

Chemical enrichment and its dynamical effects in SPH simulations



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Abstract

Any realistic modeling of galaxy formation requires a proper and self-consistent treatment of different processes such as star formation, chemical evolution and a metallicity-dependent radiative cooling. A considerable effort is presently devoted to improve the implementation of such processes in cosmological simulations of structure formation. Here we present new modeling methods for chemical enrichment and gas cooling that take into account the detailed chemical composition, and not only the total metallicity.

1. Gas cooling

RADIATIVE cooling is the most important way in which the chemical enrichment affects the dynamics of the gas. Any treatment of chemical evolution must include the dependence of the cooling function on the gas composition. The most common approach consists of including its dependence on the total metallicity (Lia et al. 2002; Scannapieco et al. 2005), assuming fixed rates (either solar or primordial) for the relative abundances. This approach, however, does not account for the different metal mixtures relevant to galaxy formation, arising from primordial abundances, metals production inside stars, their mixing from galactic winds and from the diffusion of metals through the gas, etc. Indeed, figure 1 shows the cooling rate for individual SPH particles extracted from a cosmological simulation. The cooling rate has been computed by using Mappings III (Sutherland & Dopita 1993) and taking into account the detailed chemical composition of each particle. It can be seen from this figure that, for a given total metallicity with different metal mixtures, the cooling rate values covers a range of about one magnitude order.

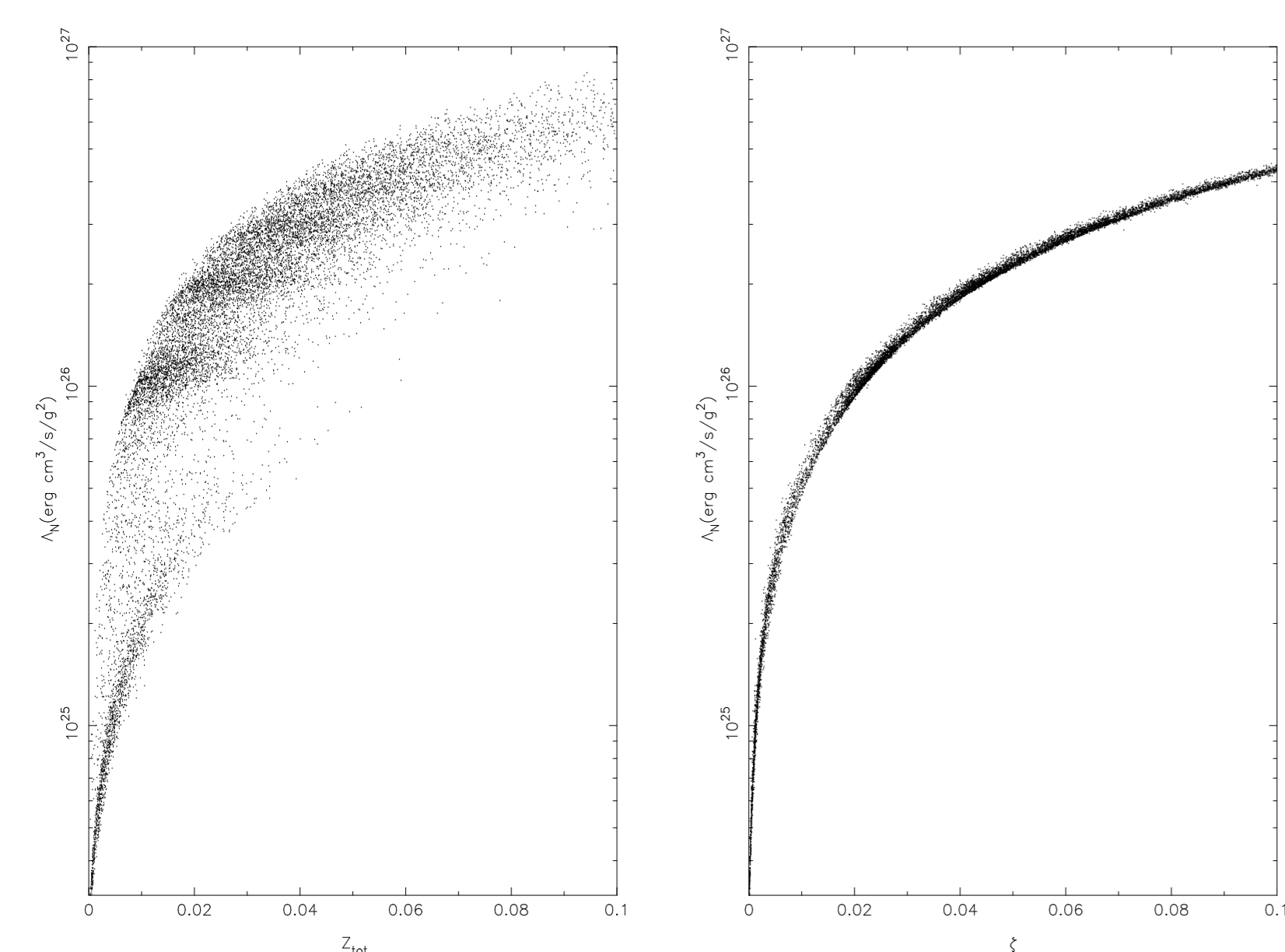


Figure 1: Dependence of the normalised cooling rate on the metallicity at $10^{5.5} K$. Each point is computed for a different composition obtained from a self-consistent cosmological simulation. On the left panel, the cooling rate is represented against the total metallicity. On the right panel against the ζ parameter defined in eq. 1.

Computing the cooling function $\Lambda_N(T, \vec{Z})$, with $\vec{Z} = (Z_1, Z_2, \dots, Z_m)$ and $m \sim 16$ would take too much resources in a simulation. Fortunately, at each temperature, the cooling function is dominated by only a few chemical species, and in principle it can be expressed in terms of a few parameters. By applying a dimension reduction regression (DDR) algorithm (Weisberg 2002) for each considered temperature (91 in the range $10^4 \div 10^{8.5} K$), we found (see left panel of figure 1) that the composition dependence of Λ_N can be reduced to a single metallicity parameter

$$\zeta(T) = \vec{c}(T) \cdot \vec{Z}. \quad (1)$$

Here the dimension reduction coefficients $\vec{c}(T)$ are obtained from the DDR algorithm by evaluating the statistical weight of each element on the total cooling function. These m coefficients and the cooling function $\Lambda_N(T, \zeta(T))$ can be easily tabulated for each temperature.

Using the above tabulated data, the radiative cooling has been implemented in our code by using an integral algorithm (Thomas & Couchman 1992) based on:

$$\int_u^{u-\Delta u^{cool}} \frac{du^{cool}}{\Lambda_N(u, \zeta(T))} = -\frac{\Delta t}{\rho}. \quad (2)$$

where Δt is the timestep, ρ is the density of the SPH particle and Δu^{cool} is its change in internal energy due to cooling.

This formalism assumes constant density over the timestep, but accounts for variations in the temperature.

The integral appearing in eq. 2 has to be computed on-line (during the simulation); it cannot be pre-computed, since one needs to know the full composition of the gas to obtain the metallicity parameter $\zeta(T)$.

2. Chemical Enrichment

Pre-computed yield tables (Lia et al. 2002; Martínez-Serrano et al. 2005; Scannapieco et al. 2005) are almost always computed from stellar evolution models (e.g., Portinari et al. 1998; Marigo 2001; Gavián et al. 2005) with different total metallicities, but assuming solar proportions for the elemental abundances. In spite of this, the “ Q_{ij} matrix” formalism (Talbot & Arnett 1973; Ferrini et al. 1992; Portinari et al. 1998) allows to take into account possible differences of chemical composition within a given total metallicity. This formalism links any ejected species to all its different nucleosynthetic sources, allowing the model to scale the ejecta with respect to the detailed initial composition of the star particle.

For a single star, the Q_{ij} matrix is defined as

$$Q_{ij} = \frac{M_{ij,exp}}{X_j M}$$

where X_j is the initial mass abundance of species j and $M_{ij,exp}$ is the amount of species i synthesized starting from j and eventually expelled.

To use the Q_{ij} matrix in cosmological simulations we must derive the ejections of a given element i out of its “precursors” j for a single stellar population (SSP):

$$e_i(\tau) = \Phi(M) \left(-\frac{dM}{d\tau} \right) \sum_j Q_{ij}(M) X_j, \quad (3)$$

where $\Phi(M)$ denotes the IMF and $M = M(\tau)$ is the mass of a star with lifetime τ .

The elements newly synthesized by a star particle over a simulation timestep Δt can be computed by integrating 3 over Δt . The corresponding yields are used to modify the nearest gas neighbour composition. This procedure is applied until that, following a probabilistic method similar to that of Lia et al. (2002), the star particle is converted to a gas-again particle. This has the advantage of avoiding the need for “hidden” stellar content in gas particles: baryonic particles are, either gas, either stars.

3. Results

To test the proposed algorithms, we have run several self-consistent cosmological simulations with different chemical evolution and cooling algorithms:

- The original probabilistic algorithm as described in (Lia et al. 2002). It is metallicity dependent but does not take into account the specific composition of the particles.
- Our modified code, as described in Martínez-Serrano et al. (2005). In this approach particles return their newly produced elements over their whole lifetime, instead of only at the time of their death, as in the previous one.
- The same code as in (b), but introducing the “ Q_{ij} matrix” formalism for the chemical enrichment.
- The same code as in (b), but introducing the composition-dependent cooling described in this work.

We have studied the most massive elliptic-like object (ELO) at redshift $z = 1$ for each run. From the comparison of figures 2.1 and 2.2, one can appreciate that the original algorithm gives a broader distribution of the total metallicity, while keeping the mean values approximately equal. Both results seems compatible with observations (Gregg et al. 2004). The reduction in metallicity dispersion can also be appreciated if we look at figures 2.3 and 2.4, where one can see that even if the global trend is similar for both distributions, the spread in the distribution for a given radius is much wider for method (a). Such extreme values of the metallicity quickly saturate the implemented chemical enrichment and cooling functions.

The composition-dependent algorithms for chemical enrichment and cooling are compared in the last two figures where it can be appreciated that even if the same density structure (2.6) is obtained for the three (b, c, and d codes), the metallicity gradient (2.5) is reduced significantly with the introduction of the composition-dependent cooling. This may indicate a change in the build-up process of the object.

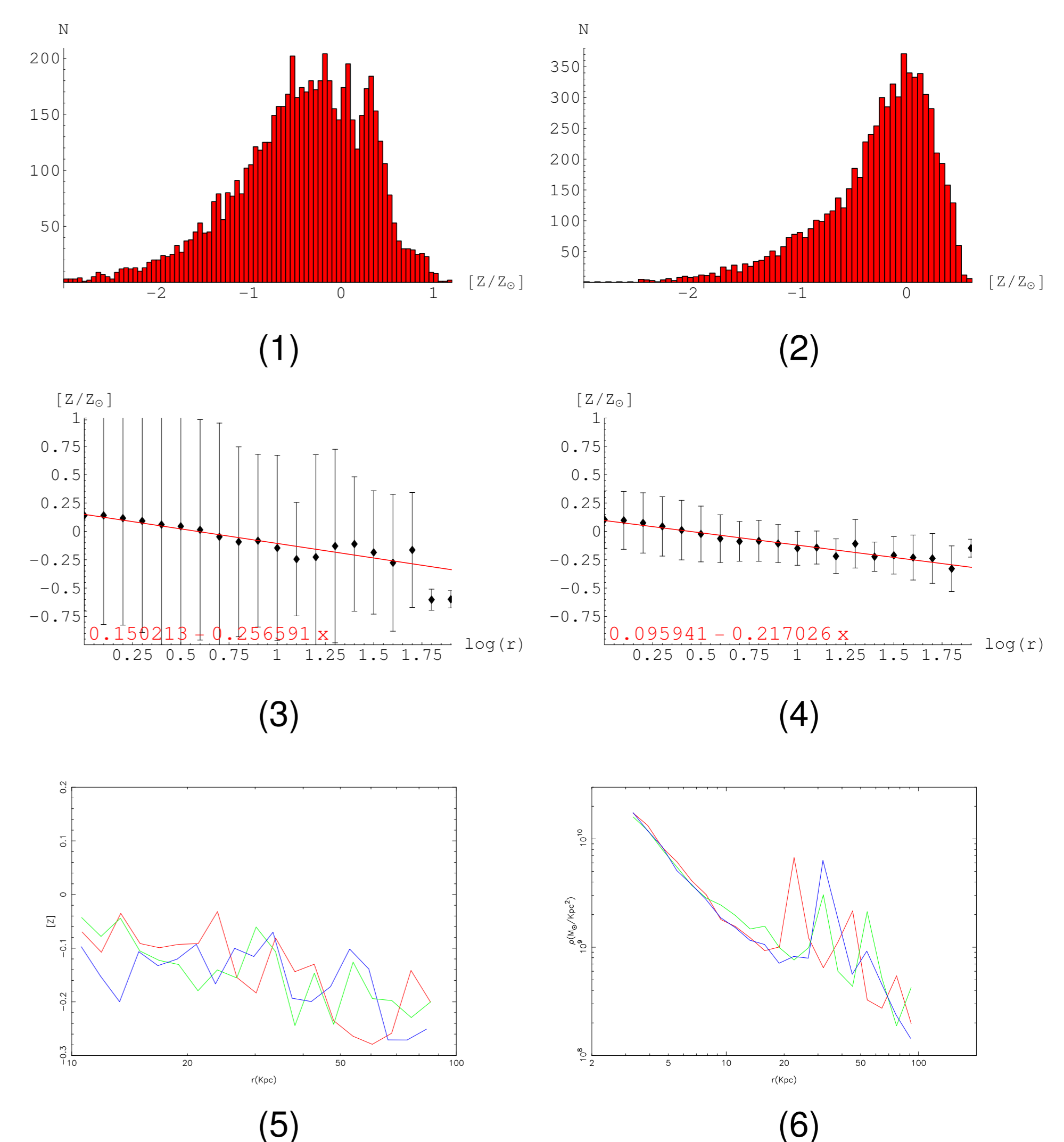


Figure 2: Results of the simulations: (1) and (2) the distribution of total metallicities for the original (a), and modified (b) algorithms; (3) and (4) gradient of total metallicity, for (a) and (b) algorithms, with 1-sigma error bars; (5) gradient of total metallicity for algorithms (b), (c) and (d), in red, green and blue, respectively. Slope values are $\Delta \log Z / \Delta \log r = \{-0.21, -0.17, -0.12\}$; (6) density profile for the stellar component. The colors are as in the previous subplot.

4. Conclusions

We have presented new algorithms and simulations that address, in a self-consistent way, the cooling and chemical enrichment in cosmological simulations of galaxy formation. By introducing the newly synthesized elements over the lifetime of star particles, we manage to significantly reduce the dispersion found in the original method.

The new cooling method takes into account the full composition of the gas. It seems to introduce structural differences in the distribution of metals over an ELO, lowering the metallicity gradients. Further work is needed to statistically study this effect

The new chemical enrichment algorithm leads to the same mean metallicity as the other methods proposed in literature, with a significant reduction in data spread.

Future work will include treatment of energy feedback from supernovae, and higher resolution disk simulations, where the “ Q_{ij} matrix” formalism may prove valuable.

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