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The refill of superbubble cavities

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ABSTRACT

In this paper we study the late evolution of model galaxies after a single episode of star formation of different durations. The aim of the paper is to discover the timescale needed to refill with cold gas the center of the galaxy. This timescale strongly depends on the amount of gas initially present inside the galaxy and ranges between 125 and 600 Myr. A H I hole can therefore survive several hundred Myr after the last SNII has exploded. If, as a consequence of the refill of the center of the galaxy, a second episode of star formation occurs, it pollutes the surrounding medium in a very short timescale (of the order of 10−15 Myr), at variance with what happens if the center of the galaxy is still occupied by hot and tenuous gas.

Key words. hydrodynamics – ISM: abundances – ISM: bubbles – ISM: jets and outflows – galaxies: evolution

1. Introduction

After an episode of star formation (hereafter SF), the energy released by SN explosions and stellar winds produces large cavities of hot gas (visible in H I as holes), surrounded by a cold H I shell. However, in many dwarf irregular galaxies (hereafter dIrr) there are H I holes not associated with young star clusters (e.g. M 101, Kamphuis et al. 1991; Holmberg II, Rhode et al. 1999; LMC, Kim et al. 1999).

The energy input rate after an episode of SF declines with time, therefore the hot cavity looses pressure and the shell tends to recede towards the center of the SF region. This refill process strongly depends on the considered energy sources. Superbubbles solely produced by SNeII experience a buoyancy of the hot gas at the end of the SF phase and the central region can be completely refilled with cold gas. This process occurs in a timescale of the order of a few 10^8 yr (D'Ercole & Brighenti 1999, hereafter DB99). Also Hunter & Gallagher (1990) speculated on the final fate of a supershell, based on simple dynamical arguments and estimated a refill timescale of the order of $\sim 5 \times 10^7$ yr. The assumption of an energy source coming also from SNeIa (which should indeed be numerous in irregular galaxies; see e.g. Mannucci et al. 2005) changes the thermodynamical behaviour of the gas in the center of galaxies. For instance, Recchi et al. (2001) found that in some cases the break-out of the galaxy occurred only as a consequence of the energy input from SNeIa, while the SNeII, exploding in a colder and denser medium, could radiatively loose a very large fraction of the initial explosion energy.

In some cases, the overpressurized regions produced by the ongoing SF develop galactic winds. Galactic winds are defined as outwards-directed flows of gas, whose expansion velocities reach the escape velocity, therefore supposed to definitely leave the parent galaxy. In stratified media (i.e. if the density profile in the vertical direction is $\rho_z \propto z^{-x}$), a galactic wind develops for profiles steeper than $x = 2$ (Koo & McKee 1992). However, the final fate of the outflowing gas depends on poorly constrained details about the environment surrounding the galaxy and about interactions with other galaxies and it is hard to distinguish, both theoretically and observationally, galactic winds from normal outflows. However, the refill of a superbubble is not affected at all by the final fate of the outflowing gas, therefore this distinction is not important in our work.

The refill of the center of the galaxy changes also drastically the chemical evolution of dIrrs. If previous episodes of SF carve a very large cavity, the release of metals from dying stars occurs in a very hot medium. Under these conditions, the cooling timescale of the newly produced metals is very large and, in the presence of a galactic wind, these metals can be directly carried out of the galaxy (Recchi et al. 2005, hereafter Paper I). Consequently, the chemical enrichment of the galaxy is not influenced by the ongoing production of metals and the chemical composition only reflects the enrichment from the first episodes of SF. However, if the preceding generations of stars do not provide enough energy to create a galactic wind and to produce a large cavity of hot gas, the impact of the following episode of SF can be significant (Recchi et al. 2002). The same occurs if the gap between two episodes of SF is large enough to allow the refill of the center of the galaxy with cold and dense gas.

In this paper, we simulate the evolution of a galaxy after a single episode of SF of different duration, in order to

Table 1. Model parameters and refill timescales.

Model[a]	H I mass (10^8 $M_\odot$)	SF duration (Myr)	SF rate ($M_\odot$ yr^{-1})	Refill timescale (Myr)
LS	1.	25	0.5	415
LL	1.	200	0.05	600
HS	1.8	25	0.5	125
HL	1.8	200	0.05	200

[a] The identification of a model is made through the notation XY, where X indicates the gas mass ("L" for low and "H" for high) and Y indicates the duration of the SF episode ("S" for short and "L" for long).

establish what is the typical refill timescale when the energy input of SNeIa is considered. In Sect. 2 we introduce the model, in Sect. 3 we give our definition of *refill timescale*, in Sect. 4 we present our results and finally in Sect. 5 some conclusions are drawn.

2. The model

We simulate a SF region and the late evolution of the hot cavities by means of a 2-D hydrodynamical code in cylindrical coordinates, described in detail in Paper I and references therein. The set-up of the model is taken from Paper I, namely it reproduces the main features (H I mass and distribution, total dynamical mass) of the dIrr galaxy NGC1569. In particular, the distribution of gas is approximately ellipsoidal, with a ratio between minor and major axis of ~0.5, in agreement with observations (Reakes 1980). Such a flattened initial distribution of gas favours the development of a galactic wind in the polar direction, where the pressure gradient is steepest. Although the aim of this paper is not to simulate the detailed chemical and dynamical evolution of this specific object (as done in Paper I), NGC1569 is a good and well-studied example of a post-starburst galaxy (Israel 1988), therefore a good benchmark to study the refill process after an episode of SF. In order to develop a physical feeling for the dependence of this process, we test two possible values of the total H I mass: ~10^8 $M_\odot$ (models labeled "L") and ~1.8×10^8 $M_\odot$ (models labeled "H"). According to the works of Angeretti et al. (2005) we concentrate on the SF occurring in the central part of the galaxy, although we do not intend to reproduce in detail the SF history of NGC1569. We consider single SF episodes of different duration and intensity. We consider either models in which the SF lasts 25 Myr at a rate of 0.5 $M_\odot$ yr^{-1} (second label "S"), or models in which the duration of the SF is 200 Myr at a rate of 0.05 $M_\odot$ yr^{-1} (second label "L"). Therefore, for instance, the model labeled "LS" is characterized by a total H I mass of ~10^8 $M_\odot$ and a SF rate of 0.5 $M_\odot$ yr^{-1} lasting for 25 Myr. Model parameters are summarized in Table 1.

The SNeIa rate is calculated according to the so-called Single-Degenerate scenario (namely C−O white dwarfs in binary systems that explode after reaching the Chandrasekhar mass because of mass transfer from a red giant companion). This rate, in the case of short SF episodes, peaks after ~10^8 yr and then declines proportionally to ~$t^{-1.8}$ (Greggio & Renzini 1983; Matteucci & Recchi 2001). The chemical evolution of our models is also followed, coupling the hydrodynamical simulations with chemical yields coming from SNeII, SNeIa and intermediate-mass stars. In agreement with Paper I, the sets of yields we adopt for massive and intermediate-mass stars are the ones calculated by Meynet & Maeder (2002). Details on how to trace the chemical enrichment of gas in this kind of simulations can be found in Paper I and references therein.

3. Definition of refill timescale

According to Paper I, in this work, all the energy and mass input occurs in the central 200×200 pc^2 of the galaxy. This assumption comes from the fact that presumably the SF occurring in the center of NGC1569 comprises the SF of the whole galaxy (see Paper I; Greggio et al. 1998). We will therefore define as *refill timescale* the time elapsed from the end of the SF phase to the moment at which the physical size of the hot cavity becomes smaller than the initial 200×200 pc^2, namely the time after which, in spite of the input of energy from SNeIa, a fraction of the central star forming region has temperatures below 2×10^4 K.

4. Results

4.1. A typical evolutionary sequence

As a representative example of the expected evolution of a galaxy as a consequence of the energy input of SNeIa, we consider here model HL, namely the model with a large total H I mass and an episode of SF lasting 200 Myr at a rate of 0.05 $M_\odot$ yr^{-1}. Snapshots of the evolution of this model are shown in Fig. 1. As one can discern from the first panel, the combined energy of SNeIa and SNeII is able to break-out of the galaxy at $t \sim 160$ Myr and a weak galactic wind is formed. The superbubble starts funneling through the H I due to the initial stratification of the ISM (see Sect. 2) and to the structuring of the gas formed by the ongoing dynamical instabilities. The energy supply by SNeII ends at $t \sim 230$ Myr (200 Myr is the duration of the SF; ~30 Myr is the lifetime of a 8 $M_\odot$ star, the smallest able to give rise to a SNII in our models). After this time interval, SNeIa still provide enough energy to sustain the outflow (panel 2). The funnel begins to shrink at $t \sim 300$ Myr and at ~340 Myr the outflow has almost completely disappeared (panel 3). At ~400 Myr the cavity has approximately the original size of the SF region (panel 4) and from now on it recedes further towards the center. The last panel of Fig. 1 shows the density contours a $t \sim 440$ Myr and at this time the cavity of hot gas (with temperatures of the order of 10^5−$10^{5.5}$ K) has a

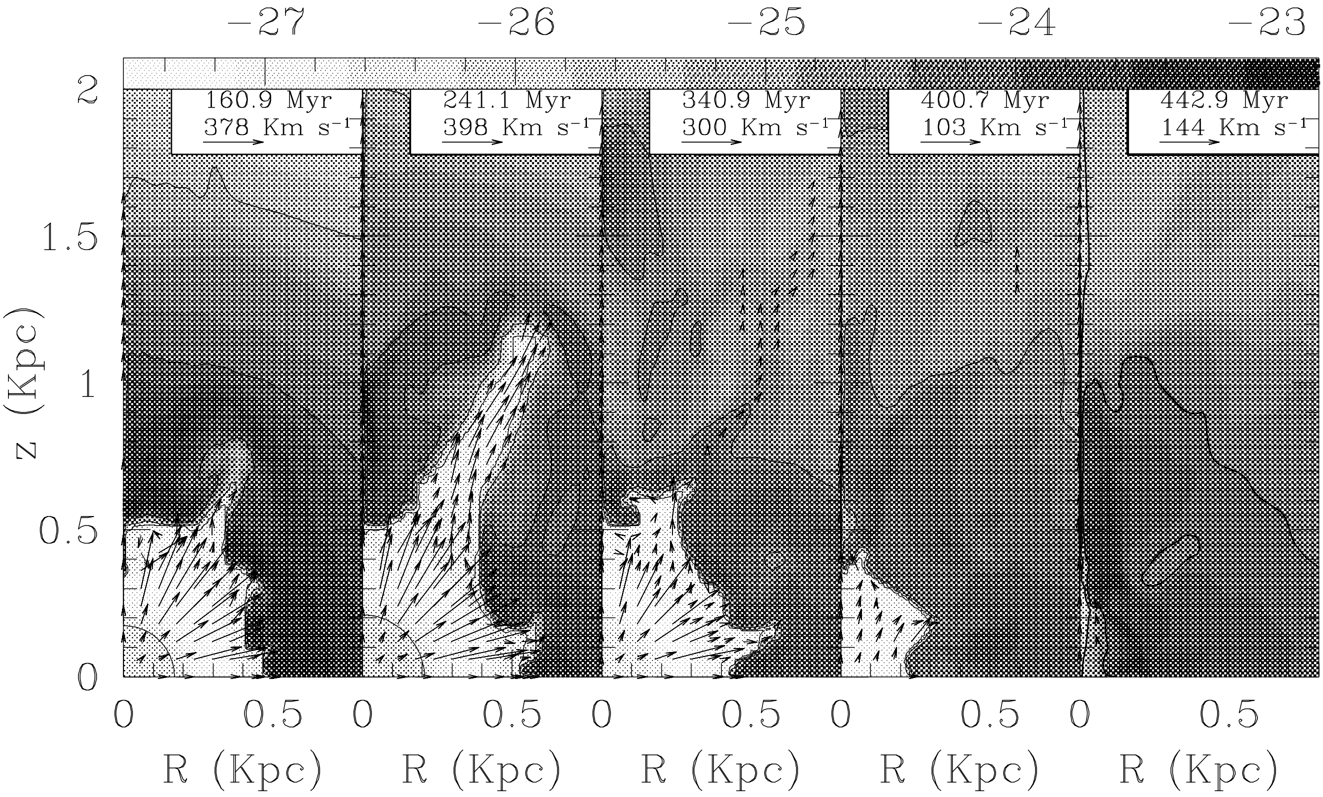

Fig. 1. Density contours and velocity fields for model HL (see Table 1) at five different epochs (evolutionary times are labelled in the box on the upper right corner of each panel). The logarithmic density scale is given in the strip on top of the figure. In order to avoid confusion, velocities with values lower than 1/10 of the maximum value (indicated for each panel in the upper right box) are not drawn.

size of approximately 100 × 200 pc^2; smaller than the SF region. According to the definition given in Sect. 3, the refill of the cavity has occurred. This result might however depend on the dispersion of SNeIa progenitors (not taken into account in this work). Assuming a velocity dispersion of a few km s^{-1} the progenitors can travel a few hundreds pc after ~100 Myr.

The inflow velocity of the cold gas toward the center of the galaxy is modest (of the order of 5−10 km s^{-1}) (approximately the sound speed of the cold gas), therefore the ram pressure associated with this flow is of the order of $p_{\mathrm{ram}} = \rho_{\mathrm{infall}} \cdot v^2_{\mathrm{infall}} \sim 10^{-13}$ erg cm^{-3}. This value is three to five orders of magnitudes smaller than the ram pressure associated with the inflows simulated by Tenorio-Tagle & Munoz-Tunon (1997). The inflows considered by these authors should therefore have a different origin, such as the infall of a high-velocity cloud directly into the center of a galaxy or a violent large-scale disturbance in a galactic potential due to a close encounter (Larson 1987).

It is also worth pointing out that the galactic potential well is dominated by a quasi-isothermal dark halo with a core radius of 1 kpc (see Paper I for details), therefore the gravitational acceleration in the center of the galaxy is small. The infall of cold gas along the disk is then mainly driven by the pressure gradient originating from the pressure loss of the cavity once the supershell breaks out (MacLow & McCray 1988). However, one has to emphasize that in these simulations, at variance with similar studies considering only SNeII as a source of energy (e.g. DB99), there is no buoyancy of the hot gas at the end of the SF, since SNeIa provide continuously energy.

4.2. The evolution of the other models

In the last column of Table 1 we report of the refill timescale for each of the considered models. The refill timescale, as expected, strongly depends on the total mass of H I gas at the beginning of the simulation. For the extreme model HS (high total H I mass, short SF), the refill occurs already ~100 Myr after the SNeII ceased. The tabulated refill timescales associated with the "H" models are consistent with the ones derived for the standard model studied by DB99, in spite of the fact that no SNeIa were considered in their simulations. This is due to the fact that their assumed luminosity in the starburst phase (which lasts 30 Myr in their models) is ~10 times larger than the one adopted in our simulations. DB99 also considered a model with a weaker starburst (their model SB1) and in this case the cavity begins to shrink immediately after the end of the energy input phase and the cold gas reaches the origin at $t \sim 70$ Myr, much earlier than in our simulations. The models characterized by a lower H I mass show larger refill timescales, which bring the theoretical interval between the beginning of the SF and the replenishment of the SF region close to 1 Gyr in the case of a prolongated SF (model "LL").

4.3. The impact of a new episode of SF on a refilled cavity

As demonstrated in Recchi et al. (2004) and in Paper I, if a new episode of SF occurs in a hot cavity, the metals newly

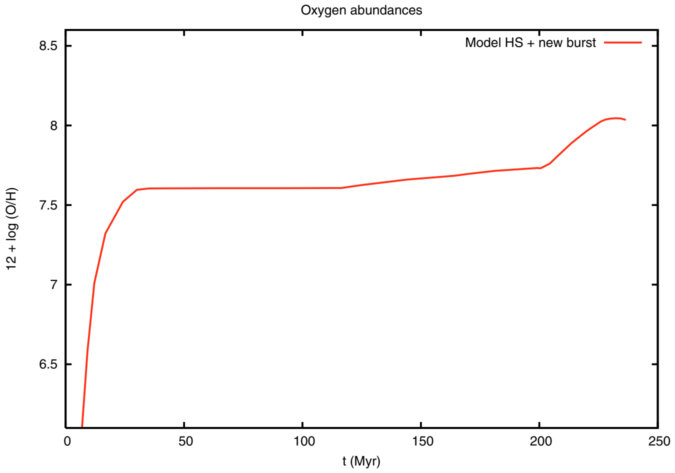

Fig. 2. Evolution of 12 + log (O/H) for model HS (see Table 1) with a second episode of SF at t = 200 Myr.

synthesized in the ongoing starburst are not detectable by the optical spectroscopy since they are either directly channelled through the galactic funnel, or they are found in a too hot medium. This is not the case when the gap between the two episodes of SF is large enough to allow the refill of the cavity. In this case, the starburst injects metals in a much colder and denser medium, where thermal conduction, thermal instabilities and eddies allow a fast cooling of the metals and an effective mixing with the surrounding unpolluted gas. In order to show this, we run a model in which, starting from the end of model HS (see Table 1) we add a second burst of SF, with the same characteristics as the first one, namely, a SF duration of 25 Myr with a rate of 0.5 $M_\odot$ yr^{-1}. The onset of this new SF occurs at ~200 Myr, when most of the central 200×200 pc^2 of the galaxy are filled with cold gas.

In Fig. 2 we plot the evolution of 12 + log(O/H) for this model, until an evolutionary time of ~240 Myr. As one can see in this plot, the chemical composition changes significantly ~10−15 Myr after the onset of the last burst of SF. The oxygen composition increases suddenly as a consequence of the input of freshly produced metals by the ongoing SF. The mixing timescale of the metals produced in this last episode of SF is therefore of the order of 10−15 Myr, in agreement with what is found by Recchi et al. (2001) in the case of a single instantaneous burst.

5. Conclusions

In this paper we have analyzed the late evolution of a galaxy after a single SF episode in order to explore the timescale needed to refill the cavity in the center of the galaxy with cold gas once the SF has ceased. This timescale strongly depends on the amount of gas initially present inside the galaxy and ranges between 125 (model with a large initial amount of H I and short and intense SF) and 600 Myr (model with a smaller initial H I mass and milder and long SF). This means that large H I holes (like the ones observed in many dIrr galaxies) can survive a few hundred Myr after the last OB stars have died. The refill of the cavity is mostly due to the pressure gradient created after the superbubble breaks out the disk.

A SF occurring in the refilled cavity would produce metals which mix with the surrounding unpolluted medium in a timescale of the order of 10−15 Myr, at variance with what happens if the center of the galaxy is still occupied by hot and diluted gas.

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