CARBON IN THE ENVELOPES OF WHITE DWARFS

Francesca D'Antona

Osservatorio Astronomico di Roma, Italy
and
Department of Astronomy
University of Illinois at Urbana Champaign

Current theory of stellar evolution predicts that stars of initial masses up to 4-6 $M_\odot$ evolve into Carbon-Oxygen White Dwarfs surrounded by a Helium envelope and, possibly, by a Hydrogen envelope. It also predicts that the mass of the Helium envelope which remains on the star at the end of its double shell burning evolution is a function of the Carbon-Oxygen core mass (Paczynski 1975). It can be shown that this mass can be reduced - but only slightly - during the following evolution of the star towards the White Dwarf region, either by nuclear burning or by mass loss (D'Antona and Mazzitelli 1979). During the White Dwarf stage, Helium convection grows into White Dwarfs having Helium atmospheres. The maximum extension of Helium convective mass is a function of the mass of the star (Fontaine and Van Horn 1976; D'Antona and Mazzitelli 1975,1979). It turns out that the Helium envelope remnant mass is always at least three orders of magnitude larger than the maximum Helium convective mass, whatever the mass of the star may be. This statement is unlikely to be changed by refinements either in the theory of double shell burning or in the theory of White Dwarf envelope convection.

If there were any White Dwarfs with a Helium envelope as small as the maximum convective envelopes, convective mixing would occur between the Helium layers and the Carbon core, and models predict that the surface composition would be changed to almost pure Carbon (D'Antona and Mazzitelli 1979; Vauclair and Fontaine 1979). In fact, no pure Carbon spectra of White Dwarfs are known. The Carbon abundance in λ4670 stars, which is probably not larger than 0.1% by mass (Bues 1973,1978) must find its origin in mechanisms different than the mixing between the envelope and the core.

It is tempting to relate the Carbon abundance in λ4670 White Dwarfs to the conspicuous Carbon abundance left in the Helium intershell of White Dwarf progenitors during thermal pulses (Iben 1977). Abundances as large as 10-30% are predicted. Even if some of these White Dwarfs come from low mass progenitors, as implied by their belonging to the old disk population, the Carbon mass fraction can be as large as 20% (Schönberner 1979). Even if the timescales of diffusion of Carbon with respect to Helium indicates that Carbon should have ample time to sink below the maximum depth reached by the Helium convection zone (Fontaine and Michaud 1979), no one has properly evaluated the effect of diffusion starting

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from such large Carbon abundances. Furthermore, the large Carbon to Oxygen ratio found in λ4670 (Bues 1973) would be in agreement with the predictions of stellar evolution.

It is easy to realize that White Dwarfs in cataclysmic binaries also preserve their large Helium envelopes, if the formation of the short period system occurs as described by Paczynski (1976) or Ritter (1976). This fact has important consequences for nova systems. The only successful models of very fast novae (Starrfield et al. 1978) require that the Hydrogen envelope of the White Dwarf be considerably enriched in CNO elements. A common explanation of this enrichment was the mixing of the Hydrogen rich matter with the Carbon core of the White Dwarf, either during the accretion phases (Colvin et al. 1977), or during the nova outburst itself (Starrfield et al. 1978). According to the previous statement, this mixing can never occur, as no White Dwarf can be born with a pure Carbon envelope or, furthermore, with a Helium envelope so small that it be mixed with the core during the White Dwarf cooling.

Furthermore, just noticing that the nova outburst must be a recurrent phenomenon in every system (Ford 1978), it is easy to dismiss the possibility that fast novae are associated either with the first nova outburst only (when the Hydrogen envelope can be a remnant of double shell evolution with dredging up - Iben 1976) or with the outburst immediately following a Helium shell pulse in the White Dwarf itself. Also in the latter case there would be enrichment in Carbon of the Hydrogen layer by dredging up, but one cannot expect Helium shell pulses to be very frequent with respect to Hydrogen outbursts (less than one in a hundred). Neither of these mechanisms accounts for the frequency of fast novae.

The only conditions under which Carbon enriched material can be present at <u>each</u> nova outburst in a system, is for the <u>accreting</u> material to be Carbon enriched. It is commonly accepted that White Dwarfs in novae are massive (Robinson 1976), in excess of 1 $M_\odot$. This indicates that their progenitors must have been stars of initial mass larger than about 3 $M_\odot$, if steady mass loss is taken into account (Fusi-Pecci and Renzini 1976). During the Helium thermal pulses phase, the White Dwarf progenitor has enriched its Hydrogen rich envelope in Carbon by dredging up the products of nuclear processing in the Helium intershell (Iben 1976). The following phases of mass exchange with the secondary, which must occur in order to form the cataclysmic binary, may well have contaminated the chemical composition of the secondary star; when mass exchange from the secondary to the White Dwarf --and the nova phase-- begin, the matter accreting onto the White Dwarf can be Carbon enriched.

In order to have an idea of the maximum CNO enhancement predictable in this evolutionary scheme, let me make the most favourable hypotheses for the binary system. First of all, notice that the mass exchange between the components, just prior to the formation of the cataclysmic system, is a "fast" process. When the giant fills its Roche lobe, the mass loss rates can be as large as 10^{-3}-10^{-2} $M_\odot$/yr (Paczynski and Sienkievicz 1972; Webbink 1978); even a very massive envelope is lost in 10^2-10^3 years. For a typical interflash period of 10^2 yr --when the core mass

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is 1.25 - 1.30 $M_\odot$ -- the giant can suffer 1-10 more pulses during this phase. Comparing this number to the number of pulses suffered during the previous evolution ($2\text{-}3\times10^3$) it is evident that the Carbon abundance in the transferring envelope cannot be further altered, and is fixed to the value reached during the single star evolution, up to the point in which contact with the Roche lobe is reached.

To achieve the maximum CNO enhancement, assume:
i) contact is reached just before the phase in which the star would eject a planetary Nebula;
ii) the mass transfer converts the envelope composition of the secondary into the composition of the primary envelope, without dilution into the convective envelope of the secondary (either due to its structure or induced by the mass transfer itself -Webbink 1977).
From table 9 of Iben and Truran 1978 the maximum Carbon enhancement is reached in the envelope of an initial mass 5 $M_\odot$, when it ejects a Planetary Nebula leaving a core of 1.36 $M_\odot$. In the ejected envelope --which in our case is partially transferred to the secondary-- they obtain $\bar{Y}_{12} = C/C_\odot = 12$. From this value, one can infer $\bar{Y}_{CNO} = CNO/CNO_\odot \simeq 4$, as the sum of Nitrogen and Oxygen does not vary too much during the evolution. This value seems far too low with respect to the factor required by Starrfield et al. (1978).

To maximize the possible CNO enrichment, one must notice that it is largely dependent on the value of λ, the fraction of dredged up mass with respect to the mass processed during the interpulse phase; this λ is a function of the core mass, and can be estimated on the basis of lower limits only, due to the lack of model computation for core masses larger than 0.96 $M_\odot$. Since this law of dredging up remains somewhat arbitrary, one can modify it to estimate the maximum enhancement. This task is not so obvious as it would seem, as, if λ approaches 1 too closely, the core mass does not increase rapidly enough to compete with steady mass loss, and the maximum initial mass for the formation of a Planetary nebula increases. The situation is even less clear if one takes into account that the large increase in CNO modifies the structure of the star in a way which can be envisioned only qualitatively. The main effect is that the increase of the opacities in the external layers leads to an increase in the radius of the star for a given core mass. This in turn enhances the mass loss rate. These two effects cannot be avoided by lowering too much the coefficient in the mass-loss rate formula (Reimers 1977), which, although largely uncertain, is calibrated on many different kinds of astrophysical evidence (Renzini 1978). As it seems rather improbable that the largest White Dwarf progenitor exceeds about 6 $M_\odot$, the λ must be chosen in order to satisfy this constraint.

The parameter λ has been varied in the program and program inputs described by Iben and Truran 1978. The resulting Carbon enhancement must be viewed as the maximum possible in a not completely unreasonable scheme of evolution. Starting from a 6 $M_\odot$ initial mass, the enhancements are $\bar{Y}_{12} = 14$ ($\bar{Y}_{CNO} = 5$) when the core mass reaches 1.25 $M_\odot$, and rise to $\bar{Y}_{12} = 33$ ($\bar{Y}_{CNO} = 12$) when the core mass reaches 1.37 $M_\odot$ and the star would eject a Planetary Nebula. It is to be stressed that, if very fast nova models cannot be built with such CNO abundances, even this scheme is unable to account for the occurrence of fast novae.

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REFERENCES

Bues, I. 1973, Astr. Ap., 28, 181.
Bues, I. 1978, Paper presented at the "3rd European Workshop on White Dwarfs", Tel Aviv University, Israel.
Colvin, J., Van Horn, H.M., Starrfield, S., and Truran, J.W. 1977, Ap.J., 212, 791.
D'Antona, F., and Mazzitelli, I. 1975, Astr. Ap., 42, 165.
D'Antona, F., and Mazzitelli, I. 1979, Astr. Ap., 74, 161.
Fontaine, G., and Michaud, G. 1979, Ap.J., in press.
Fontaine, G., and Van Horn, H.M. 1976, Ap.J. Suppl. 31, 467.
Ford, H.C. 1978, Ap.J., 219, 595.
Fusi Pecci, F., and Renzini, A. 1976, Astr. Ap., 46, 447.
Iben, I., Jr. 1976, Ap.J., 208, 165.
Iben, I., Jr. 1977, Ap.J., 217, 788.
Iben, I., Jr., and Truran, J.W. 1978, Ap.J., 220, 980.
Paczynski, B. 1975, Ap.J., 202, 558.
Paczynski, B. 1976, in "Structure and Evolution of Close Binary Systems", (Dordrecht-Holland: D. Reidel Publ. Co.), p. 75.
Paczynski, B., and Sienkiewicz, R. 1977, Acta Astr., 22, 73.
Reimers, D. 1977, Astr. Ap., 61, 217.
Renzini, A. 1978, invited paper at the 4th European Regional meeting in Astronomy: Stars and Star Systems, Uppsala.
Ritter, H. 1976, M.N.R.A.S., 175, 279.
Robinson, E.L. 1976, Ann. Revs. Astr. Ap., 14, 119.
Schönberner, D. 1979, Astr. Ap., in press.
Starrfield, S., Sparks, W.M., and Truran, J.W. 1978, Ap.J., 226, 186.
Vauclair, G., and Fontaine, G. 1979, Ap.J., 230, 563.
Webbink, R.F. 1977, Ap.J., 211, 486.
Webbink, R.F. 1978, paper presented at the IAU Colloquium No. 46 "Changing Trends in Variable Star Research", Hamilton, New Zealand.