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Carbon-to-iron Ratio in Extreme Population II Stars*

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Summary. The synthetic spectrum technique applied to the molecular feature of the CH$(A^2\Delta - X^2\pi)$ band near λ4300 Å was employed to obtain carbon abundances in some very old, extremely metal deficient halo stars.

The unevolved stars in the current sample show the null-hypothesis result $[C/M] \simeq 0.0$, whereas for the evolved ones carbon depletions appear as a signature of mixing effects.

Key words: population II stars – synthetic spectra

I. Introduction

Carbon and nitrogen anomalies detected in evolved population I (e.g., Lambert and Ries, 1980) and population II stars (e.g., Carbon et al., 1980) seem to indicate that the material processed in the CNO tri-cycle is brought from deep layers to the surface through a mixing process. The mechanism responsible for this mixing at the red giant stage is however not perfectly identified. Observational determinations of the stage of stellar evolution at which it starts to operate and comparison between results for halo stars and globular cluster stars may shed some light on the question.

If mixing does not occur, observational tests on CNO abundances in population II stars may provide information on the kind of object through which the primordial matter was astrated, before the formation of the oldest extant stars, which show a non-zero metallicity. Some accurate networks of nucleosynthesis products were constructed for the physical conditions of stars of different masses, and the yields can be tested by confrontation with observations. As regards the carbon abundance, solar carbon-to-iron ratios are predicted by some currently existing models, such as those of Wagoner (1968), Talbot and Arnett (1974), and Arnett (1978, hereafter A 78). Determinations of C abundances in unevolved halo stars seem, in fact, to converge to this value (Sneden, 1974; Hearnshaw, 1975; Peterson and Sneden, 1978). On the other hand, as stressed by Tinsley (1979, hereafter T 79), by taking into account the fact that the different primary elements are produced by stars of different lifetimes, a slight overabundance of carbon relative to iron should be expected for the oldest stars.

It must be mentioned that abundances derived for globular cluster stars show intracluster inhomogeneities (e.g., Peterson, 1980), as well as inhomogeneities of the protoglobular gas as is the case, for example, of 47 Tuc, probably CNO-rich (Pilachowski et al., 1980). Thus, an additional difficulty in interpreting CNO data stems from possible inhomogeneities of the gas, which would be hard to detect in halo stars, as their birthplaces are not well defined. Any inferences concerning primordial matter in the Galaxy, from CNO abundances in halo stars, cannot be considered definitive until a statistically meaningful sample is available.

A small number of metal-deficient halo stars are known and only a dozen are more deficient than $[M/H] = -2.3$ dex (Cayrel de Strobel et al., 1980), where $[X] = \log(X_{\mathrm{star}}/X_0)$, X being any quantity.

In this work C abundances are obtained for one moderately deficient halo star HD 76932 and four extremely metal-deficient stars HD 84903, HD 128279, HD 184711 and the well-known giant HD 122563, included in the sample in order to have a basis of comparison with other work.

II. Observations and Stellar Models

All plates are baked IIaO-Kodak, obtained with the coudé spectrograph at the 1.50 m telescope of ESO (La Silla), with a reciprocal dispersion of 12 Å/mm.

The plates were read in the region $\lambda\lambda$4000–4400 Å with the ESO's microdensitometer GRANT (Genève), and the reductions were made according to the procedures described by Spite and Spite (1977).

Model stellar parameters were obtained by interpolation in the grid of line-blanketed model atmospheres computed by Peytremann (1974) and Bell et al. (1976), whereas the stellar parameters reported in Table 1 are taken from Barbuy (1978), Spite and Spite (1978) and Wolffram (1972).

III. The Spectrum Synthesis Programme and Input Line Data

The programme for spectral synthesis of the molecular features of interest was built up from that for atomic lines of Spite (1967). LTE, formation of lines by pure absorption and H/He = 10 (by number) are assumed.

Molecular and atomic data, abundances of each element, the model stellar atmosphere and Doppler broadening velocity are required as input data. The molecular dissociation equilibrium

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* Based on observations obtained at the European Southern Observatory, La Silla, Chile

Table 1. Atmosphere parameters for the program stars and carbon abundances obtained in this work

HD	θ_{eff}	$\log g$	ξ_{mic} (km s^{-1})	[Fe/H]	[C/H]	[C/Fe]	Δ [C/Fe]
76932	0.86	3.5	1.0	−1.1	−0.8	+0.3	0.0
84903	1.12	0.8	3.0	−2.6	−3.2	−0.6	−0.08
122563	1.10	1.2	1.8	−2.75	−2.95	−0.2	−0.06
128279	1.00	2.5	1.0	−2.5	−2.35	+0.15	0.0
184711	1.15	0.6	3.0	−2.3	−2.8	−0.5	−0.16

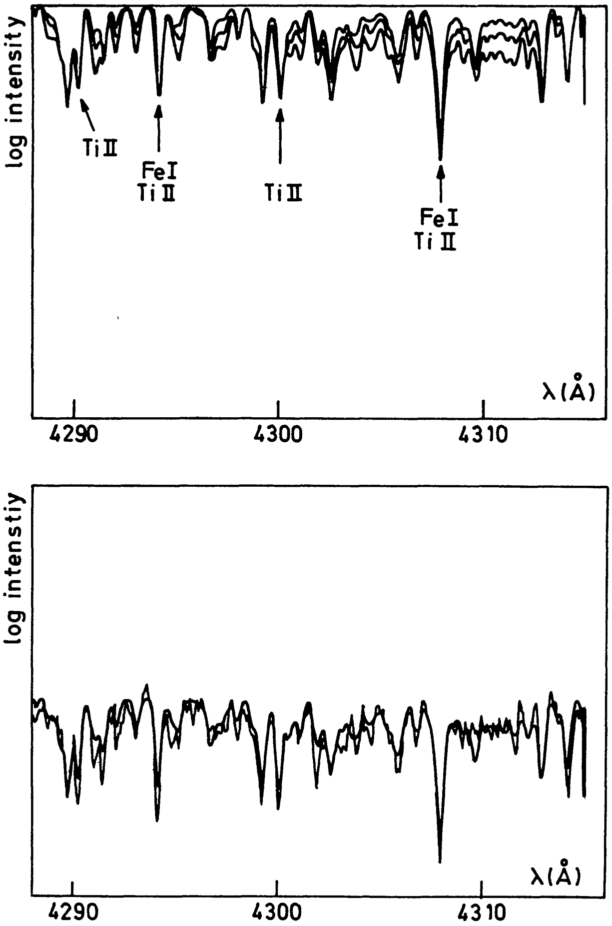

Fig. 1a and b. CH spectrum of HD 84903 in the region λλ4288–4315 Å: **a** synthetic spectra calculated using [C/Fe] = −0.9, −0.6, and −0.3 dex (some of the strongest atomic lines are indicated). **b** The solid line is the observed spectrum and the heavy line corresponds to the synthetic spectrum where [C/Fe] = −0.6 dex

calculations are performed following Tsuji (1973), where thirty one molecules are considered. The final output are the fluxes at each wavelength λ, computed in steps of 0.02 Å and integrated over all optical depths.

The continuous opacity sources include absorption by H, H$^-$, H$_2^-$, He$^-$, electron scattering and Rayleigh scattering by H and H$_2^-$.

The molecular contribution in the wavelength region λλ4288–4315 Å considered here consists of rotational line transitions of the (0, 0), (1, 1) and (2, 2) vibrational bands in the *A–X* electronic system of the molecule CH. This spectral region includes seven sets of CH unblended features, as indicated by Hearnshaw (1973).

Wavelengths were taken from the line identification tables of Moore and Broida (1959). The molecular dissociation energy and the Franck-Condon factors were taken from Huber and Herzberg (1979) and McCallum et al. (1970), respectively. The electronic oscillator strength was derived from the lifetime measurements by Brzozowski et al. (1976).

Hund's case (b) of angular momentum coupling for these transitions is assumed, and the Hönl-London factors were calculated from the formulae of Schadee (1964). The number density of CH molecules in a particular electronic, vibrational and rotational state is given by Tatum (1967).

For the atomic data, all lines given in Moore et al. (1966) atlas (MMH) were included, the unidentified lines being systematically attributed to Fe I, with excitation potential $\chi_{\mathrm{ex}} = 3.0$ eV, which seems a reasonable guess. As preliminary values for the atomic oscillator strengths *gf*, laboratory measurements and values from calculations of solar equivalent widths W_0 which matched the solar atlas (MMH) were taken. A subsequent adjustment to the solar spectrum (Delbouille et al., 1973) was carried out by changing iteratively the *gfs* and damping constants through a line by line comparison between calculated and observed spectra.

The final solar synthetic spectrum so obtained shows a good agreement with observations, using either the model by Holweger and Müller (1974) or the HSRA model (Gingerich et al., 1971) and the CNO abundances $\log\varepsilon(\mathrm{C}) = 8.67$, $\log\varepsilon(\mathrm{N}) = 7.99$, $\log\varepsilon(\mathrm{O}) = 8.92$ from Lambert (1978).

IV. Determination of Carbon Abundances

Once the line list of atomic and molecular data is established, the synthesized profiles for each star are obtained by introducing the stellar model atmosphere and elemental abundances into the spectrum synthesis programme; the profiles are then convolved with the spectrograph instrumental profile by a gaussian of half-width 0.2 Å at half-maximum. Initially all elements are set as deficient as the overall metal deficiency, i.e., [X/H] = [M/H] (X being any element). The carbon abundance is changed until a good fit between observed and generated synthetic spectra is obtained. The synthesized *G*-band for HD 84903 is shown in Fig. 1 for different values of the carbon abundance (where [O/Fe] = 0.0), and the results are given in Table 1.

V. Error Analysis

The uncertainty in the values of [M/H] employed here, deduced from high resolution spectra, is of the order of ±0.2 dex (see references in Sect. II); the error in the fit of synthetic to observed spectra is estimated to be ±0.1 dex, whence an uncertainty of ±0.3 dex is assigned to the carbon abundances obtained here. The star HD 122563 results less deficient by +0.2 dex with respect to the value obtained by Sneden (1974) but the difference is within the error bars.

Other sources of error could be: (a) Uncertainty in the assumed ratio O/H: observational data on oxygen abundances in unevolved halo stars indicate [O/Fe] > 0 (Sneden et al., 1979). Wallerstein and Pilachowski (1978) obtained an oxygen-to-iron ratio of +0.8 dex for giants in M 5, although a scatter was found for other clusters. A value of +0.6 dex is deduced for stars in M 92 (Carbon et al., 1980) and of +0.8 dex for the planetary nebula in the old globular cluster M 15 (Hawley and Miller, 1978).

For HD 122563 the value [O/Fe] = +0.6 dex obtained by Lambert et al. (1974) is applied; calculations for [O/Fe] = +0.0 and +0.6 dex for the other stars studied here were carried out, since O abundances determinations are not available. The partial pressure of carbon for stars cooler than $T_{\mathrm{eff}} \simeq 4500$ K is sensitive to the O/H ratio assumed, due to association of CO molecules. The difference Δ[C/Fe] resulting in the carbon abundances obtained by assuming [O/Fe] = 0.6 are indicated in column eight of Table 1. It is seen from this table that this increases the carbon abundance by a factor Δ[C/Fe] $\lesssim 0.15$ dex.

(b) non-LTE effects: From observations of center-to-limb variations of solar lines, Withbroe (1967) concluded that departures from LTE affect only negligeably the CH lines. On the other hand, the computations by Bell et al. (1979) for cold, metal-deficient giant stars, in which molecular photodissociation and formation of lines by pure scattering are considered, show that the LTE assumption may lead to an underestimation of ~0.2 dex in the value of [C/Fe]. The results in Table 1 should thus be taken as a lower limit, but remembering that the non-LTE discrepancy will be partly cancelled by the fact that the calculations are done differentially with respect to the Sun.

VI. Discussion of Results

a) The Unevolved Stars

We are interested here in the primary elements ^{12}C, ^{16}O, and Fe: while a general agreement in the literature is found for the production of oxygen by massive stars (Dearborn et al., 1978; Iben and Truran, 1978; A 78; T 79), the different authors disagree in their assumptions concerning the ranges of stars' masses that contribute to C and Fe enrichment. Chevalier (1976) presents evidences for production of Fe by intermediate mass stars that end as type I supernovae and CNO by the more massive stars that end as type II supernovae. C, O, and Fe are all supposed to be produced by massive stars in the calculations by Talbot and Arnett (1974) and A 78. According to Iben and Truran (1978), thermally pulsing stars of intermediate mass eject about half ^{12}C, while more massive ones produce the other half. In the scenario proposed by T 79 all Fe would be built by intermediate mass stars, while carbon would be contributed by three classes of objects: high mass stars (the amount of ^{12}C being ejected is here smaller than that of ^{16}O), intermediate mass and low mass stars; in this latter model carbon is expected to be overabundant relative to iron in the oldest stars.

Available carbon-to-iron ratios in halo stars are plotted in Fig. 2, as a function of surface gravity log$g$. Data for stars of log$g \gtrsim 2.5$ in this figure as well as estimation of C abundances from C I lines by Sneden et al. (1979) show the [C/Fe] = 0.0 result. The unevolved stars HD 76932 and HD 128279 present a slight overabundance of carbon relative to iron, which is however less than the uncertainty of 0.3 dex, thus corroborating previous results. This would mean that most of C and Fe are enriched in the Galaxy by stars of similar lifetimes; given the evidences for production of most of iron by intermediate mass stars, this being confirmed by [O/Fe] > 0 determined in metal-poor stars, the suggestion of Iben and Truran of an important contribution of carbon from intermediate mass stars seems plausible. In other words, C would be a pseudo-secondary, i.e., a primary element ejected by stars of long time scales of evolution (Lequeux, 1980).

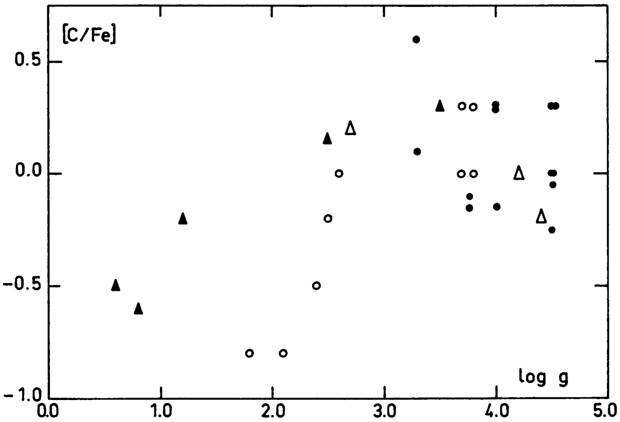

Fig. 2. [C/Fe] versus surface gravity for halo stars. References: *filled triangles*, this work; *open circles*, Sneden (1974); *filled circles*, Peterson and Sneden (1978); *open triangles*, others (Tomkin and Bell, 1973; Pagel and Powell, 1966; Harmer and Pagel, 1970)

At last, it must be pointed out that the early enrichment of the Galaxy might have been produced by a first generation of very massive stars. The predictions by Wagoner (1968) indicate a null carbon-to-iron ratio, although a very small quantity of CNO elements is produced in such objects in the calculations by Wallace and Woosley (1980).

b) The Evolved Stars and the Mixing

It can be seen in Fig. 2 that the very evolved giants HD 84903, HD 184711 and HD 122563 show less conspicuous deficiencies than the less evolved ones studied by Sneden (1974). From all the available data, it can be said that the carbon abundance in halo stars falls by a factor of about four at the red giant branch stage (RGB); within the uncertainties involved, it can be considered of the same order of carbon depletions of three to ten detected in the metal-poor globular clusters M 92 and NGC 6397 (Carbon et al., 1980; Bell et al., 1979).

Carbon depletions of this order as well as the value of ^{12}C/^{13}C = 5 found for HD 122563 by Lambert and Sneden (1977) cannot be explained by the standard convective mixing occurring on the first ascent of the RGB (Iben, 1964, 1967), which leads to a value of 30 for the isotopic ratio and to a decrease from 5 to 3.5 of the ^{12}C/^{14}N ratio for population II stars (e.g. Dearborn et al., 1975). Other mechanisms possibly operating along the RGB could be the meridional mixing (Sweigart and Mengel, 1979), turbulent diffusion (Genova and Schatzman, 1979), mass loss or thermal instabilities of short time scales. The field halo giants for which

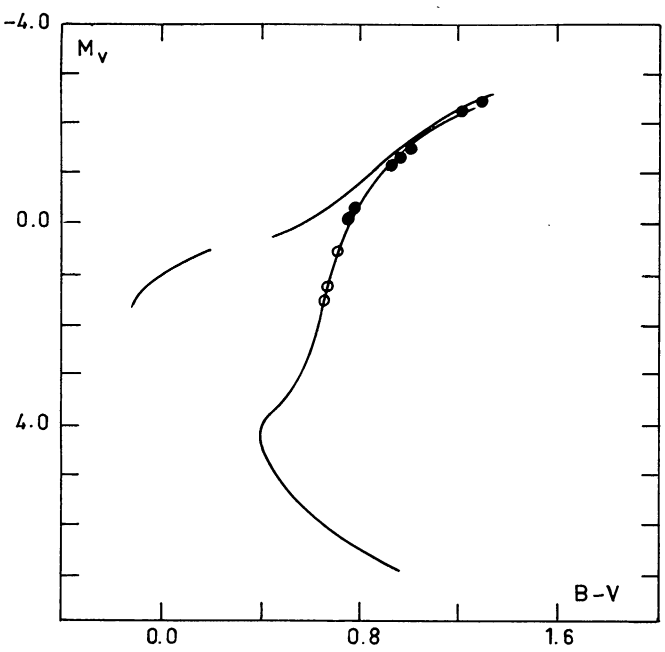

Fig. 3. Position of field halo stars in the HR diagram of M92. Filled circles represent the mixed stars and open circles the unmixed ones

carbon depletions are determined and some unmixed stars of surface gravity near $\log g = 2.5$ are plotted in the HR diagram of M92 as shown in Fig. 3. The absolute magnitudes are estimated by assuming that a halo star of a given $(B-V)$ is comparable to a star of the same colour index belonging to this similarly metal-poor cluster. It appears that the mixed stars lie above a limit placed between $0.0 < M_v < 0.5$ mag, which might be considered in agreement with the calculations by Sweigart and Mengel.

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