Chemical abundance patterns in Local Group galaxies within cosmological simulations

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Resumen / En el contexto del modelo cosmológico de concordancia, la formación de estructura en el universo es el resultado de la amplificación, por efectos gravitatorios, de pequeñas perturbaciones en el campo de densidad primigenio. Esto resulta en la formación de estructuras conocidas como halos de materia oscura, donde el gas colapsa y forma estrellas, dando lugar a galaxias. Las simulaciones numéricas son una herramienta importante en el estudio teórico de la formación y evolución de galaxias. En este trabajo describimos la implementación de un modelo de enriquecimiento químico en simulaciones cosmológicas del Grupo Local de última generación. Éstas incluyen modelos de subgrilla para los procesos físicos más relevantes. Analizamos la evolución química y morfológica de dos galaxias con masas viriales similares a nuestra Vía Láctea. Para cada una de las componentes estelares (disco, bulbo y halo), establecemos conexiones entre su historia de formación y su evolución química. Encontramos que el enriquecimiento de elementos α (O, Mg, Si) ocurre en etapas tempranas de la evolución, pues sus principales productoras son estrellas de vida corta que devienen en explosiones de supernova tipo II. Hay también una contaminación gradual del resto de los elementos a medida que ocurren supernovas de tipo Ia y vientos de estrellas en la fase asintótica gigante.

Abstract / In the context of the concordance cosmology, structure formation in the universe is the result of the amplification, by gravitational effects, of small perturbations in the primeval density field. This results in the formation of structures known as dark matter haloes, where gas collapses and forms stars, giving birth to galaxies. Numerical simulations are an important tool in the theoretical study of galaxy formation and evolution. In the present work, we describe the implementation of a chemical enrichment model in a state-of-the-art cosmological simulation of the Local Group. The simulation includes sub-grid models for the most relevant physical processes. We analyze the chemical and morphological evolution of two galaxies with virial masses similar to that of our Milky Way. For each of the stellar components (disc, bulge and halo), we establish links between their formation history and their chemical evolution. We find that α-element (O, Mg, Si) enrichment happens at early stages of evolution, as their main producers are short-lived stars which end their lives as type II supernova explosions. There is also a gradual contamination with the rest of the elements as type Ia supernovae and winds of stars in the asymptotic giant branch occur.

Keywords / galaxies: structure — galaxies: abundances — methods: numerical

1. Introduction

Within the current cosmological paradigm, structure formation occurs in a hierarchical fashion, with smaller systems merging together to form bigger ones. In this context, numerical simulations are an important tool in the study of galaxy formation, as they can follow the joint evolution of dark matter and baryons in a consistent way, naturally capturing processes such as mass accretion and mergers.

During the last years, the possibility of obtaining detailed information on the chemical properties of stars in the Milky Way, as well as in external galaxies, opened up an important area in studies of galaxy formation. Chemical elements are synthesized in stellar interiors and ejected into the interstellar medium (ISM) in supernova explosions and stellar winds. As stars form, they inherit the metallicity of the ISM at that time: by analysing the chemical abundances of stars of different age we can reconstruct the formation history of a galaxy. On the other hand, by looking at the gaseous abundances of galaxies at different times, we can infer the properties of the ISM and understand the effects of the physical processes acting at a given cosmic time.

In this work, we study the chemical properties of a Milky Way-mass galaxy, using a simulation of the Local Group which is part of the CLUES project. We study the abundances of various chemical elements at the present time, as well as the chemical patterns of the different stellar components – disc, bulge and stellar halo. This conference proceeding abridged paper is organized as follows. In Sec. 2 we describe the simulation, in Sec. 3 we present our results and in Sec. 4 we give our conclusions.

2. The simulation

In this project, we used a simulation of the Local Group that uses initial conditions of the CLUES project (e.g.

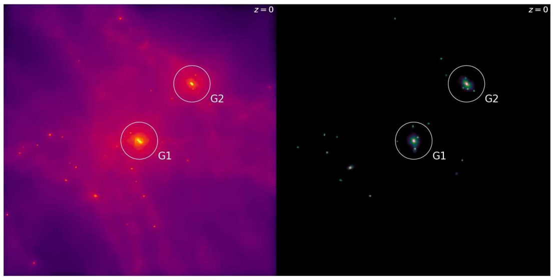

Figure 1: *Left panel:* density projection of the gas. *Right panel:* density projection of the stars. Both correspond to the simulated Local Group, for $z = 0$.

Scannapieco et al. 2015). The simulation describes the formation of the Local Group, where two Milky Way-sized galaxies form. The galaxies are referred to as G1 and G2 and are, at $z = 0$, separated by a distance of ~ 1 Mpc (see Fig. 1).

The simulation was run using the state-of-the-art code GADGET 3 (Springel et al., 2008) and the chemical enrichment model of Poulhazan et al. (2018). The relevant physical processes which act below the resolution of the simulations are implemented as sub-grid models, namely: star formation, metallicity-dependent gas cooling, supernovae explosions, stellar winds from giant stars and their associated chemical enrichment. The gas' hydrodynamical equations are solved using the Smoothed Particle Hydrodynamics (SPH) technique.

We take into account 3 types of chemical enrichment events: type II and type Ia supernovae (SNe II and SNe Ia respectively), and winds from stars in the Asymptotic Giant Branch (AGB winds). These are all implemented through discrete enrichment events, as follows:

- SNe II take place shortly after a stellar population's birth ($\tau \sim 10^6$ yr), with lifetimes depending slightly on metallicity (Portinari et al., 1998). Stars with $M_* \geq 8$ M$_\odot$ are considered SNe II progenitors. All
- in a star particle are considered to occur simultaneously at the average lifetime of the population.
- SNe Ia occur once per star particle at a time stochastically determined by a bimodal delayed time distribution (Mannucci et al., 2006).
- AGB winds gradual enrichment is modelled by 3 discrete events occuring at 10^{-1}, 1 and 10 Gyr since the star particle's birth. In these events, stars in the $0.8 - 7\,\mathrm{M}_\odot$ mass range expel 25%, 55% and 20% of their total mass, respectively.

The yields implemented are mass and metallicity dependant for AGB winds (Marigo, 2001) and SNe II (Portinari et al., 1998), while for SNe Ia fixed yields for each element were considered (Thielemann et al., 2003). For more details about the chemical enrichment model we refer the reader to Poulhazan et al. (2018).

SNe II events also provide an energetic feedback in the form of 10^{51} ergs distributed among nearby gas particles.

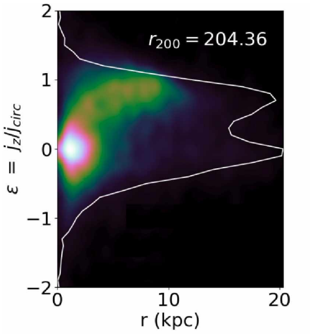

Figure 2: Distribution of star particles in the $r - \varepsilon$ plane. The white line shows the circularity distribution added up for all radii. The two distinct peaks correspond to the stellar bulge (centred at $\varepsilon \sim 0$) and the stellar disc (centred at $\varepsilon \sim 1$).

3. Results

In order to identify the different stellar components of the simulated galaxies, we classify stars according to their circularity ε, which is defined as the ratio between its circular momentum in the z-direction and the one corresponding to a circular orbit at that radius ($\varepsilon = \frac{j_z}{j_{circ}}$, where $j_{circ} = r \cdot \sqrt{GM(r)/r}$, $M(r)$ being the enclosed mass up to a certain radius r). Note that, in this work, we only show the chemical properties of G1, although results are similar for G2.

In Fig. 2 we show the radius-circularity distribution for G1. It can be seen that the bulge dominates the central part of the galaxy ($\varepsilon \sim 0$ at $r < 3$ kpc) while the disc dominates the outer region up to $r \sim 10$ kpc ($\varepsilon \sim 1$). We consider stars with $\varepsilon > 0.5$ to be part of the stellar disc. The remaining ones are considered to be part of the bulge for $r < 10$ kpc and part of the stellar halo for $r > 10$ kpc.

We find that there are clear differences in the chemical abundances of the three stellar components. This can be seen in Fig. 3, where we show the distribution of [Fe/H], [C/Fe] and [Si/Fe]. Note that the main source of Fe are SNe Ia, while AGB winds and SNe II are the main contributors of C and Si, respectively.

From the [Fe/H] distribution we can infer that the stellar halo is the component with the lowest Fe enrichment: this results from the fact that the stellar halo is composed of the oldest stars, and has a high contribution of stars formed in smaller systems with lower iron levels. The stellar halo also has low C levels, as stars did not have time to be enriched with AGB winds, and is α-enriched, due to fast enrichment with SNe II. On the other hand, the disc and the bulge have higher [Fe/H] levels, the former having the highest C enrichment among all stellar components (C is mainly produced by AGB winds, so as the disc forms gradually and at long timescales, it can be enriched via AGB winds). Finally, the bulge has intermediate C abundances, this component has a large contribution of old and intermediate age stars.

Note that, in these plots, the red dotted lines indicate the relative abundance levels corresponding to first generation SNe II yields, so stars nearing this value can

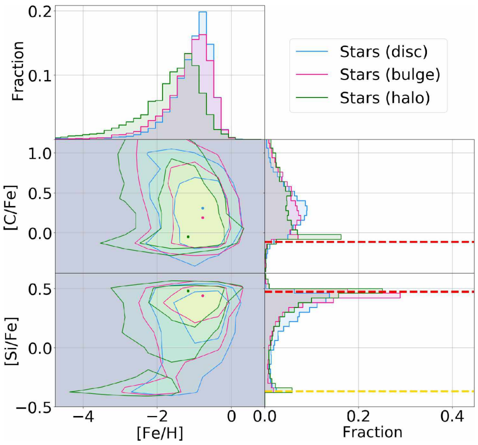

Figure 3: *Upper left panel:* relative abundance distributions for [Fe/H] for the three stellar components. *Middle and lower right panels:* [C/Fe] and [Si/Fe] distributions, respectively. *Middle and lower left panels:* distributions in the [Fe/H]-[C/Fe] and [Fe/H]-[Si/Fe] planes, respectively. The red dotted lines mark the relative abundance level of yields corresponding to first generation SNe II, while the yellow one shows the level associated to SNe Ia events.

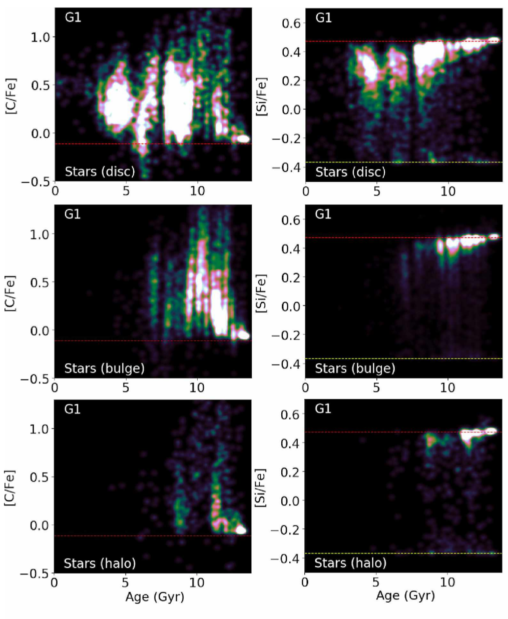

Figure 4: *Left panels:* distribution of stars from the three stellar components in the age-[C/Fe] plane. *Right panels:* distributions in the age-[Si/Fe] plane.

be interpreted as being formed from gas that was only contaminated early on (as the metallicity dependance of the SNe II yields changes the relative abundances of the ejecta for subsequent stellar generations).

The plot also shows the Si abundances, that we use as a representative of the α-elements, which are mainly produced by SNe II. The [Si/Fe] distribution is dominated by the first generation SNe II yield relative abundance level and, as the gradual Fe contribution from SNe Ia takes place, [Si/Fe] levels decline to reach their minimum at the yellow-dotted line, which indicates the relative abundance level corresponding to SNe Ia yields. The broader appearance of the disc [Si/Fe] distribution is once again consistent with younger stars being in the disc, formed from gas which has received more SNe Ia enrichment. The stellar halo [Si/Fe] displays a peak towards the yellow dotted line, which indicates stars that have formed from gas particles which *only* received SNe Ia feedback. Finally, the bulge shows an intermediate level of enrichment with α-elements.

As explained above, the abundances for the different components are partly the result of the different typical ages of their stars. In Fig. 4 we show the stellar distributions in the age-[C/Fe] and the age-[Si/Fe] planes (the age of a star particle is the time elapsed from it's creation to $z = 0$). This figure confirms that the disc is the component with the youngest stars, the halo has a mostly old stellar population, and the bulge is mainly old but has also contribution of intermediate age stars. From this plot we see that the [C/Fe] peak in the halo distribution shown in Fig. 3 does correspond to very old stars. It is also evident that the oldest stars show the relative abundance levels corresponding to first generation SNe II, and that the gradual contribution of AGB winds is evidenced in the growth of [C/Fe] levels for younger stars. The same is true for the decline of [Si/Fe] levels owing to Fe enrichment from SNe Ia.

4. Conclusions

We studied the chemical abundance patterns of two Milky Way-sized galaxies in a Local Group simulation, and investigated their relation to the formation history. Both galaxies have 3 well-defined stellar components: the disc, the bulge and the stellar halo. We find that α-element enrichment occurs early on, due to the fact that SNe II progenitors are short-lived, while Fe and C enrichment is given in a more gradual fashion, in accordance with the longer time scales of SNe Ia and AGB wind events. This explains the different chemical patterns observed in the disc – containing the youngest stars —, the bulge and the stellar halo – both of which contain mostly old stars.

Acknowledgements: The authors acknowledge support by the Agencia Nacional de Promoción Científica y Tecnológica (ANPCyT, PICT-201-0667).

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