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The influence of stellar energetics and dark matter on the chemical evolution of dwarf irregulars

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Abstract. A chemical evolution model following the evolution of the abundances of H, He, C, N, O and Fe for dwarf irregular and blue compact galaxies is presented. This model takes into account detailed nucleosynthesis and computes in detail the rates of supernovae of type II and I. The star formation is assumed to have proceeded in short but intense bursts. The novelty relative to previous models is that the development of a galactic wind is studied in detail by taking into account the energy injected into the interstellar medium (ISM) from both supernovae and stellar winds from massive stars as well as the presence of dark matter halos. Both metal enriched and normal winds have been considered.
Our main conclusions are: *i)* a substantial amount of dark matter is required in order to avoid the complete destruction of such galaxies during strong starbursts, and *ii)* the energy injected by stellar winds and type Ia supernovae into the ISM is negligible relative to the total thermal energy, and in particular to the type II supernovae, which in fact, dominate the energetics during starbursts.

Key words: galaxies: abundances – galaxies: dwarf – galaxies: evolution – galaxies: irregular – cosmology: dark matter

1. Introduction

Dwarf irregulars galaxies (DIG) and blue compact galaxies (BCG) are very interesting objects to study galaxy evolution, for they are easier to model because of their generally small sizes and simple structures. Their stellar populations appear to be mostly young, their metallicity is low and their gas content is large. All these features indicate that these galaxies are poorly evolved objects, and may have undergone discontinuous or gasping star formation activity. In particular, BCG are the most luminous among dwarf irregular galaxies: their very low metal content, large gas fraction and very blue colours, suggest that star formation may have proceeded in short and intense bursts of activity (Searle et al. 1978). On the other hand, DIG seem to show a 'gasping' activity of star formation (Tosi et al. 1992). In the last few years a great deal of theoretical models for DIG and BCG appeared in the literature. By means of analytical models, Matteucci and Chiosi (1983) first studied the effects of galactic winds on the chemical evolution of these galaxies, and suggested, among other hypotheses, that galactic winds of variable intensity could explain the observed spread in the physical properties of these galaxies. In the following years, by means of numerical models, Matteucci and Tosi (1985), Pilyugin (1992, 1993) and Marconi et al. (1994), studied the effects of galactic winds on the chemical evolution of such galaxies and confirmed the previous results. In these papers the possibility of metal enriched winds was also considered and favoured relative to the normal galactic winds. This metal enriched wind hypothesis, in fact, allowed them to explain the observed He abundances versus metal abundances. However, none of these studies had taken into account either the energy injected by supernovae and stellar winds into the ISM or the presence of dark matter halos which are of fundamental importance for the development of a galactic wind. The galactic winds were just assumed to occur every time the starburst was active.

Dark matter in dwarf irregular galaxies seems to be quite important as shown by recent data indicating an increasing amount of dark matter with decreasing luminosity (Skillman 1996), and therefore it cannot be ignored in chemical evolution models. Kumai and Tosa (1992) also explored the possibility of dark matter in these galaxies in a very simple way, and suggested that various amounts of dark matter could explain the observed spread in the Z versus $\log(M_{gas}/M_{tot})$ relation.

The energetics of supernovae and stellar winds and their interaction with the ISM, is a difficult problem, still not quite understood. The only existing models of chemical evolution taking into account the stellar energetics relative to the occurrence of galactic winds, are those developed to study the chemical and photometric evolution of elliptical galaxies (Arimoto and Yoshii 1987; Matteucci and Tornambé 1987; Angeletti and Giannone 1990; Ferrini and Poggianti 1994; Bressan et al. 1994; Gibson 1994, 1997). In these models, some specific assumptions relative to the amount of energy transferred into the ISM are made. Gibson (1994) has shown that the energetics from stellar winds is negligible in massive ellipticals whereas it could be important in smaller ones. For this reason it seems worthwhile to explore

Send offprint requests to: F. Matteucci the effects of both supernovae and stellar winds on the evolution of dwarf irregulars and blue compact galaxies.

The aim of this paper is to take into account both the stellar energetics and the presence of dark matter in modelling the chemical evolution of dwarf irregular galaxies. The development of a galactic wind will therefore be calculated in detail and the existence of metal enriched or differential winds will be taken into account. By differential wind we intend a wind carrying out only some heavy elements, in particular those produced by type II supernovae which are the predominant supernovae during a starburst (Marconi et al. 1994) and eject material at much higher velocities than normal stellar winds. Therefore, under this assumption elements such as nitrogen and helium, which are restored by low and intermediate mass stars through stellar winds, will not leave the star forming region whereas oxygen and the other α-elements, ejected during type II supernova explosions are likely to be ejected outside the region and perhaps outside the galaxy. Iron will only in part leave the star forming region since only a fraction of this element is produced by SNe II, whereas the bulk of it comes from SNe Ia. It should be again said that the differential wind assumption has proven to be the most viable solution to the helium problem in blue compact galaxies (see Pilyugin 1993 and Marconi et al. 1994).

The paper is organized as follows: in Sect. 2. we will present the observational data concerning dwarf irregulars and blue compact galaxies, in Sect. 3. we will describe the chemical evolution model and the nucleosynthesis prescriptions, in Sect. 4. we will give our model results and finally in Sect. 5. we will draw some conclusions.

2. Data sample

The data we refer to for the comparison with log(N/O) versus 12+ log(O/H) are taken from Kobulnicky and Skillman (1996).

Thuan at al. (1995) presented high quality spectrophotometric observations of 15 supergiant HII regions in 14 BCG. We compared our model results with their data relative to O and Fe. Their data showed that none of the ratios N/O, Fe/O, Ne/O, Ar/O, S/O, depends on the oxygen abundance indicating that abundance ratios in these galaxies show the pollution only from massive stars and that all the elements, including nitrogen, should have a primary origin (see paragraph 3.1). However, there is a warning concerning this kind of interpretation which implicitely assumes that the star formation history in all the objects considered has been the same. In fact, it is very likely that the star formation history has been different in different galaxies and therefore one can draw this kind of conclusions only after comparing with detailed chemical evolution models.

We compared our predicted log(C/O) versus 12+log(O/H) with data from Garnett et al. (1995) who presented UV observations of 7 HII regions in low-luminosity dwarf irregular galaxies and the Magellanic Clouds (HST data). This allowed them to measure the carbon abundances and discuss the evolution of the C/O ratio in these galaxies. They found that the C/O ratio increases continuously with increasing O/H and suggested that this can be due to the fact that in the most metal poor galaxies massive star nucleosynthesis predominates (oxygen production), while in more metallic objects the delayed contribution of intermediate mass stars to carbon is more evident. However, their comparison with chemical evolution models is not really appropriate since they have adopted, for such comparison, models relative to the solar neighbourhood, where the star formation mechanism and evolution are definitively different from those of dwarf irregular galaxies. We considered also recent data on C/O measured in the NW and SE components of IZw18 by Garnett et al. (1997), again obtained by means of ultraviolet spectroscopy (HST data).

3. Theoretical prescriptions

To calculate the chemical evolution of the star forming region of DIG and BCG, we used an improved version of the model presented in Marconi et al. (1994). The main features of our chemical evolution model are the following:

1. one-zone, with instantaneous and complete mixing of gas inside this zone;
2. no instantaneous recycling approximation, i.e. the stellar lifetimes are taken into account;
3. the evolution of several chemical elements (He, C, N, O, Fe) due to stellar nucleosynthesis, stellar mass ejection, galactic wind powered by supernovae and stellar wind and infall of primordial gas, is followed in details.

If G_i is the fractional mass of the element *i* in the gas, its evolution is given by the equations:

$$\dot{G}_i = -\psi(t)X_i(t) + R_i(t) + (\dot{G}_i)_{inf} - \dot{G}_{iw}(t) \tag{1}$$

where $G_i(t) = M_g(t)X_i(t)/M_L(t_G)$ is the gas mass in the form of an element *i* normalized to a total luminous mass $M_L = 10^9 M_\odot$ and $t_G = 15\mathrm{Gyr}$ is the present time.
The quantity $X_i(t) = G_i(t)/G(t)$ represents the abundance by mass of an element *i* and by definition the summation over all the elements present in the gas mixture is equal to unity. The quantity $G(t) = M_g(t)/M_L(t_G)$ is the total fractional mass of gas.

The star formation rate we assume during a burst, $\psi(t)$, is defined as:

$$\psi(t) = \Gamma G(t) \tag{2}$$

where Γ is the star formation efficiency (expressed in units of Gyr^{-1}), and represents the inverse of the timescale of star formation, namely the timescale necessary to consume all the gas in the star forming region.

The rate of gas loss via galactic winds for each element is assumed to be simply proportional to the amount of gas present at the time t:

$$\dot{G}_{iw} = w_i \, G(t) \, X_{iw}(t) \tag{3}$$

where $X_{iw}(t) = X_i(t)$ is the abundance of the element *i* in the wind and in the interstellar medium (ISM); w_i is a free parameter describing the efficiency of the galactic wind and expressed in Gyr^{-1}. We have considered normal and differential winds: in the first case, all the elements are lost at the same efficiency ($w_i = w$). In the second case, the value of w_i has been assumed to be different for different elements: in particular, the assumption has been made that only the elements produced by type II SNe (mostly α-elements and one third of the iron) can escape the star forming region. We have made this choice following the conclusions of Marconi et al. (1994), who showed that models with differential winds can better explain the observational constraints of blue compact galaxies in general. The conditions for the onset of the galactic wind are studied in detail and described in paragraph 3.2.

The chemical evolution equations include also an accretion term:

$$(\dot{G}_i)_{inf} = C \frac{(X_i)_{inf} e^{-(t/\tau)}}{M_L} \quad (4)$$

where $(X_i)_{inf}$ is the abundance of the element *i* in the infalling gas, assumed to be primordial, τ is the time scale of mass accretion t_G is the galactic lifetime, and C is a constant obtained by imposing to reproduce M_L at the present time t_G. The parameter τ has been assumed to be the same for all dwarf irregulars and short enough to avoid unlikely high infall rates at the present time ($\tau = 0.5 \cdot 10^9$ years). The presence of infalling gas in these systems can be justified by the existence of large HI halos.

Finally, the initial mass function (IMF) by mass, $\phi(m)$, is expressed as a power law:

$$\phi(m) = A\, m^{-(1+x)} \quad (5)$$

We considered two cases for the IMF:

1. the exponent $x = 1.35$ over the mass range $(0.1 \div 100)\, M_\odot$ (Salpeter 1955 IMF), and
2. $x = 1.35$ over the mass range $(0.1 \div 2)\, M_\odot$, and $x = 1.70$ over the mass range $(2 \div 100) M_\odot$ (Scalo 1986 IMF).

A is the normalisation constant, obtained with the following condition:

$$A \int_{m_L}^{m_U} m^{-x}\, dm = 1 \quad (6)$$

3.1. Nucleosynthesis prescriptions

The $R_i(t)$ term of the Eq. (1) represents the stellar contribution to the enrichment of the ISM, i.e. the rate at which the element *i* is restored into the ISM from a stellar generation (see Marconi et al. 1994). This term contains all the nucleosynthesis prescriptions:

1. for low and intermediate mass stars ($0.8 M_\odot \leq M \leq M_{up}$) we have used Renzini and Voli's (1981) nucleosynthesis calculations for a value of the mass loss parameter $\eta = 0.33$ (Reimers 1975), and the mixing length $\alpha_{RV} = 1.5$. The standard value for M_{up} is 8 $M_\odot$;
2. for massive stars ($M > 8 M_\odot$) we have used Woosley's (1987) nucleosynthesis computations but adopting the relationship between the initial mass M and the He-core mass M_{He}, from Maeder and Meynet (1989). It is worth noting that the adopted $M(M_{He})$ relationship does not substantially differ from the original relationship given by Arnett (1978) and from the new one by Maeder (1992) based on models with overshooting and $Z = 0.001$. These new models show instead a very different behaviour of $M(M_{He})$ for stars more massive than 25 $M_\odot$ and $Z = 0.02$, but our galaxies never reach such a high metallicity;
3. for the explosive nucleosynthesis products, we have adopted the prescriptions by Nomoto et al. (1984) and Thielemann et al. (1993), model W7, for type Ia SNe, which we assume to originate from C-O white dwarfs in binary systems (see again Marconi et al. 1994 for details).

As already said, nitrogen is a key element to understand the evolution of galaxies with few star forming events since it needs relatively long timescales as well as a relatively high underlying metallicity to be produced. The reason is that N is believed to be mostly a secondary element (secondary elements are those synthesized from metals originally present in the star and not produced *in situ*, while primary elements are those synthesized directly from H and He). Up to now N has been considered secondary in massive stars and mostly secondary and probably partly primary in low and intermediate mass stars (Renzini and Voli 1981). However, some doubts exist at the moment on the amount of primary nitrogen which can be produced in intermediate mass stars due to the uncertanties related to the occurrence of the third *dredge-up* in asymptotic giant branch stars (AGB). In fact, if Blöcker and Schoenberner (1991) calculations are correct, the third *dredge-up* in massive AGB stars should not occur and therefore the amount of primary N produced in AGB stars should be strongly reduced (Renzini, private communication).

As a consequence, the only way left to produce a reasonable quantity of N during a short burst (no longer than 20 Myr) is to require that massive stars produce a substantial amount of primary nitrogen. This claim was already made by Matteucci (1986) in order to explain the [N/O] abundances in the solar neighbourhood. Recently, Woosley and Weaver (1995) have indicated that massive stars can indeed produce primary nitrogen, and Marconi et al. (1994) and Kunth et al. (1995) have taken into account this possibility. In this paper we also have considered this possibility and, since quantitative predictions are not yet available, we have used the same parametrization adopted by Marconi et al. (1994) and Kunth et al. (1995).

3.2. Energetics

We define as "galactic wind" any gas flow carrying material outside the galaxy. Such flows, which are not necessarily hot, have been recently detected in several blue compact galaxies (Kunth et al. 1998).

Our model presents a new formulation of galactic winds relative to previous published models of this type (Matteucci and Tosi 1985 and Marconi et al. 1994). In particular, we adopted the prescriptions developed for elliptical galaxies (Matteucci and Tornambé 1987; Gibson 1994, 1997): galaxies develop galactic winds when the gas thermal energy $E_g^{th}(t)$, exceeds its binding energy $E_g^b(t)$, i.e. when:

$$E_g^{th}(t) \geq E_g^b(t) \tag{7}$$

A detailed treatment of the energetics of the ISM is considered, in order to compute the gas thermal energy:

$$E_g^{th}(t) = E_{SN}^{th}(t) + E_{sw}^{th}(t) \tag{8}$$

we calculated the energy fraction deposited in the gas by stellar winds from massive stars $E_{sw}^{th}(t)$, and by supernova explosions $E_{SN}^{th}(t)$. Here the supernova contribution is given by:

$$E_{SN}^{th}(t) = E_{SNII}^{th}(t) + E_{SNIa}^{th}(t) \tag{9}$$

where:

$$E_{SNII}^{th} = \int_0^t \epsilon_{SN} R_{SNII}(t')\, dt' \tag{10}$$

$$E_{SNIa}^{th} = \int_0^t \epsilon_{SN} R_{SNIa}(t')\, dt' \tag{11}$$

$$E_{sw}^{th}(t) = \int_0^t \int_{12}^{m_{up}} \phi(m)\psi(t')\epsilon_w\, dm\, dt' \tag{12}$$

$R_{SNII}(t)$ and $R_{SNIa}(t)$ are the rates of supernova (II and Ia) explosion, $\phi(m)$ is the IMF and $\psi(t)$ is the star formation rate. The type Ia and II SN rates are calculated according to Matteucci and Greggio (1986). The energy injected and effectively thermalized into the ISM from supernova explosions (ϵ_{SN}) and stellar winds from massive stars (ϵ_w), are given by the following formulas:

$$\epsilon_{SN} = \eta_{SN}\, E_0 \tag{13}$$

$$\epsilon_w = \eta_w\, E_w \tag{14}$$

where E_0 is the total energy released by a supernova explosion, E_w is the energy injected into the ISM by a typical massive star through stellar winds during all its lifetime, and η_{SN} and η_w are the efficiencies of energy transfer from supernova and stellar winds into the ISM, respectively. We adopted a formulation for ϵ_{SN} and ϵ_w which is described in detail in appendix.

Our formulation refers to an ideal case characterized by an uniform ISM, and no interaction with other supernova explosions or interstellar clouds. When a supernova explodes the stellar material is violently ejected into the ISM and its expansion is gradually slowed down by the ISM. The energy released by the supernova explosion is assumed to be $E_0 = 10^{51}\, erg$, while the energy effectively transferred and thermalized into the ISM is given by Eq. (13) and depends on the assumed value for η_{SN}. The main parameters used to derive η_{SN}, as described in the appendix, are: the initial blast wave energy $E_{51} = E_0/(10^{51}\, erg)$, the interstellar gas density n_0, and the isothermal sound speed in the ISM $c_{0,6} = c_0/(10^6 cm\, s^{-1})$.

For typical values of these parameters $E_{51} = 1$, $n_0 = 1\, cm^{-3}$ and $c_{0,6} \simeq 1$ we obtained the following range of possible values for η_{SN}:

$$\eta_{SN} = 0.007 \div 0.13 \tag{15}$$

In particular, we have adopted an intermediate value of $\eta_{SN} = 0.03$ which we assume to be the typical SN energy transfer efficiency.

The energy injected into the ISM by a typical massive star through stellar winds during all its lifetime is estimated to be:

$$E_w = L_w\, t_{MS} \tag{16}$$

where t_{MS} is the time the star spends in Main Sequence and L_w is the stellar wind luminosity. By using the arguments developed in the appendix, we obtained:

$$\eta_w = 0.3\, (L_{36})^{2/3}\, n_0^{-1/2}\, c_{0,6}^{-5/2} \tag{17}$$

if we assume a $20 M_\odot$ star as a typical massive star contributing to the stellar winds then $L_{36} = L_w/(10^{36}\, erg\, s^{-1}) = 0.03$, $t_{MS} = 7.9 \cdot 10^6\, yr$ with $n_0 = 1\, cm^{-3}$ and $c_{0,6} = 1$, we obtain:

$$E_w \simeq 10^{49}\ erg \quad and \quad \eta_w = 0.03 \tag{18}$$

Therefore, in our formulation we adopted:

$$\epsilon_{SN} = 0.03 \cdot 10^{51}\ erg \tag{19}$$

and

$$\epsilon_w = 0.03 \cdot 10^{49}\ erg \tag{20}$$

It is worth noting that the assumed value for E_w is in agreement with that calculated by Gibson (1994) for a star of initial mass $M = 20 M_\odot$.

The introduction of dark matter halos with variable amounts and concentrations of dark matter is considered when we compute the binding energy of interstellar gas, $E_g^b(t)$:

$$E_g^b = W_L(t) + W_{LD}(t) \tag{21}$$

The two terms on the right of the equation take in account the gravitational interaction between the gas mass $M_g(t)$, and the total luminous mass of the galaxy $M_L(t)$, and between the gas mass and the dark matter M_d:

$$W_L(t) = -0.5\ G\ \frac{M_g(t) M_L(t)}{r_L} \tag{22}$$

$$W_{LD}(t) = -G\ \tilde{w}_{LD}\, \frac{M_g(t) M_d}{r_L} \tag{23}$$

where $\tilde{w}_{LD} \simeq \frac{1}{2\pi} S[1 + 1.37S]$.

G is the gravitational constant, and $S = r_L/r_d$ is the ratio between the effective radius of luminous matter and the effective radius of dark matter. These equations are taken from Bertin et al. (1991) and are valid for S defined in the range $0.10 \div 0.45$. It is worth noting that the original formulation of Bertin et al. (1991) was thought for massive elliptical galaxies, and that it is not necessarily the right one for dwarf irregulars. However, we used such a formulation since theoretical formulations for the binding energy of dwarf irregulars are not available.

4. Model results

Our study of the evolution of BCG and DIG starts from the results obtained by Marconi et al. (1994): *i)* the star formation is assumed to proceed in short and intense bursts of activity, which may induce galactic winds; *ii)* metal enriched and normal winds have been considered. In particular, for the metal enriched winds the assumption is made that galactic winds carry mostly the nucleosynthesis products of supernovae of type II, with the consequence of removing elements such as oxygen but not elements such as helium and nitrogen which are mainly produced in low and intermediate mass stars, and ejected through stellar winds.

The novelty is that *i)* galactic winds are powered both by supernova explosions (SNII and SNIa) and stellar winds from massive stars, and that *ii)* we consider the presence of dark matter halos in these galaxies.

In order to understand the observed distribution of N/O, C/O *versus* O/H, and of [O/Fe] *versus* [Fe/H], we computed different galaxy models by varying some parameters such as the number of bursts, the duration of each burst, the star formation efficiency, the galactic wind efficiency, the dark matter mass and distribution, and finally, the IMF exponent.

We first considered three sets of *standard models* characterized by 1, 3, 5, 7 and 10 bursts of a duration of 20, 60 and 100 Myr, whereas the other parameters were fixed by the results presented in Marconi et al. (1994). In particular, the IMF is the Salpeter one, and the star formation efficiency is $\Gamma = 1\,\mathrm{Gyr}^{-1}$. The galactic wind is differential, namely w_i is different from zero only for the α-elements ejected through type II supernova explosions. In particular, for the elements studied here, w_i is zero for N and He, whereas it is $w_i = 1$ for O, Ne, Na, Mg and Si, is $w_i = 0.97$ for C, since carbon is partly produced and ejected by low and intermediate mass stars through stellar winds, and is $w_i = 0.3$ for Fe since only $\simeq 30\%$ of this element is produced by SNe II. The ratio between dark and luminous matter is assumed to be 10 and that between the luminous and dark core radius is $S = 0.3$ for the three sets of standard models. Normal galactic winds instead require w_i to be the same for all the chemical elements. From now on we will indicate the models with differential winds by a capital D, (e.g. $w_i = 10D\mathrm{Gyr}^{-1}$ indicating the value for the α-elements).

Among our standard models, those with burst duration $\Delta t_b = 20\ Myr$ never developed galactic winds, and those with $\Delta t_b = 100\ Myr$ predicted the destruction of the galaxy (i.e. when the thermal energy of gas is larger than the binding energy of the galaxy) when a large number of bursts was assumed (in particular when $n_b \geq 7$); on the contrary, models with $\Delta t_b = 60\ Myr$ never predicted galaxy destruction and developed galactic winds for $n_b \geq 5$. As a consequence of this, we chose to examine only models with $\Delta t_b = 60\ Myr$.

We started then from our standard models and varied several parameters such as the star formation efficiency, the wind efficiency, the amount and distribution of dark matter. We found that in order to reproduce the observed spread of $\log(N/O)$ and $\log(C/O)$ $versus$ $12 + \log(O/H)$ and $[O/Fe]$ $versus$ $[Fe/H]$, the most important parameter is the star formation efficiency. We computed two series of models characterized by two different IMF: the Salpeter (1955) and the Scalo (1986) function. To reproduce the observed spread in all three diagrams, we needed a star formation efficiency (Γ) between 0.1 and 7 Gyr^{-1} when using the Salpeter IMF, and between 1 and 10 Gyr^{-1} when using the Scalo IMF. The best value for the wind parameter was $w_i = 1D\mathrm{Gyr}^{-1}$.

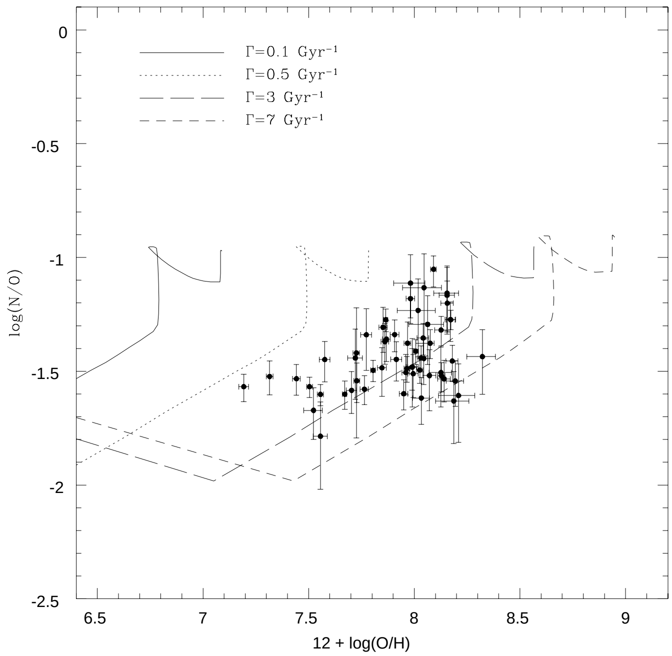

Fig. 1. Two 0.06 Gyr burst models: Salpeter IMF, $R = 10$, $S = 0.3$, $w_i = 1D\mathrm{Gyr}^{-1}$. We present the observed distribution of $\log(N/O)$ vs. $12 + \log(O/H)$ and the variation range of the star formation efficiency of our models: $\Gamma = 0.1 \div 7\,\mathrm{Gyr}^{-1}$. The data points are from Kobulnicky and Skillman (1996), the error bars are also indicated.

Consider first the Salpeter IMF case: we computed models with 1, 2, 3, 5 and 7 bursts, and tested the importance of the presence of the dark matter. Greater is the amount of dark matter, deeper is the galaxy potential and higher the gas binding energy. Therefore, the thermal energy required to develop the galactic wind has also to be higher. We found that if the amount of dark matter is the same as that of the luminous matter ($R = M_d/M_L = 1$) any model predicts galaxy destruction during the first starburst if the star formation efficiency is high ($\Gamma \geq 5$). This upper limit of Γ depends of course on the number of bursts: models with many bursts, are characterized by a great consume of gas through star formation activity, so they must have lower star formation rates to keep bound than models with just one or two bursts. We previously said that we need $\Gamma = 0.1 \div 7\ \mathrm{Gyr}^{-1}$ to explain the observed spread of the abundances ratios. So, let us consider the presence of a greater amount of dark matter: ten times the luminous matter ($R = 10$). In this case none of the models characterized by 1 or 2 bursts and $\Gamma = 0.1 \div 7\ \mathrm{Gyr}^{-1}$ predicts galaxy destruction during starbursts, whereas those with 3 or more bursts sometimes do. Considering an even

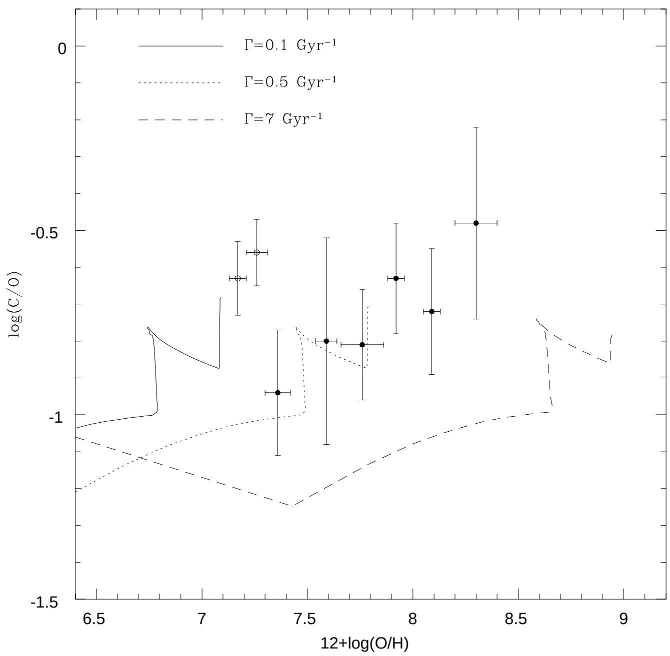

Fig. 2. Two 0.06 Gyr burst models: Salpeter IMF, $R = 10$, $S = 0.3$, $w_i = 1D\mathrm{Gyr}^{-1}$. We present the observed distribution of $\log(C/O)$ vs $12 + \log(O/H)$ and the variation range of the star formation efficiency of our models: $\Gamma = 0.1 \div 7\,\mathrm{Gyr}^{-1}$. The data points are from Garnett et al. 1995) (filled symbols) and Garnett et al. (1997) (open symbols). The error bars are also indicated.

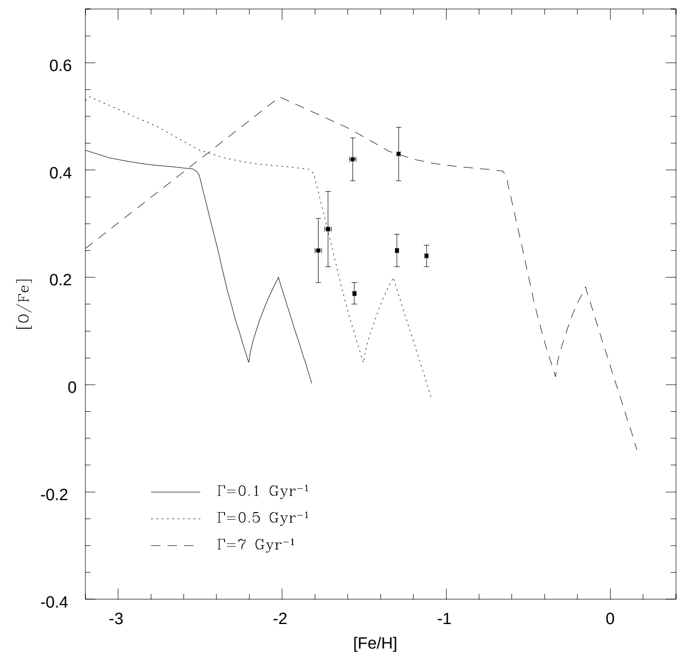

Fig. 3. Two 0.06 Gyr burst models: Salpeter IMF, $R = 10$, $S = 0.3$, $w_i = 1D\mathrm{Gyr}^{-1}$. We present the observed distribution of $[O/Fe]$ vs $[Fe/H]$ and the variation range of the star formation efficiency of our models: $\Gamma = 0.1 \div 7\,Gyr^{-1}$. The data points are from Thuan et al. (1995) and the error bars are also indicated.

Table 1. Salpeter IMF models characterized by $S = 0.3$, $w_i = 1D\mathrm{Gyr}^{-1}$: we indicate the range of variation of the star formation efficiency (Γ, expressed in Gyr^{-1}) for different values of R and n_b, and the development of the galactic wind (GW).

	$R = 1$		$R = 10$		$R = 50$	
n_b	Γ	GW	Γ	GW	Γ	GW
1	$0.1 \div 5$	yes	$0.1 \div 7$	no	$0.1 \div 7$	no
2	$0.1 \div 3$	yes	$0.1 \div 7$	yes	$0.1 \div 7$	no
3	$0.1 \div 1$	yes	$0.1 \div 5$	yes	$0.1 \div 7$	no
5	$0.1 \div 1$	yes	$0.1 \div 3$	yes	$0.1 \div 7$	yes
7	≤ 0.1	yes	$0.1 \div 1$	yes	$0.1 \div 7$	yes

greater amount of dark matter, fifty times the luminous matter ($R = 50$), none of the models predicts galaxy destruction for any value of the star formation efficiency $\Gamma = 0.1 \div 7\ \mathrm{Gyr}^{-1}$.

In Table 1 we summarize the range of variation of the star formation efficiency and the occurrence of the galactic wind for different values of the number of bursts and different amounts of dark matter for stable models (i.e. the galaxy never blows up). In column 1 is presented the number of bursts ($n_b = 1$, 2, 3, 5, 7), in column 2 the range of variation of the star formation efficiency (Γ) and in column 3 we indicate if models develop the galactic wind or not. This same scheme is reproduced three times, for $R = 1,\ 10$ and 50.

Therefore, one interesting result of our study is the fact that the presence of dark matter halos around dwarf irregulars and blue compact galaxies seems to be required in order to avoid total destruction due to the energy injected by supernova explosion and stellar winds during starbursts, especially in objects which suffered more than one starburst. In particular, we find that in models characterized by one or two bursts the quantity of dark matter should vary between one and ten times the amount of the luminous matter, according to the assumed star formation efficiency. This is in agreement with the amount of dark matter derived observationally (Skillman 1996). On the other hand, models with a number of bursts between 3 and 7 require an amount of dark matter which could be even 50 times the luminous matter. Moreover, the distribution of dark matter in our formulation, is described by the parameter $S = r_L/r_d$, and we find that S can vary between 0.1 and 0.4.

Fig. 1 shows the range of variation of the star formation efficiency for standard models characterized by two 0.06 Gyr bursts (occurring at $t = 1,$ and 5 Gyr), $R = 10$, $S = 0.3$, $w_i = 1D\mathrm{Gyr}^{-1}$ and the Salpeter IMF. We notice the peculiar sawtooth behaviour, indicating the alternation of the active star formation periods (during the bursts) and the quiescent periods (during the interbursts). During the starbursts, the star formation rate is high, and the SNe of type II dominate in the chemical enrichement of O, Fe, N and C, while during the interbursts, when the star formation is not acting, only the elements like C, N, or Fe, are produced mostly by low and intermediate mass stars. In this case the abundance of these elements increases relative to the oxygen abundance, and this is exactly what we observe in all the figures presented here. The observed spread of N/O abundance ratio, reported in Fig. 1, is quite well reproduced if $\Gamma = 0.5 \div 7\,\mathrm{Gyr}^{-1}$.

Figs. 2 and 3 show the C/O and the [O/Fe] abundance ratios relative to the same models, respectively. In these cases we can notice how the observed spreads are quite well reproduced if $\Gamma = 0.1 \div 1\ \mathrm{Gyr}^{-1}$ for C/O and if $\Gamma = 0.3 \div 3\ \mathrm{Gyr}^{-1}$ for [O/Fe]. These differences are probably due to the few data available in literature for C and Fe abundances and to uncertainties present in the nucleosynthesis calculations.

On the other hand, Figs. 4, 5 and 6 show the same models but with the Scalo IMF, reproducing the N/O, C/O and [O/Fe] abundance ratios. In this case the best results are obtained with $\Gamma = 1 \div 10\ \mathrm{Gyr}^{-1}$. However, while the [O/Fe] observed spread is quite well reproduced (Fig. 6), the C/O and in particular the N/O abundance ratios are worsely reproduced than by the Salpeter IMF models (Figs. 2 and 1).

On the basis of our study we can conclude that models with the Salpeter IMF are favoured relative to those adopting the Scalo one, since these latter do not explain all the spread present in the N/O vs O/H diagram. The models with the Salpeter IMF require a star formation efficiency $\Gamma = 0.1 \div 7\ \mathrm{Gyr}^{-1}$ and a dark to luminous matter ratio $R = 1 \div 50$.

In our analysis of the best model we have also considered the relation between metallicity (Z) and the gas mass fraction ($\mu = M_{gas}/M_{tot}$ with $M_{tot} = M_L + M_d$). Matteucci and Chiosi (1983) discussed the problem of reproducing the observed spread existing in the $Z - \mu$ diagram and suggested that different wind rates, different infall rates and different IMF from galaxy to galaxy could equally well explain the spread. However, they did not consider the role played by the dark matter. On the other hand, Kumai and Tosa (1992) suggested that the observed spread could be explained with the presence of variable amounts of dark matter: they proposed that the dark matter fraction should vary from galaxy to galaxy as $f_D = M_d/M_{tot} = 0.40 \div 0.95$. Our results agree with Kumai and Tosa (1992) and, as one can see in Fig. 7, where it is shown that the dark matter can vary between 1 and 50 times the luminous matter ($R = 1 \div 50$) in order to reproduce the spread. This means that the parameter f_D should vary in the range $f_D = 0.50 \div 0.98$.

The second main result of our study concerns the energetics of interstellar gas: the ISM receives energy from both supernova explosions and stellar winds from massive stars. In Fig. 8 we can notice the interstellar gas thermal energy relative to its binding energy and the total galaxy binding energy. When the thermal energy equates the gas binding energy, the galaxy develops the galactic wind. When a supernova explodes it injects almost $10^{51}\ erg$ into the ISM, but just some percents (see paragraph 3.) of this energy are transformed into thermal energy of the gas. The question about stellar winds from massive stars is still under debate. As already discussed, we considered here a typical massive star ($M \simeq 20 M_\odot$) and assumed that it may inject into the ISM something like $0.03 \cdot 10^{49}\ erg$ through stellar winds during all of its life, and our results in this case suggest that the total thermal energy due to stellar winds from massive stars, is negligible if compared to the component due to supernovae of type II and Ia. Supernovae of type Ia also do not contribute significantly, as shown in Fig. 9 where the different contributions to the thermal energy due to the SNeII, the SNeIa and the stellar winds are presented. This would mean that both stellar winds and SNeIa play a negligible role in the evolution of these systems.

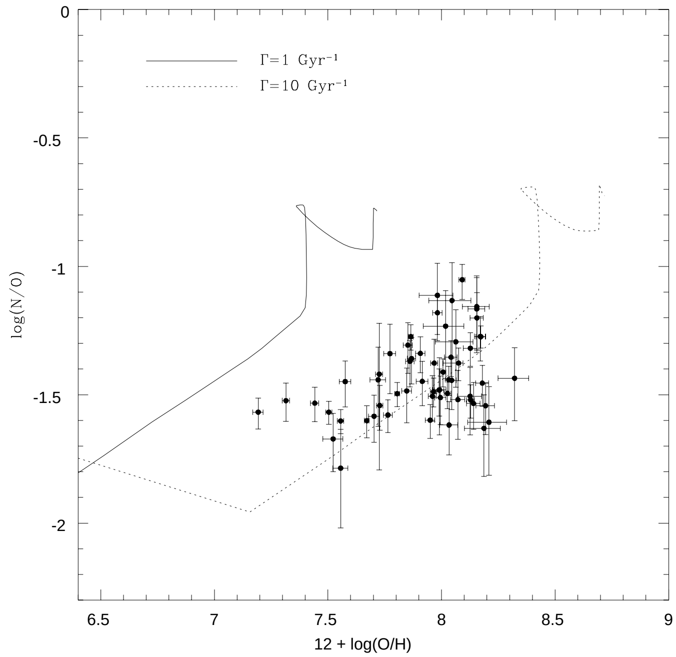

Fig. 4. Two 0.06 Gyr burst models: Scalo IMF, $R = 10$, $S = 0.3$, $w_i = 1D\mathrm{Gyr}^{-1}$. We present the observed distribution of $\log(N/O)$ vs. $12 + \log(O/H)$ and the variation range of the star formation efficiency of our models: $\Gamma = 1 \div 10\,\mathrm{Gyr}^{-1}$. The data points are the same as in Fig. 1.

In agreement with the Marconi et al. (1994) results, our results also favour differential galactic winds, but we find that the wind efficiency parameter w_i has to be lower ($w_i \leq 1\mathrm{Gyr}^{-1}$) than in Marconi et al. (1994).

Finally in Fig. 10 is reported the characteristic behaviour of type II supernova rates: each peak corresponds to a burst of star formation. In Fig. 11 instead typical type Ia supernova rates are presented and we can notice how type Ia supernovae explode also during the interbursts periods. Considering Salpeter models characterized by $R = 50$, $S = 0.3$, and $w_i = 1D\mathrm{Gyr}^{-1}$, we find that the present value of SNeIa rate varies between $0.32 \cdot 10^{-9}$ and $0.67 \cdot 10^{-4}\ yr^{-1}$, depending on the values of both the star formation efficiency and the number of bursts. In particular, in Table 2 we indicate the range of variation of the present value of type Ia SNe rate (R_{SNIa}) for different values of the number of bursts ($n_b = 1, 2, 3, 5, 7$) and $\Gamma = 0.1 \div 7\mathrm{Gyr}^{-1}$.

5. Summary

In this paper we attempted to model the chemical evolution of dwarf irregulars and blue compact galaxies. In particular, we considered the presence of dark matter halos and of the different contributions to the interstellar gas energy due to supernovae (II and Ia) and stellar winds from massive stars. The comparison

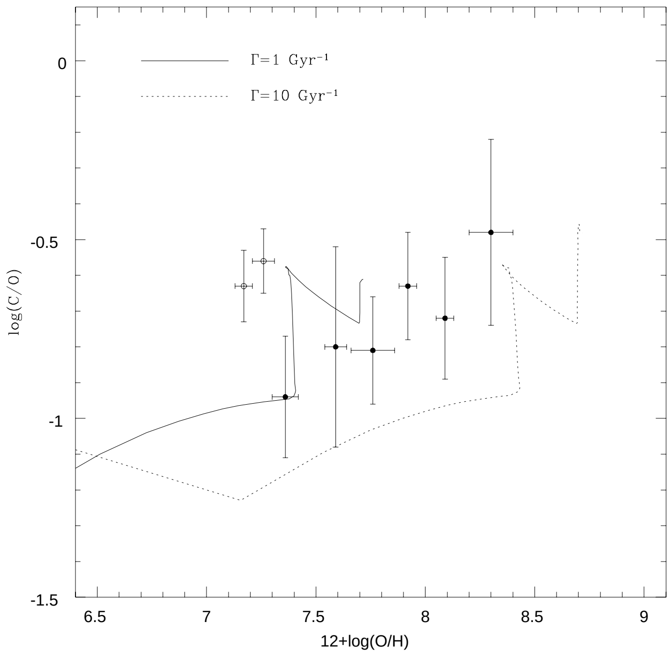

Fig. 5. Two 0.06 Gyr burst models: Scalo IMF, $R = 10$, $S = 0.3$, $w_i = 1D\mathrm{Gyr}^{-1}$. We present the observed distribution of $\log(C/O)$ vs. $12+\log(O/H)$ and the variation range of the star formation efficiency of our models: $\Gamma = 1 \div 10\,\mathrm{Gyr}^{-1}$. The data points are the same as in Fig. 2.

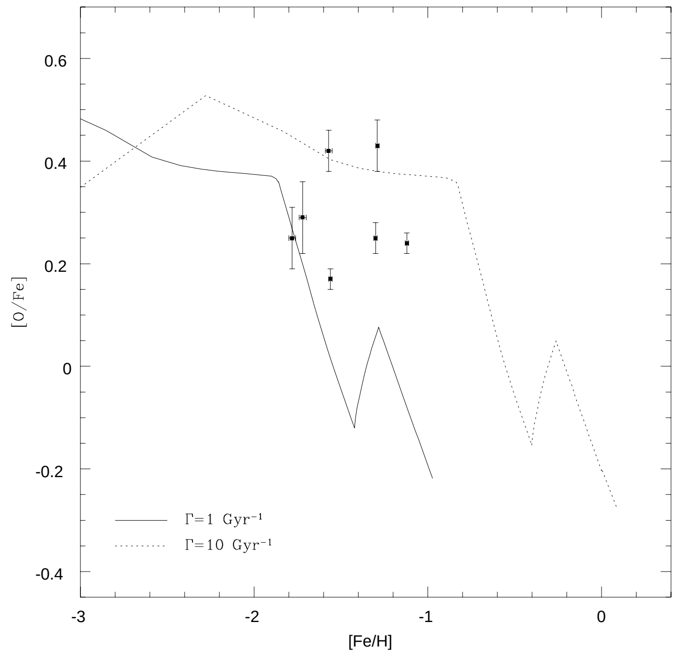

Fig. 6. Two 0.06 Gyr burst models: Scalo IMF, $R = 10$, $S = 0.3$, $w_i = 1D\mathrm{Gyr}^{-1}$. We present the observed distribution of $[O/Fe]$ vs. $[Fe/H]$ and the variation range of the star formation efficiency of our models: $\Gamma = 1 \div 10\,\mathrm{Gyr}^{-1}$. The data points are the same as in Fig. 3.

Table 2. Range of variation of type Ia supernova rates (R_{SNIa}) for different values of the number of bursts (n_b). The star formation efficiency is $\Gamma = 0.1 \div 7\,\mathrm{Gyr}^{-1}$.

n_b	$R_{SNIa}\ (yr^{-1})$
1	$0.32 \cdot 10^{-9} \div 0.80 \cdot 10^{-5}$
2	$0.37 \cdot 10^{-6} \div 0.31 \cdot 10^{-5}$
3	$0.24 \cdot 10^{-5} \div 0.82 \cdot 10^{-4}$
5	$0.25 \cdot 10^{-5} \div 0.68 \cdot 10^{-4}$
7	$0.30 \cdot 10^{-5} \div 0.67 \cdot 10^{-4}$

with the available data on the abundances and abundance ratios of elements such as He, N, C, O, and Fe allowed us to conclude that DIG and BCG must contain a substantial amount of dark matter in order to be gravitationally bound against the intense starbursts, that galactic winds powered by supernovae and stellar winds from massive stars are preferably enriched (differential), and that the energy contribution from type Ia supernovae to the total thermal energy of the gas is negligible relative to the type II supernova component. We found also that the stellar wind contribution is negligible relative to that of the type II supernovae.

In summary, our models suggest:

– a number of bursts $n_b = 1 \div 10$;
– a star formation efficiency $\Gamma = 0.1 \div 7\,\mathrm{Gyr}^{-1}$;
– differential galactic winds mostly powered by supernovae of type II, with a wind efficiency parameter $w_i \leq 1\,\mathrm{Gyr}^{-1}$;
– a ratio between dark matter and luminous matter $R = 1 \div 50$; in particular, for one or two bursts models we find $R = 1 - 10$ whereas for multi-burst models (up to 7) $R > 10$ is required.
– a dark matter distribution given by the ratio between luminous effective radius and dark effective radius $S = 0.1 \div 0.4$;
– Salpeter IMF is favoured relative to Scalo IMF: in fact the observed abundance ratios are better reproduced by Salpeter models than by Scalo models, in particular the spread of N/O abundance ratio.

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Appendix

In order to calculate the energy gained by the ISM after an isolated SN explosion we consider the expansion of the SNR through an uniform medium of number density n_0 and isothermal sound speed $c_0 = 10^6 c_{0,6}$ cm s^{-1}. Initially the temperature of the remnant is very high and the energy radiated away is negligible as compared to the explosion energy E_0; this phase is called ‘adiabatic’ and is described by the Sedov solution, $R_\mathrm{s} \propto t^{2/5}$. As the remnant expands its temperature decreases and eventually the radiative losses from the swept-up dense shell become relevant at the cooling time given by (cf. Cioffi and Shull 1991):

$$t_\mathrm{c} = 1.49 \times 10^4 \frac{E_{51}^{3/14}}{n_0^{4/7} \zeta^{5/14}}\ \mathrm{yr}$$

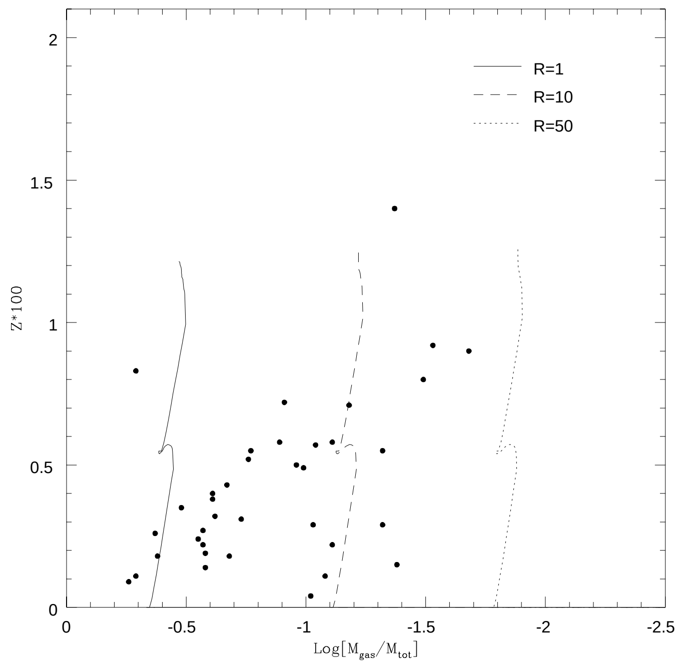

Fig. 7. Two 0.06 Gyr burst models: Salpeter IMF, $\Gamma = 5\ \mathrm{Gyr}^{-1} S = 0.3, w_i = 1DGyr^{-1}$. We present the observed distribution of Z versus $\log \mu$ ($\mu = M_{gas}/M_{tot}$). The models are characterized by a different amount of dark matter: $R = 1, 10, 50$. The data points are from Matteucci and Chiosi (1983).

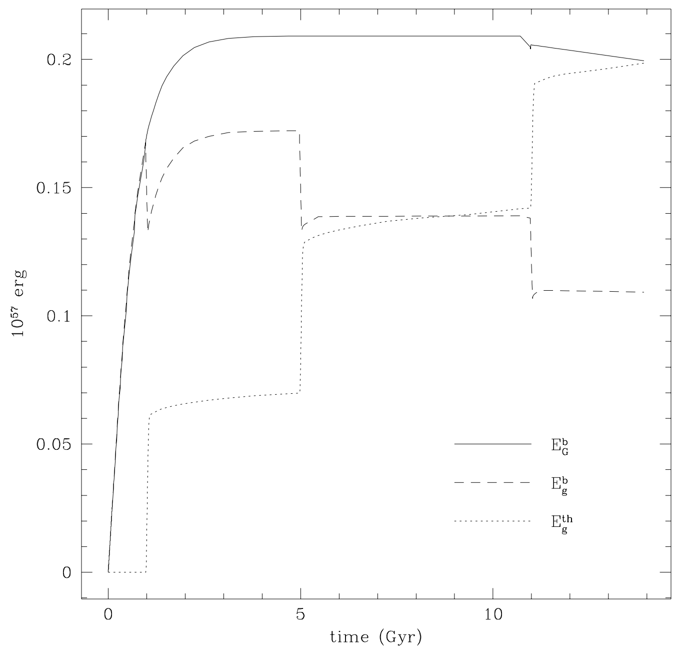

Fig. 8. Three 0.06 Gyr burst model, characterized by: Salpeter IMF, $\Gamma = 5$, $R = 10$, $S = 0.3$, $w_i = 1D\mathrm{Gyr}^{-1}$. The bursts occur at $t = 1, 5$ and 11 Gyr. We present the galaxy binding energy (E^b_G), the interstellar gas binding energy (E^b_g) and the interstellar gas thermal energy (E^{th}_g). The time of occurence of the galactic wind correspond to the time at which $E^{th}_g = E^b_g$.

where $E_0 = 10^{51} E_{51}$ erg and ζ is the metal abundance relative to the solar abundance.

For $t > t_\mathrm{c}$ most of the mass and the kinetic energy of the SNR is contained by the thin, cold, massive expanding shell, while the interior cavity is filled with hot diluted gas that contains most of the thermal energy. At this stage the hot bubble has a very long cooling time and cools adiabatically as it expands pushing the outer shell. We thus assume that its thermal energy varies as $E_\mathrm{th} \propto R_\mathrm{s}^{-2}$ and neglect a correction $\propto t^{-4/7}$ due to the effect of cooling (Cioffi et al. 1988). This is compatible with the other simplifying assumptions made in our evaluation of the SN efficiency. The remnant therefore expands as $R_\mathrm{s} \propto t^{2/7}$ in this 'snow plow' phase. At a later time the pressure inside the cavity becomes equal to the external pressure and the remnant stalls. We define the stalling radius as the radius at which the shell velocity is equal to c_0. As long as the SNR expands supersonically, the ISM outside the remnant is not aware of its presence and the fraction of the SN explosion energy which is not cooled off remains locked inside the cavity. At merger, the shell dissipates its remaining kinetic energy and its thermal energy (we assume that the shell temperature does not become lower than the temperature of the unperturbed ISM, so that its thermal energy is three times the kinetic energy at the stalling radius) which adds to the thermal content of the ISM. The efficiency is thus given by the ratio of this shell energy to the explosion energy. With the assumptions above it is found:

$$\eta_\mathrm{SN} = 0.12 E_{51}^{2/35} n_0^{-4/35} \zeta^{-8/35} c_{0,6}^{4/5}$$

It may happen that the remnant pressure becomes lower than the external pressure before the merger. In this case the remnant enters in the 'momentum conserving' phase, $R_\mathrm{s} \propto t^{1/4}$. Spitzer (1968) has shown that, in the limiting case in which the 'snow plow' phase is entirely skipped and the 'momentum conserving' phase starts just after t_c, the efficiency is given by $\frac{c_0}{5 v_\mathrm{c}}$, where v_c is the remnant velocity at t_c. In our notations we get:

$$\eta_\mathrm{SN} = 0.005 E_{51}^{-1/14} n_0^{-1/7} \zeta^{-3/14} c_{0,6}$$

Thus, the 'true' efficiency will be intermediate between the two above. Andersen and Burkert (submitted), in describing the evolution of the ISM of the dwarf galaxies, assume $\epsilon_\mathrm{SN} = 0.08$ independent of the environment, but find that the exact value is not of importance.

Before to explode, stars earlier than B0 ($M > 20\,M_\odot$) suffer considerable mass loss ($\dot{M} \sim 10^{-5} - 10^{-6}\ M_\odot\ \mathrm{yr}^{-1}$) through supersonic winds ($v_\mathrm{w} \sim 10^5 - 10^6$ km s^{-1}), carving large, hot bubbles (Weaver et al., 1977) and injecting large amounts of energy into the ISM. In fact, as the wind impinges on the ISM, a reflected shock forms which thermalizes the wind itself. This rarefied, hot, pressurized gas fills the expanding cavity which is surrounded by a thin, cold, dense shell formed by the swept up gas of the ISM. As the expansion proceedes the radiative losses increase and the inner pressure decreases until eventually the bubble stalls. As for the SNR case, we calculate the kinetic energy of the dense shell pushed by the expanding bubble when it becomes sonic. To obtain the wind efficiency ϵ_w the shell energy is then divided by the total mechanical energy of the

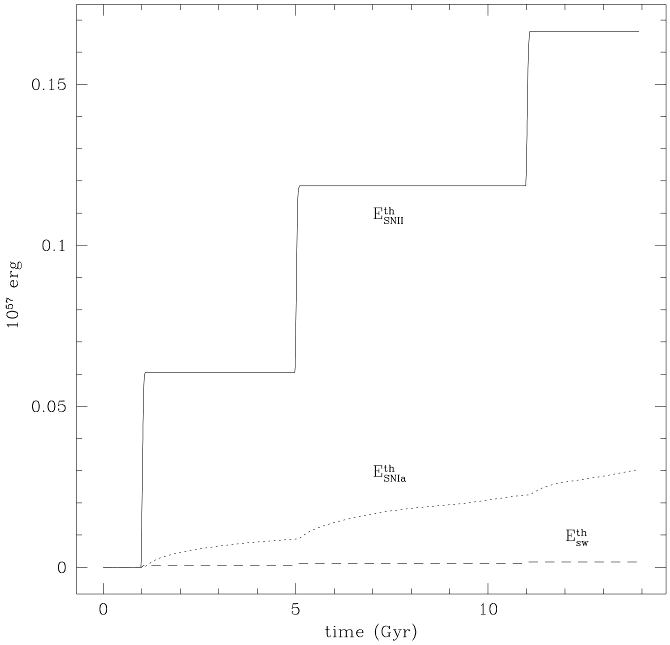

Fig. 9. Three 0.06 Gyr burst model, characterized by: Salpeter IMF, $\Gamma = 5$, $R = 10$, $S = 0.3$, $w_i = 1D\mathrm{Gyr}^{-1}$. The bursts occur at $t = 1, 5$ and 11 Gyr. We present the SNIa and the stellar winds contributions to the total thermal energy relative to the SNeII contribution: note that the stellar winds contribution is smaller than the one due to the SNeIa.

wind $t_{\rm MS} L_{\rm w}$, where $t_{\rm MS}$ is the time spent by the star on the main sequence, and $L_{\rm w} = 10^{36} L_{36}$ erg s^{-1} is the wind mechanical luminosity. From the classical 'energy conserving' solution of Weaver et al., $R \propto t^{3/5}$, we get:

$$\eta_{\rm w} = 0.3 L_{36}^{2/3} n_0^{-1/2} c_{0,6}^{-5/2}.$$

To obtain the above relation we assumed $T_{\rm MS} = 4.4 L_{36}^{-1/6}$ (McKee et al. 1984). As in the case of SNRs, the above efficiency represents an upper limit; in fact, 'momentum conserving' bubbles ($R \propto t^{1/2}$) may be realized if a substantial enhancement of radiative losses occurs for some reason such as cloudy medium (McKee et al. 1984) or non steady cooling (e.g. D'Ercole 1992). In this case the hot gas quickly cools and the shell is pushed by the ram pressure of the wind that impinges directly on it. The efficiency then becomes:

$$\eta_{\rm w} = 4.7 \times 10^{-4} L_{36}^{2/3} n_0^{-1/2} V_{2000}^{-3/2} c_{0,6}^{-1},$$

where V_{2000} is the wind velocity in units of 2×10^8 cm s^{-1}

We finally point out that in principle the SN efficiency worked out above could not be valid for exploding stars more massive than 20 $M_\odot$ because the remnant interacts with the bubble rather than with the uniform ISM. If however we consider 20 $M_\odot$ as representative of massive stars ($L_{36} = 0.03$), then the maximum bubble radius is rather small (~ 10 pc), shorter of the radius where the SNR becomes radiative ($\sim$ 15 pc) and much shorter than the radius at which it stalls ($\sim$ 60 pc). If, moreover, heat conduction is active, the bubble tends to be replenished during the red supergiant phase of the star (D'Ercole 1992). We thus consider the above estimate of $\epsilon_{\rm SN}$ rather accurate for our purposes.

In conclusion, it worth noticing that the efficiencies of both winds and SN energy deposition into the ISM are computed as-

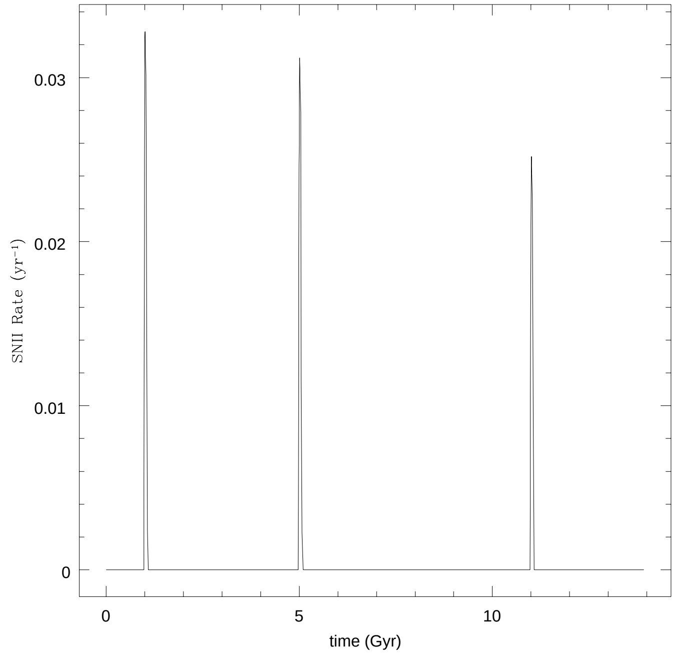

Fig. 10. Three 0.06 Gyr burst model, characterized by: Salpeter IMF, $\Gamma = 5$, $R = 10$, $S = 0.3$, $w_i = 1D\mathrm{Gyr}^{-1}$. The bursts occur at $t = 1, 5$ and 11 Gyr. We present the rate of type II supernova explosion as a function of time. The units of the SN rate are $SNeyr^{-1}$

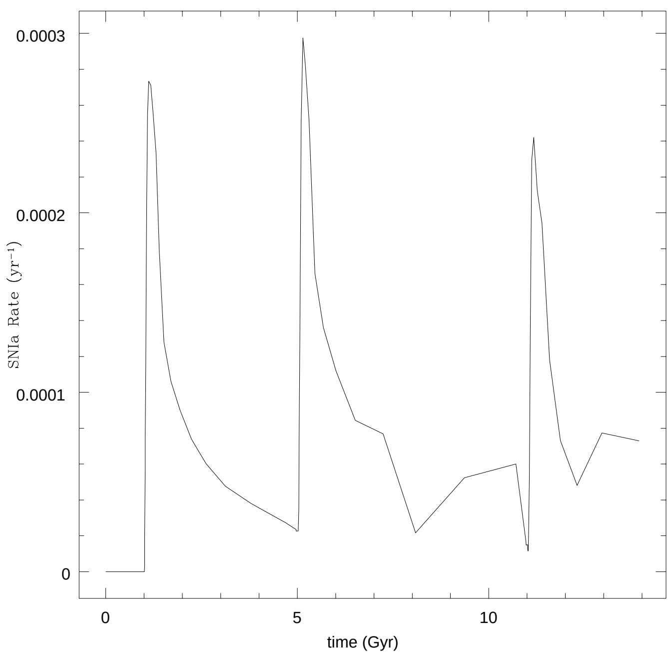

Fig. 11. Three 0.06 Gyr burst model, characterized by: Salpeter IMF, $\Gamma = 5$, $R = 10$, $S = 0.3$, $w_i = 1D\mathrm{Gyr}^{-1}$. The bursts occur at $t = 1, 5$ and 11 Gyr. We present the rate of type Ia supernova explosion as a function of time. The units of the SN rate are $SNeyr^{-1}$

suming a low filling factor of the wind bubbles and SN remnants. In this case they never interact to each other during their evolution and low values of the efficiencies seem rather unavoidable. However the assumption of a low filling factor may be simplistic. If the rate of star formation is high enough, bubbles and SNRs interact before stalling, creating a net of hot rarefied tunnels in which dense cold clouds remain embedded. The "next generation" of bubbles expand mostly in the hot gas and their efficiency may be as high as 100% because radiative losses are greatly reduced. In this case the evolution of this two phases medium must be studied following the recipe given by Begelman and McKee (1990) and McKee and Begelman (1990), taking into account the heat conduction. We have actually undertaken this kind of analysis (D'Ercole et al. in preparation)

References

Angeletti L., Giannone P., 1990, A & A, 234, 53
Arimoto N., Yoshii Y., 1987, A & A, 173, 23
Arnett, W.D., 1978, Ap.J., 219, 1008
Begelman, M.C., McKee, C.F., 1990, Ap.J., 358, 375
Bertin G., Saglia R.P., Stiavelli M., 1991, Ap.J., 384, 423
Blöcker T., Schönberner D., 1991, A & A, 244, L43
Bressan A., Chiosi, C., Fagotto, F., 1994, Ap.J. Suppl., 94, 63
Cioffi D.F., McKee C.F., Bertschinger E., 1988, Ap.J., 334, 252
Cioffi D.F., Shull J.M., 1991, Ap.J. 367, 96
Ciotti L., D'Ercole A., 1989, A & A, 215, 347
D'Ercole A., 1992, M.N.R.A.S., 255, 272
Ferrini F., Poggianti B.M., 1993, Ap.J., 410, 44
Garnett D.R, Skillman E.D., Dufour R.J. et al., 1995, Ap.J., 443, 64
Garnett D.R, Skillman E.D., Dufour R.J., Shields G.A., 1997, Ap.J., 481, 174
Gibson B.K., 1994, M.N.R.A.S., 271, L35
Gibson, B.K., 1997, M.N.R.A.S., 290, 471
Kobulnicky H.R., Skillman E.D., 1996, Ap.J., 471, 211
Kumai X. and Tosa X. 1992, A & A, 257, 511
Kunth D., Matteucci F. and Marconi, G., 1995, A & A, 297, 634
Kunth D., Mas-Hesse M., Terlevich E. et al., 1998, astro-ph 9802253
Maeder A., Meynet, G., 1989, A & A, 210, 155
Maeder A., 1992, A & A, 264, 105
Marconi G., Matteucci F., Tosi M., 1994, M.N.R.A.S., 270, 35
Mas-Hesse J.M., Kunth D., 1991, A.A.S.S., 88, 399
Matteucci F., 1986, M.N.R.A.S., 221, 911
Matteucci F., Chiosi C., 1983, A & A, 123, 121
Matteucci, F., Greggio, L., 1986, A & A, 154, 279
Matteucci F, Tornambe' A. 1987, A & A, 185, 51
Matteucci F., Padovani P. 1993, Ap. J., 419, 485
Matteucci F., Tosi M., 1985, M.N.R.A.S., 217, 391
McKee C.F., van Buren D., Lazareff B., 1984, Ap.J.Lett., 278, L115
McKee C.F., Begelmann M.C., 1990, Ap.J., 358, 392
Nomoto K., Thielemann F.K., Yokoi K., 1984, Ap.J., 286, 644
Pilyugin L.S., 1992, A & A, 260, 58
Pilyugin L.S., 1993, A & A, 277, 42
Reimers D., 1975, Mem.R.Sci. Liege 6 eme Ser., 8, 369
Renzini A., Voli M., 1981, A & A, 94, 175
Salpeter E.E., 1955, Ap.J., 121, 161
Scalo J.M., 1986, Fundam. Cosmic Phys., 11, 1
Searle L., Sargent W.L.W., Bagnuolo W.G., 1978, Ap.J., 179, 427
Skillmann E.D., 1996, ASP Conference Series, University of Minnesota, ed. by E.D. Skillman
Spitzer L. Jr., 1968, *Diffuse Matter in Space*, Wiley, New York
Thielemann F.K., Nomoto K., Hashimoto M., 1993, in *Origin and Evolution of the Elements* ed. N. Prantzos et al., Cambridge Univ. press, p.297
Tosi M., Greggio L., Focardi G., Marconi G., 1992, in IAU Symp. *Stellar Populations of Galaxies* ed. B. Barbuy and A. Renzini, Kluwer, p. 207
Thuan T.X., Isotov, Y.I., Lipovetsky, V.A., 1995, Ap.J., 445, 108
Weaver R., McCray R., Castor J., Shapiro P., Moore R., 1977, Ap.J., 218, 377
Woosley S.E., 1987, in *Nucleosynthesis and Chemical Evolution* 16th Saas-Fee Advanced Course, Geneva Observatory, p.1
Woosley S.E e Weaver T.A. 1995, Ap.J. Suppl., 101, 181