SUPERNOVA OUTFLOWS IN GALAXY FORMATION

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Abstract.

We investigate the generation of galactic outflows by supernova feedback in the context of SPH cosmological simulations. We use a modified version of the code GADGET-2 which includes chemical enrichment and energy feedback by Supernova. We find that energy feedback plays a fundamental role in the evolution of galaxies, heating up the cold material in the centre of the haloes and triggering outflows which efficiently transport gas from the centre to the outskirts of galaxies. The impact of feedback is found to depend on the virial mass of the system with smaller systems, such as dwarf galaxies, being more strongly affected. The outflows help to establish a self-regulated star formation process, and to transport a significant amount of metals into the haloes and even out of the systems. According to our results, energy feedback by supernovae could be the mechanism responsible for the chemical enrichment of the intergalactic medium.

1 Introduction

The important impact of supernova (SN) explosions on the evolution of galaxies has been discussed by numerous numerical works during the last years (e.g. Katz & Gunn 1991; Cen & Ostriker 1992, 1999; Yepes et al. 1997). On one hand, SNe constitute the main source of heavy elements in the Universe, and the presence of metals in diffuse gas can accelerate the gas condensation in potential wells, since the cooling rate of baryons depends sensitively on metallicity (Sutherland & Dopita 1993). On the other hand, the injection of energy into the interstellar medium by SN explosions provides an efficient mechanism to heat up material in the centre of the haloes and to transport it to the outskirts of galaxies. These outflows are thought to play a crucial role in the subsequent evolution of galactic systems, helping to establish a self-regulated star formation process and triggering a redistribution of mass and metals.

Observationally, it is found that the intergalactic medium is contaminated with metals. Since metals are produced in stellar interiors and ejected into the star forming regions deep inside galactic potential wells, an efficient mechanism for transporting metals to the low-density intergalactic medium is needed in order to explain the observed contamination. Strong SN outflows constitute a natural explanation for the presence of metals in the intergalactic medium.

We use numerical Smoothed Particle Hydrodynamics (SPH; Gingold & Monaghan 1977; Lucy 1997) simulations which take into account chemical enrichment and energy feedback by SN in order to study the impact of SN explosions on the evolution of galaxies and the chemical enrichment patterns of the stellar populations, as well as the gas in the interstellar and the intergalactic media. Numerical codes including chemical and energy feedback have already become an important tool for studying the effects of SN feedback in the cosmological context. However, SPH codes have encountered severe complications in realistically accounting for SN explosions, with the energy feedback being particularly difficult to describe. Previous works have shown that a simple injection of thermal energy into the cold gas has only a small effect on the hydrodynamics, as a consequence of the short cooling times of the dense cold gas, which thermalizes the feedback energy very quickly (e.g. Kay et al. 2002; Marri & White 2003; Springel & Hernquist 2003). We have developed a new model which is aimed at improving the description of SN feedback, allowing us to overcome some failures of previous approaches without introducing any scale-dependent parameter (Scannapieco et al. 2005a,b). In this work, we analyse the effects of SN explosions on the evolution of isolated disc-type systems, focusing on the star formation activity and the impact of the outflows on the dynamical and chemical evolution of galaxies.

This article is organized as follows. In Section 2, we summarise the main characteristics of our model for chemical enrichment and energy feedback by supernova. In Section 3, we analyse the properties of galactic objects of different virial mass, in relation to the star formation activity and metal distribution. Finally, in Section 4 we give our conclusions.
2 Numerical Models

We use a novel model for chemical enrichment implemented in the code GADGET-2 (Springel & Hernquist 2003, Scannapieco et al. 2005a,b) in order to study the impact of supernova feedback on the formation of galaxies. The code includes metal-dependent cooling, star formation, chemical enrichment and energy feedback by Type II and Type Ia supernovae. The model is tied to an explicit multiphase treatment (Marri & White 2003) for the gas components and includes a treatment of a cosmological UV background.

Here we briefly describe our model for chemical enrichment and energy feedback. The interested reader is referred to Scannapieco et al. (2005a,b) for details. At each integration time-step of the code, we calculate the number of exploding Type II and Type Ia supernovae, accounting for the associated chemical and energy production. We assume that SNII explode within a time-step of integration of the code, while SNIa life-times are selected randomly from a given range (Scannapieco et al. 2005a). Each SN injects $10^{51}$ ergs of energy into the surrounding gas. Our model for SN feedback is based on an explicit segregation of the gas surrounding an exploding star particle into a cold-dense phase and a diffuse phase for the purpose of releasing its energy and chemical production. These phases are loosely referred to as cold and hot, and are defined in the following manner: the cold phase is formed by the gas with $T < 2 T_\star$ and $\rho > 0.1 \rho_\star$ ($T_\star = 4 \times 10^4$ K, $\rho_\star = 7 \times 10^{-26}$ g cm$^{-3}$), while the rest of the gas is considered to be part of the hot phase. Note that these phases are determined only for exploding star particles at the time of metal and energy distribution. In our model, we assume that the feedback energy is dumped in given proportions into the cold and the hot phases of the exploding stars: a fraction $\epsilon_c$ is dumped into the cold phase while the remaining $\epsilon_h = 1 - \epsilon_c$ goes into the hot one. For the hot phase, the injection of feedback energy is simultaneous with the explosion. In contrast, for each particle in the cold phase, we define a reservoir in which the energy received by successive explosions is accumulated. When this energy is sufficient for the particle to reach the entropy of its hot neighbours, the particle is promoted to the hot phase, and the reservoir energy is dumped into its internal energy. This promotion scheme drives a transformation of gas from the cold-dense phase to the hot-diffuse one (Scannapieco et al. 2005b). Note that the scheme for energy feedback does not introduce any ad-hoc parameter, and there is only one free parameter to assume: $\epsilon_c$ (or equivalently $\epsilon_h$). Metals are also distributed into the hot and cold phases of the exploding stellar particles accordingly to the corresponding fractions ($\epsilon_h$ or $\epsilon_c$). However, the chemical release occurs always simultaneously with SN explosions.

The simulations also include a multiphase treatment for the gas component similar to the model of Marri & White (2003), which is based on an explicit decoupling of the gas with different hydrodynamical properties. Within the scheme, we explicitly prevent gas particles of being neighbours if their entropies differ by more than a given factor. The model is found to be insensitive to the value used for the decoupling within physically motivated limits. In our model, a better defined hot phase is allowed to form, even within cold regions (Scannapieco et al. 2005b).

3 Results

In order to investigate the performance of our SN feedback model, we simulate the evolution of isolated disc-type galaxies. The initial conditions are generated by radially perturbing a spherical distribution of superposed dark matter and gaseous particles in order to give rise to a density profile of the form $\rho(r) \sim r^{-1}$. The sphere is initially in solid body rotation with an angular momentum characterised by a spin parameter of $\lambda \approx 0.1$. We have simulated systems of both $10^{12}$ and $10^{10}$ M$_\odot h^{-1}$ virial mass ($h = 0.7$), 10 per cent of which is in the form of baryons, and with a ~9000 particle resolution for both the gaseous and the dark matter components. For the $10^{12}$ M$_\odot h^{-1}$ system, this yields a mass resolution of about $10^8$ M$_\odot h^{-1}$ and $10^7$ M$_\odot h^{-1}$ for the dark matter and gas particles, respectively. We adopt maximum gravitational softenings of 1.50, 0.75 and 1.13 kpc $h^{-1}$ for dark matter, gas and stars, respectively. For the $10^{10}$ M$_\odot h^{-1}$ mass system, the softenings were correspondingly rescaled.

For all tests, we have used the same star formation and SN parameters: a star formation efficiency of $c = 0.1$, a SNIa rate of 0.001 relative to SNII and a life-time interval for SNIa of [0.1,1] Gyr. In order to test the dependence of the model on the feedback parameter $\epsilon_c$, which sets the fraction of energy and metals distributed into the cold phase, we have performed simulations with $\epsilon_c = 0.1, 0.5$ and 0.9. For comparison, we have also run simulations without including the energy feedback treatment. In Table II we summarise the main feedback parameters of the simulations.

In the left panel of Fig. we show the star formation rates for our $10^{12}$ M$_\odot h^{-1}$ virial mass systems. From this figure we can see that the inclusion of feedback always leads to a decrease in the star formation activity. This is a consequence of the injection of energy by SNe which heats up the gas surrounding the explosions. As a result, the density of the cold gas from which stars are formed decreases, reducing in turn the star formation activity. We can also see that as we inject a larger fraction of the energy into the cold phase (i.e. as the $\epsilon_c$ value increases), the decrease in the star formation rate is stronger. In the extreme case of $\epsilon_c = 0.9$, the star formation rate is significantly reduced after the formation of the first stars. Later on, the gas is able to cool down again, triggering a starburst. We find that the final stellar mass fraction of the test run with $\epsilon_c = 0.1$ is 20 per cent lower than its counterpart in the test without feedback, while tests with $\epsilon_c = 0.5$ and 0.9 lead to a reduction of $\sim 50$ per cent with respect to the no feedback test.
Table 1: Main characteristics of the test simulations: virial mass, input feedback parameters $\epsilon_c$ and $\epsilon_h$ (for the feedback tests $\epsilon_h = 1 - \epsilon_c$), and mass of gas with positive total energy, normalized to total baryonic mass (unbound gas fraction, $f_{\text{unbound}}$).

| $M_{\text{vir}}$ [$M_\odot \, h^{-1}$] | $\epsilon_c$ | $\epsilon_h$ | $f_{\text{unbound}}$ |
|---------------------------------|------------|-------------|-----------------|
| $10^{12}$                       | 0.0        | 0.0         | 0.02            |
| $10^{12}$                       | 0.1        | 0.9         | 0.34            |
| $10^{12}$                       | 0.5        | 0.5         | 0.56            |
| $10^{12}$                       | 0.9        | 0.1         | 0.53            |
| $10^{10}$                       | 0.0        | 0.0         | 0.00            |
| $10^{10}$                       | 0.1        | 0.9         | 0.98            |
| $10^{10}$                       | 0.5        | 0.5         | 0.62            |
| $10^{10}$                       | 0.9        | 0.1         | 0.87            |

Figure 1: Star formation rate for our tests of $10^{12}$ (left panel) and $10^{10}$ (right panel) $M_\odot \, h^{-1}$ virial mass galaxies, for runs with no feedback (solid lines) and with feedback and different input parameters: $\epsilon_c = 0.1$ (dotted lines), $\epsilon_c = 0.5$ (dashed lines) and $\epsilon_c = 0.9$ (dotted-dashed lines).

In the case of the $10^{10} \, M_\odot \, h^{-1}$ system, we find that the effects of feedback are more extreme, as can be seen from the right panel in Fig. 1. In this case, there is a stronger dependence of the results on the input feedback parameter. For $\epsilon_c = 0.1$ (i.e. 10 per cent of the feedback energy is injected into the cold phase), most of the hot gas is accelerated outwards before it can collapse. The gas that is able to cool gives rise to the remaining level of star formation, which leads to an almost negligible final stellar mass fraction. Note that in this case, the cold gas receives only 10 per cent of the feedback energy, so it is unlikely that it can receive enough energy to be heated up. In the test with $\epsilon_c = \epsilon_h = 0.5$, the energy injected after the first stars helps to reduce the star formation rate but the system is able to cool down and collapse later. In this case, the interplay between radiative cooling and heating by SN leads to a series of starbursts, setting a self-regulated mechanism for the star formation. This bursty behaviour is consistent with observational results of dwarf galaxies which find that the star formation is delayed in such low mass systems and recent starbursts can develop (Kauffmann et al. 2003). Finally, if the bulk of the SN energy is injected into the cold phase ($\epsilon_c = 0.9$), most of the gas is heated up and swept away from the system very quickly, leading to a negligible final fraction of stars. It is interesting to note that if we inject most of the energy either into the cold or the hot phase, the final stellar mass formed is very small in both cases.

So far we have analysed how the star formation rates can be self-regulated depending on the virial mass of the systems as a result of the injection of energy triggered by SN explosions. Here, we discuss the strength of the outflows generated by the feedback. For this purpose we calculate the unbound gas fraction, defined as the mass of gas with positive total binding energy (kinetic plus gravitational) normalized to the total baryonic mass, as an estimator of the feedback strength. We find that the fraction of unbound gas varies with the details of the SN energy injection and the mass of the system. In Table 1 we show the fraction of unbound gas, normalized to total baryonic mass, from our tests of both virial mass and for different choices of the feedback parameter, after 0.7 Gyr $h^{-1}$ of evolution. From the results of the $10^{12} \, M_\odot \, h^{-1}$ virial mass system we can see that the unbound
gas fraction increases with the value of $\epsilon_c$, so the fraction of unbound material increases when a larger fraction of the energy is dumped into the cold phase. In these tests, regardless of the $\epsilon_c$ value, we find that $\sim 30$ per cent of the unbound gas has $|v_z| > 500$ km s$^{-1}$ after the starburst, where $|v_z|$ is the absolute value of the z-velocity. Note that if energy feedback is not included, there is no efficient mechanism to transport material out of the system, and the fraction of unbound gas is negligible. In the case of the $10^{10} \ M_\odot \ h^{-1}$ virial mass system, we find that the test with $\epsilon_c = 0.5$ has an unbound gas fraction of 60 per cent, while in the other feedback tests $\sim 90$ per cent of the gas content is expelled from the system, preventing the gas collapse. Hence, in our model the strength of the outflows depends on the virial mass as well as on the input feedback parameter.

The outflows constitute an effective mechanism to transport metals to the outskirts of galaxies. Note that the outflows are generated in the inner parts of the systems where the gas is highly contaminated. Hence, if outflows are able to transport a significant fraction of the gas outwards, they can contaminate the haloes. In Fig. 2 we show metallicity maps for our test of the $10^{12} \ M_\odot \ h^{-1}$ system run with $\epsilon_c = 0.5$, for three different times. It is clear from this figure that metals are effectively transported outwards in our model, enriching the outer parts of the systems. Note that the outflows are mostly perpendicular to the disc plane.

Based on our results, we argue that energy feedback could be responsible for the existence of metals in the intergalactic medium. As an example, we show in Fig. 3 a metallicity map up to 300 kpc $h^{-1}$, for our test of $10^{12} \ M_\odot \ h^{-1}$ mass and $\epsilon_c = 0.5$, after 1 Gyr $h^{-1}$ of evolution. From this figure, we can see that enriched gas has been effectively transported outwards and has even escaped from the potential well of the system. From these initial conditions of isolated galaxies we cannot reliably constrain the spatial extent of the contamination. We plan to study cosmological simulations for this purpose (Scannapieco et al. 2005c).

4 Conclusions

We have analysed the impact of supernova explosions on galaxies using SPH cosmological simulations which include chemical enrichment and energy feedback. We have run simulations of isolated galaxies from idealized initial conditions of both $10^{10}$ and $10^{12} \ M_\odot \ h^{-1}$ virial mass, and studied their star formation histories and metal distributions.

Our model for SN feedback is able to heat up material in the centre of the systems and to produce substantial outflows of gas. For a given feedback input parameter (which sets the fraction of energy dumped into the cold gas), the strength of the outflows is found to depend on the virial mass.

The outflows drive a redistribution of the gas, lifting cold material from the centre of the haloes, heating it up and transporting it to the outskirts of galaxies. As a result, a significant fraction of the gas is swept away from the centre of the systems, reducing the cold gas density and consequently the star formation rate. The outflows therefore help to establish a self-regulated star formation process.

According to our results, the effects of SN feedback on the formation of dwarf galaxies should be crucial. In our tests of $10^{10} \ M_\odot \ h^{-1}$ mass systems, we find that SN feedback is able to either stop the star formation activity, to reduce it and give rise to a more or less continuous (and low) level, or to trigger a series of starbursts, depending on the input feedback parameter.

The outflows triggered by SNe also leave imprints on the chemical enrichment patterns. Since they are generated in the centre of the haloes where the material is highly contaminated, the outflows transport an important fraction of enriched material outwards. This leads to a chemical contamination of the haloes and
could even explain the existence of metals in the intergalactic medium. In order to study this process in detail and to predict the large-scale distribution of metals, it will be necessary to consider fully self-consistent cosmological simulations.

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