FULL TITLE
ASP Conference Series, Vol. **VOLUME**, **YEAR OF PUBLICATION**
NAMES OF EDITORS

AGB stars and the chemical evolution of galaxies

Monica Tosi

INAF - Osservatorio Astronomico di Bologna, Via Ranzani 1, I-40127 Bologna, Italy

Abstract. Asymptotic Giant Branch (AGB) stars are important players in the chemical evolution modelling of galaxies, because they are major producers of several chemical elements and excellent tracers of the structure and of the star formation activity of their parent galaxies. A few examples on the importance of AGB stars are presented in this review, together with a number of open problems affecting chemical evolution model predictions related to the element enrichment by AGB stars: the evolution of ^{4}He and Na in globular clusters, the evolution of ^{3}He and the carbon isotopes in the Galactic disk, and the evolution of N and O in different types of galaxies. The need of homogeneous and complete sets of yields is emphasized.

1. Introduction

There are several reasons why galaxies and galaxy modellers care about Asymptotic Giant Branch stars. AGB stars trace the halo stellar distribution (see Demers in this volume), thus indicating what is the size and the dynamics of the system; they trace intermediate-age stars (see Grebel, this volume), thus showing if and how much star formation (SF) activity has occurred in the region 0.5 - 1 Gyr ago; they are the major site of production of several chemical elements (see Busso and Lattanzio in this volume) and fundamental contributors to the stellar nucleosynthesis yields, which, in turn, are the main ingredients of chemical evolution models.

This review is focussed on the third point, which is the most important one for chemo-dynamical models of galaxy evolution. Let me however mention how important it is to trace intermediate age and old populations. IZw18 is the most metal poor star-forming galaxy ever discovered. Being very blue and full of gas, it was often considered a local counterpart of primeval galaxies and a really young system, with SF activity begun only a few Myr ago. However, when HST optical photometry became available, AGB stars were found (Aloisi, Tosi, & Greggio 1999) and then confirmed with near-infrared HST photometry (Ostlin 2000). The presence of AGB stars undisputably demonstrated that IZw18 is not as young as originally thought and must have started forming stars at least 0.5 - 1 Gyr ago.

Here, I will describe the effects of AGB stars as interstellar medium (ISM) polluters with reference to the evolution of a few interesting elements: ^{3}He, ^{4}He, ^{12}C, ^{13}C, N and Na. The galaxy evolution models described here are all *standard*, in the sense that they do not explicitely treat dynamical aspects. It is however

becoming increasingly clear that to understand galaxy evolution dynamical and hydrodynamical effects cannot be left aside.

2. AGB stars as ISM polluters: ^{4}He, Na and the evolution of globular clusters

In recent years there has been an increasing interest on the possibility of a second generation of stars in some globular clusters. Some of the observed properties of globular clusters are indeed considered evidence of a second SF event. For instance, the anticorrelation between the sodium and oxygen abundances measured in stars of several clusters (e.g. Carretta, Bragaglia, & Cacciari 2004, and references therein) has been interpreted as the consequence of the cluster self-enrichment, if the gas replenishment from the retention of stellar ejecta is sufficient to allow for further SF. In this scenario, the stars born during the second SF episode form from mostly (if not entirely) recycled gas and their initial chemical compositions reflect the yields of the stars mostly contributing to the cluster self-enrichment. Gratton et al. (2001) and D'Antona et al. (2002) suggested that high Na enrichment and significant O depletion are most naturally explained if the major culprits of the cluster self-pollution are relatively massive AGB stars. The stars with more O and less Na would be those formed in the first generation, while the stars with less O and more Na would be those formed in the second generation. D'Antona et al. (2002) further suggested that the second generation would be significantly enriched also in helium (again as a consequence of the predominance of AGB star ejecta in the gas available for SF) and that this could explain the Horizontal Branch morphology of clusters with extreme blue tails. Other authors, however, have argued that the winds of massive stars have more chances than AGB stars to adequately pollute the cluster's medium without the side effects of requiring unusual initial mass functions and stellar remnants (e.g. Prantzos & Charbonnel 2006). Appropriate chemo-dynamical models are required to test advantages and disadvantages of the various hypotheses.

The discovery of a second, bluer Main Sequence (MS) in ω Centauri (Bedin et al. 2004), together with that of multiple subgiant and red giant branch (RGB) sequences, also calls for the existence of multiple stellar generations, with the additional striking surprise, provided by high-resolution spectroscopy, that the bluer MS is 0.3 dex less metal poor than the *standard* red MS (Piotto et al. 2005). Piotto et al. argue that the only way to allow for the measured colour shift between the two MSs with the measured metallicity difference is to let the bluer MS be much more helium rich than the other, with a difference in the helium mass fraction ΔY=0.14. If we attribute to the red MS a primordial He mass fraction of Y=0.24, this implies that the blue MS should have Y=0.38: an abundance higher than in any other observed star cluster or galaxy !

Would AGB stars be able to provide such a huge helium enhancement ? It is very unlikely. However, ω Centauri is definitely not a normal globular cluster; may be not a cluster at all, but the remnant of a nucleated dwarf galaxy captured and stripped by the Milky Way, with the current cluster actually being the original nucleus of the satellite. Bekki & Norris (2006) have recently shown that the observed properties of ω Centauri cannot be explained without considering

the strong dynamical interactions with the Galaxy. The actual question then is whether the medium, out of which subsequent stellar generations have formed, was enriched by ω Centauri own stars or by the stars of the host dwarf originally surrounding it. Whether the polluters were AGBs, massive stars or supernovae is in this case a second level issue.

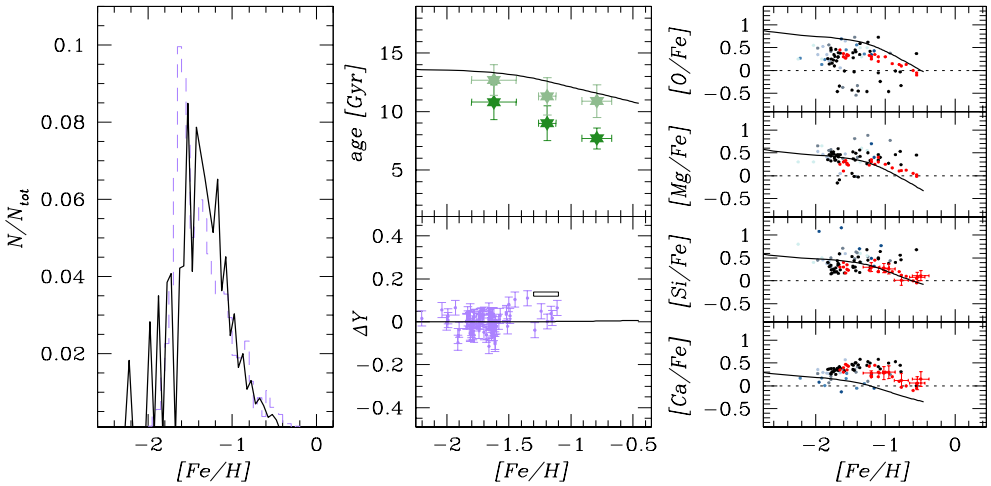

Figure 1. Predictions from chemical evolution models (solid lines) for ω Centauri compared with the corresponding observational data (dots and dashed lines). Left panel: the stellar metallicity distribution from Sollima et al. (2005); central top panel: age-metallicity relation from Hilker et al. (2004); central bottom panel: helium vs iron from Piotto et al. (2005, box) and in RR Lyraes (dots; from Sollima et al. 2006); right panel: abundance ratios vs iron from several literature sources.

We are currently modelling the chemical evolution of ω Centauri (Romano et al., in preparation) considering it as a dwarf galaxy and following the approach presented by Romano, Tosi, & Matteucci (2006, hereafter, RTM06) for other dwarfs. We adopt the SF history derived from the Sollima et al. (2005) data and allow for both galactic winds and infall of metal poor gas. The model predictions are compared with the observational mass, age-metallicity relation, metallicity distributions, chemical abundances and abundance ratios. In agreement with Bekki & Norris results, in no way are we able to obtain model predictions consistent with the data if we consider ω Centauri as an isolated system. On the other hand, by considering it as the residual of a nucleated galaxy stripped by the Milky Way 10 Gyr ago, we reproduce rather well all the data, except the extremely high He abundance of the blue MS. To achieve this goal, new ad hoc assumptions are needed and will be the subject of further efforts, involving appropriate assumptions on the fate of the stellar ejecta and new stellar yields for both high and intermediate mass stars. Our current, preliminary results are shown in Fig.1.

3. AGB stars as ISM polluters: ^{3}He, ^{12}C and ^{13}C

ω Centauri may require special yields and evolutionary conditions to be explained, but the need of improved yields is a much more general problem. Examples of important elements for which improved yields are badly needed are the He, C, N and O stable isotopes.

In the late nineties it has been shown (e.g. Galli et al. 1997; Tosi 2000, and references therein) that to let the predictions of Galactic chemical evolution models reproduce the low ^{3}He abundances measured in Galactic HII regions a mechanism is needed, able to drastically reduce the ^{3}He production normally predicted for low-mass stars. Such a mechanism was suggested by e.g. Charbonnel (1995) and Wasserburg, Boothroyd, & Sackmann (1995) to be the consequence of extra-mixing at work in RGB stars, possibly as a consequence of rotation. To reconcile the low HII regions abundances with the high ^{3}He measured in a few Planetary Nebulae (PNe), the extra-mixing should affect about 90% of low mass stars. Since this extra-mixing implies not only a significant ^{3}He depletion, but also a larger conversion of ^{12}C into ^{13}C in such a large fraction of stars, it is important to check whether the corresponding yields are consistent with the carbon ratios observed in PNe.

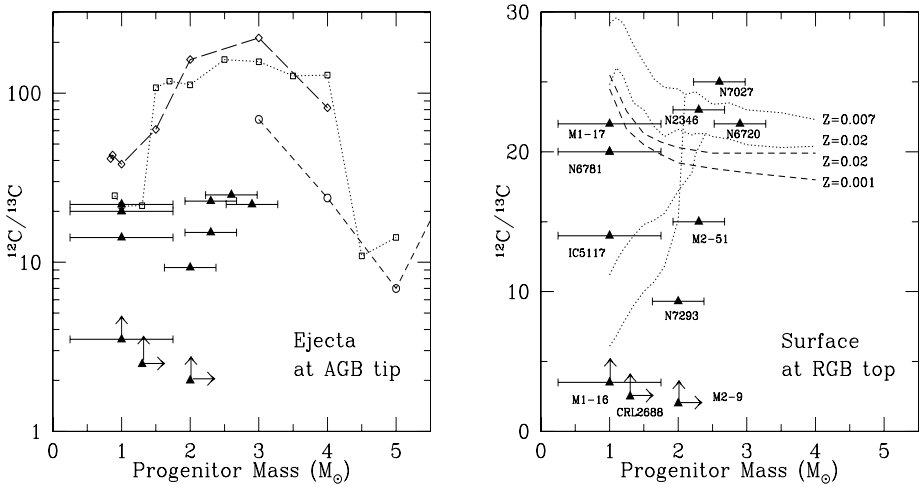

Figure 2. From Palla et al. (2000): carbon isotopic ratios measured in PNe (dots with error bars in both panels) compared with stellar nucleosynthesis predictions. The curves in the left-hand panel show the ratio predicted without deep-mixing just before the PN ejection by Marigo (2001), long-dashed, van den Hoek & Groenewegen (1997), dotted, and Forestini & Charbonnel (1997), dashed. The dotted curves in the right-hand panel show the ratio predicted at the end of the RGB phase by Boothroyd & Sackman (1999), with (the curves falling down to low ratios) and without deep-mixing (those staying at high ratios).

In Fig.2 the carbon isotopic ratios measured by Palla et al. (2000) in several PNe are compared with the predictions from various theoretical yields. It is apparent that the standard nucleosynthesis predictions of the left-hand panels over-

produce the carbon ratio, while the deep-mixing predictions by Boothroyd & Sackman (1999) in the right-hand panel nicely fit the data. This nice fit is however misleading, because Boothroyd & Sackman's computations reach only the RGB tip and not the final evolutionary phases. The carbon abundances can be significantly affected by the remaining evolution. Unfortunately, no yields taking deep-mixing into account have been calculated beyond the RGB and none of the yields computed up to the final phases include the deep-mixing effect. In other words, a direct check of the existence of the extra-mixing and of the solution to the ^{3}He problem, with all its cosmological consequences, is currently unfeasible !

4. AGB stars as ISM polluters: nitrogen versus oxygen

Nitrogen and oxygen are important tracers of the chemical evolution of galaxies. Not only are they among the most abundant elements; they are also measurable, from the emission lines of HII regions (and PNe in some cases), in galaxies up to rather large distances, where they are often the only available metallicity indicators. Oxygen is mainly produced by massive stars, whilst nitrogen is mostly synthesized by intermediate-mass stars. In the framework of the simple model of galaxy evolution (Tinsley 1980) the enrichments of primary elements are independent of each other, whilst the growth of a secondary element goes as the square of the growth of a primary. The double nature (primary and secondary) of the N production became apparent when the N and O measured in HII regions of a number of spirals (Díaz & Tosi 1986), including the Milky Way, and of late-type dwarf galaxies (Matteucci & Tosi 1985) were compared with the predictions of adequate chemical evolution models: a significant fraction (between 30% and 60%) of N must be primary to explain the rather flat trend of N/O vs O/H inferred from HII regions in both late-type dwarfs and individual spirals. The straight lines in the left-hand panel of Fig.3 show least-squares fits to the N/O vs oxygen abundances derived by Díaz & Tosi (1986) from the HII regions in the Galaxy, M31, M33, M101, NGC2403 and IC342 (for more accurate and updated data see Pilyugin, Thuan, & Vilchez 2003). The fits for these individual spirals are overplotted on a very recent version of the N/O vs O/H diagram including results from the Sloan Digital Sky Survey (Liang et al. 2006).

The N/O vs O/H diagram is sometimes interpreted as an evolution plot. However, the oxygen abundance in abscissa cannot be taken as a proxy for time. In fact, each of the plotted dots corresponds to an HII region, whose abundance reflects the final (current) result of the whole history of chemical enrichment in the host galaxy region. Such history is known to be quite different for different types of galaxies, since it depends on SF history, gas accretion (infall) and loss (winds), interactions with companions, etc. As such, the position of each point in the plot depends on the different evolutions of different galaxies, and not only on the nature (primary or secondary) of the N nucleosynthesis (see also Edmunds & Pagel 1978; Pilyugin, Thuan, & Vilchez 2003).

Much attention has been payed to the metal-poor end of the N/O vs O/H diagram, where late-type metal-poor dwarfs are located, to discuss either the possibility of primary production of N in massive stars, or the possible connection

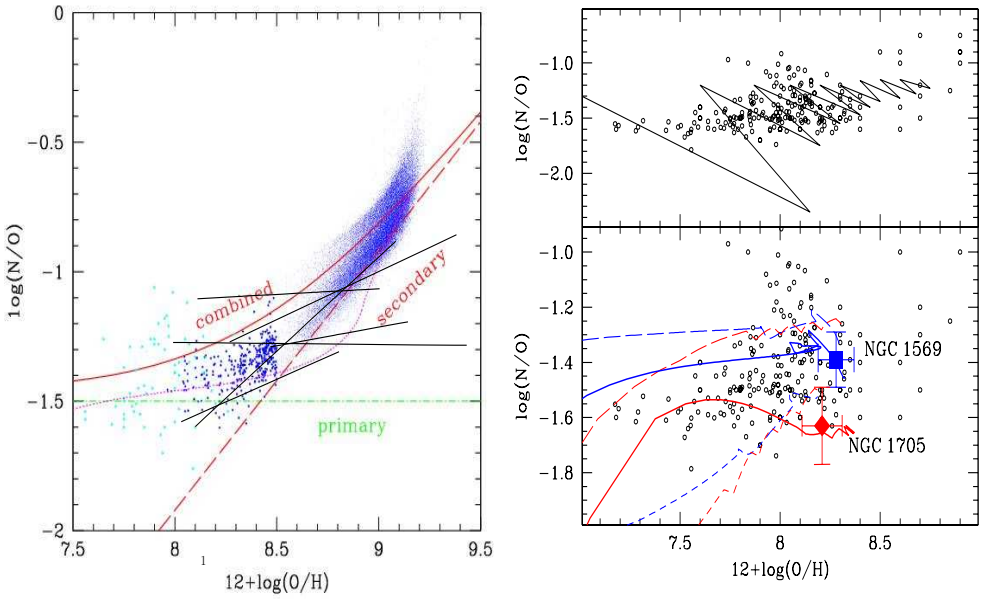

Figure 3. N/O vs O/H in different galaxies as derived from HII region observations (dots). The plot on the left-hand panel is from Liang et al. (2006) and shows the SDSS data as dots. The thick straight lines show the trends in individual spirals from Díaz & Tosi (1986). The right-hand panels are blow-ups of the metal-poor region of the diagram and the lines show some of the effects of galaxy evolution (see text for details).

between late-type dwarfs and Damped Lyman-α systems. The plots on the right-hand side of Fig.3 show some of the effects on the N and O abundances occurring during galaxy evolution. The lines shown in the two diagrams on the right correspond to the predictions of different chemical evolution models for the time behaviour of oxygen and nitrogen in a late-type dwarf galaxy. The top-right panel compares with the abundances measured from the HII regions observed in late-type dwarfs (dots) the model predictions by Pilyugin (1993) for a generic Blue Compact galaxy experiencing about ten SF bursts. It shows how the HII region self-enrichment and the different timescales for the stellar ejection and subsequent diffusion in the ISM of oxygen and nitrogen lead to a saw-tooth shape for the N/O ratio as a function of oxygen.

The bottom-right panel show instead the predictions by RTM06 for the starburst dwarf NGC 1569 (always the line with higher N/O for each line-type; blue in the colour version of the figure) and the Blue Compact dwarf NGC 1705 (always the line with lower N/O for each line-type; red in the colour version of the figure). The big symbols with error bar indicate the corresponding values derived from HII regions in NGC 1569 (blue square) and NGC 1705 (red diamond). The other points correspond to HII regions values in other late-type dwarfs. Different line-types correspond to different assumptions on the stellar yields or on the galactic wind efficiency. See RTM06 for references and details. All the lines show model predictions for the evolution of oxygen and nitrogen with time

and it is apparent how much the time behaviour can be different from a simple fit to the current N/O vs O/H distribution inferred from HII regions.

In spite of the different classification, NGC 1569 and NGC 1705 have quite similar properties (see e.g., Annibali et al. 2003; Angeretti et al. 2005, and references therein): similar gas and star masses, metallicity, IMF, SF history with very strong recent activity, and observational evidence of similarly strong galactic winds. Yet, they have quite different N/O ratios, which require different evolutionary assumptions. The long-dashed lines in the bottom-right panel of Fig.3 show the model predictions based on the standard yields by van den Hoek & Groenewegen (1997) for intermediate mass stars. Clearly a standard N production may be consistent with the N/O ratio observed in NGC 1569, but un-reconcilable with the low N/O of NGC 1705. If we consider yields with smaller N production, even in the extreme case of those by Meynet & Maeder (2002) where the hot-bottom burning phase has not been computed, the models overpredict the N/O ratio observed in NGC 1705 (short-dashed lines). A better fit to the observed abundances is obtained (RTM06) if not only the nitrogen production in intermediate mass stars is relatively low, as predicted for instance by the *minimal* hot-bottom burning case proposed by van den Hoek & Groenewegen (1997), but also a higher efficiency of nitrogen loss in the galactic wind is allowed in NGC 1705 than in NGC 1569 (solid lines).

Detailed chemical evolution models of individual dwarfs, such as those shown here for NGC 1569 and NGC 1705, have become possible only recently, mostly thanks to HST, which has allowed to derive their SF histories back to quite early epochs. Two kinds of models for individual galaxies can be computed: *standard* chemical evolution models (e.g. Carigi, Colin, & Peimbert 1999; Lanfranchi & Matteucci 2003; Romano, Tosi, & Matteucci 2006) and *chemo-dynamical* models (e.g. Recchi et al. 2002, 2006). The former have the drawback of a simplistic treatment of star and SN feedbacks and gas motions, the latter have the problem that the timescales appropriate for hydrodynamics make it prohibitive, in terms of CPU time, to follow the system evolution over more than 1 Gyr. The challenge in the next few years is to improve both types of approaches and get a more realistic insight of how stars and gas evolve, chemically and dynamically, in their host galaxies.

5. The need for improved yields

In the previous sections, some examples of the uncertainties affecting the predictions of chemical evolution models have been presented. Part of these uncertainties are due to the lack of complete and homogenous sets of stellar yields for various initial metallicities. To compute adequate chemical evolution models of whatever galaxy, we need homogeneous chemical yields for all the major isotopes, for the whole range of stellar masses, for many initial compositions and taking into account all the most relevant processes occurring in the stellar interiors until the final evolutionary phases. Such *optimal* grid of yields is far from existing. The results from stellar nucleosynthesis are steadily improving with time, with most of the processes occurring during stellar evolution being treated with increasing precision. However, the yields available to the community are still very heterogeneous and incomplete and not one single set of nucleosynthesis

predictions exists taking properly into account all the processes in all the phases of stars of all masses (say from 0.8 to 100 $M_\odot$) and at least 2-3 different metallicities (from metal poor to solar and, possibly, super solar). This circumstance not only prevents the computation of detailed self-consistent chemical evolution models for a number of key elements, but can even lead to misleading results. The potential risk can be visualised by comparing with each other the yields provided by different authors and the corresponding normalizations through an IMF.

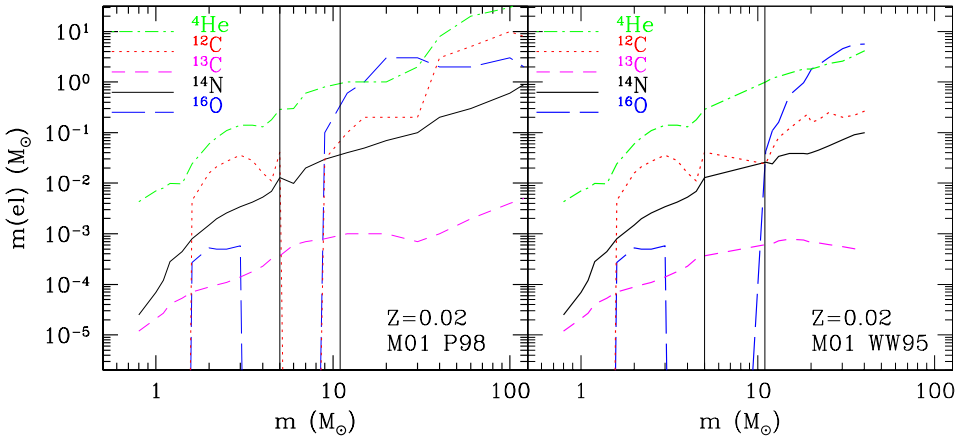

Figure 4. Stellar yields: ejected mass of newly synthesized element as a function of the stellar initial mass. Left-hand panel: the case of the homogeneous sets of solar yields by Marigo (2001) and Portinari, Chiosi, & Bressan (1998) covering the whole mass range. Right-hand panel: the *standard* case of incomplete coverage with inhomogeneous sets (Marigo 2001; Woosley & Weaver 1995) which do not consider initial masses with $5 < M/M_\odot < 11$ (the lines plotted in this mass range are linear interpolations) and beyond 40 $M_\odot$.

The left-hand panel of Fig.4 shows a subset of the solar yields presented by Portinari, Chiosi, & Bressan (1998) for massive and quasi-massive stars and by Marigo (2001) for low and intermediate mass stars. This is the best case in literature of self-consistent yields for all masses, based on the same stellar evolution models and input physics. What is normally available in the literature is a collection of yields for partial mass ranges, each computed under different assumptions and often for different metallicities. A typical case is shown in the right-hand panel of Fig.4, where the solar yields by Marigo (2001) for low and intermediate mass stars are now combined with those by Woosley & Weaver (1995) for massive stars. Two problems are immediately apparent. First, stars in the mass range $5 < M/M_\odot < 11$ have not been computed by either Marigo or Woosley & Weaver, which implies that to use this combination of yields one must interpolate over this mass interval. Second, massive stars do not go beyond 40 $M_\odot$ and to higher masses one must therefore extrapolate. The latter issue might not have overwhelming consequences in the modelling of the recent chemical evolution of the Milky Way, since any reasonable IMF predicts

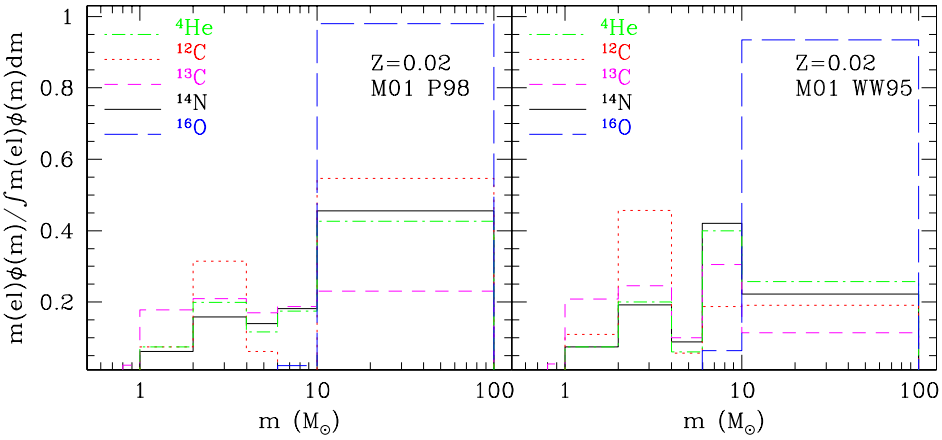

Figure 5. Fractional ejected mass of newly synthesized element weighted with Tinsley (1980) IMF. Left-hand panel: the case of the homogeneous sets of solar yields by Marigo (2001) and Portinari, Chiosi, & Bressan (1998). Right-hand panel: the case of the inhomogeneous, non adjacent sets by Marigo (2001) and Woosley & Weaver (1995).

very few stars more massive than 40 $M_{\odot}$, but can be extremely relevant for very early epochs, when the most massive stars were the only polluters. The former problem has very serious implications because stars in the 5 – 11 $M_{\odot}$ range are the most effective contributors to the ISM chemical enrichment. In Fig.5 the yields of Fig.4 have been weighted with Tinsley's (1980) IMF. The linear interpolation performed to cover the 5 – 11 $M_{\odot}$ interval absent in the Marigo/Woosley&Weaver combination results in a bump (right-hand panel) in the contribution of these stars to the enrichment of He, N and O which is totally absent in the left-hand panel, where the homogeneous sets of yields are shown. This enhanced contribution is most likely spurious and can lead to a significant overprediction of the elements mostly produced by stars of these masses.

To overcome these problems, we strongly encourage the community of stellar nucleosynthesis experts to provide homogeneous yields for all stellar masses, computed up to the final evolutionary phases and for several initial metallicities.

Acknowledgments. Some of the results described here have been obtained thanks to pleasant and recurrent collaborations with A. Aloisi, D. Galli, F. Matteucci, F. Palla, D. Romano and L. Stanghellini. I am grateful to Corinne Charbonnel for many useful conversations on the stellar yields and to Donatella Romano for her invaluable help. Part of these researches was funded through INAF-PRIN-2005.

References

Aloisi, A., Tosi, M., & Greggio, L. 1999, AJ, 118, 302

Angeretti, L., Tosi, M., Greggio, L., Sabbi, E., Aloisi, A., & Leitherer, C. 2005, AJ, 129, 2203

Annibali, F., Greggio, L., Tosi, M., Aloisi, A., & Leitherer, C. 2003, AJ, 126, 2752
Bedin, L.R., Piotto, G., Anderson, J., Cassisi, S., King, I.R., Momany, Y., & Carraro, G. 2004, ApJ, 605, L125
Bekky, K. & Norris, J.E. 2006, ApJ, 637, L109
Boothroyd, A.I., & Sackman, I.-J. 1999, ApJ, 510, 232
Carigi, L., Colin, P., & Peimbert, M. 1999, ApJ, 514, 787
Carretta, E., Bragaglia, A., & Cacciari, C. 2004, ApJ, 610, L25
Charbonnel, C. 1994, A&A, 282, 811
Charbonnel, C. 1995, ApJ, 453, L41
D'Antona, F., Caloi, V., Montalban, J., Ventura, P., & Gratton, R. 2002, A&A. 395, 69
Díaz, A.I. & Tosi, M. 1986, A&A, 158, 60
Edmunds, M.G. & Pagel, B.E.J. 1978, MNRAS, 185, 77
Forestini, M., & Charbonnel, C. 1997, A&AS, 123, 241
Galli, D., Stanghellini, L., Tosi, M., & Palla, F. 1997, ApJ477, 218
Gratton, R.G., et al. 2001, A&A, 369, 87
Hilker, M., Kayser, A., Richtler, T., & Willemsen, P. 2004, A&A, 422, L9
Lanfranchi, G.A., & Matteucci, F. 2003, MNRAS, 345, 71L
Liang, Y.C., Yin, S.Y., Hammer, F., Deng, L.C., Flores, H., & Zhang, B. 2006, astro-ph/0607074
Meynet, G., & Maeder, A. 2002, A&A, 390, 561
Marigo, P. 2001, A&A. 370, 194
Matteucci, F., & Tosi, M. 1985, MNRAS217, 391
Nomoto, K., Hashimoto, M., Tsujimoto, T., Thielemann, F.-K., Kishimoto, N., Kubo, Y., & Nakasato, N. 1997, Nucl.Phys.A., 616, 79c
Ostlin, G. 2000, ApJ, 535, L99
Palla, F., Bachiller, R., Stanghellini, L., Tosi, M., & Galli, D. 2000, A&A, 355, 69
Pilyugin, L.S. 1993, A&A, 277, 42
Pilyugin, L.S., Thuan, T.X., & Vilchez, J.M. 2003, A&A, 397, 487
Piotto, G. et al. 2005, ApJ, 621, 777
Portinari, L., Chiosi, C., & Bressan, A. 1998, A&A, 334, 505
Prantzos, N. & Charbonnel, C. 2006, A&A, 458, 135
Recchi, S., Matteucci, F., D'Ercole, A., & Tosi, M. 2002, A&A, 384, 799
Recchi, S., Hensler, G., Angeretti, L., & Matteucci, F. 2006, A&A, 445, 875
Romano, D., Tosi, M., & Matteucci, F. 2006, MNRAS, 365, 759 (RTM06)
Sollima, A., Borissova, J., Catelan, M., Smith, H.A., Minniti, D., Cacciari, C., & Ferraro, F. R. 2006, ApJ, 640, L43
Sollima, A., Pancino, E., Ferraro, F. R., Bellazzini, M., Straniero, O., & Pasquini, L. 2005, ApJ, 634, 332
Tinsley, B.M. 1980, Fund.Cosm.Phys., 5, 287
Tosi, M. 2000, in The Light elements and their evolution, IAU Symp. 198, L. da Silva, R. de Medeiros, & M. Spite eds, p.525
van den Hoek, L.B., & Groenewegen, M.A.T. 1997, A&AS, 123. 305
Wasserburg , G.J., Boothroyd, A.I., & Sackmann, I.-J. 1995, ApJ, 447, L37
Woosley, S.E., & Weaver, T.A. 1995, ApJS, 101, 181