A NEW CHEMODYNAMICAL TOOL TO STUDY THE
EVOLUTION OF GALAXIES IN THE LOCAL UNIVERSE

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Abstract. We present some preliminary results obtained with a new galactic chemodynamical tool under development. In the framework of non-instantaneous recycling approach, we follow the interactions due to star formation and feedback processes. One of the main original features of our code is that we record the abundance evolution of several chemical elements. This allows us to build cooling functions dependent on the real abundances of individual elements. We illustrate the need for such metal-dependent cooling functions using a toy model made of a star cluster embedded in a two-phase gas cloud. Our results suggest that computing cooling rates according to individual abundances of chemical elements can influence the star formation rate.

1 Introduction

Dynamical and chemical evolution of galaxies are closely related. The complex spatial distribution of metals in galaxies reflect strong ties. Indeed, heavy elements, synthesized by successive generations of stars, enrich the interstellar medium (ISM) through stellar winds and supernova explosions. Density waves, shear, gravitational perturbations are then responsible to mix the ISM and dissolve young stellar clusters. Furthermore the metal enrichment affects the thermal evolution of the gas because cooling rates are very sensitive to the chemical composition. Besides mass feedback, stars are also responsible for energy feedback which both influences the dynamics and the temperature of the gas. Therefore we need to compute chemical and dynamical evolution self-consistently.

Figure\textsuperscript{1} shows the different physical interactions between the stars and the ISM handled with our tool. It is designed to be coupled with an hybrid particle-mesh N-body + smooth particle hydrodynamics (SPH) code to compute high-resolution chemodynamical simulations of galaxies. We will describe the two components (star and gas) and the different aspects of the interplay between them.

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2 Evolution of stellar populations

In our simulations, stars are in fact collisionless particles of masses comparable to typical stellar clusters. The mass and energy released from stellar particles are distributed to the neighbouring gas particles. Energy feedback from both the stellar winds and the supernovae is considered. The time evolution of all relevant quantities is computed with the evolutionary synthesis code Starburst99 v5.1 (Leitherer et al. 1999, Vázquez & Leitherer 2005). The choice of Starburst99 was motivated by the possibility to obtain the time evolution of mass lost by a single stellar population (SSP) for several individual chemical elements, namely H, He, C, N, O, Mg, Si, S, and Fe. Starburst99 is, at our knowledge, the only public code to provide them. Moreover, it offers a large choice of inputs and outputs. We can choose, in particular, the timescale of star formation (instantaneous in our case), the IMF (a multi-power-law), the metallicity of the SSP (5 metallicities are available from 0.02 to 2.5 solar metallicity), the stellar evolutionary tracks (Padova or Geneva). We can obtain the time evolution of SNe rates, the energy losses from stellar winds and SNe, the mass losses for several chemical elements, the number of ionizing photons, the SSP spectra. Only SNII and SNIb losses are provided by Starburst99 but feedback from SNIa will be soon implemented directly in our code with different recipes.

Let us consider a stellar population characterized by a Kroupa IMF with exponents (1.3, 2.3) and mass boundaries (0.1, 0.5, 100 M⊙). We consider all the gas
We consider all the gas ejected from birth to 5 Gyr. These ratios are shown for several chemical elements and for SSP of different initial metallicities.

released by the stellar population (stellar winds and SNe) from birth to 5 Gyr. \( m_X \) is the mass fraction of the element \( X \) among all the metals i.e. the ratio between the mass of the element \( X \) (\( M_X \)) and the total mass of metals (\( M_Z \)). \( m_X(Z_\odot) \) is the same ratio but for a gas with solar metallicity. Typical mass fraction at solar metallicity are H (7.06 \( 10^{-1} \)), He (2.75 \( 10^{-1} \)), C (3.03 \( 10^{-3} \)), N (1.11 \( 10^{-3} \)), O (9.59 \( 10^{-3} \)), Mg (5.15 \( 10^{-4} \)), Si (6.53 \( 10^{-4} \)), S (3.96 \( 10^{-4} \)) and Fe (1.17 \( 10^{-3} \)).

In Fig. 2 we display the ratio \( m_X/m_X(Z_\odot) \) in the released gas for several elements and for different initial metallicities of the stellar population. By definition, if the abundance ratios of metals in the released gas are the same as for solar composition, \( m_X/m_X(Z_\odot) \) should be equal to 1. However, the metal abundance ratios are not solar in the released gas. In particular, for high metallicities the released gas is particularly enriched in carbon, silicon and sulfur. This gas will be mixed with the rest of the ISM resulting in a gas with non-solar abundance ratios.

3 Interstellar medium description

The ISM is approximated by a two-phase model: an isothermal warm phase (\( 10^3 \) K) and a hot phase whose temperature is allowed to vary between \( 10^4 \) K and \( 10^8 \) K. We assume that the two phases are fully mixed because the typical size of SPH particles (several parsecs) does not allow to resolve them. Thus, each SPH particle contains both a warm and a hot phase. The warm ISM mass fraction can increase (condensation) or decrease (evaporation) due to thermal conduction (Cowie et al. 1981). It also obviously decreases when star formation operates because star particles are created in the warm phase. The hot phase is heated by the photo-electric heating from grains and PAHs (Wolfire et al. 1995) and by stellar feedback.
due to stellar winds and supernovae. We decide to inject all the released mass and energy from stars into the hot phase of the gaseous neighbouring particles. The redistribution of energy between the two phases is achieved at the next timestep thanks to all physical processes described above. Moreover, a fraction of the stellar energy feedback can be converted to mechanical energy that can affect directly the velocity field of the surrounding gas.

It is well known that cooling rates are sensitive to the chemical composition of the gas. At solar composition the cooling rate is greater by more than an order of magnitude for some temperatures than for a gas without metals (Fig. 3, left panel). As for SSP evolution, standard cooling functions used in chemodynamical studies are generally computed for different metallicities but keeping solar abundance ratios (e.g. Boehringer & Hensler, 1989) or with solar abundance ratios and enhanced abundances for some specific elements (e.g. Sutherland & Dopita, 1993). Hence we need to take into account the real abundances of each element in the gas to build more realistic cooling functions whichever the chemical composition. We thus consider the hot phase of the ISM as an optically thin gas in collisional ionization equilibrium. Cooling calculations are performed in the temperature range $10^4$ K to $10^8$ K. Computing cooling rates with Mappings III for each gas particle at each timestep of a chemodynamical simulation is a very CPU time consuming task. Therefore we use a recipe to reconstruct cooling rates on the fly from individual abundances of elements (see Champavert & Wozniak, 2007 for a full description). In short, this recipe comes down to a linear combination of individual cooling curves precomputed with Mappings III. The relative errors between our reconstructed cooling curves and those calculated with Mappings III remain below a few percent (Fig. 3, right panel). Thus, they are comparable to others coming from, for instance, the hydrodynamical scheme.

**Fig. 3. Left panel:** Cooling rates as a function of temperature computed with Mappings III for different metallicities. The abundances used in calculations are taken from Sutherland & Dopita (1993). **Right panel:** Percentage of relative errors made when reconstructing cooling function with our recipe for different chemical compositions.
4 Star formation recipes

We assume that star formation occurs if the following criteria are satisfied. The region must be contracting ($\nabla v < 0$). It has to be unstable according to the Toomre's instability criterion (Toomre, 1964): $Q \leq \lambda$. We take $\lambda = 1.4$ derived from observation by Kennicutt (1990). The gas must be cold enough: $T < 10^4$ K with $T$ the mean gas temperature of a SPH particle. This threshold has been chosen because of our cooling functions which are only available for $T \geq 10^4$ K for the moment. Finally the gas particle must belong to a giant molecular cloud (Gerritsen & Icke, 1997). A gas particle is assumed to be part of a giant molecular cloud (GMC) if a mass of the cloud containing this particle, i.e. the mass of this particle with its gaseous neighbours, is larger than $2.5 \times 10^6$ M$_\odot$, typical mass of a big GMC. When a gas particle fulfills all these conditions, it becomes eligible for star formation. However, a stellar particle is formed only after a delay equal to a free-fall time ($t_{ff}$) to mimic the gravitational collapse of the molecular cloud. The mass of the new stellar particle is set to $n \times 10^4$ M$_\odot$ where $n = t_{ff}(\text{GMC})/t_{ff}(\text{part})$ is the number of elemental stellar clusters formed in the GMC. We obviously need a warm phase more massive than $n \times 10^4$ M$_\odot$ because the mass needed to form stars is deducted only from the warm phase. Each new stellar particle inherits the chemical composition from the gas in which it was born.

However, the evolution of a SSP, as predicted by Starburst99, only depends on the global metallicity $Z$ because stellar evolutionary tracks are generally computed with solar abundance ratios or with a particular enhancement for some elements which is unavoidably different from what we obtain with our code. In order to be able to self-consistently compute the chemical evolution of individual elements in the future, we will obviously need data from evolutionary tracks including variations on the abundances of individual elements. At the moment, when a gas particle should form a new stellar particle, we have to assign the global metallicity of the gas to the new particle. For a given metallicity and IMF, we compute linear interpolations between values pre-calculated with Starburst99 to obtain the mass and energy losses of the SSP.

5 A test model

Let us now illustrate one of the main properties of our tool. We consider a gas particle of $10^7$ M$_\odot$ with 30% of mass in the warm phase. The density of the hot phase is 0.005 cm$^{-3}$. At $t = 0$, the gas is made of hydrogen (77%) and helium (23%), its temperature is $10^4$ K and a stellar particle of $1.4 \times 10^5$ M$_\odot$ is born. The star formation delay is constant (10 Myr) and all the subsequent stellar particles formed have the same mass ($1.4 \times 10^5$ M$_\odot$). All other parameters are described in Sect. 2. We have calculated the evolution for 2 models. In model A, the cooling rate depends only on $Z$ with solar abundance ratios. In model B, cooling rates are obtained according to the real abundances of chemical elements.

Figure 4 shows the evolution of the mean temperature of the warm and hot phase (left panel), of the stellar mass (middle panel) and of the warm mass frac-
Cooling is clearly less efficient when we handle the abundances of elements leading to a higher mean gas temperature. This therefore leads to a lower star formation rate since the mean temperature remains for a longer time above the temperature threshold for star formation ($10^4$ K for our models). At $t = 1$ Gyr, the cumulated stellar mass formed in model A is about 1.25 times greater that for model B. As this longer timescale alters the star formation history, the warm gas mass fraction also evolves differently.

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