Chemo-dynamical simulations of dwarf galaxy evolution

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In this review I give a summary of the state-of-the-art for what concerns the chemo-dynamical numerical modelling of galaxies in general and of dwarf galaxies in particular. In particular, I focus my attention on (*i*) initial conditions; (*ii*) the equations to solve; (*iii*) the star formation process in galaxies; (*iv*) the initial mass function; (*v*) the chemical feedback; (*vi*) the mechanical feedback; (*vii*) the environmental effects. Moreover, some key results concerning the development of galactic winds in galaxies and the fate of heavy elements, freshly synthesised after an episode of star formation, have been reported. At the end of this review, I summarise the topics and physical processes, relevant for the evolution of galaxies, that in my opinion are not properly treated in modern computer simulations of galaxies and that deserve more attention in the future.

1. Introduction

Galaxies are extremely complex astrophysical objects. In order to study the evolution of galaxies, a deep understanding of many physical processes, covering a broad range of spatial and temporal scales, is required. On the smallest scales, electromagnetic radiation and particle-particle and particle-radiation interactions determine the thermal and ionisation status of the interstellar medium (ISM). On the largest scales, galactic winds and environmental effects (interactions with neighbouring galaxies and with the intracluster medium) regulate the mass budget of the galaxy and strongly affect its metallicity. Many other key physical processes such as star formation, feedback, gas circulation and stellar dynamics operate on intermediate spatial and temporal scales.

This review paper gives a summary of ingredients, methods, results and challenges encountered in the study of the chemical and dynamical evolution of galaxies, with particular emphasis on the study of dwarf galaxies (DGs). The main focus of this review is the theoretical study of the chemo-dynamical evolution of galaxies by means of computer simulations. For a broader and more comprehensive summary of properties and physical processes in galaxies, the book “Dwarf galaxies: keys to galaxy formation and evolution” (Springer) can be consulted.

The last three decades have seen an enormous surge of activity in the study of DGs, the most numerous galaxy species in the Universe. Advanced ground-based and space-born observatories have allowed the observation of these faint objects in the local volume with incredible detail. From a theoretical perspective, the interest in the study of DGs is manifold. Their shallow potential well allows an easier venting out of freshly produced metals than in more massive galaxies. Thus, DGs are perhaps significant polluters of the intracluster and intergalactic medium ([118], but see [87]). According to the hierarchical scenario for galaxy formation, dwarf galaxy-sized objects are the building blocks to form larger galaxies. DGs do not possess very prominent spiral structures or significant shear motions, hence the study of the star formation in these objects is somewhat easier than in spiral galaxies.

Besides providing key information about the kinematics of gas in galaxies, spectroscopy allows the determination of the metallicity and of the abundance ratios of specific elements. This is a very useful information because chemical abundances provide crucial clues to the evolution of galaxies. The increasing availability of large telescopes made possible the systematic study of extragalactic H II regions and other objects in external galaxies. In this way, variations of chemical composition between different galaxies and in different positions within a single galaxy could be studied. Integral field spectroscopy in this sense is a fundamental step forward. Detailed maps of the chemical abundances within a single galaxy can be obtained. In order to understand the origin of such distributions of metals, one often has to resort to the work and models of theoreticians.

Although a few basic properties of galaxies can be understood with simple analytical and semi-analytical considerations, the enormous complexity of galactic physics can only be handled (in part) with the help of numerical simulations. This is especially true for what concerns the chemical evolution of galaxies. Simple closed-box models [312] can provide a first-order explanation for the global metallicity in a galaxy, but the spatial distribution of metals can not be addressed with these simplified tools. On the other hand, due to the large number of processes one has to take into account, numerical simulations make generally use of results taken from other research fields and combine them in such a way that a detailed description of the evolution of galaxies can emerge. The process of simulating galaxies is thus analogous to the process of cooking. To prepare a culinary dish, ingredients must be accurately chosen, the necessary equipment must be in place, a number of steps and operations must be performed to combine the ingredients and some times a personal touch is added and standard cookbook recipes are modified in order to obtain a special effect.

For chemo-dynamical simulators of galaxy evolution, the main ingredients are:

- the initial conditions
- the set of equations to solve
- a description of the star formation process
- the mass distribution of newly born stars (the initial mass function or IMF)
- a description of the chemical feedback from stars to gas
- a description of the energy interchange processes between stars and gas. There are many processes one might take into account but all of them are usually referred to as feedback. This includes also feedback processes related to the presence of supermassive black hole and active galactic nuclei (AGN). These kind of processes are usually dubbed AGN feedback.
- a description of the interactions between the galaxy and the surrounding environment (galaxy-galaxy interactions, ram-pressure stripping due to an external inter-galactic medium, gas infall and so on)

In this review, I will consider in some detail some of these ingredients and I will describe how they have been parametrised and implemented in numerical simulations of galaxies. Ingredients related to the chemical evolution of galaxies will be treated with particular care. In the description of these ingredients, some personal bias will be applied and higher priority will be given to the most relevant ingredients for the simulation of DGs. In particular, AGN feedback will be only very briefly mentioned.

In the process of preparing a dish, the necessary equipment (pans, pots and stove) must be in place and the quality of the equipment affects the final outcome. This is also true for the numerical simulation of galaxies, where the main equipment is a computer. More often, a cluster of computers equipped with fast processors is necessary. Besides having a fast computer, appropriate algorithms and sophisticated numerical methods must be in place in order to efficiently solve the complex equations describing the evolution of galaxies. Some of these methods will be summarised in this review, too. Again, besides a very brief survey of most widely adopted methods, specific tools required for the study of the chemo-dynamical evolution of galaxies will be described with more care.

Numerical simulations always address specific issues in the evolution of galaxies, trying to give answers to open problems or trying to provide explanations to observed properties and characteristics of galaxies or groups of galaxies. In this review I will give a summary of the state-of-the-art for what concerns some of these specific issues. In particular, I will focus on the conditions for the development of galactic winds and on the fate of heavy elements, freshly produced during an episode of star formation.

The organisation of this paper is thus quite simple: there is a Section for each ingredient: initial conditions (Sect. 2), the equations (Sect. 3), the star formation (Sect. 4), the initial mass function (Sect. 5), the chemical feedback (Sect. 6), the mechanical feedback (Sect. 7) and the environmental effects (Sect. 8). In each section, commonly adopted methodologies and recipes will be introduced and some key results of past or ongoing studies will be summarised. In Sect. 9 I will summarise some relevant results of numerical investigations of DGs concerning galactic winds and their consequences. Finally, in Sect. 10 some conclusions will be drawn.

2. The initial conditions

Nowadays it is pretty common to find in the literature studies of the formation and evolution of galaxies in a cosmological context, meaning that initial conditions consist of a scale-free or nearly scale-free spectrum of Gaussian fluctuations as predicted by cosmic inflation and with cosmological parameters determined from observations of the cosmic microwave background radiation obtained by spacecrafts such as WMAP [123, 275]. However, the most detailed and sophisticated cosmological simulations to date, such as the Millennium-II simulation [30] and the Bolshoi simulation [119] have force resolutions of the order of 1 kpc. This is barely enough to resolve large galaxies, but it is clearly insufficient to solve in detail DGs, whose optical radii are some times smaller than that. A lot in resolution can be gained by zooming in and re-simulating small chunks of a large cosmological box [61, 284, 286]. This method is gaining pace and has been applied by various groups to DGs [169, 213, 245]. Still, at the present time the best way to accurately simulate a DG is by numerically studying it as a single isolated entity [180, 233, 252, 256, 287, 306].

Numerical studies of galaxies in isolation assume some initial configuration of gas density, temperature and stellar distribution. This initial configuration is an equilibrium status of the system. Starting from an equilibrium condition is clearly necessary in order to pin down the effect of perturbing phenomena (star formation, environmental effects, AGN feedback, and so on).

A common strategy is to consider a rotating, isothermal gas in equilibrium with the potential generated by a fixed distribution of stars and/or of dark matter [159, 261, 315]. Rotating gas configurations are usually better described by means of a cylindrical coordinate system (R, ϕ, z). Often, axial symmetry is assumed. The relevant equation to solve in order to find the density distribution of gas $\rho(R, z)$ is thus the steady-state (time independent) Euler equation

$$\frac{1}{\rho}\nabla P + (\mathbf{v} \cdot \nabla)\mathbf{v} = -\nabla\Phi, \quad (1)$$

where P is the pressure, $\mathbf{v}$ is the bulk velocity of the gas and Φ is the total gravitational potential. In this equation, only the component v_ϕ of the velocity must be considered because it gives centrifugal support against the gravity. Eq. 1 in fact implies that the gravitational pull is counter-balanced by the combined effect of pressure gradient and centrifugal force.

Most of the authors assume Φ to be independent of ρ. This means that the self-gravity of the gas is not considered. A typical justification of this choice is "The omission of self-gravity is reasonable, given that the baryonic-to-dark matter ratio of the systems is ~ 0.1." [79]. However, even if the total mass of a DG is dominated by a dark matter halo, within the Holmberg radius (the radius at which the surface brightness is 26.5 mag arcsec^{-2}), most of the galaxy is made of baryons [206, 297], so the inclusion of gas self-gravity in the central part of a DG appears to be important. I will come back to this point later in this section. For the moment it is enough to take note of the fact that the assumption that Φ is independent of ρ greatly simplifies the calculation of the steady-state density configuration. Furtermore, a barotropic equation of state $P = P(\rho)$ and a dependence of the azimuthal velocity v_ϕ with known quantities is commonly assumed.

A widely used strategy is to assume that $v_\phi = e v_{circ}$, where $v_{circ} = \sqrt{R \frac{d\Phi}{dR}}$ is the circular velocity and e is the spin parameter that determines how much the galaxy is supported against gravity by rotation and how much it is supported by the pressure gradient. A typical value for e is 0.9, independent on the height z [295, 314]. [293] assume that $e = 0.9$ in the plane of the galaxy, but it drops exponentially with height in order to have non-rotating gas halos. It is however important to remark that, according to the Poincare'-Wavre theorem [13, 147, 302], the rotation velocity of any barotropic gas configuration (including thus also isothermal configurations) in rotating equilibrium must be independent of z. In other words, it is possible to construct a centrifugal potential to add to Φ in Eq. 1 only if the circular velocity is independent on z.

Other authors [58] solve instead the equilibrium equation in the plane:

$$v_\phi^2 = v_{circ}^2 - \frac{R}{\rho}\left|\frac{dP}{dR}\right|_{z=0}, \quad (2)$$

and assume the azimuthal velocity to be independent of z, in compliance with the Poincare'-Wavre theorem. The density at any z is then found integrating the z-component of the hydrostatic equilibrium equation, for any R. Some authors then [67, 109, 306] set the gas in rotation around the z-axis, using the average angular momentum profile computed from cosmological simulations [37].

A different approach is followed by [7]. Initially, there is no balance between gravity and pressure and the gas collapses into the midplane. Supernovae (SNe) go off, principally along the disk and this drives the collapsed gas upwards again. Eventually, upward and downward flowing gas come into dynamical equilibrium. Some multi-phase simulations [94, 155] adopt a similar approach for the diffuse component, i.e. the distribution of diffuse gas starts far from equilibrium. Then, it relaxes on a few dynamical time scales to a quasi-equilibrium state, which represents the initial conditions for the simulation.

One should be aware of the limitations of an equilibrium model without gas self-gravity. Most of the numerical simulations treat self-consistently the process of star formation. Since star formation occurs when the gas self-gravity prevails over pressure, neglecting the gas self-gravity in the set up of the model is clearly inconsistent. Moreover, without self-gravity, there is the risk of building gas configurations which would have never been realized if self-gravity were taken into account. In order to solve these problems, Vorobyov et al. [331] explicitly took into account gas self-gravity to build initial equilibrium configurations. The gravitational potential Φ is composed of two parts, one is due to a fixed component (dark matter and eventually also old stars), one (Φ_g) is due to the gas self-gravity. The gas gravitational potential Φ_g is obtained by means of the Poisson equation

$$\nabla^2\Phi_g = 4\pi G\rho. \quad (3)$$

The gas density distribution is thus used to calculate the potential, but this potential is then included in the Euler equation to find the gas distribution. Clearly, an iterative procedure, analogous to the classical self-consistent field method [200], is necessary to converge to an equilibrium solution.

For a given mass $M_{\rm DM}$ of the dark matter halo, many solutions are possible, according to the initial assumption about the density distribution of the gas. However, the self-gravitating equilibrium configurations always have a maximum allowed gas mass $M_{\rm max}$, unlike the case of non-self-gravitating equilibria which can realize configurations with unphysically high gas masses. Moreover, only for some of the solutions, star formation was found to be permissible by Vorobyov et al. (two star formation criteria based on the surface gas density and on the Toomre parameter were assumed). The minimum gas mass $M_{\rm g}^{\rm min}$ required to satisfy the star formation criteria was found to be mainly dependent on the gas temperature $T_{\rm g}$, gas spin parameter e and degree of non-thermal support. $M_{\rm g}^{\rm min}$ was then compared with $M_{\rm b}$, the amount of baryonic matter (for a given $M_{\rm DM}$) predicted by the ΛCDM theory of structure formation. Galaxies with $M_{\rm DM} \geq 10^9\ M_\odot$ are characterised by $M_{\rm g}^{\rm min} \leq M_{\rm b}$, implying that star formation in such objects is surely possible as the required gas mass is consistent with what is available according to the ΛCDM theory. On the other hand, models with $M_{\rm DM} \leq 10^9\ M_\odot$ are often characterised by $M_{\rm g}^{\rm min} \gg M_{\rm b}$, implying that they need much more gas than available to achieve a state in which star formation is allowed. In the framework of the ΛCDM theory, this implies the existence of a critical dark matter halo mass below which the likelihood of star formation drops significantly ([331], see also [208, 263, 347]).

3. The equations

In order to follow the evolution of a galaxy, the basic equations to solve are of course the Euler equations, namely the standard set of equations (conservation of mass, momentum and energy) governing inviscid flows. Viscosity in astrophysical plasmas is in fact usually very small. It can be large in some localised system, for instance in accretion disks, but on a larger, galactic-wide scale the ISM can be considered inviscid and there is no need to invoke the Navier-Stokes equations. Conversely, astrophysical plasmas are usually very turbulent [73]. In spite of that, also the use of turbulence models in simulations of galaxies is still quite limited. The main reason for that is the lack of a satisfying characterisation and modelling strategy for the compressible turbulence. Progress in this field is however constant and very sophisticated turbulence models have been applied recently to astrophysical problems [32, 33, 88, 103, 104, 187, 251]. Important first steps have been performed also in the simulation of turbulent gas in galaxies [29, 126, 160, 231, 252].

Since a large volume fraction of the ISM of star forming galaxies is ionised, a description of the electromagnetic interactions is clearly required. This is most often realized by means of the so called ideal magneto-hydrodynamical equations, where various ions are treated as a single fluid, the conductivity of the ionised gas is assumed to be very large and the plasma is assumed to be frozen in the magnetic field. Many modern hydrodynamical codes, such as ZEUS [290], FLASH [85, 153], RAMSES [83, 305], ATHENA [289], just to name a few, solve the ideal magneto-hydrodynamical equations. The inclusion of magnetic fields affects the dynamics of gas in a galaxy in many ways. (*i*) Magnetic fields strongly reduce the transverse flow of charged particles, hence the thermal conduction in directions orthogonal to field lines [278]. Thermal conduction along field lines remains unaltered compared to non-magnetised gases. (*ii*) Magnetic tension forces tend also to suppress dynamical instabilities parallel, but not perpendicular, to field lines [63]. Magnetic fields might also inhibit the break-out of hot bubbles and superbubbles [108]. Also the mixing between the hot bubble and the surrounding cold supershell can be reduced due to the presence of magnetic fields. (*iii*) The magnetic pressure $B^2/8\pi$ plays an important role in the gas dynamics. It is in fact comparable with the thermal pressure and, if the magnetic field is not too weak, it is the dominant form of pressure for temperatures below ~ 200 K [8].

Not so much is known about magnetic fields in DGs. Starbursting DGs such as NGC1569 [114] or NGC4449 [46] are known to have magnetic fields with strengths as high as few tens of μG, whereas quiescent DGs have much weaker magnetic fields (a few μG, [117, 118]). Magnetic fields are probably not the main drivers of DG evolution, at least during periods of quiescent or weak star formation.

Since our knowledge of galaxies almost exclusively depends on their emitted (or absorbed) radiation, radiation hydrodynamics clearly allows a description of galaxies which is more complete and easier to compare with observations. The radiation hydrodynamical equations are more complex than the Euler equations. A few textbooks exist, in which these equations and related numerical methods are described in detail [43, 107, 188]. Many authors who attempted to solve them made simplifying assumptions about the matter-radiation coupling.

The simplest possible way to include the effects of radiation in hydrodynamical simulations is to assume that the gas is optically thin. The only effect of radiation is thus to reduce the available thermal energy of the gas, i.e. radiation acts only as an energy sink. Many works in the literature are devoted to the calculation of the cooling function of an optically thin plasma [23, 258, 296] and these functions are used to calculate the rate of thermal energy loss as a function of density, temperature and chemical composition. A further commonly adopted assumption is the on the spot approximation [280], according to which the photons produced in recombination processes do not propagate but are immediately absorbed locally. In this way, the transport of these photons must not be considered and the equations to solve simplify considerably. The heat produced by the radiation is transported out according to a law similar to the thermal conduction. This approximation turns out to be valid as long as the particle density is sufficiently high, i.e. when the optically thick limit applies. There are various examples of radiation hydrodynamical simulations which make use of the on the spot approximation [81, 82, 92, 157, 328]. A step forward is the so called flux limited diffusion, where the optically thin and optically thick limits are connected by appropriate flux limiter functions [84, 138, 342]. Although radiation hydrodynamics is clearly very relevant and might quite substantially change our understanding of galaxy formation and evolution of galaxies [44, 116, 344], the inherent complexity has so far limited the use of radiation hydrodynamical equations in galaxy simulations.

Of course, gas is not the only component of a galaxy.

Stars and, very often, dark matter must be considered, too. The gravitational potential they generate has been already considered in Sect. 2. However, their dynamics can be very important, as well. The relevance of a live dark matter halo for the evolution of a galaxy is not clear and many authors still assume a fixed dark matter halo. Conversely, it is clear that the stellar dynamics plays an important role in the evolution of a galaxy, at least if one is interested in time spans larger than a few tens of Myr. This has been demonstrated for instance by Slyz [271] by means of a clear numerical experiment. According to this study, spurious results can be obtained if one does not allow stars to move from their natal sites. In particular, the energy of Type II Supernovae (SNeII) is, in this case, always released in regions of high densities (because in these regions it is more likely to form stars, see Sect. 4), where cooling rates are high. This leads to the so-called overcooling problem (see also Sect. 7). This problem can be simply avoided if one allows stars to move during their lifetimes and, hence, SNeII to explode in environments other than their natal ones (in particular, to explode in less dense environments).

A widely used strategy to follow the dynamics of stars (and of dark matter particles) is to consider individual stars, or more often, populations of stars, as point masses and to follow their orbits by means of standard N-body integration techniques. This approach is straightforward in SPH simulations of galaxies but it is widely used also in grid-based codes. However, in grid-based codes there is the problem that star particles must be mapped to the mesh in order for the global gravitational potential to be calculated. Once the gravitational potential is computed, it is then interpolated back to the particles. This process can lead to a loss of accuracy due to the required interpolations, it might spuriously generate entropy if the particle resolution is too low to adequately sample the density field [282] and it increases the communication overhead in massively parallel simulations [190]. A possible remedy in grid-based codes is the stellar hydrodynamical approach [39, 144]. With this approach, the stars are treated as a collisionless fluid and their evolution is regulated by the moments of the Boltzmann equation. This approach has been used many times to simulate galaxies [243, 307, 332, 333]. Recently, Mitchell et al. [190] implemented this method into the FLASH code. Numerical tests confirmed the validity of this approach and the advantages over the more conventional particle schemes.

Another very important aspect of the evolution of galaxies is the multi-fluid, multi-phase treatment. Stars and gas exchange mass, momentum and energy during the whole life of the stars. Moreover, various gaseous phases are known to exist in the ISM and phase transformations occur continuously during the life of a galaxy. Eventually, the gas in the ISM is composed of many different elements, with various ionisation states. A complete treatment of the galaxy evolution must take into account the various phases of a galaxy and all possible exchange processes among them. In the classical chemodynamical approach, put forward by Hensler and collaborators [39, 98, 307] stars and various gas phases (typically a cold and a warm-hot phase) co-exist within a single grid and exchange mass, momentum and energy according to physically-based recipes. The dynamics of the various phases might or might not be the same. Typically, the various gas phases share the same velocity field whereas the dynamics of the stars are different. This approach has been refined over the years and many groups use it to simulate galaxies , with various degrees of sophistication [94, 99, 209, 248, 259, 316]. Nowadays, chemodynamics is a widely used term that generically refers to simulations in which some treatment of the chemical evolution is included [78, 112, 120, 226, 317]. Although these codes clearly represent a step forward with respect to more traditional single-fluid simulations, still they lack the complexity of the multi-phase chemodynamical codes described above.

4. The star formation

In spite of still many open questions, enormous progresses have been made in the last decade in simulating the process of star formation [16, 17, 25, 91, 135, 136]. However, the level of detail and the resolution reached by these works can not be matched by galactic simulations. Suitable parametrisations of the star formation need to be implemented. It is also worth mentioning that many papers dealing with simulations of galaxies do not self-consistently calculate the star formation, but use prescribed star formation rates (SFRs) or star formation histories (SFHs). These are either based on the reconstructed SFH of specific galaxies [225, 228], or are simple functions of time such as instantaneous bursts or exponentially declining SFRs [79, 159, 227, 318]. This is a viable possibility if the star formation process itself is not the focus of the numerical study.

A star formation law scaling with some power of the gas volume or surface density is often assumed. This relation is based on the observation of star formation indicators in local galaxies [113] and is often called the Kennicutt-Schmidt law. To be more precise, the Kennicutt-Schmidt law implies that:

$$\Sigma_{\rm SFR} \propto \Sigma_g^n, \tag{4}$$

where $\Sigma_{\rm SFR}$ is the SFR surface density and Σ_g is the gas surface density. The value of n reported by Kennicutt [113] is 1.4±0.15. In many works, a dependence on the total volume density [64, 174, 175, 298] or on the molecular gas density [100, 133, 137, 218] is also assumed. A dependence on the molecular gas density appears to be particularly relevant because there is a tight correlation between the H_2 and the SFR surface densities [21]. Moreover, in spiral galaxies, often the Toomre criterium is used to identify regions prone to star formation [331], or $\Sigma_{\rm SFR}$ is assumed to be $\propto \Omega\Sigma_g$, where Ω is the circular frequency [216, 345]. Eventually, the spatial distribution of a molecular cloud seems to play a critical role in determining its star formation activity [140], but the dependence of the SFR on the structure of a molecular cloud appears to be very difficult to implement in numerical simulations.

In hydrodynamical simulations, many authors still follow the star formation recipes of Katz [110], namely (see also Katz et al. [111]):

- The gas density must be larger than a certain threshold
- The particle must reside in an overdense region
- The gas flow must be converging ($\nabla \cdot \mathbf{v} < 0$)
- The gas particle must be Jeans unstable: $\frac{h}{c_s} > \frac{1}{\sqrt{4\pi G\rho}}$, where h is the dimension of the gas particle (smoothing length for SPH simulations and the grid cell size for grid-based methods) and c_s is the local sound speed

With small variants, this recipe has been applied in most of galaxy simulations [89, 270, 288, 301, 334]. The Jeans criterium appears to be particularly relevant, otherwise artificial fragmentation and, hence, spurious star formation can arise [38, 321]. However, the implementation of this criterium some times leads to unrealistic SFRs [288].

Often, a star formation law of the type:

$$\psi(t) = c_* \frac{\rho}{t_{\rm dyn}}, \tag{5}$$

is assumed, where $\psi(t)$ is the SFR and c_* is the star formation efficiency [57, 248, 288]. Here $t_{\rm dyn}$ is a typical star formation timescale given by the free-fall timescale, the cooling timescale or a combination of both. Notice that the free-fall time scale is proportional to $\rho^{-1/2}$, thus a star formation very similar to the Kennicutt-Schmidt law can be obtained in this way (see also [71]). Notice also that observed laws (such as the Kennicutt-Schmidt law Eq. 4) involve surface densities, whereas theoretical models and simulations generally work with volume density laws such as Eq. 5 and not necessarily these two formulations are equivalent. Typically adopted values for c_* in Eq. 5 are quite low, ranging between 0.1 and 0.01 [288]. This is also the ratio between the gas consumption time scale and $t_{\rm dyn}$. This assumption is in agreement with the conclusion, deduced from observations, that only a small fraction of gas in molecular clouds can be converted into stars [74, 196]. The star formation efficiencies are larger (of the order of 0.3) if one considers only the dense cores of molecular clouds [5]. Global star formation efficiencies tend to be even lower in DGs (see also Sect. 2 and below in this Section).

Since the cooling timescale depends on the gas temperature, a dependence of the star formation with the temperature is implicit in Eq. 5. It is of course very reasonable to assume that the SFR depends on the temperature, since star formation occurs in the very cold cores of molecular clouds. For this reason, some authors even assume a temperature threshold, above which star formation cannot occur [2, 230, 288]. However, one should be aware of the fact that simulations still do not have the capability to spatially resolve the cores of molecular clouds. The temperature of a star forming region is thus simply the average temperature of a region of gas, with size equal to a computational unit (gas particle in a SPH simulation or grid cell in grid-based codes), encompassing the star forming molecular cloud core. For this reason, typical temperature thresholds are of the order of 10^3–10^4 K, at least two orders of magnitude larger than typical molecular core temperatures.

Some authors adopt a more complex temperature dependence. For instance, Köppen et al. [124] derive:

$$\psi(t) = c_* \rho^2 e^{-T/T_s}, \tag{6}$$

where the transition temperature $T_s = 1000$ K implies that the star formation is very low in regions with $T > T_s$. Notice that, in this case, c_* does not have the same dimensions (and the same meaning) of the c_* introduced in Eq. 5. This star formation recipe, coupled with the feedback from stellar winds and dying stars (see Sect. 7), nicely leads to self-regulation of the star formation process. In fact, a large SFR increases the feedback, which in turn strongly reduces further star formation whereas, if the feedback is low, the temperature does not increase and star formation is more efficient.

Eventually, theoretical works [72] suggest that the star formation efficiency can depend on the external pressure, simply because gas collapse is favoured in environments with large pressures. This hypothesis is supported by the observational fact that the molecular fraction depends on the gas pressure [22, 149] and, as noticed above, the surface density of molecular gas strongly correlates with the SFR [21]. DGs are usually characterised by lower pressures compared to larger galaxies, thus the predicted star formation efficiency is lower. This finding is in agreement with other lines of evidence, showing that DGs are quite inefficient in forming stars (see Skillman et al. [267] for a review). The pressure dependence on the star formation efficiency has been used in Harfst et al. [94].

5. The initial mass function

Once the stars are born, a mass distribution must be assumed. In fact, the chemical and mechanical feedback of massive stars substantially differ from the feedback of low-and intermediate-mass stars (see next subsections), thus it is crucial to know how many stars are formed per each mass bin. Actually, the IMF is often combined with the SFR to obtain the so-called birthrate function $B(m,t)$ [174, 312], which gives the number of stars formed per unit stellar mass and per unit time. Usually, the time dependence is described by the SFR, whereas the mass dependence is determined by the IMF. However, one should already point out that, according to some lines of evidence, the IMF could depend on time, too (see below).

The IMF $\xi(m)$ was originally defined by Salpeter [242] as the number of stars per unit logarithmic mass that have formed within a specific stellar system. Thus, the total mass of stars with masses between m and $m+dm$ is $\xi(m)dm$. A very useful concept is also the IMF in number $\varphi(m)$, giving the number of stars in the interval $[m, m+dm]$. Clearly, $\xi(m) = m\varphi(m)$. Salpeter found out that $\xi(m) \propto m^{-1.35}$ for $0.4\ \mathrm{M}_\odot < m < 10\ \mathrm{M}_\odot$. This estimate has been refined over the years [45, 130, 246, 312] and nowadays a commonly used parametrisation is the so-called Kroupa IMF [129], namely a three-part power law $\xi(m) \propto m^{-\gamma}$ with $\gamma = -0.7$ in the interval $0.01\ \mathrm{M}_\odot < m < 0.08\ \mathrm{M}_\odot$ (i.e. in the brown dwarf domain), $\gamma = 0.3$ for $0.08\ \mathrm{M}_\odot < m < 0.5\ \mathrm{M}_\odot$, and finally $\gamma = 1.3$ (very similar to the Salpeter slope) for stellar masses larger than $0.5\ \mathrm{M}_\odot$.

The paper of Romano et al. [238] clearly shows how different IMFs can change the fraction of stars in various mass bins (see their table 1). IMFs predicting smaller fractions of massive stars produce less α-elements, because these elements are mainly synthesised by SNeII. This is evident in fig. 6 of [238], which shows the evolution of [α/Fe] vs. [Fe/H] for model galaxies characterised by different IMFs. Since more massive stars means more SNeII, clearly the IMF affects the energetics of a galaxy, too. This has been shown in many simulations [253, 304, 317, 343]. In particular, flat IMFs tend to produce higher fractions of massive stars and, hence, larger SNeII luminosities. The energy supplied by SNeII could be enough to unbind a fraction of the ISM and produce a galactic wind (see also Sect. 9).

It is important to point out that, usually, numerical simulations adopt a fixed value for the IMF upper stellar mass $m_{\rm up}$, irrespective of how much gas has been converted into stars. However, $m_{\rm up}$ should depend on the mass of the newly formed stellar particles, for the simple reason that only massive star clusters can host very massive stars. A correlation between the stellar cluster mass $M_{\rm cl}$ and the upper stellar mass is indeed observationally established and can be reproduced by simply assuming that $m_{\rm up}$ is the mass for which the IMF in number $\varphi(m)$ is equal to 1 [131]. Weidner & Kroupa [337] found that the theoretically derived $M_{\rm cl}$-$m_{\rm up}$ relation nicely reproduces the available observations (their figs. 7 and 8; see also [340]). Clearly, this assumption can greatly affect the outcomes of simulations, but, to the best of my knowledge, it has never been explored in detail in hydrodynamical simulations of galaxies.

Since a correlation between the most massive cluster in a galaxy and the SFR ψ is also observationally established [338], the logical consequence is that the galaxy-wide IMF in a galaxy must depend on the SFR, too. In particular, the IMF is time-dependent and is given by the integral of the IMFs of single star cluster, which are assumed to always be a Kroupa IMF, but with different upper masses $m_{\rm up}$, depending on the star cluster mass. An upper cluster mass limit depending on ψ is then assumed. Given a mass distribution of embedded clusters $\varphi_{\rm cl}(M_{\rm cl})$ (giving the number of star clusters in the interval $[M_{\rm cl},\ M_{\rm cl}+dM_{\rm cl}]$), the global, galactic-scale IMF (integrated galactic IMF or IGIMF) is given by:

$$\varphi_{\rm IGIMF} = \int_{M_{\rm cl,inf}}^{M_{\rm cl,sup}(\psi)} \varphi\left(m < m_{\rm up}(M_{\rm cl})\right) \varphi_{\rm cl}(M_{\rm cl}) dM_{\rm cl}, \tag{7}$$

(see [131, 220, 336] for details. Notice also that in the original papers the IMF in number is designed with ξ instead of with φ). The IGIMF turns out to be steeper than the Kroupa IMF assumed in each star cluster and the difference is particularly significant for low values of the SFR. Notice however that the IMF tends to become top-heavy when the SFR is very high [339]. The effect of the IGIMF on the chemical evolution of galaxies has been already explored in a few papers [42, 125, 220, 221]. It turns out that the IGIMF is a viable explanation of the low metallicity [125] or of the low α/Fe ratios [220] observed in DGs. The main reason is that DGs have on average lower SFRs and this, in turn, implies steeper IMFs, characterised by a lower fraction of massive stars. The production of metals and, in particular, of α-elements, is considerably reduced.

Chemo-dynamical simulations of galaxies can give a more complete picture of the evolution of DGs and of the effect of the IMF (and of the IGIMF, in particular). Fig. 1 shows the comparison of the results of two chemo-dynamical simulations, with and without adopting the IGIMF. Methods, assumptions and initial conditions are taken from [228]. In particular, the main structural properties of the shown model galaxies resemble the blue compact DG IZw 18 (see [207, 330] for a summary of observed properties of this galaxy). The SFH is shown in the upper left panel. This particular dependence of the SFR with time has been chosen again in agreement with the reconstructed SFH of IZw 18 as derived by [4] (but see [6] for a more recent determination of the SFH in IZw 18). According to this SFH, the IGIMF predicts variations of the upper stellar mass and of the average IMF slope as shown in the middle and lower panels, respectively.

The evolution of gas-phase abundances and abundance ratios in a simulation adopting these IGIMF prescriptions

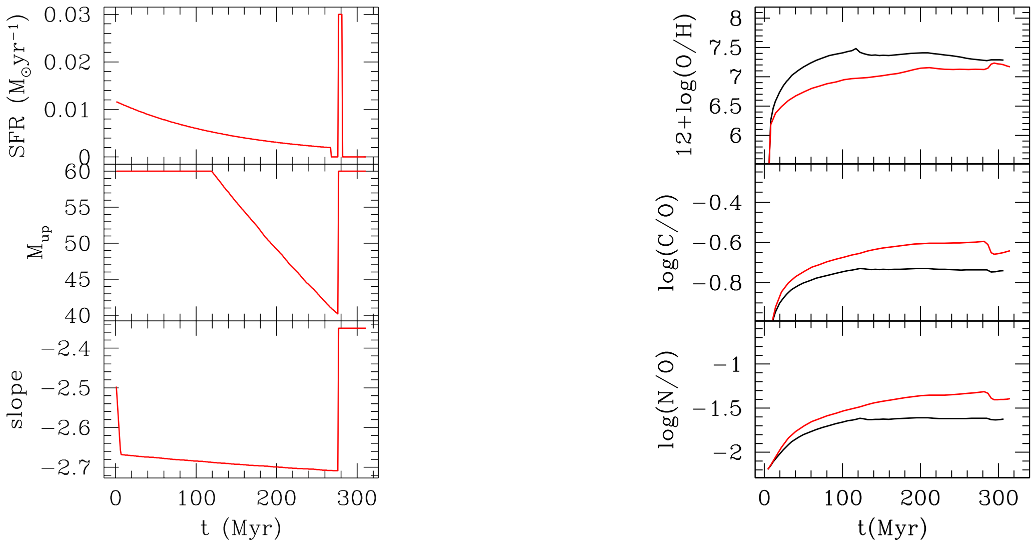

FIG. 1: The effect of the IMF on the evolution of galaxies. **left)** The adopted SFR (upper panel), together with the upper stellar mass $M_{\rm up}$ (in $M_{\odot}$, middle panel) and the average slope of the IMF (in number, lower panel) calculated for the IGIMF galactic model (red lines in the right panels). **right)** Predicted evolution of abundances and abundance ratios for a IGIMF galactic model (red lines). Plotted are the evolution of oxygen (upper panel), carbon-to-oxygen ratio (middle panel) and nitrogen-to-oxygen ratio (lower panel). The black line represents the evolution of a model with a time-independent Salpeter IMF (i.e. with a slope of -2.35).

is shown in the right panels (red lines) and compared with the results obtained with a model adopting a standard, time-independent Salpeter IMF (black lines). Since the IGIMF is steeper (and poorer in massive stars) than the Salpeter IMF, the initial phases are characterised by a lower production of oxygen and, consequently, higher values of C/O and N/O. However, due to the higher feedback, the model with Salpeter IMF experiences a galactic wind at $t \simeq 120$ Myr. Since galactic winds tend to be metal-enriched (see also Sect. 9), the onset of the galactic wind is characterised by a decrease in O/H. The galactic wind does not occur in the IGIMF run due to the reduced number of SNeII. At $t \simeq 280$ Myr a burst of star formation occurs (see upper left panel). In the Salpeter IMF run, most of the freshly produced metals are channelled out of the galaxy and do not contribute to the chemical enrichment. In the IGIMF run instead, the metals newly synthesised during the burst do contribute to the chemical enrichment and this causes a sudden increase of the oxygen abundance (and a sudden decrease of C/O and N/O). More detailed simulations, exploring wider parameter spaces, can show other effects of the IGIMF. In particular, the simulations shown in Fig. 1 assume a pre-defined SFH, but it is clear that the adoption of the IGIMF can affect the onset of the star formation, too, because it affects the energetics of the ISM. Numerical simulations of galaxies with IGIMF and with star formation recipes as described in Sect. 4 would surely predict different SFHs as compared with models with SFR-independent IMFs. This has been shown already in chemical evolution models [42] but this effect can be even more dramatic in chemo-dynamical simulations.

It is also important to point out that, in Eq. 7, only the global, galactic-scale SFR is required to calculate the IGIMF. However, the star formation process is usually very inhomogeneous within a galaxy, with regions of very enhanced star formation. Clearly, the formation of massive stars is more likely in regions of high star formation density. It is reasonable thus to expect that the IMF varies not only with time, but also with location within a galaxy. This approach has been used for instance by Pflamm-Altenburg et al. [212] to explain the cut-off in Hα radiation in the external regions of spiral galaxies (where the SFRs are milder). Observational evidence of the variation of the IMF within galaxies is given by Dutton et al. [69]. To finish, several lines of evidence point towards a dependence of the IMF on the metallicity, too [132, 168], in the sense that the IMF appears to become top-heavy in metal-poor environments. Clearly, the chemo-dynamical simulations of galaxies with spatially and temporally variable IMFs can give us new, different perspectives and insights to understand the evolution of galaxies.

6. The chemical feedback

In order to follow the chemical evolution of a galaxy, it is without any doubt important to know how stars with different masses enrich the ISM with various chemical elements. The term stellar yields is commonly used to indicate the masses of fresh elements produced and ejected by a star of initial mass m and metallicity Z. However, the term yields was originally introduced to indicate the ratio between the mass of a specific chemical element ejected by a stellar generation and the mass locked up in remnants (white dwarfs, neutron stars and black holes; see also Sect. 9).

Many groups in the past few decades calculated the stellar yields of both massive and intermediate-mass stars for different metallicities [102, 121, 151, 152, 185, 198, 217, 232, 346]. Unfortunately, except for a handful of elements whose nucleosynthesis in stars is well understood, yields of other elements calculated by different authors can vary by orders of magnitude. This is especially true for the majority of the iron-peak elements, but also for much more abundant species such as carbon and nitrogen (see the review of Nomoto et al. [198]). Of course, model predictions are significantly affected by the choice of the set of yields. This has been shown by Romano et al. [239] by means of neat and clear numerical tests (see their figs 3 and 15, for instance). One of the most significant sources of uncertainty in the calculation of stellar yields is the presence of stellar mass loss. Massive stars with solar metallicity might in fact lose a large amount of matter rich of He and C, thus subtracting those elements to further processing, which would eventually lead to the production of oxygen and other heavy elements. The models of Maeder [162] for instance predict that a 40 $M_\odot$ star ejects only ~ 2 $M_\odot$ of O, whereas in most of nucleosynthetic calculations without winds [151, 219, 346] the production of oxygen is a factor of ~ 3 larger.

The yields from dying stars not only directly affect the chemical composition of the ISM in chemo-dynamical evolution of galaxies, but can also affect the dynamics by means of chemical feedback. The main effect is due to cooling. In fact, it is known that the cooling function of an optically thin plasma has a strong dependence on metallicity, at least in the temperature range between $\sim 10^4$ and 10^5 K [23, 258, 296]. Moreover, different chemical elements contribute differently to the plasma radiative emission. Clearly, the assumption of different yields in chemo-dynamical models affects the chemical composition of the ISM, which in turn changes the cooling timescales. An example of the effect of different sets of yields on the dynamical evolution of galaxies is given in Fig. 2. Two models of galaxy evolution (taken from the suite of simulations of Recchi et al. [230]) differ only in the adopted nucleosynthetic prescriptions for intermediate-mass stars: [185] (MM02) on the left panels and [102] (VG97) on the right panels. Yields of high-mass stars are in both cases taken from [346]. Feedback from SNeII and stellar winds creates a network of cavities and tunnels. The superbubble evolution is faster in the MM02 model. Indeed, MM02 produces on average more metals, therefore leading to larger cooling rates. On the one hand, it reduces the thermal energy content inside the superbubble, but on the other hand this increased cooling favours the process of star formation, leading to a more powerful feedback. The latter effect prevails, and a larger energy is available in model MM02 to drive the expansion of the supershell. Within the timespan of 100 Myr covered by these two simulations, the differences between the two models are not huge. They are, however, non-negligible and they tend to increase with time. This simple test shows the effect of chemical feedback on the evolution of a galaxy, an aspect that has been often overlooked in the literature.

One should also be aware that other forms of chemical feedback operate in galaxies. The photoelectric emission from small dust grains and PAHs can substantially contribute to the heating of the ISM [9]. The amount of dust and PAH in a galaxy strongly correlates with its metallicity [154] and, consequently, the metallicity affects the photoelectric heating of the gas. It is commonly assumed that for ISM metallicities below $Z_{\rm cr} \sim 10^{-5}$ $Z_\odot$, the star formation process is substantially different and leads to a top-heavy IMF producing, on average, very massive stars, the so-called PopIII stars [255]. As the ISM metallicity approaches $Z_{\rm cr}$, the transition to a Salpeter-like IMF occurs.

Under some circumstances, chemical reactions can affect the chemical evolution, as well. Astrochemistry is a vibrant and very active astrophysical discipline [68, 311] and nowadays the details of many important atomic and molecular reactions occurring in the ISM are known. Although the chemistry of the dense gas in clouds is very rich and variegate, less happens in the more dilute diffuse gas. Global, galactic-scale simulations usually do not require the implementation of complicated reaction networks. However, the presence of dust can significantly affect the chemical evolution. It is in fact well known that a large fraction of some chemical elements (particularly Fe, Co, Ni, Ca, C and Si) is locked into dust grains [244]. Clearly, it is impossible to have a complete picture of the evolution of these chemical elements in the ISM without considering the dust. There have been several works about the chemical evolution of galaxies with dust [41, 70, 214, 348, 349]. It is more complicated to include dust into chemo-dynamical simulations of galaxies. On the one hand, still not much is known about the sources and composition of interstellar dust [311]. On the other hand, the physics of the dust-gas coupling is still poorly known and typically assumed drag forces lead to numerical problems [189]. In spite of these difficulties, progresses have been made and simulations of

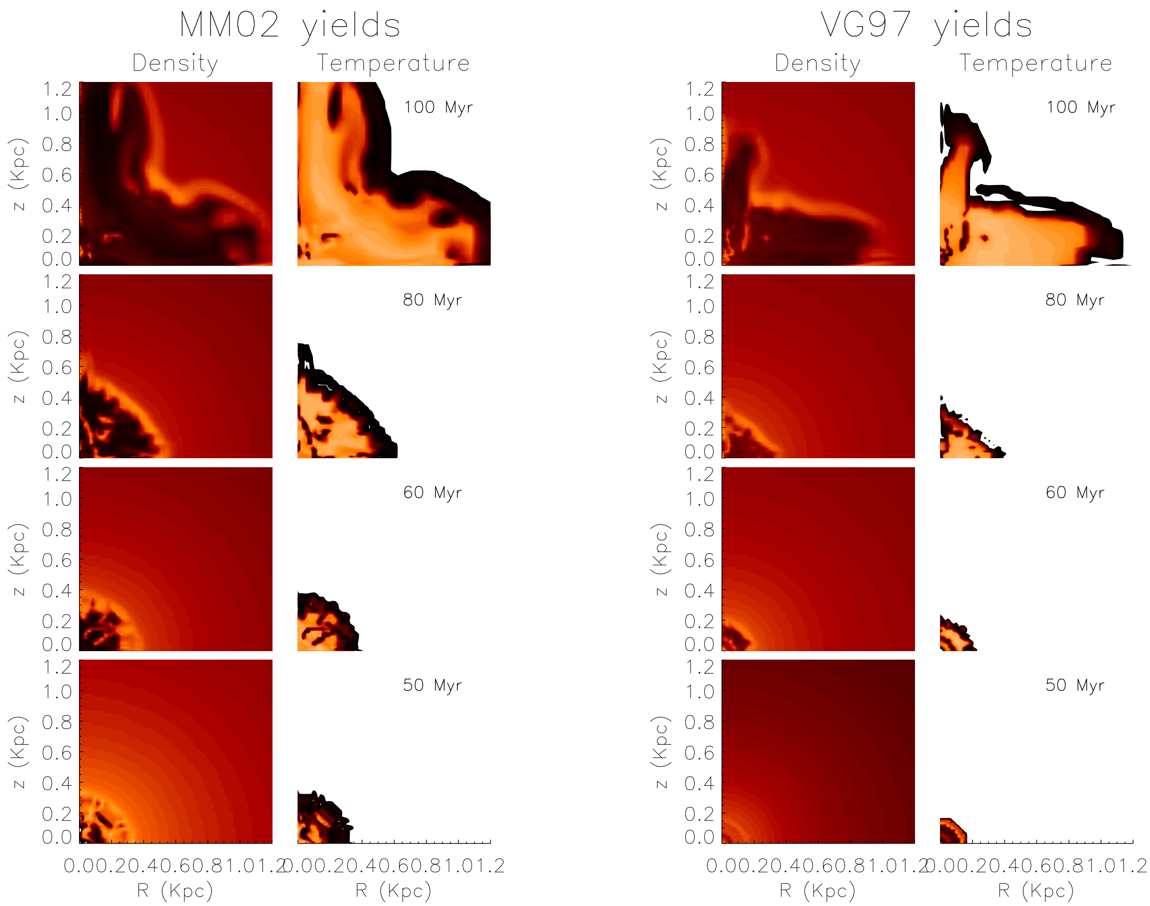

FIG. 2: Density and temperature contours at 4 evolutionary times (labelled on each of the right panels) for a model adopting MM02 (left) and VG97 (right) yields, respectively. The (logarithmic) density scale (in g cm^{-3}) ranges between -27 (dark) and -23 (bright). The (logarithmic) temperature scale (in K) ranges between 3 and 7.

galaxies taking into account dust are becoming available [141, 308]. Clearly, this is a field where more needs to be done. Observations of dust in our own Galaxy and in external galaxies are becoming extremely accurate and the astronomical community is in dire need of detailed chemo-dynamical simulations of dusty gases in order to help interpreting the observations.

7. The mechanical feedback

Explosions of SNe (of both Type Ia and II) and stellar winds are the main drivers of the ISM dynamics, at least in DGs (in larger galaxies, AGNs might play a fundamental role). Unfortunately, for the foreseeable future, galactic-scale simulations will not be able to solve individual SN remnants or the effect of the wind from individual stars. Hence, heuristic, sub-grid recipes are needed to treat the mechanical feedback. This is a complex and still active research field. Although feedback prescriptions have been found to address specific issues [54, 89], no recipe appears to be widely applicable and physically justifiable. Comparison studies have been performed [116, 249, 300], and the overall conclusion (see in particular the Aquila comparison project, [249]) is that the outcomes of numerical simulations crucially depend on the feedback prescriptions and none of the considered codes is able to satisfactorily reproduce the observed properties of the baryonic component of galaxies.

Broadly speaking, feedback schemes can be divided into two categories: kinetic feedback [3, 52, 283] and thermal feedback [191, 230, 269, 288]. Kinetic feedback schemes are mostly used in SPH simulations (but see [67]). The SN explosion energy is transformed into kinetic energy of neighbouring particles. A kick is given to a few neighbouring particles, which move after the kick with a prescribed velocity, along a random direction. The problem with this scheme is that it is not physically justifiable and it is not easy to create galactic winds, unless kick velocities are chosen along prescribed directions.

In thermal feedback schemes instead, the SN energy is used up to heat the ISM. A well-known drawback of this scheme is that the cooling timescale of the particles affected by this thermal feedback is typically very short (often shorter than the timesteps of the simulation). The input energy is thus radiated away before it can be converted to kinetic energy. This leads to the so-called overvcooling problem [111]. Various authors have tried to remedy to this problem by simply switching off the cooling [230, 274, 288]. The inefficiency of thermal feedback is usually attributed to poor spatial resolution: the energy is deposited in gas that is too dense, because the hot, low-density, bubbles that fill much of the volume of the multi-phase ISM are missing. In fact, in models in which the multi-phase description of the ISM is taken into account a decoupling of the different thermal phases can be realized (some times arbitrarily) and the overcooling problem can be avoided [195, 248].

Another possibility to overcome the overcooling problem is the use of radiative feedback schemes [101]. Eventually, also cosmic rays have been suggested as an additional source of feedback [26, 65, 106]. Also a correct inclusion of stellar dynamics can be a way to avoid the overcooling problem (see Sect. 3). A much broader discussion would deserve the description of the feedback from the central AGN. This kind of feedback has gained popularity in the last decade. It appears in fact to be a useful recipe to use in semi-analytical models of structure formation [51]. However, it is not clear how significant the AGN feedback can be for the evolution of low-mass galaxies. Scaling relations [77, 181] indicate that DGs possess very small central massive black holes. It is very likely that all these forms of feedback occur in real galaxies. However, before implementing them in simulations, one should be confident that the underlying physics is well understood and that reasonable parametrisations can be used.

Although feedback schemes are widely debated in the literature, less problematic appears to be the amount of energy a SN explosion deposits into the ISM. A value of 10^{51} erg is assumed as it represents the typical SN explosion energy $E_{\rm SN}$ [53, 293]. It is however worth reminding that SN kinetic explosion energies (theoretically calculated or deduced from observations) cover a very broad range, from a few 10^{48} ergs of the faintest SNe to the 10^{52} ergs or more of the hypernovae [199].

Some authors adopt a thermalization efficiency $\epsilon_{\rm SN}$, in order to account for the radiative energy losses during the early phases of the evolution of a SN remnant. A commonly adopted value of $\epsilon_{\rm SN}$ is 0.1 [243]. Indeed, the simulations of Thornton et al. [310] suggest that only $\sim 10\%$ of the SN explosion energy can be used up to thermalize the ISM. However, detailed simulations of the impact of isolated stars on the ISM [81, 96, 127] show that the energy transfer efficiency can be even lower than 1%. A different approach, where the contribution of a whole population of stars is considered [183] clearly shows that $\epsilon_{\rm SN}$ must be a function of time. During the early phases of galactic evolution, the SN remnants expand in a very dense and cold ISM. SN remnants evolve in isolation and radiative losses are very large. Only a small fraction of the SN explosion energy goes to increase the thermal budget of the ISM. When the ISM becomes hotter and more porous, radiative losses are less significant. Various SN remnants quickly coalesce and form a superbubble. Within this superbubble, the sound speed is large. If a SN explodes inside the superbubble, the time it takes for the SN shock velocity to become equal to the sound speed is very short. This is the time at which the shock loses its identity and the energy of the SN remnant can be transfered to the ISM. Clearly, in this situation the SN remnant does not have time to radiate away a large fraction its energy, which can be thus efficiently converted into thermal energy of the ISM once the SN shock velocity becomes equal to the local sound speed.

Simple analytical estimates of the thermalization efficiency as a function of the ambient density and temperature are possible [31, 146, 226, 279, 292]. Again, these formulae show that $\epsilon_{\rm SN}$ is strongly reduced if the ambient density is large and the temperature is low. A more quantitative evaluation of $\epsilon_{\rm SN}$ for a single, isolated galaxy can be obtained as follows. The stalling radius R_s is defined as the radius at which the expansion velocity of the SN shock equals the local sound speed. At this radius, the material inside the SN shock can be causally connected with the external ISM and a transfer of energy can occur. R_s can be evaluated as [47]:

$$R_s \simeq 4.93 R_{\rm pds} \left(\frac{E_{\rm SN}^{1/14} n_0^{1/7} Z^{3/14}}{c_s} \right)^{3/7}. \tag{8}$$

Here, the SN explosion energy is expressed in units of 10^{51} ergs, the ambient density n_0 in cm^{-3}, the metallicity Z in units of the solar metallicity and the sound speed c_s in units of 10^6 cm s^{-1}. $R_{\rm pds}$ is the radius of the SN shock at the moment in which cooling becomes important. Assuming that most of the SN energy at this stage is in the form of kinetic energy of the shell the energy available to thermalize the ISM is:

$$E_{\rm kin} = \frac{2}{3} \pi R_s^3 \rho_0 c_s^2. \tag{9}$$

The thermalization efficiency is now simply the ratio between this residual energy and the initial explosion energy $E_{\rm SN}$. Using the value of $R_{\rm pds}$ given by [47], one obtains:

$$\epsilon_{\rm SN} \simeq 0.02 E_{\rm SN}^{-5/98} n_0^{-54/49} Z^{-15/98} c_s^{5/7}. \tag{10}$$

This calculation is surely approximate. In particular, the ISM porosity and the possibility that various SN remnants merge have not been taken into account. However, additional corrections could be included and a more physically motivated description of the thermalization efficiency, depending on the local thermodynamical conditions, could be obtained.

Eventually, the expansion of ionisation fronts could be taken into account, as well. Simple formulae could be devised to describe the variation of the Strömgren radius surrounding a single massive star or an association of stars [143, 280]. Within this radius the cooling is indeed strongly suppressed because Ly continuum photons are used up on the spot to ionise hydrogen atoms and only photons from the Balmer series onwards can leave the H II region. Combining these formulae with the formulae describing the evolution of SN shocks and winds from massive stars seems to be theoretically possible. This method is perhaps a viable solution of the overcooling problem. Of course, once radiative hydrodynamical codes will have enough resolution to solve individual H II regions and SNeII remnants, these analytical considerations will be superfluous. However, this seems not to be possible in the foreseeable future.

To finish this section, it is important to remind that the rate of energy release from SNe and stellar winds is as important in galaxy simulations as the way this energy is converted into ISM energy. It is commonly assumed that all the stars with masses larger than a certain threshold mass $m_{\rm thr}$ explode as SNeII at the end of their lifetimes. This assumption, together with prescribed stellar lifetime functions, makes the calculation of SNII rates quite straightforward. Two sources of uncertainty must be outlined. One is the stellar lifetime function, which is still quite uncertain and model-dependent. Romano et al. [238] demonstrated however that uncertainties in the lifetimes of massive stars are not so significant and do not crucially affect the results of galaxy evolution models. More critical is the choice of $m_{\rm thr}$. A commonly adopted value is 8 $M_\odot$ but, since there is still not much known about the fate of stars in the mass interval [8:12] $M_\odot$, $m_{\rm thr}$ could be as high as 12 $M_\odot$. For a Salpeter IMF extending until 100 $M_\odot$, $\sim$ 78 % more SNeII go off if $m_{\rm thr} = 8$ $M_\odot$ instead of $m_{\rm thr} = 12$ $M_\odot$. Clearly, this is a non-negligible fraction.

Even more uncertain and less standardised are the feedback recipes from stellar winds and Type Ia SNe (SNeIa). Many authors even neglect these energy contributions. However, the energetic input of stellar winds is very important to establish self-regulation in the star formation process (Köppen et al. [124], see also Sect. 4). Many authors take into account stellar winds, either adopting suitable parametrisations based on observations [307], or adopting the results of models such as Starburst99 [148], which give the mechanical energy from stellar winds released by a single stellar population or due to a continuous episode of star formation. This approach has been followed, for instance, by [230, 293]. Since the stellar wind luminosity decreases with metallicity [139, 142], neglecting stellar winds is perhaps acceptable in simulations of very metal-poor DGs.

Type Ia SNe play a very important role in the evolution of galaxies, as they are the major contributors of iron, a widely used metallicity proxy [174]. Since the lifetime of SNeIa progenitors can be as long as many Gyrs [335], they represent a source of energy more evenly distributed in time than SNeII. The relevance of SNeIa for the dynamical evolution of galaxies has been shown for instance by Recchi & Hensler [222]. Many papers neglect the contribution of SNeIa as they are interested in the early evolution of galaxies and SNeIa are not assumed to occur on short timescales [159]. However, evidence is mounting [163, 177, 178, 250] that a significant fraction of SNeIa explode on timescales shorter than 100 Myr. Thus, SNeIa should be considered in chemo-dynamical models even if the time-span of the simulation is of the order of 100 Myr.

A convenient parametrisation of the SNeIa rate is [90, 240]:

$$R_{Ia}(t) = \int_{t_{\rm min}}^{t} A_{Ia}(t-\tau) D(t-\tau) \psi(\tau) d\tau, \qquad (11)$$

where $t_{\rm min}$ is a suitably chosen minimum timescale for the occurrence of SNeIa (typically 30 Myr), A_{Ia} is a normalisation constant and D is the so-called delay time distribution (DTD), i.e. the distribution of time intervals between the birth of the progenitor system (usually a binary system made of two intermediate-mass stars) and the SNIa explosion. According to Eq. 11, the DTD is thus proportional to the SNIa rate following an instantaneous burst of star formation. Unfortunately, the form of the DTD is still very uncertain, although some observations [164, 319] suggest the DTD to be inversely proportional to the elapsed time, i.e. $D(t) \propto t^{-1}$. Studies of the chemical evolution of galaxies have been performed [24, 176, 178], showing that the adoption of different DTDs drastically changes the outcome of the simulations. It is not difficult to imagine that even more drastic differences could be obtained in chemo-dynamical simulations of galaxies. The role of various DTDs on the evolution of galaxies is another aspect that has been barely considered so far in chemo-dynamical simulations and that, perhaps, deserves more attention.

8. Environmental effects

Galaxies are sociable entities; galaxies out there on their own are quite rare. Most of them are found in galaxy clusters and groups. In order to fully understand the evolution of galaxies, the study of the galactic environment is thus paramount. The environment not only includes neighbouring galaxies, but also the tenuous gas between galaxies (the intergalactic medium, IGM, or intra-cluster medium, ICM in cluster environments). There are many reasons why the study of galaxy interactions and mergers is very important for our understanding of the Universe as a whole. Perhaps one of the most important ones is that the largely accepted cosmological model, a Λ dominated Cold Dark Matter based Universe, explicitly predicts that galaxies should form hierarchically in the merger process. However, the theoretical study of interactions and mergers is usually the realm of cosmological simulations and I refer the readers to the many books and review papers devoted to the argument [14, 28, 48, 80, 272, 294].

One of the clearest evidences of the environmental effects is the morphology-density relation [66], according to which the fraction of early-type galaxies in clusters increases with the local density of the environment. Another key observational result is the star formation-density relation [10, 299], in the sense that star formation seems to be strongly reduced in dense environments. Moreover, cluster galaxies are H I deficient compared to their field counterparts. The deficiency increases towards the cluster centre. These and other observational facts (see also [27, 105] for reviews) clearly indicate that one or more processes in cluster and group environments remove gas from galaxies or make them consume their gas more quickly. One possibility is that the dense environment promotes tidal interactions (galaxy-galaxy or galaxy-cluster). It has been shown that these interactions can remove matter from galactic halos quite efficiently [40, 184, 281, 325]. Another possible physical mechanism able to remove gas in dense environment is the combined effect of multiple high-speed encounters with the interaction of the potential of the cluster as a whole, a process that has been named "harassment" [192, 193].

By combining different processes, Boselli & Gavazzi [27] concluded that the most probable mechanism able to explain the observational differences between galaxies in clusters and in the field is ram-pressure stripping, namely the kinetic pressure that the ICM exerts on the moving galaxies. If the ram-pressure is larger than the restoring gravitational force (per unit surface) acting on a gas parcel of a galaxy moving through the ICM, this gas parcel is stripped off the galaxy [93]. There have been many simulations exploring the effect of ram-pressure stripping, with different settings and degrees of sophistication [1, 75, 128, 180, 215, 236, 237, 257, 273]. There are many indications that ram-pressure stripping is a key process, able to radically modify the evolution of DGs. Many authors even put forward the idea that ram-pressure stripping can convert gas-rich DGs into gas-poor ones. These ideas are comprehensively summarised in many excellent reviews [97, 179, 267, 268] and I refer the reader to these reviews for further details.

For the purposes of this review paper, it is more convenient to briefly summarise the results of the simulations of Marcolini and collaborators [165, 166]. These authors performed simulation of flattened, rotating DGs subject to ram-pressures typical of poor galaxy groups. Interestingly, despite the low values of the ram-pressure, some DGs can be completely stripped after 100-200 Myr. However, regions of very large surface density can be found at the front side of DGs experiencing ram-pressure stripping. This enhanced density can easily lead to a burst of star formation. If the DG experiences a galactic wind (see also Sect. 9), several parameters regulate the gas ejection process, such as the original distribution of the ISM and the geometry of the IGM-galaxy interaction. Contrary to the ISM content, the amount of the metal-rich ejecta retained by the galaxy is more sensitive to the ram-pressure action. Part of the ejecta is first trapped in a low-density, extraplanar gas produced by the IGM-ISM interaction, and then pushed back on to the galactic disc. Clearly, the interplay between galactic winds and environment is quite complex and very few studies address this issue in detail (see however [254]). This is another research field in which, in my opinion, more can be done. In particular, results of small-scale detailed simulations of individual galaxies could be used in large-scale simulations of galaxy clusters and groups, where the interaction processes between individual galaxies and the ICM cannot be appropriately resolved. This is for instance the approach followed by Creasey et al. [50], who simulate the feedback effect of SNe in a single galaxy in order to improve sub-grid models of feedback in large-scale simulations. This approach should perhaps be further extended. Also simulations like the ones of Marcolini et al. (or similar "wind tunnel" experiments) could be used to better constrain the galactic wind-ICM interactions and improve galactic cluster-scale simulations.

9. Galactic winds

Galactic winds are streams of high speed particles often observed blowing out of galaxies. They are also thought to be the primary mechanism by which energy and metals are deposited into the intracluster and intergalactic medium (see also Sect. 8). Local example of galactic winds are NGC1569 [341], NGC253 [172], NGC6810 [291] and, of course, the archetypal galactic wind in M82 [49]. There is clear evidence for galactic winds in the spectra of several z > 1 galaxies [156]. Probably, the fraction of galaxies experiencing galactic winds was larger at high redshifts [158, 210, 211]. A review of many observational (and theoretical) aspects of galactic winds is given in Veilleux et al. [329].

The mechanical feedback from SNe and stellar winds is the most probable driver of galactic winds in DGs, although other (perhaps accompanying) mechanisms, such as radiation pressure and cosmic rays, are possible and have been put forward [35, 65, 197, 260, 323]. There is a large (and ever growing) number of hydrodynamical simulations of galactic winds in the literature [12, 101, 241, 323]. Many of them, especially in the past, targeted specifically dwarf galaxy-sized objects [58–60, 159, 194, 261]. A quite common outcome of these simulations is that the energy deposited by SNe and stellar winds creates large bubbles of hot, highly pressurised gas. This gas pushes the surrounding ISM and, under favourable conditions, a large-scale outflow can emerge. If the outflow velocity is large enough, the gas entrained in it leaves the parent galaxy. A galactic wind has been created. If instead the wind velocity is not high enough, the gravitational pull eventually prevails and a galactic fountain is formed instead. Galactic fountains are more likely in large spiral galaxies like our own Milky Way and have been also extensively studied in the past [18, 34, 182, 277, 303]. Given the more reduced gravitational pull, galactic winds are more likely than galactic fountains in DGs. The threshold velocity for the formation of a galactic wind is typically set equal to the escape velocity. However, one should be aware that the motion of gas parcels in galactic winds is not ballistic and the escape velocity can give only an order-of-magnitude estimate of the velocity required to escape the galactic potential well.

Many authors [56, 145, 324] have speculated that, since the binding energy of typical DGs is equal to the explosion energy of just a few SNe, galactic winds can occur very early in DGs and can even lead to a quick transition from gas-rich to gas-poor DGs. However, there are three clear failings of this scenario: (*i*) it fails to explain the observed morphology-density correlation (see Sect. 8), (*ii*) it fails to explain the fact that all observed gas-poor DGs of the Local Group possess a large fraction of intermediate-mass stars (see [171, 313] for reviews on stellar populations of Local Group DGs), (*iii*) if the galactic wind occurs very early, Type Ia SNe do not have time to enrich the ISM (see Sect. 8). Since Type Ia SNe are the major sources of iron, one would expect very high [α/Fe] ratios in the stars of DGs. Exactly the contrary is observed: stellar populations in DGs are characterised by very low [α/Fe] ratios [309, 313]. Indeed, many simulations of the development of galactic winds in DGs cited above agree on the fact that the fraction of ISM ejected out of a galaxy as a consequence of a galactic wind must be low. An excellent and still very relevant review about the effect of galactic winds in DGs is given by Skillman [266].

However, hydrodynamical simulations of DGs showed that the galactic winds are often able to expel a large fraction of metals, freshly produced during the star formation activity. This is mostly due to the fact that, if the initial DG gas distribution is flattened (as observed in gas-rich DGs), the galactic wind will preferentially expand along a direction perpendicular to the disk (the direction of the steepest pressure gradient, see also below). Most of the disk gas is not affected by the galactic wind. On the other hand, the freshly produced metals can be easily channelled along the funnel created by the galactic wind. Several papers in the literature have attempted to quantitatively address this point and study the effect of galactic winds on the circulation and redistribution of metals in DGs. The main results of the often-cited work MacLow & Ferrara [159] are that, even in the presence of a strong galactic wind driven by SNeII, the ejection efficiency of unprocessed gas is almost always close to zero. It is different from zero only for the smallest considered galaxies (due to their very shallow potential well). On the other hand, the ejection efficiency of freshly produced heavy elements is almost always close to one. Silich & Tenorio-Tagle [261] found instead that galactic winds do not develop in most of the models, mainly due to the presence of a hot gaseous halo surrounding the galaxy. The effect of off-centred SN explosions and SN explosions distributed over most of the disk was also studied in the literature [79]. Metal ejection efficiencies are reduced in this case, due to more efficient cooling. Wind efficiencies are found to be low even if SN is injected directly into supersonic turbulence [252].

The ejection efficiencies of individual chemical elements was investigated, too [226]. As a consequence of very short starbursts, galactic-scale outflows carry out of the galaxy mostly the chemical elements produced by dying stars during the most recent episodes of SF, with large escape fraction of metals with delayed production, like Fe and N (see also [322]). In fact, a significant fraction of α-elements, quickly produced by SNeII, mix locally before the development of a galactic wind (see also [234]). Metals produced by SNeIa and intermediate-mass stars can be instead easily channelled along the already-formed galactic wind and do not suffer much mixing with the walls of the wind. The situation is much less clear-cut in the presence of multiple bursts of star formation [227] or of complex SFHs [228]. One should be aware of the fact that turbulence can play a decisive role in the process of mixing metals, a mechanism usually called turbulent mixing [62]. However, it is a considerable experimental, theoretical, modelling, and computational challenge to capture and represent turbulent mixing and not much has been done in this direction for astrophysical flows (but see [11, 204, 205]).

An estimate of the probability of the development of a galactic wind can be obtained as follows (see [76, 161, 226]). Take for simplicity a source of energy producing a constant luminosity L. Assume also that the density and the metallicity of the ISM is uniform and that its vertical density distribution has a scale height H. The energy input creates a superbubble which is assumed to be spherical and characterised by a radius R. By means of standard, textbook formulas for the evolution of a superbubble without radiative losses (i.e. $R \sim t^{-3/5}$), the time for the radius R of the superbubble to reach H is readily calculated:

$$t_{\mathrm{D}} \sim H^{5/3} \left(\frac{\rho}{L}\right)^{1/3}. \tag{12}$$

However, radiative losses, in general, can not be neglected. The radiative losses of the hot cavity can be more relevant for the dynamics of the superbubble than the radiative losses of the shocked material. The cooling timescale of the superbubble can be estimated as:

$$t_{\rm c} \sim 16(\beta Z)^{-35/22} L^{3/11} n^{-8/11}\ {\rm Myr}, \qquad (13)$$

where L in this formula is in units of 10^{38} erg s^{-1} and n in cm^{-3}. Here, β is a numerical factor (of the order of unity) that takes into account the fact that the cooling gas might be out of ionisation equilibrium. Clearly, if $t_{\rm c}$ is much shorter than $t_{\rm D}$, the superbubble loses much of its pressure before the supershell can reach H and a large-scale outflow can not occur. By combining Eqs. 12 and 13 one obtains an approximate criterion for the occurrence of a galactic wind, namely:

$$L \gg 0.03 n^{7/4} (\beta Z)^{21/8} H^{11/4}. \qquad (14)$$

Although this derivation is quite approximate, the large dependence of the threshold luminosity on H is a solid result. The vertical distribution of gas strongly affects the development of a galactic wind (more than other factors). A galaxy characterised by a very thin disk experiences outflows much more easily than a roundish galaxy. This result matches the physical intuition that in flat galaxies a large-scale outflows easily develops along the direction of steepest pressure gradient (i.e. perpendicularly to the disk), whereas in spherical galaxies the pressure gradient is isotropic and either the outflows occurs along all directions, or the superbubble remains confined inside the galaxy. Indeed, simulations of spherical (or almost spherical) DGs have shown that it is not easy to create galactic winds, even if the energy input is significant [167] or the galaxy does not have a dark matter halo [99, 230]. Although the importance of the disk thickness for the development of outflows was soon recognised, this aspect has not been fully explored in the past in numerical investigation (but see [186, 224, 256, 262, 293, 327]).

In Recchi & Hensler [223] we specifically addressed the role of gas distribution on the development of galactic winds and on the fate of freshly produced metals. We found that the gas distribution can change the fraction of lost metals through galactic winds by up to one order of magnitude. In particular, disk-like galaxies tend to lose metals more easily than roundish ones. In fact, the latter often do not develop galactic winds at all and, hence, they retain all the freshly produced metals. Consequently, the final metallicities attained by models with the same mass but with different gas distributions can also vary by up to one dex.

Confirming previous studies, we also show that the fate of gas and freshly produced metals strongly depends on the mass of the galaxy. Smaller galaxies (with shallower potential wells) more easily develop large-scale outflows, so that the fraction of lost metals tends to be higher. An example of the results of these investigations is given in Fig. 3. The gas density distribution for nine galaxy models differing on the degree of flattening and the initial baryonic mass, after 100 Myr of galactic evolution is shown in this figure (see figure caption for more details). The effect of geometry on the development of galactic winds is clear from this figure: the density distribution in the models in the bottom row (flat models) is clearly elongated. In one case a galactic wind is already blowing. The models in the upper row are instead still roundish. Clearly, as described before, if a large-scale outflow is formed, freshly produced metals can be easily lost from the galaxy. Any time a galactic wind is formed, the ejection efficiency of metals is larger (some times much larger) than the ejection efficiency of the ISM, confirming that galactic winds must be metal-enhanced. The fact that galactic winds are metal-richer than the global ISM has been observationally verified [170, 201].

The fact that the galactic winds are metal-enriched is a commonly accepted result. It has been proposed as one of the main mechanisms leading to the so-called mass-metallicity relation, according to which the metallicity of a galaxy grows with its mass. Since galactic winds are metal-enhanced and since DGs experience more easily galactic winds, clearly one has to expect that DGs are metal-poorer than larger galaxies [276, 320]. Although the effect of metal-enriched galactic winds on the chemical evolution of galaxies might be already clear from the previous paragraphs, a more quantitative analysis can be performed, based on simple analytical considerations. Assuming linear flows, i.e. assuming that infall rates and outflow rates in and out of galaxies are proportional to the SFR ψ, a set of differential equations can be found for the time evolution of the total baryonic mass M_t, total gas mass M_g and total mass in metals M_Z within a galaxy (see [173, 229]):

$$\begin{cases} \frac{dM_t}{dt} = (\Lambda - \lambda)(1-R)\psi(t) \\ \frac{dM_g}{dt} = (\Lambda - \lambda - 1)(1-R)\psi(t) \\ \frac{dM_Z}{dt} = (1-R)\psi(t)[\Lambda Z_A + y_Z - (\lambda\alpha + 1)Z] \end{cases} \qquad (15)$$

Here, Λ and λ are proportionality constants relating the SFR to the infall and outflow rate, respectively. Z_A is the metallicity of the infalling material and R is the fraction of the considered stellar populations locked into long-living stars and remnants. y_Z is the stellar yield, in this case defined as the ratio between the mass of a specific chemical element ejected by a stellar generation and the mass locked up in remnants ([312], see also Sect. 6). Finally, α is the parameter that takes into account metal-enriched galactic winds, i.e. is the increase of metallicity of the wind compared to the ISM. Besides this last factor, the equations are standard, textbook equations for the simple-model evolution of a galaxy [174, 203, 312] and analytical solutions can be found. An analytical solution can be found even including this further factor α (see Recchi et al. [229], eq. 12). If one assumes that the

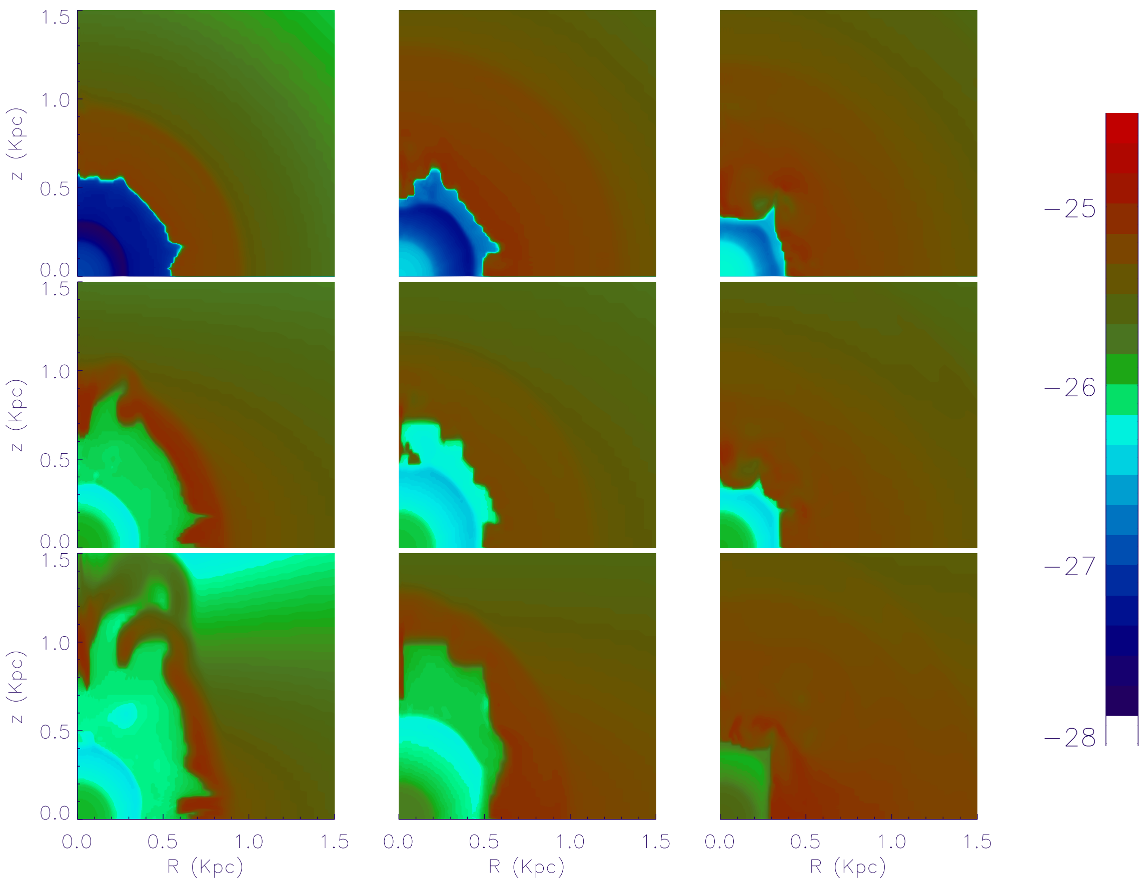

FIG. 3: Gas density distribution for nine galaxy models differing on the degree of flattening and the initial baryonic mass, after 100 Myr of galactic evolution. The first column represents models with 10^7 $M_\odot$ of initial baryonic mass, the middle column shows the gas distribution for models with mass 10^8 $M_\odot$, and the right-hand column displays the models with 10^9 $M_\odot$. The top rows of models are characterised by a roundish initial distribution. The middle rows show models with an intermediate degree of flattening, and the bottom rows are characterised by a flat initial distribution. The left-hand strip shows the (logarithmic) density scale (in g cm^{-3}).

SFR ψ is proportional to the total gas mass M_g through a proportionality constant S (see Sect. 4), the final result is:

$$\frac{Z(t)}{y_Z + \Lambda Z_A} = \frac{1 - \left[(\Lambda - \lambda + 1) - (\Lambda - \lambda)e^{h(t)}\right]^{\frac{\Lambda + (\alpha-1)\lambda}{\Lambda - \lambda - 1}}}{\Lambda + (\alpha - 1)\lambda}$$
$$h(t) = (\lambda + 1 - \Lambda)(1 - R)St. \qquad (16)$$

This solution has been plotted in Fig. 4 for $\Lambda = 0$, $\lambda = 2$, $S = 1$ Gyr^{-1} and $R = 0.26$ (from [346]). The strong effect of α (a factor of ~ 20) on the final metallicity of the galaxy is evident from this figure. Clearly, this kind of modelling can only give an approximate idea about the chemical evolution of galaxies and that full chemo-dynamical simulations are required for a deeper insight and understanding of the metal enrichment process. However, this kind of analytical calculations are nowadays quite popular, as they enlighten in a simple way complex correlations among galaxies [55, 150, 276].

10. Conclusions and outlook

In this review I presented a summary of the state-of-the-art for what concerns the chemo-dynamical modelling of galaxies in general and of dwarf galaxies in particular. I have devoted one Section for each of the main ingredients of a realistic simulation of a galaxy, namely: (*i*) initial conditions (Sect. 2); (*ii*) the equations to solve (Sect. 3); (*iii*) the star formation process (Sect. 4); (*iv*) the initial mass function (Sect. 5); (*v*) the chemical feedback (Sect. 6); (*vi*) the mechanical feedback (Sect. 7); (*vii*) the environmental effects (Sect. 8). In each section, commonly adopted methodologies and recipes have been introduced and some key results of past or ongoing studies have been summarised. Moreover, some key results concerning the development of galactic winds and the fate of heavy elements, freshly synthesised after an episode of star formation, have been summarised in Sect. 9.

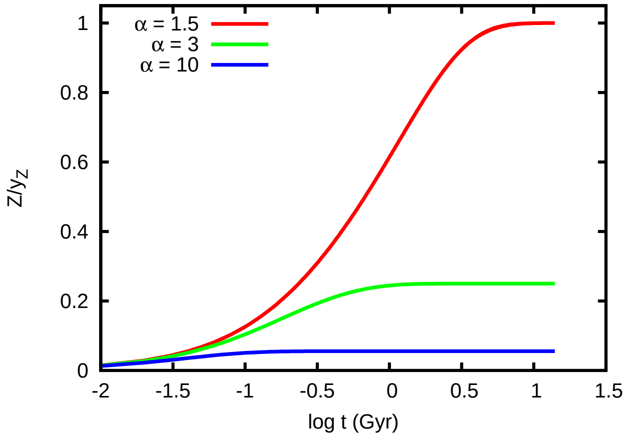

FIG. 4: The metallicity of a galaxy, as a function of time, for models with metal-enriched galactic winds. This plot shows the solution of Eq. 16 for three different values for the enrichment parameter α.

Throughout this review, I outlined topics, physical processes and ingredients that in my opinion are not properly or adequately treated in modern simulations of galaxy evolution. I summarise below the topics that in my opinion deserve more attention:

- **Inclusion of self-gravity** in building initial equilibrium configurations. This is clearly an important step towards building more realistic initial configurations and, as described in Sect. 2, the difference between models with and without self-gravity can be extremely large. Of course, taking self-gravity into account in building initial equilibrium configurations is computationally demanding. However, it is clearly a necessary step in simulations in which the star formation process is treated in detail, as the gas self-gravity is the main driver of the star formation process. Of course, galactic simulations in a cosmological context do not need any special recipe to build initial configurations.

- **Inclusion of turbulence** in galactic simulations. There is no doubt that the gas in galaxies is turbulent, therefore it is necessary to devote more efforts to a proper modelling of (compressive) turbulence in galaxies. As mentioned in Sect. 7, turbulence is also a key ingredient to study the process of circulation and mixing of heavy elements in galaxies; it thus helps to interpret more properly observational data, such as the ones obtained by means of integral field spectroscopy. As reported in Sect. 3, some galactic simulations with a proper treatment of turbulence have been already performed. However, in these simulations chemistry is usually treated in a very crude and approximate way. The inclusion in these simulations of methods and recipes about the production and circulation of heavy metals adopted in other chemodynamical simulations, appears to be feasible. Moreover, some of the assumptions and equations used to simulate turbulence in the ISM are based on experimental results on incompressible turbulence. A more focused study of physical processes and modelling of compressible turbulence in the ISM is arguable and I am sure that in the next years we will experience great progresses in this field.

- **A multi-phase, multi-fluid treatment of the ISM** in galaxy simulations. Realistic simulations of galaxies should take into account the multiphase nature of the ISM in galaxies and the complex network of reactions between stars and various gas phases. This has been done in some simulations, particularly thanks to the work of Hensler and collaborators (see e.g. [94, 98, 243, 259, 307]). These works unveiled the complexity of true multiphase simulations of galaxies. Yet, these complex simulations are necessary in order to reproduce more faithfully the ISM. Tanks to enormous progresses in the field of multi-phase simulations in other branches of physics (see e.g. the monographs [36, 122, 285]) I hope that we can witness a boost of true multi-phase, multi-fluid galactic simulations in the next years.

- **Inclusion of dust.** As already mentioned in Sect. 6, many works about the chemical evolution of galaxies [41, 70, 214, 348, 349] include dust and show how important this component is to interpret data about the chemical composition of galaxies. It is very likely that the inclusion of dust can drastically change also the results of chemodynamical evolution of galaxies and can dramatically improve our knowledge about the physics of the dust-gas interaction and about the circulation of metals in galaxies. In spite of useful attempts, current state-of-the-art numerical simulations of galaxies do not take dust into account (but see [19, 20]). A proper inclusion of dust is difficult and can also lead to numerical problems. However, in other branches of astrophysics some of these numerical issues have been solved and sophisticated simulations of gas-dust mixtures have been performed [202, 264, 265, 326]. It would be extremely beneficial for the astronomers working on simulations of galaxies to learn from these works and improve the treatment of dust physics and dust-gas interactions in galactic simulations. It is also worth noticing that the publicly available Pencil Code [32, 33, 95] already includes relevant dust physics. A wider use of this code for simulating ISM in galaxies is certainly arguable.

- **A more self-consistent treatment of the IMF.**

Recent, detailed simulation of the ISM with a proper treatment of the star formation process [15, 16, 134] are able to recover the main shape and features of the IMF. In these simulations, thus, the IMF is not assumed a priori but is self-consistently reproduced. Galaxy-wide simulations do not have an adequate spatial resolution, therefore some simplifying assumptions about the IMF need to be made. Yet, it appears to me that a lot is known about physical properties and mass distribution of stellar clusters in galaxies, and these can be used to constrain the formation mechanisms of star clusters in galactic simulations. Within each clusters, the observationally-based maximum-mass vs. cluster mass ($m_{\rm max} - M_{\rm cl}$, [132, 337, 340]) relation can be used to link the upper stellar mass within each cluster to the cluster mass. This appears to be a simple and physically motivated exercise, that can significantly change the outcome of a galactic simulation. Finally, the full IGIMF theory as developed by Kroupa and collaborators (see Sect. 5 and [132] for a review) can be implemented in numerical simulations. As shown in Sect. 5 with a simple example, the results can drastically change compared to simulations adopting an universal IMF. In spite of some attempts [20], almost nothing has been done in this field.

- **Feedback recipes.** This is a very vibrant and active field of research, with new methods and implementations appearing weekly in the preprint archives. However, it seems to me that some ingredients and topics are receiving less attention than they deserve. In particular, before concentrating on methods and algorithms to inject energy into the ISM (the kinetic, thermal and radiative feedback schemes described in Sect. 7) I think one should be sure that all relevant sources of energy are included and properly treated. In particular (*i*) Type II SNe are always included but it is usually not appreciated how much the total energy coming from SNeII can change if the threshold mass $m_{\rm thr}$ above which SNeII can explode is changed. As shown in Sect. 7, a change in $m_{\rm thr}$ can lead to a change in total SNII energy by a factor of almost 2. It is also not always appreciated how uncertain is the fraction of the SNII explosion energy that can effectively thermalize the ISM. Some analytical estimates of this fraction are available in the literature (see also Sect. 7) and I think it could be very useful to use more often and more consistently these kinds of analytical estimates. (*ii*) Type Ia SNe are often neglected and, if they are considered, no systematic study of the dependence of the results of the simulations on the Type Ia SN rates is available in the literature. This appears to be a simple and yet quite useful exercise. (*iii*) Stellar winds from massive and intermediate-mass stars can also contribute very significantly to the energy budget of a galaxy, in particular if the metallicity is not extremely low. This ingredient, too, is often neglected or not properly considered in galactic simulations. The availability of softwares like Starburst99 [148] makes the inclusion of stellar winds in numerical simulations quite simple.

- **Synergy between galactic scale and cluster scale or cosmological simulations.** As mentioned in Sect. 8, results of detailed simulations of individual galaxies could be used in simulations of galaxy clusters, groups or even in cosmological simulations, in order to improve the sub-grid recipes of these large-scale simulations. In particular, details of the formation of galactic winds and their impact on the external intergalactic or intracluster medium (see Sect. 9) can be extremely beneficial in large-scale simulations where these effects are usually treated very crudely.

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