM) in galaxies can be swept up by the mechanical energy of multiple supernova (SN) explosions and stellar winds. If the velocity achieved by this swept-up ISM reaches the escape velocity of the galaxy, we are in the presence of a galactic wind. Large-scale galactic outflows have been observed in the most active starburst galaxies both in the local Universe (Dahlem et al. 1998) and at high redshifts (Pettini et al. 2000). Although the first theoretical studies of galactic winds were applied to elliptical galaxies (e.g. Mathews & Baker 1971), it has long been argued that they are more effective in dwarf galaxies (DGs) since their potential wells are shallower and it is easier to overcome the escape velocity (Larson 1976). It has also been speculated that this physical process determines the mass-metallicity relation (Dekel & Silk 1986).

If the ISM in a galaxy is stratified, the swept-up gas expands preferentially along the steepest density slope, i.e. the direction perpendicular to the galaxy plane. A number of hydrodynamical simulations of the development of galactic winds in stratified media have been performed in the last two decades (i.e. MacLow & Ferrara 1999, hereafter MF99; D’Ercole & Brighenti 1999; Fragile et al. 2004 and references therein). As a result of these simulations, some consensus has been reached that galactic winds are not capable of removing a large fraction of the ISM from a galaxy but they are able to eject a significant fraction of the metal-enriched gas produced during the SF episode (but see Silich & Tenorio-Tagle 1998 for a different view). In particular, after the work of MF99 it is believed that the DGs with masses smaller than $\sim 10^8$ M\textsubscript{☉} are able to expel the majority of the metals freshly produced after the episode of SF whereas only for galaxies as small as $\sim 10^6$ M\textsubscript{☉} the ejection of a large fraction of the ISM initially present inside the galaxy is possible.

In spite of the important theoretical progress made on this field in the last years, the theory of the galactic winds has proven to be much more complex than depicted above and the results of MF99 must be seen, in most of the cases, as oversimplified. In this contribution we analyze the following questions, not addressed in the previously mentioned literature:
• What is the late evolution of superbubbles and what is the final fate of the superbubble cavities?
• How does the multi-phase ISM, in particular the coexistence of hot gas with embedded clouds, affect the development of galactic winds?
• What is the relation between the geometry of a galaxy (in particular its flattening) and the development of bipolar galactic winds?

2. The refill of superbubble cavities

After the energetic SN explosions and stellar winds have swept up the ISM of a galaxy, a large cavity filled with hot gas is left behind. The energy input rate after an episode of SF declines with time, therefore, the hot cavity loses pressure and the supershell tends to recede towards the center of the SF region. Superbubbles solely produced by SNeII experience a buoyancy of the hot gas at the end of the SF phase and the central region can be completely refilled with cold gas in a timescale of the order of $\sim 10^8$ yr or less (D’Ercole & Brighenti 1999). However, the occurrence of SNeIa, which explode with much longer delays compared to the SNeII (see e.g. Matteucci & Recchi 2001) can change the thermodynamical behavior of the gas in the center of galaxies. By means of detailed numerical simulations we have analyzed the late evolution of a galaxy after a single SF episode in order to explore the timescale needed to refill the hot cavity, taking into account both SNeII and SNeIa (Recchi & Hensler 2006). Although our simulations are not adaptive, we have performed a thorough spatial resolution study (see an example of compared snapshots at different resolutions in Fig. 1) and we have verified that at a resolution of $\sim 10$ pc the main physical phenomena included in the code are numerically properly treated. This is therefore the average numerical resolution we have used in our simulations.

![Figure 1](image-url)  
**Figure 1.** Density contours after 50 Myr of evolution for model galaxies at different spatial resolutions (labeled in pc at the top right corner of each panel). The density scale (in g cm$^{-3}$) is on the upper right panel.

As a typical evolutionary sequence of the refill process we show in Fig. 2 snapshots of a model with a moderate SF episode ($0.05$ $\text{M}_\odot$ yr$^{-1}$) lasting 200 Myr. The combined energy of SNeIa and SNeII is able to break-out of the galaxy at $t \sim 160$ Myr (first panel). The superbubble starts funneling through
the H\textsubscript{i} due to stratification of the ISM. After the additional time interval during which SNeII explode, i.e. after $\sim 230$ Myr, SNeIa still provide enough energy to sustain the outflow (panel 2). The funnel begins to shrink at $t \sim 300$ Myr and at $\sim 340$ Myr the outflow has almost completely disappeared (panel 3). At $\sim 400$ Myr the cavity has approximately the original size of the SF region (panel 4) and from now on it recedes further towards the center, therefore the refill timescale of this model is $\sim 200$ Myr. The refill of the cavity is mostly due to the pressure gradient created after the superbubble breaks out the disk.

The refill timescale however strongly depends on the amount of gas initially present inside the galaxy and on the duration and intensity of the SF episode and ranges between 125 (model with a large initial amount of H\textsubscript{i} and short and intense SF) and 600 Myr (model with a smaller initial H\textsubscript{i} mass and milder and long SF). This means that large H\textsubscript{i} holes (like the ones observed in many dIrr galaxies) can survive a few hundred Myr after the last OB stars have died.

A SF occurring in the refilled cavity would produce metals which mix with the surrounding unpolluted medium in a timescale of the order of 10–15 Myr, therefore any further episode of SF would stem out of a metal-enriched ISM. This is at variance with what happens if the center of the galaxy is still occupied by hot and diluted gas because, in this case, most of the metals are either directly ejected outside the galaxy through galactic winds or are confined in a too hot medium, therefore cannot contribute to the chemical enrichment of the warm ionized medium (see e.g. Recchi et al. 2006). More details can be found in Recchi & Hensler (2006).

![Figure 2](image_url)

**Figure 2.** Density contours and velocity fields for a model illustrating the process of refilling the superbubble cavities (see text) at five different epochs (evolutionary times are labelled in the box on the upper right corner of each panel). The density scale is given in the strip on top of the figure.

## 3. The effect of clouds in a galactic wind on the evolution of gas-rich dwarf galaxies

Although the multi-phase nature of the ISM, in particular its clumpiness, is observationally well established in DGs (Cecil et al. 2001; Leroy et al. 2006), most of the hydrodynamical simulations of galactic winds have focused on flows in homogeneous media, although several attempts to perform multi-phase hydrodynamical simulations have been made in the past, particularly, using the so-called chemodynamical approach (Theis et al. 1992; Hensler et al. 2004).
We simulated models with structural parameters similar to the well-known gas-rich DGs I Zw 18 and NGC 1569. These galaxies have been already modelled (Recchi et al. 2004; 2006) but considering only a diffuse medium, without clouds. We increased arbitrarily the gas density of some specific regions of the computational grid, in order to create a “cloudy” phase. We either perturbed the initial gaseous distribution or continuously created clouds, at a rate which equals the SF rate, giving them an infall velocity of 10 km s\(^{-1}\) along the polar direction. We addressed the question how and to which extent this “cloudy gas phase” alters the results obtained in the above mentioned papers, in particular for what concerns the development of galactic winds and the chemical evolution of the galaxy.

The clouds are subject to a variety of disruptive phenomena like evaporation, formation of shocks, development of dynamical instabilities (in particular the Kelvin-Helmholtz instability) and expansion due to the larger pressure compared to the surrounding interstellar medium, therefore their average lifetime is relatively short. Nevertheless, they affect significantly the dynamical and chemical evolution of a galaxy. In fact, the clouds, when they evaporate inside the superbubble, produce mass loading, increase the mean density of the cavity gas and, therefore, enhance the radiative energy losses. This results in a significant decrease of the total thermal energy (of the order of ~ 20 – 40% compared to the diffuse models), therefore less energy is available to drive the development of a large-scale outflow.

On the other hand, the relative motion of supershell and clouds can structure and pierce the expanding supershell, in particular, in models with the setup of infalling clouds. By this, holes and fingers are created, as perceivable in Fig. 3. These holes destroy the spherical symmetry initially present and favor the rushing out of the highly pressurized gas contained in the cavity. Therefore, in spite of the reduced thermal energy budget, the creation of large-scale outflows is not suppressed but, in most of the explored cases, only slightly delayed. A complete suppression of the development of the galactic outflow happens only if we consider a very large cloud falling in the galaxy along the polar direction (Recchi et al. 2006). The pressure inside the cavity is reduced compared to diffuse models, therefore in any case the total amount of ejected pristine ISM (i.e. the low-metallicity gas not
produced by the ongoing SF) is very small. However, the piercing of the supershell can lead to an ejection efficiency of freshly produced metals as high as the one attained by diffuse models, therefore, the diminished thermal energy of these models does not imply that a larger fraction of metals is retained inside the galactic regions. On the other hand, since the clouds are assumed to have primordial chemical composition, their destruction and mixing with the surrounding medium reduces the total chemical composition without altering the abundance ratios (see also Köppen & Hensler 2005). This produces a final metallicity $\sim 0.2 – 0.4$ dex smaller than the corresponding diffuse models. For details see Recchi & Hensler (2007).

4. The effect of geometry

The development of bipolar galactic winds is favored by a flat galaxy geometry since, in this case, there is a direction in which the work required to extract gas out of the galaxy potential well is particularly small, whereas in spherical galaxies the energy produced by the SF must be high enough to expel the gas in all directions. Numerical simulations of the evolution of such spherical galaxies have shown that the ISM pressure can confine the supershell inside the galaxy (see e.g. Marcolini et al. 2006, Recchi et al. 2007). Of course, the flatter the galaxy, the steeper the pressure gradient along the polar direction, and therefore the easier it is to produce bipolar galactic winds. This issue has been already analyzed by means of numerical simulations (see e.g. Strickland & Stevens 2000). However there is no systematic study in the literature about the effect of geometry on the development of galactic winds, neither it has been analyzed how it affects the chemical evolution of galaxies.

We have performed simulations of the evolution of DGs, with equal mass of $\sim 4 \cdot 10^8 M_\odot$, whose initial gas distribution is ellipsoidal, with constant semi-major axis (1 kpc) and variable semi-minor axis. In particular, we have analyzed 5 different values of the semi-minor axis: 1 kpc (spherical model), 800 pc, 600 pc, 400 pc and 200 pc (flattest model). For each model we have assumed a constant SF rate of $0.025 M_\odot$ yr$^{-1}$ and we have run the simulation for 500 Myr. In Fig. 4 we show the density distribution of gas for each of these models after 200 Myr of evolution. As expected, the flatter the galaxy is, the more intense and extended the galactic wind is. In particular, the spherical model does not show any sign of outflow whereas the flattest model shows a galactic wind extending up to $\sim 4$ kpc in the polar direction. However, also in the flattest model, the total amount of ISM expelled from the galaxy at the end of the simulation is only $\sim 15\%$.

However, as we have seen in the previous sections, a large fraction of the freshly produced metals can be channelled along the galactic wind, therefore the ellipticity of the galaxy can have important consequences on the chemical evolution. The spherical model does not produce outflows, therefore it retains all the produced metals. For the flattened models instead the loss of metals is significant and it increases proportionally to the ellipticity of the parent galaxy. The flattest galaxy retains at the end of the simulation only about one third of the metals produced during the SF episode. We have also considered models with short and intense SF (with a rate of $0.5 M_\odot$ yr$^{-1}$ lasting for 25 Myr) and the results are qualitatively the same, namely the spherical model does not produce outflows whereas the flattened models show an ejection efficiency of metals increasing with the ellipticity, with the flattest model losing $\sim 60\%$ of the metals produced by the burst of SF through the galactic wind.

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Figure 4. Density contours after 200 Myr of evolution for models differing on the semi-minor axis of their initial configurations (semi-minor axis indicated on top of each panel). The density scale is on the upper right panel.

References

[1] Cecil G, Bland-Hawthorn J, Veilleux S and Filippenko A V 2001, ApJ, 555, 338
[2] Dahlem M, Weaver K A and Heckman T M 1998, ApJS, 118, 401
[3] Dekel A and Silk J 1986, ApJ, 303, 39
[4] D’Ercole A and Brighenti F 1999, MNRAS, 309, 941
[5] Fragile P C, Murray S D and Lin D N C 2004, ApJ, 617, 1077
[6] Hensler G, Theis C and Gallagher J S III 2004, A&A, 426, 25
[7] Köppen J and Hensler G 2005, A&A, 434, 531
[8] Larson R B 1976, MNRAS, 176, 31
[9] Leroy A, Bolatto A, Walter F and Blitz L 2006, ApJ, 643, 825
[10] Mac Low M-M and Ferrara A 1999, ApJ, 513, 142 (MF99)
[11] Marcolini A, D’Ercole A, Brighenti F and Recchi S 2006, MNRAS, 371, 643
[12] Mathews W G and Baker J C 1971, ApJ, 170, 241
[13] Matteucci F and Recchi S 2001, ApJ, 558, 351
[14] Pettini M, Steidel C C, Adelberger K L, Dickinson M and Giavalisco M 2000, ApJ, 528, 96
[15] Recchi S and Hensler G 2006, A&A, 445, L39
[16] Recchi S and Hensler G 2007, A&A, 476, 841
[17] Recchi S, Hensler G, Angeretti L and Matteucci F 2006, A&A, 445, 875
[18] Recchi S, Matteucci F, D’Ercole A and Tosi M 2004, A&A, 426, 37
[19] Recchi S, Theis C, Kroupa P and Hensler G 2007, A&A, 470, L5
[20] Silich S A and Tenorio-Tagle G 1998, MNRAS, 299, 249
[21] Strickland D K and Stevens I R 2000, MNRAS, 314, 511
[22] Theis C, Burkert A and Hensler G 1992, A&A, 265, 465