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Research Note

Evolution of the surface abundance of carbon in mass-exchanging binaries

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Summary. The evolution of the carbon abundance at the surface of both components of a mass-transferring (Algol-type) binary is examined. Distinction is made between case A and case B of mass transfer, in view of the different timescales involved. In the mass accreting component thermohaline mixing is adopted when matter with decreasing hydrogen abundance is deposited on the surface.

It is shown that at the surface of the loser a very low C-abundance is present, while at the surface of the gainer different regimes occur. On the average the expected C-abundance of the gainer is clearly lower than the solar value, but far above the value at the surface of the loser. The variation in time during the mass-transfer process is compared to the values, derived from observations of several Algol systems. Uncertainties from both the observations and from the limited number of available theoretical models, are discussed.

Key words: stars: binaries – evolution – structure of stars – mass loss

1. Introduction

Since the early computations on mass transfer in close binaries it is known that the mass transfer between the components of a close binary affects their surface chemical composition (see Paczyński, 1971; Plavec, 1968). Indeed, the computations of close binary evolution predict that nuclear processed layers are exposed at the surface of the loser and transferred to the gainer. Perturbations of the CNO isotopes induced by the CNO tri-cycle are likely to be observed at the surface of the originally more massive component. Observational data, derived from detailed spectral analysis of mass losing components are rather scarce, but confirm the theory (cf. Lambert, 1982; Parthasarathy et al., 1983; Balachandran et al., 1986).

Within the framework of simple transfer of mass in a binary system, one may expect a similar chemical composition of the atmospheres of both components. However, Cugier and Hardorp (1987) found -0.4 ± 0.20 dex for the mass-gaining components of β Per and λ Tau, whereas theoretical models of mass gaining stars point to values of about -2.0 and < -1.1 dex. The difference between the observed and predicted abundances of carbon may be due to the mixing of the carbon depleted transferred material with the intrinsically normal material of the mass accreting star.

In previous studies of accretion of mass in close binary systems, only the changes of the hydrogen and helium abundances were investigated (Kippenhahn et al., 1980; Doom and De Greve, 1981; Hellings, 1983). In the present paper we therefore estimate the abundance of carbon in the photosphere of mass accreting stars using a few theoretical models of semidetached systems.

2. Models of semidetached systems

The models used in this paper, describing the evolution of four systems with an initial mass of the primary component (loser) equal to $M_{li} = 9.0\,M_{\odot}$, were calculated by Packet (1988). Different mass ratios and orbital periods were chosen to obtain both case AB and the early case B of mass transfer. An initial chemical composition X = 0.70 and Y = 0.27 was adopted. Furthermore, conservative exchange of mass was assumed. Two sequences in the case B of mass transfer (sequence 1: $P_i = 3.13$ d, $q_i = 0.9$ and sequence 2: $P_i = 2.98$ d, $q_i = 0.6$) have already been described by De Greve (1986). The evolution program was the same as the one used by De Greve et al. (1985, see also De Greve, 1986; Packet, 1988). Both components of the binary system are calculated simultaneously for each model in an evolution sequence. It is important to note that thermohaline mixing has been applied when helium-rich material is accreted by the gainer (Veronis, 1965; Ulrich, 1972; Kippenhahn et al., 1980). The program does not give any detailed information on the nucleosynthesis of the different elements, except the abundance by mass of H and He. We therefore recalculated the evolution of the mass-losing component with the program of Prantzos et al. (1986), giving information on all isotopes up to ^{22}Si, involved in hydrogen and helium burning.

The sequence 3 ($P_i = 2.38$ d, $q_i = 0.9$) follows a classical pattern in the case AB of evolution. Mass transfer starts at the moment $t = 2.357\ 10^7$ yr when the central hydrogen abundances (by mass) are $X_c = 0.14$ and $X_c = 0.27$, for resp. loser and gainer. Some $5.682\ 10^5$ yr after the onset of mass transfer the loser attains

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Table 1. Important mass values for the four sequences described in Sect. 2: M_i = initial value, M_7 = mass at the moment when the hydrogen surface abundance is lower than the original value; M_f = remnant mass at the end of the mass transfer. For the definition of the sequences see text, l and g denote loser and gainer, respectively. All values are expressed in solar masses

	Sequence 1		Sequence 2		Sequence 3		Sequence 4	
	M_l	M_g	M_l	M_g	M_l	M_g	M_l	M_g
M_i	9.0	8.1	9.0	5.4	9.0	8.1	9.0	5.4
M_7	3.7	13.4	3.1	11.3	3.3	13.8	3.1	11.3
M_f	1.5	15.6	1.5	12.9	1.1	16.0	1.0	13.4

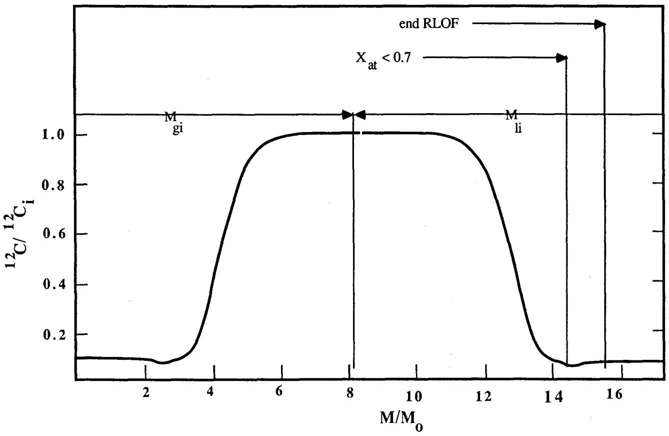

Fig. 1. Carbon abundance as a function of mass for both components of the close binary system 9.0 $M_\odot$ + 8.1 $M_\odot$, $P_i = 3.13$ d, at the onset of mass transfer. The region from $M_r = 0$ to $M_r = M_{gi} = 8.1\,M_\odot$ corresponds to the originally less massive component (gainer), whereas the carbon distribution of the loser is plotted from 8.1 $M_\odot$ (surface) to 17.1 $M_\odot$ (center). The first occurrence of hydrogen depleted layers ($X_{at} < 0.7$) and the end of the Roche Lobe Overflow are indicated

a mass $M_l = 3.46\,M_\odot$, with $X_c = 0.11$, whereas the central hydrogen content in the gainer increases from $X_c = 0.27$ to 0.54 with an increase of the convective core from 1.27 to 4.02 $M_\odot$. The surface abundance of hydrogen of the loser, X_{at}, begins to decrease at $t = 2.6174\ 10^7$ yr when $M_l = 3.25\,M_\odot$ and $X_c = 0.07$. At the end of phase A ($t = 2.962\ 10^7$ yr) $M_l = 3.13\,M_\odot$ and $X_c = 0.01$. The phase B of mass transfer begins at $t = 2.967\ 10^7$ yr and lasts up to $t = 3.115\ 10^7$ yr. At the end of the phase B the surface hydrogen abundance of the loser ($M_l = 1.10\,M_\odot$) is equal to $X_{at} = 0.16$.

The system with initial mass ratio $q_i = 0.6$ and $P_i = 2.27$ d (sequence 4) shows a similar behaviour. Mass transfer (phase A) starts at $t = 2.351\ 10^7$ yr when $X_{cl} = 0.14$ and $X_{cg} = 0.55$. The surface hydrogen abundance of the loser begins to decrease near the end of the fast mass transfer episode when $M_l = 3.06\,M_\odot$, $X_c = 0.12$. The phase A lasts up to $t = 3.023\ 10^7$ yr. The remnant mass M_l after this phase is equal to 2.76 $M_\odot$. The phase B begins at $t = 3.082\ 10^7$ yr and ends at $t = 3.261\ 10^7$ yr with $M_l = 1.05\,M_\odot$ and $X_{at} = 0.16$. For the four sequences, a summary of some important mass values is given in Table 1.

3. Depletion of carbon

During the main sequence phase of evolution of massive stars ^{12}C is transformed to ^{14}N in the CN part of the CNO tri-cycle, above the convective core. The region within which ^{12}C is being reduced to an equilibrium value with respect to ^{14}N expands outward with time to greater mass fraction, but becomes essentially fixed at the moment when the central hydrogen content has dropped by about 15%. This is caused by envelope expansion and temperature decrease in the CN burning region. Quantitatively the same behaviour was found for all models with masses from 2.25 to 15 $M_\odot$ (cf. Iben, 1967 and references given therein). We verified this result using the program for stellar evolution with more up-to-date physics, used by Prantzos et al. (1986). The detailed nuclear network of the program allows the determination of the ^{12}C-profile during the evolution, as a function of the mass fraction. Models of single stars and of mass-losing primaries in a close binary system were calculated. The results not only confirm the rapid fixation of the ^{12}C-profile at almost constant mass fraction within the star, as found by Iben, but also allowed us to derive the ^{12}C-profiles for the models described in Sect. 2. Figure 1 shows the carbon abundance as a function of mass for both components in sequence 1 (cf. Sect. 2) at the moment of the onset of mass transfer. The region from $M_r = 0$ (core) to $M_r = M_{gi} = 8.1\,M_\odot$ (surface) corresponds to the originally less massive component (gainer), whereas the carbon distribution of the loser is plotted from $M_r = 8.1\,M_\odot$ (surface) to $M_r = 17.1\,M_\odot$ (core). If no mixing takes place, the last distribution determines the surface abundance of carbon of the two components during slow mass transfer. In particular, this refers to the layers of the loser with carbon depleted material, which are transferred to the gainer after exchange of about 2 $M_\odot$. This occurs roughly at the time that the loser attains its minimum luminosity (cf. De Greve, 1986, Fig. 6.7). Near the end of the fast mass transfer phase the surface carbon underabundance will be about −1.5 dex. At this time the surface hydrogen abundance begins to decrease and an inversion of the mean molecular weight μ develops in the gainer. Because a layer with a positive gradient $d\mu/dr$ is secularly unstable, mixing sets in (Kippenhahn et al., 1980). This instability is sometimes referred to as the Rayleigh-Taylor instability (cf. Chandrasekhar, 1961, Chap. X) and was referred to as "quasi-convection" in Cox and Guili (1968, Sect. 18.2 a). When the inversion of the μ gradient develops, the convective core of the gainer extends up to 3.94 $M_\odot$, and a much steeper gradient of carbon abundance is present near $M_r = 3.94\,M_\odot$, than in the original distribution shown in Fig. 1. Using the evolution of the X-profile in the gainer of sequence 1, the value of the carbon surface abundance of that star can easily be calculated, starting from the C-profile in Fig. 1. The estimated carbon surface abundance (^{12}C/^{12}C$_i$) is shown in Fig. 2. A quite similar behaviour was found for sequence 2 (see Fig. 3 for the carbon profiles at the onset of mass transfer, and Fig. 4 for the surface abundance of carbon for the gainer as a function of time). In both cases mixing of matter is absent only during the first 20% of the total time of the mass transfer phase, and, as one can see from Figs. 2 and 4, a large depletion of carbon is present at the surface only during a few percent of the total time. At the onset of mixing the carbon abundance increases from 3% to 80% of the original value and the rest of the mass transfer is characterized by a slow decrease of carbon abundance down to a factor 0.6 to 0.7.

Sequences 3 and 4 (cases AB of mass transfer) reveal a different behaviour. The evolution of the carbon surface abundance for the respective gainers of these systems is shown in Figs. 5 ($q_i = 0.9$) and 6 ($q_i = 0.6$). For the sequence 3 a fairly long timescale occurs, during which carbon is markedly depleted (2.16 10^6 yr). For

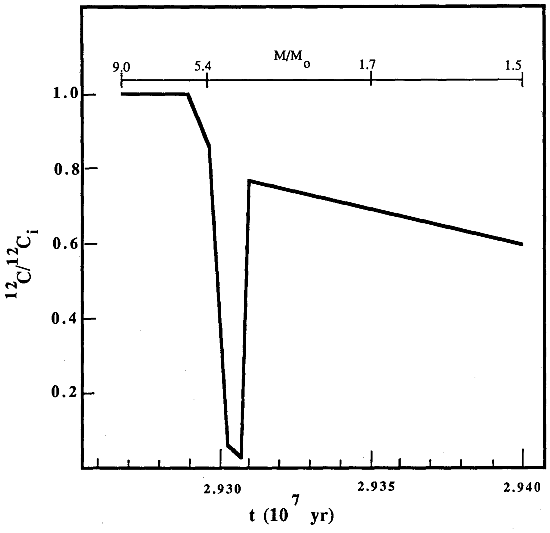

Fig. 2. Carbon surface abundance of the gainer of the system $9.0\,M_\odot + 8.1\,M_\odot$, $P_i = 3.13$ d, as a function of time, during a case B of mass transfer (in fraction of the initial value). The mass of the loser is indicated to show the amount of mass transferred

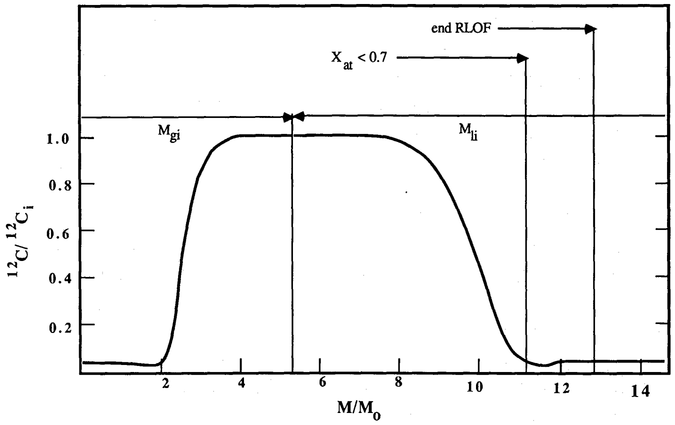

Fig. 3. The same as Fig. 1, but for the system $9.0\,M_\odot + 5.4\,M_\odot$, $P_i = 2.98$ d

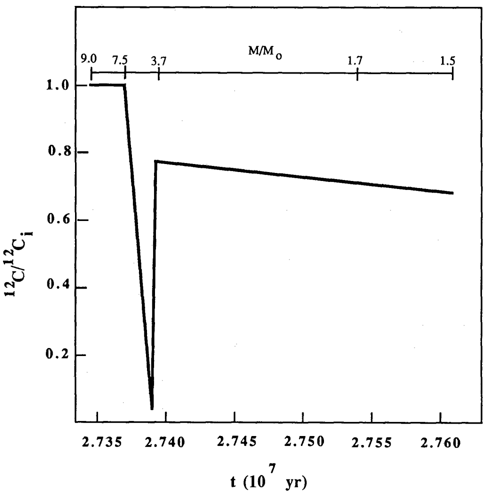

Fig. 4. The same as Fig. 2, for the system $9.0\,M_\odot + 5.4\,M_\odot$, $P_i = 2.98$ d

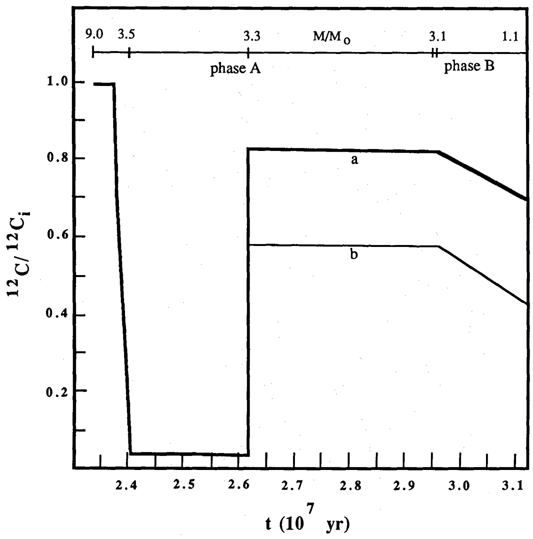

Fig. 5. Carbon surface abundance of the gainer of the system $9.0\,M_\odot + 8.1\,M_\odot$, $P_i = 2.38$ d, as a function of time, during a case AB of mass transfer. The line marked "a" was obtained under the assumption that no significant conversion of C to N takes place above the convective core, during the mass transfer, "b" shows the abundance in the opposite case

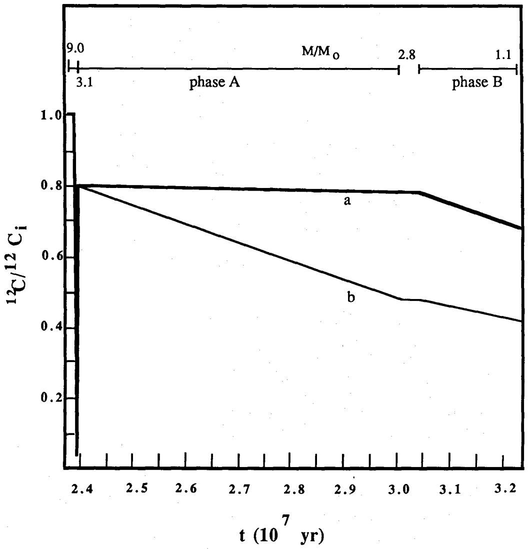

Fig. 6. The same as Fig. 5, for the system $9.0\,M_\odot + 5.4\,M_\odot$, $P_i = 2.27$ d

sequence 4 this phase lasts only about $4.3\;10^4$ yr. The lines marked by "a" in Figs. 5 and 6 were obtained under the assumption that no significant conversion of ^{12}C to ^{14}N takes place above the convective core, during mass transfer. However, the timescale of slow mass transfer (of the order of a few million years) is sufficiently long to allow this conversion to be effective. It affects carbon depletion in a way shown by means of the line "b" on the figures. As a result, carbon depletion reaches a factor of 0.4 at the end of the mass transfer.

4. Comparison with observations

Up to now, only a few carbon abundance determinations of Algol-type stars are available. From a comparison of the observed ^{1}H, ^{4}He, ^{12}C, ^{14}N, and ^{16}O abundances with the calculated interior

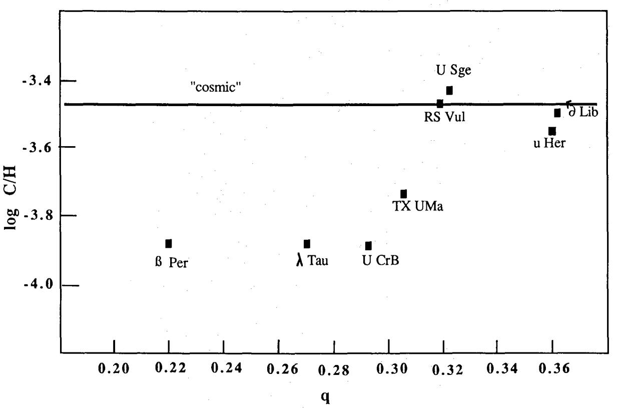

Fig. 7. Measured carbon abundance in Algol-type systems, as a function of the mass ratio (here defined as $q = M_l/M_g$). Data are taken from Cugier and Hardorp (1988) and Cugier (1988, preprint)

abundances of evolved stellar models. Balachandran et al. (1986) conclude that the 2 $M_\odot$ primary (loser) component (B8 II) of β Lyr is the exposed core of an originally much more massive star. The mass accreting component is a disk-shaped object displaying a continuum, but its spectrum has not been detected. Carbon deficiency and nitrogen enrichment was also found for the mass losing stars of U Cep and U Sge (cf. Parthasarathy et al., 1983), indicating that these evolved components have lost mass down to layers previously processed by CN.

A carbon abundance analysis for mass-gaining components of Algol-type binaries was initiated by Plavec (1983, cf. also Dobias, 1985, and Cugier and Molaro, 1984). A comparative study of β Per and λ Tau with single B-type stars, performed by Cugier and Hardorp (1988), indicates a carbon deficiency of -0.40 ± 0.20 dex in both Algols. Furthermore, Cugier (1988, preprint) found that U CrB shows the same carbon abundance as β Per and λ Tau. TX UMa shows a carbon depletion of about 0.3 dex, whereas δ Lib, U Sge, RS Vul and u Her have essentially a cosmic abundance of carbon. Figure 7 shows log ^{12}C/H as a function of the observed mass ratio, $q = M_l/M_g$. The data are taken from Cugier and Hardorp (1988) and Cugier (1988, preprint). As one can see from this figure all systems with $0.22 < q < 0.31$ have ^{12}C abundances in the gainers clearly lower than the cosmic value, but far above the expected ones if no mixing is assumed (cf. Cugier and Hardorp, 1988). In the case of thermohaline mixing the carbon abundance in the mass-gaining stars can be estimated from Figs. 2 and 4–6. On the average, if mass fractions $M_r > 0.7$ are exposed by the losers, the surface carbon abundance of the gainers is approximately equal to its initial value (i.e. no significant depletion of carbon is expected, $^{12}\mathrm{C}/^{12}\mathrm{C}_i \sim 1.0$). The mass fraction $M_r \sim 0.5$ corresponds to a low carbon abundance at the surface of gainer ($^{12}\mathrm{C}/^{12}\mathrm{C}_i \leqq 0.05$), whereas $M_r \sim 0.4$ corresponds to the beginning of the mixed phase ($^{12}\mathrm{C}/^{12}\mathrm{C}_i \sim 0.8$). The fraction $M_r \sim 0.3$ corresponds to an abundance fraction of carbon of 0.7 (case B) to less than 0.5 (case AB). A large carbon depletion ($^{12}\mathrm{C}/^{12}\mathrm{C}_i \leqq 0.05$) in the gainer is present only during a few percent of the total time of the mass transfer phase, so that the chance of observing a system at this episode is small. However, it should be noted that the sequence 3 shows a different behaviour as explained in Sect. 3. After mixing the rest of the mass transfer produces only a small decrease of carbon abundance. This means that the surface chemical composition of the gainer is not markedly dependent on the further actual mass ratio of the system. For instance, for sequence 1 we have $^{12}\mathrm{C}/^{12}\mathrm{C}_i = 0.77$ when the mass ratio equals 0.28, and $^{12}\mathrm{C}/^{12}\mathrm{C}_i = 0.68$ at the end of the mass transfer when $q = 0.10$. The observed carbon abundances shown in Fig. 7 can therefore be explained qualitatively in terms of thermohaline mixing. A more detailed comparison requires a detailed evolutionary model with appropriate mass, mass ratio and period. Indeed, the examples described in Sects. 2 and 3 show that both the initial period and the mass ratio influence the time evolution of the carbon surface abundance of the gainer.

5. Conclusion

The observed carbon depletion of mass-losing components in Algol-type stars may be explained as a result of conversion of ^{12}C to ^{14}N while these stars were on the main sequence. Furthermore, a large scale mixing of matter in mass accreting components is suggested. As a result of mixing of the CNO processed material with the intrinsically normal material of a mass accreting star, dilution of CNO anomalies are expected in gainers.

The present computations show that in Algol-type systems large, but also small underabundances of carbon may be observed at the surface of the gainer, depending on the initial parameters of the system and on the mass fraction removed from the mass losing star. We emphasize that the thermohaline mixing, applied in the envelope of the gainer, only gives a first order approximation. Indeed, other mixing mechanisms may be active such as ordinary diffusion, mixing due to differential rotation (Packet, 1981), mixing as a result of turbulence during the accretion process, etc.

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