Expected abundance patterns from the first generation of stars

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Resumen / Se cree que las primeras estrellas en el Universo (Población III) fueron responsables de sintetizar los primeros elementos pesados, creando por lo tanto las condiciones químicas sobre las que la segunda generación de estrellas se formó. Uno de los objetivos de las investigaciones actuales es restringir de mejor manera la función de masa inicial de las estrellas de población III, utilizando los patrones de abundancia de estrellas extremedamente pobres en metales. Esencial para modelar su influencia en la historia cósmica. Aquí presentamos un conjunto de predicciones para las razones de abundancia de carbono y europio, suponiendo diferentes tipos de función de masa inicial, parametrizada mediante el índice α, masa máxima y masa mínima. Discutiremos brevemente el espacio de parámetros consistente con datos de las estrellas extremadamente pobres en metales conocidas hasta ahora.

Abstract / The first stars in the Universe (Population III) are thought to be responsible for synthesizing the first heavy elements, thereby creating the chemical conditions from which the second generation of stars has formed. One of the aims of current investigations is to better constrain the Initial Mass Function of Population III stars from the observed abundance patterns of extremely metal poor stars, which is essential to model their influence on cosmic history. We present a set of predictions for the abundance ratios of carbon and europium yields, assuming different types of initial mass function, parametrized by the index α, and the upper and lower mass cutoff. We will briefly discuss the parameter space that is consistent with the extremely metal poor stars known so far.

Keywords / nuclear reactions, nucleosynthesis, abundances — stars: early-type

1. Introduction

Population III, or Pop. III, stars are the first generation of stars, believed to have formed around 380 Myr after the Big Bang (WMAP and Planck).

These stars were responsible for synthesizing the first heavy elements and giving way to the origin of complex structures by acting as the initial source of the reionization of the Universe. At the end of their lives, massive stars exploded as supernovae ejecting all their material into the intergalactic medium, setting the chemical conditions where the second generation of stars was formed.

Depending on their masses, stars can have different fates, which translates into several ways of chemically affect the environment (Heger & Woosley, 2002). 10-35 $M_\odot$, non-rotating stars finishes its life as type II supernova; in the range of $100 - 250$ $M_\odot$ the star is partially or completely disrupted due to pair-antipair instability, ejecting all the material inside the core. In this scenario, stars with ≤ 150 $M_\odot$ go into a state of pulsational pair-instability, where it is not clear if they spread any metal or not; stars with masses around 35-100 $M_\odot$ and higher than 250 $M_\odot$ are predicted to die as a black hole and yield no nucleosynthesis products to the interstellar medium.

To understand how this stellar population enriched the Universe it is crucial to better constrain their initial mass function, therefore modeling their impact on cosmic history. Nevertheless, direct observations of these stars are still elusive, which has led to believe that the first stars are very massive, thus they are not expected to live for a long time. A second interesting possibility is that Pop. III stars consist of low-mass objects, and thus they may still remain in the present Universe masked by older stellar population.

Studies in the field of elemental abundances of extremely metal-poor (EMP) stars can help to constrain the evolution of Pop. III stars, as they are believed to carry the nucleosynthetic signature of the first stars. In particular, studies of elements with $Z > 26$, are important to understand the processes that form them (s-/r-process) and when they began to occur.

Extensive observations of metal-poor stars have enabled us to classify them according to distinctive features, such as their carbon abundance. Some of them have been found to exhibit an enriched carbon abundance, [C/Fe] $> +0.7$, commonly known as carbon enhanced metal-poor stars (hereafter, CEMP stars). The latter also consist of further sub-classes, depending on the enrichment presented of both s- and/or r-process elements (CEMP-s, CEMP-r and CEMP-s/r), or if the stars have a typical solar abundance of neutron capture elements (CEMP-no; [Ba/Fe] 0.0) (originally defined by Beers & Christlieb (2005)). Observational data have suggested that CEMP-no stars to arise from an intrinsic process, linking them as direct descendants to the first stars (Norris et al. (2013) for a summary of the evidence on this claim). One of the possible origins proposed is the 'mixing and fall-back' model, in which a first generation star explodes as supernova without the sufficient energy to expelled all the synthesize material in its core, therefore only external layers, rich in lighter elements, are released while heavy material is captured and falls back onto the neutron star or black hole.

Here we calculate [Eu/Fe] and [C/Fe] ratios, focusing on the initial mass function (IMF) prescriptions that could in principle explain the abundances imprinted in the most metal-poor stars we currently know.

2. Methodology

We employ the following formula to describe the IMF:

$$\phi(M) = \phi_0 M^{-1+\alpha}. \quad (1)$$

We explore four values for the index α, this is $\alpha = 3$ (Salpeter-IMF), $\alpha = 2$, $\alpha = 1$ and $\alpha = 0$ (logarithmically flat IMF). The equation is normalized as,

$$\int_{M_{low}}^{M_{up}} M\phi(M)dM = c, \quad (2)$$

where M_{low} and M_{up} represent the low-mass and high-mass cutoffs, respectively. The low-mass limit was varied from 5 to 20 $M_\odot$ and the maximum mass from 25 to 300 $M_\odot$.

Three different sets of stellar yields are adopted: The work of Nomoto et al. (2006) gives information for primordial stars between 13-40 $M_\odot$. Heger & Woosley (2002) is very elaborated for stars between 140-260 $M_\odot$, that lead to pair-instability supernovae for different masses of the helium cores, while Karlsson et al. (2013) covers the rest of the mass range.

In the case of Eu, we test two models considering the contribution of different progenitor masses for the SNe, with constant Eu yields over the whole selected mass range. Stellar yields in massive low-metallicity stars were taken from Cescutti et al. (2006), who consider production for stars between 10-25 $M_\odot$ as the progenitors of this element (MEu1). In addition, we adopt yields from the work of Argast et al. (2004) in order to see the variations in the expected abundance patterns of n-capture elements, when considering the metal production of lower mass core-collapse SNe (i.e., 8-10 $M_\odot$) combined with r-process yields from core-collapse SNe in the range of 20-25 $M_\odot$ (MEu2).

The total yield for element X is given as:

$$X_{tot} = \sum_i N_i X_i. \quad (3)$$

Here X_i is the yields for a single star in the i-th mass interval, in units of solar masses, and N_i is the number of stars in the i-th mass range.

We note that all above interpretations assume single, non-rotating stars. The effects of rotation in zero-metallicity stars will not be addressed here, however, we point out the importance of including it in further models for comparison, as it may change significantly the results (Stacy et al., 2011). We adopt the typical definitions of elemental abundances and ratios. The absolute abundance is determined as the number of atoms of element X per 10^{12} hydrogen atoms, $A(X) = \log_{10}(N_X/N_H) + 12.0$. The logarithmic abundance ratio relative to the solar ratio for element X and Y is defined as $[X/Y] = \log_{10}(N_X/N_Y)_\star - \log_{10}(N_X/N_Y)_\odot$. We use solar abundances from Asplund et al. (2009).

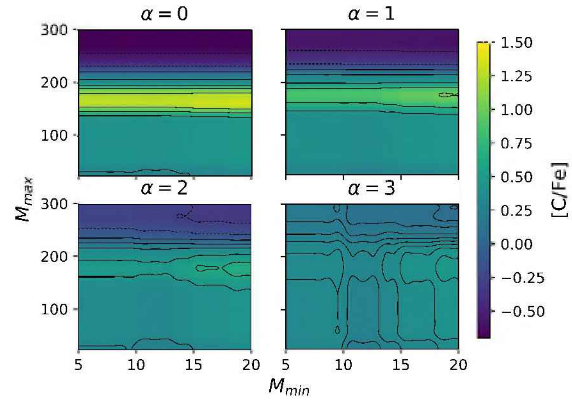

Figure 1: [C/Fe] for different prescriptions of the IMF. The x-axis represent M_{min} and y-axis M_{max}. The contour lines indicate zones of an enhanced [C/Fe]. Notice that [C/Fe] is very sensitive to the upper mass limit for a flatter IMF (i.e., $\alpha = 0$), where it also reaches both of its extreme values.

3. Results

3.1. Carbon

Abundances of carbon and oxygen have been suggested to be the key elements to distinguish between different star formation modes, as carbon and oxygen are indeed the most efficient coolants in case of metal-enriched clouds (Bromm & Loeb, 2003; Omukai et al., 2005).

In Fig. 1, we present several values for the relative abundances of carbon. The results are obtained with four different IMF models. Notice that [C/Fe] is overall super-solar, however, it drops drastically if we consider extreme values for the upper mass cutoff in a flat IMF (top left panel of Fig. 1). The window to reproduce CEMP stars carbon abundances is reached mostly at low values of α.

3.2. Europium

Europium is a heavy, neutron-capture element and peculiar for the reason that it is produced almost entirely by the r-process (roughly 95% of solar europium has been produced via the r-process, Mashonkina et al., 2003). In spite of the fact that Eu lines are weak, thus very often it is possible to derive only upper limits, this element is important to distinguish between r-process scenarios, due to its insensitivity to other production sites.

Fig. 2 present [Eu/Fe] abundance ratios for several IMFs. The contour lines denotes zones of enrichment. Notice that in this model, europium production is limited to a very narrow range of masses (10-25 $M_\odot$), making [Eu/Fe] vary widely between the chosen mass limits.

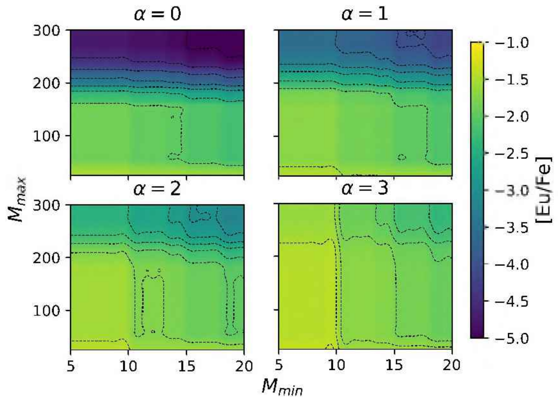

Figure 2: MEu1: [Eu/Fe] predicted by adopting the four different IMFs. The x-axis represent M_{min} and the y-axis M_{max}. Contour lines indicate zones of over-density.

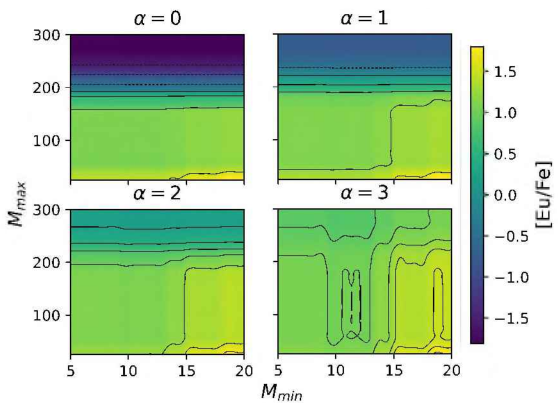

Figure 3: MEu2: [Eu/Fe] for different prescriptions of the IMF, considering stars of 8-10 $M_{\odot}$ and 20-25 $M_{\odot}$.

This is also visible when observing the extreme cases, where [Eu/Fe] has a difference of almost 4 orders of magnitude. On the other hand, when the Pop. III IMF is extended down to lower masses, we obtain a window of enhanced ratios, which covers more area in the case of a Salpeter-like choice for the index α. Based on the selection of masses proposed by Argast et al. (2004), the order of [Eu/Fe] increases significantly as shown in Fig. 3, with a strong dependence on the minimum mass.

3.3. Abundance ratios by CEMP-no stars

In the following analysis, we compare the results obtained by our different models to the observed abundance ratios of some of the extremely-metal poor stars we currently now. Our sample data has been extracted from the available literature, in particular Yoon et al. (2016) and references therein. In total we use 87 CEMP-no stars with [Fe/H] -2.5 and at least an upper limit for [Eu/Fe] 1.0. Claimed binary systems are not considered here to avoid mixing on different paths of formation.

Roughly 70 % of the data presents [C/Fe] between 0.7 and 1.3. The median of the entire sample is [C/Fe]= 0.99. In the case of europium, as Eu lines get very weak at [Fe/H] -3, Eu detections are mostly constrained only by upper limits. The median of the sample is 0.21, which falls in the range of the model considering low (8-10 $M_{\odot}$) and high-mass (20-25 $M_{\odot}$) core-collapse SNe. Combining these constraints we can mark an upper limit for the M_{max} of roughly 200 $M_{\odot}$, while the lower mass cutoff is not well restricted in our models. However, our results discard Pop. III stars as objects of several hundreds of solar masses. The index of the IMF, on the other hand, is satisfied for both cases with $\alpha = 1 - 2$.

4. Discussion

If the chemical abundances we observe in extremely metal-poor stars can be reconciled with the yields of Pop. III stars, it can allow to constrain the masses that the first generation of stars should have had in the past and the form of the initial mass function (Iwamoto et al., 2005).

Past studies have focused on recreating the abundance ratios found in EMP stars, considering a single or a few prescriptions for the IMF. Here we vary the IMF in order to understand how this choice affects subsequent stellar evolution. We were able to reproduce abundances consistent with CEMP-no metal-poor stars found in the Universe, which are believed to born directly out of the gas of first-generation stars. Model MEu1 fell slightly short on the [Eu/Fe] ratio, even for some extreme cases, favoring the presence of only less-massive stars. On the contrary, MEu2 fits better the observed abundances for the CEMP-no stars. Nevertheless, further models have to be done taking into account elements as nitrogen, oxygen or barium, in order to place a stricter restriction on the form of the IMF of the first stars.

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