Galactic Winds and Circulation of the ISM in Dwarf Galaxies

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ABSTRACT

We study, through 2D hydrodynamical simulations, the feedback of a starburst on the ISM of typical gas rich dwarf galaxies. The main goal is to address the circulation of the ISM and metals following the starburst. We assume a single-phase rotating ISM in equilibrium in the galactic potential generated by a stellar disk and a spherical dark halo. The starburst is assumed to occur in a small volume in the center of the galaxy, and it generates a mechanical power of \(3.8 \times 10^{39} \text{ erg s}^{-1}\) or \(3.8 \times 10^{40} \text{ erg s}^{-1}\) for 30 Myr. We found, consistently with previous investigations, that the galactic wind is not very effective in removing the ISM. The metal rich stellar ejecta, instead, may be efficiently expelled from the galaxy and dispersed in the intergalactic medium.

Moreover, we found that the central region of the galaxy is always replenished with cold and dense gas after a few 100 Myr from the starburst, achieving the requisite for a new star formation event in \(\approx 0.5 – 1 \text{ Gyr}\). The hydrodynamical evolution of galactic winds is thus consistent with the episodic star formation regime suggested by many chemical evolution studies.

We also discuss the X-ray emission of these galaxies and find that the observable (emission averaged) abundance of the hot gas underestimates the real one if thermal conduction is effective. This could explain the very low hot gas metallicities estimated in starburst galaxies.

Key words: hydrodynamics - galaxies: irregular - galaxies: ISM - galaxies: starburst

1 INTRODUCTION

Many gas rich dwarf galaxies are known to be in a starburst phase, or are believed to have experienced periods of intense star formation in the past (e.g. Gallagher & Hunter 1984; Thuan 1991; Tosi 1998, and references therein). These galaxies, classified as “blue compact dwarf (BCD) galaxies” or “HII galaxies”, are thus excellent laboratories to investigate the feedback of vigorous star formation on the interstellar medium (ISM).

Massive stars inject enormous amount of energy in the ISM through stellar winds and when they explode as type II supernovae (SNe); the impact of such an energy input on the galactic ISM may, in principle, be devastating. In fact it is often found that the total energy released during a starburst is greater than the gas binding energy. Yet many dwarf galaxies in a post-starburst phase are still gas rich. As Skillman & Bender (1995) pointed out, observational evidence (e.g. Marlowe et al. 1995; Martin 1996) are still insufficient to substantiate a disruptive impact of galactic winds on the ISM. Clearly, simple energetic considerations do not catch the essential nature of the feedback process, and detailed, time dependent hydrodynamical models are needed.

Galactic winds are thought to have a key role in the formation and evolution of dwarf galaxies (Dekel & Silk 1986, Babul & Rees 1992, Matteucci & Chiosi 1983). In general, understanding the physics of the feedback of massive stars on the ISM is a key problem in cosmological theories of galaxy formation (Yepes et al. 1997, Cole et al. 1994). Gas outflows from dwarf galaxies are also suggested to be an important factor for the production and enrichment of the intergalactic medium (Trentham 1994). However, persuasive arguments against this conclusion are given by Gibson & Matteucci (1997), and the origin of metals in clusters of
galaxies is still a matter of debate (Brighenti & Mathews 1998).

The fate of the (metal rich) material ejected by massive stars is of crucial importance in understanding the chemical evolution of these galaxies (Tosi 1998), in particular the low a-elements abundance and the ‘strange’ values of (He/H) and (N/O) vs. (O/H). These problems have been encompassed invoking a ‘differential ejection’, in which the enriched gas lost by massive stars escapes from the galaxy as galactic wind, while some (or most) of the original ISM is unaffected.

Recent hydrodynamical simulations have verified that, under many circumstances, galactic winds are able to eject most of the metal rich gas, preserving a significant fraction of the original ISM (MacLow & Ferrara 1998, hereafter MF; De Young & Heckman 1994; De Young & Gallagher 1991). Sillich & Tenorio-Tagle (1998) and Tenorio-Tagle (1996), instead, found that even the metal-rich material is hardly lost from galaxies, since it is at first trapped in the extended halos and then accreted back onto the galaxy.

To investigate this subject further, we present here new high resolution calculations, addressing the ultimate fate of the ISM and SN ejecta, and their mixing, in a realistic starbursting dwarf galaxy. We investigate in detail the different phases of the gas flow, with particular emphasis on the late evolution, evolving the simulations for 500 Myr after the starburst event. We consider the effect of the dark matter, gas rotation, thermal conduction and different starburst strengths. We also discuss the X-ray emission and its diagnostic for the abundance of the hot gas, a particularly exciting topic in view of the forthcoming launch of AXAF and XMM.

We aim at investigating the evolution of galactic winds in a general way, without focusing on any specific object. Thus, we select the parameters of the galactic models (total mass, ISM mass and distribution, etc.) to be representative of the class of dwarf galaxies. Nevertheless, it can be useful to compare some of our results to a real, representative object. An ideal galaxy is NGC 1569, a nearby, well studied starburst galaxy.

Several independent lines of evidence indicate that NGC 1569 is in a post-starburst phase (Israel 1988, Israel & de Bruyn 1988, Waller 1991, Heckman et al. 1995; Greggio et al. 1998), with the major starburst activity ceased ~ 5 – 10 Myr ago. Hα observations of NGC 1569 show (young) bubbles complexes, filaments and arcs throughout the volume of the galaxy (Tomita, Ohta & Saito 1994), suggesting a diffuse star formation. Heckman et al. (1995) found that the Hα emission of NGC 1569 can be separated in a quiescent component, permeating the starbursting region of the galaxy, and a more violent component, far more extended and with velocities up to 200 km s⁻¹. This high velocity component is interpreted to be ionized shells of superbubbles and provides a direct evidence of a galactic-scale outflow.

Heckman et al. (1995) and Della Ceca et al. (1996) detected X-ray emission, extending for 1–2 kpc along the optical minor axis of NGC 1569, thus probing the hot gas phase directly. This hot gas (T ≈ 10⁷ K) is the signature of the violent SN activity on the ISM.

As in almost all studies to date, we make a number of simplifying assumptions in calculating our models. First, the ISM is assumed to be homogeneous and single phase. Second, we neglect the selfgravity of the gas, even if the gas mass is of the same order of the stellar mass. Third, the starburst is instantaneous and concentrated in a small region at the center of the galaxy. While none of these hypotheses is likely to be strictly correct, they allow for a more direct comparison with previous works, and still make possible the calculation of models retaining the basics attributes of real galactic winds. We will relax some of these assumptions in a future paper in preparation.

2 GALAXY MODELS

Many ingredients play an important role in determining the hydrodynamical evolution of the galactic wind. Among others, the density distribution of the ISM in the pre-burst galaxy, the energy injection rate of the newly formed stars, the gravitational potential of the galaxy and the effectiveness of transport processes in the gas, like thermal conduction.

A thorough exploration of the parameter space would require an enormous amount of computational resources and it is beyond the scope of this paper. Thus, we hold approximately constant the stellar and ISM masses of the model galaxies (M∗ = 1.7 × 10⁶ M⊙ and MISM ∼ 1.3 × 10⁸ M⊙), although MISM is a crucial factor for the late evolution of the system (De Young & Heckman 1994; MF). Instead, we vary some of the others parameters as described below.

2.1 The gravitational potential and the gas distribution

The gravitational potential for our standard model is due to two mass distributions: a spherical quasi-isothermal dark matter halo plus a stellar thin disk.

The halo density is given by ρh(r) = ρho/[1 + (r/rc)²], and we chose a central density ρho = 4.34 × 10⁻²⁵ g cm⁻³ (6.4 × 10⁻³ M⊙ pc⁻³). The halo core radius is assumed to be rc = 1 kpc. The dark halo is truncated at r = 20 kpc.

The total dark mass is thus ∼ 2 × 10⁹ M⊙, while the halo mass inside the galactic region (defined hereafter as a cylinder R < 2.2 kpc and |z| < 1.1 kpc, approximately the optical size of NGC 1569) is only 0.66 × 10⁹ M⊙.

For simplicity, we assume that the stars are distributed in an infinitesimally thin Kuzmin’s disk with surface density

$$\Sigma_*(R) = \frac{r_* M_*}{2\pi (R^2 + r_*^2)^{3/2}}$$

where r* = 2 kpc is the radial scalelength and M* = 1.7 × 10⁶ M⊙ is the total stellar mass, a typical value for dwarf galaxies. Although this mass distribution is clearly a rough approximation of real stellar disks, it does not degrade the accuracy of the large scale hydrodynamical flow. The stellar potential generated by this mass distribution is

$$\Phi_*(R, z) = -\frac{G M_*}{\sqrt{R^2 + (r_* + |z|)^2}}$$

(Binney & Tremaine 1987).

It turns out that the stellar mass inside the galactic region is M*gal ∼ 3.13 × 10⁷ M⊙, about half of the dark halo mass and about a factor of four less than the gas mass.
inside the same volume (see below). The dark halo totally dominates the mass budget at larger radii.

The ISM is assumed to be single-phase and in equilibrium with the potential described above. In real dwarf galaxies the neutral ISM is supported against gravity partly by rotation and partly by the HI velocity dispersion (see Hoffman et al. 1996), with maximum rotational velocity that typically exceeds the velocity dispersion by a factor of few. Thus, in the standard model (hereafter model STD) we allow the ISM to rotate, to investigate the role played by the angular momentum conservation on the late phase of the evolution, when (once the energy output is ceased) the gas tends to recollapse toward the central regions (see section 3.1). The temperature of the unperturbed ISM is set to $T_0 = 4.5 \times 10^5$ K.

To build a rotating ISM configuration in equilibrium with the given potential, we first arbitrarily assume a gas distribution in the equatorial plane ($z = 0$) of the form $\rho(R, z) = \rho_0/[1 + (R/R_c)^2]^{1/2}$, where the central value is $\rho_0 = 3.9 \times 10^{-24}$ g cm$^{-3}$ and the gas core radius is $R_c = 0.8$ kpc. The rotational velocity in the equatorial plane is then determined from the condition of equilibrium:

$$v_\phi^2 = v_c^2 - \frac{R \, dp}{\rho \, dR} \bigg|_{z=0}$$

where $v_c = \sqrt{R \, d\Phi/dR}$ is the circular velocity and $p$ the thermal gas pressure. The rotational velocity is assumed to be independent of $z$. The density at any $z$ is then found integrating the $z$-component of the hydrostatic equilibrium equation, for any $R$. The edge-on and face-on profiles of the resulting gas column density are shown in Fig. 1. We note that this model, having an extended gaseous halo, resembles the models worked out by Silich & Tenorio-Tagle (1998).

The circular velocity for this mass model increases with $R$, reaching the maximum value of $\sim 20$ km s$^{-1}$ at $R \sim 4$ kpc and staying almost constant for larger $R$. The rotational velocity $v_\phi$ shows a similar radial behaviour, but with a maximum value $v_\phi \sim 15$ km s$^{-1}$.

The total gas mass inside the galactic region is $M_{\text{ISM,gal}} \sim 1.32 \times 10^8$ M$_\odot$, a typical amount for dwarf galaxies (Hoffman et al. 1996), and in close agreement with the mass inferred for NGC 1569 in particular (Israel 1988). The total gas mass present in the numerical grid (extending to 25 kpc in both $R$ and $z$ directions) is $M_{\text{ISM, tot}} \sim 6 \times 10^8$ M$_\odot$.

The gas distribution qualitatively resembles that used by Tomisaka & Ikeuchi (1988). It has a low density region around the $z$-axis (see Fig. 2a), which acts as a collimating funnel for the hot outflowing gas (Tomisaka & Bregman 1993, Suchkov et al. 1994). This is due to the assumption that $v_\phi$ does not depend on $z$. The funnel, however, influence the gas dynamics only at very large distances above the galactic plane (i.e. for $z \gtrsim 10$ kpc) and does not invalidate the results presented in sections 3 and 4.

In order to address the influence of an intracluster medium (ICM) confining the galactic ISM, we calculate model PEXT (section 4.3). In this simulation we replace all the cold ISM (distributed as described above) having a thermal pressure $P \leq 10^{-13}$ dyn cm$^{-2}$ with a hot, rarified ICM with $p_{\text{ICM}} = 8 \times 10^{-36}$ g cm$^{-3}$ and $T_{\text{ICM}} = 10^8$ K. In this case the cold ISM is confined to a roughly ellipsoidal region with major and minor semiaxes 2 kpc and 1 kpc, respectively. The galactic ISM mass is now only $M_{\text{ISM,gal}} = 1.05 \times 10^8$ M$_\odot$, while the total mass of gas in the grid is $M_{\text{ISM, tot}} \sim 1.16 \times 10^8$ M$_\odot$.

In addition to the models described above, we use a different galaxy model (model B) to investigate the effect of the absence of dark matter and rotation. The isothermal ISM in hydrostatic equilibrium in the potential well generated by the same stellar distribution as in model STD. The central gas density is $\rho_0 = 1.1 \times 10^{-23}$ g cm$^{-3}$, and the gas mass inside the galactic region is $1.4 \times 10^8$ M$_\odot$, approximately as in model STD. Due to the lack of rotational support, the gas distribution is now more concentrated than in model STD (see the ISM column density in Fig. 1), and the total gas mass inside the grid is $M_{\text{ISM, tot}} = 2.3 \times 10^8$ M$_\odot$. We also run a model identical to model B, but including heat conduction (model BCOND).

![Figure 1. Column density of the initial ISM. Heavy solid line: model STD seen edge-on; heavy dashed line: model STD seen face-on; light solid line: model B seen edge-on; light dashed line: model B seen face-on.](image-url)
Table 1. Models physical and numerical parameters.

| Code    | STD  | SB1 | PEXT | B     | BCOND |
|---------|------|-----|------|-------|-------|
| MISM    | 6.0  | 4.87| 1.16 | 2.3   | 2.3   |
| MISM,gal| 1.32 | 1.32| 1.05 | 1.4   | 1.4   |
| M*      | 1.7  | 1.7 | 1.7  | 1.7   | 1.7   |
| M_DH    | 20   | 20  | 20   | 0     | 0     |
| L_{imp} | 37.6 | 3.76| 3.76 | 37.6  | 37.6  |
| Rotation| YES  | YES | YES  | NO    | NO    |
| N_R    | 405^2 | 505^2| 405^2 | 480×540 | 410×530 |
| ΔR_{min} | 10   | 3   | 10   | 2     | 2     |
| ΔR_{2kpc} | 25   | 17  | 25   | 22    | 22    |
| R_{max} | 25   | 14.9| 25   | 23    | 11.4  |
| z_{max} | 25   | 14.9| 25   | 42    | 38    |
| Code    | ZEUS | ZEUS| ZEUS | BO    | BO    |

$M_{\text{ISM}}$ is the initial ISM mass present in the computational grid; $M_{\text{ISM,gal}}$ is the ISM mass in the galactic region $R < 2.2$ kpc and $|z| < 1.1$ kpc; $M_*$ is the assumed stellar mass; $M_{\text{DH}}$ is the dark matter halo mass. All masses are given in units of $10^8 M_\odot$. $L_{\text{imp}}$ is the energy input rate in $10^{39}$ erg s$^{-1}$. $N_R$ and $N_z$ are the number of cells in the $R$-direction and $z$-direction. $\Delta R_{\text{min}} = (\Delta z_{\text{min}})$ is the central zone size in pc. $\Delta R_{2\text{kpc}} = (\Delta z_{2\text{kpc}})$ is the width in pc of the zone at $(R,z)=(2$ kpc, 0) or $(R,z)=(0, 2$ kpc). $R_{\text{max}}$ and $z_{\text{max}}$ are the total dimensions of the grid in kpc. In the last row is indicated the hydrocode used (ZEUS-2D or the Bologna code).

According to LH, if all stars with initial mass greater than 8 $M_\odot$ end their lives as type II supernovae, the total number of SNII events produced by the starbursts is $\sim 4000$ and $\sim 40000$ for SB1 and SB2.

The total energy deposited after 30 Myr is $\sim 3.56 \times 10^{54}$ erg and $\sim 3.56 \times 10^{55}$ for SB1 and SB2. These values must be compared with the binding energy of the gas present in the numerical grid in the standard model, $E_{\text{bind}} \sim 5.3 \times 10^{54}$ erg, and with the binding energy of the gas inside the galactic region $\sim 1.8 \times 10^{54}$ erg.

After 30 Myr, the total mass returned to the ISM by stellar winds and type II SNe in the model by LH, again with $Z = 1/4 Z_\odot$ and a Salpeter IMF, is $4.81 \times 10^5 M_\odot$ and $4.81 \times 10^5 M_\odot$ for SB1 and SB2. With our assumed $M_*$, however, we inject $9 \times 10^5 M_\odot$ and $9 \times 10^5 M_\odot$ for models SB1 and SB2 respectively. Thus, we overestimate the mass return rate by a factor $\sim 2$ with respect to the LH model.

However, the hydrodynamical evolution of our models is not sensitive to such a discrepancy, as well as our estimate of the efficiency of ISM and metal ejection (although the pollution degree of the ISM may be affected).

While our assumed starburst model is fairly consistent with the detailed theoretical models by LH, it is important to note that real galaxies have generally a much more complex star formation history. The assumption of instantaneous, point-like burst appears particularly severe. For example, Greggio et al. (1998) found that the bulk of the starburst in NGC 1569 proceeded at an approximately constant star formation rate of 0.5 $M_\odot$ yr$^{-1}$ for 0.1 – 0.15 Gyr (assuming a Salpeter IMF from 0.1 to 120 $M_\odot$), until $\sim 5 – 10$ Myr ago, when the star formation in the field ended. It implies that $\sim 5 – 7.5 \times 10^7 M_\odot$ of gas has been converted into stars.

† Alternatively, we can think to a starburst with a double amount of mass turned into stars, and to an efficiency in the energy deposition rate of $\sim 0.5$.

Moreover, Hα observations of NGC 1569 show (young) bubbles complexes, filaments and arcs distributed throughout the volume of the galaxy (Tomita et al. 1994), suggesting a diffuse, wide scale star formation.

Galactic wind models powered by a point-like energy source are nevertheless useful as first step toward the full complexity of the problem, and for a direct comparison with previous studies. Simulations with spatially and temporally extended star formation will be the subject of a forthcoming paper.

2.3 The numerical simulations

To work out the models presented in this paper we used two different 2-D hydrocodes. The first one has been developed by the Numerical Group at Bologna Astronomical Observatory and the (1-D) core of the scheme is described in Bedogni & D’Ercole (1986). This code and its successive extensions have been applied to a variety of astrophysical problems (e.g. Brighenti & D’Ercole 1997, D’Ercole & Ciotti 1998). The second code employed is ZEUS-2D, a widely used, well tested scheme developed by M. Norman and collaborators at LCSA (Stone & Norman 1992). We always found consistent results among the codes, as expected from the numerous hydrodynamical tests performed with the Bologna code (Brighenti 1992).

We solve the usual hydrodynamical equations, with the addition of a mass source term and a thermal energy source term; the hot gas injected expands to form the starburst wind with the appropriate mechanical luminosity $L_{\text{imp}}$. These equations are described in details in, e.g., Brighenti & D’Ercole (1994). The (constant) mass and energy source terms are given respectively by $\alpha = M/V$ and $\epsilon$. Here $V$ is the volume of the source region, chosen to be a sphere of radius $50$ pc, centered at $(R,z) = (0,0)$, and $\epsilon = L_{\text{imp}}/M$.

To keep track of the gas lost by the stars formed in the starburst (the ejecta), we passively advect it solving an auxiliary continuity equation for the ejecta density $\rho_j$. Both the codes used spread shocks over 3-4 zones and contact discontinuities over 4-10 zones.

In our models the angular momentum is treated in a fully consistent way (see Stone & Norman 1992 for the details about the resolution of the angular momentum equation). Thus, contrary to some of the previous studies (Tomisaka & Ikeuchi 1988, Tomisaka & Bregman 1993), we do not use a reduced gravitational force to mimic the rotational support of the ISM.

To take into account the thermal conduction (model BCOND) we adopt the operator splitting method. We isolate the heat diffusion term in the energy equation and solve the heat transport equation, alternatively along the $z$ and $R$ direction separately, through the Crank-Nicholson method which is unconditionally stable and second order accurate. The system of implicit finite difference equations is solved according to the two-stage recursion procedure (e.g. Richmeyer and Morton 1967). Following Cowie & McKee (1977), we adopt saturated fluxes to avoid unphysical heat transport in presence of steep temperature gradients.

We ran the models on a cylindrical grid (coordinates $R$ and $z$), assuming axial symmetry. We use reflecting boundary conditions along the axes and outflow boundary conditions at the grid edges. To better resolve the central region,
the lateral side being denser (is present along the shell, from the equator to the pole, with a superbubble.

hot gas and they do not necessarily trace the edges of the out by MF, these filaments of dense gas are immersed in the solution of these features, whose actual density is expected to be higher than that found in our computations. As pointed out by MF, the roughly oblate ISM configuration of our model forces the superbubble to expand faster along the polar direction, acquiring the classical bipolar shape at late times (Fig. 2b,c,d). At earlier times, however, the density distribution favours a diagonal expansion, generating a curious boxy morphology (Fig. 2a).

When the energy input from the starburst ends (at t = 30 Myr, Fig. 2a), almost the whole galactic region (R < 2.2 kpc, |z| < 1.1 kpc) is filled by the freely expanding wind, a situation clearly unrealistic, due to our simple ISM model. In real galaxies we expect that this region hosts a complicated multiphase medium. Israel & van Driel (1990) found a relatively small hole (with diameter ∼ 200 pc) in the H I distribution, associated with the super star cluster N 1569A and likely caused by the action of SN II and stellar winds of the star cluster.

The shocked ISM shell is accelerating through the steep density gradient of the unperturbed ISM, and this acceleration promotes Rayleigh-Taylor (R-T) instabilities. The shell tends to fragment and relatively dense (n ≤ 0.5 cm⁻³), cold (T ∼ 10⁴ K) filaments are clearly seen in Fig 2a at (z, R) ∼ (1.3) kpc. The numerical resolution of this simulation is not appropriate to follow the real formation and evolution of these features, whose actual density is expected to be higher than that found in our computations. As pointed out by MF, these filaments of dense gas are immersed in the hot gas and they do not necessarily trace the edges of the superbubble.

At t=30 Myr the whole shocked ISM shell is radiative. Following the trend of the external ISM, a density gradient is present along the shell, from the equator to the pole, with the lateral side being denser (n ∼ 1.5 cm⁻³) and the polar region more rarefied (n ∼ 0.002 cm⁻³). At this time, the optical appearance of the system, if kept ionised (for example by a low level star formation activity, hot evolved stars, etc.), would be that of an incomplete shell, the polar portion being too rarefied to be observable, given its low emission measure (EM ∼ 0.01 cm⁻⁶ pc for the shell and EM < 30 cm⁻⁶ pc for the filaments).

The radiative external shock is too slow (v_shock ≤ 180 km s⁻¹) to emit X-ray. This is contrary to the results by Suchkov et al. (1994), who claim that most of the X-ray radiation comes from the shocked ISM. The different behaviour in our models is due to the lower (by an order of magnitude) L_{inp} considered, probably more appropriate for a dwarf galaxy. As explained in section 3.4, we also find that the hot ISM is the most important contributor to the X-ray luminosity. However, it is not heated by shocks, but by mixing with the shocked wind at the contact discontinuities. At later times the outer shock accelerates through the steep density gradient, and heats the ISM to X-ray temperatures. On the other hand, this happens only when the X-ray luminosity has dropped to very low and uninteresting values (cf. Fig. 6).

Fig. 2b shows the density distribution at t = 60 Myr. The steep density gradient along the z-direction induces a

3 THE STANDARD MODEL (STD+SB2)

3.1 The dynamics of the ISM

As the starburst wind starts blowing, the classical two shocks configuration is achieved, in perfect analogy to the star wind bubble theory (Dyson & de Vries 1972, Weaver et al. 1977). The freely expanding wind encounters the reverse shock and is heated to T ∼ 5 × 10⁷ K, while the external shock sweeps the ISM. The shocked starburst wind and the shocked ISM are separated by a contact discontinuity. The reverse shock is always approximately spherical, since the short sound crossing time in the shocked wind region keeps the pressure almost uniform. The shape of the forward shock, instead, depends on the ISM density distribution. The roughly oblate ISM configuration of our model galaxy forces the superbubble to expand faster along the polar direction, acquiring the classical bipolar shape at late times (Fig. 2b,c,d). At earlier times, however, the density distribution favours a diagonal expansion, generating a curious boxy morphology (Fig. 2a).

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Fig. 2b shows the density distribution at t = 60 Myr. The steep density gradient along the z-direction induces a

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radiative-adiabatic transition of the polar portion of the external shock. The cold filaments are slowly moving forward, and their density decreases to maintain the pressure equilibrium with the expanding hot gas; now the densest filaments have \( n \approx 0.04 \text{ cm}^{-3} \).

The shell is increasingly thicker with time. In fact, while the outer edge is still expanding, with \( v \approx 25 \text{ km s}^{-1} \), the inner edge of the shell near the equatorial plane is already receding toward the center with a velocity \( v \approx 10 \text{ km s}^{-1} \). This backward motion, due to the drop of the pressure inside the expanding hot bubble, will eventually cause the collapse of the cold gas back inside the galactic region, as evident in Fig. 2d (see also MF). The details of the collapse are shown in Fig. 3 and described below.

Fig. 2c and 2d show the density at 100 and 200 Myr respectively. The external shock assumes a pronounced cylindrical shape because of the collimating effect of the low density region around the z-axis (section 2.1). The polar shock crossed the numerical grid edge (at \( z = 25 \text{ kpc} \)); however, being the motion supersonic, the numerical noise generated at the grid boundary does not propagate back. Moreover, given the very low densities in that region, the amount of gas lost from the grid is completely negligible.

The temperature of the hot, X-ray emitting gas decreases with time, \( T \sim 5 \times 10^5 \text{ K} \) during the active energy injection phase (\( t \lesssim 30 \text{ Myr} \)). At later times, radiative losses and especially expansion lower the temperature (\( T \lesssim 10^5 \text{ K} \) at 60 Myr; \( T \lesssim 2 \times 10^6 \text{ K} \) at 100 Myr; \( T \lesssim 10^6 \text{ K} \) at 200 Myr). ASCA observations of NGC 1569 (Della Ceca et al. 1996) indicate that the diffuse X-ray emission comes from a luminosity weighted temperature (Strickland & Stevens 1998). We warn that all the model temperature values quoted are mass weighted and may not represent the “observable” ones.

No more supported by the hot gas pressure, the cold ISM recollapses at \( t \sim 150 \text{ Myr} \), filling again the galactic region. We show a zoomed view of the central part of the grid in Fig. 3. In panel a the density contours and the velocity field are shown at \( t = 140 \text{ Myr} \), just before the cold gas reaches the center. In panel b the same quantities are shown at \( t = 200 \text{ Myr} \). In Fig. 3a the cold tongue is approaching the center at \( v \approx 40 \text{ km s}^{-1} \), with a Mach number \( M \approx 10 \).

The density in the collapsing gas increases with \( R \), from \( n \sim 2.3 \times 10^{-3} \text{ cm}^{-3} \) at \( (R,z) = (0.5,0) \text{ kpc} \), to \( n \sim 7.5 \times 10^{-3} \text{ cm}^{-3} \) at \( (R,z) = (1,0) \text{ kpc} \), to \( n \sim 2.3 \times 10^{-2} \text{ cm}^{-3} \) at \( (R,z) = (2,0) \text{ kpc} \). At \( t = 150 \text{ Myr} \) the cold gas reaches the center and shock. Hereafter the accretion proceeds through a cylindrical shock wave.

At \( t = 200 \text{ Myr} \) the cold gas is still flowing toward the center with \( v \approx 15 \text{ km s}^{-1} \), building a (transient) conical structure around the z-axis (Fig. 3b). The mean density on the equatorial plane in the galactic region is \( n \approx 0.025 \text{ cm}^{-3} \), and it is still growing with time. Panels c and d show the subsequent evolution (\( t = 250 \text{ Myr} \) and \( t = 300 \text{ Myr} \) respectively). The collapse is the result of the pressure drop in the hot bubble, due to its expansion along the polar direction. Between \( t = 60 \text{ Myr} \) and \( t = 100 \text{ Myr} \) the pressure of the hot gas decreases by more than one order of magnitude (from \( \sim 6 \times 10^{-13} \) to \( \sim 10^{-15} \text{ dyn cm}^{-2} \)). The cold gas, no longer supported by the hot phase, is driven back to the center mainly by its own pressure, rather than the galactic gravity.

We have verified that the collapse is not a spurious numerical effect due to strong radiative losses at the numerically broadened contact discontinuities. To this purpose we run a simulation identical to the standard model, but with the radiative cooling turned off. For this adiabatic model we found that the collapse time is again \( \sim 150 \text{ Myr} \). The ISM recollapse is thus an unavoidable phenomenon for all the models considered in this paper.

It is interesting to follow the circulation of the gas. The mass of the ISM in the galactic region, at \( t = 200 \text{ Myr} \), is \( M_{\text{ISM,gal}} \sim 0.034 \times 10^8 \text{ M}_\odot \), about a factor of \( \sim 40 \) lower than the initial gas mass in the same volume (note that it does not mean that the ejection efficiency \( f_{\text{ISM}} \) is 1/40, since what matters in estimating \( f_{\text{ISM}} \) is the amount of ISM effectively bound to the galaxy, as described in the next section). However, at \( t = 200 \text{ Myr} \) the cold gas is still flowing toward the center (Fig. 3b); for instance, at \( t = 300 \text{ Myr} \) we found \( M_{\text{ISM,gal}} \sim 0.096 \times 10^8 \text{ M}_\odot \). At \( t = 500 \text{ Myr} \), the final time of our simulation, \( M_{\text{ISM,gal}} \sim 0.27 \times 10^8 \text{ M}_\odot \), a factor of \( \sim 5 \) lower than the initial gas mass in the same volume.

We can speculate further on the fate of the cold gas falling back to the center at late times. The face-on surface density of the central ISM is an increasing function of time (Fig. 4), since material continues to accrete until the end of our simulation (\( t = 500 \text{ Myr} \)); we could not follow the evolution further because of our limitation in computational resources). It has been suggested that above a critical ISM surface density \( \Sigma_{\text{crit}} \sim 5 \times 10^{20} \text{ cm}^{-2} \), the star formation in dwarf galaxies is very efficient (Gallagher & Hunter 1984, Skillman 1987, 1996). At \( t = 200 \text{ Myr} \) the face-on surface density peak in our model is \( \Sigma \sim 10^{20} \text{ cm}^{-2} \), and it grows slowly to \( 6 \times 10^{20} \text{ cm}^{-2} \) at \( t = 500 \text{ Myr} \). Thus, we can hypothesize that the threshold surface density is reached in a time of the order of 1 Gyr, after that a new burst of star formation may start. This scenario is roughly consistent with many studies of the star formation history in BCD galaxies, which indicate that stars are formed mainly through several discrete, short bursts, separated by long (\( \sim \) few Gyrs) quiescent periods (see the review by Tosi (1998) and references therein).

### 3.2 The ISM ejection efficiency

A key point in the galactic wind theory is the ability of the starburst in ejecting the ISM (see Skillman & Bender (1995) and Skillman (1997) for a critical review about this subject).

We estimate the ISM ejection efficiency calculating, at some late time, for example \( t = 200 \text{ Myr} \), the mass of ISM \( M_{\text{hot}} \) which has velocity or sound speed greater than the local escape velocity. We assume that this gas (and the gas that already left the grid) will be lost by the galactic system (see also MF). It is important to note that \( M_{\text{hot}} \) calculated in this way should be considered only a rough estimate of the amount of gas leaving the galaxy, since dissipative effects may lower the ejection efficiency, and the escape velocity depends critically on the poorly known size of real dark matter halos. The ISM ejection efficiency, \( f_{\text{ISM}} \), is then defined as \( M_{\text{hot}}/M_{\text{initial}} \), where \( M_{\text{initial}} \) is the total gas mass present on the whole grid at \( t = 0 \) (we neglect the contribution of...
Figure 3. Density contours and velocity field for the central region of model STD at 140 Myr, 200 Myr, 250 Myr and 300 Myr.

Figure 4. Face-on column density of model STD at three different times. Dotted line: 200 Myr; dashed line: 300 Myr; solid line: 500 Myr.

the ejecta, whose total mass is only \( \lesssim 0.2 \% \) of the initial mass. We note that this operative definition for \( f_{\text{ISM}} \) is grid dependent, since \( M_{\text{initial}} \) increases with the volume covered by the numerical grid.

At \( t=200 \) Myr we find \( f_{\text{ISM}} = 0.058 \): evidently even a powerful starburst as the one considered for this model is not effective in removing the interstellar gas.

However, as pointed out in the previous section, the gas mass inside the galactic region can be significantly lower than the initial value, even long after the starburst event: thus, the efficiency in removing the ISM from the central regions may be considerably greater than \( f_{\text{ISM}} \). However, for other models (see section 4.3), the galaxy is able to recover most of the original ISM mass after \( \approx 100 \) Myr.

3.3 The enrichment

In a similar way we have estimated the ejection efficiency of the metal-rich stellar ejecta, \( f_{\text{ej}} \). At \( t = 200 \) Myr we found \( f_{\text{ej}} = 0.46 \): the galaxy is less able to retain the enriched stellar ejecta than its own original ISM. This finding supports the selective winds hypothesis, and it is in qualitative agreement with others numerical simulations (De Young & Gallagher 1990; De Young & Heckman 1994; MF).

It is interesting to investigate the spatial distribution of the ejecta material. We found that at \( t = 200 \) Myr \( \sim 7.3 \times 10^5 M_\odot \) of stellar ejecta are present on the numerical grid, about 80 % of the total material released by the starburst. However, the ejecta mass in the galactic region is only \( M_{\text{ej,gal}} \sim 5.15 \times 10^4 M_\odot \), less than 0.6 % of the total amount ejected (9 \( \times 10^5 M_\odot \))! Since gas continues to flow toward the central region, the mass of the ejecta in the galactic region increases slightly with time. At \( t = 300 \) Myr, for instance, we found \( M_{\text{ej,gal}} \sim 1.29 \times 10^4 M_\odot \), and \( M_{\text{ej,gal}} \sim 3.6 \times 10^4 M_\odot \) at \( t = 500 \) Myr. We conclude that, while a significant fraction of the ejecta is retained by the relatively deep potential of the dark halo, most of it resides in the outer regions of the system, in a phase so rarefied to be virtually unobservable.

The cold gas collapsing at late times, and filling the
galactic region, has been only slightly polluted by the stellar ejecta. To characterize the pollution degree we introduce the local ejecta fraction as $Z = \rho_{ej}/\rho$, where $\rho_{ej}$ is the density of the ejecta. The average ejecta fraction in the galactic region, at $t = 200$ Myr, defined as $<Z_{gal}> = M_{ej,gal}/M_{ISM,gal}$, is $Z \sim 1.4 \times 10^{-3}$. The cold galactic ISM, probably the only component detectable at late times because of its relatively high density, shows only a small degree of enrichment.

We can estimate the increase in the metal abundance generated by the starburst from the total number of SNII, which we assume to be the only source of metals. The iron production and circulation is particularly worthwhile, because the metallicity estimated through X-ray spectra of the hot gas phase ($T \sim 10^7$ K) are especially sensitive to iron through the Fe-L complex at $\sim 1$ keV. For the sake of simplicity we shall neglect the iron produced by SNIa, whose iron release timescale is believed to be of the order of one Gyr (Matteucci & Greggio 1986), a time much longer than those considered in this paper.

In section 2.2 we estimated a total number of SNII $\sim 4000$ and $\sim 40000$ for SB1 and SB2 respectively (adopting the same IMF as in LH). The yields of metals from SNII are rather uncertain, especially for iron and oxygen, because of the complications in the late evolution of massive stars and nuclear reactions rates. A compilation of IMF averaged yields, i.e., the mean ejected mass of a given element per SN, can be found in Loewenstein and Mushotzky (1996). Given the approximate nature of the calculations presented in this paper, we simply adopt $<y_{Fe} > = 0.1$ M$_{\odot}$ and $<y_{O} > = 1$ M$_{\odot}$ as reasonable values for averaged iron and oxygen yields. We assume that the metals are well mixed within the ejecta, whose abundances (by mass and relative to H) are $Z_{Fe,ej} \sim 3.4 Z_{Fe,\odot}$ and $Z_{O,ej} \sim 4.6 Z_{O,\odot}$, where we adopt the meteoritic solar abundances from Anders & Grevesse (1989).

In Fig. 5 we show the iron gas abundance distribution at $t = 200$ Myr, assuming that the original ISM has $Z_{Fe,0} = 0$ (i.e. we calculate the increment in the metallicity caused by the starburst ejecta). The iron abundance is highly inhomogeneous, both in the hot and cold phase. It ranges from very low values $Z_{Fe,0} \lesssim 0.01 Z_{Fe,\odot}$ to the pure ejecta value $Z_{Fe} = 3.4 Z_{Fe,\odot}$. The hot phase metallicity is supersolar with typical values $Z_{Fe} = 1.5 - 2.5 Z_{Fe,\odot}$. It is puzzling that recent ASCA observations of the outflows in starburst galaxies indicate that the metal abundance of the hot gas is rather low. We discuss this point in the next section.

While the numerical diffusion may affect somewhat the absolute values of $Z_{Fe}$, we believe that the spatial variations of the metallicity are real. The oxygen abundance pattern is identical to that of iron, due to our assumption of perfectly mixed ejecta, but with different minimum and maximum values ($0 - 4.6 Z_{O,\odot}$).

The cold gas replenishing the galactic region has average metallicity $<Z_{Fe,0}> \lesssim 0.005 Z_{Fe,\odot}$ ($<Z_{O,0}> \sim 0.01 Z_{O,\odot}$), so that a successive instantaneous starburst event would form stars only slightly more metallic than the previous stellar generation.

### 3.4 The X-ray emission and hot gas metallicity

A detailed investigation of the X-ray emission of the hot gas is beyond the scope of this paper. The intrinsic diffusion of the numerical scheme spreads contact discontinuities, separating the hot and cold phases, over several grid points. This fact prevents us to consistently calculate X-ray luminosities ($L_X$) and emission averaged abundances of the hot phase. In fact, the gas inside the broadened contact discontinuities (a mixture of the ejecta and the pristine ISM), being relatively dense and with temperatures of the order of $10^6$ K, turns out to dominate $L_X$.

It is important to note that several physical processes, not considered in this simulation, smear out hydrodynamical discontinuities, mixing cold and hot ISM, and producing a gas phase with intermediate temperature and density. Most important are thermal conduction and turbulent mixing (Begelman & Fabian 1990). Thus, the undesired numerical diffusion qualitatively mimics real physical effects.

We consider explicitly the heat conduction in section 4.3, but we are not in the position to make quantitative estimates on the influence of turbulent mixing layers on $L_X$.

With this limitation in mind we can nevertheless gain some insights on the properties of the X-ray emission of starbursting galaxies. The X-ray luminosity of several models (see below), calculated in the straightforward way as $L_X = \int \epsilon_R(T)dV$, is a decreasing function of time (here $\epsilon_R(T)$ is the Raymond-Smith emissivity in the ROSAT band). All models shown in Fig. 6 share the same trend: at first $L_X$ drops gently until $t = 30$ Myr and then, when the energy input stops, $L_X$ decreases rapidly to unobservable values.

The most interesting observables is the emission averaged metallicity. In order to compare our data with observations, we define the emission averaged ejecta fraction $<Z>_{X} = (1/L_X) \int Z \epsilon_R dV$ (it is a measure of the gas...
abundance. It is almost constant with time up to 30 Myr, with typical values of 0.04-0.06, and then it increases steadily up to $\sim 0.5$ at $t = 100$ Myr, when, however the X-ray luminosity is so weak to make the detection virtually impossible. This very low ‘metallicity’ clearly indicates that most of the X-ray emission comes from original ISM mixed with stellar ejecta.

To isolate the contribution of the ejecta material to $L_X$ and $< Z >_X$, we recalculated these two quantities using the ejecta density $\rho_{ej}$ (instead of the gas density) in the calculation of the X-ray emissivity. Now $L_X$ is a factor $\sim 100$ lower than before, and $< Z >_X$ is now much larger, approaching unity. Note that this does not mean that the ISM heated by the outer shock is the main contributor to $L_X$ (see below). It demonstrates instead that diffusion processes mix the ISM with the shocked ejecta, and the material in these mixing layers makes most of the $L_X$.

In the last few years the ROSAT, ASCA and BeppoSAX satellites provided detailed X-ray observations of starburst galaxies. While for dwarf galaxies the hot gas abundance cannot be unambiguously determined (e.g. Della Ceca et al. 1996), for brighter starburst galaxies the counts statistics is high enough to make this task possible (Ptak et al. 1997; Tsuru et al. 1997; Okada, Mitsuda & Dotani 1997; Persic et al. 1998). A somewhat surprising result of all these observations is that the iron abundance is invariably small, typically less than 0.1 solar. This low metallicity can easily be understood if the X-ray emission is dominated by the layer of shock-heated ISM, as pointed out by Suchkov et al. (1994). However, this is not a general result, and it does not hold for our models in particular, since the external shock is too slow to heat the ISM to X-ray temperatures (section 3.1). Thus, in model STD the only X-ray emitting gas is expected to be the (shocked) ejecta of the stars formed in the starburst, and its metallicity is thus expected to be quite high. This abundance discrepancy forces the theoretical models to move toward a higher level of complexity.

Low X-ray abundances can be explained in several ways. First, it seems reasonable that thermal conduction and turbulent mixing give rise to a mass loaded flow (Hartquist, Dyson and Williams 1997, Suchkov et al. 1996) with low emission averaged metallicity, provided that the cold gas mixed with the hot phase is nearly primordial. In this case the emission averaged temperature of the hot gas is expected to be low (few $10^6$ K); see section 4.3. Second, the hot gas might be severely depleted by dust. Stellar outflows and SN ejecta are observed to form dust (e.g. Clegg 1989; Colgan et al. 1994), and the dust sputtering time $t_{sp} \sim 2 \times 10^3 a_{um}/n$ yr (where $a_{um}$ is the dust grain radius, Draine & Salpeter 1979; Itoh 1989) in the hot phase may be long enough to make most of the iron still locked into grains after few $10^7$ yr. Another possibility is that the estimated abundances are not accurate. Strickland & Stevens (1998) analysed the synthetic ROSAT X-ray spectrum of a simulated wind-blown bubble, finding that simple fits may underestimate the metallicity by more than one order of magnitude. The inadequacy of 1-T models in estimating the gas abundance has been demonstrated also by Buote & Fabian (1998) and Buote (1999) in the context of hot gas in elliptical galaxies and groups of galaxies. Indeed, Dahlem, Weaver & Heckman (1998) used multi-components models to fit ROSAT PSPC + ASCA spectra of seven starburst galaxies and found that low metallicities are no more required, and nearly solar abundances are entirely consistent with the data. Their findings support the idea that the inferred low abundances are caused by the undermodelling of X-ray spectra.

4 OTHER MODELS

4.1 Model SB1

With this simulation we investigate the effect of a weaker starburst on the ISM of a dwarf galaxy. This model is identical to model STD, but the starburst mechanical luminosity is a factor of ten lower. This starburst may be more typical among dwarf galaxies. We reduce the mechanical luminosity lowering the mass loss rate by a factor of ten (see §2.2).

We anticipate that in this model the radiative cooling at the contact discontinuities, artificially broadened by numerical diffusion, is now important, and causes the hot bubble to slowly collapse.

Fig 7a shows the density distribution at $t = 30$ Myr, when the energy and mass input turns off. As in model STD, dense tongues of shocked ISM penetrate in the hot bubble as a result of R-T instabilities. As expected, the superbubble is now much smaller than in model STD, and it is expanding less rapidly. The hydrodynamical evolution is illustrated in the other panels of Fig. 7. At $t = 60$ Myr (Fig. 7b) the internal edge of the shocked ISM shell is receding toward the center with $v \sim 25$ km s$^{-1}$. The cold gas reaches the origin at $t \sim 70$ Myr, much earlier than in model STD. We find that the ISM collapse is slightly accelerated by the spurious energy losses mentioned above. To address the importance of this undesired numerical effect, we recalculated the Model SB1 without radiative cooling (the adiabatic model). These

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two extreme models should bracket the reality. For this adiabatic model the replenishing of the central region occurs at 
$\sim t \sim 85$ Myr.

Fig. 7c shows the ISM density at $t = 100$ Myr. The hot, rarefied bubble is almost totally shrunk; the hot gas mass is now only $4.4 \times 10^{6} \, M_{\odot}$ (it was $\sim 2.7 \times 10^{4} \, M_{\odot}$ at $t = 30$ Myr). At the same time the adiabatic model contains $\sim 2.6 \times 10^{5} \, M_{\odot}$ of hot gas. The cold ISM continues to move ordinarily toward the $z$-axis, and it encounters a weak accretion shock at $R \sim 0.1$ kpc.

The density distribution at 200 Myr is shown in Fig. 7d. No more hot gas is present (while in the adiabatic model $M_{\text{hot}} \sim 4.8 \times 10^{3} \, M_{\odot}$, and it is decreasing with time as the result of the numerical diffusion). The accretion shock has moved forward to $R \sim 1$ kpc, where the cold ISM is still accreting with $v \sim 10$ km s$^{-1}$. The face-on surface density in the galactic region varies from $2.5 \times 10^{21}$ cm$^{-2}$ at the very center, to $4 \times 10^{20}$ cm$^{-2}$ at $R = 2$ kpc. The number density in the central region is about 0.35 cm$^{-3}$. As in model STD the central surface density is slowly increasing with time, approaching the critical value for the onset of effective star formation activity. Thus, also for this model, the secular hydrodynamical evolution indicates the possibility of recurrent starburst episodes. The time between successive starburst events in this model is shorter than in model STD, being only few 100 Myr.

At $t = 200$ Myr the ISM ejection efficiency $f_{\text{ISM}}$ is essentially zero: all the gas is cold and it is moving with a velocity lower than the escape velocity ($f_{\text{ISM}} = 1.8 \times 10^{-3}$ for the adiabatic model). The gas mass inside the galactic region is $M_{\text{ISM,gal}} = 6.5 \times 10^{7} \, M_{\odot}$, about half of the mass present initially. Since the gas is still accreting, the central ISM mass increases with time: at $t = 300$ Myr we have $M_{\text{ISM,gal}} = 8.0 \times 10^{7} \, M_{\odot}$.

Thus, in the case of moderate starburst strength, the galaxy is able to recover most of the original ISM in a relatively short time. The evolution of this model is qualitatively similar to that of model STD, but is now accelerated and, as expected, the galactic ISM ‘forgets’ the starburst quicker.

The circulation of the stellar ejecta is qualitatively similar to that of the standard model. However, now $f_{\text{ej}} = 0.003$: almost all the metals produced by the starburst remain bound to the galaxy. A significant fraction of the total ejecta mass ($\sim 2.4 \times 10^{4} \, M_{\odot}$, $\sim 27 \%$ of the total) is still present in the galactic region at this late time. The very low value for $f_{\text{ej}}$ is partly due to the excess of radiative losses at the contact surfaces. For the adiabatic model we find $f_{\text{ej}} = 0.14$ (still much lower than in model STD) and $M_{\text{ej,gal}} \sim 3.3 \times 10^{3} \, M_{\odot}$. In summary, we find that $f_{\text{ej}}$ is significantly lowered by the spurious extra-cooling, but the important quantity $M_{\text{ej,gal}}$ does not change greatly. The conclusion is that a significant fraction ($\sim 30 \%$) of the metals ejected is retained in the galactic region when the moderate starburst SB1 is adopted.

### 4.2 Model PEXT+SB2

With this model we investigate the evolution of a galactic wind occurring in a galaxy immersed in a hot, tenuous ICM as described in section 2.1. All the other parameters are identical to model STD. Fig. 8a shows the gas density at $t = 30$ Myr. The superbubble has already blown out in the ICM, generating a complex filamentary structure. The fastest matter penetrating in the ICM is moving with $v \approx 2000$ km s$^{-1}$. Fig. 8b and 8c show the density at $t = 60$ Myr and at $t = 200$ Myr. The portion of the cold shell blowing out in the ICM is completely disrupted by the instabilities and spreads in a large volume, due to the high expansion velocities in the rarefied medium. At 200 Myr, the original ISM survives in a toroidal structure ($1.5 < R < 8$ kpc) on the equatorial plane. The inner edge of the cold gas is receding slowly ($v \sim 20$ km s$^{-1}$) toward the center, while the outer portion is still expanding ($v \sim 40$ km s$^{-1}$). The cold gas starts to collapse toward the center, which is reached at $t \sim 270$ Myr, much later than in the previous models. The ISM column density increases more slowly than in model STD, and at $t = 500$ Myr the central peak is only $\Sigma_{\text{ISM}} \sim 2 \times 10^{20}$ cm$^{-2}$. Thus, in this case, the subsequent star formation episode might be delayed with respect to model STD.

At 200 Myr the mass of gas present in the galactic region is $M_{\text{ISM,gal}} \sim 1.9 \times 10^{6} \, M_{\odot}$, and about 1.5% is hot ($T \sim 10^{6}$ K). At the final time (500 Myr) we have $M_{\text{ISM,gal}} \sim 8.7 \times 10^{6} \, M_{\odot}$. The ejection efficiency is $f_{\text{ISM}} = 0.31$, much higher than in model STD because the absence of an extended envelope of (relatively dense) cold gas.

The mass of the metal-rich ejecta in the galaxy is...
Figure 8. Map of the logarithm of the number density for model PEXT at three different times. Labels are in kpc. The gray-scale varies linearly from -7.27 (white) to 0.20 (black). Contours are as in Fig. 2.

$M_{\text{gal}} \approx 5.8 \times 10^3 M_\odot$ ($1.8 \times 10^4 M_\odot$ at 500 Myr) and $f_{\text{ej}} = 0.83$. These values are comparable to those found for model STD. However, we find that the hot gas has been severely contaminated by the hot ICM, and $Z \lesssim 0.05$ for almost all the hot ISM. The reason for this behaviour is the high temperature of the ICM, which greatly increases the importance of numerical diffusion.

We estimate an upper limit for this effect, considering the first order upwind method (Roache 1972). The numerical diffusion coefficient is $D_{\text{upwind}} \approx c \Delta$, where $\Delta$ is the zone size. The diffusion time is $\tau_D = \Delta^2 / D \approx 30$ Myr (here $\Delta \approx 30$ pc at $R = z \approx 2.5$ kpc and $c$ is the ICM sound speed), so the numerical diffusion affects significantly this simulation, and this explains the very low values for $Z$. We conclude that for model PEXT we cannot calculate the enrichment process in a consistent way. For model STD, given the low temperature of the ISM ($4.5 \times 10^3 K$), $\tau_D$ is more than two order of magnitude longer, and the intrinsic diffusion is negligible.

We note that the physical diffusion time scale, $\tau_D = L^2 / D$, where $L$ is the typical length scale of the problem ($L \approx 1$ kpc), is very short: $\tau_D \approx 10^{-2} - 10^{-3}$ yr. This is due to the high value for $D \approx \lambda c$, where $\lambda \approx 5$ Mpc is the mean free path for the ICM (Spitzer 1962). However, even a small magnetic field reduces the mean free path to the order of the ion Larmor radius $r_L$. Only in this case we are allowed to consistently use the hydrodynamical equations. With $\lambda \approx r_L$ the physical diffusion is effectively impeded.

4.3 Model B+SB2 and BCOND+SB2

Panel a of Fig. 9 shows the gas density of model B (section 2) at 30 Myr, just at the end of the starburst activity. The free expanding wind extends so far that almost all of the galaxy is devoid of the pristine gas. There is a radial gradient in the bubble temperature: along the $z$-axis $T$ ranges from $\sim 4 \times 10^7 K$ close to the reverse shock to $\sim 10^6 K$ behind the forward shock; a similar pattern is also present along the $R$-axis, although the temperatures behind the lateral shock are lower ($\sim 10^5 K$) because of the lower velocity of the shock moving through the higher local ambient density. The average density of the hot gas filling the bubble is $\approx 10^{-4}$ cm$^{-3}$. The expansion velocity along the symmetry axis is $\sim 300$ km s$^{-1}$, and decreases toward the equatorial plane. The bubble accelerates as it expands through the decreasing ISM density profile, and the R-T unstable contact discontinuity generates relatively dense ($n \sim 10^{-2}$ cm$^{-3}$) and cold ($T \sim 10^5 K$) filaments and blobs. Actually, denser structures can be seen on the $z$ axis, but they are likely due to our assumption of vanishing radial velocity on the symmetry axis. In fact, cold gas deposited on this axis cannot be effectively removed, a well known shortcoming common to all 2D cylindrical simulations. Given the progressively increasing zones size with $z$ and $R$, it is likely that the knots density is underestimated in our simulations, especially for the condensations far from the center. At $t = 57$ Myr (Fig. 9b) there is a large region essentially devoid of gas ($n \sim 5 \times 10^{-6}$ cm$^{-3}$) surrounded by a very thick, low density shell ($n \sim 10^{-4}$ cm$^{-3}$), with a temperature $\sim 10^6 K$. The external shock is rounder than in model STD, due to the lack of the collimating effect of the funnel along the $z$-axis (cfr. Fig. 2b). The dense and cold gas near the equatorial plane is already receding toward the center with a velocity $\sim 30$ km s$^{-1}$, and a rarefaction wave is moving outward. The highest density in the shell is $\sim 10$ cm$^{-3}$ on the equator, where the expansion velocity is 10 km s$^{-1}$. Apart the cold gas on the $z$ axis, where the density reaches $\sim 30$ cm$^{-3}$, the densest filaments have $n \approx 3 \times 10^{-2}$ cm$^{-3}$. At $t \sim 75$ Myr (not shown in Fig. 9) the inflowing cold gas reaches the center, where the density is still rather low ($n \sim 10^{-2}$ cm$^{-3}$). After 106 Myr (panel c), the final time of this simulation, the hot gas is still expanding, but the central cold ISM is entirely collapsed, filling a region $|z| < 2.5$ kpc, $R < 6.5$ kpc. The galaxy has thus recovered a cold ISM distribution similar to the original one. The ISM...
mass inside the galaxy is $M_{\text{ISM,gal}} \sim 10^8$ M$_\odot$. Near the center the density reaches a few cm$^{-3}$.

About the starburst ejecta, its largest content inside the galaxy is reached at $t = 30$ Myr, with $M_{ej,gal} = 3.6 \times 10^5$ M$_\odot$. At this time $<Z_{\text{gal}}>= 2.4 \times 10^{-3}$, and it decreases steadily with time. At $t = 106$ Myr $<Z_{\text{gal}}>= 1.1 \times 10^{-3}$ while the ejecta mass is $M_{ej,gal} \sim 10^5$ M$_\odot$, about one tenth of the total gas lost by the massive stars. The ISM and metals ejection efficiency, estimated at $t = 106$ Myr, are $f_{\text{ISM}} = 0.48$ and $f_{ej} = 0.77$ respectively. While the high $f_{ej}$ is consistent with the results obtained in section 3.3, the large value for $f_{\text{ISM}}$ is striking when compared to model STD. However, this discrepancy reflects a deficiency in the definition of $f_{\text{ISM}}$, rather than a really different behaviour of the two models. As a matter of fact, model B recovers a ‘normal’ ISM before model STD! The discrepancy is due to several factors. First, in model B the massive dark halo is absent. The escape velocity is then quite low (a factor 2-4 less than in model STD) and the gas residing at large radii becomes easily unbound. Second, the ISM distribution in model B is more peaked than in model STD, and the total amount of gas present in the numerical grid is lower (cfr. section 2.1). This, in turn, means that in model B the starburst provides more energy per unit gas mass than in model STD.
model STD. We believe that the difference in $f_{\text{ISM}}$ between model STD and model B should be considered with some caution. In real galaxies, the gas at large radii, which is the source of the difference in $f_{\text{ISM}}$, can be removed by ram pressure and tidal stripping, processes not included in our simple models. Thus, the contribution of this gas to $f_{\text{ISM}}$ is rather uncertain.

The X-ray emission averaged $<Z>_x$ is much higher than $<Z>_{\text{gal}}$ and increases from $<Z>_x=0.06$ at $t=30$ Myr up to $<Z>_x \sim 0.2$ at $t \geq 50$ Myr; at later times the bubble gas cools out of the X-ray temperatures and $<Z>_x$ drops to zero at $t \sim 60$ Myr.

In Fig. 10 we show model BCOND, identical to model B but with the heat conduction activated. Again, panel a shows the density at 30 Myr. The superbubble is less extended than in model B, because of the increased radiative losses in the conduction fronts. The temperature distribution inside the superbubble is now rather flat near the equator, but a negative gradient is present along the z-direction, with the temperature in the range $10^6 < T < 10^7$ K. As in the previous models, cold structures are present due to the R-T instabilities. The density of these structures is $n \sim 3 \text{ cm}^{-3}$, while the density of the hot gas is $\sim 10^{-3} \text{ cm}^{-3}$, one order of magnitude larger than in model B. This higher density is due to the evaporation of the walls of the shocked ISM shell which ‘feed’ the inner region of the bubble. The expansion velocities are similar but lower than those of model B at the same time. Panel b shows the density at 56 Myr and can be compared with panel b of Fig. 9. The size of the superbubble remains smaller and the shape more elongated. The hot gas in the cavity is denser ($n \sim 5 \times 10^{-5} \text{ cm}^{-3}$) and slightly colder ($T \sim 2.5 \times 10^5$ K) than in the non-conductive case. The cold gas near the equatorial plane is receding toward the center, while the outer edge (where $n \sim 10 \text{ cm}^{-3}$) is still expanding. The densest filaments have $n \sim 0.1 \text{ cm}^{-3}$. Panel c shows the gas flow at 105 Myr. The cold inflowing gas has just reached the center, much later than model B. In fact, the pressure drop of the hot gas is slower in model B because the density of the hot gas is kept higher by the shell evaporation and by the slower expansion rate.

At $t = 125$ Myr, the last time of this simulation, $M_{\text{ISM,gal}} \sim 0.92 \times 10^7 M_\odot$, not far from the initial value. However, only a fraction of the galactic volume contains a cold, dense ISM. In fact, roughly half of the galaxy is still filled with the rarefied gas of the cavity, now only moderately hot ($T \lesssim 10^5$ K). At this time the ISM ejection efficiency is $f_{\text{ISM}} = 0.32$.

The peculiar structure apparent on the symmetry axis ($z \gtrsim 20 \text{ kpc}$) at $t = 105$ Myr (Fig. 10c) is a numerical artifact depending on our treatment of the heat conduction. Collisionless shocks (for instance, in supernova remnants) do not show the hot precursor which would be expected (Zel’dovich & Raizer, 1966). This means that the plasma instabilities responsible of the shock formation also inhibit the heat flow through the front itself (Cowie 1977). To mimic this phenomenon in numerical simulations, the heat conduction coefficient must vanish at the shock front. To detect the shock front position on the computational grid is an easy task in 1D simulations, but becomes rather cumbersome in two dimensions. Fortunately, the precursor length is rather short (shorter than the grid size) unless the upwind density is very low. We thus did not make any special treatment at the shock front. Effectively, the heat flux overruns the front only at late times, when the upwind density becomes rather low. However, this happens when the shock is well outside the galaxy, and our conclusions are not affected.

The ejecta content inside the galaxy is $M_{e} = 1.7 \times 10^5 M_\odot$ after 30 Myr ($<Z>_{\text{gal}} \sim 1.2 \times 10^{-3}$) and decreases steadily down to $M_{e} = 0.77 \times 10^5 M_\odot$ after 125 Myr, when $<Z>_{\text{gal}} \sim 8.3 \times 10^{-4}$. At $t = 125$ Myr we find $f_{\text{ej}} = 0.88$.

It is particularly interesting to investigate the X-ray emission for model BCOND, since now the numerical diffusivity does not affect the value of $L_X$ and $<Z>_x$ (cf. section 3.4). In fact, the thermal conduction naturally broadens the contact surfaces on length scales larger than thickness due to the numerical diffusion. The temporal variation of $L_X$ is shown in Fig. 6. $L_X$ is higher than in model B because of the emission arising in conduction fronts. The emission averaged abundance $<Z>_x$ ranges between 0.13 and 0.20 for $t \lesssim 70$ Myr. As the energy input stops, the temperatures of the hot phase quickly drops and after $t \sim 70$ Myr no more X-ray emitting gas is present. The observable emission averaged temperature of the hot gas is $<T>_x \sim 2 \times 10^6$ K for $t \lesssim 30$ Myr and drops quickly thereafter.

5 DISCUSSION AND CONCLUSIONS

The results presented here qualitatively confirm the conclusions of previous investigations on the effect of galactic winds in dwarf galaxies (e.g. MF). In general, it is found that the ISM is more robust than expected, and it is not disrupted even if the total energy input is much greater than the gas binding energy. In fact, the gas in the optical region of dwarf galaxies is only temporarily affected by the starburst, and the galaxy is able to recover a ‘normal’ ISM after a time of the order of 100 Myr from the starburst event, here assumed to be instantaneous. Our results agree well with the ‘moderate form’ of galactic wind dominated evolution of dwarf galaxies described by Skillman (1997). In Table 2 we summarize the values of the fraction of ISM and metal-rich ejecta that is lost by the galaxy.

We find that the evolution of the ISM can be separated in two phases. The first one corresponds to the energy input period (which lasts 30 Myr in our models). During this phase the superbubble expands surrounded by a fragmented and filamentary shell of cold gas. The hot gas inside the bubble and the cold shell gas are in pressure equilibrium. The second phase starts when the energy input stops: the pressure of the hot bubble, still expanding along the polar direction, drops quickly. This causes the inner portion of the shell near the equator to collapse back toward the center, replenishing the galactic region with cold gas. The collapse is driven mainly by the pressure gradient, with the gravity being of secondary importance.

The replenishment process occurs through inflow of cold gas moving parallel to the equatorial plane, thus resembling the inflows considered by Tenorio-Tagle & Munoz-Tunon (1997). However, the ram pressure associated to this flow in model STD, representative of all our models, is $\approx 10^{-14}$ dyn cm$^{-2}$, five orders of magnitude lower than those assumed by Tenorio-Tagle & Munoz-Tunon (1997). Evidently, if such massive inflows exist, they must have a different origin.

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We found that the central ISM reaches the critical column density required for rapid star formation after 0.1 - 1 Gyr from the starburst, the exact value depending on the galactic parameters, when a new starburst may start. This episodic star formation regime is necessary to account for the chemical evolution of BCD galaxies, and we have shown here that it is consistent with the hydrodynamical evolution of the ISM.

Most of the metal-rich material shed by the massive stars resides in the hot phase of the ISM, and for powerful starbursts it is easily lost from the galaxy (Table 2). We estimate that a fraction of 0.5 - 0.9 of the total metal-rich gas is dispersed in the intergalactic medium when the starburst model SB2 is adopted. However, for moderate energy input rates (model SB1), only a small fraction (\(\leq 10\%\)) becomes formally unbound. In spite of the smallest \(f_{\text{ej}}\), model SB1 has the lowest \(<Z_{\text{gal}}>\), since the total amount of ejecta is a factor of 10 lower than the other models. Most of the ejecta material is pushed to large distance from the galaxy (several kpc), and its fate is uncertain, being subject to ram pressure and tidal stripping. These processes may effectively remove material loosely bound to the galaxy.

There is some quantitative difference between our findings and those by MF. The generally lower \(f_{\text{ej}}\) found in our model is likely to be the result of our more extended gaseous halo. Their models, with a sharp truncation of the ISM, are similar to our model PEXT. The most striking disagreement is between model SB1, for which we find \(f_{\text{ej}} = 0.003\), and their model with \(M_{\text{gas}} = 10^{7} M_{\odot}\) and \(L_{\text{inp}} = 10^{39}\) erg s\(^{-1}\) which has \(f_{\text{ej}} = 1\). However, as explained in section 4.1, model SB1 suffers of some numerical extra-cooling; the same model without radiative losses gives \(f_{\text{ej}} = 0.14\), probably a more realistic value if thermal conduction is not effective. A comparison of our Fig. 7a-b with fig. 2a of MF (panel with the model \(M_{\text{g}} = 10^{5}\); \(L_{\text{inp}} = 10^{38}\), in their notations) dramatically shows the sensitivity of the superbubble dynamics (and size) on the ISM distribution.

The cold gas replenishing the central region, from which a successive starburst may form, has been only slightly polluted by the massive star ejecta, with \(<Z> \approx 4 \times 10^{-4} - 2 \times 10^{-3}\), or \(<Z_{\odot}> \approx 2 \times 10^{-3} - 10^{-2}\) \(Z_{\odot}\), with the assumptions described in section 3.3. Thus, many starburst episodes are necessary to build an average metallicity \(Z \sim 0.25 Z_{\odot}\). We determined that the origin of the X-ray radiation is model dependent. For \(L_{\text{inp}} = 10^{38}\) appropriate for typical dwarf galaxies we found that \(L_{X}\) is dominated by the ISM mixed with the shocked ejecta at the contact discontinuities.

The values listed in Table 2 demonstrate how the evolution of the ISM is not regulated by the ejection efficiency parameters \(f_{\text{ISM}}\) and \(f_{\text{ej}}\) alone. For instance, model PEXT and BCOND have similar \(f_{\text{ISM}}\) and \(f_{\text{ej}}\), but very different ISM and ejecta masses. Conversely, the gas mass evolution of model SB1 and model B is comparable, despite of dissimilar ejection efficiencies.

Comparing models STD and B, we found that a dark matter halo has little direct influence on the final behaviour of the ISM. However, dark matter and rotation determine the initial gas distribution, which is an important parameter for the flow evolution. For instance, the central region of model STD is refilled with cold gas more slowly than model B, a difference which reflects the different initial ISM distribution.

In order to evaluate how the assumption of an instantaneous burst influences our results, we run an additional model similar to STD, but with \(L_{\text{inp}} = 1.128 \times 10^{40}\) erg s\(^{-1}\), \(M = 0.009 M_{\odot}\) yr\(^{-1}\). The energy and mass sources are now active for 100 Myr, so that the total energy and mass injected are the same as in STD. With this model, which in a simple way mimics the effect of a prolonged starburst, we wish to check the sensitivity of our results on the assumption of a instantaneous starburst adopted in models illustrated in the previous sections. We found that the general dynamics is similar to that of model STD and is not described here. The ejection efficiencies, again calculated at \(t = 200\) Myr, are \(f_{\text{ISM}} = 0.055\) and \(f_{\text{ej}} = 0.40\), almost identical to those found for STD (Table 2). Thus, it appears that the instantaneous starburst hypothesis does not invalidate our general findings.

We devoted section 3.4 to discuss the complex X-ray emission arising from starburst galaxies. We warn again that for model BCOND only we can calculate the X-ray quantities in a strictly consistent way, the other models having the contact surfaces numerically spread by the intrinsic diffusion of the hydrocode (although several physical processes are thought to produce similar effect, cfr. section 3.4). In model BCOND the thermal conduction generates physically broadened interfaces between hot and cold gas. We found that the X-ray luminosities in the ROSAT band (Fig. 7) are generally less than those estimated by Della Ceca et al. (1996, 1997) for NGC 1569 and NGC 4449. It is thus suggested that a mass loading mechanism is at work in these systems (see also Suchkov et al. 1996). Moreover, the low abundances found in X-ray studies also indicate that thermal conduction (or some other process that mix cold and hot gas) is effective.

Contrary to Suchkov et al. (1994) we found that the shocked ISM layer does not contribute appreciably to the X-ray luminosity for \(t \lesssim 30\) Myr, a fact indicating that the origin of the X-ray radiation is model dependent. For \(L_{\text{inp}}\) appropriate for typical dwarf galaxies we found that \(L_{X}\) is dominated by the ISM mixed with the shocked ejecta at the contact discontinuities.
