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Studying Galactic Chemical Properties by using Cosmological Numerical Simulations

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Abstract: We developed a chemical code within GADGET2 which allows the description of the enrichment of the Universe as a function of redshift, taking into account detailed metal production by supernovae Ia and II, and metal-dependent cooling. This is the first numerical code that includes both chemical production and metal-dependent cooling in a cosmological context. By analysing the cosmic star formation rate, we found that the effects of considering a metal-dependent cooling are important, principally, for $z \lesssim 3$. In simulations where primordial cooling functions are used, the comoving star formation rate could be up to 20% lower than those obtained in runs with metal-dependent cooling functions. Within galaxy-like objects, the presence of chemical elements changes the star-formation rates and, consequently, the chemical production and patterns of stars. However, owing to non-linear evolution of the structure, the effects depend on the evolutionary history path of each galaxy-like object.

Keywords: Galaxy: dynamical and chemical evolution — methods: *N*-body simulations

1 Introduction

The dramatic build-up of observational evidence for the chemical properties of the stellar population and interstellar medium in the Universe has proved to have an important impact on the study of galaxy formation. Chemical elements are produced in stellar interiors and ejected in a quiescent or violent way after characteristic times determined by stellar evolution. Afterwards, these elements can be mixed up by other phenomena such as mergers and interactions. It is also important to notice that metal production is directly linked to the star formation history which can be also affected by the environment (Barton et al. 2000; Lambas et al. 2003). As a consequence, it is expected that chemical patterns store information of the process of galaxy formation giving rise to fossils of different order (Freeman & Bland-Hawthorn 2002).

Another important motivation for including a chemical treatment in galaxy formation models is related to the fact that baryons cool according to their metallicity. Sutherland & Dopita (1993) showed that a gas cloud with solar metallicity cools at a rate of up to few orders of magnitude more efficiently than a primordial gas cloud. Hence, the enrichment of the interstellar medium can have dynamical consequences and affect the formation of structure. In this work we focus on the assessment of the relevance of consistently taking into account a metal-dependent cooling.

Mosconi et al. (2001) developed the first detailed chemical model within a cosmological code by coupling the production of individual chemical elements in a Smooth Particle Hydrodynamics (SPH) scheme. Because of the violent character of our Universe, the development of chemical models within hierarchical scenarios turns out to be a powerful tool (e.g. Yepes et al. 1998). In this work we followed the implementation of Mosconi et al. and introduce an improved chemical model within GADGET2 (Springel & Hernquist 2002), which also takes into account the corresponding cooling processes for different isotopes, as described by Sutherland & Dopita (1993).

In Section 2 we briefly summarize the main important aspects of the chemical code. Section 3 shows the first results and Section 4 presents the conclusions.

2 The Chemical and Cooling Model

The chemical model has been implemented in GADGET2 (Springel & Hernquist 2002), which is based on a modified version of SPH that conserves entropy (energy and angular momentum). However, we do not use the authors' multiphase model. Stars are formed stochastically according to a probability function defined by the relation between cooling and dynamical time (see also Lia et al. 2001).

Our chemical model is based on the implementation described by Mosconi et al. (2001). Type II supernovae are considered to form from stars with $M > 8\,M_\odot$ and to produce metals according to Woosley & Weaver (1995) yields. A standard Salpeter Initial Mass Function has been adopted. Type Ia supernovae are assumed to originate from binary systems following the model of Thielemann et al. (1993). In this new version, instead of assuming a fixed lifetime for type Ia supernovae, as in the implementation of Mosconi et al., we randomly sample the lifetime of binary systems in the range 0.1–5 Gyr.

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Chemical elements are distributed within neighbouring particles of the gas by using a spline kernel function. In order to estimate the correct environment of stars when SN explode, we re-calculate the gaseous neighbours of the stellar particles each time chemical elements are released. In this implementation we have not included the treatment of a multiphase medium and supernova energy feedback (C. Scannapieco et al., in preparation).

A direct consequence of stellar evolution is that as stars evolve and eject material into the interstellar medium, there is a shift in the chemical composition of the interstellar medium towards media with more heavy elements, which are more efficient at cooling. Sutherland & Dopita (1993) calculated functions of the net energy radiated by gaseous components of different metallicities finding that, at a given temperature, the higher the metallicity, the larger the rate of radiated energy.

How the gas component cools is of primary importance in galaxy formation. For example, the relation between the cooling and dynamical timescales establishes which fluctuations will actually be able to collapse and form a baryonic cold structure, or when and how fragmentation of gas clouds takes place (Heger & Woosley 2002). The rate of gas cooling also plays an important role in the regulation of star formation and, consequently, on the subsequent ejection of enriched material. Taking these aspects into account, we include in our chemical code the cooling rate functions calculated by Sutherland & Dopita, allowing us to describe the evolution of the matter in a more realistic way.

We performed tests of the model by running simulations of an isolated collapse of a gaseous sphere, with a spin parameter $\lambda = 0.1$ onto a fixed Navarro–Frenk–White (1997; NFW) potential well. The disc has a total baryonic mass of $10^{10}h^{-1}\,\mathrm{M}_\odot$ and has been resolved with 2500, 10 000, and 40 000 baryonic particles, to test numerical effects. We run tests by letting the gas cool according to primordial and metal-dependent cooling functions.

We also run cosmological tests of ΛCDM cosmologies consistent with the concordance model ($\Omega_\Lambda = 0.7$, $\Omega_\mathrm{m} = 0.3$, $H_0 = 70\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$). The simulations correspond to a volume box of $10h^{-1}$ Mpc ($h = 0.7$) with 2×50^3 particles. Three different runs were performed using different cooling functions: solar, primordial, and metal-dependent. Note that we restrict this study to a comparative analysis of the main consequences of the chemical model on the star formation and metal production rates. However, we would like to stress that the cosmological tests are low-resolution ones and, consequently, gas particles might be artificially overcooling, even in primordial runs. In order to confirm the preliminary results presented in this paper, higher numerical resolution experiments will be performed and discussed in a forthcoming paper.

3 Results

We first discuss results of the simple disc formation. In Figure 1 we have plotted two projections of the spatial distribution of stars in the disc test resolved with 10 000 particles by segregating them according to their [Fe/H] abundances. Note that the distribution of stars is very similar in the three metallicity ranges: [Fe/H]< -1.5 (lower panel), $-1.5 <$ [Fe/H] < 0 (central panel), and [Fe/H] > 0 (upper panel), all of them contributing to the bulge and disc components. Note that only very low-metallicity stars can be directly linked to an old population, while high-metallicity ones can be either old or young.

In Figure 2 we show mean [O/Fe] values for the stellar populations as a function of radius in equal-space bins. We have plotted runs with primordial (solid lines) and metal-dependent (dashed lines) cooling functions during the first period of evolution. As it can be seen from this Figure, the first stars appear at the central region and have, on average, α-enhancement. However, the following generations remain with a mean around solar metallicity, except in the disc region which is dominated by iron-rich stars. Recall that we are showing averages in concentric shells. Although stars formed in both runs have different abundance patterns, these differences are within the standard dispersion. The limited impact of the metal-dependent cooling on the metal production can be also seen from the fact that the star formation histories of the two discs show no significant differences. It is clear that, at least in this idealised disc formation with no energy feedback, there are no large differences when the gas is cooled down according to its metallicity. This may be owing to the fact that metals remain within the denser regions which are anyway very efficient at cooling, while the lower-density gas in the halo does not get enriched at all. Moreover, in these experiments there are not violent events such as mergers that can help to mix up metals.

Regarding the cosmological simulations, in Figure 3 (left panel) we show the comoving star formation ρ_SFR and metal production ρ_Z rates for the three runs with solar (solid lines), primordial (dashed lines), and metal-dependent (dot-dashed lines) cooling functions. We can see that the largest difference is found for the run with fixed solar cooling and for $z \leq 3$. The ρ_SFR of the metal-dependent cooling run, can be up to $\approx 50\%$ lower than that of the solar cooling test, and up to $\approx 20\%$ higher than the primordial cooling run. Similar relations are found for the metal production rate ρ_Z. The right panel in Figure 3 shows the fraction of gas with $T > 10^5$ K in different density bins for the whole simulated volume, for the three runs with solar (solid lines), primordial (dashed lines), and metal-dependent (dot-dashed lines) cooling functions. We can see that the fraction of hot gas for the solar cooling test is significantly lower than the corresponding ones for the other tests.

From the distribution of matter of the whole simulated volume, we identified Galaxy-like objects (GLOs), defined as virialised structures at $z = 0$ by using a density-contrast algorithm. We constructed the star formation history of the GLOs and analysed the chemical properties of their stellar populations and interstellar medium. Typical GLOs comparable to the Milky Way have virial masses of the order of $10^{12}\,\mathrm{M}_\odot$. Figure 4 shows the fraction of

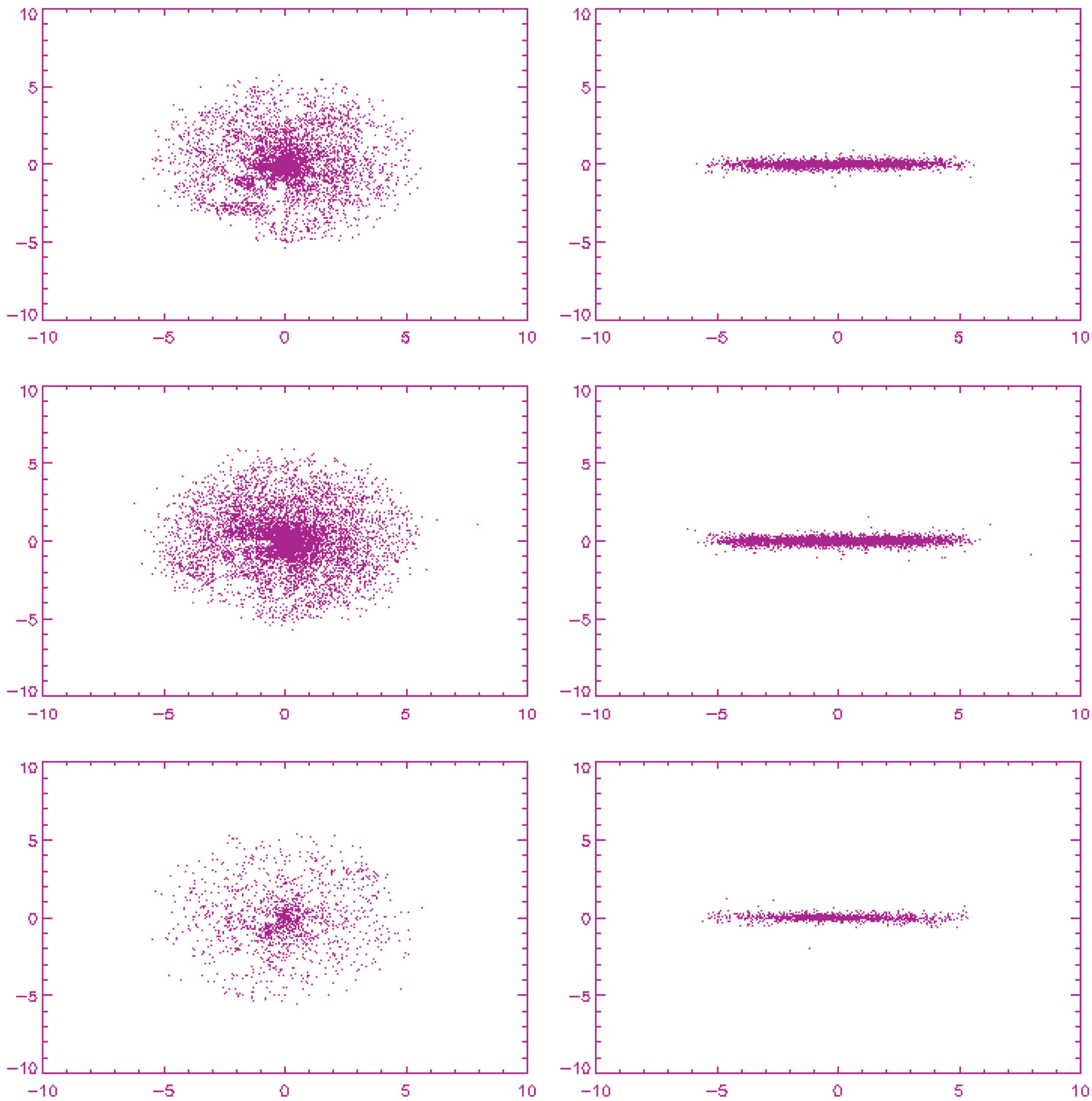

Figure 1 XY and YZ projections of the spatial distribution of stars in the isolated disc formation test within a fixed NFW potential well. Stars were segregated according to their metallicity: [Fe/H] > 0 (upper panel), $-1.5 <$ [Fe/H]< 0 (central panel), and [Fe/H]< -1.5 (lower panel). Baryons have cooled consistently with their metallicity content.

gas with $T > 10^5$ K in the analysed GLOs, as a function of their virial mass. We can see that there are differences among the three simulations with the largest gas fraction associated with the primordial cooling run, as expected. There is a trend for the fraction of warm gas to increase with virial mass.

Note that in the cosmological simulations we found more important differences between runs with primordial and metal-dependent cooling compared to the corresponding ones of the isolated disc tests. As a matter of fact the star formation histories of GLOs seem to be more affected than those of the idealised disc tests. In Figure 5 we show the star formation rate history of a typical GLO in the three runs. In the small box we have plotted the ratio of the SFR of the solar and primordial cooling to the metal-dependent one. From this figure we can see that the differences are important for $z < 3$, but do not present a regular behaviour. This result suggests that the non-linear evolution of the structure determines complex star formation histories and chemical patterns that can produce non-linear responses to the characteristics of the cooling functions.

4 Conclusions

We have implemented a chemical evolution scheme in GADGET2 which allows the description of the enrichment of baryons within a cosmological framework. We have also included the dependence of the cooling rate function of baryons on their metallicity, allowing a more realistic description of the cooling process.

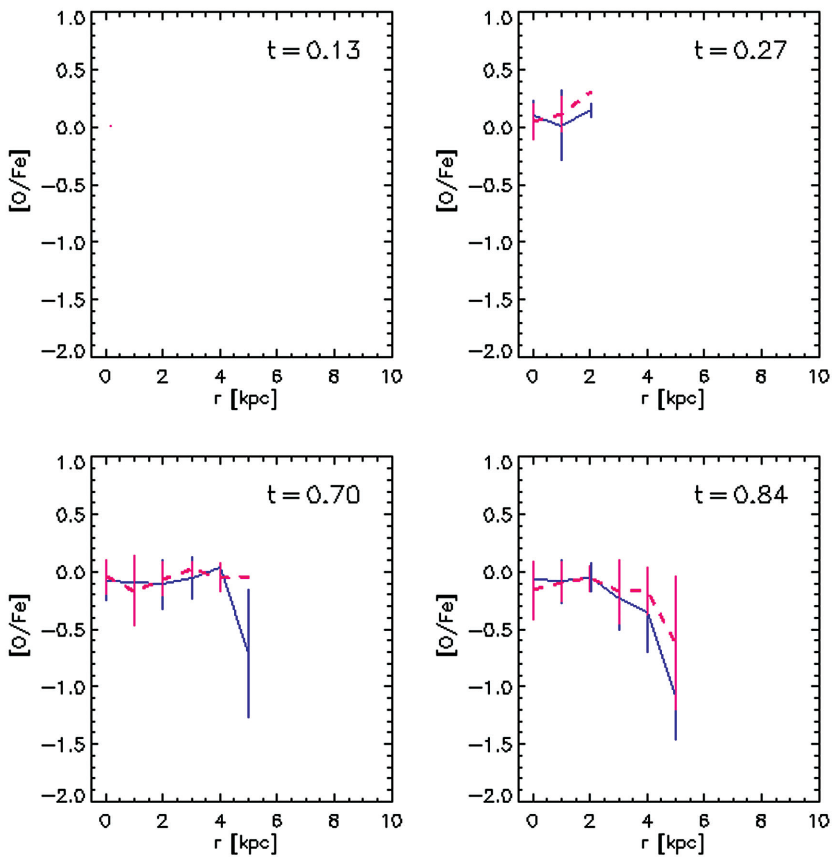

Figure 2 Mean [O/Fe] as a function of radius for the stellar population in the tests of the formation of a disc galaxy in a fixed NFW potential well, for runs with primordial (dashed lines) and metal-dependent (solid lines) cooling functions, during the first period of evolution. For each window the time is indicated in units of Gyr.

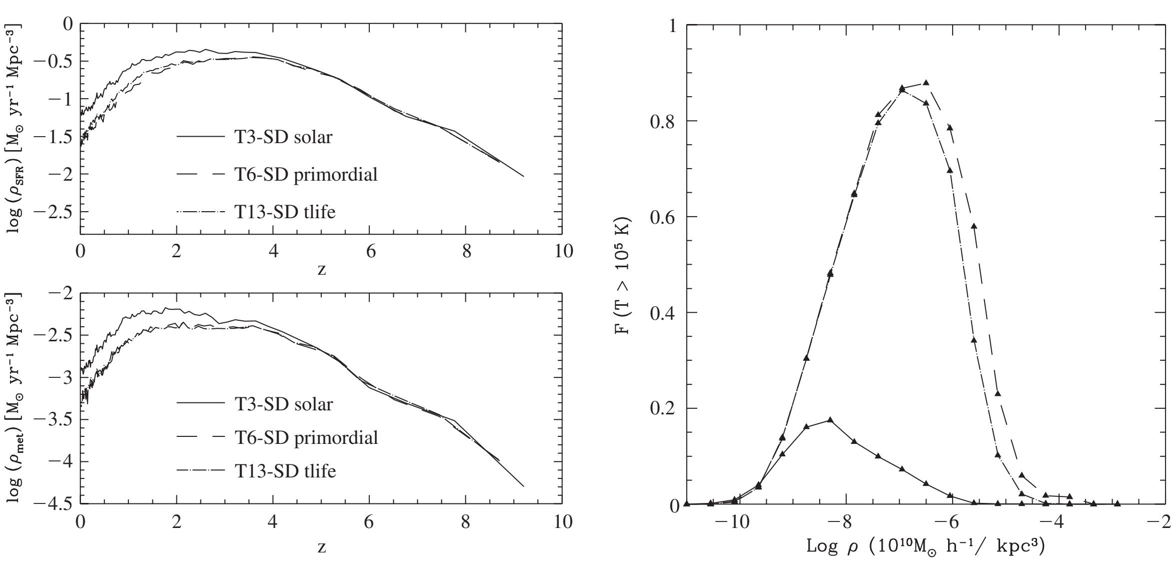

Figure 3 Comoving star formation and metal production rates for three different cosmological runs with the same initial condition. Left panel: The gas has been allowed to cool according to solar (solid lines), primordial (dashed lines), and metal-dependent (dot-dashed lines) cooling functions. The largest differences are found for $z < 3$. We found at most a difference of up to $\approx 20\%$ between the comoving star formation rates of primordial and metal-dependent cooling runs. Right panel: The gas fraction with $T > 10^5$ K in different density bins for the whole simulated volume for the solar (solid line), primordial (dashed line), and metal-dependent (dot-dashed line) cooling tests.

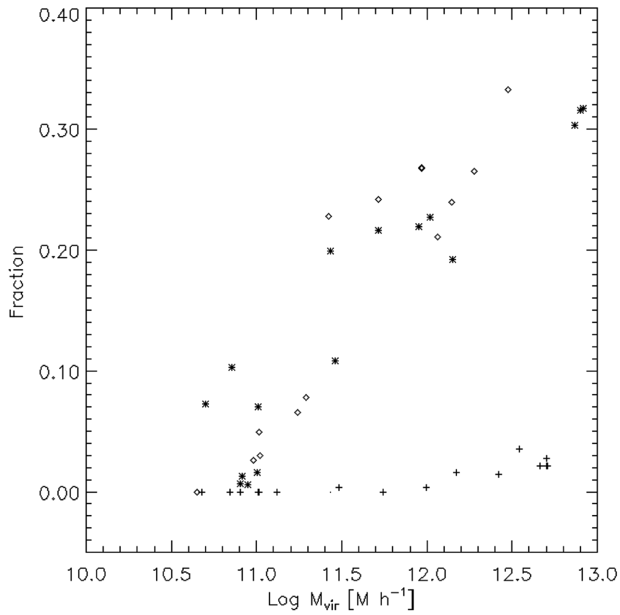

Figure 4 Fraction of hot gas ($T > 10^5$ K) in galaxy-like objects as a function of the virial mass. The galactic systems have been identified in a ΛCDM scenario where baryons have been let to cool according to primordial (diamonds), metal-dependent (asterisks), and solar (crosses) cooling functions.

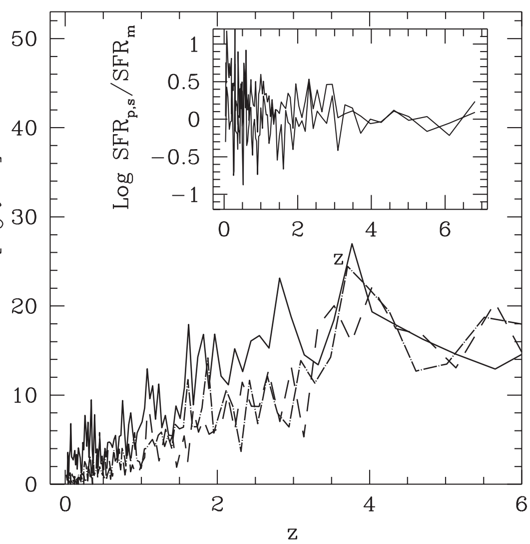

Figure 5 Star formation rate for a typical galaxy-like object in a ΛCDM scenario where baryons have been let to cool according to primordial (dashed lines), metal-dependent (dot-dashed lines), and solar (solid lines) cooling functions. In the small window we show the difference between the logarithm of the SFR of the solar (s) and primordial (p) cooling runs, with respect to the metal-dependent (m) one.

A first analysis shows that in ΛCDM scenarios, the comoving star formation rate could be underestimated by up to approximately 20%, if the primordial cooling function is adopted instead of considering a cooling function consistent with the corresponding baryonic metallicity. However, within individual galactic systems it is complicated to disentangle the effects of cooling the gas consistently from its metallicity, owing to the non-linear growth of the structure, which affects the star formation and chemical histories and the mixing of metals in a non-linear way. First results show that the star formation history could be either underestimated or overestimated by an order of magnitude depending on the particular history path. These points will be addressed in more detail in a forthcoming paper.

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