CCSN and AGB Star Yields of Nitrogen

Core-Collapse Supernova Yields

Empirically, nitrogen-to-oxygen ratios exhibit a plateau at log(N/O) $\approx$ -1.5 for log(O/H) $\lesssim$ 8 (see Fig. 1 of Vincenzo et al., 2016 comparing Berg et al., 2012, Izotov, Thuan & Guseva, 2012, and James et al., 2015 measurements).

What is the implied relation between the IMF integrated CCSN yields of nitrogen and oxygen?

The ratio of their yields can be related to the number densities of the two nuclei in the supernova ejecta via:

$$\frac{y_{\rm N}^{\rm CC}}{y_{\rm O}^{\rm CC}} = \frac{\mu_{\rm N} n_{\rm N}}{\mu_{\rm O} n_{\rm O}} \tag{1}$$

where μ_x is the mean molecular weight of a species x and n_x is the number of nuclei. Taking the ratio $n_{\rm N}/n_{\rm O}$ from these observed results yields:

$$\frac{y_{\rm N}^{\rm CC}}{y_{\rm O}^{\rm CC}} = \frac{\mu_{\rm N}}{\mu_{\rm O}} 10^{\log{\rm (N/O)}} \tag{2}$$

Though supernova ejecta may produce different isotopic ratios of N than AGB stars, potentially altering the ratio $\mu_{\rm N}/\mu_{\rm O}$, taking $\mu_{\rm N} = 14.007$ and $\mu_{\rm O} = 15.999$ from a periodic table suggests that, with the previously adopted $y_{\rm O}^{\rm CC} = 0.015$ (e.g. Weinberg, Andrews & Freudenburg, 2017; Johnson & Weinberg, 2020; Johnson et al., 2021), this suggests

$$y_{\rm N}^{\rm CC} = \frac{\mu_{\rm N}}{\mu_{\rm O}} 10^{\log{\rm (N/O)}} y_{\rm O}^{\rm CC} = \frac{14.007}{15.999} 10^{-1.5}(0.015) \approx 4.15 \times 10^{-4} \tag{3}$$

Can this be understood from theoretically predicted yields?

The left panel of Figure 1 presents the IMF-integrated yields $y_{\rm N}^{\rm CC}$ computing with VICE using the Limongi & Chieffi (2018), Sukhbold et al. (2016), Nomoto et al. (2013), and Woosley & Weaver (1995) CCSN yield tables, with Limongi & Chieffi (2018) being the only study which reports yields for rotating progenitors. Broadly, the non-rotating predictions are consistent with one another, and predict a significant metallicity dependence; the lowest metallicity progenitor from Woosley & Weaver (1995) predict somewhat higher yields overall, but this could have to do with this being the only yield set for which we can calculate only *gross* yields rather than *net* yields. The rotating progenitors from Limongi & Chieffi (2018), however, predict that the yield should be considerably enhanced by rotation. They interpret this as being due to the interplay between the core helium and hydrogen burning shells triggered by rotation-induced instabilities, which drives the synthesis of all products of CNO, not just ^{14}N (see their abstract). These yields predict a relatively metallicity-independent $y_{\rm N}^{\rm CC}$ of $\sim 5\times10^{-4}$, in surprisingly good agreement with the empirically derived value of 4.15×10^{-4}.

The right panel of Figure 1 presents the IMF-integrated nitrogen-to-oxygen ratios predicted by the same studies for the same combinations of metallicity and rotational velocity. The flat, dotted black line denotes $\log_{10}{\rm (N/O)}_{\rm CC}$ = -1.5, the value empirically derived from observations (Vincenzo et al., 2016; Berg et al., 2012; Izotov et al., 2012; James et al., 2015).

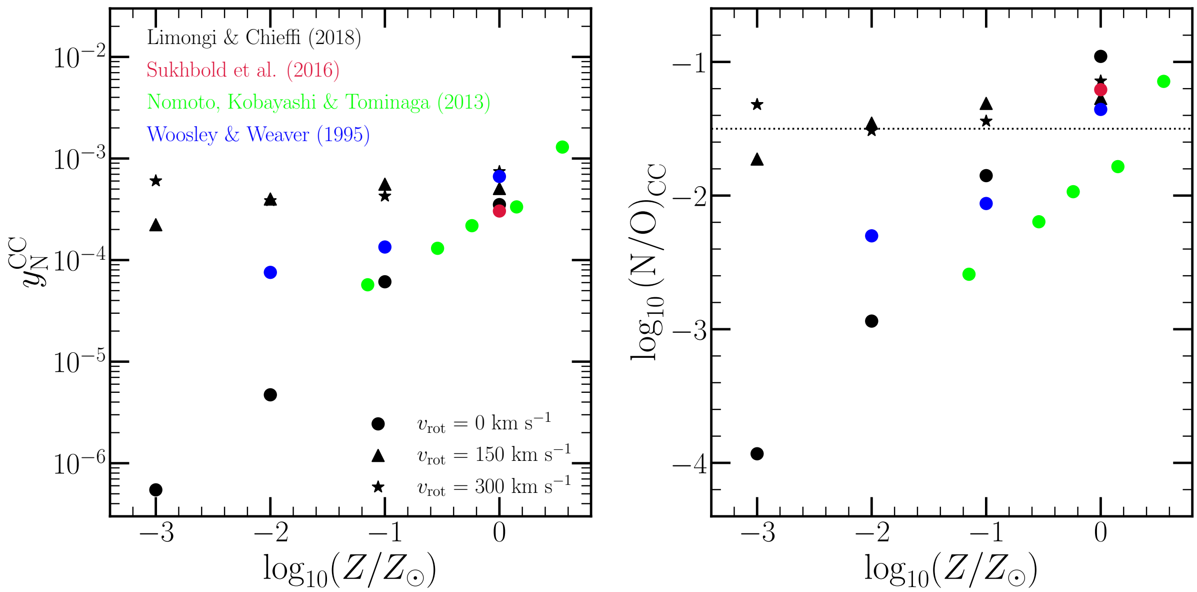

Figure 1: **Right**: IMF-integrated CCSN yields of N computed with VICE using the Limongi & Chieffi (2018) (black), Sukhbold et al. (2016) (crimson), Nomoto et al. (2013) (lime), and Woosley & Weaver (1995) (blue) yield sets. **Left**: IMF-integrated nitrogen-to-oxygen yield ratios computed with VICE for the same studies. The Limongi & Chieffi (2018) yields are calculated with progenitor rotational velocities of $v_{\rm rot} = 0$ (circles), 150 (triangles), and 300 km/s (stars). All other studies only report yields for non-rotating progenitors.

The rotating progenitor models from Limongi & Chieffi (2018) do the best job of reproducing this ratio in theoretical models of core collapse supernova ejecta; the other models do not include rotation, which appears to play a key role in establishing this empirical result.

What is the implied plateau in [N/O]?
[N/O] and log(N/O) are directly related, but one is relative to the sun while the other is just a ratio of number densities. Expanding [N/O]:

$$[{\rm N/O}] = [{\rm N/H}] - [{\rm O/H}] \tag{4a}$$

$$= \log_{10}\left(\frac{Z_{\rm N}}{Z_{{\rm N},\odot}}\right) - \log_{10}\left(\frac{Z_{\rm O}}{Z_{{\rm O},\odot}}\right) \tag{4b}$$

$$= \log_{10}\left(\frac{Z_{\rm N}}{Z_{\rm O}}\right) - \log_{10}\left(\frac{Z_{{\rm N},\odot}}{Z_{{\rm O},\odot}}\right) \tag{4c}$$

Zooming in on the $Z_{\rm N}/Z_{\rm O}$ term:

$$\log_{10}\left(\frac{Z_{\rm N}}{Z_{\rm O}}\right) = \log_{10}\left(\frac{\mu_{\rm N} n_{\rm N}}{\mu_{\rm O} n_{\rm O}}\right) \tag{5a}$$

$$= \log_{10}\left(\frac{\mu_{\rm N}}{\mu_{\rm O}}\right) + \log_{10}\left(\frac{n_{\rm N}}{n_{\rm O}}\right) \tag{5b}$$

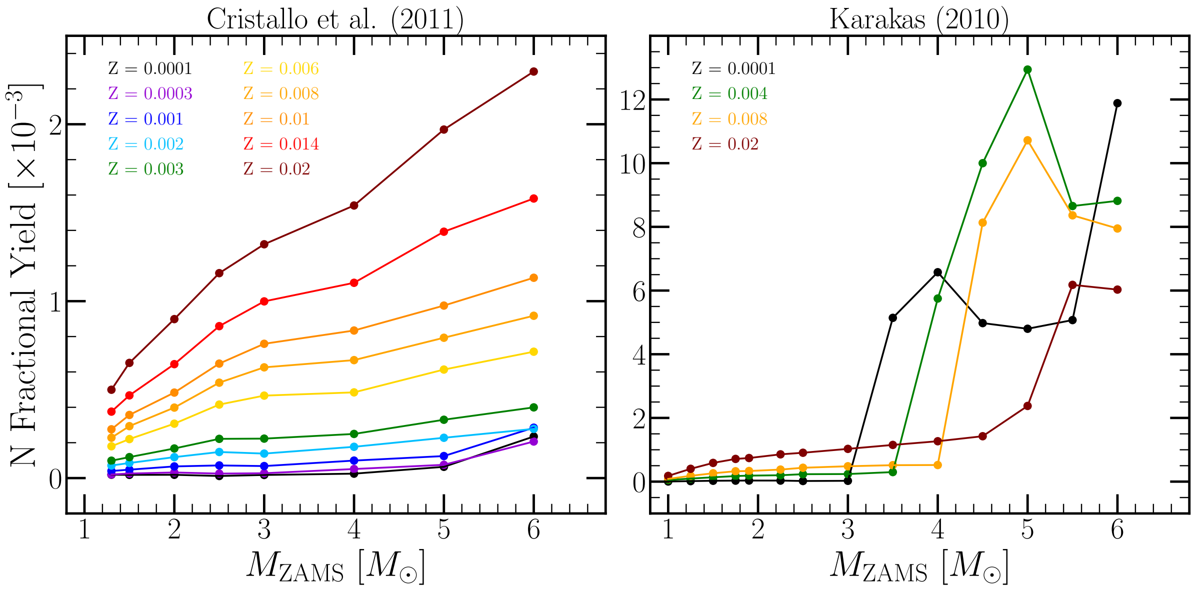

Figure 2: Fractional yields of N as a function of progenitor zero age main sequence mass at the metallicities at which Cristallo et al. (2011) (left) and Karakas (2010) report yields.

where μ and n are again the mean molecular weight and number of some species x. The term $\log_{10}(n_{\rm N}/n_{\rm O})$ is exactly the log(N/O) value which Berg et al. (2012), Izotov, Thuan & Guseva (2012), and James et al. (2015) measured to be ~-1.5. Plugging this in:

$$[{\rm N/O}] = \log_{10}\left(\frac{\mu_{\rm N}}{\mu_{\rm O}}\right) + \log_{10}\left(\frac{n_{\rm N}}{n_{\rm O}}\right) - \log_{10}\left(\frac{Z_{{\rm N},\odot}}{Z_{{\rm O},\odot}}\right) \tag{6a}$$

Taking $\mu_{\rm N} = 14.007$ and $\mu_{\rm O} = 15.999$ again, with the empirical result of $\log_{10}(n_{\rm N}/n_{\rm O})$ = -1.5 and the Asplund et al. (2009) solar photospheric composition of $Z_{{\rm N},\odot} = 6.91\times10^{-4}$ and $Z_{{\rm O},\odot} =$ 0.00572, yields the following:

$$[{\rm N/O}]_{\rm plateau} = -0.64 \tag{7}$$

Asymptotic Giant Branch Star Yields

Figure 2 presents the fractional yields of N as a function of progenitor zero age main sequence (ZAMS) mass and metallicity as reported in the FRUITY database (Cristallo et al., 2011) and by Karakas (2010). Both models show the metallicity-dependent nature of seconday nitrogen production, whose fractional yields increase with progenitor mass at fixed metallicity. Secondary nitrogen production refers to the production of ^{14}N at the expense of C and O in the CNO cycle; the nuclear reaction network of the CNO cycle:

^{12}C(p,γ)^{13}N(,β^+)^{13}C(p,γ)^{14}N(p,γ) ^{15}O(,β^+)^{15}N(p,α)^{12}C

In this chain, the ^{14}N(p,γ)^{15}O reaction is particularly slow, and for this reason, the net effect of the CNO cycle is to turn all of the C and O into ^{14}N at their expense.

By omparing the left- and right-hand panels of Fig. 2, it's clear that the Karakas (2010) predicts secondary nitrogen production to be a much stronger effect than Cristallo et al.

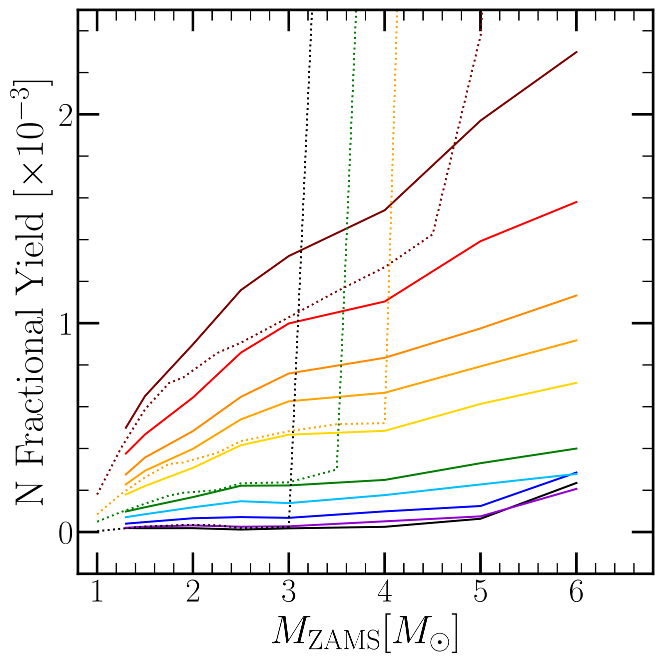

Figure 3: The same as figure 2, but with the Cristallo et al. (2011) (solid) and Karakas (2010) yields plotted on the same set of axes for comparison.

(2011); the yields from high mass stars are over an order magnitude larger in Karakas (2010) than in Cristallo et al. (2011) at all reported metallicities except solar. Karakas (2010) also predicts a much more complicated mass-dependence than does Cristallo et al. (2011). Intuitively, I would think that secondary N yields should be nothing but monotonic with metallicity. Rotation may induce some interesting effects, but unfortunately the Karakas (2010) paper makes no mention of rotation. They were primarily interested in the effect of updates to the ^{13}C(α,n)^{16}O reaction on light-element nucleosynthesis. I'm assuming this means they were using non-rotating models, but if this ends up being discussed in a paper I should email Amanda Karakas to verify.

How consistent are the two studies up to ∼3-4 $M_\odot$? Figure 3 compares the two sets of yields on the same plot, with the Cristallo et al. (2011) set shown in solid lines and the Karakas (2010) set in dotted lines. The two are broadly consistent with one another up this threshold mass, at which point the secondary nitrogen yields as reported by Karakas (2010) become considerably large in comparison.

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