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$^{13}C/^{18}O$ ratio as a litmus test of stellar IMF variations in high-redshift starbursts

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Abstract. Determining the shape of the stellar initial mass function (IMF) and whether it is constant or varies in space and time is the Holy Grail of modern astrophysics, with profound implications for all theories of star and galaxy formation. On a theoretical ground, the extreme conditions for star formation (SF) encountered in the most powerful starbursts in the Universe are expected to favour the formation of massive stars. Direct methods of IMF determination, however, cannot probe such systems, because of the severe dust obscuration affecting their starlight. The next best option is to observe CNO bearing molecules in the interstellar medium at millimetre/ submillimetre wavelengths, which, in principle, provides the best indirect evidence for IMF variations. In this contribution, we present our recent findings on this issue. First, we reassess the roles of different types of stars in the production of CNO isotopes. Then, we calibrate a proprietary chemical evolution code using Milky Way data from the literature, and extend it to discuss extragalactic data. We show that, though significant uncertainties still hamper our knowledge of the evolution of CNO isotopes in galaxies, compelling evidence for an IMF skewed towards high-mass stars can be found for galaxy-wide starbursts. In particular, we analyse a sample of submillimetre galaxies observed by us with the Atacama Large Millimetre Array at the peak of the SF activity of the Universe, for which we measure $^{13}C/^{18}O \simeq 1$. This isotope ratio is especially sensitive to IMF variations, and is little affected by observational uncertainties. At the end, ongoing developments of our work are briefly outlined.

Keywords. nuclear reactions, nucleosynthesis, abundances, galaxies: abundances, galaxies: evolution, galaxies: ISM, galaxies: starburst, stars: luminosity function, mass function

1. Introduction

More than sixty years have passed since Edwin Salpeter first introduced the concept of stellar initial mass function (IMF) in its seminal paper (Salpeter 1955), providing a convenient way to calculate the number of stars within a logarithmic mass interval. Since then, many important questions related to the fundamental nature of the IMF continue to obsess unanswered the astronomers, among which the long-standing issue of whether the IMF is universal or, rather, varies according to the environmental conditions

(Bastian *et al.* 2010). Since the initial mass of a star is the main driver of its evolution, it goes without saying how crucial the IMF is to studies of galaxy formation and evolution†.

Stars of different initial masses pollute the interstellar medium (ISM) on different timescales, with various chemicals. The net yields (matter restored to the ISM in the form of newly-produced elements per stellar generation, normalized to the total mass locked up in low-mass stars and stellar remnants) are strong functions of the adopted IMF. Therefore, in principle, the IMF shape can be recovered from its chemical imprints (Matteucci 2012). This possibility opens new windows on the IMF determination in environments where other methods (e.g., stellar counts or integrated properties, including absorption line indices and mass-to-light ratios) are not applicable (Henkel & Mauersberger 1993; Papadopoulos *et al.* 2014; Romano *et al.* 2017). In this contribution, we will deal in particular with the interpretation of $^{13}C/^{18}O$ ratios measured by us thanks to the unprecedented sensitivity of the Atacama Large Millimeter/submillimeter Array (ALMA) for a sample of four strongly-lensed submillimetre galaxies (SMGs) at redshift $z \simeq 2$–3 (Zhang *et al.* 2018). These systems are converting gas into stars very efficiently (SFRs ~ 100–$1000\ M_{\odot}\ yr^{-1}$, Ivison *et al.* 1998), but their starlight is heavily obscured by dust (Simpson *et al.* 2017), making any attempt to estimate their IMF via classical methods unfeasible. Because of their high densities, temperatures and pressures, and owing to the presence of intense radiation fields, however, these extreme starbursts are the best places where to search for clear signs of IMF variation (Papadopoulos 2010).

2. Calibration of the chemical evolution model: the Milky Way as a benchmark

Before we move to the interpretation of the abundance data for our four strong CO emitters at high*(ish)* redshifts, however, we have to calibrate our chemical evolution model against the body of observational data for the Milky Way. A careful preliminary chemical evolution study considering all the major chemical species from H to Zn (Romano *et al.* 2010), allowed the selection of the 'best stellar yield set' (among many available in the literature), namely, the one reproducing at best the majority of the chemical properties observed for a large sample of Galactic stars. As can be seen from Fig. 1, the adopted yield set, in particular, reproduces satisfactorily well the evolution of the CNO isotope ratios in the solar neighbourhood, as well as their gradients along the Galactic disc (see Romano *et al.* 2017, for details about the nucleosynthesis prescriptions and the data sources).

It is worth emphasizing that, while the origin of the main CNO isotopes is quite well known, both qualitatively and quantitatively, the yields (and, sometimes, also the production sites) of the minor isotopes are still very uncertain. The main isotopes of C and O are forged as primary elements (i.e., starting from a mixture of hydrogen and helium) in stars of all masses (^{12}C) and only in massive stars (^{16}O), respectively. The secondary isotope of C, ^{13}C, is produced, similarly to ^{14}N, mostly in intermediate-mass stars, partly as a primary and partly as a secondary product (when starting from ^{12}C seeds already present at star's birth). Low-metallicities massive stars, however, may provide huge amounts of primary ^{13}C and ^{14}N, if they rotate fast (Meynet & Maeder 2002; Limongi & Chieffi 2018). As for ^{15}N, its main production site is highly debated, with either massive stars (Pignatari *et al.* 2015) or novae (Romano & Matteucci 2003; Romano *et al.* 2017) being preferred. The minor isotopes of O, ^{17}O and ^{18}O, have a different origin, being synthesised in intermediate-mass stars, high-mass stars and novae the first, and in massive stars the second.

† We make clear at this point that in this contribution 'IMF' stands for 'galaxy-wide IMF' (see Jeřábková *et al.* 2018 for more detailed explanation; see also contribution by A. Hopkins, this volume).

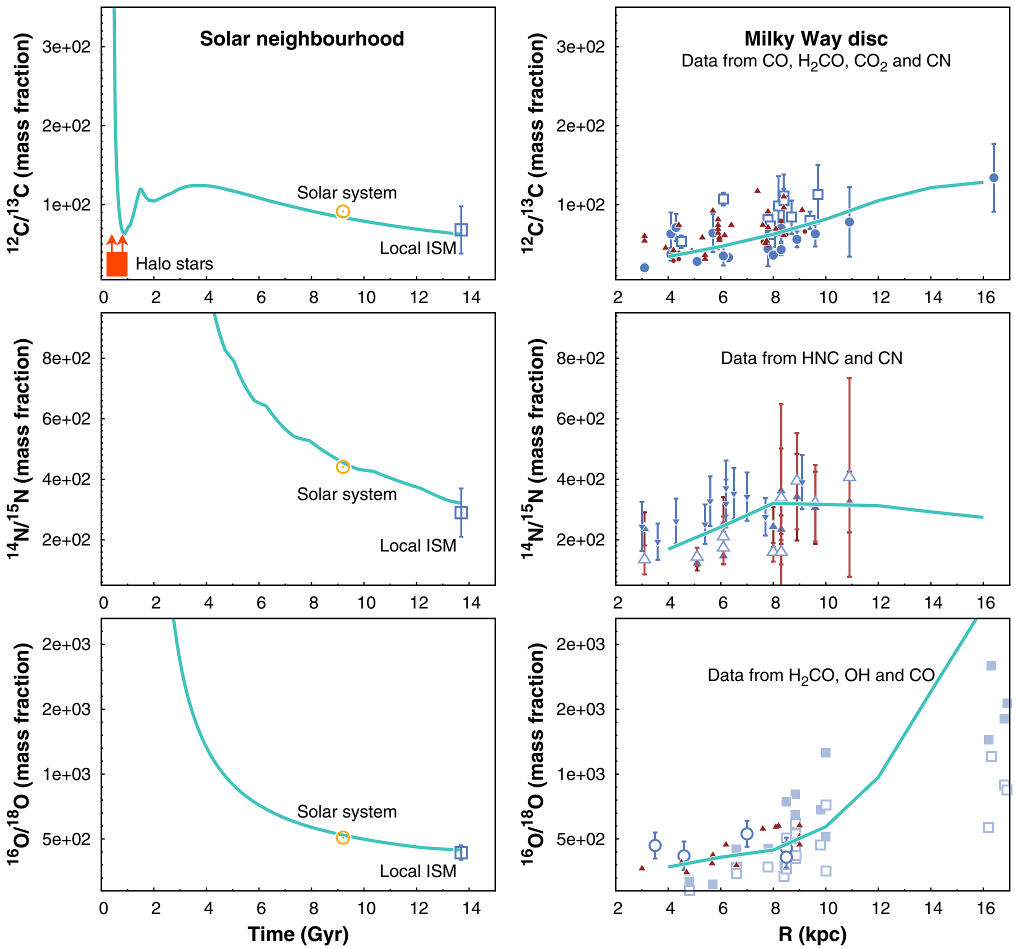

Figure 1. *Left-hand panels:* evolution of $^{12}C/^{13}C$ (top), $^{14}N/^{15}N$ (middle) and $^{16}O/^{18}O$ (bottom) in the solar neighbourhood. *Right-hand panels:* gradients of $^{12}C/^{13}C$ (top), $^{14}N/^{15}N$ (middle) and $^{16}O/^{18}O$ (bottom) across the Milky Way disc. In all panels, the predictions (solid lines) are from our best-fitting Milky Way model, while the symbols refer to the data (see Romano *et al.* 2017, for details about models and data sources).

3. An extremely low $^{13}C/^{18}O$ ratio in SMGs: a signature of a top-heavy IMF?

Once the stellar yields have been calibrated against the rich dataset available for our Galaxy, we can build up models for the prototype SMG. We want to explain the low $^{13}C/^{18}O \simeq 1$ ratio measured from simultaneous observations of ^{13}CO and $C^{18}O$ emission lines in a sample of four SMGs. This ratio has the advantage of being highly sensitive to IMF variations and little biased by differential astro-chemical and lensing effects for the bulk of the molecular gas in the target galaxies (Zhang *et al.* 2018).

We first run some models assuming the same stellar IMF adopted for the Milky Way (namely, a Kroupa 2002 IMF, with a slope $x = 1.7$ for high-mass stars), and vary the strength and duration of the starburst until a value of $^{13}C/^{18}O \simeq 1$ is obtained (we always end up with a final stellar mass of $2{\times}10^{11}$ $M_\odot$ in the model SMG). In this case, we find that a ratio of $^{13}C/^{18}O$ around unity can be obtained only with a very short burst (lasting less than 100 Myr) and unrealistically high SF rates (up to 15,000 $M_\odot$ yr^{-1}). The

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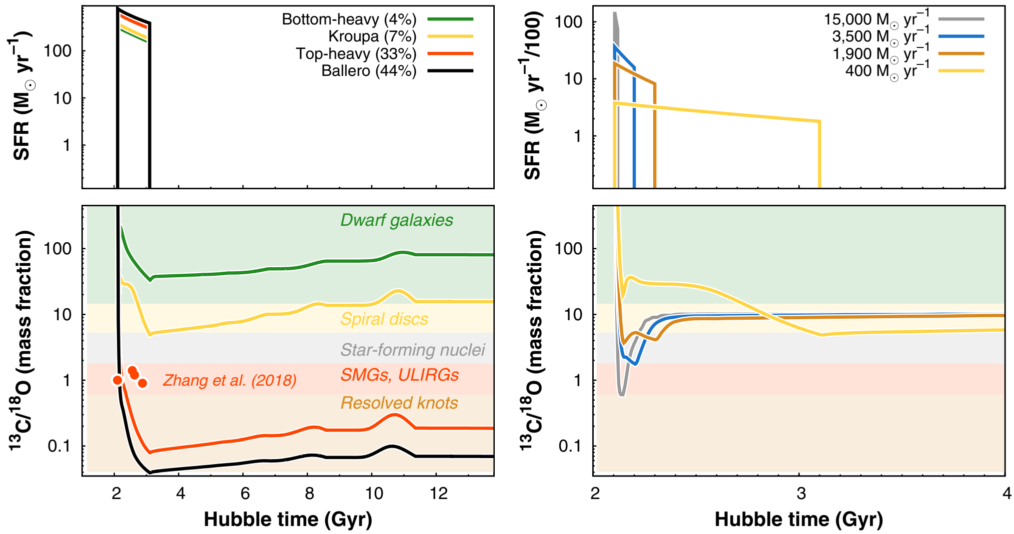

Figure 2. SF rates *(upper panels)* and evolution of $^{13}C/^{18}O$ ratio *(lower panels)* for representative SMG models, where we modify either the SF intensity and duration or the IMF high-mass slope (see text). The fraction of high-mass stars that is obtained with different IMF choices is reported in the top-right corner of the top-left panel. The red dots in the bottom-left panels show the $^{13}C/^{18}O$ ratios of the four SMGs targeted by Zhang *et al.* (2018).

ratio, moreover, suddenly increases to standard Galactic values as soon as the SF ceases, owing to the delayed release of ^{13}C from intermediate-mass stars (see Fig. 2, right-hand panels). According to our models, the only way to obtain a stable, low $^{13}C/^{18}O$ ratio in SMGs is via the assumption of an IMF skewed towards massive stars (see Fig. 2, left-hand panels, and further discussion in Zhang *et al.* 2018).

4. Conclusions and outlook

Our results that the IMF must be top-heavy in high-redshift starbursts is based on a novel approach –we measure the $^{13}C/^{18}O$ ratio in these systems in a regime free from the pernicious effects of dust and use detailed chemical evolution models to disentangle the effects of changes in the IMF or in the SF history on the predicted ratio. It must be cautioned, however, that new developments in stellar evolution and nucleosynthesis theory may still challenge our conclusions. For instance, we must consider the effects that stellar rotation may have on the yields. We are currently working on this.

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