Modern yields per stellar generation: the effect of the IMF

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ABSTRACT

Gaseous and stellar metallicities in galaxies are nowadays routinely used to constrain the evolutionary processes in galaxies. This requires the knowledge of the average yield per stellar generation, \( y_Z \), i.e. the quantity of metals that a stellar population releases into the interstellar medium (ISM), which is generally assumed to be a fixed fiducial value. Deviations of the observed metallicity from the expected value of \( y_Z \) are used to quantify the effect of outflows or inflows of gas, or even as evidence for biased metallicity calibrations or inaccurate metallicity diagnostics. Here we show that \( y_Z \) depends significantly on the Initial Mass Function (IMF), varying by up to a factor larger than three, for the range of IMFs typically adopted in various studies. This, along with the variation of the gas mass fraction restored into the ISM by supernovae (\( R \), which also depends on the IMF), may yield to deceiving results, if not properly taken into account. In particular, metallicities that are often considered unusually high can actually be explained in terms of yield associated with commonly adopted IMFs such as the Kroupa (2001) or Chabrier (2003). Moreover, if the IMF depends on the environment, then \( y_Z \) should be varied accordingly. Finally, we show that \( y_Z \) is not substantially affected by the initial stellar metallicity as long as this is higher than \( Z > 10^{-3} Z_\odot \). On the other hand, \( y_Z \) does vary significantly in primordial systems with metallicities lower than this threshold.

Key words: galaxies: evolution – galaxies: ISM – ISM: abundances – stars: abundances

1 INTRODUCTION

The analysis of the chemical enrichment of galaxies is a powerful tool to constrain galaxy evolutionary processes. The content of metals in galaxies, both in the interstellar medium (ISM) and in stars, depends critically on the past star formation history and on the net effect of outflows and inflows, which are some of the key mechanisms in shaping galaxy evolution. In order to extract valuable information from the observed metallicities, it is crucial to compare them with the amount of metals expected to be produced by the integrated star formation. To achieve this is necessary to have accurate information on the amount of each chemical element injected into the ISM by each type of star, i.e. the so-called stellar yields. Generally, most observations provide information only on the global content of metals, or on a single chemical element which is taken as representative of the global metallicity (by assuming that, for instance, the abundance of the various elements scales proportionally to the solar relative abundances). Moreover, many studies do not deal with the relative delayed enrichment of different chemical species. Therefore, the quantity that is often used is the so-called average yield per stellar generation, or net yield (generally indicated as \( y_Z \), or simply \( y \)), which is the total mass of metals that a stellar population releases into the ISM, normalized to the mass locked up into low-mass (long-lived) stars and stellar remnants.

Historically, this approach was first used in the early work of Searle & Sargent (1972), who derived the relation between gas phase metallicity \( Z \) and gas fraction \( \mu = M_{\text{gas}} / (M_{\text{gas}} + M_\star) \) for a closed box model (see Tinsley 1980, or Matteucci 2001 for a detailed analysis):

\[
Z = y_Z \ln \left( \frac{1}{\mu} \right) .
\]

This simple model is based upon the assumptions that the galaxy is one-zone and closed; the initial gas mass is of primordial chemical composition; the initial mass function (IMF) is invariant, and the mixing of the gas in the galaxy
is always instantaneous and complete, and that metals are instantaneously recycled for the formation of the new generation of stars. The latter is dubbed "instantaneous recycling approximation" (IRA; Tinsley 1980). Within this simplified (but widely used) approach the further approximation is that all stars with $m \geq 1 \text{M}_\odot$ die instantaneously, while all stars with $m < 1 \text{M}_\odot$ have infinite lifetime; this way, the effect of stellar lifetimes in the equations can be neglected and the effect subsumed into a net return fraction ($R$). These are strong assumptions but represent a good approximation for those chemical elements produced and restored into the ISM by stars with low typical lifetimes. The best example of such a chemical element is oxygen, which is also representative of the global metallicity $Z$, since it is the most abundant heavy element by mass.

The yield per stellar generation is obviously a key also in more complex analytical models of chemical evolution, which include the effect of outflows and inflows, as well as as variations of the star formation efficiency, i.e. normalization and slope of the relation between gas mass and star formation rate, (see for example, Spitoni et al. 2010, Bouché et al. 2010, Dekel et al. 2013, Peng & Maiolino 2014, Zahid et al. 2014, Ascasibar et al. 2014), as well as in numerical simulations (e.g. Kobayashi et al. 2011). The comparison of these models with the extensive observations that are providing metallicity measurements for large samples of galaxies locally and at high redshift (e.g. Savaglio et al. 2005, Maiolino et al. 2008, Troncoso et al. 2014) enable us to provide important constraints on these various processes, modulo an accurate knowledge of the yield per stellar generation.

In most of the studies, the yield per stellar generation is taken as a fixed value (typically about 0.012-0.019). However, even if the net yield is a combination of yields from different stellar masses, it is clear that it must depend on the IMF. This has sometimes been acknowledged (e.g. Henry et al. 2000; Kobayashi et al. 2011), but never really taken into consideration when using the net yield in the various models. In particular, in some works it is unclear whether the total stellar mass and the net yield are given with respect to the same IMF. Moreover, there is some evidence that the IMF may vary in different classes of galaxies. This implies that different yields per stellar generation should be used. Finally, since the stellar nucleosynthetic yield has a metallicity dependence, it is important to check the effect of metallicity on the IMF-integrated net yield.

To tackle the issues presented above, in this article we calculate yields per stellar generation for the most commonly adopted IMFs and investigate their metallicity dependence (although the latter effect is shown to be minor), by using a modern compilation of nucleosynthetic yields, which have been thoroughly tested against the best available data for galaxies in the Local Group (e.g. Romano et al. 2010). We mostly focus on the yield of oxygen, which is the element which is most commonly used as a tracer of the global metallicity, and for which the IRA approximation is appropriate. However, we will also provide the yield per stellar generation for the total mass of metals, although this should be used with caution, given the enrichment delay of various elements (e.g. iron, nitrogen, carbon, etc...), for which the IRA approximation is arguable.

In Section 2 we define the quantities we have computed in this work and specify the set of stellar yields which we have assumed and the IMFs which we have explored. In Section 3 we report and discuss our results. Finally, in Section 4 we summarize the main conclusions.

## 2 DEFINITIONS AND ASSUMPTIONS

We define as yield per stellar generation $y_i(Z)$, or net yield, the ratio of the global gas mass in the form of a given chemical element $i$ newly produced and restored into the ISM by a simple stellar population with initial metallicity $Z$ to the amount of mass locked up in low mass stars and stellar remnants (Tinsley 1980; Maeder 1992; Matteucci 2001):

$$y_i(Z) = \frac{1}{1 - R(Z)} \int_{m_{\text{low-liv}}}^{m_{\text{up}}} p_i(m, Z) \phi(m) \, dm \int_{0.1 \text{M}_\odot}^{100 \text{M}_\odot} m \, \phi(m) \, dm,$$

where:

(i) $p_i(m, Z) = \frac{M_{i,\text{tot}}(m, Z)}{m}$ is the so-called *stellar yield*, which is defined such that $m \cdot p_i(m, Z)$ represents the mass in the form of the $i$-th chemical element newly formed and ejected into the ISM by stars with initial mass $m$ and metallicity $Z$;

(ii) $\phi(m)$ is the IMF, namely the mass-spectrum over which the stars of each single stellar generation are distributed at their birth;

(iii) $m_{\text{low-liv}} = 1.0 \text{M}_\odot$ is the maximum mass of the so-called long-lived stars, which do not pollute the ISM;

(iv) $m_{\text{up}}$ is the upper mass cutoff of stars contributing to the chemical enrichment of the ISM with their nucleosynthetic products; in our standard case, we assume $m_{\text{up}} = 100 \text{M}_\odot$.

Finally, $R$ represents the so-called return mass fraction, which is defined as the total mass fraction (including both processed and unprocessed material) returned into the ISM.
by a stellar generation:

\[ R(Z) = \frac{\int_{M_{\text{long-lived}}}^{m_{\text{up}}} (m - M_R(m, Z)) \phi(m) \, dm}{\int_{0.1 \, M_{\odot}}^{100 \, M_{\odot}} m \phi(m) \, dm}, \quad (3) \]

with \( M_R(m, Z) \) being the mass of the stellar remnant left by a star with initial mass \( m \) and metallicity \( Z \).

In this work, we assume the set of stellar yields compiled by Nomoto et al. (2013), which is currently the best to reproduce the abundance patterns in the solar vicinity. It includes:

(i) for low- and intermediate-mass stars, the metallicity-dependent stellar yields of Kobayashi et al. (2006);
(ii) for massive stars, the He, C, N and O stellar yields at the various metallicities of Meynet & Maeder (2002), Hirschi et al. (2005), Hirschi (2007) and Ekström et al. (2008) while, for heavier elements, the metallicity-dependent stellar yields of Kobayashi et al. (2006).

This set of stellar yields is quite similar to the one of Nomoto et al. (2013), except for the yields of He, C, N and O from massive stars, which in our work have been computed by the Geneva group, by including the effect of mass loss and rotation. The oxygen yields of massive stars as functions of the initial stellar mass and metallicity are shown in Fig. 2 These stellar yields are available only up 60 \( M_{\odot} \) and we therefore assume in our standard case that the yields from 60 to 100 \( M_{\odot} \) are constant. Finally, the stellar yields of massive stars of Kobayashi et al. (2006) are available only up to 40 \( M_{\odot} \) and thus we keep them constant for stars with larger initial mass. We remark on the fact that very massive stars are expected to leave a black hole as a remnant; therefore, a significant fraction of stellar nucleosynthetic products in the ejecta of very massive stars may eventually fall back onto the black hole. This process might cause a reduction of the stellar yields of very massive stars.

The stellar yields of massive stars, as computed by the Geneva group, include the effect of a metallicity-dependent mass loss and rotation. The mass loss is particularly important at almost solar metallicity and above in depressing the oxygen stellar yields of the most massive stars (\( M \gtrsim 30-40 \, M_{\odot} \)), as seen in Fig. 2. In fact, mass loss increases with stellar metallicity and stars of high metal content loose H, He, but also C, through radiatively line driven winds. Therefore, the C production is increased by mass loss whereas the O production is decreased, since part of C which would have been transformed into O, is lost from the star (Maeder 1992). The effect of rotation is to produce mixing and enhance mass loss: below 30 \( M_{\odot} \), mixing induced by rotation increases the yields of the \( \alpha \)-elements (O, Mg, Ne, Si, S, Ca, and Ti); above 30 \( M_{\odot} \), rotational mass dominates and enhances the yields of He (see also Maeder et al. 2006; Meynet et al. 2010 and references therein).

We study the effect of different IMFs: the Salpeter (1955), the Kroupa et al. (1993), the Kroupa (2001), and the Chabrier (2003) IMFs, which are shown in Fig. 1 as normalized with respect to the Salpeter (1955) IMF. We have chosen these IMFs since they have been the most widely used by various authors. Moreover, these IMFs give quite different weights to different stellar mass ranges, hence they will more clearly display differences in the final predicted net yields and return mass fractions. As one can notice from Fig. 1, the Kroupa et al. (1993) IMF predicts the largest fraction of intermediate mass stars, while having the lowest number of massive stars. On the other hand, the Chabrier (2003) and the Kroupa (2001) IMFs predict a higher number of both intermediate-mass stars and massive stars than the Salpeter (1955) IMF.

3 RESULTS

In this Section we present the net nucleosynthetic yields and return fractions obtained with the IMFs and stellar yields discussed in the previous section. As mentioned above, we will focus on the yield of oxygen, since it is the element most commonly measured and taken as representative of the bulk of the metallicity, and also because it is an element for which the IRA approximation is appropriate. However, we will provide a value also for the yield of the total mass of metals, although with some cautionary warnings.

In Fig. 3 we how show how the net yield of oxygen per stellar generation varies as a function of the IMF and metallicity. Concerning the dependence on metallicity, the most interesting result is that the yield \( y_0 \) is roughly constant down to very low metallicities. This result implies that the assumption of a time-independent net oxygen yield, as generally treated in analytical models, is a reasonable one. The yield has an abrupt change going to metallicities below \( 10^{-3} Z_{\odot} \), which is an important warning when modelling the enrichment of primordial galaxies. In our work, we assume a solar metallicity \( Z_{\odot} = 0.0134 \) from Asplund et al. 2009.

On the other hand, \( y_0 \) is strongly dependent on the assumed IMF. The highest oxygen yield is obtained when adopting a Chabrier (2003) IMF, because this particular IMF contains the largest number of massive stars compared to the other IMFs explored in this paper (see Fig. 4). The IMF of Kroupa et al. (1993), instead, predicts the lowest \( y_0 \), since it contains the lowest fraction of high mass stars. In
Figure 3. In this figure, we show how the net yield of oxygen, \( y_O \), varies as a function of the metallicity \( Z \) from which the stellar generation originated, when assuming the Romano et al. (2010) set of stellar yields. We adopt a solar metallicity \( Z/Z_\odot = 0.0134 \) from Asplund et al. (2005). The solid line in magenta corresponds to the predictions with the Salpeter (1955) IMF; the dashed line in black to the Kroupa et al. (1993) IMF; the dotted line in blue to the Chabrier (2003) IMF; the dashed-dotted line in red to the Kroupa (2001) IMF, by keeping constant the stellar yields of oxygen and heavier \( \alpha \)-elements for stars with mass larger than \( 60 M_\odot \) and \( 40 M_\odot \), respectively. In order to quantify the systematic effect introduced by this assumption, we further explore how the choice of the \( m_{\text{up}} \) value affects the averaged net yield of oxygen; this is shown in Fig. 4, where \( y_O \) stands for the net yield of oxygen as averaged in the metallicity range \( 1.0 \times 10^{-5} \leq Z \leq 1.0 \times 10^{-2} \).

By looking at Fig. 4 we see that the difference between the case with \( m_{\text{up}} = 100 M_\odot \) and \( m_{\text{up}} = 40 M_\odot \) is as much as a factor of about two. The difference is only \( \sim 50 \) per cent between \( m_{\text{up}} = 100 M_\odot \) and \( m_{\text{up}} = 60 M_\odot \). We find that, when assuming the Chabrier (2003) and Kroupa et al. (1993) IMFs, the differences in \( y_O \) with different upper mass limits are almost doubled and halved, respectively, with respect to the case with the Salpeter (1955).

Figure 4. In this figure, we show how \( \langle y_O \rangle \) is predicted to vary as a function of \( m_{\text{up}} \), which is defined as the upper mass cutoff of stars contributing to the chemical enrichment of the ISM. We have computed \( \langle y_O \rangle \), by averaging the net yield of oxygen over the metallicity range \( 1.0 \times 10^{-5} \leq Z \leq 1.0 \times 10^{-2} \), within which \( y_O \) turns out to be nearly constant (see also Fig. 3). The various curves with different colours correspond to the same IMFs as in Fig. 3.

In this context, it is important to distinguish the two IMFs suggested by Kroupa. In fact the Kroupa (2001) is very similar to the IMF of Chabrier (2003) and predicts a substantially higher yield than Kroupa et al. (1993). The Salpeter (1955) IMF predicts a net yield roughly halfway between the Chabrier (2003) and Kroupa et al. (1993) IMFs.

In Table 1 we show all the values of \( y_O \) and \( y_Z \) (where \( Z \) here is the sum of all metals) as functions of the different IMFs and metallicities. We show the values of \( y_Z \) here only for reference with previous work attempting to model the total metal content of galaxies, however we caution the reader against a blind application of analytical models assuming the IRA to the total metal content. In the same Table we report also the values of the returned fraction \( R \), which is rather constant as a function of metallicity but shows some change for different IMFs.

As aforementioned, the Romano et al. (2010) compilation provide stellar yields of oxygen and heavier \( \alpha \)-elements only up to \( 60 M_\odot \) and \( 40 M_\odot \), respectively; in our “fiducial” case, reported in Table 1 we assume \( m_{\text{up}} = 100 M_\odot \), by keeping constant the stellar yields of oxygen and heavier \( \alpha \)-elements for stars with mass larger than \( 60 M_\odot \) and \( 40 M_\odot \), respectively. In order to quantify the systematic effect introduced by this assumption, we further explore how the choice of the \( m_{\text{up}} \) value affects the averaged net yield of oxygen; this is shown in Fig. 4, where \( y_O \) stands for the net yield of oxygen as averaged in the metallicity range \( 1.0 \times 10^{-5} \leq Z \leq 1.0 \times 10^{-2} \).

4 CONCLUSIONS AND DISCUSSION

Large spectroscopic samples of galaxies in the local Universe and at high redshift have greatly improved the availability of data on gas phase oxygen abundances in galaxies. The modelling of these data to infer constrainbs on gas flows and feedback in galaxies requires a secure knowledge of the net oxygen yield (as well as of metals in general) and return mass fraction.

In this article, we have used modern stellar nucleosynthetic yields to explore the effect of assuming different IMFs on the net yield of oxygen per stellar generation and on the return mass fraction. We have assumed for O, C and N the metallicity-dependent stellar yields of the Geneva group (Meynet & Maeder 2002; Hirschi et al. 2007; Hirschi 2007; Ekström et al. 2008), which include the combined effect of mass loss and rotation; for heavier elements,
we have assumed the metallicity-dependent stellar yields of Kobayashi et al. (2009).

The effect of assuming different IMFs can cause large differences in the net oxygen yield. We have found that the Kroupa (2001) and Chabrier (2003) predict the highest oxygen yield, roughly a factor of two higher than for a Salpeter (1955) IMF. On the other hand, by assuming a Kroupa et al. (1993) IMF, we obtain the smallest net yield, roughly a factor of two lower than for a Salpeter (1955) IMF.

The yield per stellar generation also depends significantly on the upper mass cutoff of stars contributing to the chemical enrichment of the ISM with their nucleosynthetic products. The differences between the case with $m_{\text{up}} = 100 M_\odot$ and $m_{\text{up}} = 40 M_\odot$ are of the order of a factor of two with the Salpeter (1955). Since the IMF of Chabrier (2003) predicts a larger number of massive stars, that difference is doubled with this IMF, whereas it is halved with the Kroupa et al. (1993) IMF, which predicts the lowest number of massive stars. If one takes into account both the variation with IMF shape and upper stellar mass cutoff, the variation of the yield per stellar generation can span more than a factor of ten.

The blooming of extensive spectroscopic surveys of local and distant galaxies have fostered the use of metallicities to constrain the star formation history, feedback processes (outflows) and gas inflows across the cosmic epoch, by comparing the observations with the expectations of analytical and numerical models. One key element in such a comparison is the yield per stellar generation, which is often assumed as a fixed value. However, our results have shown that the yield can change by a large factor. Therefore, if the yield associated with the appropriate IMF is not used, this can produce inconsistent results and large systematic errors.

We note that populations of highly enriched galaxies – whose metallicities were deemed uncomfortably high – can be easily explained by means of a large yield per stellar generation, as the one associated with commonly used IMFs, such as Chabrier (2003) and Kroupa (2001). Similarly, our results should warn about a proper use of the so-called effective yield, $y_{\text{eff}} = Z / \ln (\mu^{-1})$, which is observationally derived by inverting equation 1. In particular, the finding of $y_{\text{eff}} < y_z$ is generally modelled in terms of enriched outflows, inflow of pristine gas, or both (e.g. Tremonti et al. 2004, Erb 2008, Mannucci et al. 2009, Troncoso et al. 2014), whereas the finding of $y_{\text{eff}} > y_z$ is sometimes used as an indicator of inaccurate metallicity measurements or inappropriate metallicity calibrations. We conclude that the deviation of $y_{\text{eff}}$ from a “fiducial”, “true” yield also may be partly associated with IMF being different than assumed. For the same reason, high values of the the effective yield, may be indicative of an IMF favouring massive stars (Chabrier 2003; Kroupa 2001) and/or of a high mass cutoff of the IMF itself.

The dependence on metallicity of the yield is reassuringly small. A significant variation is only found at very low metallicities ($Z < 10^{-3} Z_\odot$), hence this may be an important aspect to take into account for models of primordial galaxies.

Our compilation of numerical values of the yield per stellar generation, for different IMFs, different upper mass cutoffs and different metallicities, will hopefully be useful to properly investigate the metallicity in galaxies across cosmic epochs, by tackling one of the (generally not acknowledged) major sources of uncertainty.

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| $Z$         | $R$ | $y_O$ | $y_z$ | $R$ | $y_O$ | $y_z$ | $R$ | $y_O$ | $y_z$ |
|------------|-----|-------|-------|-----|-------|-------|-----|-------|-------|
| IMF: Salpeter (1955) | 1.0 x 10^-8 | 0.285 | 0.036 | 0.053 | 0.436 | 0.073 | 0.107 | 0.284 | 0.023 | 0.035 | 0.411 | 0.066 | 0.097 |
| IMF: Chabrier (2003) | 1.0 x 10^-6 | 0.285 | 0.054 | 0.050 | 0.436 | 0.070 | 0.103 | 0.284 | 0.022 | 0.033 | 0.411 | 0.063 | 0.093 |
| IMF: Chabrier (2003) | 5.0 x 10^-6 | 0.285 | 0.027 | 0.040 | 0.436 | 0.056 | 0.083 | 0.284 | 0.016 | 0.026 | 0.411 | 0.051 | 0.076 |
| IMF: Kroupa et al. (1993) | 1.0 x 10^-5 | 0.285 | 0.018 | 0.028 | 0.436 | 0.039 | 0.059 | 0.284 | 0.009 | 0.017 | 0.411 | 0.035 | 0.053 |
| IMF: Kroupa (2001) | 5.0 x 10^-5 | 0.285 | 0.018 | 0.028 | 0.436 | 0.039 | 0.059 | 0.284 | 0.009 | 0.017 | 0.411 | 0.035 | 0.053 |
| IMF: Kroupa (2001) | 1.0 x 10^-4 | 0.285 | 0.018 | 0.029 | 0.436 | 0.039 | 0.060 | 0.284 | 0.009 | 0.018 | 0.411 | 0.035 | 0.054 |
| IMF: Kroupa (2001) | 5.0 x 10^-4 | 0.286 | 0.018 | 0.029 | 0.437 | 0.039 | 0.060 | 0.285 | 0.009 | 0.018 | 0.412 | 0.035 | 0.054 |
| IMF: Kroupa (2001) | 1.0 x 10^-3 | 0.286 | 0.018 | 0.029 | 0.438 | 0.039 | 0.060 | 0.287 | 0.009 | 0.017 | 0.414 | 0.035 | 0.054 |
| IMF: Kroupa (2001) | 5.0 x 10^-3 | 0.292 | 0.018 | 0.027 | 0.447 | 0.038 | 0.057 | 0.295 | 0.009 | 0.016 | 0.422 | 0.034 | 0.051 |
| IMF: Kroupa (2001) | 1.0 x 10^-2 | 0.295 | 0.018 | 0.028 | 0.451 | 0.038 | 0.060 | 0.299 | 0.010 | 0.017 | 0.425 | 0.034 | 0.054 |
| IMF: Kroupa (2001) | 2.0 x 10^-2 | 0.298 | 0.018 | 0.031 | 0.455 | 0.037 | 0.065 | 0.302 | 0.010 | 0.018 | 0.430 | 0.034 | 0.059 |
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