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SUPERNOVAE-DRIVEN WINDS IN ISOLATED GALAXIES.

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Abstract. The hierarchical model of galaxy formation, despite its many successes, still suffers from the so–called "angular momentum" and "overcooling" problems. Supernovae–driven winds and their associated feedback on galaxy formation was proposed as a possible solution. It turned out that a proper modelling of supernovae explosions within a turbulent InterStellar Medium (ISM) is a difficult task. Recent advances have been obtained using a multiphase approach to solve for the thermal state of the ISM, plus some additional recipes to account for the kinetic effect of supernovae on the galactic gas. We describe here our implementation of supernovae feedback within the RAMSES code, and apply it to the formation and evolution of isolated galaxies of various masses and angular momenta. We have explored under what conditions a galactic wind can develop, if one considers only a quiescent mode of star formation. It turns out that, because of the ram pressure of infalling material from the gaseous halo, only moderately efficient winds appear, and in rather low mass ($< 10^{11}$ $M_\odot$) dark matter haloes.

1 Introduction

Supernovae–driven winds are a key ingredient of current galaxy formation models, in order to suppress the formation of low–mass galaxies and maybe to solve the so–called "overcooling" problem in the current hierarchical scenario of structure formation in the universe. The proper modelling of galactic winds is a difficult and unavoidable task, both in semi–analytical models (Hatton et al. 2003) and in numerical simulation (Springel & Hernquist 2003; Rasera & Teyssier 2006) of galaxy formation. Observational evidence for galactic outflows have already been pointed out by several authors (Heckman et al. 2000; Adelberger et al. 2003). They are usually associated to massive starbursts, for which very strong outflows are reported: for one solar mass of star formed in the galaxy, between 1 and 5 solar masses of gas are ejected in those winds (Martin 1999). This translates into a wind efficiency, usually noted η_w, ranging from 100% to 500%. The effect of galactic outflows can also be measured in the enrichment of the InterGalactic Medium (IGM) as observed in absorption lines of quasars spectra (Bouché et al. 2006).

Despite the difficulties of modelling supernovae explosions within a turbulent, multiphase and magnetized ISM, understanding the physics of the resulting large scale outflows is also a challenge. Many questions arise: what are the conditions for a galactic wind to develop and escape from the galaxy potential well ? What is the mass ejection rate of such a wind ? What is the metallicity of the wind and other associated observational signatures ? As explored by Fujita et al. (2004) in the context of an isolated, pre-formed galactic disc, the ram-pressure of infalling material might be the main limiting factor for galactic winds to exist. Springel et al. (2003) have performed SPH simulations of isolated star forming galaxies with strong winds, with a rather extreme implementation of supernovae feedback. Our goal is here to present new simulations of galactic winds performed with the RAMSES code, using Adaptive Mesh Refinement with a state-of-the-art shock-capturing scheme (Teyssier 2002).

In this paper, we follow the approach of Springel et al. (2003), considering an isolated Navarro, Frenk & White (1996) halo in hydrostatic equilibrium, that self-consistently cools down and forms a centrifugally supported disc in its center. Star formation and the associated supernovae explosions proceed according to rather standard recipies. Our paper is organized as follows. In Sect. 2 we present our model for isolated galaxy formation, with emphasis on our adopted numerical prescriptions. In Sect. 3, we describe a simple analytical model to compute the "wind break–up epoch", as a function of the model parameters. We finally present in Sect. 4 the results we have obtained in our numerical simulations, and discuss their implications for cosmology and galaxy formation.

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2 Numerical methods

We have considered that initially gas and dark matter follow the same NFW mass density profile, with 15% of the total mass in baryons. The gas temperature profile is computed in order to ensure hydrostatic equilibrium. The concentration parameter was set to $c = 10$, independant of the halo mass. The initial angular momentum was specified using the specific angular momentum profile found by Bullock et al. (2001) in simulated dark matter haloes $j(r) \propto M(r)/M_{vir}$, normalized to the halo spin parameter $\lambda = J|E|^{1/2}/GM_{vir}^{5/2}$, for which we have considered two cases: $\lambda = 0.04$ and $\lambda = 0.1$.

The gas is radiatively cooled using a metallicity-dependant cooling function (Courty & Teyssier, in prep.), since metal enrichment by supernovae feedback is self-consistently simulated in this study. In order to take into account the thermal feedback of supernovae explosions, we have implemented a simplified form of the multiphase model of Springel & Hernquist (2003), using a polytropic equation of state for the gas in the dense rotating disc. For that purpose, we define a density threshold ($n_0 \simeq 0.1$ cm^{-3}) above which the temperature is basically fixed to the polytropic equilibrium temperature. This density threshold also defines the criterion for which gas mass is converted into star particles using a Schmidt law, with a time scale parametrized by $t_* = t_0(n_H/n_0)^{-1/2}$. In this study, we use two different values, namely $t_0 = 3$ Gyr and 8 Gyr, resulting in different overall star formation efficiencies (see Rasera & Teyssier for details).

The last process we have implemented in RAMSES is the kinetic feedback due to supernovae explosions. This numerical ingredient is central to the present study. For each star particle formed, we create "debris particles", containing both supernovae ejecta and surrounding gas entrained by the blast wave. The velocity of the "debris particles" is computed according to a local Sedov solution. Debris propagate freely as collisionless particles over a distance corresponding to a blast wave radius of 2 cells. At this moment, debris release their mass, metal content, momentum and energy to the gas cell they have reached. In this way, a rather efficient kinetic feedback can be obtained, with local Sedov blast waves superimposed to the gas velocity field.

We have performed isolated galaxy simulations with two different virial masses $10^{10}\,M_\odot$ and $10^{11}\,M_\odot$. The box length of the simulations is equal to 6 R_{vir} in order to follow the collapse of the halo over several billions years ($\simeq 6$ Gyr). As the virial mass increases, we need to increase the resolution of the code as much as possible. In consequence we have taken a 128^3 coarse grid for all our simulations with 4 levels of refinement for the $10^{10}\,M_\odot$ halo and 5 levels of refinement for the $10^{11}\,M_\odot$ halo. This corresponds respectively to a resolution of about 150 pc and 160 pc.

3 A toy model for galactic winds

Following Fujita et al. (2004), we anticipate that the infall of gas from the halo will be the key process in the success or the failure of galactic outflows. Gas infall is responsible for fuelling the star forming disc with fresh gas, and therefore controls the supernovae explosion rate in the galaxy. Gas infall also provides a source of ram pressure that can confine any outflowing material from the disc. We propose here a very simple model in which the total gas mass evolves according to the following "open box solution"

$$M_g(t) = \int_0^t \exp(\frac{u-t}{t_*})\dot{M}_{acc}(u)\mathrm{d}u\,, \quad \text{and} \quad \dot{M}_*(t) = \frac{M_g(t)}{t_*} \tag{3.1}$$

The accretion rate $\dot{M}_{acc}$ is computed assuming that each shell of our NFW halo free-falls down to the center, where the disc has formed. We then compare the supernovae luminosity in the disc to the accretion luminosity of infalling gas

$$L_w(t) = \chi \dot{M}_*(t)\eta_{sn}\frac{E_{SN}}{M_{SN}}\,, \quad \text{versus} \quad L_{acc}(t) = \frac{1}{2}\dot{M}_{acc}v_\infty^2 \tag{3.2}$$

where v_∞ is the terminal velocity of free-falling gas shells, computed using the NFW mass profile. The key parameter of the model, χ, is called the "hydrodynamical efficiency" and refers to the conversion efficiency of supernovae energy into galactic wind energy. $\eta_{SN} \simeq 10\%$ is the mass fraction of stars that explode into type II supernovae, according to standard stellar initial mass function, $E_{SN} \simeq 10^{51}$ erg is the typical energy produced by one single supernova, and $M_{SN} \simeq 10\,M\odot$ is its typical progenitor mass. The hydrodynamical efficiency is likely to be small: a large fraction of the supernovae energy must remain inside the disc, providing both thermal and kinetic feedback to the turbulent, multiphase interstellar medium. The fraction of energy that manage to

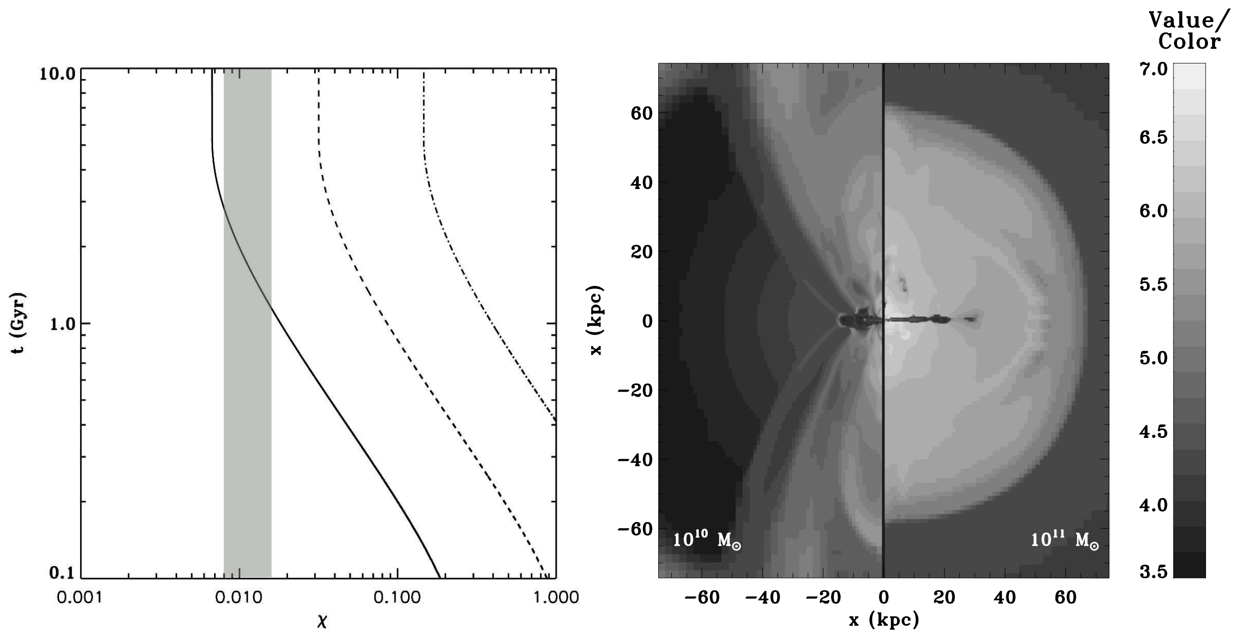

Fig. 1. *Left*: Wind break-out epoch as a function of hydrodynamical efficiency χ for three different halo masses: $10^{10}\,\mathrm{M}_\odot$, $10^{11}\,\mathrm{M}_\odot$, $10^{12}\,\mathrm{M}_\odot$ (from left to right). The shaded area corresponds to the allowed range, as demonstrated by our numerical simulations. *Right*: Comparison of the temperature map obtained at $t = 6$ Gyr for 2 different simulations, with a galactic wind breaking out of the low mass halo (left), and a galactic fountain remaining close to the disc in the high mass case (right).

escape from the dense gaseous disc will depend on the disc characteristic (thickness, size, gas content). In our simulations, these properties will be specified by the the spin parameter of the halo and by the star formation time scale of the Schmidt law. In Fig. 1, the wind break-out epoch (i.e. when the wind luminosity exceeds the accretion luminosity) is shown for various halo masses, as a function of the unknown parameter χ. One clearly sees that the smaller the hydrodynamical efficiency, the later the wind will blow out of the disc. More importantely, for each halo mass, a minimum efficiency is required in order for a wind to appear: 0.7% (resp. 3% and 15%) for a 10^{10} $\mathrm{M}_\odot$ halo (resp. 10^{11} and 10^{12}). The goal of this study is to compute this hydrodynamical efficiency using self-consistent numerical simulations of isolated galaxies.

4 Simulation results

Our various simulations draw a similar qualitative picture: a cold centrifugally supported disc form at the halo center from the inside out, whose size depends mainly on the halo spin parameter. The star formation rate in the galaxy rises sharply (see Fig. 2) and hot supernovae bubbles start to break out of the disc. After roughly 1 to 3 Gyr, either a galactic wind develops (for the low mass halo) or a galactic fountain sets in (for the high mass halo). Figure 1 shows a map of the gas temperature obtained after 6 Gyr in both cases. One clearly sees a noozle-like structure escaping from a small, thick disc in the 10^{10} M$\odot$ case, while only hot plumes and cold clumps are seen in the 10^{11} M$\odot$ case, oscillating close to a large thin disc, as they are confined by a hot, ram pressure driven atmosphere.

In Fig. 2 we have plotted the mass flux flowing out of the disc, computed in a spherical shell of size $r = [5r_s; 7r_s]$, in the $10^{10}\,\mathrm{M}_\odot$ case only, for various values of λ and t_0. The wind break-out epoch can be determined with great accuracy: it appears as a sharp rise in the mass outflow rate curve. Using our toy model, we can determine the corresponding hydrodynamical efficiency, which, depending on the simulation parameters, varies between 0.8 to 2%. Injecting these values in the toy model for a $10^{11}\,\mathrm{M}_\odot$ halo, we predict that no wind can break-out in this case. Our numerical simulations do confirm this, as they show only a galactic fountain with no gas leaving the halo potential well.

When the galactic wind is fully developped, it shows a typical nozzle shape, and the mass outflow rate reaches its asymptotic value, around 0.01 $M_\odot$/yr. One can then compute the wind efficiency, defined as $\eta_w = \dot{M}_w/\dot{M}_*$, which ranges from 10 to 20%, an order of magnitude below what is expected from Lyman Break galaxies observations (Martin 1999).

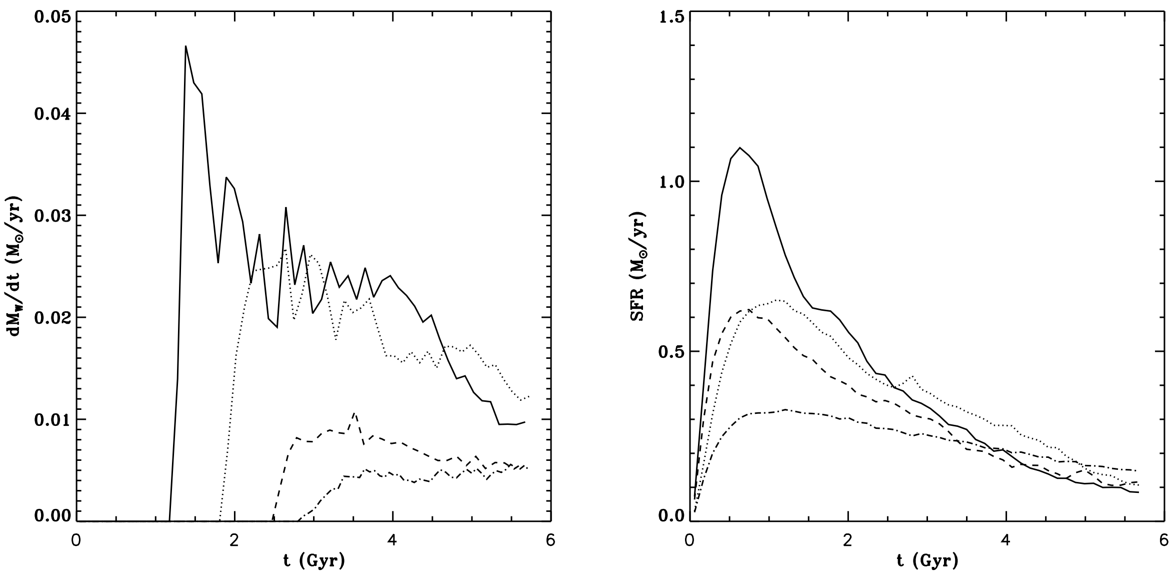

Fig. 2. Flux of mass (left) outflowing of the $10^{10}\,M_\odot$ halos calculated between $r = [5r_s; 7r_s]$ and SFR (right) for the $\lambda = 0.04$ and $t_0 = 3$ Gyr (solid line), $\lambda = 0.04$ and $t_0 = 8$ Gyr (dotted line), $\lambda = 0.1$ and $t_0 = 3$ Gyr (dashed line) and $\lambda = 0.1$ and $t_0 = 8$ Gyr (dash-dotted line).

5 Conclusion

Using a quiescent model of star formation in isolated galaxies, self-consistently simulated from a cooling NFW halo, we have studied the conditions for a galactic wind to break-out of the dark matter halo potential well. Our simulations have shown that no wind can form in halo of mass greater than $10^{11}\,M_\odot$, even for our most favorable couple of halo parameters ($\lambda = 0.04$, $t_0 = 3$ Gyr). Using a simple toy model, we understand this failure as due to the ram pressure of infalling material confining the outflowing wind. Using a more realistic cosmological setting may result into non–spherical accretion flows, and therefore to a less stringent criterion for a wind to break-out. A proper modelling of starburst (yet to be invented) might also provide an easier route for increasing the feedback efficiency of supernovae-driven outflows.

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