SNII enrichment and the star cluster mass function

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ABSTRACT
Changing the form of the star cluster mass function (CMF) can effectively change the upper end of the stellar initial mass function. The yields of from supernovae are very sensitive to the mass of the progenitor star. We show that by changing the parameters of the CMF, it is possible to change the yields of oxygen and magnesium by a factor of $\sim 1.5$ and of metals in general by a factor of $\sim 1.8$.

Key words: Stars: formation – Stars: abundances – Galaxies: abundances

1 INTRODUCTION
Virtually all stars form in clusters (Clarke, Bonnell \& Hillenbrand 2000; Lada \& Lada 2003). The type-II supernovae (SNII) of the most massive stars in these clusters are the main source of many heavy elements, in particular oxygen and $\alpha$-elements. The yields of heavy elements from these SNII depend upon the mass of the progenitor (e.g. Tsujimoto et al. 1995; Woosley \& Weaver 1995; Hoffman et al. 1999; Limongi, Straniero \& Chieffi 2000; Rauscher et al. 2002; Heger et al. 2002). Thus the yields of heavy elements will depend upon the initial mass function (IMF) of the most massive stars in clusters. Of particular interest in the study of SNII products are oxygen and magnesium that are both thought to be pure SNII products and which are relatively easy to observe.

In large elliptical galaxies N/Fe, Na/Fe and Mg/Fe seem to be about a factor of 2 supersolar (Henry \& Worthey 1999), as do Mg/Fe and O/Fe in stars of the Galactic halo and Thick disk (Prochaska et al. 2000). In the Galactic bulge, anomalies in ratios such as Mg/Ca suggest changes in the initial mass function (McWilliam \& Rich 2004), which could also play a role in the $\alpha$/Fe ratios, although their behaviour is usually attributed to differences in star formation history. In this investigation we are mainly concerned with the overall oxygen and magnesium yields, which can be deduced from the peak in the abundance distribution function of stars (Pagel 1997); this peak for Mg is evident at a somewhat greater abundance in the Galactic Bulge and the central regions of large elliptical galaxies than the approximately solar value that it has in the solar neighbourhood.

In a recent paper Kroupa \& Weidner (2003) showed that the (effective) upper IMF depends upon the cluster mass function (CMF). Low-mass clusters are unlikely to contain very massive stars as they do not have the gas reservoirs from which to form them. A $10^4M_\odot$ cluster cannot contain a star $>100M_\odot$ and is unlikely to contain stars $>30-40M_\odot$. A $10^5M_\odot$ cluster, on the other hand, is very likely to contain some stars $>100M_\odot$. This idea is supported by evidence for a truncated IMF in small clusters for stellar masses $>10M_\odot$ (Thilker et al. 2002).

In the Solar neighbourhood the CMF is a power-law with slope $\sim -2$ between $\sim 10^2$ and $10^4M_\odot$ (Lada \& Lada 2003). There is evidence that the CMF varies with galaxy type (e.g. Kennicutt, Edgar \& Hodge 1989; Thilker et al. 2002; Alonso-Herrero et al. 2002; Youngblood \& Hunter 1999).

In this paper we discuss the effect on the yields of oxygen and magnesium from SNII due to changing the CMF (and so effectively changing the upper-end IMF). In Section 2 we describe our method, in Section 3 we present the results, and in Section 4 we discuss their implications for heavy element yields in galaxies of different types and masses.

2 METHOD
We select clusters from a cluster mass function (CMF) and then populate these clusters with stars from a standard IMF. Following Kroupa \& Weidner (2003) we select star cluster masses at random from a power-law cluster mass function of the form $N(M) \propto M^{-\beta}$ between lower and upper mass limits $M_{\text{low}}$ and $M_{\text{up}}$.

Each cluster is then populated with stars drawn at random from a two-part Kroupa (2002) IMF of the form

\[
N(M) \propto \begin{cases} 
M^{-1.3} & 0.08 < M/M_\odot < 0.5 \\
M^{-2.3} & 0.5 < M/M_\odot < 150 
\end{cases}
\]

such that the slope is Salpeter down to $0.5M_\odot$ and then flattens. We ignore the brown dwarf regime as brown dwarfs, although numerous, contribute very little mass to the cluster.

Stars are added to the cluster until the total mass of
stars exceeds the cluster mass. If the sampling produces a total cluster mass more than 2% greater than the desired cluster mass, then the cluster is completely repopulated. In each Monte Carlo run, the random sampling of clusters is continued until a total of $10^9 M_\odot$ of stars has been formed.

We record the numbers of stars greater than $8 M_\odot$ and the enrichment from these stars. Initially very massive stars ($> 25 M_\odot$) are expected to lose significant amounts of material through wind-driven mass-loss (e.g. Maeder 1992; Langer & Henkel 1995). For example, the yields quoted by Maeder (1992; table 6) for stars up to $\sim 25 M_\odot$ are very similar to those from Tsujimoto et al. (1995) and Thielemann et al. (1996). Above this mass, the yields drop sharply due to the lower mass of the eventual SNII.

We take yields for oxygen (O) and metals (Z) from the combination of contents of stellar winds and final ejecta given by Maeder (1992) for solar-metallicity stars with strong mass loss (his Table 6). We assume that the yield of magnesium follows Tsujimoto et al. (1995) up to $25 M_\odot$, and that the Mg/O ratio does so above this. Between the tabulated points intermediate values are calculated by a linear interpolation. In Fig. 1 we plot the O, Z and Mg yields against the initial stellar mass. It should be noted that the assumption of these yields minimises the effects of the CMF, as it reduces the influence of very massive stars on the yields.

Models of Galactic chemical evolution in the Solar neighbourhood have mostly either used a Salpeter IMF with an upper mass cutoff (e.g. Tsujimoto et al. 1995) or a steeper function such as the Scalo (1986) IMF (e.g. Chiappini, Matteucci & Gratton 1997). We select stars from a Salpeter IMF with an upper-mass cut-off of $150 M_\odot$; effective changes in the IMF are due solely to variations in the CMF.

3 RESULTS

In Table 1 we show the effect of varying the parameters of the IMF on the number and mass of massive stars, and on the yields of O, Mg and Z.

As reported by Kroupa & Weidner (2003), the slope of the high-end mass of the IMF depends upon the form of the CMF. The lower the mass of a cluster, the lower the probability of forming very massive stars. Indeed, low-mass clusters are unable to form very high-mass stars at all. This can be seen in the fractions of SNII progenitors with initial masses greater than 20, 40 and 70 $M_\odot$ ($F(> 20)$, $F(> 40)$, and $F(> 70)$ respectively).

In Fig. 2 we compare the upper-mass IMFs of CMFs with $(\beta, M_{\text{low}}, M_{\text{up}}) = (2, 50, 10^5)$ and $(2, 10^5, 10^6)$. For a CMF with parameters $(2, 50, 10^5)$, which represents a CMF that is only able to form low-mass clusters, $F(> 20) = 19\%$, $F(> 40) = 3\%$ and $F(> 70) = 0.1\%$. For a maximum cluster mass of $100 M_\odot$, it is almost impossible to form a star more massive than a few $10$s of $M_\odot$. For a CMF with $(2, 10^5, 10^6)$, all of the clusters are massive. In this case, $F(> 20) = 29\%$, $F(> 40) = 10\%$ and $F(> 70) = 4\%$, which is close to what would be expected from pure random sampling from the Kroupa (2002) IMF without the constraint of fitting the CMF.

The mass of stars formed per SNII changes between CMFs, rising from one per $108 M_\odot$ for $(2, 50, 10^2)$, to one per $92 M_\odot$ for $(2, 10^3, 10^6)$ — a rise of $\sim 1.2$ between the most extreme CMFs.

It is a combination of the greater number of SNII per $M_\odot$ of stars and the change in the fractions of SNII progenitor masses that produces a significant change in the yields between different CMFs. Between the $(2, 50, 10^3)$ and $(2, 10^5, 10^6)$ CMFs, the O, Mg and Z yields rise by a factor of 1.57, 1.40 and 1.83 respectively.

Small differences in the yields can be seen if the slope of the CMF is varied. Between $(1.5, 50, 10^3)$ and $(2.5, 50, 10^3)$, the yields of O, Mg and Z change by a factor of $1.15 - 2.13$.

The total mass of stars forming was chosen to be $10^9 M_\odot$ in order to allow a full sampling of the CMF. If the total mass of gas which forms stars is low, then different samplings of the CMF may have a small effect on the yields. For a CMF of $(2, 50, 10^3)$ sampled only from $10^3 M_\odot$ of gas, the yields can vary by a factor of $\sim 1.2$. This variation comes solely from the random sampling of the CMF and the failure of some samples to include massive clusters and/or the success of others at doing so.

Depending on the CMF, the number of SNII occurring per cluster changes by a huge factor, between 0.6 for $(2, 50, 10^3)$, to 75 for $(2, 10^4, 10^6)$. This would be expected to play a significant role in determining the effectiveness of the feedback of both energy and metals into the galaxy. When there are few SNII per cluster, it could be expected that feedback would be relatively inefficient. Much of the energy from the SNII would be used destroying the natal cloud, rather than used in spreading energy and metals far into the ISM. When the number of SNII in a cluster is high, it may be expected that the SNII would effectively form a superbubble, the influence of which may be widespread.

The Solar abundance by mass of O is $\sim 6 \times 10^{-3}$, and of Mg is $\sim 7 \times 10^{-4}$ (Lodders 2003). The yields of oxygen are close to Solar, while the models we have used underestimate the yields of Mg compared to Solar. The exact details of the yields depend upon the models used. Whilst it would be expected that yields depend upon many factors such as the metallicity of the progenitor and the details of the mass loss, we do not think that the broad conclusions of this paper would change. Only in the highly unlikely case that yields scale with just the right power to offset the IMF could the yields be totally independent of the CMF.

4 CONCLUSIONS

We have shown that the yields of O and Mg may vary by factors of $\sim 1.5$, and of metals by $\sim 1.8$, depending on the form of the cluster mass function. This is due to the inability of low-mass clusters to form very massive stars (cf. Kroupa & Weidner 2003) thus changing the fractions of contributors of different masses to enrichment.

In the Solar neighbourhood the CMF is a power-law with slope $\sim -2$ between $\sim 10^2$ and $10^3 M_\odot$ (Lada & Lada 2003). There is evidence that the HII luminosity function (and so presumably the CMF) varies with galaxy type (e.g. Kennicutt et al. 1989; Youngblood & Turner 1999) with early-type spirals having fewer and less bright HII regions than late-type galaxies. This suggests a steeper CMF and/or a lower-mass cut-off (although this conclusion is debated by Thilker et al. 2002; their sample contains mainly late-type...
Figure 1. The yields of metals (dash-dot line), oxygen (full line) and magnesium (dashed line) against the initial stellar mass. Metal and oxygen yields are taken from Maeder (1992) solar metallicity high mass-loss models, and the tabulated masses from Maeder are marked on the oxygen line. Magnesium yields are taken from Tsujimoto et al. (1995) and Thielemann et al. (1996) up to $25M_{\odot}$, and are then taken to be 10% of the explosive yields of stars from Maeder (1992).

Table 1. For a cluster mass function with slope $\beta$ and lower and upper cut-offs $M_{\text{low}}$ and $M_{\text{up}}$ respectively, we show the mass of stars formed per SNII $M_{\text{tot}}/N_{\text{SNII}}$, the average number of SNII per cluster $N_{\text{SNII}}/N_{\text{clus}}$, the fraction of SNII with masses $>20, 40$ and $70M_{\odot}$ $F(>20), F(>40), F(>70)$, and the mass of oxygen, magnesium and metals produced per solar mass of stars formed $M_O/M_{\text{tot}}, M_{\text{Mg}}/M_{\text{tot}}$ and $M_Z/M_{\text{tot}}$.

| $\beta$ | $M_{\text{low}}$ | $M_{\text{up}}$ | $M_{\text{tot}}/N_{\text{SNII}}$ | $N_{\text{SNII}}/N_{\text{clus}}$ | $F(>20)$ | $F(>40)$ | $F(>70)$ | $M_O/M_{\text{tot}} \times 10^{-3}$ | $M_{\text{Mg}}/M_{\text{tot}} \times 10^{-3}$ | $M_Z/M_{\text{tot}} \times 10^{-3}$ |
|-------|----------------|----------------|-------------------------------|-----------------------------|----------|----------|----------|-------------------------------|-------------------------------|-------------------------------|
| 2     | 50             | $10^2$         | 108                           | 0.6                         | 19       | 3.1      | 0.1      | 5.4                           | 0.39                          | 15                            |
| 2     | 50             | $10^3$         | 97                            | 1.6                         | 25       | 7.0      | 1.8      | 7.2                           | 0.48                          | 23                            |
| 2     | 50             | $10^4$         | 95                            | 2.8                         | 27       | 8.6      | 2.9      | 7.7                           | 0.51                          | 25                            |
| 2     | 50             | $10^4$         | 95                            | 2.8                         | 27       | 8.6      | 2.9      | 7.7                           | 0.51                          | 25                            |
| 2     | $10^3$         | $10^6$         | 93                            | 5.2                         | 28       | 9.4      | 3.3      | 8.1                           | 0.53                          | 27                            |
| 2     | $10^3$         | $10^6$         | 92                            | 7.5                         | 29       | 10       | 3.8      | 8.4                           | 0.54                          | 28                            |
| 2.5   | 50             | $10^4$         | 98                            | 1.4                         | 24       | 6.9      | 2.0      | 6.9                           | 0.47                          | 22                            |
| 1.5   | 50             | $10^4$         | 93                            | 7.7                         | 28       | 9.7      | 3.5      | 8.2                           | 0.53                          | 27                            |

galaxies, however). The upper limit of the HII luminosity function also varies with galaxy type, active star forming galaxies containing significantly more giant HII regions (e.g. Alonso-Herrero et al. 2002).

It might be expected that dwarf galaxies have a CMF that has a low upper-mass cut-off. This is simply because dwarf galaxies have a far smaller reservoir of gas from which to form clusters, and the most massive clusters that they form would be expected to be fairly low. Thus dwarf galaxies would be expected to have sub-Solar yields of heavy elements.

The Solar Neighbourhood has a CMF that is close to $(2, 50, 10^4)$ as shown by Lada & Lada (2003). This CMF produces close to the observed Solar abundances of O and metals, but under-produces Mg for these models.

Massive elliptical galaxies are thought to form from major merger events (Sanders & Mirabel 1996). In such events, the star formation rate is thought to increase dramatically and super star clusters become a dominant mode of star formation. Thus, a CMF with high upper and lower-mass cut-offs may be a reasonable model for these galaxies. In such cases the yields could be a factor of $>1.5$ higher than in dwarf galaxies, and $>1.1$ higher than in normal spiral galaxies due solely to differences in the cluster mass functions.

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