THE $^{12}C/^{13}C$ RATIO IN BARIUM STARS

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ABSTRACT. It is suggested that the position of BaII stars with respect to normal red giants in the (log L, $^{12}C/^{13}C$) and ([C/Fe],$^{12}C/^{13}C$) diagrams supports the hypothesis that $^{13}C(\alpha,n)^{16}O$ was the neutron source responsible for the synthesis of the heavy elements now present in the BaII star envelopes.

It is well known that $^{12}C/^{13}C$ is a function of luminosity in first ascent giants, as a result of the first dredge-up (e.g. Lambert, 1976). The comparison between $^{12}C/^{13}C$ in BaII stars and in normal giants should thus take this luminosity effect into account. Fig.1 sums up all the data available for normal G-K giants and subgiants, extracted from Lambert (1976), Tomkin et al. (1976) and Lambert and Ries (1981). For the stars of these samples, the luminosity is derived mainly from the CaII K-line emission width (Wilson, 1976), although some other methods are also used. Concerning BaII stars, $^{12}C/^{13}C$ and luminosity are simultaneously available for only 6 *classical* BaII stars. As those data are scattered in the literature, they are summarized in Table I. Luminosities of BaII stars are derived from Eggen's (1972) (R-I, M_{bol}) relation. When available, the uncertainty on the $^{12}C/^{13}C$ ratio has been drawn in Fig.1, whereas the uncertainty on log $L/L_{\odot}$ is difficult to evaluate.

Let us consider the BaII star HD16458 (=HR774), the $^{12}C/^{13}C$ ratio of which appears to fall quite inside the range of $^{12}C/^{13}C$ ratios displayed by normal giants of the *same luminosity*[1]. In the ($^{12}C/^{13}C$, [C/Fe]) diagram (Fig. 2), this same star is found to have a strong C-overabundance (by a factor 2 to 5) with respect to normal red giants, although $^{12}C/^{13}C$ is normal!

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[1] It should be mentioned, however, that values of the order of log $L/L_{\odot}$=2.25 to 2.65 have been proposed for that star by Böhm-Vitense et al. (1984) using spectroscopically derived gravities and effective temperatures, *assuming* a mass of 2.5 $M_{\odot}$.

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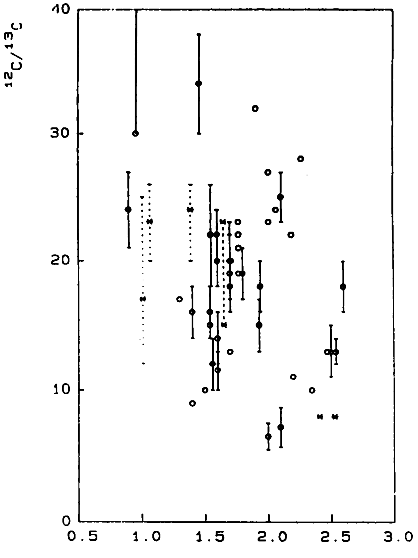

Fig.1: $^{12}C/^{13}C$ vs. luminosity

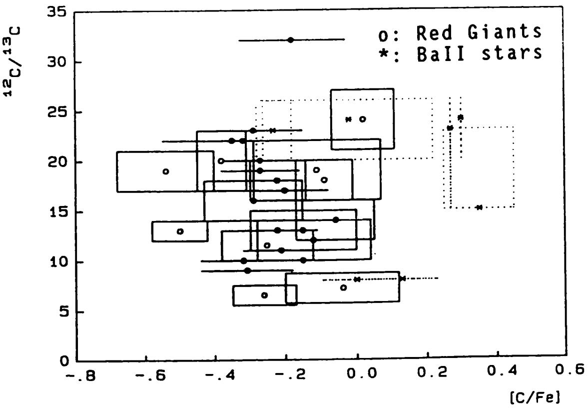

Fig.2: $^{12}C/^{13}C$ vs. $[C/Fe]_\odot$

TABLE I

Name	Sp.	M_{bol}	$\log L/L_\odot$	$^{12}C/^{13}C$	$[C/Fe]_\odot$	$[Fe/H]_\odot$
HD 16458	$K1IIIBa5_k$	0.5_c	1.65_c	23_{ab}	$.27_a$	$-.32_a$
				15_g	$.35\pm.10_g$	$-.30_g$
HD 46407	$K0IIIBa2_k$	1.9_c	1.07_c	21_a	$-.02\pm.04_a$	$.02_a$
				$23\pm3_b$	$+.27_l$	$-.42_l$
HD 101013	$K0IIIBa5_k$	2.1_c	1.01_c	$17\pm^{8}_{5}{}_h$	$-.50\pm.10_{hi}$	$.25_i$
				$13\pm1_b$		
HD 116713	$K1IIIBa3_k$	1.1_{cn}	1.39_c	20_a	$-.02\pm.24_a$	$+.15_a$
			1.43_n	$24\pm2_b$	$+.30_l$	$-.29_l$
HD 121447	$K7IIIBa5_k$	-1.7_c	2.53_c	8_g	$.00\pm.10_g$	$.05_g$
HD 178717	$K4IIIBa5_k$	-1.4_c	2.41_c	8_g	$.13\pm.10_g$	$-.18_g$

References: a) Sneden et al., 1981; b) Tomkin and Lambert, 1979; c) Eggen, 1972; g) Smith, 1984; h) Harris et al., 1985; i) Williams, 1975; k) Lü et al., 1983; l) Kovacs, 1985; n) Dominy and Lambert, 1983.

In order to understand how this paradoxical situation can be accounted for, let us consider the contamination of a giant star convective envelope by material having undergone a s-type of processing by neutrons liberated by either $^{13}C(\alpha,n)^{16}O$ or $^{22}Ne(\alpha,n)^{25}Mg$. The value of $^{12}C/^{13}C$ after such a mixing, referred to as the final $(^{12}C/^{13}C)_F$ ratio, is given by

$$(^{12}C/^{13}C)_F = [(1-g)^{12}C_I + g^{12}C_P]/[(1-g)^{13}C_I + g^{13}C_P], \qquad (1)$$

where g denotes the dilution factor of the s-processed material (abundances by number with subscripts P) into the envelope (abundances by number before contamination with subscripts I). Two special cases are of interest :

(i) if $(^{12}C/^{13}C)_P = (^{12}C/^{13}C)_I$, then $(^{12}C/^{13}C)_F = (^{12}C/^{13}C)_I$, (2)

whatever the total C abundance could be.

(ii) if the contaminating material is essentially devoid of ^{13}C (i.e. $^{13}C_P \approx 0$), then, assuming $1\text{-}g \approx 1$,

$$(^{12}C/^{13}C)_F \approx (^{12}C/^{13}C)_I \times (^{12}C_F/^{12}C_I). \qquad (2')$$

Case (ii) is relevant if the contaminating material has been processed by $^{22}Ne(\alpha,n)^{25}Mg$, since the ^{13}C abundance is very low in typical He-burning environments and $^{12}C(n,\gamma)^{13}C(n,\gamma)^{14}C$ does not favor the production of ^{13}C. Assuming further that the envelope composition before contamination is representative of normal red giants, we conclude that the $^{12}C/^{13}C$ ratio now observed in BaII stars should be that of red giants scaled by the overabundance of carbon (^{12}C) if $^{22}Ne(\alpha,n)^{25}Mg$ is the active neutron source, as indicated by Eq.(2').

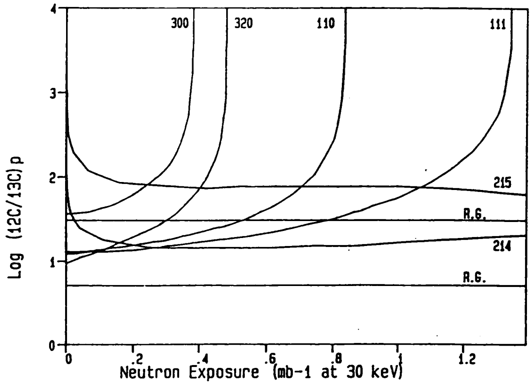

Fig.3: $(^{12}C/^{13}C)_P$ in the processed material as a function of the neutron exposure for the following sets of the parameters describing the operation of the $^{13}C(\alpha,n)^{16}O$ neutron source:
110: $T=1\times10^8$K, $^{12}C/p(0)=10.$, $\vartheta_{ing}=0$;
111: $T=1\times10^8$K, $^{12}C/p(0)=10.$, $\vartheta_{ing}=0$, $^{12}C/^4He(0)=1.$;
214: $T=2\times10^8$K, $^{12}C/p(0)=1.$, $\vartheta_{ing}=10$ $\vartheta_\alpha(^{13}C)$;
215: $T=2\times10^8$K, $^{12}C/p(0)=1.$, $\vartheta_{ing}=100$ $\vartheta_\alpha(^{13}C)$;
300: $T=3\times10^8$K, $^{12}C/p(0)=20.$, $\vartheta_{ing}=0$;
320: $T=3\times10^8$K, $^{12}C/p(0)=5.$, $\vartheta_{ing}=0.$,
with $\rho=500$ g/cm^3 and $^{12}C/^4He(0)=1/3$ (except for case 111). ϑ_{ing} is the proton ingestion timescale and $\vartheta_\alpha(^{13}C)$ is the ^{13}C lifetime for α-captures. The two horizontal lines labelled R.G. border the domain $5 \lesssim {}^{12}C/^{13}C \lesssim 30$ characterizing red giant values.

Notwithstanding their scarcity and uncertainties, the observational data appear to favor the situation described by Eq.(2) rather than that corresponding to Eq.(2′). This speaks against the ^{22}Ne(α,n)^{25}Mg neutron source, which cannot account for the mixing case with $(^{12}C/^{13}C)_F = (^{12}C/^{13}C)_I$, and thus for Eq.(2). It now remains to evaluate the virtues of ^{13}C(α,n)^{16}O in that respect. Fig.3 displays the $(^{12}C/^{13}C)_P$ ratio in the processed material during the nucleosynthesis event as a function of the neutron exposure φ at 30 keV, for various sets of the parameters describing the operation of the ^{13}C(α,n)^{16}O neutron source. That neutron source operates when protons are ingested (with a timescale ϑ_{ing}) into a ^{4}He- and ^{12}C-rich layer [characterized by the initial $^{12}C/^{4}He(0)$ and $^{12}C/p(0)$ ratios; see Jorissen and Arnould, 1986, for more details about the parametrization], as a result of the chain $^{12}C(p,\gamma)^{13}N(\beta^+)^{13}C(\alpha,n)^{16}O$. It can be seen that many $(^{12}C/^{13}C)_P$ curves cross the $5 \lesssim (^{12}C/^{13}C)_I \lesssim 30$ domain, characterizing normal red giant envelopes. Thus, a freeze out of the matter processed at $\varphi < \varphi_{max}$ before complete ^{13}C burning is just what is needed in order to keep $(^{12}C/^{13}C)_P$ in a range typical for normal red giants. The curve corresponding to case 211 does not even require such a freeze out. Mixing of such a processed material in a giant envelope then keeps the $^{12}C/^{13}C$ ratio close to its initial value.

In conclusion, the method presented here could be useful for identifying the operation of the ^{13}C(α,n)^{16}O neutron source in BaII stars, but the scatter in $^{12}C/^{13}C$, the uncertainties affecting the luminosity as well as the difficulty of distinguishing first ascent giants from core-He burning giants make it difficult to draw a definite conclusion.

REFERENCES:

Böhm-Vitense, E., Nemec, J., Proffitt, Ch.: 1984, *Astrophys.J.* 278, 726.
Dominy, J.F., Lambert, D.L.: 1983, *Astrophys.J.* 270, 180.
Eggen, O.J.: 1972, *Mon. Notices Roy. Astron. Soc.* 159, 403.
Harris, M.J., Lambert D.L., Smith, V.V.: 1985, *Astrophys.J.* 292, 620.
Jorissen, A., Arnould, M.: 1987, in *Advances in Nuclear Astrophysics*, eds. E. Vangioni-Flam, J. Audouze, M. Cassé, J.P. Chièze and J. Tran Thanh Van (Gif sur Yvette: Frontières), p. 419.
Kovacs, N.: 1985, *Astron.Astrophys.* 150, 232.
Lambert, D.L.: 1976, *Mém. Soc. Roy. Sc. Liège* IX, 6e Série, p.405.
Lambert, D.L., Ries, L.M.: 1981, *Astrophys.J.* 248, 228.
Lü, P.K., Dawson, D.W., Upgren, A.R., Weis, E.W.: 1983, *Astrophys.J.* 52, 169.
Smith, V.V.: 1984, *Astron.Astrophys.* 132, 326.
Sneden, C., Lambert, D.L., Pilachowski, C.A.: 1981, *Astrophys.J.* 247, 1052.
Tomkin, J., Luck, R.E., Lambert, D.L.: 1976, *Astrophys.J.* 210, 694.
Tomkin, J., Lambert D.L.: 1979, *Astrophys.J.* 227, 209.
Williams, P.M.: 1975, *Monthly Notices Roy. Astron. Soc.* 170, 343.
Wilson, O.C.: 1976, *Astrophys.J.* 205, 823.