THE ROLE OF STELLAR FEEDBACK IN THE FORMATION OF GALAXIES

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ABSTRACT

Although supernova (SN) explosions and stellar winds happen at very small scales, they affect the interstellar medium (ISM) at galactic scales and regulate the formation of a whole galaxy. Previous attempts of mimicking these effects in simulations of galaxy formation use very simplified assumptions. We develop a much more realistic prescription for modeling the feedback, which minimizes any ad hoc subgrid physics. We start with developing high-resolution models of the ISM and formulate the conditions required for its realistic functionality: formation of multiphase medium with hot chimneys, superbubbles, cold molecular phase, and very slow consumption of gas. We find that this can be achieved only by doing what the real universe does: formation of dense (>10 H atoms cm$^{-3}$), cold ($T \approx 100$ K) molecular phase, where the star formation happens, and which young stars disrupt. Another important ingredient is the effect of runaway stars: massive binary stars ejected from molecular clouds when one of the companions becomes an SN. Those stars can move to 10–100 pc away from molecular clouds before exploding themselves as SNe. This greatly facilitates the feedback. Once those effects are implemented into cosmological simulations, galaxy formation proceeds more realistically. For example, we do not have the overcooling problem. The angular momentum problem (resulting in a too massive bulge) is also reduced substantially: the rotation curves are nearly flat. The galaxy formation also becomes more violent. Just as often observed in quasar absorption lines, there are substantial outflows from forming and active galaxies. At high redshifts we routinely find gas with few hundred km s$^{-1}$ and occasionally 1000–2000 km s$^{-1}$. The gas has high metallicity, which may exceed the solar value. The temperature of the gas in the outflows and in chimneys can be very high: $T = 10^7$–$10^8$ K. The density profile of dark matter is still consistent with a cuspy profile. The simulations reproduce this picture only if the resolution is very high: better than 50 pc, which is 10 times better than the typical resolution in previous cosmological simulations. Our simulations of galaxy formation reach the resolution of 35 pc.

Key words: galaxies: evolution – galaxies: formation – hydrodynamics – ISM: general – methods: N-body simulations – stars: formation

Online-only material: color figures

1. INTRODUCTION

The current cosmological paradigm, the Λ cold dark matter (ΛCDM) universe, has successfully explained the overall assembly of cosmic structures (Blumenthal et al. 1984; Davis et al. 1985; Spergel et al. 2007). In this picture ordinary matter (“baryons”), which emits and absorbs light, passively follows the evolution of the dark matter. This should be corrected, if we want to make a realistic theory of galaxy formation. It is necessary to include the physics of the gas and galaxy formation into the ΛCDM paradigm, because, after all, many observational evidences of cosmic structures come from the light emitted by galaxies.

Galaxy formation is driven by a complex set of physical processes with very different spatial scales. Radiative cooling, star formation, and supernova (SN) explosions happen at scales less than 1 pc, but they affect the formation of a whole galaxy (Dekel & Silk 1986). In addition, large-scale cosmological processes, such as gas accretion through cosmic filaments, and galaxy mergers, control the galaxy assembly. As a result, a complex interplay between very different processes drives the formation of galaxies. Cosmological gas dynamical simulations have become useful tools to study galaxy formation.

In early cosmological simulations, “galaxies” formed with too small disks and a significant fraction of angular momentum was lost (Navarro & Steinmetz 2000). Kaufmann et al. (2006) argued that some of this angular momentum loss may be artificial owing to low numerical resolution. Recent improvements in both the resolution (sub-kpc scales) and modeling of the feedback have resulted in simulations with extended galactic disks (Sommer-Larsen et al. 2003; Governato et al. 2004; Robertson et al. 2004; Brook et al. 2004; Okamoto et al. 2005; D’Onghia et al. 2006; Governato et al. 2007). However, simulated galaxies are still too concentrated, and more realistic simulations with better resolution and better physics are needed to reproduce the shape of the rotation curves of observed galaxies.

Current simulations lack the necessary resolution to follow correctly the effect of SN explosions in the ISM. Because of this lack of resolution, the modeling of stellar feedback has relied on ad hoc assumptions about the effect of stellar feedback at scales unresolved by simulations (0.2–1 kpc). Early attempts to introduce stellar feedback into simulations found the obstacle of a strong radiative cooling. The energy deposited by SN explosions was quickly radiated away without any effect in the ISM (Katz 1992). Several shortcuts have been proposed to get around this overcooling problem.

The most common method is to artificially stop cooling when the stellar energy is deposited (Gerritsen & Ike 1997; Thacker & Couchman 2000; Sommer-Larsen et al. 2003; Kereš et al. 2005; Governato et al. 2007). This approach prolongs the adiabatic phase of SN explosion (the Sedov solution) to about 30 Myr. The motivation behind this ad hoc assumption is that the combination of blast waves from different SN explosions and turbulent motions produces hot bubbles much larger than individual SN remnants and last longer. All these effects are not resolved with the current resolution. They do not develop in a self-consistent way. Instead, the delay in the cooling is
introduced by hand. The problem is that other effects can be missed at the same time due to lack of resolution and an inaccurate modeling of feedback.

Another method is to introduce a subresolution model in which the energy from SN explosions is stored in an unresolved hot phase, which does not cool and loses energy through the evaporation of cold clouds (Yepes et al. 1997; Springel & Hernquist 2003). In this model, the only effect of stellar feedback is to regulate the star formation: the hot gas is coupled with the cold phase through cloud formation and evaporation. As a result, this high entropy gas is artificially trapped within the galactic disk. Thus, galactic winds are introduced in a simplified way in order to reproduce other natural effects of stellar feedback, such as galactic outflows.

An alternative approach assumes kinetic feedback instead of thermal feedback (Navarro & White 1993). In that case, the energy from SN explosions or stellar winds is transferred to the kinetic energy of the surrounding medium. This energy is not dissipated directly by radiative cooling. However, in order to resolve this effect accurately, simulations should be able to resolve the expansion of individual SN explosions or the stellar winds from individual stars. Currently, this is not possible. At larger scales, the picture is more complicated. Different blast waves from different SN explosions can collide, dissipating their kinetic energy. The same dissipation of energy happens in collisions of stellar winds in stellar clusters. So, it is commonly assumed that most of the kinetic energy from stellar feedback is dissipated into thermal energy at the smallest scales resolved by simulations. Nevertheless, this feedback-heated gas can expand. As a result, thermal energy can be transferred to kinetic energy. The net results are flows at large scales powered by the thermal feedback. However, feedback heating should dominate over radiative cooling: only in this case those flows are produced.

To summarize, the main problems of current simulations of galaxy formation are the lack of the necessary resolution and too simplified models of the complex hydrodynamic processes in the multiphase ISM.

The galactic ISM has a very wide range of densities and temperatures (for review see Cox 2005 and Ferrére 2001). Three distinct phases are distinguished: the dense cold gas (giant molecular clouds (GMCs), cold HI gas or diffuse clouds) with densities between 0.1 and 1 cm$^{-3}$ and temperatures below 100 K, the warm component with densities between 0.1 and 1 cm$^{-3}$ and temperatures of several thousands degrees, and the hot phase with temperatures above $10^5$ K and densities below $10^{-2}$ cm$^{-3}$. This multiphase medium is set by the competition of cooling and heating mechanisms and the onset of thermal instabilities. The hot ISM component ($T > 10^5$ K) is usually associated with gas heated by shocks. They can be produced by turbulent motions driven by gravitational and thermal instabilities. However, these turbulent driven shocks can only heat the gas up to $10^6$ K (Wada & Norman 2001). Only SN explosions and stellar winds can produce higher gas temperatures (McCray & Snow 1979; Spitzer 1990).

Two-dimensional and three-dimensional hydrodynamical simulations of the ISM have enough resolution (parsecs) to resolve the multiphase nature of the ISM and to explore complicated effects of stellar feedback on different scales (Rosen & Bregman 1995; Scalo et al. 1998; Korpi et al. 1999; de Avillez 2000; de Avillez & Breitschwerdt 2004, 2007; Wada & Norman 2001, 2007; Slyz et al. 2005). There is much to learn from these simulations. However, they typically focus on conditions in the solar neighborhood, which are different from what one may expect during early stages of galaxy formation. Not always they follow the whole gas cycle: cooling, star formation, and stellar feedback. For example, de Avillez & Breitschwerdt (2004) include star formation but artificially restrict the rate of SN explosions around a fixed value. However, this rate could be much higher in large star-forming regions. As a result, the effect of stellar feedback is underestimated in these regions. Nevertheless, the effect of the stellar feedback in the ISM, such as the formation of hot bubbles and superbubbles is resolved.

It is crucial to understand where and how the energy from massive stars is released back to the ISM. While a large fraction of massive stars are found in stellar clusters and OB associations, 10%–30% are found in the field, away from any molecular cloud or stellar cluster (Gies 1987; Stone 1991). Some of these stars have large peculiar velocities, up to 200 km s$^{-1}$ (Hoogerwerf et al. 2000). This is why they are called runaway stars. The current scenario of the origin of runaway stars is the ejection of these massive stars from stellar clusters. There are two possible mechanisms of this ejection. One possibility is the ejection due to an SN explosion in a close binary system (Zwicky 1957; Blaauw 1961). The second mechanism is the ejection due to dynamical encounters in the crowded regions of stellar clusters (Poveda et al. 1967). In spite of the fact that a significant fraction of the stellar feedback occurs far from star-forming regions, no attention has been paid to its effect on galaxy formation.

We first study the effect of stellar feedback in the ISM, using simulations of a kpc-scale piece of the ISM with a few parsecs resolution. Then, we check if this picture holds when the resolution is degraded to the resolution that our cosmological simulations can achieve at high redshift. Finally, we study the effect of stellar feedback in galaxy formation at high redshift using cosmological hydrodynamical simulations.

This paper is organized as follows. Section 2 describes the necessary conditions in which stellar feedback dominates over radiative cooling. Section 3 describes all details of the modeling of stellar feedback. Section 4 shows kpc-scale simulations of the ISM. Section 5 describes the cosmological simulations of galaxy formation. Finally, Section 6 is the discussion and conclusion. Throughout the paper we give quantities in physical units.

2. PHYSICAL CONDITIONS FOR THE HEATING REGIME

The thermodynamical state of the gas depends on two competing processes: heating from stellar feedback and cooling from radiative processes. They appear as source and sink terms of internal energy in the equation of the first law of thermodynamics:

$$\frac{du}{dt} + p \nabla \cdot \mathbf{v} = \Gamma - \Lambda,$$

(1)

where $u$ is the internal energy per unit volume, $p$ is the pressure of the gas, and $\mathbf{v}$ is its velocity. $\Gamma$ is the heating rate due to stellar feedback, and $\Lambda$ is the net cooling rate from radiative processes.

The heating rate from stellar feedback can be expressed as the rate of energy loss from a young and active single stellar population with a given density, $\rho_{\text{SSP}}$, young:

$$\Gamma = \rho_{\text{SSP}}^{\text{young}} \Gamma',$$

(2)
where \( \Gamma' \) is the specific rate of energy loss of the stellar population according to its age. The cooling rate can be expressed as

\[
\Lambda = n_\text{H}' \Lambda',
\]

where \( n_\text{H} \) is the hydrogen number density.

### 2.1. Heating Versus Radiative Cooling

Now, we can ask ourselves under which conditions the feedback heating dominates over the radiative losses. Using the expression, \( n_\text{H} = \rho_\text{gas}/(\mu_\text{H} m_\text{H}) \), where \( \rho_\text{gas} \) is the gas density, \( \mu_\text{H} \) is the molecular weight per hydrogen atom and \( m_\text{H} \) is the hydrogen mass, the condition for heating (\( \Lambda \leq \Gamma \)) can be expressed as:

\[
n_\text{H}' \Lambda' \leq \frac{\rho_\text{young}}{\rho_\text{gas}} \mu_\text{H} m_\text{H} \Gamma'.
\]

Using typical values, we can rewrite the condition for the heating regime in the following way:

\[
\left( \frac{n_\text{H}}{0.1 \text{ cm}^{-3}} \right) \left( \frac{\Lambda'}{10^{-22} \text{ erg s}^{-1} \text{ cm}^{-3}} \right) \leq \left( \frac{\rho_\text{young}}{\rho_\text{gas}} \right) \left( \frac{\Gamma'}{10^{34} \text{ erg s}^{-1} \text{M}_\odot^{-1}} \right).
\]

The cooling rate, \( \Lambda' \), is a strong function of gas temperature. So, the temperature and the density of the gas are two key properties in establishing the cooling or the heating regimes. The following two examples illustrate common situations.

At temperatures around 10^4 K, the cooling rate is close to its maximum value. We use \( \Lambda' = 10^{-22} \text{ erg s}^{-1} \text{ cm}^{-3} \) as a fiducial value. In this case, Equation (5) shows that the heating overcomes the cooling only at very low densities \( n_\text{H} \leq 0.1 \text{ cm}^{-3} \), optimistically assuming that the ratio of densities, \( \rho_\text{young}/\rho_\text{gas} \), is about unity. As a result, stellar feedback is not able to heat the gas beyond 10^4 K for densities higher than 0.1 cm^-3 and typical values of \( \Gamma' \). This is the well-known overcooling problem for simulations, which allow cooling only to a temperature of 10^4 K at which the star formation is assumed to happen. The energy from stellar feedback is radiated away very efficiently and the thermal feedback cannot play any role. In this case one needs to invoke “subgrid physics”—a guess how the system should react to the energy released by the stars.

The situation is completely different if the gas is allowed to cool to 100 K. The cooling is very inefficient at that temperature: \( \Lambda' = 10^{-25} \text{ erg s}^{-1} \text{ cm}^{-3} \). So, stellar feedback can produce the net gas heating even if the density is large: \( n_\text{H} \approx 100 \text{ cm}^{-3} \) for \( \rho_\text{young} \approx \rho_\text{gas} \). Our conclusion is that simulations should include cooling process below 10^4 K.

### 2.2. Local Gravity Versus Pressure Gradient

As we saw in the previous section, low densities are required in order to heat the gas beyond the peak of the cooling curve. Stellar feedback should evacuate the gas by creating an expanding bubble around young stellar clusters. However, the overpressured bubble expands only if the pressure gradient overcomes self-gravity.

If we consider an overpressured bubble of radius \( R \) in a homogeneous medium of density \( \rho \), we can derive a Jeans-instability type of condition. As a result, the bubble expands only if the difference in pressure with its surroundings, \( \Delta P \),
satisfies the following relationship:
\[
\Delta P / k \geq \frac{4\pi}{3k} G(\rho R)^2 = 10^{-1}(n_H R_{pc})^2,
\]
where \( k \) is the Boltzmann constant, \( G \) is the gravitational constant, and \( R_{pc} \) is the radius in pc. The above equation sets the conditions for the bubble expansion. For the Galactic plane the pressure is \( P / k \sim 2 \times 10^4 \text{ cm}^{-3} \text{ K} \) (Cox 2005). For example, a region of 50 pc in radius and a density of 100 cm\(^{-3}\) will only expand, if the difference in pressure is bigger than \( 2 \times 10^6 \text{ cm}^{-3} \text{ K} \). This can be achieved, if the bubble is overpressured by more than 100 times. Stellar feedback can produce this overpressured just by raising the temperature from 100 K to \( 10^4 \text{ K} \). The resulted overpressured region will expand, and the density as well as the cooling rate will decrease. So, the efficiency of stellar feedback increases, raising the temperature and pressure further.

Equation (6) also sets an upper limit on the resolution. Using the equation of state of the ideal gas \( P = n k T \), where \( n \) is the mean number density and \( T \) is the temperature of the gas, the overpressured bubble should be resolved with a spatial resolution \( X_{pc} = R_{pc}/2 \), such that the expansion is resolved:
\[
\left( \frac{X_{pc}}{75 \text{ pc}} \right)^2 \leq \left( \frac{T}{10^4 \text{ K}} \right) \left( \frac{n_H}{10 \text{ cm}^{-3}} \right)^{-1}.
\]
As a result, for typical values of these overpressured regions, the resolution should be better than \( \sim 70 \text{ pc} \). Otherwise, the bubble cannot overcome its self-gravity and cannot expand.

3. STELLAR FEEDBACK MODEL

We assume a model of thermal feedback for the injection of energy from stellar winds and SN explosions. The kinetic energy from these processes is efficiently dissipated into thermal energy due to shocks at scales below the spatial resolution.

The net thermal rate \( \Gamma - \Lambda \) is used to update the internal energy in each step of the simulation. This approach is rather different from the deposition of energy. Instead, the energy injection from stellar feedback is treated in a self-consistent way along with the radiative loses.

3.1. Heating Rate from Stellar Feedback

The heating rate from stellar feedback in a given volume element is modeled as the rate of energy loss from a set of single stellar populations present in that volume. This is just a generalization of Equation (2):
\[
\Gamma = \frac{1}{V} \sum_i M_i \Gamma(t_i),
\]
where \( M_i \) and \( t_i \) are the mass and the age of each single stellar population.

The modeling of the specific release of energy over time, \( \Gamma' \), is motivated by the results from population synthesis codes, such as STARBURST99 (Leitherer et al. 1999). Figure 1 shows different models of \( \Gamma' \) and the results of a STARBURST99 computation with a Miller-Scalo IMF from 0.1 \( M_\odot \) to 100 \( M_\odot \). The parameter \( \Gamma' \) is dominated by stellar winds from massive OB main-sequence stars and WR stars during the first few Myr. Later the energy is produced by core-collapse SNe from stars more massive than 8 \( M_\odot \). After 40 Myr, the release of energy comes from stellar winds of AGB stars and other less powerful sources, and the injection rate drops 6 orders of magnitudes. Supernovae-Ia (SNeIa) dominate the feedback at much longer timescales. We assume a peak of the SNIa rate at 1 Gyr. However, this peak is 3 orders of magnitude lower than the contribution from core-collapse SNe. This is because the energy from a population of SNIa is diluted over a much longer timescale than the energy from core-collapse SNe.

We model \( \Gamma' \) with a constant rate of \( 1.18 \times 10^{44} \text{ erg s}^{-1} M_\odot^{-1} \) over 40 Myr. This is equivalent to the injection of \( 2 \times 10^{51} \text{ erg} \) of energy from stellar winds and SN explosions per each massive star with \( M > 8 M_\odot \) during its lifetime. We assume a Miller-Scalo IMF in the mass range (0.1–100) \( M_\odot \). Note that this constant heating rate is the sum of the contributions from all massive stars in a single stellar population. We also consider a simpler model, which we call an SN model. In this case \( 10^{51} \text{ erg} \) is injected at constant rate due to stellar winds over 10 or 40 Myr. Then it follows a strong peak of energy release due to the SN explosion, in which \( 10^{52} \text{ erg} \) are released during 10 yrs—the typical age of young SN remnants. Although the total energy released is the same in both models, the SN model takes into account the explosive nature of core-collapse SNe.

3.2. A Model of Runaway Stars

The effect of runaway stars is implemented by adding a random velocity to a fraction of the stellar particles (10%–30%). This extra velocity has a random orientation and the value is taken from an exponential distribution with a characteristic scale of 17 km s\(^{-1}\). This choice is motivated by Hipparcos data (Hoogerwerf et al. 2000) and Monte Carlo simulations (Dray et al. 2005). For comparison, a Gaussian distribution is also used (Stone 1991). However, the effect of runaway stars in the ISM is not very sensitive to the details of this velocity distribution.

3.3. Radiative Cooling

Radiative cooling counterbalances feedback heating. So it is very important to have an accurate model of radiative cooling in order to study the net effect of stellar feedback in the ISM.

We use the model of radiative cooling described in Kravtsov (2003). It is a metallicity-dependent cooling plus a UV heating due to a cosmological ionizing background (Haardt & Madau 1996). The model includes Compton heating/cooling and molecular cooling. The temperature range of the model is between \( 10^2 \text{ K} \) to \( 10^9 \text{ K} \). Thus, this model includes cooling below \( 10^5 \text{ K} \) and the gas can reach the thermodynamical conditions of molecular clouds. As we saw in Section 2, this is crucial for the efficiency of the stellar feedback.

The cooling and heating rates from radiative processes are tabulated using the CLOUDY code (version 96b4; Ferland et al. 1998). As a result, the net cooling rate from radiative processes, \( \Lambda' \), is available for a given density, temperature, metallicity, and redshift.

3.4. Description of the Code

The numerical simulations were performed using the Eulerian gas dynamics + N-body Adaptive Refinement Tree code (Kravtsov et al. 1997; Kravtsov 1999, 2003). The physical processes of the gas include star formation, stellar feedback, metal enrichment, self-consistent advection of metals, cooling and heating rates from metallicity-dependent cooling and UV heating due to a cosmological ionizing background.
4. RESULTS OF ISM RUNS

Our first step in the understanding of the stellar feedback in galaxies is to estimate its effects on the ISM on small (galactic) scales. In order to do this, we run simulations of a $4 \times 4 \times 4$ kpc$^3$ piece of a galactic disk with a resolution of 14 pc. This resolution is sufficient to resolve the expansion of overpressured bubbles at the typical densities of star-forming GMCs, $n_H \sim 100$ cm$^{-3}$ (see Equation (7)). As discussed in Section 2, this expansion is a key requirement in order to get the right heating efficiency of stellar feedback. A similar SN-driven ISM model of de Avillez & Breitschwerdt (2004) with a subparsec resolution produces qualitatively similar results. The shapes of the distribution functions of gas density and temperature are very similar, as well as the fraction of volume filled with warm ($\sim 50\%$) and hot gas ($\sim 20\%$) inside a disk scaleheight of 250 pc. However, a detailed comparison is difficult because de Avillez & Breitschwerdt (2004) follow the ISM at higher heights above the galactic plane ($z < 10$ kpc), but they do not include gas self-gravity.

We use the high-resolution ISM-scale simulation as a benchmark for the effects of stellar feedback at galactic scales. Then, we run other simulations with degraded resolution and change parameters of the feedback scheme to find which configuration reproduces the same overall picture observed at high resolution. These low-resolution simulations with tuned parameters are necessary because they reproduce the effects of stellar feedback at resolutions that we can afford in cosmological simulations of galaxy formation.

4.1. Initial Conditions

We want to study the effects of stellar feedback in the typical conditions of normal disk galaxies with moderate gas surface densities. The models are not designed for starburst galaxies with large amounts of gas and with high star formation rates (SFRs). This type of study will be done in the future.

A 4 kpc box of ISM represents a significant piece of a galactic disk. The simulation resolves the dense galactic plane, where molecular clouds are formed. This is important to follow star formation correctly. At the same time, the simulation follows the gas at few kpc above the galactic plane. This height is similar to the scale height of the diffuse warm phase of the ISM (Cox 2005). The simulation includes radiative cooling and UV heating from a uniform UV field at redshift 0 as described in Section 3. Star formation happens in the highest density peaks with a density threshold of 100 cm$^{-3}$. In each star formation event, 5% of the mass in gas inside a volume element is converted into a stellar particle with a mass of $88 M_\odot$ within a time step set by the Courant condition ($\sim 2 \times 10^5$ yr). The SN model was used for stellar feedback and SNIa was not included. The metallicity was assumed solar and constant throughout the simulation.
Figure 2. Formation of a galactic chimney. Edge-on slices through the simulation show density, temperature, and velocity in the vertical direction, perpendicular to the galactic plane. The bottom panel shows gas column density. The chimney outflow is not a homogeneous, coherent flow: it is turbulent and has dense and cold clumps embedded into the flow. The core of the chimney reaches $10^7$–$10^8$ K. Outflow velocities exceed $10^3$ km s$^{-1}$. This hot material is able to escape the disk and generate a galactic wind.

(A color version of this figure is available in the online journal.)

planet defines the galactic plane for this ISM model:

$$n_H = n_0 \cosh^{-2} \left( \frac{z - z_0}{z_d} \right)$$

where $n_0$ is the gas density in that plane and $z_d$ is the scale height.

The choice of parameters sets the conditions of a quiescent normal galactic disk, $n_0 = 1$ cm$^{-3}$ and $z_d = 250$ pc. Thus, the surface density is $\Sigma_{gas} = 16 M_\odot$ pc$^{-2}$. The system is originally in hydrostatic equilibrium with a temperature of $10^4$ K. No stars are present at the beginning of the simulation. The box has open boundaries in the $z$-direction. So, all material that crosses these boundaries escapes the system.

The initial velocity field consists of a sum of plane-parallel velocity waves:

$$u_x = \sum_{i,j,k} A_x(i, j, k) \sin(\vec{k} \cdot \vec{r}) \exp \left( - \left( \frac{z - z_0}{z_d} \right)^2 \right)$$

$$u_y = \sum_{i,j,k} A_y(i, j, k) \sin(\vec{k} \cdot \vec{r}) \exp \left( - \left( \frac{z - z_0}{z_d} \right)^2 \right)$$

$$u_z = \sum_{i,j,k} A_z(i, j, k) \sin(\vec{k} \cdot \vec{r}) \exp \left( - \left( \frac{z - z_0}{z_d} \right)^2 \right).$$

The amplitudes are taken from a Gaussian field with a tilted power spectrum, $P_k \propto k^{-3}$, where $k$ is the wavenumber, $k = \sqrt{i^2 + j^2 + k^2}$. $i$, $j$, and $k$ are integers running from $-20$ to 20 (excluding 0) and $u_0 = 20$ km s$^{-1}$. This is a typical spectrum of a compressible turbulent medium (Kraichnan 1967; Vázquez-Semadeni et al. 1995).

$$A_x(i, j, k) = u_0 \frac{R_{Gauss}}{(i^2 + j^2 + k^2)^{3/2}}$$

$$A_y(i, j, k) = u_0 \frac{R_{Gauss}}{(i^2 + j^2 + k^2)^{3/2}}$$

$$A_z(i, j, k) = u_0 \frac{R_{Gauss}}{(i^2 + j^2 + k^2)^{3/2}}.$$

$R_{Gauss}$ is a random number taken from a Gaussian distribution.

4.2. Galactic Chimney Formation

At the beginning of the simulation, the gas starts moving according to the turbulent velocity field. As a result, the gas accumulates where different flows converge and molecular clouds naturally appear in form of filaments and shells. However, around $90\%$ of the volume is filled with warm and diffuse gas heated by UV background. Star formation occurs in the cores of the cold phase. Newly formed massive stars inject energy and a cavity filled with hot and very diffuse gas is formed. This over-pressured material expands and the net result is the formation of superbubbles. This hot gas cannot stay in the plane of the disk, as a result, the bubble expands faster in the direction perpendicular to the disk, because the density declines in that direction. The bubble develops into a galactic chimney (Norman & Ikeuchi 1989).
The chimney outflow does not look like a homogeneous, coherent flow. Instead, the chimney is turbulent and has dense and cold clumps embedded into the flow. Eventually, the gas expands in the halo and cools (Figure 2).

Another interesting feature seen in this model is a population of isolated bubbles in the warm medium. These are the results of individual SN explosions of runaway stars.

4.3. Star Formation Rate

After an initial burst of star formation, the SFR is nearly constant for the rest of the evolution (Figure 3). We found a low SFR surface density, $\Sigma_{\text{SFR}} = 3 \times 10^{-3} M_\odot \text{ yr}^{-1} \text{ Kpc}^{-2}$, temporally averaged over a period of $2 \times 10^5$ yr (100 time steps). This value is consistent with the expected value from the correlation between the SFR surface density and the gas surface density found in nearby galaxies (Kennicutt 1998; Kennicutt et al. 2007). For a gas surface density of $\Sigma = 12 M_\odot \text{ pc}^{-2}$ at $t = 90$ Myr, the expected value from the Kennicutt et al. (2007) fit is $\Sigma_{\text{SFR}} = 2 \times 10^{-3} M_\odot \text{ yr}^{-1} \text{ Kpc}^{-2}$. This is very close to our results.

As observers usually do, we also calculate the gas consumption timescale, $\tau = M_{\text{GMC}}/\text{SFR}$, in the simulated molecular clouds, assuming that gas with a density higher than 30 cm$^{-3}$ is mainly within GMCs. In our simulations, the amount of gas in molecular clouds is $M_{\text{GMC}} = 8 \times 10^6 M_\odot$ at $t = 90$ Myr. The SFR at that time is $\text{SFR} = 4.8 \times 10^{-2} M_\odot \text{ yr}^{-1}$. As a result, the gas consumption timescale in the simulated clouds is $\tau \approx 170$ Myr. This is quite long compared with the typical free-fall timescale inside molecular clouds, $t_{\text{ff}} = (3\pi/32G\rho)^{1/2} \approx 4$ Myr for $n_H = 100$ cm$^{-3}$.

In our simulations, the star formation efficiency over a free-fall timescale, the fraction of gas consumed in stars during a free-fall timescale, is only 2.5%. This value is consistent with observations (Zuckerman & Evans 1974). Krumholz & Tan (2007) report a range of 0.6%–2.6% for the whole population of GMCs of the MW. Our value is also consistent with an efficiency of ~3% found in simulations of GMCs of the MW. Our value is also consistent with the model of a turbulent-dominated GMC, described in Krumholz & McKee (2005). They give an efficiency per free-fall timescale of 1.5%–3% for typical values of their model.

After 100 Myr, only 10% of the gas in the simulation has been converted into stars. Our simulations still have plenty of cold ($T \leq 10^3$ K) gas after 100 Myr. The surface density of this cold gas is $\sim 5 M_\odot \text{ pc}^{-2}$. This value agrees with the surface density of molecular and atomic hydrogen of $\sim 6 M_\odot \text{ pc}^{-2}$ found at the solar radius (Ferri`ere 2001). However, the surface density of molecular gas is low, $\sim 0.5 M_\odot \text{ pc}^{-2}$, compared with the observed value of $\sim 2.5 M_\odot \text{ pc}^{-2}$ (Ferri`ere 2001). This partially explains why our star formation efficiency over a free-fall timescale is in the higher end of the observed range.

To conclude, stellar feedback is able to regulate star formation on galactic scales because it regulates the amount of gas available for star formation. Stellar feedback heats and disperses the cold and dense gas after a star formation event. In a single
Figure 4. Snapshot of the model after 113 Myr, showing the density in cm$^{-3}$ (first row), temperature in Kelvin (second row), gas velocity in the z-direction (third row), and surface density in cm$^{-2}$ (forth row). The left panels show a face-on view of the galactic plane ($z = z_0$) and the right panels show an edge-on view perpendicular to that plane. The three phases of the ISM are clearly visible: cold and dense clouds, warm and diffuse medium, and hot bubbles with very low densities. Velocities exceeding 300 km s$^{-1}$ can be seen in hot outflows at both sides of the galactic plane.

(A color version of this figure is available in the online journal.)

star formation event, a stellar particle of $\sim 90 M_\odot$ is created. This roughly means the formation of a single high-mass star embedded in a small stellar cluster. Due to the resolution limit, our simulation cannot follow the details of the star formation process below $\sim 10$ pc scales, only the overall net effect. This effect is the formation of a small stellar cluster with an efficiency of 5%. As we pointed in Section 2.1, the star formation efficiency of Galactic stellar clusters is high, regardless the details of their
Figure 5. Distribution of the gas temperature at 113 Myr. The distribution has three different peaks corresponding to three different gas phases of the ISM: cold, warm, and hot. Two vertical lines show the temperature cuts used throughout the paper at $T = 10^3$ K and $T = 10^4$ K. (A color version of this figure is available in the online journal.)

Figure 6. Density distribution at 113 Myr and the contribution of the three phases. The dotted curve shows the cold phase ($T < 10^3$ K), the dashed curve shows the hot phase ($T > 10^4$ K), and the dash-dotted curve shows the warm phase ($10^3$ K $< T < 10^4$ K). The distribution is clearly bimodal. The peaks correspond to the hot and warm phases. The cold phase dominates the high-density tail. (A color version of this figure is available in the online journal.)

formation. However, although the star formation efficiency is high, subsequent feedback processes produce a low average star formation.

4.4. Volume Filling Factors in the ISM

Figure 3 also shows that the net effect of stellar feedback is to produce the hot phase of the ISM. After the initial strong burst of star formation, this phase can cover up to 80% of the total volume. This represents almost the entire volume above a height of 400 pc from the galactic plane. However, pockets of warm gas are embedded in this hot flow even at 2 kpc away from the plane. It has the same inhomogeneous structure seen in the galactic fountain of figure 2. After 100 Myr, ~25% of the gas is able to escape the computational volume.

Most of the hot gas is lost or cooled down after 100 Myr. As a result, the volume of hot gas decreases because the star formation is low and the injection of energy is lower than in the initial burst. The simulation settles into a more quiescent regime in which the volume occupied by the warm and hot phases oscillates in a self-regulated gas cycle. In this cycle, bursts of star formation (much smaller than the initial one) produce superbubbles and galactic chimneys of hot gas. Therefore, the volume of hot gas increases. As the star formation fades, the bubbles cool down and the fraction of hot gas decreases until the next stellar burst. This pattern reflects the star formation history. The particular fraction of hot and warm phases at any moment does depend to the particular star formation history of 10–40 Myr before that moment.

4.5. Late Stages of Evolution

The latter stages of the simulation offer a more representative view of the ISM. The effect of the initial conditions is gone. Therefore, we can study the characteristics of this feedback-driven ISM. We select a snapshot at 113 Myr, after the second burst of star formation. At that moment, the warm phase covers ~60% of the volume and the hot phase filled ~40%. X-ray-emitting gas with temperatures above $10^{5.5}$ K occupies ~20% of the volume inside a height of 250 pc above the galactic plane. This is roughly consistent with ISM simulations with a 1 pc resolution (de Avillez & Breitschwerdt 2004), Galactic ISM models and observations (Ferrière 1998).

Figure 4 shows representative slices of the box. The medium is very inhomogeneous at different scales. Large bubbles of low density coexist with long filamentary structures of dense clouds. Overall, the medium covers more than 6 orders of magnitude in density and temperature. The cold phase forms dense and cold clouds near the galactic plane. The warm phase fills old cooled bubbles and low-density clouds. Finally, the hot phase is present in the form of hot bubbles of few hundred pc wide and kpc-scale chimneys. The gas in these chimneys flows away from the plane with velocities exceeding $\pm 300$ km s$^{-1}$. These bubbles even break the dense plane in hot spots surrounded by cold and dense shells. All this phenomenology associated with the hot phase is driven by stellar feedback. As a result, one effect of the stellar feedback is to sustain a three-phase ISM.

The distribution of temperature clearly shows the three main peaks of the three phases of the ISM (Figure 5). The two local minima correspond to thermally unstable gas. The minimum around $10^3$ K, between the peaks of the cold and warm phases, is produced by the competition of UV heating and radiative cooling. This corresponds to the unstable regime of the classical two-phase model of the ISM in thermal equilibrium (Cox 2005). The dip between $10^3$ and $10^4$ K results from the peak of the cooling curve. The gas cools very fast at these temperatures.
Figure 7. Distribution of gas velocity at 113 Myr. The curves represent the three gas phases as in Figure 6. Cold and warm phases have moderate velocities, mostly below 100 km s\(^{-1}\). The hot phase dominates the high-velocity tail of the distribution with velocities up to 2000 km s\(^{-1}\). These are outflows of gas which escapes the system. (A color version of this figure is available in the online journal.)

As a result, it usually appears at the interface between hot and warm gas. As an exception, old bubbles at these temperatures are present in the simulation with very low densities and far away from the plane. So, their cooling time is very long. This temperature distribution supports the temperature cuts used throughout the paper to distinguish the three phases: \(10^3\) K for the cut between cold and warm phases and \(10^4\) for the warm-hot cut. To summarize, this model of the ISM reproduces the main properties of the temperature distribution of the ISM (Cox 2005) and predicts that gas with very high temperatures \(10^7-10^8\) K exists in the cores of galactic chimneys. This gas occupies only 5% of the total volume and have a very small surface density of \(4 \times 10^{-6} M_\odot \text{pc}^{-2}\).

These three phases of the ISM are also clearly visible in the density distribution (Figure 6). We use the temperature cuts defined before to see the contribution of the different phases. Thus, the hot phase dominates the low-density range, below \(10^{-3}\) cm\(^{-3}\). The warm phase covers intermediate densities, and the cold phase dominates the high-density tail above 1 cm\(^{-3}\). The density distribution of any of the three phases cannot be described by a single lognormal distribution, as claimed in Wada & Norman (2001). Instead, a combination of several lognormal distributions may give a better approximation (Robertson & Kravtsov 2008).

The distribution of velocities (Figure 7) shows two distinct features. The warm phase contributes to a strong peak around 30 km s\(^{-1}\). The hot phase dominates the high-velocity tail. It has velocities as high as 2000 km s\(^{-1}\). The gas with velocities in this tail can easily escape the system. This gas forms hot outflows and galactic chimneys.

Finally, Figure 8 shows the distribution of the Mach number, \(M = u/c\), where \(u\) is the gas velocity and \(c\) is the sound speed. The distribution shows that 80% of the volume has supersonic motions. Almost all the warm phase, half of the hot phase and all the cold phase are supersonic flows. The subsonic range is dominated by the hot phase, In conclusion, the ISM can hold high supersonic motions, driven by stellar feedback.

4.6. Degrading Resolution

The resolution in cosmological simulations of galaxy formation is much lower than the simulations of the ISM presented before. So, we can wonder if this picture of stellar feedback can hold if the resolution is degraded. Therefore, the same ISM models have been performed with high resolution (14 pc) and with low resolution (60 pc). The fraction of volume filled with each gas phase is used as a proxy to check the global effect of stellar feedback in the ISM (Figure 9). The left panels show that the hot phase covers a significant volume in the high-resolution cases.

At low resolution and without runaway stars (top-right panel), the hot gas is almost absent from the simulation. Small filaments are not resolved and the subsequent star formation is suppressed in these areas that can easily be broken by stellar feedback. As a result, star formation is concentrated at the center of big clumps of gas. Stars inject energy in high-density regions, so this energy is radiated away without any thermodynamical effect in the medium at large (kpc) scales.

However, if the model of runaway stars is included, the hot phase is recovered at low resolution. Stars can now migrate away from high-density regions, so the injection of energy is more efficient in forming hot gas. As a result, the model with runaway stars can reproduce the effect of stellar feedback at kpc scales even at low resolution (60 pc).

If we decrease the resolution further, the hot phase is lost even if the model of runaway stars is used. For an ISM model with runaway stars and a resolution of 120 pc, the volume fraction filled with hot gas only reaches a maximum of 15%. The evolution of the volume fractions is similar to the 60 pc case without runaway stars (top-right panel of Figure 9).
Figure 9. Panels show the evolution of the volume occupied by each phase of the gas in four different models. The curves represent the three gas phases as in Figure 3. The hot phase is almost lost for the low-resolution run without runaway stars (top right panel). If runaway stars are included, the hot phase is recovered at low resolution. As a result, a fraction of runaway stars produces an effect on the global ISM and it is more evident in low-resolution runs.

This is because runaway stars usually have small velocities of \( \sim 10 \text{ km s}^{-1} \). As a result, they can only move \( \sim 100 \text{ pc} \) during their lifetimes. The effect of runaway stars is local, restricted to a few 100 pc scales. Therefore, the effect of runaway stars, as well as the efficiency of feedback, is greatly suppressed for a resolution worse than \( \sim 100 \text{ pc} \).

We found convergence in our results at \( \sim 60 \text{ pc} \) resolution only when runaway stars are included. If runaway stars are not included, the ISM model does not converge at 60 pc resolution (upper panels of Figure 9). That model needs \( \sim 4 \) times better resolution than the model with runaway stars, in order to resolve the effect of feedback at galactic scales. In that sense, runaway stars help to push the resolution convergence to lower resolution values. Therefore, we conclude that a model of runaway stars is a crucial ingredient for the stellar feedback efficiency, if the resolution is between \( \sim 20 \text{ pc} \) and \( \sim 60 \text{ pc} \), the typical resolution of our cosmological hydrodynamical simulations, which we discuss in Section 5.

4.7. The Expansion of a Hot Bubble

As an example of the conditions of the overheating regime discussed in Section 2, we can ask now how a hot bubble develops in the first place. The left panel of Figure 10 shows the physical conditions of a single volume element over 10 Myr. This volume develops a hot and dilute medium starting from a cold and dense phase. The gradients are computed using a three-point finite differences expression using the adjacent cells.

At the beginning, there are no stars present inside that volume. So, there is no feedback heating. At the same time, the density is high enough so the radiative cooling dominates over the UV background heating. As a result, the medium stays at the floor temperature of 300 K. The medium is also in hydrostatic equilibrium.

The situation drastically changes when young stars appear. They are not born inside that particular volume. Instead, they are drifting slowly from adjacent cells. The result is that this young population injects energy into the medium. So, heating dominates over cooling initially. The system responds by increasing the temperature. As a result, the cooling rate increases and the medium reaches a balance between cooling and heating rates in a very short timescale. This is because the cooling time is very short in those conditions. The net result is a medium slightly hotter than its surroundings so this overpressured region expands and the density inside that volume decreases.

Around \( 10^4 \text{ K} \), the cooling curve is a very steep function of temperature, so the temperature increases very slowly. But, at the same time, the density drops faster. As a result, the cooling rate decreases. This expansion is fueled by a roughly constant injection of energy from massive stars.

When the conditions of Equation (5) are fulfilled, the medium can pass through the peak of the cooling curve, somewhere between \( 10^4 \) and \( 10^5 \text{ K} \). After that, the gas has low density and a temperature of a few million degrees. As a result, heating dominates over cooling and a hot cavity is formed.

The right panel of Figure 10 shows a different situation. The volume is selected to be the high-density core of a molecular cloud formed in the low-resolution run shown in the top-right panel of Figure 9. Stellar feedback from the
stars formed in that core are able to heat the gas only to $10^4$ K. The gradients of pressure do not overcome gravity. The condition of bubble expansion is not fulfilled, Equation (7). As a result, the density remains high and a hot bubble cannot develop.

5. RESULTS OF COSMOLOGICAL RUNS

In previous sections, we have shown that our models of stellar feedback follow the effect of SN explosions and stellar winds in the ISM with a resolution of about 50 pc. The result is the formation of superbubbles and galactic chimneys. Both are filled with hot and dilute gas. The net result is a multiphase ISM and galactic outflows with large velocities.

Now, we can study the effect of stellar feedback in galaxy formation. We apply these feedback models in cosmological hydrodynamics simulations with a similar resolution of 35–70 pc. The simulations follow the formation of an MW-type galaxy starting from primordial density fluctuations. The computational box is $10 h^{-1}$ Mpc comoving box. We apply a zooming technique (Klypin et al. 2001) to select a Lagrangian volume of three virial radius centered in an MW-size halo at redshift 0. Then, we resimulate that volume with higher resolution. The region has a radius of about 1.5 $h^{-1}$ comoving Mpc. The simulation has about 5 million dark matter particles. They have three different masses. The high-resolution region is resolved with 3.4 million dark matter particles with a $7.5 \times 10^5 M_\odot$ mass per particle. The high-resolution volume is resolved with about 17 million volume elements at different levels of resolution. The maximum resolution is always between 35 and 70 pc. A short summary of the details of the simulations is given in Table 1. The cosmological model assumed throughout the paper has $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$, $h = 0.7$, and $\sigma_8 = 0.9$.

5.1. Heating Regime Versus Overcooling Regime

We compare two cosmological simulations with the same spatial resolution but different regimes. Table 1 shows a summary of the two simulations. The overcooling model has low star formation efficiency. In addition, the cosmological UV background according to Haardt & Madau (1996) is present over the whole evolution. Finally, a constant model of stellar feedback is used.

In the second simulation the heating regime develops. It has a high efficiency of star formation and the UV background is limited to its value at redshift 8. The SN model of stellar feedback was used in this case. We use a model of star formation in which each star formation event was treated as a random process (see the Appendix). In this way, we keep a moderate galactic SFR of $\sim 10 M_\odot$ yr$^{-1}$ inside the main galaxy at redshift 3.

The simulation in the cooling regime has a cold galactic ISM with temperature close to $10^4$ K. The simulation in the heating regime develops a three-phase ISM. Hot bubbles develop naturally. They produce galactic chimneys that combine in a galactic wind. As a result, galactic winds are the natural outcome from stellar feedback.

Figure 11 shows the main MW progenitor at redshift 3 for both simulations. The cooling model has a smooth density distribution with a small enhancement due to a pattern of spiral arms. In contrast, the multiphase model develops a clumpy medium of dense clouds surrounded by low-density bubbles. This is a multiphase medium.

5.2. Comparison of Circular Velocity Profiles

We can see now the effect of this multiphase medium in the galaxy assembly. We use the profile of circular velocity as a proxy of the mass distribution, $V_c = \sqrt{GM/R}$, where $G$ is the gravitational constant and $M$ is the mass inside a radius $R$. Figure 12 shows the profile of the circular velocity for the same galaxy in the two cases. The simulation with the overcooling problem shows a strong peak in the baryonic component of the circular velocity. Both gas and stars are very concentrated in the first kpc. In contrast, the simulation with multiphase medium has a more shallow circular velocity profile. This indicates a
Table 1
Parameters of Cosmological Models

| Parameter                        | Models                              |
|----------------------------------|-------------------------------------|
| Comoving box size                | 14.28 Mpc                           |
| Number of DM particles           | $5.4 \times 10^6$                   |
| DM particle mass                 | $7.5 \times 10^5 \, M_\odot$        |
| Number of cells                  | $17.5 \times 10^6$                  |
| Maximum resolution (proper)      | 35–70 pc                            |
| Maximum number of stars          | $3.7 \times 10^6$                   |
| Minimum mass of stellar particle | $10^4 \, M_\odot$                   |
| Model name                       | Overcooling                         |
| UV flux                          | H & M96                             |
| Star formation timescale $\tau$  | $4 \times 10^7$ yrs                 |
| Model for stellar energy release | Constant                            |
| Runaway stars                    | Not included                         |

mass in gas is $M_{\text{gas}} = 0.24 \times 10^{10} \, M_\odot$ and the baryons locked into stars accounts for only $0.14 \times 10^{10} \, M_\odot$.

5.3. Galactic Winds and Multiphase Medium

The hot bubbles in the multiphase medium develop galactic fountains that produce hot outflows with very high velocities: larger than $10^3 \, \text{km s}^{-1}$. These outflows are not produced in the cooling model. Figure 13 shows the difference in the distribution function of velocities for both cases. We take all cells at the highest levels of refinement. Therefore, we select a volume close to the galaxies in the simulations. The multiphase model has a bigger fraction of hot gas with much larger velocities than in the cooling model. These outflows contribute to the high-velocity tail of the distribution. In the cooling model, the distribution drops at 300 km s$^{-1}$, while in the hot case the tail extends beyond $10^3 \, \text{km s}^{-1}$.

These galactic-scale outflows can be seen Figure 14. It shows a slice of the simulation through the main MW-progenitor at redshift $z = 3.4$. At that redshift, its virial radius is 70 kpc and the total virial mass is $10^{11} \, M_\odot$. The gas density panel shows the galaxy embedded in a cosmological web of filaments. The galaxy at the center is blowing a galactic wind of hot and dilute gas with outflows velocities exceeding 300 km s$^{-1}$. The wind is rich in $\alpha$-elements and other products of the ejecta of core-collapse SN. These metal-rich outflows can contribute to the enrichment of the halo and the inter-galactic medium. These outflows can reach even higher velocities and can escape the galactic halo and enrich the inter-galactic medium. The galactic wind is produced by the combination of different galactic chimneys anchored in the multiphase ISM of the galaxy.

Figure 15 shows this multiphase ISM. Cold and dense clouds coexist with low-density bubbles filled with very hot gas. Warm gas with intermediate densities and temperatures filled areas of low star formation and inflows of gas with almost primordial composition.

5.4. Density Profile Consistent with a Cuspy Profile

Figure 16 shows the inner profile of density of the different components of the galaxy: dark matter, gas and stars at redshift 5. The density slope of the dark matter profile is consistent with a cuspy profile. In contrast, Mashchenko et al. (2008) reported the formation of a core rather than a cusp in the central $\sim 300$ pc of a much smaller galaxy at high redshift ($\sim 10^9 \, M_\odot$ at $z = 6$) in an SPH cosmological simulation. In their case, the mechanism that removes the cusp is gravitational heating from large fluctuations.
in the gravitational field. These fluctuations are produced by bulk motions of gas clumps driven by stellar feedback (Mashchenko et al. 2006). These motions remove episodically 90% of the mass from the central 100 pc after each burst of star formation. However, these gas clumps can be overproduced in simulations if the local Jeans length is not resolved (Truelove et al. 1997). This produces an artificial gas fragmentation and big clumps of stars. An excessive clumpiness can artificially increase the efficiency of this gravitational heating. In our simulations, we prevent this artificial fragmentation by the implementation of a pressure floor that increases the effective Jeans length to the resolution limit (Robertson & Kravtsov 2008). However, a direct comparison between our results and Mashchenko et al. (2008) is difficult because we follow the formation of a much bigger galaxy ($\sim 10^{10} M_\odot$ at $z = 5$), in which the effect of this gravitational heating driven by stellar feedback is less important. Therefore, these gravitational heating driven by stellar feedback cannot be ruled out in low-mass and gas-rich starburst galaxies.

6. SUMMARY AND CONCLUSIONS

We study the role of SN explosions and stellar winds in the formation of galaxies. Our approach is to model these processes without the ad hoc assumptions typically used on stellar feedback. Unlike many currently used prescriptions, we do not stop cooling in regions where the energy from stellar feedback is released (Thacker & Couchman 2000; Brook et al. 2004; Keres et al. 2005; Governato et al. 2007). Moreover, instead of using a subresolution model of a multiphase medium (Springel & Hernquist 2003; Cox et al. 2006), we resolve that multiphase medium. This is a more straightforward way to model stellar feedback. It eliminates many ad hoc assumptions.
This approach also produces naturally the outcomes usually associated with stellar feedback: hot bubbles, chimneys, and galactic winds.

Feedback heating has an effect in the ISM only when it dominates over radiative cooling. Section 2 shows the necessary conditions for this heating regime (Equation (5)–(7)). We find that a model of cooling below $10^4$ K is a key ingredient to fulfill these conditions. Thus, by resolving the conditions of molecular clouds ($T \approx 100$ K and $n_H > 10$ cm$^{-3}$), we resolve the conditions, in which stellar feedback is more efficient in the ISM on galactic scales.

We perform parsec-resolution simulations of a piece of a galactic disk in order to see the effects of stellar feedback and to test our models. When we use a realistic feedback and high resolution, the system has a low SFR and it forms hot superbubbles of 100 pc scales and kpc-scale galactic chimneys. We found that the cores of these chimneys reach temperatures of $10^7$–$10^8$ K, very low densities ($n_H < 10^{-4}$ cm$^{-3}$), and outflow velocities exceeding $10^3$ km s$^{-1}$.

Then, we degrade the resolution to see if this picture of multiphase ISM holds at a resolution that we can achieve in cosmological simulations. We found that runaway stars help to spread the effect of stellar feedback. They usually explode as SNe in low-density regions, a few 100 pc away from their natal molecular cloud. This is an effect found in nature (Stone 1991), which enhances the feedback. So, it should be included in any realistic model of stellar feedback.

Thermal feedback from young stars is able to produce long timescales of gas consumption by dissipating the star-forming gas. As a result, although this gas has high star formation efficiency, subsequent feedback processes produce a low SFR, averaged over all cold and dense gas. For example, in the simulations of the ISM described in Section 4, the gas with a density above the density threshold for star formation can form stars with high efficiency. However, the average star formation efficiency in the simulated clouds is roughly 2.5% over a free-fall timescale (Section 4.3). This is roughly consistent with estimations of the star formation efficiency in molecular clouds (Zuckerman & Evans 1974; Krumholz & McKee 2005; Krumholz & Tan 2007).

In cosmological simulations (Section 5), we find a moderate galaxy SFR, $SFR = 10 M_\odot$ yr$^{-1}$ and a significant amount of cold
and dense star-forming gas, $M_{\text{dense gas}} = 10^9 M_\odot$ inside a 5 kpc star-forming disk at redshift 3. These values are consistent with observations of nearby starburst galaxies. Using the observed relation between the SFR and the amount of star-forming gas of Gao & Solomon (2004), the SFR expected for $10^9 M_\odot$ of cold and dense gas is $20 M_\odot$ yr$^{-1}$. This is close to the value found in your simulations. Moreover, the galactic gas consumption timescale of dense gas, $M_{\text{dense gas}}/\text{SFR}$ is $\sim 100$ Myr. This is consistent with observed values in local starburst galaxies, which are usually used as analogs of star-forming galaxies at high redshift (Kennicutt 1998).

In our simulations, star formation proceeds in a way consistent with observations of star-forming galaxies (Kennicutt 1998). From the numbers given above, the gas surface density of the star-forming disk of 5 kpc radius at redshift 3 is $\Sigma_{\text{gas}} = 13 M_\odot$ pc$^{-2}$. Using the Kennicutt fit for nearby star-forming galaxies (Kennicutt 1998), the expected value for the SFR surface density is $\Sigma_{\text{SFR}} = 10^{-2} M_\odot$ yr$^{-1}$ Kpc$^{-2}$. The measured value from the simulations is $\Sigma_{\text{SFR}} = 1.3 \times 10^{-1} M_\odot$ yr$^{-1}$ Kpc$^{-2}$. Although this value is an order of magnitude higher than the expected value from the fit, it is still within the intrinsic spread found in observations. As a result, our simulated high-redshift galaxy seems more compact than the average star-forming galaxy at low redshift.

Our cosmological simulations with this model of stellar feedback do not have the overcooling problem. The fraction of cold baryons (stars and gas with a temperature below $10^4$ K) inside the virial radius at $z = 5$ is 0.6 times the cosmological value ($f_{\text{cosmo}} = 0.15$). This is consistent with galaxy mass models (Klypin et al. 2002). Instead of a cold disk, we produce a multiphase ISM with the same features seen in the simulations of the ISM described in Section 4: cold clouds, hot superbubbles, and galactic chimneys. The angular momentum problem is also reduced. Instead of a compact object with a strong peak in the rotation curve, we produce more extended galaxies with nearly flat rotation curves. Baryons are less concentrated when stellar feedback plays a role in the formation of galaxies. At the same time, the density profile of dark matter is still consistent with a cuspy profile.

In this picture, galactic chimneys powered by stellar feedback combine into a galactic wind. So, galactic winds appear as the natural outcome of stellar feedback in starburst galaxies at high redshifts. We found typical outflow velocities of 300 km s$^{-1}$ with some exceptional examples of outflows exceeding 1000–
2000 km s$^{-1}$. This is consistent with observation of outflows at high redshift (Law et al. 2007). From a sample of $\approx$100 galaxies at redshift $1.9 < z < 2.6$, C. C. Steidel et al. (2007, in preparation) find a mean outflow velocity of 445 km s$^{-1}$. Some cases have velocities of 1000 km s$^{-1}$.

This picture is only reproduced if the resolution is high enough to resolve the physical conditions of densities and temperatures of molecular clouds. Our cosmological simulations reach a resolution of 35 pc, which is 10 times better than the typical resolution in previous cosmological simulations (Sommer-Larsen et al. 2003; Abadi et al. 2003; Robertson et al. 2004; Brook et al. 2004; Okamoto et al. 2005; Governato et al. 2007).

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APPENDIX

A MODEL OF STAR FORMATION FOR SCALES BELOW 100 pc

A successful model of star formation in simulations should take into account the spatial resolution. For example, in typical cosmological simulations with a resolution of $\sim$1 kpc, the star formation is averaged over a large piece of ISM. These simulations should have a star formation model with a low star formation efficiency in order to reproduce the global efficiencies found in nearby galaxies. Observations of quiescent galactic disks show long gas consumption timescales averaged over a significant piece of a galaxy, $\tau_{\text{global}} = \Sigma_{\text{gas}}/\Sigma_{\text{SFR}} \sim 1$ Gyr, where $\Sigma_{\text{SFR}}$ is the SFR surface density and $\Sigma_{\text{gas}}$ is the gas surface density (Kennicutt 1998; Kennicutt et al. 2007). At the same time, for starburst galaxies, the global gas consumption timescale is much shorter, $\tau_{\text{global}} = 0.1$ Gyr (Kennicutt 1998).

However, if the resolution is high enough to resolve the regions where star formation mainly occurs, GMCs, the star formation efficiency can be much higher: the timescales for the formation of Galactic stellar clusters are around few Myr and 10%–40% of the gas is consumed (Greene & Young 1992; Elmegreen et al. 2000). As a result, simulations which can resolve the sites of star formation should have a high star formation efficiency only in the high-density regions, where molecular clouds can form (Tasker & Bryan 2006). In practice, the maximum resolution that we can afford is between 30–70 pc. This limits the maximum density that our simulations can resolve. For example, if we consider a typical GMC of $10^5 M_\odot$ (Rosolowsky et al. 2007), the mean density averaged over 30 and 80 pc scales will be 10–200 cm$^{-3}$. This gives an idea of the typical densities where star formation occurs in our simulations.

In our code, star formation is allowed in a time step, $d\tau_{\text{SF}}$, which is equal to the time step of the 0-level of resolution. This time step is controlled by the Courant condition for hydrodynamics and in our cosmological simulations, $d\tau_{\text{SF}} = 1$–2 Myr. During this period of time, a stellar particle can form only where the density and temperature reach a given threshold: $\rho_{\text{gas}} > \rho_{\text{SF}}$ and $T_{\text{gas}} < T_{\text{SF}}$. Even in these cold and dense regions, each star formation event is treated as a random event with a probability $P_T$ to occur. We roughly approximate the fact that regions with higher densities have a higher probability to host star formation events by assuming a simplified formula:

$$P_T = \frac{\rho_{\text{gas}}}{100 \rho_{\text{SF}}}. \quad (A1)$$

In this way, the number of stellar particles remains in a value that is not computational prohibited. In the formation of a single stellar particle, the SFR is proportional to the gas density (Kravtsov 2003):

$$\frac{d\rho_{\text{young}}}{dt} = \frac{\rho_{\text{gas}}}{\tau}, \quad (A2)$$

where $\rho_{\text{young}}$ is the density of new stars, $\rho_{\text{gas}}$ is the gas density, and $\tau$ is a constant star formation timescale. The density and temperature thresholds used are $\rho_{\text{SF}} = 0.035 M_\odot$ pc$^{-3}$ ($n_{\text{H}} = 1$ cm$^{-3}$) and $T_{\text{SF}} = 10^4$ K. In spite of the fact that we allow star formation starting at $10^4$ K, in practice the vast majority (>90%) of “stars” form at temperatures below 1000 K and more than half of the stars form below 300 K and densities larger than 10 cm$^{-3}$.

As described in Section 2.1, the ratio $\rho_{\text{young}}/\rho_{\text{gas}}$ should be $\sim$0.1–0.5 for typical conditions of dense, star-forming gas. Only in this case thermal feedback can produce overpressured hot bubbles in the sites of star formation, Equation (5). Based on Equation (A2), this ratio of densities can be expressed as

$$\frac{\rho_{\text{young}}}{\rho_{\text{gas}}} = \frac{d\tau_{\text{SF}}}{\tau}. \quad (A3)$$

As a result, thermal feedback is only efficient in dense, cold, star-forming gas if $d\tau_{\text{SF}}/\tau \sim 0.1–0.5$. This sets the value of $\tau$, because $d\tau_{\text{SF}}$ is set by the conditions of hydrodynamics, as explained before: $d\tau_{\text{SF}} = 1$–2 Myr. Therefore, the value
of $\tau$ should be in the range 2–20 Myr, consistent with the gas consumption timescales during the formation of Galactic stellar clusters (Greene & Young 1992; Elmegreen et al. 2000). However, this high local efficiency of star formation in high-density regions produces the observed low global efficiency, $\tau_{\text{global}} = 0.1–1$ Gyr, as discussed in Section 4.3.

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