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ALMA Constrains the Stellar Initial Mass Function of Dusty Starburst Galaxies

Zhi-Yu Zhang[1,2]
Donatella Romano[3]
Rob J. Ivison[2,1]
Padelis P. Papadopoulos[4,5]
Francesca Matteucci[6,7,8]

[1] Institute for Astronomy, University of Edinburgh, Royal Observatory Edinburgh, UK
[2] ESO
[3] INAF–Osservatorio di Astrofisica e Scienza dello Spazio di Bologna, Italy
[4] Department of Physics, Aristotle University of Thessaloniki, Greece
[5] Research Center for Astronomy, Academy of Athens, Greece
[6] Department of Physics, University of Trieste, Italy
[7] INAF–Osservatorio Astronomico di Trieste, Italy
[8] INFN, Sezione di Trieste, Italy

The stellar initial mass function (IMF) is fundamental to all measurements of cosmic star formation, which involves an extrapolation from rare, massive stars ($M_* > 8\ M_\odot$) to the full stellar mass spectrum. Classical determinations of a galaxy's IMF are limited to ultraviolet, optical and near-infrared wavelengths, and these cannot be adopted for dust-obscured galaxies with intense, ongoing star formation, even in the local Universe. The unprecedented sensitivity of the Atacama Large Millimeter/submillimeter Array (ALMA) allows us to detect weak emission from ^{13}CO and C^{18}O isotopologues, which offer a sensitive, relatively dust-free, probe of the IMF. Globally low ^{13}CO/C^{18}O ratios for all our targets — dusty starburst galaxies at redshifts ~ 2–3 — alongside a detailed chemical evolution model imply that stars formed in extreme starburst environments are significantly biased towards massive stars compared to ordinary star-forming spiral galaxies. We have combined information from the coldest interstellar medium (at tens of Kelvins) with the physics of nucleosynthesis in hot stars (at tens of millions of Kelvins), to delineate the formation and evolution of galaxies. This opens up a new window to probe the stellar IMF of galaxies with ALMA and it challenges our understanding of fundamental parameters governing galaxy formation and evolution, such as star formation rates, and the timescales for gas depletion and dust formation.

The stellar initial mass function

First introduced by Edwin Salpeter (Salpeter, 1955), the stellar initial mass function is an empirical probability function which describes the relative numbers of stars that form in different mass ranges during a single star formation episode. The determination of the shape of the IMF — whether it is constant and universal or it depends on the physical conditions in the interstellar medium (ISM) out of which the stars form — is of the utmost importance for modern astrophysics, because of its fundamental role in all theories of star and galaxy formation.

Though neatly defined (more or less) from a theoretical point of view (Kroupa, 2001), the IMF is not easily derived from direct star counts (Bastian et al., 2010). Many challenges must be overcome in order to convert the observed stellar luminosities into stellar masses, where uncertainties in stellar distances, ages, metallicities, extinctions and the possibility of unresolved binary systems severely hamper our ability to measure the present-day mass function of a given stellar population. Furthermore, the effects of a complex star formation history and finite stellar lifetimes must be taken into account to recover the IMF from the present-day mass function. For example, the more massive a star, the less time it takes to evolve off the main sequence; at the same time, low-mass stars — with lifetimes comparable to the age of the Universe — continue to populate the present-day mass function. This readily introduces a bias against high-mass objects.

Deducing the shape of the IMF from its chemical imprint

Estimating the IMF directly is therefore anything but a trivial task. On top of this, direct observations of stellar light are not always possible.

The most massive and luminous galaxies that shine at high redshift — for instance, those producing stars at tremendous rates (for example, in excess of 1000 $M_\odot$ yr^{-1}, see Ivison et al., 1998) — have their ultraviolet and optical stellar light heavily obscured by dust (see Figure 1). However, according to theories and cosmological simulations, it is in exactly these systems where the most extreme IMF variations would arise. Are there any other sensible, indirect methods to probe the IMF in these important, dust-shrouded systems?

Luckily, carefully selected chemical abundances (see the next sections) can be measured at millimetre/submillimetre wavelengths — a regime relatively free from the pernicious effects of dust; these provide a fossil imprint of the chemical enrichment processes and an indirect constraint on the prevailing stellar IMF in those extreme environments. It is well known (for example, Tinsley, 1980) that stars in different mass ranges produce different elements in different proportions and on different timescales, with the initial chemical composition of the stars also playing a role. Indeed, in the last three decades, systemic variations of the IMF slope have been explored with the aid of increasingly refined galactic chemical-evolution models. These attempt to explain, for instance, the overabundance of magnesium with respect to iron in local elliptical galaxies, where magnesium is synthesised on short timescales by massive stars and iron is produced mostly on long timescales by type Ia supernovae with relatively low-mass progenitors, or the low metallicities measured in gas-rich, star-forming dwarf galaxies. However, differences in star formation timescales and/or galactic outflows have sometimes shown to act in a similar way, making it very difficult to prefer a variable IMF over other possibilities (Matteucci, 1994).

Carbon, nitrogen and oxygen production in stars, and mixing in the ISM

The seven stable isotopes of carbon, nitrogen and oxygen (the CNO elements) are produced solely by nucleosynthesis in stars. On galactic scales, ^{13}C and ^{18}O are released predominately by low- and intermediate-mass stars ($M_* < 8\ M_\odot$) and massive stars ($M_* > 8\ M_\odot$), respectively (Kobayashi et al., 2011). This is due to the differing energy barriers in nuclear

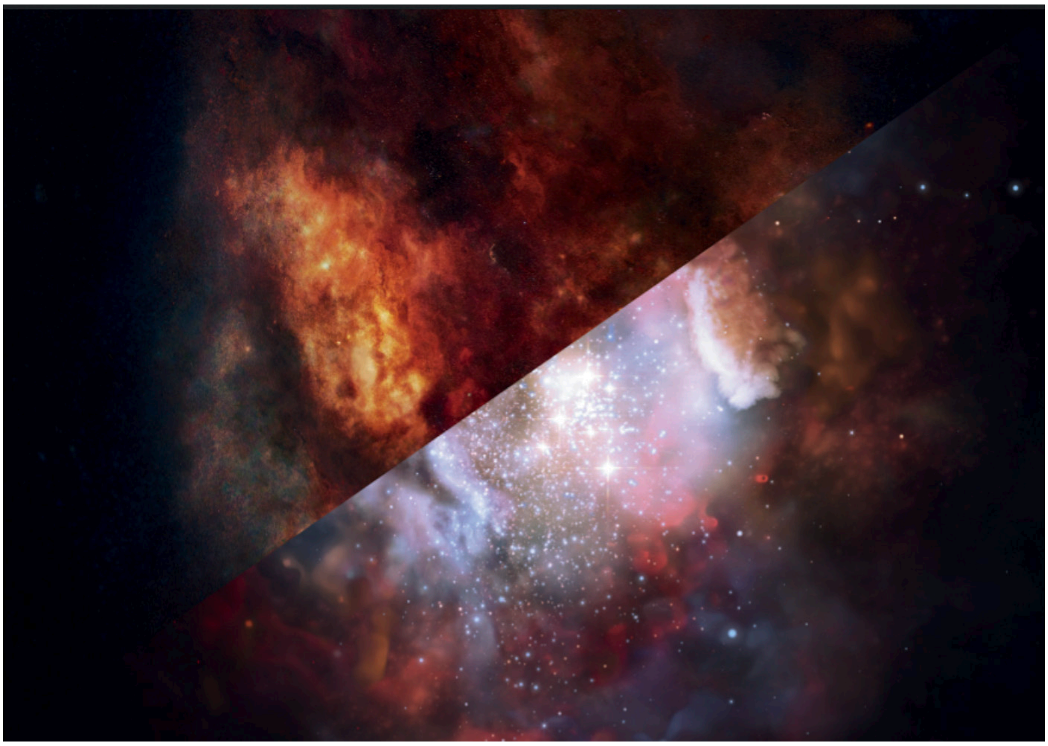

Figure 1. Artist's impressions of a dusty starburst galaxy. The star formation rate is supposedly a few hundred $M_\odot$ yr^{-1}. The dusty curtain obscures the optical and ultraviolet (and, sometimes even the near-infrared) light from stars and only emission at much longer wavelengths, i.e., from submillimetre/millimetre to centimetre can escape. Classical, direct measurements of the present-day mass function are simply not possible for such galaxies.

reactions and the mass-dependent evolution of stars.

^{13}C is mostly synthesised as a secondary element, i.e., its production needs the pre-existing seed of the primary element, ^{12}C, to be present at a star's birth. However, ^{13}C also has a primary production channel, if synthesised directly from ^{12}C produced through helium burning in the star itself. This may happen at the base of the convective envelopes of asymptotic giant branch (AGB) stars going through periodic episodes of dredge-up (Renzini & Voli, 1981), or in low-metallicity, fast-rotating, massive stars, in which rotation triggers the production of primary ^{13}C by allowing the diffusion of ^{12}C produced in He-burning zones into zones burning hydrogen (Chiappini et al., 2008).

Massive stars dominate the production of ^{18}O (Timmes et al., 1995), which is mostly synthesised as a secondary element in the early stages of helium burning, starting from any pre-existing ^{16}O. Therefore ^{18}O production is strongly dependent on the initial stellar metallicity.

These isotopes are then ejected into the ISM via stellar winds, where they form molecules in the same way as their major isotopes. Measurements of ^{13}CO and C^{18}O — isotopologues of carbon monoxide, ^{12}C^{16}O or CO — in the ISM can thus be used to trace the relative ^{13}C and ^{18}O abundances produced by successive generations of stars.

In theoretical work by Romano et al. (2017), we reassessed the relative roles of stars in different mass ranges in the production of the rare CNO isotopes, ^{13}C, ^{15}N, ^{17}O and ^{18}O, along with the more abundant ^{12}C, ^{14}N and ^{16}O. We used a proprietary galactic chemical evolution code for the Milky Way and stellar yields from the literature for massive stars, AGB stars and novae to show that the available isotopic data for the local ISM, protosolar nebula, metal-poor stars and abundance gradients across the Galactic disc can be reproduced satisfactorily with a suitable choice of yields. Moreover, we showed that our models could be extended to constrain the stellar IMF of star-forming galaxies across cosmic time. Among the remaining uncertainties, an unknown star formation history is particularly tricky to deal with. However, if galaxies are caught during the earliest stages of their evolution, the uncertainties are significantly reduced.

ALMA observations of ^{13}CO and C^{18}O towards dusty starbursts

Starburst galaxies in the local Universe most likely had prior episodes of cosmological evolution, so the elementary abundances in their ISM could be affected by a complex star formation history may not strictly be related to the current episode of star formation. We selected a sample of dusty starburst galaxies at $z \sim 2$–3, with less than 3 Gyr of cosmic time available for prior episodes of evolution. So they are expected to have relatively clean and simple star formation histories. Owing to the weakness of the isotopologue lines (^{13}CO and C^{18}O), we selected the four strongest CO emitters in the literature, which are all gravitationally lensed systems with their signals amplified by factors of ~ 3–10.

We performed simultaneous observations of ^{13}CO and C^{18}O emission lines, using ALMA in its relatively compact array configurations, in the spring of 2015 (Zhang et al., 2018). Between 10 and 30 minutes were spent on each target per observation. We manually calibrated all data using the Common Astronomy Software Applications (CASA) package[1] (v. 4.7.1) following standard procedures. The final angular resolution spanned 1.6 to 3.7 arcseconds, corresponding to spatial resolutions of ~ 14–30 kpc at z ~ 2. We optimised for sensitivity, both in the observations and in the data reduction, so the final images have limited angular resolution — most targets are unresolved or only marginally resolved.

Most targeted lines are detected robustly with signal-to-noise (S/N) > 5. Only two targeted lines are marginally detected at ~ 4-σ level; $J = 3 \rightarrow 2$ from SDP.17b (HATLAS J090302.9–014127) and $J = 5 \rightarrow 4$ from SPT 0103–45 (SPT-S J010312–4538.8). However, the high-J transitions show consistent results at higher S/N, so we can be confident about the observed line ratios. See Figure 2 for an example of our ALMA detections of ^{13}CO and C^{18}O, $J = 3 \rightarrow 2$.

Literature data on ^{13}CO and C^{18}O in various galaxies

We compiled a collection of line flux ratios from the literature, $I(^{13}\mathrm{CO})/I(\mathrm{C}^{18}\mathrm{O})$ at the same J transitions, in various types of gas-rich galaxies. Figure 3 shows the $I(^{13}\mathrm{CO})/I(\mathrm{C}^{18}\mathrm{O})$ ratio as a function of infrared luminosity, L_{IR} (i.e., the apparent star formation rate traced by massive stars).

Discs of nearby normal spiral galaxies have $I(^{13}\mathrm{CO})/I(\mathrm{C}^{18}\mathrm{O})$ line ratios of ~ 7–10, similar to that of the Milky Way's disc (Jiménez-Donaire et al., 2017). Galaxies with extremely high star-forming activity (≥ 100–500 × Milky Way) all have much lower ratios, close to unity (Henkel et al., 2014). The lowest $I(^{13}\mathrm{CO})/I(\mathrm{C}^{18}\mathrm{O})$ ratio, an upper limit of 0.5, is found in a starburst knot — the central 500-parsec region of the nearby ultra-luminous infrared galaxy IRAS 13120–5453 (Sliwa et al., 2017). Gas-rich dwarf galaxies, such as the Magellanic Clouds and IC 10, show the highest ratios of $I(^{13}\mathrm{CO})/I(\mathrm{C}^{18}\mathrm{O})$, greater than 30. $I(^{13}\mathrm{CO})/I(\mathrm{C}^{18}\mathrm{O})$ shows a clear decreasing trend with L_{IR}, or the apparent star formation rate traced by massive stars.

Both the ^{13}CO and C^{18}O lines are excited predominantly by collisions with H_2 molecules, so they share identical excitation conditions. These lines are optically thin, given their low abundances. Their abundances are not biased by differential astro-chemical effects and differential lensing effects for the bulk of the molecular gas in galaxies. So the line ratio of $I(^{13}\mathrm{CO})/I(\mathrm{C}^{18}\mathrm{O})$ can be used safely to trace the abundance ratio of ^{13}CO/^{18}O in the ISM.

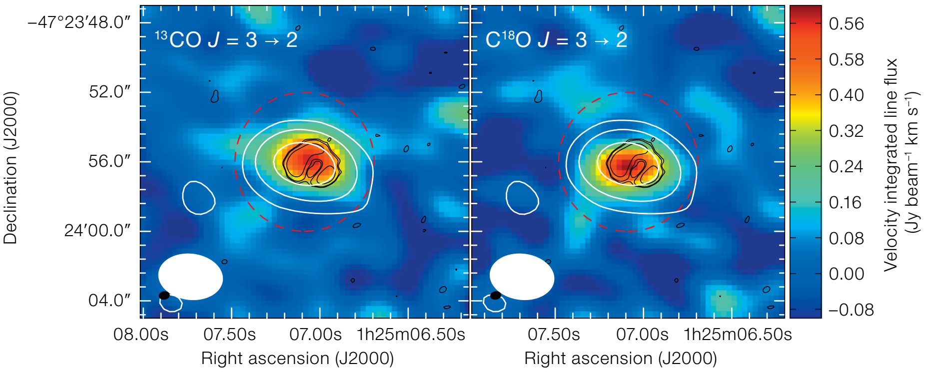

Figure 2. Velocity-integrated flux map (zero moment) of ^{13}CO and C^{18}O for the $J = 3 \rightarrow 2$ transition in SPT 0125–47. White contours show the low-resolution 94-GHz continuum, tracing the rest-frame cold dust emission. Black contours show the high-resolution 336-GHz continuum image, obtained from the ALMA archive, presenting the Einstein ring structure produced by the gravitational lensing effect.

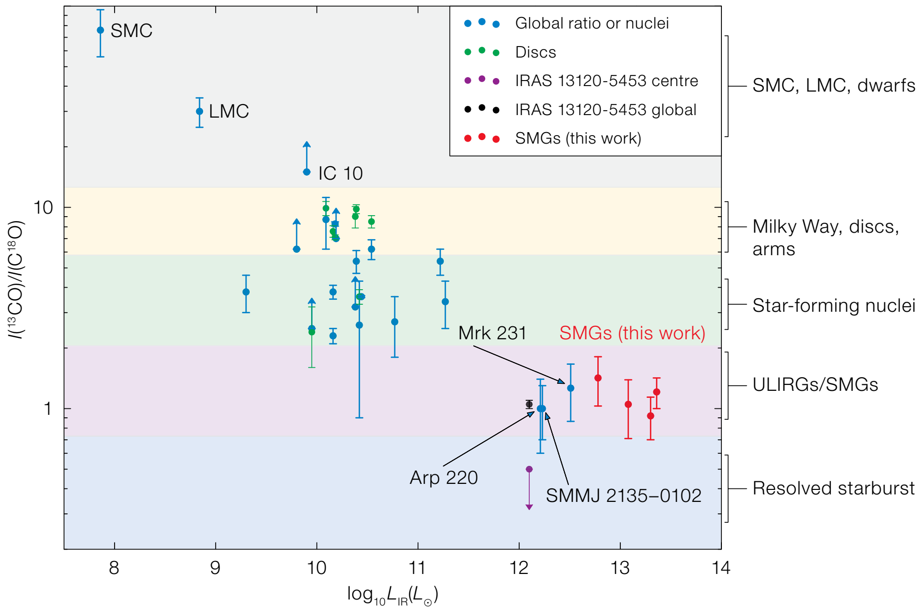

Figure 3. $I(^{13}\mathrm{CO})/I(\mathrm{C}^{18}\mathrm{O})$ as a function of intrinsic infrared luminosity (rest-frame 8–1000 μm, L_{IR}). Our lensed starburst sample is plotted with red symbols. The $I(^{13}\mathrm{CO})/I(\mathrm{C}^{18}\mathrm{O})$ measurements of nearby star-forming galaxies, galactic nuclei (Jiménez-Donaire et al., 2017), local Ultraluminous infrared galaxies (ULIRGS; Henkel et al., 2014), a lensed submillimetre galaxy (SMG), SMM J2135–0102 (Danielson et al., 2013), gas-rich dwarf galaxies, the Magellanic Clouds (SMC and LMC) and IC 10, are presented for comparison.

Such a systematic variation of isotopologue abundance ratios over galaxy-sized molecular hydrogen reservoirs indicates a change of the stellar IMF from the canonical one found in normal star-forming systems like the Milky Way. To verify this, the degeneracy with star formation history needs to be taken into account, because the lifetimes of stars can also bias the final abundances in the ISM.

Galactic chemical evolution

How much variation does the star formation history induce in the ^{13}C/^{18}O ratio, compared to any changes due to variations of the IMF slope? To answer this

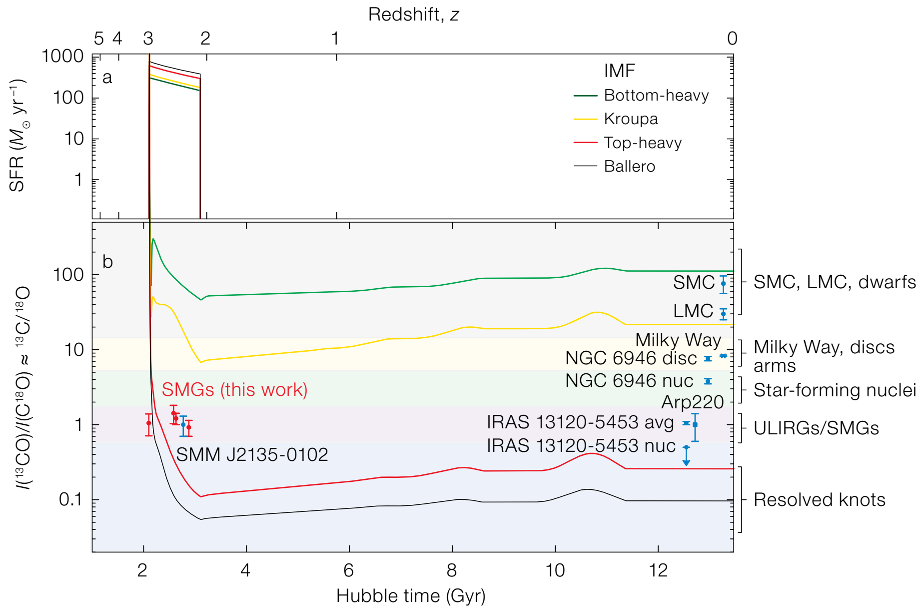

Figure 4. Evolutionary tracks of $^{13}C/^{18}O$ abundance ratio in the ISM, using various IMFs. Coloured lines correspond to different IMFs. a) Modelled starburst history, which started evolving 2 Gyr after the Big Bang, grew to a total stellar mass of 10^{11} $M_\odot$ and stopped forming stars 1 Gyr later. SFR is the star formation rate. b) Corresponding $^{13}CO/C^{18}O$ (as a proxy of $^{13}C/^{18}O$) abundance ratio as a function of redshift, following different IMFs. Our lensed starburst sample is plotted with red symbols. Blue dots show the $^{13}CO/C^{18}O$ ratios measured in a few representative local galaxies.

question, we adopt a galactic chemical evolution model that accurately includes the isotopic yields across the full range of stellar mass, taking into account the differential release of different elements into the ISM as a function of a star's lifetime, and the initial metallicity, as well as any prior galactic evolution. We have benchmarked the model against the rich isotopic datasets of the Milky Way and shown it can reproduce the Galactocentric gradients of isotopic abundance ratios, and all the relevant local disc data (Romano et al., 2017).

With such a well-calibrated model, we can safely build up an extreme case for the evolution of the $^{13}C/^{18}O$ abundance ratio for a pure starburst, as shown in Figure 4. To do that, we evolve a galaxy from $z \sim 3$ (2 Gyr after the Big Bang) for a span of 1 Gyr, with a high star formation rate, until it reaches a total stellar mass of 10^{11} $M_\odot$. Star formation is stopped completely after that, and the relic evolves passively to $z \sim 0$. This model was repeated with four different types of IMF, from bottom-heavy (biased towards low-mass stars) to top-heavy (biased towards massive stars), including the canonical Kroupa IMF that can reproduce average Galactic conditions (Kroupa, 2001).

With the Kroupa IMF, the evolved $^{13}C/^{18}O$ ratio reaches the range observed in the discs of the Milky Way and nearby normal spiral galaxies. However, only a top-heavy IMF can reproduce the $I(^{13}CO)/I(C^{18}O)$ observed in starburst galaxies, near and far. The extremely low $I(^{13}CO)/I(C^{18}O)$ ratio measured in the centre of IRAS 13120–5453 can be explained with the top-heavy and the Ballero IMF (Ballero et al., 2007), which could reproduce the chemical abundances of stars in the Galactic bulge.

Outlook and implication

Our results — finding a top-heavy IMF in dusty starburst systems across cosmic time, where classical IMF measurement methods cannot be applied — are consistent with the results from other, less dusty, less extreme starburst systems, such as ultra-compact dwarf galaxies, progenitors of early-type galaxies, and compact starbursting stellar associations in the Large Magellanic Cloud.

The systematic variation of the IMF in different galaxy types has an obvious dependency on their star formation properties. The IMF can no longer be assumed to be universal, with a constant canonical form, as commonly applied in most cosmological simulations. Moreover, all measurements of cosmic star formation rate and stellar mass, and their derivatives, must be re-assessed urgently. For example, the star formation rates in starburst galaxies are derived from classical tracers, which extrapolate observables from massive stars using an assumed IMF. These need to decrease by a factor of at least a few, and the gas-depletion times must then increase by the same factor. As a result, most fundamental parameters in the field of galaxy formation and evolution must be re-addressed, exploiting advances in stellar physics.

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Links

[1] CASA software: https://casa.nrao.edu/index.shtml