Dynamical and chemical evolution of gas-rich dwarf galaxies

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ABSTRACT
We study the effect of a single, instantaneous starburst on the dynamical and chemical evolution of a gas-rich dwarf galaxy, whose potential well is dominated by a dark matter halo. We follow the dynamical and chemical evolution of the ISM by means of an improved 2-D hydrodynamical code coupled with detailed chemical yields originating from type II SNe, type Ia SNe and single low and intermediate mass stars (IMS). In particular we follow the evolution of the abundances of H, He, C, N, O, Mg, Si and Fe. We find that for a galaxy resembling I Zw18, a galactic wind develops as a consequence of the starburst and it carries out of the galaxy mostly the metal-enriched gas. In addition, we find that different metals are lost differentially in the sense that the elements produced by type Ia SNe are more efficiently lost than others. As a consequence of that we predict larger \([\alpha/Fe]\) ratios for the gas inside the galaxy than for the gas leaving the galaxy. A comparison of our predicted abundances of C, N, O and Si in the case of a burst occurring in a primordial gas shows a very good agreement with the observed abundances in I Zw18 as long as the burst has an age of \(\sim 31\) Myr and IMS produce some primary nitrogen. However, we cannot exclude that a previous burst of star formation had occurred in I Zw18 especially if the preenrichment produced by the older burst was lower than \(Z = 0.01\) \(Z_\odot\). Finally, at variance with previous studies, we find that most of the metals reside in the cold gas phase already after few Myr. This result is mainly due to the assumed low SNII heating efficiency, and justifies the generally adopted homogeneous and instantaneous mixing of gas in chemical evolution models.

Key words: galaxies: individual: I Zw18 – hydrodynamics – ISM: abundances – ISM: bubbles.

1 INTRODUCTION
Dwarf irregular galaxies (DIG) are playing an increasingly central role in understanding galaxy evolution. This kind of galaxies generally has a low metallicity (from 0.5 \(Z_\odot\) to 0.02 \(Z_\odot\)), a high gas content (up to \(\sim 10\) times the stellar content) and their stellar populations appear to be mostly young. All these features indicate that these galaxies are poorly evolved objects.

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 recent past. These galaxies are generally called blue compact dwarf (BCD) galaxies (Sandage & Binggeli 1984). In general, dwarf gas-rich galaxies, given their simple structures and small sizes, are excellent laboratories to investigate the feedback of starbursts on the interstellar medium (ISM), and to study their chemical evolution. The aim is to reproduce the observed abundance ratios, to trace their recent star formation history and to discover if these galaxies could be the source of the intracluster gas (Gibson & Matteucci 1997).

Many authors have tried to connect late-type gas-rich (DIG and BCD) and early-type gas-poor dwarf galaxies (dwarf ellipticals and dwarf spheroidals) in an unified evolutionary scenario. The favourite theory about ISM depletion in gas-rich dwarf galaxies is based

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on the starburst-driven mass loss. The basis of this model, proposed by Larson (1974) and then applied specifically to dwarfs by Vader (1986) and Dekel & Silk (1986), is that the ISM is blown out of the galaxy by the energetic events associated with the star formation (stellar winds and supernovae). The well-known correlation between mass and metallicity found for both late-type and early-type dwarf galaxies (Skillman, Kennicutt & Hodge 1989) is a natural result of the increasing inactivity of massive galaxies to retain the heavy elements produced in each stellar generation. At the present time it is not yet clear if galactic winds are really the key point for understanding the formation and evolution of dwarf galaxies (see Skillman & Bender 1995 and Skillman 1997 for critical reviews about this point), but they certainly play an important role, regulating the mass, metal enrichment and energy balance of the ISM.

Observational evidences in support of the presence of outflows have been found recently in a lot of gas-rich dwarf galaxies, like NGC1705 (Meurer et al. 1992), NGC1569 (Israel 1988), IZw18 (Martin 1996) and many others. In their search for outflows in dwarf galaxies, Marlowe et al. (1995) pointed out that this kind of phenomena is relatively frequent in centrally star-forming galaxies. Again, they note a preferential direction of propagation along the galaxy minor axis. In spite of these observational evidences, it is often difficult to establish if the gas will leave definitively the parent galaxy. In order to understand the final fate of both the swept-up gas and the metals ejected during the starburst and to study possible links between early and late-type dwarfs, numerical simulations are needed.

There are a lot of recent hydrodynamical simulations concerning the behaviour of the ISM and the metals ejected by massive stars after a starburst. These simulations generally agree on the fact that galactic winds are not so effective in removing the ISM from dwarf galaxies, but disagree on the final fate of the metal-enriched gas ejected by massive stars. Many authors (D’Ercole & Brighenti 1999, hereafter DB; MacLow & Ferrara 1999, hereafter MF; De Young & Heckman 1994; De Young & Gallagher 1990) have found that galactic winds are able to eject most of the metal-enriched gas, preserving a significant fraction of the original ISM. Other authors (Silich & Tenorio-Tagle 1998; Tenorio-Tagle 1996) have suggested that the metal-rich material is hardly lost from the galaxies, since it is first trapped in the extended haloes and then accreted back on to the galaxy.

However, all these models consider only the effects of stellar winds and SNIa explosions on the dynamics of the ISM. In this paper we present models which take into account also the energetic contribution and the feedback from intermediate-mass stars and SNeIa, using the most up-to-date supernova rates. The effect of SNIa explosions is certainly fundamental for the late dynamical evolution of the ISM (up to $\sim 500$ Myr after the burst), even if their number is small.

There is an extensive literature about the chemical evolution of starburst and blue compact dwarf galaxies (see e.g. Matteucci & Chiosi 1983; Matteucci & Tosi 1985; Olofsson 1995). Pilyugin (1992, 1993) and Marconi et al. (1994) suggested the idea that the spread in the chemical properties of these galaxies, in particular the observed spread in He/H vs. O/H and N/O vs. O/H, could be due to self-pollution of H II regions coupled with ‘enriched’ or ‘differential’ galactic winds.

Therefore it is interesting to test the differential wind hypothesis with an hydrodynamical approach. In our models we are able to follow the evolution in space and time of the abundances of several chemical elements (H, He, C, N, O, Mg, Si, Fe); in particular we follow, with suitable tracers, the gas released by stars of different initial mass. The chemical composition of each of these tracers is obtained by adopting the nucleosynthesis prescriptions from various authors (Woosley & Weaver 1995, hereafter WW; Renzini & Voli 1981, hereafter RV; Nomoto, Thielemann & Yokoi 1984, hereafter NTY).

In section 2 we describe the model and the assumptions adopted in our simulations. The results are presented in section 3 and compared with the observational constraints available for the BCG I Zw18. A discussion is presented in section 4 while some conclusions and future improvements of the model are discussed in section 5.

2 ASSUMPTIONS AND EQUATIONS

2.1 The gravitational potential and the gas distribution

It is convenient, for computational reasons, to model BCD galaxies. In these galaxies, in fact, the starburst occurs near the optical centre and the ISM structure is highly axisymmetric. In particular, we will focus on the galaxy I Zw18 which is a well-studied, very metal-poor BCD galaxy. I Zw18 shows very blue colors ($U - B = -0.88$, Van Zee et al. 1998), which are indicative of a dominating very young stellar population, although one cannot exclude an underlying older one (Aloisi et al. 1999). Therefore, I Zw18 is an excellent candidate to compare with a single-burst model, although our model cannot reproduce the real galaxy in detail.

Many ingredients play an important role in the dynamical evolution of the ISM: the galactic structure (stellar component, gaseous component, dark halo), the energy and mass injection rate of newly formed stars and the size of the starburst region.

We model the ISM of I Zw18 assuming a rotating gaseous component in hydrostatic isothermal ($T_0 = 10^3$ K) equilibrium with the galactic potential and the centrifugal force. The potential well is the sum of two components. The first is given by a spherical, quasi-isothermal dark halo truncated at a distance $r_{ch}$, in order to obtain a finite mass:

$$\rho_h (r) = \rho_{ho} \left[ 1 + \left( \frac{r}{r_{ch}} \right)^2 \right]^{-1},$$

(1)

where $r = \sqrt{R^2 + z^2}$ and $r_{ch}$ is the core radius of the dark component (we are using cylindrical coordinates). According to values found in literature for the total mass of I Zw18 (Lequeux & Viallefond 1980; Van Zee et al. 1998, hereafter VZ)
1998), the halo mass is assumed to be $6.5 \times 10^8 \, M_\odot$. Since we do not take into account the self gravity of the gas, in order to reproduce the oblate distribution of gas inside IZw18 (Van Zee et al. 1998), we introduce a fictitious ‘stellar’ component described by an oblate King stellar profile:

$$\rho_*(R, z) = \rho_{*0} \left[ 1 + \left( \frac{R}{R_*} \right)^2 + \left( \frac{z}{z_*} \right)^2 \right]^{-\frac{3}{2}},$$

(2)

where $R_*$ and $z_*$ are the core radius along the $R$-axis and the $z$-axis respectively. This profile is truncated at the tidal radii $R_t$ and $z_t$, in order to obtain a finite mass $M_* = 6 \times 10^7 \, M_\odot$. This structure is flattened along the $z$-axis and we assume $R_*/z_* = R_*/z_* = 5$ and $R_*/R_* = z_*/z_* = 4.29$. All the structural parameters of our galactic model are summarized in Table 1. The atomic number density of the neutral ISM is defined as $n_g = \frac{n}{\mu m_\odot}$, where $\rho$ is the ISM mass density and $\mu = 7/11$ is the mean mass per particle of the fully ionized gas, assuming a primordial abundance.

Although this structure is rather flat, its potential is rounder. The gas settled in such a potential assumes an oblate structure resembling that of the ISM of IZw18 in a region $R \leq 1 \, \text{Kpc}$ and $z \leq 730 \, \text{pc}$, which we call ‘galactic region’. We note however that the elongation is also due to the assumed rotation of the gas which is responsible for the flaring at large radii (see Fig. 1, upper panel). Details of how to build such an equilibrium configuration can be found in DB. The lower panel in Fig. 1 shows the resulting column density of the ISM.

We ran several models varying the gas mass and the burst luminosity. We discuss in detail three of them, M1, M2 and M3 (see Table 2). We also describe model MC, similar to M1, in which heat conduction is allowed.

2.2 The equations

To describe the evolution of the gas we solve the time-dependent, Eulerian equations of gasdynamics with source terms, that we write in the form:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = \alpha \rho_*, \quad (3)$$

$$\frac{\partial \rho \mathbf{v}}{\partial t} + \nabla \cdot (\rho \mathbf{v} \otimes \mathbf{v}) = \alpha \rho \mathbf{g} + (\gamma - 1) \nabla \varepsilon + \alpha \rho_* \mathbf{v}_*, \quad (4)$$

$$\frac{\partial \mathbf{m}}{\partial t} + \nabla \cdot (\mathbf{m} \otimes \mathbf{v}) = \rho \mathbf{g} - (\gamma - 1) \nabla \varepsilon + \alpha \rho_* \mathbf{v} + \nu, \quad (5)$$

$$\frac{\partial \varepsilon}{\partial t} + \nabla \cdot (\varepsilon \mathbf{v}) = - (\gamma - 1) \varepsilon \nabla \cdot \mathbf{v} - L + \alpha \rho_* \left( \epsilon_0 + \frac{1}{2} \varepsilon \mathbf{v}^2 \right), \quad (6)$$

where $\rho$, $\mathbf{m}$ and $\varepsilon$ are the density of mass, momentum and internal energy of the gas, respectively. The parameter $\gamma = 5/3$ is the ratio of the specific heats, $\mathbf{g}$ and $\mathbf{v}$ are the gravitational acceleration and the fluid velocity, respectively. The source terms on the r.h.s. of equations (3)–(6) describe the injection of total mass and energy in the gas due to the mass return and energy input from the stars. In our simulations the burst is located in the centre of the galaxy, therefore both energy sources (SNeII and SNeIa) and mass return are concentrated inside a small central sphere of $\sim 40 \, \text{pc}$ of radius. We treat both sources as continuous, although the SNIa rate is rather low ($\sim 1.6 \, \text{Myr}^{-1}$, see section 2.3.1). However, an a posteriori analysis of our results, following Mac Low & McCray (1988), reveals that the continuous energy input assumption is still valid during the SNIa stage. $V$ being the volume of the burst, $\rho_* = M_{\text{burst}}/V$, where $M_{\text{burst}}$ is the total mass of stars formed during the burst (see next section), $\mathbf{v}_*$ is the circular velocity of these stars, and $\alpha(t) = \alpha_0 (t) + \alpha_{SNII}(t) + \alpha_{SNIa}(t)$ is the sum of specific mass return rates from stars and SNe, respectively (see next section), $\epsilon_0$ is the injection energy per unit mass due to the stellar random motions and to SN explosions (see next section). Finally, $L = n_m \Lambda (T)$ is the cooling rate per unit volume, where for the cooling law $\Lambda (T)$ we follow the approximation to the equilibrium cooling curve given by Mathews & Bregman (1978).

$g^i$ represents the mass density of the $i$ element, and $\alpha^i$ the specific mass return rate for the same element, with $\sum_i \alpha^i = \alpha$. Eq. (4) represents a subsystem of $N$ equations which follow the hydrodynamical evolution of $N$ different ejected elements (namely H, He, C, N, O, Mg, Si and Fe). This enables us to calculate the abundance of the ejecta relative to the pristine ISM.

To integrate numerically the eqs. (3)–(6) we used a 2-D hydrocode, based on the original work of Bedogni & D’Ercole (1986). We adopted a non-uniform cylindrical axisymmetric grid whose meshes expand geometrically. The first zone is $\Delta R = \Delta z = 5 \, \text{pc}$ and the size ratio between adjacent zones is 1.03.
Table 1. Galactic parameters

| Model | $M_{\text{burst}}(M_\odot)$ | $M_\odot(M_\odot)$ | $n_{g0}(\text{cm}^{-3})$ | $E_b(\text{erg})$ |
|-------|----------------|----------------|-----------------|----------------|
| M1    | $6 \times 10^5$ | $1.7 \times 10^7$ | 1.81            | $1.5 \times 10^{51}$ |
| M2    | $3.6 \times 10^5$ | $1.7 \times 10^7$ | 1.81            | $1.5 \times 10^{53}$ |
| M3    | $6 \times 10^5$ | $4.6 \times 10^6$ | 0.49            | $4 \times 10^{52}$ |

Table 2. ISM parameters

|M | $M_\odot(M_\odot)$ | $n_{g0}(\text{cm}^{-3})$ | $E_b(\text{erg})$ |
|---|----------------|-----------------|----------------|
| M | $M_\odot(M_\odot)$ | $n_{g0}(\text{cm}^{-3})$ | $E_b(\text{erg})$ |
| M1 | $6 \times 10^5$ | $1.7 \times 10^7$ | 1.81 | $1.5 \times 10^{51}$ |
| M2 | $3.6 \times 10^5$ | $1.7 \times 10^7$ | 1.81 | $1.5 \times 10^{53}$ |
| M3 | $6 \times 10^5$ | $4.6 \times 10^6$ | 0.49 | $4 \times 10^{52}$ |

$M_\odot$ is the ISM mass inside the galactic region defined in the text, $M_{\text{burst}}$ is the mass of the stars formed during the burst and $n_{g0}$ is the central atomic number density. $E_b$ is the binding energy of the gas inside the galaxy.

2.3 The starburst

For the sake of simplicity we focus on a single, instantaneous, starburst event located at the centre of the galaxy. The stars are all born at the same time but they die and restore material into the ISM according to their lifetimes.

Here we will describe the main assumptions about the initial mass function (IMF), stellar lifetimes and nucleosynthesis prescriptions adopted to calculate $\alpha_*$ and $\alpha_{\text{SN}}$.

2.3.1 Mass return

In order to obtain the number $dN$ of stars with initial masses in the interval $dM$, we adopt the Salpeter (1955) initial mass function (IMF) $\phi(M) = \frac{dN}{dM}$ assumed to be constant in space and time:

$$\phi(M) dM = BM^{-(1+x)} dM,$$

where $x = 1.35$, and $B$ is the normalization constant obtained from:

$$\int_{0.1}^{40} M \phi(M) dM = M_{\text{burst}},$$

With $M_{\text{burst}} = 6 \times 10^5 M_\odot$ we get a mass of $\sim 1.5 \times 10^5 M_\odot$ for the stars with masses larger than 2 $M_\odot$, in agreement with the estimate of the stellar content in IZw18 by Mas-Hesse & Kuntz (1996). Since the stellar yields are calculated only for stellar masses not larger than 40 $M_\odot$ (WW), we adopt this value as an upper limit in eq. (8). Given the very low number of stars more massive than this limit, the chemical and dynamical evolution of the gas is not affected by this choice.

We assume that all the stars of initial mass between 8 and 40 solar masses end their lifecycle as type II supernovae. The SNII rate is defined as:

$$R_{\text{SNII}}(t) = \phi(M) |\dot{M}|,$$

where $M$ represents the mass of the dying stars at the time $t$. The mass return rate from SNII is then given by:

$$\alpha_{\text{SNII}}(t) = R_{\text{SNII}}(t) \Delta M/M_{\text{burst}}.$$ (10)

Here $\Delta M$ is the mass restored into the ISM by a star of initial mass $M$, and is defined as $M - M_{\text{rem}}$, where $M_{\text{rem}}$ is the mass of the stellar remnant.

In terms of single elements we have:

$$\alpha^i_{\text{SNII}}(t) = R_{\text{SNII}}(t) \Delta M_i/M_{\text{burst}},$$ (11)

where $\Delta M_i$ is the mass restored by a star of mass $M$ in the form of the specific element $i$.

The specific mass return from stars with $M < 8 M_\odot$ is given by:

$$\alpha^*(t) = \phi(M) |\dot{M}| \Delta M/M_{\text{burst}}.$$ (12)

and:

$$\alpha^i_*(t) = \phi(M) |\dot{M}| \Delta M_i/M_{\text{burst}},$$ (13)

where, again, $M$ is the mass of the dying stars at the time $t$.

To calculate the time derivative of the mass in eqs. (9), (12) and (13) we adopt the stellar lifetimes given by Padovani & Matteucci (1993):

$$t(M) = \begin{cases} 1.2 M^{-1.85} + 0.003 \text{ Gyr} & \text{ if } M \geq 8 M_\odot, \\ 10^{f(M)} \text{ Gyr} & \text{ if } M < 8 M_\odot, \end{cases}$$ (14)

where $f(M) = \begin{cases} 0.334 - \sqrt{1.79 - 0.2232 \times (7.764 - \log(M))} & \text{ if } M \geq 8 M_\odot, \\ 0.116 & \text{ if } M < 8 M_\odot. \end{cases}$

To obtain the quantity $\Delta M$ appearing in eq. (10) and eq. (12) we took into account the results of WW for massive stars ($M \geq 10 M_\odot$) and RV for low and intermediate mass stars ($0.8 \leq M/M_\odot \leq 8$), which give the mass restored into the ISM by the stars at the end of their lifetime. For the range $8 M_\odot \leq M \leq 10 M_\odot$ we have adopted suitable interpolations between the previous two sets of data.

In WW the total ejected masses (processed and unprocessed) are given for each chemical element. In general, however, in nucleosynthesis papers only the ‘yield’ is given, namely the fraction in mass of a given element $i$ which is newly formed and ejected by a star of initial mass $M$, the quantity $P_M$. In this case, the ejected total masses are computed in the following way:

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\[ \Delta M_i = \Delta MX_i + MP_{i,\text{burst}}, \]  \hspace{1cm} (15)  

where \( X_i \) is the original abundance of the element \( i \) in the star. This is the case of the yields of RV.

From the tables of WW (which contain also the products of explosive nucleosynthesis) and RV we have derived several relations between the initial stellar mass and the mass restored into the ISM in the form of chemical elements for single stars of masses between 0.8 and 40 \( M_\odot \), obtained by fitting the tabulated values with an eighth degree polynomial. The results are shown in Figs. 2–4 for different initial chemical compositions and different mixing length parameters. This enables us to obtain the temporal behaviour of \( \alpha'_{\text{SN}}(t) \) and \( \alpha_{\text{SNH}}(t) \) for each element \( i \). The total mass ejection rates obtained by summing over all the chemical elements are: \( \alpha_{\text{SNH}}(t) \propto t^{-0.27} \) and \( \alpha_{\text{SN}}(t) \propto t^{-1.36} \) (see also Ciotti et al. 1991).

Finally, in analogy with eq. (10) we define the specific mass return from the SNeIa as:

\[ \alpha_{\text{SNIa}}(t) = 1.4R_{\text{SNIa}}(t)/M_{\text{burst}}, \]  \hspace{1cm} (16)  

and:

\[ \alpha_{\text{SNIa}}^*(t) = R_{\text{SNIa}}(t)\Delta M_i/M_{\text{burst}}, \]  \hspace{1cm} (17)  

where the mass ejected by each SNIa is assumed to be 1.4 \( M_\odot \) (the Chandrasekhar mass). According to the single degenerate model (SD), SNe Ia are assumed to originate from C-O white dwarfs in binary systems which explode after reaching the Chandrasekhar mass as a consequence of mass transfer from a red giant companion. This kind of supernova explosion occurs only after the death of stars of initial mass less or equal than 8 \( M_\odot \), which is \( \sim 29 \) Myr after the burst. \( R_{\text{SNIa}}(t) \) is given by the following formula, obtained by the best-fitting of the SNIa rate computed in detail numerically by the model of Bradamante et al. (1998), when applied to the case of a single starburst:

\[ R_{\text{SNIa}}(t) = 4.2 \times 10^{-9} \left( \frac{t_b + 1}{15} \right)^{-1.9} \text{yr}^{-1}, \]  \hspace{1cm} (18)  

where \( t_b \) is the time expressed in Gyr.

It is worth noting that the SNIa rate in BCG is practically unknown and therefore it is very difficult to choose the right fraction of binary systems, in the IMF of such galaxies, of the type required to originate SNeIa. The rate of eq. (18) corresponds to the rate of Greggio & Renzini (1983) for a starburst with a fraction of binary systems \( A = 0.006 \). This rate switches on somewhat more gradually than in our approximation, reaching a maximum after \( \sim 40 \) Myr (see Greggio & Renzini, fig. 1), but this difference has no consequences in the dynamical evolution of our models. To show this, we ran a model (not shown in this paper), up to \( \sim 80 \) Myr, using the rate computed by Greggio & Renzini and the differences with the results shown in section 3 were negligible. With our assumed rate, SNeIa contribute by \( \sim 60 \) per cent of the total iron production after 15 Gyr, in agreement with predictions for the solar neighbourhood (Matteucci & Greggio 1986).

In summary, stars in different mass ranges contribute to galactic enrichment in a different way:

\begin{table}[h]
\centering
\caption{Nucleosynthesis prescriptions}
\begin{tabular}{ccc}
\hline
Case & \( Z \) & \( \alpha_{\text{RV}} \) \\
\hline
A & 0 & 0 \\
B & 0 & 1.5 \\
C & 0.01 \( Z_\odot \) & 0 \\
D & 0.01 \( Z_\odot \) & 1.5 \\
\hline
\end{tabular}
\end{table}

\( Z \) is the abundance of the unprocessed gas. If \( Z = 0 \), we assume \( X = 0.77, Y = 0.23 \). The solar abundances adopted are taken from Anders & Grevesse (1989).

(i) For low and intermediate stars (0.8 \( M_\odot \leq M \leq 8 \ M_\odot \)) we have used the RV nucleosynthesis calculations for a value of the mass loss parameter \( \eta = 0.33 \) (Reimers 1975) and the mixing length \( \alpha_{\text{RV}} = 0 \) and \( \alpha_{\text{RV}} = 1.5 \). The initial chemical composition is either \( Z = 0 \) or \( Z = 1/100 \ Z_\odot \). These stars mainly produce He, C, N and s-process elements (not considered here). In particular, N is a ‘secondary’ element, namely produced from the original C and O present in the star at birth. Therefore, for zero metallicity initial chemical composition no N would be produced. However, there is the possibility of producing N in a ‘primary’ way, namely starting from the C and O newly formed in the star. This is the case of the IMS which can produce primary N during the third dredge-up episode in conjunction with the hot-bottom burning, during the thermal-pulsing phase occurring when these stars are on the asymptotic giant branch (AGB) (case \( \alpha_{\text{RV}} = 1.5 \) of RV). Moreover, massive stars can also produce primary N, as suggested by Matteucci (1986). In the nucleosynthesis prescriptions of WW there is some primary N from massive stars but is negligible.

(ii) For massive stars (\( M > 10 \ M_\odot \)) we have adopted the case B in the WW nucleosynthesis results, focusing our attention on the models with \( Z = 0 \) and \( Z = 1/100 \ Z_\odot \). These stars are responsible for the production of the \( \alpha \)-elements (O, Mg and Si) and for part of the iron. The stars in the mass range 8 \( M_\odot \leq M \leq 10 \ M_\odot \) produce mainly He and some C, N and O.

(iii) For type Ia SNe we have followed the results of NTY adopting their model W7. In this model, every type Ia SN restores into the ISM \( \sim 1.4 \ M_\odot \) of gas. Most of this gas is ejected in the form of Fe (\( \sim 0.6 \ M_\odot \)) and the rest is in the form of elements from C to Si.

In Table 3 we present a brief summary of the nucleosynthesis prescriptions adopted in our models. Note that each of these cases can be adopted for the three different hydrodynamical models. Thus, for instance, hereafter with model M1B we intend the hydrodynamical model M1 with the chemical option B.

2.3.2 Energy input

The energy input into the ISM due to the stellar activity is taken into account in eq. (6) through the term
CASE A \((Z=0, \alpha_{RV}=0)\)

Figure 2. Yields from massive and intermediate stars (data taken from WW and RV yields) together with our fits (eighth degree polynomial best-fittings) for the case A. \(M_{ej}\) is the total mass of gas ejected by the star and corresponds to \(\Delta M\) as defined in the text.

\[ \epsilon_0 = 3kT_0/2\mu, \text{ where } k \text{ is the Boltzmann constant.} \]

The injection temperature can be written as:

\[ T_0 = (\alpha_\ast T_\ast + \eta_{SN II} kT_{II} + \eta_{SN Ia} kT_{Ia})/\alpha, \quad (19) \]

where \(kT_\ast, kT_{II}\) and \(kT_{Ia}\) are the energy per unit mass in the ejecta of stars, SNeIa and SNeII, respectively (see e.g. Loewenstein & Mathews 1987 for more details). \(\eta_{II}\) and \(\eta_{Ia}\) represent the efficiency with which the energy of the stellar explosions is transferred into the ISM for SNeII and SNeIa, respectively. We assume that \(10^{51}\) erg of mechanical energy are produced during the explosion of both types of supernova. However, we assume \(\eta_{II} = 0.03\); only 3 per cent of the energy explosion is available to thermalize the ISM, while the rest is radiated away. This prescription is taken from the work of Bradamante et al. (1998), who studied in detail the chemical evolution of blue compact galaxies. Actually, some debate is present in literature about the efficiency of the SNII in heating the ISM in starbursts. We thus run also a model with \(\eta_{II} = 1\) which however is not successful in describing IZw18, as discussed at the end of section 3.1.5.

For the SNIa explosions, instead, we assume \(\eta_{Ia} = 1\) because the SNRs expansion occur in a medium already heated and diluted by the previous activity of SNIa.

It is worthwhile to note that we neglected the energetic contribution of stellar winds from massive stars, according to the results of Bradamante et al. (1998) who showed that the injected stellar wind energy is negligible relative to the SN energy in this kind of galaxies and to the results of Leitherer et al. (1999). This is mostly a consequence of the low initial metallicity adopted \((Z = 0 \text{ or } Z = 0.01 \ Z_\odot)\), because the mass loss from stars strongly depends on their metallicity (see e.g. Portinari et al. 1998 and references therein).

3 SIMULATIONS

3.1 Dynamical results

Our reference model is M1. In addition, we run two other models, M2 and M3, which have the same potential well (see Table 2). In model M2 the mass \(M_{\text{burst}}\) of gas turned into stars is halved in comparison with M1. In this case two competing effects are expected. On one
Figure 3. Yields from massive and intermediate stars for the case B.

In order to discuss the hydrodynamical behaviour of the gas we recall briefly a few results about bubble expansion in stratified media (Koo & McKee 1992, and references therein). The freely expanding wind produced by the starburst interacts supersonically with the unperturbed ISM thus creating a classical bubble (Weaver et al. 1977) structure in which two shocks are present. The external one propagates through the ISM giving rise to an expanding cold and dense shell, while the inner one thermalizes the impinging wind producing the hot, rarefied gas of the bubble interior. The shocked starburst wind and the shocked ISM are separated by a contact discontinuity. The density gradient of the unperturbed ISM being much steeper along the $z$ axis, the expansion of the outer shell occurs faster along this direction. A bubble powered by a constant wind with velocity $V_w$, mass loss rate $\dot{M}$, and mechanical luminosity $L_w = 0.5\dot{M}V_w^2$ is able to break out from a gaseous disc if $L_w > 3L_b$, where the critical luminosity is $L_b = 17.9\rho_0H_{\text{eff}}^3C_0^3$, $C_0$ is the sound speed of the unperturbed medium and $\rho_0$ is its central density. $H_{\text{eff}}$ is the effective scale length of the ISM distribution in the vertical ($z$) direction and is defined as:

$$H_{\text{eff}} = \frac{1}{\rho_0} \int_0^\infty \rho dz.$$  

In our models $H_{\text{eff}} \sim 300$ pc. If the wind luminosity is larger than $L_n \sim 0.35mL_b$, where $m = V_w/C_0$, the wind blows directly out of the planar medium, at least in directions close to the axis. If, instead, $L_w < L_n$ the formation of a jet is possible, in which the wind is shocked and then accelerated again to supersonic speeds through a sort of de Laval nozzle created by the shocked ambient medium. Kelvin-Helmholtz instabilities tend to distort the nozzle, and stable jets can exist only for $\beta = \ldots$.
CASE C (Z=0.01 Z⊙, αRV=0)

\[ C_h/C_0 \lesssim 30, \] where \( C_h \) is the cavity sound speed (Smith et al. 1983).

### 3.1.1 Model M1

For model M1 \( L_b = 2.8 \times 10^{36} \) erg s\(^{-1}\). Actually, \( L_w \) is not constant in our simulations. However, as a representative value, for the wind powered by SNeII we have \( L_w \sim 2 \times 10^{38} \) erg s\(^{-1}\) (cf. Fig. 9) and \( m \sim 300 \), thus the bubble carved by this wind is able to break out. Note that \( L_w < L_n \), so that a jet-like structure is expected. As shown in Fig. 5, a jet actually propagates with a shock velocity \( V_s \sim 3 \times 10^6 \) cm s\(^{-1}\) after 30 Myr. This figure also shows that the bubble shell on the symmetry plane has reached the maximum allowed value (Koo & McKee 1992) \( R_{max} = 0.72 H_{eff} (L_w/L_b)^{1/6} \sim 440 \) pc.

The SNII wind lasts a relatively short time (29 Myr), and is then replaced by a weaker SNIa wind with \( L_w \sim 2 \times 10^{37} \) erg s\(^{-1}\) (cf. Fig. 9) and \( m \sim 200 \). The existing jet cannot be sustained by this wind and is inhibited before breaking out. The bubble as a whole stops to grow, and the incoming shocked wind pushes a large fraction of the hot SNII ejecta against the dense and cold cavity walls. Thus most of these ejecta would be located close to the cavity edge. The thermal evolution of these ejecta is difficult to assess. Given the spread of contact discontinuities due to the numerical diffusion, the ejecta partially mixes with the cold wall of the cavity, so that a large fraction of these metals cools off (cf. Fig. 14). Actually, as discussed by DB, several physical processes, such as thermal conduction and turbulent mixing, produce a similar effect. In section 3.2 we consider explicitly heat conduction, but neglect the turbulent mixing (Breitschwerdt & Kahn 1988, Kahn & Breitschwerdt 1989, Begelman & Fabian 1990, Slavin, Shull & Begelman 1993) which is very complex and nearly impossible (and probably even meaningless out of a fully 3D simulation) to implement into the code.

The bubble inflated by the SNIa wind is likely to break out through a nozzle. We note, however, that the gas distribution in front of the bubble along the \( z \) direction is modified by the expansion of the outer shock generated by the previous SNII activity; although the powerful SNII wind is ceased, this shock continues to expand with increasing velocities \( (V_s \sim 10^7 \) cm s\(^{-1}\) at \( t = 342 \) Myr) because of the steep gradient of the unperturbed ISM density profile. At these shock velocities, the post-shock gas cools quickly and its temperature is \( T = 10^5 \) K (the minimum allowed in our computations) everywhere with the exception of a ‘rim’ behind

\[ \text{Figure 4. Yields from massive and intermediate stars for the case C.} \]
the shock, where \( T \sim 3 \times 10^5 \) K. The density gradient of the upwind gas experienced by the SNIa bubble is shallower, and the break out is contrasted. This can be seen in Fig. 5, where the hot bubble is shown to grow very little up to \( t \sim 300 \) Myr.

The gas in the bubble radiates inefficiently because of its low density \( (n \sim 3 \times 10^{-4} \text{ cm}^{-3}) \) and its temperature is \( \sim 2 \times 10^6 \) K. Shears are present at the contact surface between hot and cold gas, which is thus Kelvin-Helmholtz unstable. For this reason the cavity is irregularly shaped at this stage.

Subsequently, since the surrounding cold gas is in expansion, the hot gas is finally able to break out carving a long tunnel. This tunnel has the de Laval nozzle structure, with the transverse section increasing with \( z \). We note the presence of Kelvin-Helmholtz instabilities at the wall of the nozzle. This is due to the fact that \( \beta \sim 30 \), so the nozzle is only marginally stable.

The shocked wind is accelerated again to supersonic speeds through this nozzle (velocities \( V \sim 4 \times 10^7 \text{ cm s}^{-1} \) and mach numbers \( M \sim 8 \)). When the jet is well developed \( (t = 342 \) Myr in Fig. 5b), the minimum radius of the nozzle is \( R_n \sim 100 \) pc.

The acceleration of the cold shell in front of the jet causes it to be disrupted by the Rayleigh-Taylor instabilities, and the hot gas leaks out. Contrary to the previous works where the SNIa activity was not considered, at these late times the central galactic region is not yet replenished by the cold surrounding gas. Taking into account equation (18), we stress that this will happen after \( \sim 2 \) Gyr, when \( L_w = 2 L_b \).

In Fig. 9 we have plotted mass, energy and luminosity budget inside the galaxy. From the central panel of this figure we note that the energy of SNe never becomes larger than the binding energy, although some gas is definitively lost from the galaxy, as it is apparent from the numerical simulation. This indicates that ballistic arguments cannot be adopted properly to calculate ejection efficiencies. In fact, an element of fluid can acquire energy at the expense of the rest of the gas through opportune pressure gradients, thus increasing its velocity beyond the escape velocity.

The thermal energy shows in particular two drops at \( t \sim 30 \) Myr and at \( t \sim 160 \) Myr. The second drop reflects a decrease in the hot gas content, while the first one cannot be associated at any particular hot gas loss. In fact this drop coincides with the discontinuity SNII/SNIa, when the specific energy injection falls by a factor \( \sim 10 \). Thus the thermal content of the bubble decreases via radiative cooling, although its temperature remains larger than \( 2 \times 10^4 \) K, which is the threshold adopted to define hot regions in the upper panel of Fig. 9. The fall-off at \( t \sim 160 \) Myr is instead due to the presence of large eddies which move part of the hot gas outside the galaxy. We finally point out that at the beginning of the SNII activity the X-ray emission is absent (see lower panel of Fig. 9) because the energy injection is not able to rise the cavity temperature over \( T = 7 \times 10^7 \) K, which is the threshold adopted to define the X-ray emitting gas.

3.1.2 Model M2

In this model, \( L_b \) is the same as in M1, but \( L_w \) is a factor of 0.6 lower. The dynamical evolution is rather similar to that of the previous model. Obviously the bubble is smaller at the end of the SNII activity. Quite surprisingly, however, the nozzle carved by the SNeIa breaks out earlier than in M1. Note that in this case \( L_w/L_b < 10 \), and the nozzle is stable and well shaped. Actually, this condition is equivalent to the condition \( \beta \lesssim 30 \) expressed above (Koo & McKee 1992) and, for this model, we find \( \beta \sim 25 \). Kelvin-Helmholtz instabilities are present, but they are carried away by the flow before they can grow significantly. Less energy is dissipated by the turbulence and is more easily channelled through the nozzle.

3.1.3 Model M3

Because of the lower ISM density, we have \( L_b = 7.5 \times 10^{35} \text{ erg s}^{-1} \) for this model, so that \( L_w > L_b \) during the SNII stage. In this case the galactic wind breaks out rather vigorously, and the evolution of the gas is similar to that found in other theoretical works (Suchkov et al. 1994, De Young & Heckman 1994, MF, DB). A prominent lobe is formed, which is similar to that described by Mac Low, McCray & Norman (1989) in their fig. 2. The shell accelerates and becomes Rayleigh-Taylor unstable, expelling the hot interior. The breakup occurs at the polar cap, where the ISM has the lower density and pressure. The hot gas which blows out of the bubble produces the jet-like structure visible in Fig. 7a. Note that the outer shock initially is rather slow \( (V_s \sim 5 \times 10^6 \text{ cm s}^{-1}) \), and then accelerates somewhat up to \( V_s \sim 1.6 \times 10^7 \text{ cm s}^{-1} \). Thus, also in this model the shocked gas never reaches high temperatures and most of the lobe volume is cold.

Fig. 7b shows the late dynamical evolution of the gas. The gas flow expands along a conical configuration, inside a solid angle which remains constant during all the simulation. The ISM outside this funnel remains substantially unperturbed. Actually, the aperture of the cone in our model is evidently dictated by the assumed structure of the ISM and could be not realistic. However, given that no falling back or fountain is expected by the expelled material which is kept in expansion by the SNeIa, the final chemical characteristics of the gas inside the galaxy are not affected by the exact structure of the ‘chimney’.

Concerning the distribution along the \( z \) direction, the lobe of outflowing gas can be grossly divided in three regions. The most external, far from the galaxy, is bounded by the outer shock and hosts mainly shocked, low-density external medium. The inner region is filled with gas ejected by SNeIa and low-mass stars. Between these two regions there is the gas of the ‘first’ bubble (where the ejecta of SNII are present), which is quickly cooled to low temperatures. At \( t \sim 150 \) Myr, the shell of the small bubble breaks, like the first one, and the hot gas flows forward into the lobe rising its temperature up to \( 10^7 \) K.

Just before breaking out, the superbubble reaches
Figure 5. Density contours and velocity fields for the model M1 at different epochs. The density scale (logarithmic) is given in the strip on top of the figure. In order to avoid confusion, we draw only velocities with values greater than 1/10 of the maximum value. This is true also for Figg. 6, 7 and 8.
Figure 6. As Fig. 5, but for model M2.
Figure 7. As Fig. 5, but for the model M3.
Figure 8. As Fig. 5, but for the model MC.
the edge of the galaxy even along the $R$-axis, pushing out all the unprocessed gas present, and almost all the galaxy is covered by the hot cavity. As the breakout occurs, the bubble shrinks slightly and part of it comes back into the galactic region producing the rise of the mass of hydrogen and the other elements (cf. Fig. 11). This happens in coincidence with the pressure decrease in the SNIa bubble following the rupture of the unstable shell, as discussed above.

### 3.1.4 Model MC

In Fig. 8 we show model MC, identical to model M1 but with the heat conduction activated. In order to take into account the thermal conduction, we solve the heat transport term through the Crank-Nicholson method which is unconditionally stable and second order accurate (see DB for more details). In this model the cavity is less extended than in M1 because of the increased radiative losses due to the evaporation front. During the SNII stage the bubble never extends beyond $H_{\text{eff}}$. Thus the “nose” present in M1 does not develop, and the bubble has a more round aspect (Fig. 8a). Thermal conduction smooths temperature inhomogeneities and the cavity is more regularly shaped also at later times (see Fig. 8b). Less energy is dissipated through eddies, and the final break out is slightly anticipated compared to model M1. The resulting outflow is stable and well-shaped. The fraction of cold ejecta does not change substantially compared to model M1 (see section 3.2 for a discussion about this point).

### 3.1.5 ISM ejection efficiencies

It is useful to define the efficiency of gas removal from the galaxy. This efficiency cannot be unambiguously defined as in the case of ballistic motions because of dissipative effects which may play a very important role (DB). For this reason we simply define the efficiency $f_{\text{ISM}}$ by dividing the mass of the gas which has left the galaxy by the total mass of the ISM. In a similar way we calculate the efficiency in the ejection of material from SNIa ($f_{\text{SNIa}}$), intermediate-mass stars ($f_{\text{IMS}}$) and SNIa ($f_{\text{SNII}}$).

The upper panels of Fig. 11 shows the masses of the different elements removed from the galaxy as functions of time. The relative proportions between masses of different elements is essentially that expected by a Salpeter IMF and is not substantially affected by selective dynamical losses. For the model M1B, we point out that the mass of metals lost from the galaxy declines after reaching a maximum at $t \sim 200$ Myr. This maximum is mirrored by a minimum in the masses of metals inside the galaxy. This behaviour is due to the fact that, at this time, the large hot blob visible in Fig. 5b (second panel) extends over the galactic edge ($R$ direction) thus inducing a large loss of ISM (mostly H and He). We calculate the efficiency at $t \sim 200$ Myr and at the end of the simulation ($t \sim 375$ Myr), obtaining $(f_{\text{ISM}}, f_{\text{SNII}}, f_{\text{SNIa}}, f_{\text{IMS}}) = (0.43, 0.38, 0.25, 0.38)$ and $(f_{\text{ISM}}, f_{\text{SNII}}, f_{\text{SNIa}}, f_{\text{IMS}}) = (0.07, 0.17, 0.20, 0.26)$, respectively. Thus, at $t \sim 200$ Myr the products of the SNII and IMS have been ejected more easily than the products of SNeIa. This is of course due to the fact that SNII material is located in a region closer to the galactic centre. After the break up all the efficiencies decrease, and in particular $f_{\text{SNII}}$ shows the greatest reduction. In fact, the SNII ejecta inside the galaxy are ‘incorporated’ into the cold, dense shell of the cavity and do not experience any substantial further dynamical evolution (see discussion in section 3.1.1 and Fig. 5b); at the break out the bubble shrinks and its walls recede entirely in the galaxy, increasing its content of SNII ejecta. Contrary to the expectations, the higher efficiency is given by $f_{\text{IMS}}$ instead of $f_{\text{SNIa}}$. This is due to strongly unsteady behaviours of the nozzle wall.

In model M2, where a nearly steady flow is obtained, we actually have $f_{\text{SNII}} < f_{\text{IMS}} < f_{\text{SNIa}}$. At $t \sim 300$ Myr it is $(f_{\text{ISM}}, f_{\text{SNII}}, f_{\text{SNIa}}, f_{\text{IMS}}) = (0.06, 0.32, 0.12)$ in this model. For this model the difference in efficiencies between the total gas and metals is particularly striking and indicates that the differential galactic wind assumption, adopted in several one-zone chemical models, is a natural outcome in this scenario. In particular we note that at late times the galaxy is...
almost completely replenished by gas. In fact, as apparent in Fig. 6b, the nozzle has a rather small section ($R_a \sim 85$ pc) and the volume of the cavity is negligible in comparison with the galactic volume. The more regular hydrodynamical behaviour reflects also in the more regular temporal trend of the ejected masses. Note that, as expected, in M2 the galactic wind starts later in comparison with M1.

Model M3 predicts of course the maximum amount of metals lost and is also the first in which the break out occurs. The striking minimum in the metal contents of the galaxy occurring at $t \sim 130$ Myr is due to the dynamical behaviour of the bubble shell, as discussed above. The efficiencies for the model M3 at the end of the simulation ($t \sim 470$ Myr) are ($f_{\text{ISM}}, f_{\text{SNII}}, f_{\text{SNeA}}, f_{\text{SNM}}$) = $(0.77, 0.85, 0.97, 0.87)$. Finally, we mention that, as outlined in section 2.3.2, we run a model (not shown here) similar to M1, but with $\eta_1 = 1$. At the end of the SNII stage, the galaxy is almost devoided of gas (a part for the tenuous galactic wind). The time-scale for the galactic replenishment (the SNIa wind cannot preserve an empty region so large) is at least $R_a/C_0 \sim 200$ Myr. Actually, due to the retarding effect of the centrifugal force, in our simulation most of the galaxy is replenished after $\sim 450$ Myr. The age of the (last) burst occurred in I Zw18 is estimated to be $\lesssim 27$ Myr (see below), thus its actual content of gas rules out the possibility of an high $\eta_1$. Note that our assumption that all energy injection occurs in the central region leads to the most effective gas removal for a given luminosity (Strickland & Stevens 1999). Models with a more realistic burst diffuse across the galaxy will be presented in a next paper.

### 3.2 Instantaneous versus delayed mixing

In the previous models a large fraction of the stellar ejecta cools quite soon and a rapid mixing is expected given the relatively short diffusion time at these temperatures (for a comparison of the diffusion times in the different ISM phases, see for example Tenorio-Tagle 1996). This is an important point in view of the confrontation of the results of our models with the observable abundances of I Zw18 (cf. section 4.2), and deserves some discussion.

Rieschick & Hensler (2000), for instance, presented a chemodynamical model of the ISM of a dwarf galaxy in which the metal enrichment undergoes a cycle lasting almost 1 Gyr. This model is based on the scenario described in Tenorio-Tagle (1996). In this scenario the break out is inhibited and the SNII ejecta (SNeIa are not considered), mixed with hot evaporated ISM, are located inside a large cavity which extends above (and below) the galactic disc. Typical parameters of this cavity are the linear size $d > 1$ kpc, the density $n_c = 10^{-2}$ cm$^{-3}$ and the temperature $T_c = 10^5$ K. After the last SN explosion, strong radiative losses occur. However, given the density and temperature fluctuations in the hot medium, cooling acts in a differential way. This leads to condensation of the metal-rich gas into small molecular droplets ($R_c \sim 0.1$ pc, $M_c \sim 1 M_\odot$) able to fall back and settle on to the disc of the galaxy. With the next exploding stellar generation, the droplets are dissociated and disrupted, and their gas is eventually mixed in the HII regions.

Here we point out some caveats concerning this scenario which should be taken into account.

**Thermal conduction** - Thermal conduction, if not impeded by magnetic fields and/or plasma instabilities, introduce, together with radiative losses, the characteristic Field length (Begelman & McKee 1990, Lin & Murray 2000)

$$\lambda_F = \left( \frac{3n(T)T}{n^2 \beta R T} \right)^{1/2}$$

where $\kappa(T) = 6 \times 10^{-7} T^{2.5}$ erg cm$^{-1}$ K$^{-1}$ is the classical thermal conductivity (Spitzer 1956) and $n$ the gas density. The cooling rate scales linearly with the metal content $\zeta$ of the gas ($\zeta = 1$ for solar abundance). The parameter $\beta$ takes into account the possibility that the cooling gas may be out of ionization equilibrium; Borkowski, Balbus & Fristrom (1990) have shown that $\beta$ may be as high as 10 through conductive fronts.

Clouds undergo evaporation unmodified by radiative losses if they are sufficiently small, $R_c < \lambda_F$. Assuming $T_c = 10^5$ K and $n_c = 10^{-2}$ cm$^{-3}$, Tenorio-Tagle obtains $R_c < 10$ pc for the radius of the overdense zones at the beginning of their implosion. Adopting $\beta = 1$ and $A = 1.6 \times 10^{-18} T^{-0.7}$ erg cm$^{-3}$ s$^{-1}$ for $10^5 \leq T \leq 10^7$ K (Mac Low & McCray 1988), we obtain $\lambda_F \sim 38$ pc. Even assuming $\beta = 10$, $\lambda_F \sim 44$ pc remains larger than $R_c$. Thus the rate of conductive heat input exceeds that of the radiative losses and the cloud collapse is inhibited. This result derives from the general property of the evaporation to stabilize thermal instabilities (Begelman & McKee 1990). Actually, Tenorio-Tagle obtained $R_c \sim 10$ pc as a lower limit for the radius value of clouds able to implode. As a consequence, perturbations with a size larger than $\lambda_F$ can actually grow. A non negligible fraction of gas mass would condense only for a rather flat size spectrum of the fluctuations.

We point out that, even if droplets actually form, they evaporate in a time $\tau_e = M_c / M$. Droplets have rather small final radii of order 0.1 pc (Tenorio-Tagle 1996). In this case they undergo the saturated evaporation

$$M = 1.22 \times 10^{-14} T^{2.5} R_c \sigma^{-5/8} \chi 10^{-7} \left( T / 1.54 \times 10^{5} \right)^2 / (n R_c)$$

the saturation parameter (Cowie, McKee & Ostriker 1981). For $M_c \sim 1 M_\odot$ we have $\tau_e \sim 40$ Myr, comparable to the dynamical time $\tau_d$ (see below). Thus all the droplet material, or at least a large fraction of it, returns into the hot phase before reaching the galactic plane.

**Drag disruption** - Suppose that thermal conduction is impeded and that droplets with final $R_c \sim 0.1$ pc actually form and fall toward the galactic plane. During their descent the droplets experience a drag reaching a terminal speed $V_t \sim (4 R_c / d)^{1/2} V_c$, where $\chi = 10^5$ is the ratio of the droplet density to the hot gas density, $d \sim 1$ kpc is the droplet distance to the galactic plane, and $V_c$ is the circular velocity of the halo potential. The motion
of the droplet relative to the hot gas leads to mass loss through Kelvin-Helmholtz instability. For wavelengths \( \lambda \sim R_e \) the stripping time-scale is \( t_\tau \sim R_e \lambda^{0.5} / V_i = \tau_d (R_e / d)^{0.5} \) (cf. Lin & Murray 2000), where \( \tau_d = d / V_i \) is the dynamical time. The droplets are thus disintegrated before they settle to the galactic plane, returning to the hot diluted phase. Larger droplets may not be able to attain their terminal velocity, but even in this case we have \( \tau_d / \tau_e \sim \chi^{0.5} R_e / d < 1 \).

As an aside, we note that, if a large fraction of the hot gas becomes locked into droplets, the pressure of the remaining diluted phase reduces and the cavity shrinks. Whether the bubble deflates slowly or suddenly and producing turbulence depends on the droplet formation efficiency. Thus, the scenario depicted by Tenorio-Tagle of a nearly steady hot cavity with size of \( > 1 \) kpc waiting for the onset of radiative cooling could be incorrect. Part of the droplets could be overrun by the edge of the imploding bubble, undergoing an even faster stripping.

Let us consider now the results shown in the present paper. Contrary to the scenario sketched above, the ejecta cool rapidly without leaving the galaxy (until the break-out, which occurs at late times) and without undertaking a long journey before mixing with the ISM. How much these results are reliable? Mac Low & McCray (1988) showed that a conductive bubble expanding in an uniform medium becomes radiative (i.e. radiates an energy comparable to the thermal energy content of the shocked wind) after a time:

\[
t_R \sim 16 (\beta \zeta)^{-35/22} L_{38}^{7/11} n^{-8/11} \text{ Myr},
\]

when the cavity radius is:

\[
R_R \sim 350 (\beta \zeta)^{-27/22} L_{38}^{4/11} n^{-7/11} \text{ pc}.
\]

For \( t > t_R \) the bubble goes out of the energy conserving regime, although a fully momentum conserving regime is never attained. Considering model M1, we assume \( \beta = \zeta = 1, L_{38} = 2 \) and \( n = 1.8 \text{ cm}^{-3} \), and we obtain \( t_R = 12.6 \) Myr and \( R_R = 310 \) pc. Thus, in the case of an uniform unperturbed medium the bubble interior would cool quite early, when it is still well inside the galaxy.

Mac Low & McCray also considered the expansion in a stratified medium. Equating the radius of a spherical bubble to approximately one scale height \( H \) they define the dynamical time

\[
t_D \sim H^{2/3} (\rho / L_w)^{1/3}.
\]

Then the ratio of cooling to dynamical time-scales is:

\[
\frac{t_R}{t_D} = 8.22 n^{-35/33} L_{38}^{20/33} \left( \frac{H}{100 \text{ pc}} \right)^{-5/3} (\beta \zeta)^{-35/22}, \quad (21)
\]

(note that the numerical coefficient in this expression slightly differs from that obtained by Mac Low & McCray). For model M1 we obtain \( t_R / t_D \sim 1.08 \) during the SNII stage. Thus a non negligible fraction of the wind luminosity is radiated away (see also Fig. 9), and the break out does not occur. For M3, where \( n \sim 0.5 \), we have \( t_R / t_D \sim 4.2 \), and the situation, in principle, is less clear-cut (see, however, below in this section).

Although models M1, M2, M3 do not take explicitly into account heat conduction, yet they obtain results according to the above scenario. In fact, as pointed out in section 3.1.1, numerical diffusion simulates thermal conduction originating spurious radiative losses which otherwise would be absent. Of course, this spurious cooling does not reproduce quantitatively the same amount of radiation lost through a real heat conduction front, and the fraction of cold ejecta obtained in our models could be larger than the correct one. Some algorithms may be conveniently adopted to reduce this effect. Consistent advection (Stone & Norman 1992) is implemented in our code and helps in reducing somewhat the diffusion, making it consistent for the all advected quantities (mass, momentum, energy). We also made tests modifying the cooling algorithm in presence of unresolved contacts, following Stone & Norman (1993). Although the fraction of cold ejecta reduces of 15 per cent, most of the metals (\( \sim 80 \) per cent) remains cold. We point out, however, that in presence of an unresolved conduction front, the above algorithm may lead to an excessive reduction of the radiative losses (see below).

In any case the intrinsic diffusion of the code may be alleviated but not eliminated by algorithms as those described. In principle, more realistic models can be done explicitly adding the physical terms which produce diffusion. For this reason we also ran model MC, where the heat transfer is included. In this model the amount of cold metals does not change appreciably. However, although model MC is useful to understand the stabilizing effect of heat conduction on a turbulent flow, it turns out to be inadequate to obtain the correct cooling rate at the conduction front. Consider the temperature profile of a “standard” bubble \( T_{b2}(1 - r/r_b)^{2/5} \) (Weaver et al. 1977), where \( T_b = 10^6 \) K is the central temperature, and \( r_b = 300 \) pc is the bubble radius (cf Fig. 7). The cooling curve maximum occurs at \( T \sim 2 \times 10^5 \) K. This temperature is found at \( r / r_b = 0.98 \), i.e. at a distance of 6 pc to the cold shell. At a distance of 300 pc the mesh size is \( \sim 15 \) pc, and the conduction front is not resolved properly. Thus, we also ran models MCH and MCHH (not shown here) with heat conduction and with a uniform grid with mesh size of 2 and 1 pc respectively. These models were computed only up to the end of the SNII activity because of the large number of grid points involved.

The four panels in Fig. 10 show the profiles along the galactic plane (\( z = 0 \)) of several quantities for models M1, MC, MCH and MCHH at nearly 30 Myr. As expected, the resolution of the temperature profile is not improved in MC and the temperature jump remains unresolved. In MCH, instead, this jump extends over 2-3 meshes and in MCHH over 4-5, as expected. The fraction of cold ejecta is 0.95, 0.95, 0.93, 0.92 for M1, MC, MCH, MCHH respectively. Although the greater accuracy, the fraction of cold ejecta in MCH and MCHH is only few percent lower than in M1. This occurs because the bubble is “genuinely” radiative, and an high spatial resolution may retard a little the cooling, but cannot avoid it.

We stress once more (cf. section 3.1.1) that it is very difficult to give the correct description of the contact discontinuity at the outer edge of the hot cavity,
for the presence of complex hydrodynamical phenomena occurring there. These phenomena tend to produce a finite thickness of the contact, giving rise to a substantial cooling otherwise absent. The correct evaluation of such a cooling is however very difficult to assess. Even restricting ourselves on the simple case of heat conduction, the possible lack of ionizing equilibrium and the numerical diffusion both increase radiative losses. The first effect is physical and could be described solving step by step the time dependent set of ionization equation. The second is a spurious result due to numerical diffusion of the code which must be reduced as much as possible. We believe that our convergence test (cf. fig. 10), as well other 1D tests not shown here, indicates that our results are significative. We are aware of the fact that more refined simulations may produce somewhat different values of the cooled mass of the ejecta, but we think that the large fraction of resulting cooled ejecta is a genuine result.

As pointed out above, equation (21) gives an ambiguous prevision about the behaviour of M3. We therefore ran also this model on a uniform grid with 2 pc resolution (up to $t = 30$ Myr) adding heat conduction. The overall dynamics of the superbubble remains the same, and the fraction of cold ejecta turns out to be 6 per cent lower than in the low resolution model. We thus conclude that the results obtained by our models are reliable.

At the end of this section we mention the effects expected in the case of a non-uniform initial ISM. Actually, gas clouds are embedded in the pervasive diffuse gas of the galaxy. However, a correct numerical treatment of the interaction between these clouds and the ambient gas introduces enormous complications in the description of the involved physics and needs full 3D computations with a huge number of meshes. We here just make some simple considerations following McKee, Van Buren & Lazareff (1984). These authors describe the behaviour of a bubble generated by an O star and expanding in a cloudy medium. Because of the flux of ionizing photons emitted by the star, the nearby clouds undergo photoevaporation and accelerate away through the rocket effect. Essentially no cloud survives up to a radius $R_h$, and the gas density inside this radius increases to a value $0.5n_{\text{ini}}$, i.e. half of the mean density the cloud gas would have if it were homogenized. The wind bubble evolution depends on the value of $L_\text{w} = L_\text{w}^* / L_\text{St}$, where $L_\text{St} = 1.26 \times 10^{39} (S_{29}/n_{29})^{1/3}$ and $S_{29}$ is the rate at which the star emits ionizing photons in units of $10^{39}$ s$^{-1}$. For weak winds ($L_\text{w} \ll 1$) the bubble radius is smaller than $R_h$ and it evolves “normally” (Weaver et al. 1977). For moderate winds ($L_\text{w} \sim 1$) the bubble expands to the edge of the cloud distribution because photo-evaporated gas induces radiative losses reducing the pressure. Finally, for $L_\text{w} \gg 1$ the bubble rapidly engulfs a number of clouds and radiates away most of its internal energy. This scenario cannot be directly applied to a star burst as a whole. In fact clouds are also present inside the star formation region, partially screening the flux of ionizing photons escaping from this region. However, even assuming that this effect is negligible, in our model $L_\text{w} \sim 3$. We in fact computed $S_{29}$ running remotely at the site www.stsci.edu/science/starburst99 (Leitherer et al. 1999) a burst model tailored on that assumed here. The number of UV photons produced by massive stars remains nearly constant ($S_{29} = 584$ s$^{-1}$) up to 5 Myr, and then drops as $t^{-4}$. For $n_{29} = 1.8$ cm$^{-3}$ close to the galactic disc, we have $L_\text{St} = 7 \times 10^{37}$ erg s$^{-1}$, lower than $L_\text{w}$. Of course, along the z direction $R_h$ could move much further, but the ionizing flux starts to decline rather soon, and the cloud distribution remains nearly unaffected. Thus the bubble is expected to become radiative sooner than in the case of a smoothly distributed ISM.

In conclusion, in the scenario of our models, most of the metals actually cool off in a few Myr. It is worth noting that this result depends essentially on the assumption of a low heating efficiency of SNIIs. In the model similar to M1, but with $\eta_1 = 1$ (sect. 2.3.2), the break out quickly occurs and the metals have no time to cool. In fact, following Eq. (21), in this case the bubble results to be adiabatic and not radiative. Thus the SN efficiency value is crucial, and a future paper will be devoted to it (D’Ercole & Melioli, in preparation).

### 3.3 Chemical results

In Fig. 10 is shown the evolution of the element abundances for the models M1B, M2B and M3B. In this figure, the evolution of the masses and the abundances in the form of the various elements is shown. It is interesting to note that the mass of the lost metals for the model M3B is larger than that retained from the galaxy, whereas it is the contrary for models M1B and M2B. This means that the initial conditions, namely the assumed burst luminosity and gas mass in the galaxy, are playing a very crucial role in the development and evolution of the galactic wind. The abundances are calculated as $[Z/H]$ , where $Z$ indicates the abundance of the following elements, O, C, N, Mg, Si and Fe, relative to the solar abundances of Anders & Grevesse (1989), and as $12+\log(Z/H)$, which is the notation normally used for the abundances in extragalactic H II regions. These abundances are derived in the following way: for the galactic abundances we have averaged in the previous defined galactic region (approximatively an ellipsoid with major semi-axis of 1 Kpc and minor semi-axis of 730 pc), whereas for the abundances leaving the galaxy the integral is made over the rest of the grid.

The $\alpha$-elements show a very similar evolution and this is due mostly to their common origin. The $\alpha$-elements are, in fact, mainly produced by massive stars (see Figg. 2-4), and thus their abundances inside the galaxy grow in the first 6-7 Myr – the time interval where most of massive stars die – then show a slowly decreasing trend, with however a little maximum around 100 Myr. This behaviour is related to the dynamics of gas flows described before.

The evolution of iron is not too different with respect to the evolution of the $\alpha$-elements although this element is substantially produced by SNeIa. This is due to the fact that at the end of our simulations the iron produced by SNIa is only $\sim 30$ per cent of the total, because the bulk of SNeIa appears at later times. The
evolution of N shows a sharp increase at around 29 Myr which corresponds to the lifetime of a 8 $M_\odot$ star, which is the first star producing a substantial amount of N (of primary origin). For times less than 29 Myr the N production is negligible.

4 DISCUSSION

We want to compare now our models with observational data found in literature for the galaxy IZw18.

4.1 Morphology and dynamics
Figure 11. Time evolution of several quantities for the models M1B, M2B and M3B (first, second and third column, respectively). The upper panels show the evolution of the mass of various elements outside the galaxy, while the masses inside the galaxy are shown by the second row of panels. The third and the last rows of panels illustrate the behaviour of the ISM abundances (relative to the sun and by number, respectively).

To compare our dynamical results we should first summarize the structural and dynamical properties of I Zw18. I Zw18 has a ‘peanut-shaped’ main body, consisting of two starbursting regions (Dufour et al. 1996). There are also two H II regions (also called NW and SE), associated with the main body, but shifted ~ 1 arcsec east of the brightest continuum emission (Martin 1996). The Hα emission is bipolar-shaped along a direction orthogonal to the main body, and show clear evidences of shell structures. In fact a prominent shell stretches 15 arcsec (720 pc) north-northeast from the northwest H II region and bright Hα emission extends symmetrically south-southwest from the NW region (Martin 1996). Moreover a partial shell of 3.6 arcsec of diameter (173 pc) protrudes from the north-west side. The H I velocity field (Van Zee et al. 1998; Viallefond et al. 1987) shows a significant velocity gradient along minor axis, suggesting a flow in this direction (Meurer 1991).
We first note that the distance of 720 pc between the shells and the NW H\textsc{ii} region is quite compatible with models M1, M2, M3 (in these models, after 31 Myr, the bubble has covered a distance of \(\sim 600\)–\(800\) pc along the \(z\)-axis). Martin, starting from geometrical considerations, found a shell speed of 35–60 Km s\(^{-1}\), and in our model M1, after 31 Myr, the velocity of the outer shock along the \(z\)-axis is approximately 30 Km s\(^{-1}\), in agreement with the observations. We note instead that the model MC does not develop an outflow along the \(z\) direction (see Fig 8a), and this is due to the fact that the bubble never extends beyond \(H_{\text{eff}}\), as explained in section 3.1.4. Actually, the uncertainties on the real value of \(H_{\text{eff}}\) in IZw18 are significant and a small reduction of \(H_{\text{eff}}\) could lead to the formation of an outflow also for model MC.

These comparisons between observation and theory depend strongly on the adopted distance of IZw18. In a recent work, Izotov et al. (1999) found that the distance of IZw18 should be at least 20 Mpc, twice the distance generally adopted for this galaxy. With this new distance, Color-Magnitude Diagram (CMD) studies give an age, derived from the main sequence turn-off, of 5 Myr for the main body. They suppose that the star formation in the main body has started \(\sim 20\) Myr ago in the NW edge, propagating then toward the SE direction and then triggering the main starburst \(\sim 5\) Myr ago. This estimate is also consistent with the stellar population analysis of Hunter & Thronson (1995).

Here we have assumed a coeval stellar population, so we cannot correctly verify the hypothesis of Izotov et al., but in our models a slightly pre-enriched burst with an age of 5 Myr cannot account for the observed abundances and the nearly flat metallicity gradient observed in IZw18 (see next section). Moreover, with the new estimated distance the above-mentioned shell structures double their dimensions and it is hard to reproduce these morphological features with a burst 5 Myr old.

### 4.2 Chemical abundances

In Table 4 the abundance ratios log(C/O), log(N/O), log(Si/O) as well as 12+log(O/H) predicted by our models are reported. At the beginning of section 3 we described several factors which affect the metal content of the ISM. From an inspection of Fig. 11 and Table 4 we conclude that a reduction in the burst luminosity produces a reduction in the total abundances, while a decrease in the ISM mass leads to an increase of the metallicity.

In Table 4 the observed abundances of IZw18 are also reported. However, only the model M1 (cases A,B,C,D) should be compared with IZw18, since the total mass and the gas mass of this model have been chosen to match this galaxy. Before to continue the discussion on our results, we point out that the abundances shown in Table 4 refer to the whole gas into the galaxy, while the comparison with the data should be valid only for the cold (\(T < 2 \times 10^4\) K) phase. In fact, chemical composition of stellar winds and supernovae ejecta are mainly measured through the relative intensities of usual \([\text{O}\text{ii}],[\text{O}\text{iii}],[\text{S}\text{ii}]\) and \([\text{N}\text{ii}]\) forbidden lines compared to H and He recombination lines, but this approach is sensitive only to emission from warm, photo- or shock-ionized gas at \(\sim 10000\) K (Kobulnicky & Skillman 1997).

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**Table 4.** Predicted abundances in the galactic region after 31 Myr for models M1, M2, M3. We also show the results for model MC (with nucleosynthetic prescriptions B), in order to emphasize the similarities with model M1B. Only models M1 and MC should be compared with IZw18. These values are compared with some abundances found in literature for IZw18.

| 12+log(O/H) | log C/O | log N/O | log Si/O | Fonts |
|-------------|--------|--------|---------|------|
| 7.12        | −0.47  | −5.24  | −1.40   | M1A  |
| 7.12        | −0.58  | −1.52  | −1.40   | M1B  |
| 7.51        | −0.57  | −1.46  | −1.29   | M1C  |
| 7.51        | −0.63  | −1.33  | −1.29   | M1D  |
| 6.90        | −0.49  | −5.02  | −1.40   | M2A  |
| 6.90        | −0.58  | −1.61  | −1.40   | M2B  |
| 7.36        | −0.54  | −1.31  | −1.30   | M2C  |
| 7.36        | −0.58  | −1.24  | −1.30   | M2D  |
| 7.67        | −0.49  | −5.22  | −1.38   | M3A  |
| 7.67        | −0.59  | −1.60  | −1.38   | M3B  |
| 7.97        | −0.64  | −1.90  | −1.26   | M3C  |
| 7.97        | −0.71  | −1.61  | −1.26   | M3D  |
| 7.12        | −0.58  | −1.49  | −1.39   | MC   |
| 7.24        | −0.54  | −1.54  | −1.54   | DH   |
| 7.17/7.26   | −1.54/−1.60 | −1.54/−1.60 | SK   |
| 7.17/7.26   | −1.54/−1.60 | −1.54/−1.60 | SK   |

References: DH: Dufour & Hester (1990); SK: Skillman & Kennicut (1993); G97: Garnett et al. (1997); G95: Garnett et al. (1995).
However, although the metal abundances in the hot regions are quite large, reaching also extrasolar values (cf. Fig. 14), in our models the majority of the metals is in the cold gas phase. Thus the abundances in Table 4 are essentially the same as those in the cold gas, and their comparison with the observed metallicities is meaningful. Note that, in making such a comparison, we suggest that the present time burst in IZw18 can be responsible of the observed chemical enrichment in the H\textsc{ii} regions. This is in agreement with the arguments illustrated in section 3.2, and at variance with previous suggestions of different authors (see e.g. Larsen et al. 2000). Recent observations (Pettini & Lipman 1995; Van Zee et al. 1998), although uncertain, indicate an oxygen abundance in the H\textsc{ii} regions of IZw18 comparable with that in the H\textsc{ii} regions, in agreement with our predictions.

Table 4 reports the abundances of our models after 31 Myr. The lifetime of a 8 $M\odot$ star is approximately 29 Myr, according to eq. (14). Therefore, since at $Z = 0$ secondary N is not produced and primary N from massive stars is negligible, only for ages larger than 29 Myr we can expect some N which is the one produced in a primary fashion by IMS during the third dredge-up episode. As one can see from Table 4, the abundances and abundance ratios predicted by the yields for $Z = 0$ and $\alpha_{RV} = 1.5$ (model M1B) are in good agreement with those measured in IZw18, thus we could conclude that the abundances in this galaxy are compatible with only one burst, the first, but only if the burst age is of the order of 31 Myr. In fact, for times shorter than that the N abundance is too low and for times larger the agreement worsens.

The abundance of C and particularly the predicted C/O ratio in model M1B is in very good agreement with observations at variance with previous works (Kunth et al. 1995). The difference between the low abundance of $^{12}$C predicted by Kunth et al. (1995) and here is, in our opinion, due to the fact that the total amount of stars produced there was smaller ($M_{\text{burst}} = 2 \times 10^5 M\odot$) and less in agreement with the observations than that produced here ($M_{\text{burst}} = 6 \times 10^5 M\odot$), therefore we predict higher abundances for all the elements. In addition, the yields for massive stars used here are different from those used in Kunth et al. (1994) (those of Woosley 1987). It is also worth mentioning that the estimated ages for the present burst in IZw18 are between 15 and 27 Myr (Martin 1996) in good agreement with our suggestion, although other authors suggest as short as 5 Myr (Izotov et al. 1999; Stasińska & Schaerer 1999).

In order to see if we can exclude a previous burst besides the present one in IZw18, as suggested by previous papers (Aloisi et al. 1999; Kunth et al. 1995), or a recent burst coupled with a low but continuous star formation (Legrand 1999), we computed the expected ISM abundances for a preenriched gas with $Z = 0.01 Z\odot$ and we show in Table 4 the abundances for this case at an age of 31 Myr (cases C and D). The results for the C case show that at an age of 31 Myr the abundance of oxygen is too high; the results at the end of the simulation (375 Myr for model M1) give better values for oxygen and N/O but they predict a too high C/O. If one assumes then $Z = 0.01 Z\odot$ and $\alpha_{RV} = 1.5$ (case D), the agreement worsens at any age since one predicts a too high N/O ratio while the rest is practically unchanged. Therefore, we have two considerations: first, the single first burst hypothesis seems to give the best agreement with observations as long as primary N production in IMS is considered; second, we cannot really exclude a previous burst before the present one, or at least we cannot exclude a burst which enriched only slightly the ISM. In other words, the preenrichment should be less than $Z = 0.01 Z\odot$. From the previous discussion, it arises that the best age for the burst in IZw18 should be around 31 Myr.

At this age the abundance gradient in a region of 600 pc is almost flat, at least if the galaxy is seen edge-on (see Fig. 12), in agreement with what is observed in IZw18 (Legrand 1999). Actually, if a bipolar-shaped expanding bubble is present in IZw18, the inclination of the symmetry axis with respect to the normal to the observer would be very small (Martin 1996, suggested an inclination of $10^\circ$).

Finally, in Fig. 13 we show the predicted [\alpha/Fe] vs. time and vs. [Fe/H] for the gas inside and outside the galaxy, corresponding to the results of Models M1B, M2B and M3B. The interesting feature of this figure is that the [\alpha/Fe] ratios in the gas outside the galaxy are lower than those in the gas inside the galaxy. This is due to the fact that Fe, in particular that produced by type Ia SNe, is lost more efficiently than \alpha elements.

We shall also note in these two figures the peculiar behaviour of silicon relative to the other \alpha-elements. Silicon is, in fact, synthetized by SNeIa at variance with what happens for O and Mg, which are mainly produced by SNeI (see Gibson et al. 1997). This is the reason for the relatively low and flat [Si/Fe] ratio as a function of [Fe/H].

\section{Conclusions}
We have studied the dynamical and chemical evolution of a dwarf galaxy as due to the effect of a single, instantaneous, point-like starburst occurring in its centre. We
adopted galactic structural parameters which resemble those of IZw18, the most unevolved dwarf blue compact galaxy known locally. We ran different models, which differ for the burst luminosity and the ISM mass. We considered the mass and energy inputs from the single low and IMS, the SNeII and the SNeIa (white dwarfs in binary systems) and we followed the evolution of the gas and its chemical abundances (H, He, C, N, O, Mg, Si and Fe) in space and time for several hundreds Myr from the burst.

Our results can be summarized as follows:

(i) The starburst can inject enough energy into the ISM to trigger a metal enriched galactic wind: the metals synthetized and ejected through supernova explosions leave the galaxy more easily than the unprocessed gas. This result is not new since it has already been suggested by previous works (e. g. MF and DB). However, our new result is that the SNIa products have the largest ejection efficiency (more than the products of type II SNe), with the consequence that the [$\alpha$/Fe] ratios in the gas outside the galaxy are predicted to be...

Figure 13. Predicted [$\alpha$/Fe] vs. time and vs. [Fe/H] for models M1B, M2B, M3B (first, second and third raw respectively) for both expelled gas and ISM.
lower than those inside. This is due to the fact that SNeIa produce a substantial fraction of iron.

(ii) The energy injection in the ISM by SNII has a rather low efficiency. Instead, the energetic contribution of SNeIa, in spite of their relatively small number (a total of 240 SNeIa against 4900 SNeII), has important consequences in the dynamical behaviour of the galaxy. Since the SNIa explosions occur in a medium heated and diluted by the previous activity of SNeII, the thermal energy of the explosions is easily converted into kinetic energy and so the gas reaches quickly the outer regions of the bubble along the galactic chimney. DB showed that after the end of SNII activity, a fraction of the gas tends to recollapse toward the central region of the galaxy, achieving the threshold density for a new star formation event \( \left[ N(H) \right] > 10^{21} \text{ cm}^{-2} \) (Skillman et al. 1988; Saitō et al. 1992) in \( \sim 0.5-1 \text{ Gyr} \). With the energetic contribution of SNeIa, it is not possible to reach, at least for the time considered in our simulation, such a threshold in column density (it can be obtained only after many Gyr).

(iii) One single burst, occurring in a primordial gas, with an age of \( \sim 31 \text{ Myr} \) reproduces quite well both the dynamical structures and the abundances in I Zw18. This value is consistent with other independent age estimates for the burst (Martin 1996). From the nucleosynthetic point of view the age of 31 Myr ensures that there is enough time for the primary N from IMS to be produced and ejected. The adopted yields for massive stars (Woosley & Weaver 1995) include some primary N, but its amount is negligible. This result suggests that I Zw18 is probably experiencing its first major burst of star formation, although we cannot exclude a previous burst (see Aloisi et al. 1999) of moderate intensity, which enriched the gas to a metallicity \( Z < 0.01 Z_\odot \).

(iv) At variance with previous studies we find that

\begin{figure}[h]
\centering
\includegraphics[width=\columnwidth]{fig14.png}
\caption{Abundance evolution in hot and cold regions for the model M1B. The threshold temperature is \( 2 \times 10^4 \text{ K} \).}
\end{figure}
the majority of metals (in mass) are found in the cold gas. In fact, mainly because of the low SNII efficiency, the wind superbubble remains several hundreds of Myr inside the galaxy before the break out occurs. Moreover, the superbubble becomes radiative after a few Myr, and most of the SNII ejecta cool without leaving the galaxy (SNII ejecta, instead, are shown to be vented more easily). Given the relatively short mixing time, the abundances predicted by our models for the cold gas are those that should be compared with the abundances observed in IZw18. Actually, they are in very good agreement with the observed ones. This result supports the common assumption made in chemical evolution models of an instantaneous mixing.

Future improvements of this work will include models with continuous bursts, sequential bursts, as well as an instantaneous mixing.

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