CAN STELLAR YIELDS ACCURATELY CONSTRAIN THE UPPER LIMIT TO THE INITIAL MASS FUNCTION?

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ABSTRACT

Recent determinations of the upper mass limit to the local initial mass function (IMF) claim a value of $m_U = 50 \pm 10 M_\odot$, which is based on direct comparisons of the observed oxygen and iron abundances in metal-poor stars with the predicted stellar yields from Type II supernovae (SNe). An unappreciated uncertainty in these analyses is the input physics intrinsic to each SNe grid and its effect on stellar nucleosynthesis. We demonstrate how such uncertainties, coupled with the uncertain metal-poor halo star normalization, only allow us to set an approximate lower limit to $m_U$ of $\sim 30 M_\odot$; for reasonable IMF slopes, the allowable range is shown to be poorly constrained, with $m_U \approx 30-200 M_\odot$.

Subject headings: nuclear reactions, nucleosynthesis, abundances — stars: luminosity, mass function — stars: supernovae — Galaxy: evolution

1. INTRODUCTION

The initial mass function (IMF), a measure of the distribution of masses at formation of a given stellar generation, is one of the key components of galaxy evolution modeling. Despite its importance, an accurate determination of the IMF remains one of the most elusive problems in modern astronomy. This elusiveness is manifested both in ongoing attempts to understand its physical underpinnings (e.g., Padoan, Nordlund, & Jones 1997), as well as in simply characterizing its shape and mass limits from an observational tack (e.g., Kroupa, Tout, & Gilmore 1993; Scalzo 1986).

In its simplest form, the IMF can be considered a power law of the form $n(m) \propto m^{-(1+x)}$, where $n(m)df$ is the number of stars born in the mass interval $m-(m+dm)$. The goal for theorists and observers alike then is the determination of the slope of this function $x$, as well as its upper and lower limits ($m_u$ and $m_l$, respectively).

While the slope of the IMF, at least in the solar neighborhood (and for masses greater than a few solar masses), would appear to lie somewhere in the range $1.3 \leq x \leq 1.7$ (Salpeter 1955) to $1.3 \leq x \leq 1.7$ (Kroupa et al. 1993), and while the lower mass limit is close to $m_l \approx 0.2 M_\odot$ (Bahcall et al. 1994), the upper mass limit $m_u$ still remains highly uncertain. Even a cursory examination of the literature corroborates this point, with values in the range $m_u \approx 20-200 M_\odot$ suggested by a variety of direct and indirect techniques (e.g., Maeder & Meynet 1989; Klapp & Corona-Galindo 1990; Pagel et al. 1992; Maeder 1992; Massey, Johnson, & Dugia-Eastwood 1995; Kudritzki 1997).

A hybrid approach to determining $m_u$, combining predictions of the theoretical yields from Type II supernovae (SNe) with the observed abundances in the metal-poor stars (i.e., those that bear the clear imprint of yield “pollution” from these same SNe, with no “dilution” from Type Ia SNe, whose progenitor lifetimes are considerably longer than the Type II timescales), has been the subject of a recent series of papers (Tsujimoto et al. 1995, 1997; Yoshii, Tsujimoto, & Nomoto 1996). The premise here is that because Type II SNe $z$-element (e.g., O, Mg, Ne) yields are a strong function of progenitor mass, whereas products of explosive burning (e.g., Fe, Si, Ca) are less so, the IMF-weighted average of their ratios must necessarily also depend strongly on $x$ and $m_u$. Tying these yield “averages” to the halo abundances then, in principle, provides a unique indirect probe for the upper mass limit to the IMF.

Following this technique, Tsujimoto et al. (1997) recently concluded that the upper mass limit to the IMF in the solar neighborhood is $m_u = 50 \pm 10 M_\odot$. To do so, they made explicit use of the Tsujimoto et al. (1995) compilation of Type II SNe yields. What was not fully appreciated in their study, however, was just how dependent their result was on this particular yield compilation and the adopted halo abundance normalization. It is to this lack of appreciation that our current study is addressed.

After providing a minimal introduction to the model ingredients in § 2.1, we demonstrate in §§ 2.2 and 2.3 that this technique results in $m_u = 50 \pm 10 M_\odot$ only for the Tsujimoto et al. (1995) yields, which are combined with a halo normalization of $[O/Fe]_h = +0.41$. Duplicating the analysis with “competing” yield compilations that sample a wide variety of convection and mass-loss treatments (e.g., Woosley & Weaver 1995; Langer & Henkel 1995; Arnett 1996) clearly demonstrates that Tsujimoto et al. (1997) have significantly underestimated the uncertainty associated with their determination of $m_u$. Our results are summarized in § 3.

2. ANALYSIS

2.1. The Basic Formalism

The observed oxygen-to-iron abundance ratio in halo dwarfs and giants, $[O/Fe]_h$, can be linked (see Tsujimoto et al. 1997, hereafter for details) to the theoretical Type II SNe yields $m_{O}^i$ and $m_{Fe}^i$, via

$$\frac{O}{Fe}_h = \left(\frac{O}{Fe}_\odot\right) \times 10^{[O/Fe]_h} \times \frac{m_{O}^i}{m_{Fe}^i} \times \frac{m_{O}^i m_{Fe}^i}{m_{O}^i m_{Fe}^i} \times 10^{x} \times \frac{dm}{dm},$$

where the coefficient $(O/Fe)_{Fe} = 7.55$ is the solar (meteoritic) mass fraction ratio from Anders & Grevesse (1989) and $x$ is the slope of the IMF (recall § 1).

1 Tsujimoto et al. (1997) extend this “hybrid” approach to simultaneously constrain the IMF mass limits $m_u$ and $m_l$, as well as the slope $x$. We shall only be concerned with the $m_u$ determination in what follows, primarily for brevity, but also because the lower mass constraint rests squarely on uncertain low-metallicity photometric calibrations.
By specifying the low-metallicity “plateau” value for [O/Fe]$_h$ (e.g., Fig. 11 of Timmes, Woosley, & Weaver 1995; Fig. 2 of Bessell, Sutherland, & Ruan 1991) and the IMF slope $x$, equation (1) provides a unique upper mass limit $m_U$ for a given Type II SNe yield compilation.

2.1.1. Ingredients

Essentially, there are only two input ingredients that interest us in what follows: (1) the source of Type II SNe yields (right-hand side of eq. [1]) and (2) the halo’s “plateau” [O/Fe]$_h$ (left-hand side of eq. [1]). Let us briefly comment on the latter ingredient first.

There is no debate about the reality of the $x$-element overabundance seen in halo dwarfs and giants [i.e., (O/Fe)$_h$ $\approx +0.2$], but there does remain a factor of $\approx 2$ uncertainty about its asymptotic “plateau” value for [Fe/H] $\leq -3$. T97 adopt [O/Fe]$_h = +0.41$,$^2$ but it is apparent that this depends somewhat on the sample selection. Visual inspection of Figure 11 of Timmes et al. (1995), Figure 2 of Bessell et al. (1991), and Figure 1 of T97, each drawn from slightly different sources, shows that the plateau lies roughly in the range [O/Fe] $\approx +0.4$–0.6; i.e., the T97 value of +0.41 appears to lie on the lower end of the plateau “distribution.” T97 did not demonstrate how the predicted changes as a function of this halo “normalization,” a point to which we return in § 2.3, where we duplicate their analysis using [O/Fe]$_h = -0.60$ (i.e., the value favored by Bessell et al. 1991).

The Type II SNe yields are the primary input into equation (1). T97 adopt their earlier 1995 yield compilation (Tsujimoto 1995, hereafter T95), which itself is an offshoot of the Thielemann, Nomoto, & Hasimoto (1996) models. The solid curves in Figure 1 represent the T95 oxygen and iron yields adopted in the T97 analysis.

However, it is readily apparent, as even a cursory glance at Figure 1 should show, that there still remain substantial uncertainties in the yield compilations for Type II SNe. These differences have already been described in detail by Arnett (1995), Langer (1997), and Gibson, Loewenstein, & Mushotzky (1997), to name just a few.

T97 assume that these differences can be reconciled by considering what they (mistakenly) assume is the maximal deviation from their canonical (T95) yields. This deviation is taken to be a mass-independent 30% excess added to their oxygen yields; iron, however, is assumed to be invariant. T97 justify this 30% excess as the “extreme,” since Woosley & Weaver’s (1995; hereafter WW95) [Fe/H] = +0.0 oxygen yields are roughly 30% greater than those of T95 (also [Fe/H] = +0.0).$^3$ Herein lie several (intertwined) problems.

First, solar metallicity yields are inappropriate for the discussion at hand: T97 attempt to constrain $m_U$ by comparing the abundance ratios in metal-poor stars [i.e., (Fe/H) $\leq -2$] with the yields predicted from [Fe/H] = +0.0 Type II SNe models. A more appropriate course of action is to consider a much lower metallicity grid of models. Because T95 do not compute [Fe/H] $< +$0.0 models, T97 could not explicitly consider metallicity effects.

If we compare (properly) the T95 oxygen yields with the WW95 subsolar metallicity grid, the 30% “excess” adopted by T97 is no longer relevant. Figure 1 shows that the WW95 [Fe/H] = −4.0 models have oxygen yields virtually indistinguishable from the [Fe/H] = +0.0 models of T95, except for $m \approx 35 M_\odot$, where the WW95 model now lies systematically below the T95 model.

These subtle differences in the WW95 and T95 oxygen yields are interesting in their own right (e.g., Langer 1997) and are certainly encapsulated by the 30% error budget adopted by T97. Unfortunately, a more fundamental flaw made by T97 was in assuming that all of the uncertainty in the oxygen yields could be accounted for by this 30% factor. The problem with assuming that the T95 oxygen yields form a lower envelope, with the WW95 yields forming the upper, can best be appreciated by referring to the two other primary sources of SNe models besides those of T95 and WW95, i.e., Langer & Henkel (1995, hereafter LH95) and Arnett (1996, hereafter A96).

In Figure 1, we can see that both LH95 and A96 agree (roughly) with one another$^4$ but lie a factor of $\sim 3$ below the

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2 The T97 claim that they adopt [O/Fe]$_h = +0.41$ is not entirely correct since their code does not follow O and Fe, per se, but only the isotopes $^{16}$O and $^{56}$Fe, thereby underestimating the true iron yield by $\approx 10\%$ (and oxygen by a smaller amount). This has the effect that instead of using (O/Fe)$_h = 7.55$ in eq. (1), T97 use (O/Fe)$_h = 8.20$ [i.e., ($^{16}$O/$^{56}$Fe)$_h = 8.20$]. By itself, this is not a problem; the problem arises (also hereafter and Henkel hereafter LH95, A96) in specifying the low-metallicity “plateau” value for [O/Fe].

3 The treatment of convection, the adopted $^{12}$C($\alpha$, $\gamma$)$^{16}$O reaction rate, and the initial evolutionary state of the models were all significantly different in T95 compared with LH95 or A96. LH95 also considered subsolar metallicity models and self-consistent mass loss, both of which the others did not.
}

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{Oxygen (upper four curves) and iron (lower three curves) yields as a function of progenitor mass for the primary yield compilations considered here: T95 = Tsujimoto et al. (1995); LH95 = Langer & Henkel (1995); A96 = Arnett (1996); WW95 = Woosley & Weaver (1995); M92 = Maeder (1992). The models of M92, LH95, and A96 are only evolved up to the completion of oxygen burning; hence an iron yield is not directly associated with either grid. We indirectly associate Arnett’s (1991) iron yields with his newer 1996 oxygen yields. See text for details.}
\end{figure}
T95 and WW95 predictions. This factor of 3 uncertainty in the oxygen yields is a far cry from the 30% uncertainty advocated by T97 but is entirely in keeping with that found by Langer (1997), which is an invaluable resource for those interested in properly assessing the origin of the large uncertainties in different modelers’ oxygen yields. In the same vein, a useful comparison of the primary differences in the model input physics can be found in Table 2 of Gibson et al. (1997). At this point, we are not advocating one grid of oxygen yields over another, nor are we simply drawing attention to the fact that T97 have underestimated its uncertainty.

Figure 1 reflects the present-day state of the art, as far as oxygen yields go, and can be considered to be the modern equivalent of Wang & Silk’s (1993) Figure 1. The similarity of the Arnett (1978), Woosley & Weaver (1986), and Thielemann, Nomoto, & Hashimoto (1994) oxygen yields, reflected in the latter figure, is not in dispute, but it should also be readily apparent (from our Fig. 1) that supplementing the current analogs of these older models (i.e., A96, WW95, and T95, respectively) with the new models of LH95 demonstrates that the agreement is no better than a factor of ~2–3 at a given initial mass, in agreement with that found by Langer (1997).

Pursuing further this factor of ~3 uncertainty in oxygen yields, it is instructive to consider the “evolution” of said yields as a function of grid “epoch” for the models from one of the key contributors to the field. Figure 2 parallels Figure 1 in that the predicted oxygen yield as a function of progenitor mass is shown. This time, however, we restrict ourselves solely to the various compilations published by Dave Arnett. We note that it is the 1978 compilation (A78He; Arnett 1978, hereafter A78) that was shown in Wang & Silk’s (1993) Figure 1. The primary difference between the three grids based on evolving helium cores (i.e., those labeled with a subscript He) is the adopted a posteriori zero-age main sequence (ZAMS) mass–He core mass relation, although reaction rates and convection have been modified somewhat in the most recent grids. Here we can already see a factor ~2 evolution in the predicted yields. Arnett’s first grid of models that evolved self-consistently from the ZAMS (i.e., subscript ZAMS, also shown in Fig. 1) provides further evidence for the difficulties involved in linking the predicted yields from evolved helium cores to a progenitor ZAMS mass.

A second assumption contained within the T97 analysis is that the iron yields are approximately invariant and best represented by those of T95. Iron predictions are particularly problematic because the exact location of the mass cut leads to enormous uncertainties (Thielemann et al. 1996). However, for the sake of self-consistency in the input physics, we have not made the same a priori assumption regarding iron’s invariance, and we have attempted to match the oxygen predictions with iron from the same grid. This is easy in the case of T95 and WW95, since they follow the evolution right through core collapse and explosive nucleosynthesis. Of the different Arnett grids described herein, only Arnett (1991, hereafter A91) included a specific entry for iron, so hereafter that specific entry is used for A78, A91, and A96 also. Proper self-consistency with Arnett’s yields will be restored after he applies core collapse and explosive nucleosynthesis to the new A96 model grid.

We are now in a position to anticipate some of the conclusions of § 2.2. To do so, we weight the mass-dependent oxygen and iron yields of Figures 1 and 2 by some canonical IMF, which we will take to be of the slope favored by Salpeter (1955), i.e., x = 1.35, with Type II SNe progenitors assumed to span the mass range 10–50 $M_\odot$. The resulting IMF-weighted masses of oxygen and iron—i.e., $\langle O \rangle$, $\langle Fe \rangle$, and $\langle O/Fe \rangle$—(and their logarithmic ratios relative to the solar ratio) for each of the yield “pairs” discussed thus far are listed in Table 1. The subscripts ZAMS and He refer to the initial evolutionary state of the models, i.e., zero-age main sequence or simple helium cores.

The factor of ~3 uncertainty due to oxygen (and to a lesser extent, that due to iron) is immediately apparent in the third and fourth columns, and their combination leads to a factor of ~2 uncertainty in the IMF-weighted [$O/Fe$].

Recalling that T97, using the T95 yields, assumed a metal-poor normalization for equation (1) of [$O/Fe$]$_h$ $\approx$ +0.4 and subsequently found $m_c$ $\approx$ 50 $M_\odot$, it should not be surprising to see that our entry in Table 1 for T95, which was generated using $m_c$ = 50 $M_\odot$, has an IMF-weighted [$O/Fe$] similar to the T97 adopted halo value. Conversely,

![Fig. 2.—Oxygen yields as a function of progenitor mass, from the four compilations of Arnett (A78, A91, A96He, A96ZAMS). Only the A96ZAMS grid was evolved self-consistently from the ZAMS, while the remainder were evolved helium cores with an assumed a posteriori ZAMS mass–He core mass relation.](image)

**TABLE 1**

| Source | [$Fe/H$] | $\langle O \rangle$ | $\langle Fe \rangle$ | $\langle O/Fe \rangle$ |
|--------|---------|---------------------|---------------------|---------------------|
| T95ZAMS | $+0.0$ | $1.810$ | $0.091$ | $+0.42$ |
| M92ZAMS | $-1.3$ | $1.508$ | $n/a$ | $n/a$ |
| WW95ZAMS | $-4.0$ | $1.445$ | $0.087$ | $+0.34$ |
| LH95ZAMS | $-1.0$ | $0.841$ | $n/a$ | $n/a$ |
| A78He + A91He | $+0.0$ | $1.711$ | $0.068^a$ | $+0.52$ |
| A91He + A91He | $+0.0$ | $1.189$ | $0.068^a$ | $+0.37$ |
| A96He + A91He | $+0.0$ | $0.983$ | $0.068^a$ | $+0.28$ |
| A96ZAMS + A91He | $+0.0$ | $0.678$ | $0.068^a$ | $+0.12$ |

Note.—n/a = not applicable.

* IMF slope $x = 1.35$, over the range 10–50 $M_\odot$.

* Source of oxygen yields.

* Metallicity of models from which oxygen yields were derived.

* IMF-weighted yield mass, in $M_\odot$.

* Arnett (1991) [$Fe/H$] = $+0.0$ iron yields.
and A96\textsubscript{He} values lying between A78\textsubscript{ZAMS} and A96\textsubscript{ZAMS}. Because the dependence of \(m_U\) on the IMF slope \(x\) is stronger in the non-T95 yields (especially for A96\textsubscript{ZAMS}), for the Kroupa et al. (1993) slope (i.e., \(x = 1.7\)) \(m_U\) is more strongly affected. The value favored by the T95 compilation (i.e., 62 \(M_\odot\)) is replaced, in this case, by values ranging from \(\sim 95 \ M_\odot\) for WW95, to \(\geq 200 \ M_\odot\) for A96\textsubscript{ZAMS}. To summarize, only if one assumes that the T95 yields are the definitive representation of low-metallicity massive star nucleosynthetic yields can one conclude that the upper mass limit to the solar neighborhood IMF is \(m_U = 40–60 \ M_\odot\). By adopting, in turn, the three other primary yield sources (i.e., WW95, LH95, and A96), we sample a much fairer representative input physics “parameter space,” which leads to the more sobering range of allowable values for \(m_U\) of \(\sim 30–200 \ M_\odot\). Even if we force the Salpeter (1955) IMF slope (i.e., \(x = 1.35\)) to hold, the uncertainty in the yields still only allows us to constrain \(m_U\) to the range \(\sim 30–130 \ M_\odot\). This yield dependence of the determination of \(m_U\) was not appreciated in the original analysis by T97.

It is interesting to question how one might recover a result of \(m_U \approx 40–60 \ M_\odot\) when adopting the A96\textsubscript{ZAMS} yields. Assuming that the oxygen is inviolate, it is apparent from inspection of Table 1 that we are required to reduce the IMF-weighted iron yield by a factor of \(\sim 2\). This cannot be of the form of a blanket, mass-independent reduction since we are constrained by the observations of SNe 1987a and 1993) (Thielemann et al. 1996). Only by setting the iron yield to zero for \(m \leq 12 \ M_\odot\) and \(m \geq 30 \ M_\odot\) (i.e., retaining the 15, 20, and 25 \(M_\odot\) iron predictions of A91 but ignoring the contribution from other masses), can we reduce the A96\textsubscript{ZAMS} prediction for \(m_U\) from \(\sim 130–200 \ M_\odot\) to that found using T95 (i.e., \(m_U \approx 40–60 \ M_\odot\)).

In passing, we should note that linear interpolation for both oxygen and iron were assumed in equation (1). If, however, one adopts a logarithmic interpolation scheme similar to that employed by Yoshii et al. (1996), one finds that logarithmic interpolation tends to lower the predicted values for \(m_U\) by \(\sim 10\%–25\%\) for reasonable IMF slopes.

2.3. Quantifying the Dependence of \(m_U\) on the Halo Normalization

T97 did not consider how their conclusions might be influenced by the adopted mean “halo” [O/Fe] (eq. [1]). Recall that the solid curve in Figure 3 supported \(m_U \approx 48–62 \ M_\odot\) for IMF slopes \(x \approx 1.3–1.7\), for the T95 yields and a normalization of [O/Fe] = +0.41.

If instead of adopting the favored halo normalization of T97, we took that of Bessell et al. (1991), i.e., (O/Fe) = +0.60, we would recover the “T95; +0.60” curve of Figure 3. In other words, this \(\sim 0.2\) dex (i.e., \(\sim 60\%\)) higher normalization for the T95 yields increases the predicted \(m_U\) by between \(\sim 60\%\) (from 48 to 75 \(M_\odot\) for \(x = 1.3\)) and \(\sim 140\%\) (from 62 to 148 \(M_\odot\) for \(x = 1.7\)) in the same conclusion is reached when we adopt the WW95 yields, as shown by the “WW95; +0.60” curve of Figure 3. A general rule of thumb for Salpeter (1955) IMF slopes (i.e., \(x = 1.35\)) is that a given percentage increase in the halo normalization is accompanied by the same percentage increase in the predicted \(m_U\), regardless of yield source. For slopes \(x \approx 1.7\), the increase in \(m_U\) with increasing normalization is generally \(\sim 2–3\) times greater.

If we simply take the halo normalization to be [O/Fe] = +0.5 ± 0.1 and accept the T97 allowable range
of IMF slopes (i.e., $x \approx 1.3\text{--}1.6$), Figure 3 would lead us to conclude that $m_U \approx 40\text{--}120 M_\odot$ better represents the valid range of $m_U$ for the T95 yields. We feel that this would have been a more realistic range than the $m_U \approx 40\text{--}60 M_\odot$ claimed by T97.

3. SUMMARY

T97 have recently revitalized interest in using IMF-weighted Type II SNe yields as a direct probe of said IMF’s upper mass limit in comparison with the observed abundance ratios in metal-poor Galactic stars. The beauty of this technique lies partially in its simplicity—for a given IMF slope, there is effectively only one free parameter, the yield source. Adopting the yields, found T95 T97 

While we do agree with T97 that the lower limit to $m_U$ is $\approx 40 M_\odot$ (or $\approx 30 M_\odot$ if we adopt the extreme A78 yields), our more realistic exploration of input physics “space” demonstrates that we simply cannot constrain the upper limit to $m_U$ to anything better than $\approx 60\text{--}200 M_\odot$. Taken together, we can only conclude that, by this technique alone, $m_U \approx 30\text{--}200 M_\odot$ (again, for IMF slopes $x = 1.3\text{--}1.6$). Fixing the IMF slope to that of Salpeter (1955), we can only constrain $m_U$ to lie somewhere between $\approx 30$ and $\approx 130 M_\odot$.

While this technique is promising (provided existing discrepancies in Type II SNe yields are eliminated), at the present time, unfortunately, this technique by itself does not substantially improve or constrain our understanding of the upper mass limit to the solar neighborhood IMF.

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A secondary concern is the inherent assumption of T97 that the halo normalization $[\text{O/Fe}]_h = +0.41$ has no associated uncertainty. Since values as high as $[\text{O/Fe}] = +0.6$ are still favored by some, this $\sim 60\%$ uncertainty should be taken into account. For a Salpeter (1955) slope, there is (roughly) a one-to-one correspondence between the halo normalization uncertainty and the corresponding predicted upper mass limit uncertainty.