THE POINT ON THE THEORETICAL CHANGES OF SURFACE CHEMISTRY DURING MASSIVE STAR EVOLUTION

André Maeder
Geneva Observatory, CH-1290 Sauverny

1. INTRODUCTION

For main sequence stars, the central nuclear processing generally has no effect on surface abundances. Later in the evolution, the newly synthetized elements may be revealed at the stellar surface by processes such as mass loss, convective dredge-up, overshooting, diffusion, rotational and tidal mixing, etc. The changes of CNO abundances are the most conspicuous and the easiest to observe spectroscopically; some abundance ratios like C/N, O/N may undergo changes by more than 10^2. On the whole, surface chemistry is a most powerful diagnostics of stellar evolution, model assumptions and nuclear cross sections.

2. MAPPING OF CNO ABUNDANCES IN THE HR DIAGRAM

For massive stars, the peeling-off by stellar winds (1) contributes to big changes of chemical abundances (2, 3, 4, 5, 6, 7). Several of the quoted works present the time evolution of surface chemistry and reference is made to them for detailed information. Figs. 1 and 2 illustrate the changes of the $^{12}C/^{14}N$ and $^{16}O/^{14}N$ ratios along the evolutionary tracks in the HR diagram for models (7) with moderate overshooting, i.e. with an overshooting distance $d_{over}=0.25\ H_p$ (8). Similar data for models without (6) or with considerable overshooting (5) exist, and such mappings can also be made for other interesting chemical ratios. Along the tracks, we distinguish the following abundance sequence:

-1. Initial cosmic abundances: C/N=4, O/N=9 in mass fraction (as always here).

-2. Intermediate abundances: for initial $M \geqq 60\ M_\odot$ the transition from a cosmic to an equilibrium C/N ratio ($\cong 10^{-2}$) is abrupt near the end of the main sequence. For O/N, the transition is more progressive. Changes of minor species due to the Ne-Na, Mg-Al cycles also occur (9, 5). For $M \leqq 40\ M_\odot$, changes of abundances only occur from the red supergiant (RSG) stage and onwards, convective dilution in large envelopes making these changes rather limited and stepwise. A

https://doi.org/10.1017/S0252921100093489 Published online by Cambridge University Press

second plateau may be produced if the intermediate fully convective zone appears at the stellar surface. Many other changes of abundances occur like the strong decrease in ^{3}He, ^{15}N and ^{18}O.

-3. CNO equilibrium: it can be reached by massive stars in the Luminous Blue Variable (LBV) stage and by WN stars. The changes in H and He contents are rather smooth and cases of CNO equilibrium with H (LBV and WNL stars) and without H (WNE stars) may be distinguished (see also §6).

-4. Products of partial He-burning: they are visible only in WC and WO stars. C and O appear prominently at the stellar surfaces. The appearance of these elements is predicted to be quite fast because there is usually a large chemical discontinuity at the edge of the He-burning core (cf. 3).

On the whole, the smaller the initial mass, the earlier the above itinerary through the abundance sequence is stopped. Also, a star with overshooting behaves to first order like a more massive star without overshooting.

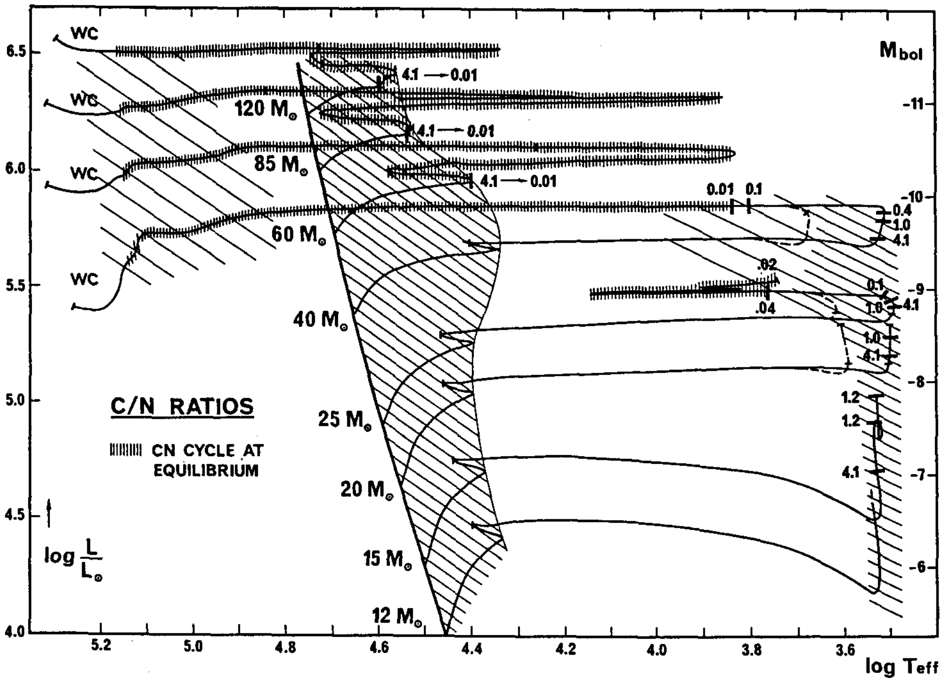
3. O-STARS: DO SOME EVOLVE HOMOGENEOUSLY?

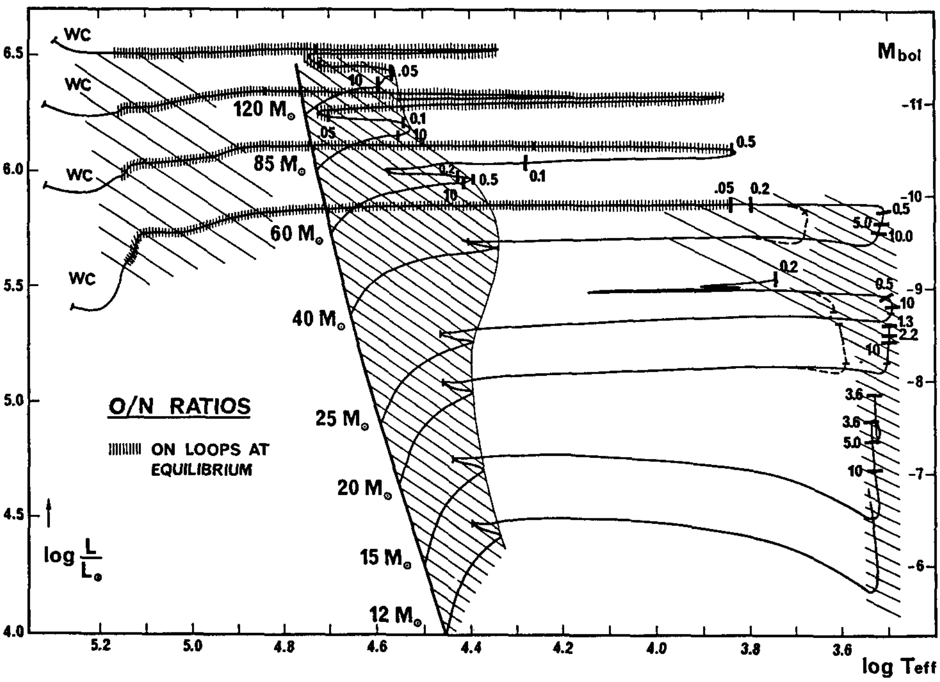
Models with initial masses $M<80\ M_{\odot}$ and no overshooting keep their original abundance during main sequence (MS) evolution (6). Above this mass, models predict CNO equilibrium only near the end of the MS phase. For an overshooting of $d_{over}=0.25\ H_p$, this limit is about 60 $M_{\odot}$ (cf. Figs. 1 and 2). On the whole, both these results agree with the observations that most MS O-stars have solar abundances (e.g. 10, 11, 12).

The subgroups of OBN and OBC show N or C enhancement (13). Do the OBC have just the original unmodified abundance, while the so-called normal O-stars already exhibit evidence of mild CNO processing? This is an attractive suggestion (14); to be fully confirmed it would need detailed abundance analyses for a large group of O-stars in young clusters. Four ON stars, analysed in detail (12), show C/N, O/N ratios and He contents typical of advanced CNO processing. Quite unexpectedly, two of these ON stars lie close to the zero-age sequence.

Suggestions have been made that ON stars result from mass transfer in close binaries (13, 15), from mass loss by stellar winds (16), or from convective overshooting (17). The models in Figs. 1 and 2, which include overshooting and mass loss at the observed rates, clearly show that these two processes are unable alone to account for

https://doi.org/10.1017/S0252921100093489 Published online by Cambridge University Press





<u>Figs. 1 and 2</u>: The values of the abundance ratios $^{12}C/^{14}N$ and $^{16}O/^{14}N$ along the evolutionary tracks (7).

https://doi.org/10.1017/S0252921100093489 Published online by Cambridge University Press

the ON stars close to the zero-age sequence. This is especially interesting since the occurrence of N-rich stars as blue stragglers close to the zero-age sequence seems quite general (e.g. 18, 19, 20). The possibility of these stars belonging to a second star generation in the clusters is unlikely in view of their very high chemical peculiarity.

From both the location of the ON blue stragglers in the HR diagram and their large N-enhancement, it has been suggested (19) that these stars evolve close to chemical homogeneity. As possible mechanism, distorsions either due to rotation or tidal interaction in binaries could induce baroclinic instabilities (21), i.e. instabilities occurring when the surfaces of constant pressure and temperature do not coincide. Thus matter can move freely in a horizontal direction and create a two-dimensional turbulence. At small scales, the cascade of turbulence produces a three-dimensional diffusion (21). Evolutionary models including such a diffusive mixing induced by rotation indicate (19) that full mixing may occur in cases of high rotation. The relative role of rotation, tidal mixing and mass transfer in the formation of ON blue stragglers is still to be evaluated. In any case, the homogeneous evolution of a fraction of O-stars would have great implications for nucleosynthesis and galactic chemical evolution.

4. BLUE SUPERGIANTS IN RELATION WITH SN 1987 A

Stars in the location of LBV (luminous blue variable), i.e. blue supergiants with $M_{bol} \leq -10$, are predicted to exhibit CNO equilibrium abundances (cf. Fig. 1 and 2), whether or not overshooting is present. The observations (22) for η Carinae and the models agree, which confirms the evolutionary status of this intriguing object as a post-MS supergiant.

Blue supergiants on the first redwards tracks are predicted to have normal cosmic abundances, whether or not overshooting is present. According to the models (6, 7), the blue supergiants exhibiting CN equilibrium and ON intermediate values should be in a post red supergiant (RSG) stage. (This statement could be revised if such stars have undergone some substantial diffusion). Interestingly, the pulsation properties of blue supergiants on the first and second crossing are also different (23).

There are very few detailed abundance analyses for blue supergiants. A study for two stars indicates (24) one star with normal abundance and the other with marked evidence of CNO processing.

https://doi.org/10.1017/S0252921100093489 Published online by Cambridge University Press

Two blue supergiants in the LMC also show (25) CNO processed elements. These few results show that at least some blue supergiants are in a post RSG stage. This is quite interesting in relation with the large N/C and N/O ratios shown by UV spectra (26, 27) of SN 1987 A, which also support the idea that the SN precursor was in a post RSG stage. Analyses for a large number of blue supergiants are necessary to give the percentage of stars on the blue- and redwards crossing. A list of candidate blue supergiants in young clusters has been selected (6).

5. RED SUPERGIANTS: TEST OF NUCLEAR CROSS SECTIONS

RSG are predicted to exhibit CNO processed elements with various rates of dilution according to initial mass. In a given area of the HR diagram, the predicted C/N and O/N ratios present some significant scatter (cf. Figs. 1 and 2). Thus great care has to be taken about conclusions drawn from the comparisons between models and observations. The M1.5 Iab stars α Ori and α Sco have C/N, $^{12}C/^{13}C$ and O/N ratios characteristic of CNO processing (28, 29). The observed values indicate more advanced nuclear processing than predicted; however care has to be taken regarding these conclusions, for the reasons given above.

The comparisons for ^{16}O, ^{17}O, ^{18}O in the two mentioned red supergiants show (6) rough agreement between observations and models regarding the isotopes ^{16}O and ^{18}O. For ^{17}O the predicted abundance is too high by a factor of about 25. A discussion of the various intervening reactions suggests (6) that the reaction rate of $^{17}O(p,\alpha)^{14}N$ has to be pushed to its higher resonant limit (factor f=1).

6. WR STARS: DIFFERENT SENSITIVITY OF WN AND WC STARS TO MODEL PHYSICS

Various comparisons (30, 2, 31, 32, 5, 6, 7) of models and observations confirm that the sequence of WN, WNE, WC and WO is consistent with a progression in the exposition of nuclearly processed materials:

WNL (WN6-WN9): H, He, N
WNE (WN2-WN6): He, N, no H left
WC : He, C, O, no H and no N left
WO : same as WC, but with larger O/C

Some exceptions to this scheme exist. Moreover, the range of initial masses does not seem to be identical for stars of various subtypes.

https://doi.org/10.1017/S0252921100093489 Published online by Cambridge University Press

For WN stars, the typical abundance ratios are C/He = (1.8-3.9)$\cdot10^{-4}$, N/H = (1.3-1.7)$\cdot10^{-2}$, C/N = (1.1-2.9)$\cdot10^{-2}$ and C/O = 0.25-1.3 in mass fraction (7). These ratios depend very little on initial masses, on the exact mass loss rates, on overshooting etc. They are essentially model-independent as normally expected for equilibrium ratios. All model results agree well with observations, particularly for the C/N ratio, which is the most accurate observationally. This is not a success for the models, it just means that the abundances in WN stars are not a very constraining test for the model assumptions such as mixing. However, the above agreement implies that the cross sections for CNO burning are correct, which in itself is an essential result for stellar evolution.

During the WC stage, the chemical abundances change quite a lot, since materials which are more and more processed are progressively revealed at the stellar surface. The values of C/He and O/C at the beginning of the WC phase are very sensitive to overshooting: the larger the cores, the lower the initial C/He and O/C ratios (e.g. 7). One has C/He = 0.9-3, 0.3-3, 0.1-2.5 for models with no, moderate and large overshooting respectively (e.g. 6, 7, 5).

There have recently been many new observations for C/He in WC stars (33, 34), which give C/He ratios in the range 0.4-2.4. The value of the lower boundary is in favour of models with moderate overshooting, a conclusion which is also supported by cluster sequences in the HR diagram and the number ratio of WN and WC stars (7).

IRAS data for NeIII at 15.8 μ give a Ne/He ratio of 0.05 in mass fraction (35), in agreement with model predictions (5, 6, 7). However, from ground-based data for NeIII at 12.8 μ, a ratio of Ne/He = 0.005 has been obtained (36). Who is right? If this last result is true, it raises the interesting question in which form are the ashes of CNO elements. If most ^{22}Ne has been converted into ^{25,26}Mg (which is normally not predicted), this would imply that through the reaction ^{22}Ne (α, n) ^{25}Mg, WC stars may synthetize more s-elements than expected (cf. also 5).

REFERENCES

1. Chiosi, C., Maeder, A. 1986, Ann. Rev. Astron. Astrophys. 24, 329
2. Noels, A., Gabriel, M. 1981, Astron. Astrophys. 101, 215
3. Maeder, A. 1983, Astron. Astrophys. 120, 113
4. Greggio, L. 1984, in *Observational Tests of the Stellar Evolution Theory*, IAU Symp. 105, eds. A. Maeder and A. Renzini, p. 329

https://doi.org/10.1017/S0252921100093489 Published online by Cambridge University Press

5. Prantzos, N., Doom, C., Arnould, M., de Loore, C. 1986, Astrophys. J. 304, 695
6. Maeder, A. 1987, Astron. Astrophys. 173, 287
7. Maeder, A., Meynet, G. 1987, Astron. Astrophys. 182, 243
8. Mermilliod, J.C., Maeder, A. 1986, Astron. Astrophys. 158, 45
9. Dearborn, D.S.P., Blake, J.B. 1985, Astrophys. J. 288, L21
10. Kane, L., McKeith, C.D., Dufton, P.L. 1980, Astron. Astrophys. 84, 115
11. Dufton, P.L., Kane, L., McKeith, C.D. 1981, Mon. Not. R. Astr. Soc. 194, 85
12. Kudritzki, R.P. 1985, in *Production and Distribution of C, N, O Elements*, ESO Workshop, eds. I.J. Danziger, F. Matteucci, K. Kjär, p. 277
13. Walborn, N.R. 1976, Astrophys. J. 205, 419
14. Walborn, N.R. 1987, this meeting
15. Bolton, C.T., Rogers, G.L. 1978, Astrophys. J. 222, 234
16. Dearborn, D.S.P., Eggleton, P.P. 1977, Astrophys. J. 213, 448
17. Doom, C. 1982a, Astron. Astrophys. 116, 303, 308
18. Schild, H., Berthet, S. 1986, Astron. Astrophys. 162, 369
19. Maeder, A. 1987, Astron. Astrophys. 178, 159
20. Mathys, G. 1987, Astron. Astrophys., in press
21. Zahn, J.P. 1983, in *Astrophysical Processes in Upper MS Stars*, 13th Saas-Fee Course, eds. B. Hauck and A. Maeder, Geneva Obs., p. 253
22. Davidson, K., Dufour, R.J., Walborn, N.R., Gull, T.R. 1984, in *Observational Tests of the Stellar Evolution Theory*, IAU Symp. 105, eds. A. Maeder and A. Renzini, p. 261
23. Lovy, D., Maeder, A., Noels, A., Gabriel, M. 1984, Astron. Astrophys. 133, 307
24. Lennon, D.J., Dufton, P.L. 1986, Astron.Astrophys. 155, 79
25. Kudritzki, R.P. 1987, in *ESO Workshop on SN 1987 A*, ed. J. Danziger, in press.
26. Cassatella, A. 1987, in *ESO Workshop on SN 1987 A*, ed. J. Danziger, in press
27. Kirshner, R.P. 1987, this meeting
28. Harris, M.J., Lambert, D.L. 1984, Astrophys. J. 281, 739
29. Lambert, D.L., Brown, J.A., Hinkle, K.H., Johnson, H.R. 1984, Astrophys. J. 284, 223
30. Vanbeveren, D., Doom, C. 1980, Astron. Astrophys. 87, 77
31. Smith, L.J., Willis, A.J. 1983, Astron. Astrophys. Suppl. 54, 229
32. Conti, P.S., Leep, E.M., Perry, D.N. 1983, Astrophys. J. 268, 228
33. Smith, L.F., Hummer, D.G. 1987, Astrophys. J., in press
34. Torres, A.V. 1987, Astrophys. J., in press
35. Van der Hucht, K.A., Olnon, F.M. 1985, Astron. Astrophys. 149, L17
36. Barlow, M.J. 1987, preprint

https://doi.org/10.1017/S0252921100093489 Published online by Cambridge University Press