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LIMITS ON THE C^{12}/C^{13} RATIO IN METAL-DEFICIENT STARS

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ABSTRACT

Lower limits for the ratio C^{12}/C^{13} have been determined for eight metal-deficient stars. These limits are inconsistent with the predictions of nearly all of the universal models considered by Wagoner, Fowler, and Hoyle (1967) unless at least one generation of massive, rapidly evolving stars existed before the formation of any of the program stars.

Wagoner, Fowler, and Hoyle (1967) have completed an analysis of the synthesis of elements at high temperature in the initial universe and in certain types of supermassive stars. In both cases, for all values of the adjustable parameters, the isotopic ratio C^{12}/C^{13} is very close to unity, except the case of a supermassive star which initially consists entirely of He^4, where only C^{12} is produced. Furthermore in some cases the mass fraction C/H is comparable to that observed in the most metal-deficient stars.

We have attempted to obtain lower limits for the ratio C^{12}/C^{13} in subdwarfs, which are among the oldest objects in the Galaxy. It is possible that the gas from which these weak-line stars condensed had already been contaminated by material processed in an earlier generation of stars; we would then expect an isotopic ratio C^{12}/C^{13} greater than 4.3 as a result of stellar nucleosynthesis. If synthesis has proceeded as described by Wagoner *et al.* (excluding the one case noted above for which no C^{13} is produced) and if there was no previous generation of massive, rapidly evolving O stars, we should obtain an average isotopic ratio close to unity.

We have computed the isotopic shifts between the rotational lines $K = 10$ to $K = 30$ of each branch of the (0,0), (1,1), and (2,2) $A^2\Delta$–$X^2\Pi$ CH bands near 4200 Å, with the aid of formulae given by Herzberg (1950). We have included terms of up to order $(1 - \rho^4)$ where

$$\rho = \sqrt{\mu_{12}/\mu_{13}}$$

and μ_{12} and μ_{13} are the reduced masses for $C^{12}H$ and $C^{13}H$, respectively. These shifts range in absolute value from 0.2 to 1.0 Å. The shifts calculated for the R-branch of the (0,0) band differ by less than 0.1 Å from those measured by Richter and Tonner (1967).

Tracings were made of Palomar plates exposed by J. L. Greenstein from 4222 to 4300 Å for each of the program stars listed in Table 1. We used the David Mann microphotometer of the Harvard College Observatory, which has a device for the digital output of the density. The density readings were then plotted by a computer, together with the wavelength for each sample, and any entries on a line list close to the sample wavelength. The identification line list consisted of all lines from the *Revised Multiplet Table* (Moore 1959) in the wavelength region under consideration (excluding only those of very high excitation such as Cl II), the $C^{12}H$ rotational lines in this region, whose wavelengths were taken from the *Revised Rowland Table* (Moore, Minnaert, and Houtgast 1966), and the $C^{13}H$ lines, whose wavelengths we had predicted. In some cases we have

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also looked for features of the $C^{13}N^{14}$ band near 3874 Å (Ganiaris, Bashkin, and Waddell 1966). Although the CN band is very strong in spectra of late-type stars for solar metal content, it is reduced in strength in subdwarfs by a factor of approximately $(Z/Z_{sun})^2$, and hence its absence cannot significantly increase the lower limit for C^{12}/C^{13} obtained from examination of the CH band.

No definite indication of the presence of C^{13} was obtained for any of the program stars. We have assigned the lower limits for C^{12}/C^{13} given in the sixth column of Table 1 on the basis of the depression below the apparent continuum at the positions of several relatively unblended $C^{13}H$ features. Because of severe problems of overlapping lines, even in these metal-deficient cool objects, we cannot assign higher lower limits in spite of the high dispersion of the plate material. The limits to some extent reflect the strength

TABLE 1

LOWER LIMITS OF THE RATIO C^{12}/C^{13}

Star	Plate	Dispersion (Å/mm)	T_{eff}	$(Z\odot/Z)$	Lower Limit C^{12}/C^{13}	Ref.*
HD 2665	Pc 8253	9	4800	37	7	K
HD 5916	Pb 5329²	4.5	4400	10	8	R†
HD 6582 (μ Cas)	Pb 5323	4.5	5100	4	6	C
HD 6755	Pc 8253	9	5200	11	8	K
HD 19445	Pb 2345	4.5	5800	60	4	CS
HD 65583	Pb 4360²	4.5	5300	2	13	SS†
HD 122563	Pb 3230a	4.5	4200	200–600	5	P
HD 140283	Pb 4609 Pb 3176	4.5	5600	150	3	CS

* References for T_{eff} and $Z\odot/Z$:
C, J. G. Cohen (1967), unpublished.
CS, J. G. Cohen, and S. E. Strom, *Ap. J.*, in press.
K, D. Koelbloed (1967), *Ap. J.*, **149**, 299.
P, B. E. J. Pagel (1965), *R.O.B.*, No. 104.
R, N. Roman (1955), *Ap. J. Suppl.*, **2**, 195.
SS, S. E. Strom and K. M. Strom (1967), *Ap. J.*, **150**, 501.

† These are stars for which no detailed abundance analysis has been performed. The reference is for values of $U-B$ and $B-V$, which have been transformed into T_{eff} by a method described in SS, and into $Z/Z\odot$ with the aid of Wallerstein's (1961) correlation.

of the $C^{12}H$ band, which increases as the effective temperature decreases. It is unfortunate that two of the three most metal-deficient stars have T_{eff} greater than 5500° K, so that the $C^{12}H$ band is very weak.

We have obtained tracings of several Balmer lines for HD 140283 only. Since the hydrogen lines are quite narrow, we can deduce an upper limit for the deuterium abundance. No shift in the line-center wavelength was seen for Hγ, Hδ, or H_8. In addition, though any line over 15 mÅ would be clearly detectable, no lines were observed at the wavelengths of the corresponding deuterium lines. We therefore conclude that the ratio D/H is less than 1/150 for this very metal-poor star. This is not surprising, since any deuterium initially present in the atmosphere will be carried by convection to a depth where it is destroyed during the phase of contraction toward the main sequence (Bodenheimer 1965).

Our lower limits to C^{12}/C^{13}, together with the large metal deficiency of many of the program stars, are inconsistent with the predictions of the models considered by Wagoner *et al.* except for the case of a supermassive star composed of initially He^4, where only C^{12} is produced. Therefore if any of the other universal models described by Wagoner *et al.* are valid, a previous generation of rapidly evolving massive stars must have existed before the condensation of any of the program stars.

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