OXYGEN ISOTOPES FROM MASSIVE STARS

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Abstract. We investigate the yields of the three stable oxygen isotopes ^{16,17,18}O and their dependence on weakly constrained physical ingredients in pre-supernova models. We show that the ^{16}O yield is sensitive to assumptions on convection used in evolutionary models for massive stars. In addition to that, stellar wind mass loss affects the ^{16}O yield of Galactic stars initially more massive than $\sim 30\,M_{\odot}$. We show that the production factor of ^{17}O in massive stars is strongly increasing with metallicity, contrary to the expectation of a constant production factor for secondary isotopes. The ^{18}O yield is extremely sensitive to the treatment of convection in regions of varying mean molecular weight in the stellar interior. The Galactic distribution of all three oxygen isotopes has a large diagnostic potential for chemical evolution models, but also for uncertain stellar physics as mass loss and convection.

1. Introduction

Roughly half of the mass of all elements heavier than helium in the Galaxy consists of oxygen, which is thus the dominant metal. Most of the oxygen constitutes of the isotope ^{16}O. The solar system isotopic oxygen ratios are (^{16}O : ^{17}O : ^{18}O) = (2500 : 5.6 : 1); cf. Anders & Grevesse (1989). ^{16}O, obtained as a primary isotope by $\alpha(2\alpha)^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$ during helium burning, is predominantly produced in massive stars — i.e. stars massive enough to evolve to core collapse (cf. Langer & Woosley 1996). They expel most of their C/O-core in a supernova explosion, while it remains locked in the white dwarf remnant left behind by less massive stars (cf. e.g., Maeder 1992). Note that observational evidence for both, the primary production and the high mass origin of ^{16}O, comes from the high [O/Fe] ratios observed in very metal poor stars (e.g., Gratton & Ortolani 1986).

Both stable neutron-rich oxygen isotopes, ^{17}O and ^{18}O, are thought to be of secondary origin, i.e. their production requires heavy elements to be present in the initial composition of the star. ^{17}O is produced during hydrogen burning (cf. Clayton 1968) while ^{18}O is produced by α-capture on ^{14}N. As in the Galaxy today, and more so at earlier epochs, ^{16}O is the dominant metal in the interstellar medium, ^{17}O and ^{14}N are mainly produced from ^{16}O via the CNO cycle, and since ^{18}O is formed from ^{14}N, ^{16}O is the primary seed for both, ^{17}O and ^{18}O. A major difference between these isotopes comes from the fact that ^{18}O is produced by α-capture *and* destroyed by α-capture, i.e. it can reside only in a very narrow temperature range in the stellar interior, while ^{17}O is destroyed by α-

capture at similar temperatures as ^{18}O, but it is produced at hydrogen burning temperatures.

The production of both isotopes requires the operation of the CNO cycle, which occurs in stars more massive than $\sim 1.2\,M_\odot$. Therefore, it is presumed that stars with initial masses in the range $1.2\,M_\odot \lesssim M_{\rm ZAMS} \lesssim 10\,M_\odot$ have contributed to the Galactic ^{17}O and ^{18}O abundances (Henkel et al. 1994, Prantzos et al. 1996). In the case of ^{17}O, this is well supported by stellar models, since ^{17}O is dredged up into the H-rich stellar envelope on the red giant branch (e.g., El Eid 1994), which is subsequently lost due to stellar winds. The contribution of the intermediate-mass stars to the ^{18}O enrichment is much less clear, since ^{18}O lives between the H- and He-burning nuclear shell sources, and its survival depends critically on the still poorly understood mixing events between these shell sources during the so called thermal pulses (e.g., Vassiliadis & Wood 1993). Intermediate mass stars may even effectively destroy rather than produce ^{18}O (cf. Prantzos et al. 1996). Therefore, it is clear that intermediate mass and massive stars contribute significantly to the ^{17}O production, while the situation is unclear for ^{18}O.

The temporal evolution of the three stable oxygen isotopes has been considered in models of the Galactic chemical evolution (Timmes et al. 1995, Prantzos et al. 1996), which requires the knowledge of the isotopic yields as function of the stellar mass and metallicity. In the present paper, we investigate the production of the oxygen isotopes in massive stars. As in intermediate mass stars, the production of all oxygen isotopes is subject to uncertainties. However, in contrast to the case of intermediate mass stars, which evolve through the complicated thermal pulse phase, we can quantitatively investigate the uncertainties in the case of massive stars. We show that the yields of all three isotopes are strongly affected by at first glance unexpected physical effects. In Sect. 2 we outline that the ^{16}O production depends strongly on the applied convection model, while its mass loss dependence produces a metallicity dependence of the absolute ^{16}O yield which is atypical for a primary isotope (Sect. 3). In Sect. 4, we investigate the unexpected metallicity dependence of the ^{17}O production factor, and in Sect. 5 we demonstrate the enormous sensitivity of the ^{18}O yield on convective mixing. In Sect. 6 we conclude that a joint effort to consistently model the oxygen isotopes in stellar and chemical evolution calculations has the potential to resolve longstanding open questions in both fields of astrophysical research.

2. The ^{16}O yields in present massive star models

The amount of ^{16}O produced by a massive star depends strongly on **a)** the mass of the C/O-core at the time of iron core collapse and **b)** the C/O-ratio established in the C/O-core at core-He exhaustion. Both factors can be influenced in various ways. While the C/O-core mass is a strong function of the He-core mass and of the convection model, the C/O-ratio of core-He burning is sensitive to the ^{12}C$(\alpha,\gamma)^{16}$O nuclear reaction rate and — again — the employed convection model. While we postpone the discussion of the dependence of the ^{16}O yield on stellar wind mass loss to Section 3, let us in the following compare the results of models where mass loss is unimportant.

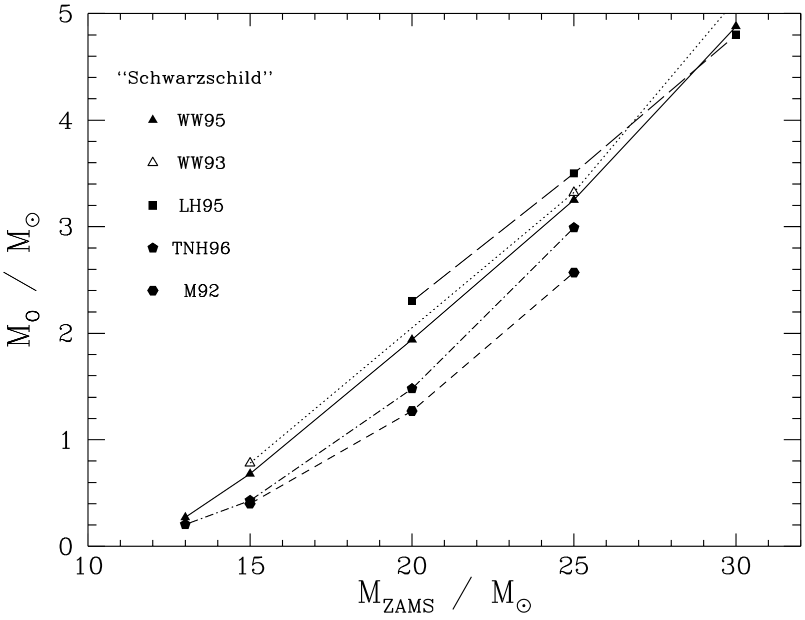

Figure 1. Oxygen yield M_O in solar masses as function of the initial stellar mass $M_{\rm ZAMS}$ according to five different sets of stellar models (cf. references for author labeling) for which the oxygen yield is unaffected by stellar wind mass loss ($M_{\rm ZAMS} \lesssim 30\,M_\odot$) and in which the effect of mean molecular weight gradients on convection is ignored (Schwarzschild criterion for convection) or assumed to be weak.

Fig. 1 shows the ^{16}O yields M_O obtained by various authors for solar metallicity stars in the initial mass range $13\,M_\odot \leq M_{\rm ZAMS} \leq 30\,M_\odot$ computed with the Schwarzschild criterion for convection (or similar assumptions). While all models shown agree in the general trend of an almost linear increase of M_O with increasing initial mass, there is a considerable scatter for a given value of $M_{\rm ZAMS}$. E.g., at $M_{\rm ZAMS} = 20\,M_\odot$ — around which the product of metal mass output times IMF statistical weight is largest — the discrepancy in the oxygen yields of different authors is roughly $1\,M_\odot$, with values ranging from $1.27\,M_\odot$ (Maeder 1992; henceforth M92) to $2.3\,M_\odot$ (Langer & Henkel 1995; LH95). A similar scatter is found at $M_{\rm ZAMS} = 25\,M_\odot$.

An understanding of the differences of the oxygen yields of different authors is not easily obtained. E.g., one might expect that calculations using a faster ^{12}C$(\alpha,\gamma)^{16}$O-rate would obtain a larger oxygen mass; however, Fig. 1 shows that the opposite is the case. While M92 and Thielemann et al. (1996; TNH96) used the Caughlan et al. (1985) rate which is roughly 1.4 times faster than the rate used by Woosley & Weaver (1995; WW95) and LH95, they obtained much less oxygen. It is even more surprising that M92, who applied "convective core overshooting" and thus arrives at larger core masses, obtains the smallest oxygen yields.

While the origin of the latter discrepancy could not be resolved on the basis of the published data, the small oxygen yields of TNH96 may be related to the fact that they only compute helium cores of a fixed mass $M_{\rm He}$ rather than complete stars. This appears to have two major drawbacks: firstly, they have to adopt a $M_{\rm He}(M_{\rm ZAMS})$-relation; for a given ZAMS mass their He-core mass appears to be somewhat smaller than the final He-core masses of the models presented in the other papers discussed here. E.g., at $M_{\rm ZAMS} = 25\,M_\odot$: $M_{\rm He}({\rm LH95}) = 8.4\,M_\odot$, $M_{\rm He}({\rm WW95}) = 9.1\,M_\odot$, and $M_{\rm He}({\rm M92}) = 9.7\,M_\odot$, while TNH96 relate a $8\,M_\odot$ helium core with a $25\,M_\odot$ star. Secondly, in a realistic model the He-core mass is not constant but grows with time by substantial amounts. In a $20\,M_\odot$ star, e.g., it grows from $4\,M_\odot$ to more than $6\,M_\odot$, i.e. by more than 50% (e.g., Langer 1991). This leads to different trajectories in the $\rho_c - T_c$-diagram during He-burning and to different growth rate of the He-burning convective core and consequently to differences in the rate of mixing of α-particles into the He-burning region.

Finally, the oxygen yield is also depending on assumptions on the mass of the compact remnant which remains bound after the supernova explosion. While WW95 and TNH96 evolve their models until iron core collapse and through the supernova explosion and can thus derive a remnant mass best, M92 and LH95 stop their calculations after carbon and oxygen burning, respectively, and apply a remnant mass C/O-core mass relation. At $M_{\rm ZAMS} = 25\,M_\odot$, the small oxygen yield of M92 may be partly related to the large adopted remnant mass in this model — $2.72\,M_\odot$, compared to values between 1.8 and $2.1\,M_\odot$ in the other three cases — (this explanation fails, however, at $M_{\rm ZAMS} = 20\,M_\odot$), while those of LH95 are generally somewhat smaller than WW95's.

The comparison of the ^{16}O yields of models of different authors in Fig. 1 reveals already discrepancies of the order of a factor of 2. Fig. 2 illustrates its uncertainty due to a physical effect which has not been considered in the models shown in Fig. 1: in calculations which apply the Schwarzschild criterion for

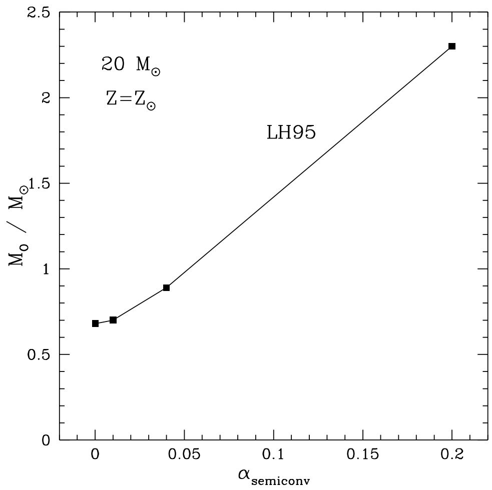

Figure 2. Oxygen yield of four solar metallicity $20\,M_\odot$ models of LH95, computed with various values of the semiconvective mixing parameter $\alpha_{\rm semiconv}$, which determines the time scale of mixing in semiconvective regions (cf. Langer et al. 1983). $\alpha_{\rm semiconv} = 0$ means the time scale is infinite (no mixing in semiconvective regions and Ledoux criterion for convection). The entry for the largest value of the semiconvection parameter corresponds to the Schwarzschild criterion for convection, i.e. $\alpha_{\rm semiconv} = \infty$; it is arbitrarily placed at $\alpha_{\rm semiconv} = 0.2$.

convection the effect of mean molecular weight barriers to slow down convective mixing through these barriers is ignored. On the other extreme, such mixing is practically prevented in case the Ledoux criterion for convection is used. Semi-convection models allow a mixing through these barriers on a certain time scale which, in the mixing scheme of Langer et al. (1983), is inversely proportional to an (uncertain) efficiency coefficient $\alpha_{\rm semiconv}$. Fig. 2 shows that the ^{16}O yield is strongly depending on this parameter. In the case of a solar metallicity 20 $M_\odot$ star, the ejected ^{16}O mass varies from 0.68 $M_\odot$ to 2.3 $M_\odot$, i.e. by more than a factor of 3. This effect and its order of magnitude are confirmed in the calculations of Weaver & Woosley (1993; WW93). They find the oxygen yields to differ by factors 3.7 and 1.8 in calculations at 15 and 25 $M_\odot$, respectively (cf. also Fig. 3), depending on the efficiency of semiconvective mixing.

We conclude that, despite the ^{16}O yield of massive stars seems — at first glance — to be easily evaluated since it basically depends on the C/O-core mass, it may be as uncertain as by a factor of 3 in the stellar mass range which is most relevant for the ^{16}O budget of galaxies. In the next Section, we show that for $M_{\rm ZAMS} \gtrsim 30\,M_\odot$, the situation becomes even more complex due to effects of stellar mass loss.

3. The ^{16}O yield and stellar wind mass loss

The ^{16}O yield of a massive star remains basically unaffected by stellar mass loss as long as it maintains hydrogen-rich surface layers, because the evolution of the He-burning core is essentially determined by the evolution of the He-core mass (cf. M92, Woosley et al. 1993). However, stars with $M_{\rm ZAMS} \gtrsim 30\,M_\odot$ may — at $Z \simeq Z_\odot$ — lose their entire H-rich envelope and evolve into so called Wolf-Rayet (WR) stars. WR stars have such strong mass loss that they can effectively blow off a substantial part of their mass (Langer 1989) — and thus of their He-core. Consequently, these objects eject much of the helium inside the He-core before it can be burnt into metals, and later much of the carbon which is synthesized during core helium burning before it can be processed further into oxygen. WR mass loss thus increases the helium and ^{12}C yields at the expense of ^{16}O.

This effect can be clearly seen in Fig. 3, where the oxygen yields of stars with and without mass loss are compared (separately for models with slow and fast semiconvective mixing). For the assumption of very efficient mass loss, M92 obtained 2.1 $M_\odot$ of oxygen out of a 40 $M_\odot$ star, while WW95 obtain 7.6 $M_\odot$ for the case of a similar remnant mass as that in M92.

As the stellar mass loss rates are likely to be higher at larger metallicity Z, the quenching of the ^{16}O yield due to mass loss is strongly Z-dependent. This is comprehensively shown in the models of M92 (cf. also Meynet et al. 1994), and its significance in models of Galactic chemical evolution has been demonstrated by Prantzos et al. (1994).

4. ^{17}O production as function of the stellar metallicity

As stated in Section 1, ^{17}O is produced as a secondary isotope in the CNO cycle, and its final abundance depends primarily on the initial ^{16}O abundance in the star. However, the latter statement holds only for a fixed burning temperature.

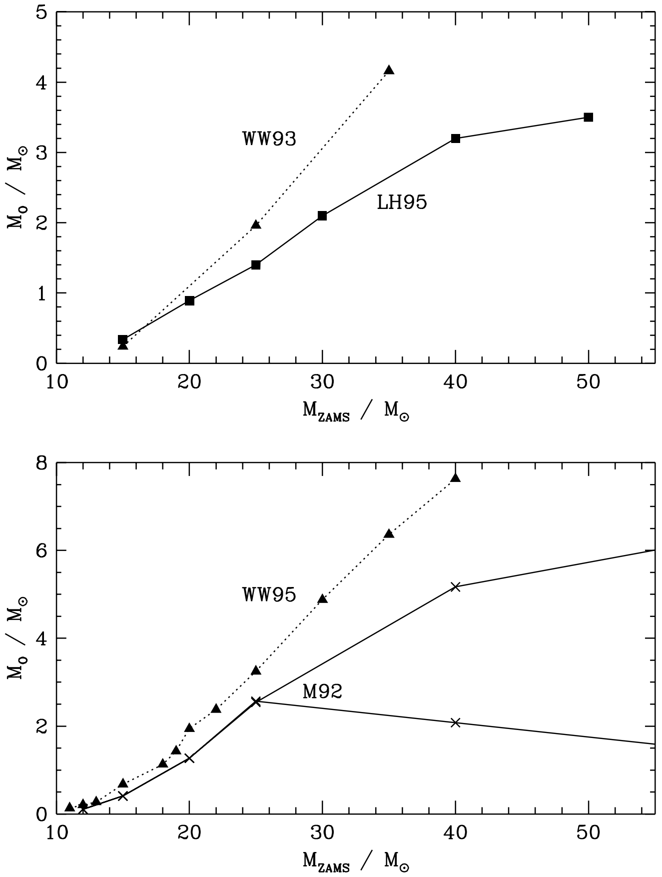

Figure 3. Comparison of the oxygen yield M_O as a function of the initial stellar mass M_{ZAMS} for models with and without stellar wind mass loss, and assuming a remnant mass of the order of $2\,M_\odot$. Upper panel: Models with slow semiconvective mixing. WW93's models are computed without mass loss, LH95 included mass loss. Lower panel: Models with fast semiconvective mixing resp. Schwarzschild criterion for convection. WW95 neglected mass loss, M92 explored models with standard and excessive mass loss.

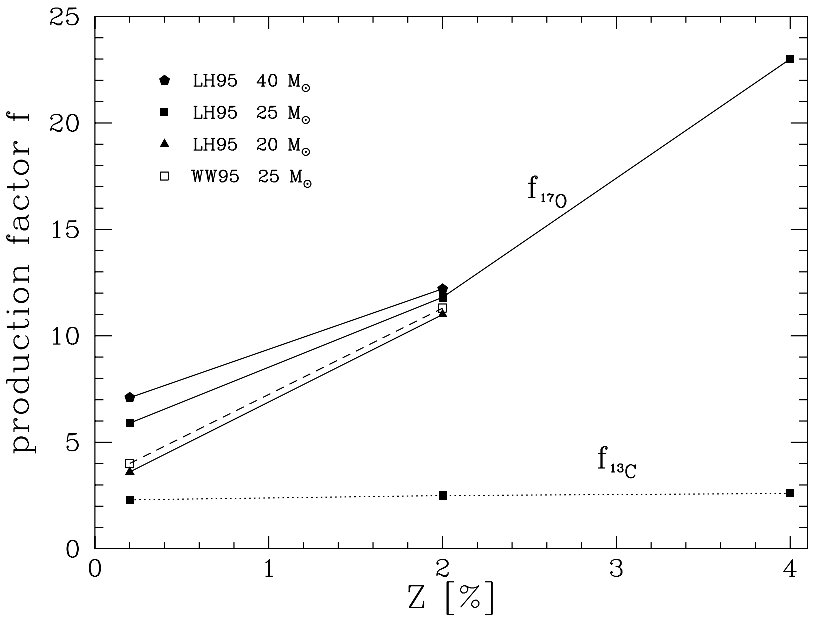

Figure 4. Dependence of the ^{17}O production factor (ratio of the ejected versus the initial amount of ^{17}O) on the initial stellar metallicity Z, according to models of LH95 and WW95. The steep increase with Z is atypical for secondary isotopes. This is demonstrated by comparison with the ^{13}C production factor of the $25\,M_\odot$ models of LH95 (dotted line), which shows no dependence on Z.

That the situation of ^{17}O is more complex can be seen in Figure 4, which displays the ^{17}O production factor for various stellar masses as function of the initial stellar metallicity Z. Note that the initial metal distribution in the models of LH95 is the solar distribution scaled according to the actual metallicity.

Since the initial amount $M_{\rm in}$ of a metal isotope in a star is proportional to Z, and the produced and expelled amount $M_{\rm out}$ of a secondary isotope is also proportional to Z, its production factor $f = M_{\rm out}/M_{\rm in}$ should be independent of Z. This is in fact so for many secondary isotopes as can be seen at the example of ^{13}C in Fig. 4. However, this figure shows also that — in contrast to the expectation — the ^{17}O production factor increases strongly with metallicity.

Let us compare the behavior of ^{17}O to that expected for a primary isotope. In this case, again $M_{\rm in} \propto Z$, but the production does not depend on the initial metal content, i.e. $M_{\rm out} \simeq const.$, and thus $f \propto \frac{1}{Z}$. I.e., the production factor of a primary isotope decreases with increasing Z. This is just opposite to the behavior of ^{17}O. ^{17}O is thus not behaving like a primary nor like a secondary isotope; its production factor f is roughly proportional to Z, and thus $M_{\rm out} \propto Z^2$. I.e., ^{17}O may be called a "super-secondary" isotope.

What is special about ^{17}O, in particular in comparison to all other secondary CNO isotopes which show, as ^{13}C in Fig. 4, a clean secondary behavior? The overproduction of secondary CNO nuclei is basically determined by the CNO equilibrium abundance distribution (cf. Clayton 1968). An inspection of the CNO equilibrium abundances of the secondary CNO isotopes in Figure 3 of Arnould & Mowlavi (1993) shows that the ^{17}O equilibrium concentration — in contrast to that of all other secondary isotopes — is extremely temperature sensitive. In particular, it is strongly decreasing for increasing temperature. Since the nuclear energy production rate in the CNO cycle is proportional to the metallicity (Clayton 1968) but the luminosity of a main sequence star is mainly fixed by its mass (Kippenhahn & Weigert 1990), the H-burning temperature in massive main sequence stars of a given mass is larger for lower metallicity. $25\,M_{\odot}$ stars in the Z-range considered in Fig. 4 (0.2% ... 4%) vary in their central temperature at a time where the central hydrogen mass fraction is 50% in the range (42 ... 36)$\times 10^6$ K. We conclude that the decreased temperature in massive H-burning stars of larger metallicity results in a larger ^{17}O equilibrium abundance and thus in a larger ^{17}O production.

We should note that the absolute value of the ^{17}O production factor depends on the still uncertain ^{17}O+p nuclear cross section (cf., Aubert et al. 1996); however, the general trend discussed here is likely to be independent of that.

5. How to produce ^{18}O ?

The production of ^{18}O is perhaps even more complex than that of the other oxygen isotopes. First, it is always destroyed during hydrogen burning with the CNO cycle. As stated in Section 1, it is produced by α-capture on ^{14}N. However, it is also destroyed by α-capture, through $^{18}{\rm O}(\alpha,\gamma)^{22}{\rm Ne}$. Therefore, ^{18}O can exist only in a very narrow temperature interval in the stellar interior. Moreover, it is destroyed in all layers which are convectively coupled to the main helium burning energy source, i.e. in the He-burning convective core and in convective He-shells. This is the reason why the production of ^{18}O depends critically on the semiconvective mixing parameter $\alpha_{\rm semiconv}$ (cf. Section 2). For larger values of this parameter, the mentioned convection zones have larger spatial extents and destroy more ^{18}O. Fig. 5 shows that this effect is extremely strong. While, in a $20\,M_{\odot}$ star at $Z = Z_{\odot}$, 57 times the initial amount of ^{18}O is ejected in the SN explosion in the case the Ledoux criterion for convection is used without semiconvective mixing ($\alpha_{\rm semiconv} = 0$), almost nothing is produced in case the Schwarzschild criterion for convection is applied ($\alpha_{\rm semiconv} = \infty$). Note that this effect has also been found in the models of WW93.

Perhaps, this extreme sensitivity of the ^{18}O production on the convective mixing criterion can turn out to be very useful. In case massive stars are the main producers of ^{18}O, even order of magnitude chemical evolution arguments might be used to constrain the uncertain but extremely important parameter $\alpha_{\rm semiconv}$ in stellar models. According to present day yields of low and intermediate-mass

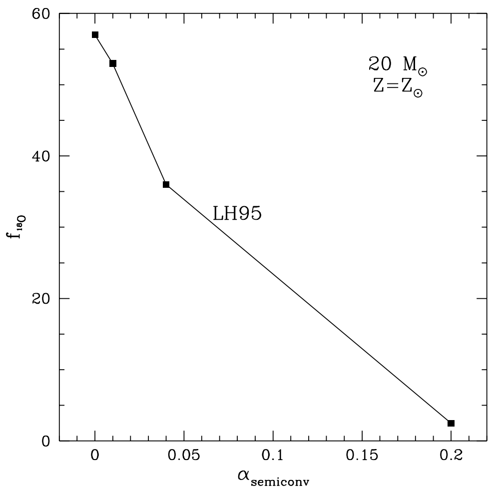

Figure 5. ^{18}O production factor (cf. Fig. 4) in solar metallicity $20\,M_\odot$ models of LH95, as function of the semiconvective mixing parameter $\alpha_{\rm semiconv}$ (cf. Fig. 2; note especially that the entry for the largest value of $\alpha_{\rm semiconv}$ corresponds to $\alpha_{\rm semiconv} = \infty$).

stars (cf. Prantzos et al. 1996), these don't produce any ^{18}O but rather destroy it. Some of the massive star models of LH95 computed with the Schwarzschild criterion also are net destructors of ^{18}O. Thus, the consideration of hindering effects of mean molecular weight barriers on convective mixing seems to be required to understand the production of ^{18}O to the extent it is presently observed in the Galaxy.

6. Conclusions

We have seen in the previous sections that the production of all three stable oxygen isotopes in massive stars is affected by at first glance unexpected physical effects. The ^{16}O yield can currently, for a given stellar mass and metallicity, not be predicted better than within a factor of 2 or 3 (cf. Section 2). Further, it depends — despite of its primary character — on the metallicity through the Z-dependence of stellar winds (cf. Section 3). A decreasing oxygen yield with increasing metallicity should lead to a negative slope of the [O/H] vs. [Fe/H] relation (assuming here a clean primary behavior of iron) which is on fact observed (cf. Timmes et al. 1995). Though this observation is usually explained with the onset of iron production due to Type Ia supernovae (cf. also Edmunds et al., for an alternative explanation), there may be an impact of the Z-dependent oxygen yields on this feature.

For ^{17}O, we showed that its component produced in massive stars behaves in a "super-secondary" way (Section 4), i.e. its yield increases stronger than linear with Z, for $0.1 \lesssim Z/Z_\odot \lesssim 2$. And ^{18}O is hard to produce at all; it may be mainly destroyed in low and intermediate mass stars, while in massive stars its production depends on assumptions on convection (Section 5). There are no low metallicity halo star observations to test the chemical evolution of these isotopes, but radio observations of molecular clouds give the intriguing result that the $^{18}O/^{17}O$ ratio is constant ($\simeq 3.5$) throughout the Galactic disk, with the solar system having a different ratio of $\simeq 5.5$ (Henkel & Mauersberger 1993, Wilson & Rood 1994). Prantzos et al. (1996) studied the Galactic evolution of the CNO isotopes and conclude that "there is simply no universal nucleosynthesis mechanism capable to explain" this result. I.e., especially the evolution of ^{18}O remains far from being understood, and its exploration involves at the same time the physics of evolving galaxies and of mixing processes in massive stars.

New light on the production of the oxygen isotopes may be shed by a new generation of massive star models which include effects of differential rotation and thereby triggered internal mixing processes, the presence of which appears to be well established observationally (cf. Fliegner et al. 1996). Preliminary results (Langer et al. 1996) indicate that the production of all three oxygen isotopes may be strongly affected by rotational mixing; the investigation of these effects and their mass and metallicity dependence has been started and first results are expected in the near future.

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