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THE $^{12}C/^{13}C$ RATIO IN STELLAR ATMOSPHERES. VIII. THE VERY METAL-DEFICIENT GIANT HD 122563

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ABSTRACT

High-resolution Digicon spectra of the CH 4300 Å band in the metal-deficient giant HD 122563 are analyzed for the atmospheric $^{12}C/^{13}C$ ratio. Nine ^{13}CH lines are identified. A ratio $^{12}C/^{13}C$ = 5 ± 2 is deduced. This low value shows that the present atmosphere has been seriously affected by internal mixing and processing. This extreme mixing is not predicted by stellar evolutionary calculations. It is suggested that the anomalous abundances of CNO may be explained on the assumption that modified products of He burning in the core or in a shell have been mixed to the surface.

Subject headings: stars: abundances — stars: individual — stars: late-type — stars: weak-line

I. INTRODUCTION

HD 122563, the brightest very metal-poor star, has been extensively studied (Wallerstein *et al.* 1963; Pagel 1965; Wolffram 1972). Aside from significant over-deficiencies of the *s*-process elements (Zr, Ba, and Ce, for instance), all metal abundances appear to have an underabundance[1] [M/H] ≈ −2.7. However, large variations have been reported among the abundances of the light elements carbon (Wolffram 1972; Sneden 1973), nitrogen (Sneden 1973), and oxygen (Lambert, Sneden, and Ries 1974). Basic data for HD 122563 are summarized in Table 1. The large overabundance (relative to the heavy metals) of nitrogen together with the moderate carbon underabundance suggest that the surface is contaminated with nuclear processed material. In order to investigate further the abundance peculiarities among the light elements, a determination of the $^{12}C/^{13}C$ ratio has been made.

The CH $A\,^2\Delta$–$X\,^2\Pi$ system near 4300 Å was used for this study because the CN violet and red systems are too weak in this star. The CH lines have been used in previous studies of Arcturus (Lambert and Dearborn 1972; Krupp 1973). Attempts (Richter and Tonner 1967; Lambert and Mallia 1968; Iverson 1976) have also been made to extract the solar $^{12}C/^{13}C$ ratio from these lines. New high-resolution observations (Tomkin and Lambert 1977) of CH in late-type giants, subgiants, and dwarfs show that semiquantitative estimates of the $^{12}C/^{13}C$ ratio can be obtained that are in agreement with the more precise estimates obtainable from the CN red system lines (cf. Tomkin, Luck, and Lambert 1976).

Cohen and Grasdalen (1968) attempted to derive $^{12}C/^{13}C$ ratios in several metal-poor stars including HD 122563. No ^{13}CH lines were positively identified. Their limit was $^{12}C/^{13}C > 5$ for HD 122563 based upon photographic spectra with a resolution of about 0.1 Å. Here we employ new spectra at a higher resolution and an improved signal-to-noise ratio to identify ^{13}CH and derive a high ^{13}C content ($^{12}C/^{13}C \approx 5$), which is consistent with the previously reported lower limit.

The isotope ratio is insensitive to atmospheric parameter uncertainties because comparison is made of the line intensities from lines originating in identical, or similar, rotational and vibrational levels in parent and isotopic molecules. Errors in stellar temperatures, pressures, line oscillator strengths, and molecular dissociation energies affect each molecule nearly identically. The $^{12}C/^{13}C$ ratio is therefore a solid indicator of the presence of CNO-cycle processed material at the surface of a star.

[1] Standard notation is adopted: $[X] = \log_{10} X(\text{star}) - \log_{10} X(\text{Sun})$.

TABLE 1
BASIC DATA FOR HD 122563

Quantity	Value	Source
T(K)	+4600 ± 150	Wolffram 1972
Log g	+1.2 ± 0.4	Wolffram 1972
[Fe/H]	−2.75 ± 0.3	Wolffram 1972
ξ (km s^{-1})	+2.6 ± 0.4	Wolffram 1972
Log ($L/L_\odot$)	+2.8:	Wolffram 1972
[C/Fe]	−0.4 ± 0.4	Sneden 1973
[N/Fe]	+1.2 ± 0.4	Sneden 1973
[O/Fe]	+0.6 ± 0.4	Lambert *et al.* 1974
$^{12}C/^{13}C$	+5 ± 2	This study

II. OBSERVATIONS

High-resolution spectra were obtained with the McDonald Observatory 2.7 m telescope and the Tull coudé spectrometer. The Digicon detector (Tull, Choisser, and Snow 1975) was used with an echelle grating which yielded a spectral resolution of 0.08 Å. The noise level of the coadded spectral scans was approximately 2% of continuum. Additional spectra, obtained with the Digicon and an ordinary coudé grating, were also inspected.

III. THE $^{12}C/^{13}C$ RATIO

The first task in the analysis was to identify with confidence the ^{13}CH features. The rotational and vibrational constants of Krupp (1974) were used to predict the rotational line positions of the 0–0, 1–1, and 2–2 vibrational bands of the $A\,^2\Delta - X\,^2\Pi$ system for both the ^{12}CH and ^{13}CH molecules. These constants reproduced very well the measured wavelengths of lines of each molecule (Gerö 1941; Richter and Tonner 1967; Iverson 1976). A comparison of the ^{13}CH line positions with the high-resolution stellar spectra yielded about 20 possible ^{13}CH features. The predicted 0–0 and 1–1 ^{13}CH lines always fell where an absorption feature occurred in the spectrum of HD 122563; no ^{13}CH prediction turned out to be in a region of actual continuum in the star. Next, all absorption features were eliminated that could plausibly be identified with atomic absorbers listed in the solar catalog (Moore, Minnaert, and Houtgast 1966) and the compendium of the atomic lines of Kurucz and Peytremann (1975). The remaining pure ^{13}CH features on the spectral scans are listed in Table 2.

The possibility of alternative identifications for the weak ^{13}CH lines was considered. For all atomic lines in the Kurucz and Peytremann (1975) compilation near the ^{13}CH wavelengths, an equivalent width, W_λ, was predicted using a model atmosphere (see below). Oscillator strengths were set by the requirement that each possible contaminant provide the complete solar feature (if no solar line appeared in Moore, Minnaert, and Houtgast [1966], $W_\lambda = 1$ mÅ was adopted). Abundances for HD 122563 were taken from Pagel (1965) and Wolffram (1972). The maximum predicted equivalent width was $W_\lambda = 1.4$ mÅ. A vast majority of the lines gave $W_\lambda \leq 0.4$ mÅ. Such predictions are upper limits because (1) the oscillator strengths are maximum values which exceed the Kurucz and Peytremann semiempirical values (some surely violate the f sum rule!); and (2) the ^{13}CH line provides a substantial or dominant contribution to several of the solar lines. The key to the identification question is that neutral lines are weakened severely in HD 122563; e.g., a low-excitation Fe I line providing $W_\lambda = 25$ mÅ in the Sun is reduced to $W_\lambda = 0.5$ mÅ in HD 122563. Although the few interfering ionized lines weaken by a smaller factor, none appears to be a serious contaminant. A majority of these lines come from rare earths that are markedly more deficient than iron (Pagel 1965).

The possibility can be discounted that the ^{13}CH lines are ^{12}CH lines from higher members of the $\Delta v = 0$ sequence. The strongest lines of the 3–3 band with $W_\lambda \approx 2$ mÅ and the other bands fall outside the spectral intervals of interest. In stars with strong CH lines, such higher bands could be a nuisance and, unfortunately, measured or reliable predicted wavelengths are unavailable in the literature.

Additional support for the ^{13}CH identifications comes from the Arcturus spectrum. Two independent studies (Lambert and Dearborn 1972; Krupp 1973) have shown that lines ascribed to ^{13}CH provide a $^{12}C/^{13}C$ ratio that is consistent with the ratio provided by the CN red system (Day, Lambert, and Sneden 1973; Griffin 1974) and the CO vibration-rotation lines (Hinkle, Lambert, and Snell 1976). Furthermore, one or two of the ^{13}CH lines appear to be excellent ^{13}C

TABLE 2

CH FEATURES USED IN CURVE-OF-GROWTH ANALYSIS

Identification	$\log [\sum gf\,10^{-\theta\chi}/a(\lambda)]$	$\lambda(^{12}CH)$	$\log W_\lambda/\lambda(^{12}CH)$	$\lambda(^{13}CH)$	$\log W_\lambda/\lambda(^{13}CH)$
$R_{dc}(16)$, 1–1	−2.11	4223.1	−5.65	...	...
$R_{cd}(16)$, 1–1	−2.11	...	...	4221.8	−6.03 ?
$R_{cd}(14)$, 0–0	−1.65	4223.5	−5.11	4224.0	−5.88
$R_{dc}(14)$, 0–0	−1.65	4224.9	−5.21	...	...
$R_{dc}(15)$, 1–1	−2.07	4227.9	−5.42	4228.3	−5.89 ?
$R_{cd}(13)$, 0–0	−1.61	...	...	4230.3	−5.71
$R_{dc}(13)$, 0–0	−1.61	...	...	4231.4	−5.58
$R_{cd}(14)$, 1–1	−2.04	4231.6	−5.34	...	...
$R_{dc}(14)$, 1–1	−2.04	4232.9	−5.33	...	...
$R_{dc}(12)$, 0–0	−1.58	...	...	4237.6	−5.93
$P_{dc}(13)$, 0–0	−1.84	...	...	4370.7	−6.07
$P_{cd}(13)$, 1–1	−2.23	4370.2	−5.56	...	...
$P_{1cd}(10)$, 2–2	−2.89	4371.8	−6.35 ?	...	...
$P_{cd}(14)$, 0–0	−1.85	4372.8	−5.23	...	...
$P_{dc}(14)$, 0–0	−1.84	4374.2	−5.23	...	...
$P_{cd}(15)$, 0–0	−1.87	4375.6	−5.24	...	...
$P_{1cd}(11)$, 2–2	−2.89	4376.4	−6.01 ?	...	...
$P_{dc}(15)$, 0–0; $P_{cd}(15)$, 1–1; $P_{dc}(11)$, 2–2	−1.67	4377.2	−5.16	...	...
$P_{cd}(16)$, 0–0	−1.90	4378.3	−5.43	4377.8	−6.07
$P_{dc}(15)$, 1–1	−2.26	4378.9	−5.71	...	...
$P_{dc}(16)$, 0–0	−1.90	4380.1	−5.33	4379.6	−5.93 ?
$P_{cd}(17)$, 0–0; $P_{cd}(16)$, 1–1	−1.78	4380.8	−5.18	...	...

indicators in stars with a much lower ^{13}C abundance (Tomkin and Lambert 1977). These tests and comparisons suggest that the identification of ^{13}CH in HD 122563 is correct.

Equivalent widths for the ^{12}CH and ^{13}CH features are given in Table 2. The continuum level is readily located in this weak line spectrum. A warning, however, must be given that the very small equivalent widths especially of the ^{13}CH lines make the derived $^{12}C/^{13}C$ ratio somewhat dependent on the continuum placement.

The initial analysis adopted a direct curve-of-growth technique, since the weak CH features employed fall on the linear portion of the curve of growth. A plot was constructed with $\log W/\lambda$ as ordinate and $\log (\sum gf 10^{-\chi\theta}) - \log a(\lambda)$ as abscissa. The first abscissa term is the familiar *gf*-value and the Boltzmann factor involving the excitation potential (χ) and the reciprocal temperature (θ). The summation is necessary to add the contributions from all lines of a blended feature. The term $\log a(\lambda)$ is a small correction factor that allows for the wavelength dependence in the equivalent width of a line as the wavelength varies across the interval 4220 to 4380 Å. This factor was evaluated using the model atmosphere of Wolffram (1972). An excitation temperature $\theta = 1.20$, also predicted by the model computations, was adopted. The $^{12}C/^{13}C$ ratio is insensitive to errors in θ. The CH *gf*-values are products of the band oscillator strengths $f(v', v'')$ and Hönl-London rotational line strength factors. Band oscillator strengths were calculated from accurate radiative lifetime measurements of Brzozowski *et al.* (1976); Hönl-London factors were computed using the code written by Whiting (1973). Finally, the molecular constants of Krupp (1974) provided the needed excitation potentials. Since all lines are weak, the $^{12}C/^{13}C$ ratio is not dependent on the assumed microturbulent velocity.

The abscissa and ordinate for each feature are given in Table 2, and the curves of growth are shown in Figure 1. More ^{12}CH lines were used than ^{13}CH lines because more stringent criteria were applied to the very weak ^{13}CH features. The displacement of the curves of growth gives the ratio $^{12}C/^{13}C = 5 \pm 2$. The actual error is probably greater than is indicated by the scatter of points in Figure 1, owing to the above-mentioned dependence of the ^{13}CH equivalent widths on the continuum level. The significant result is that the $^{12}C/^{13}C$ ratio is substantially less than 10.

The curve-of-growth analysis was confirmed by a spectrum synthesis of the interval 4227 Å–4238 Å. This includes the useful ^{13}CH feature at 4231.4 Å—the *R*(13) doublet from the 0–0 band. This doublet appears to be dominated by the ^{13}CH contribution in the Sun (Richter and Tonner 1967; Lambert and Mallia 1968; Iverson 1976) and in G and K giant stars of differing $^{12}C/^{13}C$ ratios (Tomkin and Lambert 1977). Furthermore, no detectable line is seen in similar spectra of the metal-deficient dwarf Gmb 1830 (HD 103095) (see Fig. 2), and only a very weak feature is seen in the CH subgiant HD 216219, which exhibits slight overabundances of the *s*-process elements. This

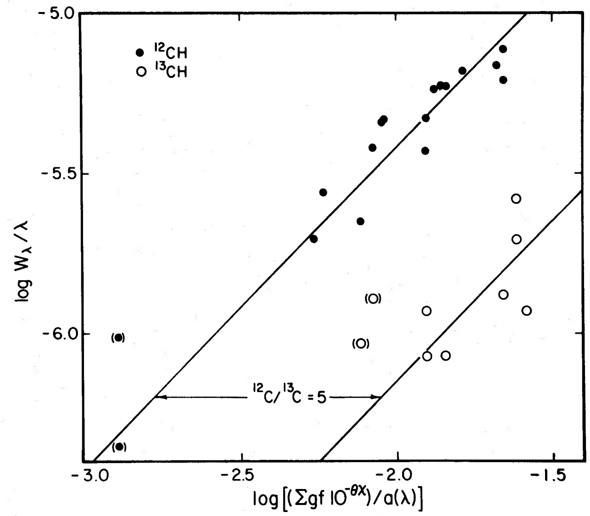

FIG. 1.—The CH curve of growth in HD 122563. *Filled circles*, the ^{12}CH lines; *open circles*, the ^{13}CH lines. Parentheses around a data point indicate an uncertain measurement of the equivalent width. The two solid lines represent the best straight-line curve-of-growth fits to the data points.

behavior pattern and the lack of a plausible contaminant and alternative atomic identification strongly suggest that the feature is due to ^{13}CH. The synthesized region (Fig. 2) also include the *R*(12) ^{12}CH and ^{13}CH doublets.

The observed spectrum was obtained by coadding four separate spectral scans. The resolution of the spectra is 0.08 Å and the rms signal-to-noise ratio is about 75. The line list for the synthetic spectra was compiled from Krupp's (1974) CH line predictions and from the atomic line list of Kurucz and Peytremann (1975). The CH oscillator strength and excitation potential computations have been previously discussed. The oscillator strengths of the atomic lines are, as usual, either poorly determined or not determined at all. The following procedure was adopted: (1) if an atomic line had a recently determined experimental oscillator strength, that value was used without change; (2) for the majority of lines which have no well-determined oscillator strength, initial *gf*-values were taken from Kurucz and Peytremann (1975). These were checked by comparing a synthetic spectrum of Gmb 1830 with the observed spectrum for that star. This synthesis used a model atmosphere of Peytremann (1974) which closely corresponded to the model parameters derived by Tomkin and Bell (1973). Small (always less than a factor of 3) adjustments were made in the atomic *gf*-values to match the Gmb 1830 spectrum.

The HD 122563 spectrum synthesis combined this line list with the model atmosphere derived by Wolffram (1972). The predicted spectra for $^{12}C/^{13}C =$ 90, 10, and 4 and are compared in Figure 2 with the observed spectrum. A high ^{13}C content is evident from this comparison. A low $^{12}C/^{13}C$ ratio was also obtained from a comparison of several lower resolution spectral

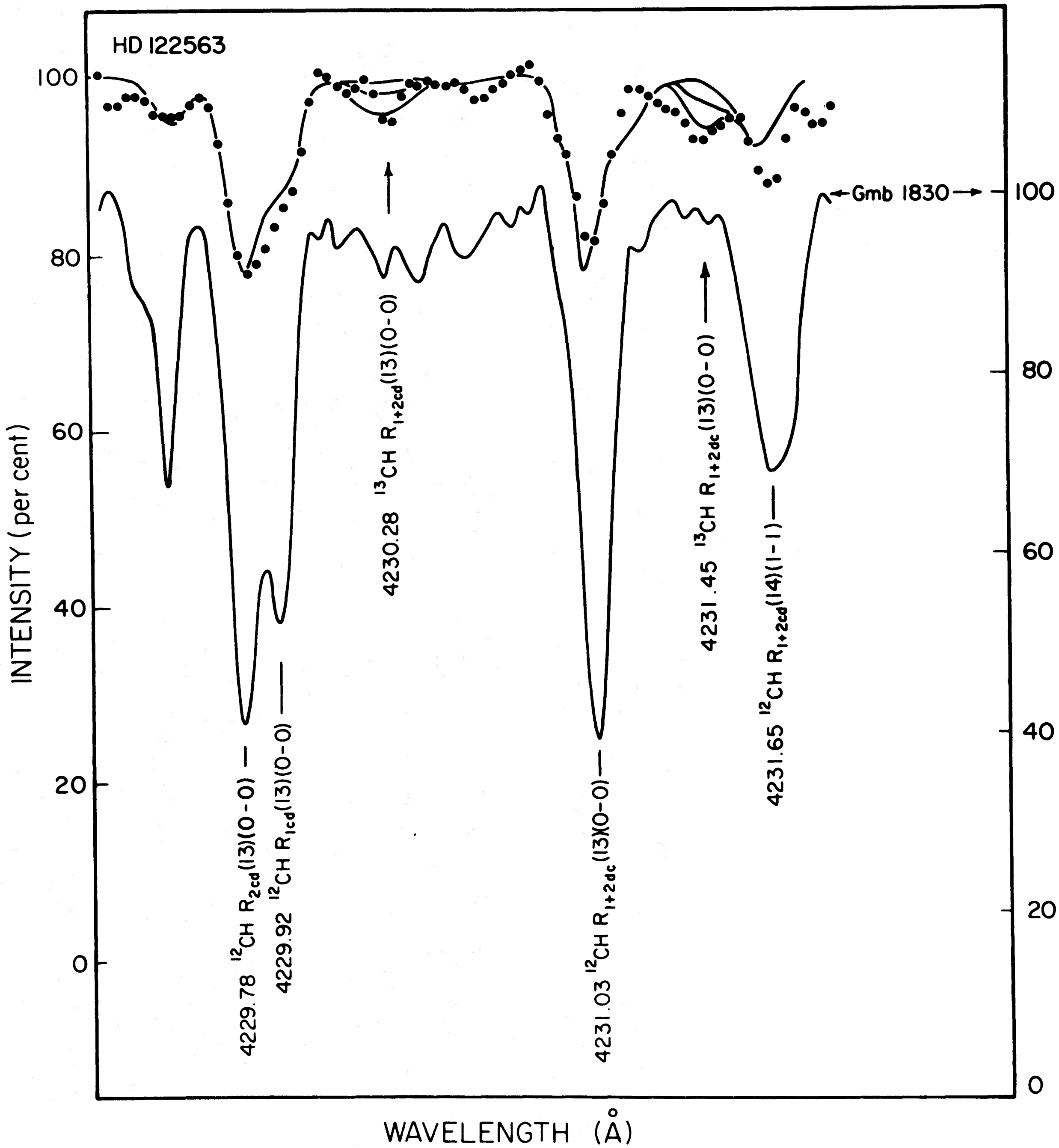

FIG. 2.—Synthetic and observed spectra for the 4230 Å spectral region. For HD 122563, the solid dots are the observations, and the solid lines are synthetic spectra computed for $^{12}C/^{13}C$ ratios of 90, 10, and 4 (in order of strengthening of the spectrum). Also shown is the observed spectrum of Gmb 1830. CH lines are identified. Metallic lines were included in the synthesis but are not identified on the figure. Arrows point to two weak ^{13}CH features.

scans with synthetic spectra of the ^{12}CH and ^{13}CH features only.

IV. DISCUSSION OF THE $^{12}C/^{13}C$ RESULT

The preceding analysis has demonstrated that the $^{12}C/^{13}C$ ratio in HD 122563 is very low, probably around 5. This result confirms and extends the earlier discoveries of abundance anomalies in the CNO group of elements. The abundance anomalies are probably caused by internal mixing and processing. The following arguments may exclude the possibility that HD 122563 was formed from a gas cloud enriched in ^{13}C

and N. Gmb 1830 is an unevolved main-sequence star with an overall metallicity [M/H] = −1.3 (Tomkin and Bell 1973) and a high $^{12}C/^{13}C$ ratio; the limit $^{12}C/^{13}C \geq 90$ is consistent with Figure 2 and other spectra. Wannier *et al.* (1976) report a probable enhancement of the ^{13}C content in the present interstellar clouds ($^{12}C/^{13}C \approx 40$) as compared with $^{12}C/^{13}C \approx 89$ for the solar system (i.e., the value in the interstellar medium 4.5×10^9 years ago). A monotonic decrease in the $^{12}C/^{13}C$ ratio in the interstellar medium with increasing galactic age is predicted by simple models (Audouze, Lequeux, and Vigroux 1975; Vigroux, Audouze, and Lequeux 1976) as evolved stars return material that is ^{13}C enriched. These models also predict a N increase which would imply [N/Fe] < 0 for the original atmosphere of HD 122563. Observational determination of the nitrogen contents of metal-poor stars (Sneden 1974; Clegg 1975) has shown that generally [N/Fe] ≲ 0.0. Therefore, the most plausible assumption is that the gross overabundances of ^{13}C and N in HD 122563 are products of its internal evolution.

Such arguments excluding a low initial $^{12}C/^{13}C$ ratio rely on a standard model for the Galaxy. Cohen and Grasdalen's (1968) original search for ^{13}C was motivated by the suggestion of Wagoner, Fowler, and Hoyle (1967) that supermassive objects may have dominated the nucleosynthesis before the formation of the Galaxy. A prediction was that $^{12}C/^{13}C \approx 1$. Clearly, the new result is consistent with Cohen and Grasdalen's (1968) conclusion that at least one generation of ordinary massive stars must have processed the alleged supermassive object products before the birth of the Population II stars observed today. A worse case still for the supermassive object synthesis is the low ^{13}C content of Gmb 1830, as mentioned above.

The luminosity of HD 122563, $\log L/L_\odot \approx 2.8$ (Wolffram 1972), places it in the ambiguous region of the H-R diagram in which it may be on either the first or second ascent of the giant branch. Now available results (Dearborn, Lambert, and Tomkin 1975) for stars on the first ascent (say, $\log L/L_\odot \lesssim 1.6$) show a ratio $^{12}C/^{13}C \approx 20$ to 30, which is consistent with theoretical predictions. At higher luminosities where evolutionary assignments are ambiguous for low-mass stars, a wide range in derived $^{12}C/^{13}C$ ratios (~3 to 30) is found (Dearborn, Lambert, and Tomkin 1975; Tomkin, Luck, and Lambert 1976). The low $^{12}C/^{13}C$ (say, ≲18) ratios are not yet understood; Lambert (1976) and Tomkin, Luck, and Lambert (1976) outline some possible explanations. The sparse statistics provide an indication that the metal-poor stars have systematically lower $^{12}C/^{13}C$ ratios, e.g., Arcturus and γ Leo. HD 122563 would be consistent with this suspicion; however, it may not be entirely fair to compare this extremely metal-deficient star with more mildly deficient giants.

Present CNO abundances in HD 122563 are not consistent with CNO-cycle processing and the hypothesis of normal initial abundances ([C/Fe] = [N/Fe] = [O/Fe] = 0.0). In particular, the extreme N enhancement [N/Fe] ≈ 1.2 cannot be generated on this hypothesis: [N/Fe] ≈ +0.7 is the upper limit, and this requires total conversion of the initial carbon. More N can be produced by the destruction of O (Caughlan 1965), but the observed [O/Fe] ≈ +0.6 appears to exclude this possibility. There is evidence to support the assumption of normal initial carbon contents ([C/Fe] ≈ 0.0) in metal-poor stars (Cohen 1968; Sneden 1974). As previously discussed, nitrogen is normal or underabundant in main-sequence metal-poor stars (Sneden 1974; Clegg 1975). The oxygen deficiency in metal-poor stars may not be as great as the overall metal deficiency (Peimbert 1974; Lambert, Sneden, and Ries 1974), but available observations refer to evolved stars.

Dearborn, Bolton, and Eggleton (1975) have shown that thermal instabilities in the hydrogen-burning shell surrounding a degenerate helium core of a metal-deficient 0.75 $M_\odot$ star can produce envelope $^{12}C/^{13}C$ ratios of less than 10, after about 30 mixings. They do not comment on the amount of ^{14}N produced by their model; however, they state that the interior temperatures are too low to process oxygen into nitrogen. Therefore their model cannot explain the large overabundance of nitrogen in HD 122563.

The observed light-element anomalies in this star may be explained on the assumption that HD 122563 has mixed to the surface some modified products of helium burning in the core or in a shell. Before ignition of the helium, when on its first ascent up the giant branch, the atmosphere of HD 122563 probably had a modest enhancement of nitrogen, a slight depletion of carbon, $^{12}C/^{13}C \approx 20$, and a normal oxygen content. Its surface abundances would appear much like those in the normal giants studied by Greene (1969). Upon helium ignition, the assumption is that the ^{12}C from the helium-burning zones was converted into ^{13}C or ^{14}N and mixed to the surface, along with essentially untouched ^{16}O. In this manner, one may explain the gross nitrogen enhancement alongside the only modest carbon depletion, as well as the very low $^{12}C/^{13}C$. Obviously this is not the only scenario which may be drawn for HD 122563, and there are many unanswered questions such a simple model ignores. A chief difficulty is that theoretical stellar evolution models cannot easily attain mixing from the cores to the envelopes.

Future observational efforts will be centered on the following: (1) reobserving the oxygen forbidden lines in HD 122563 with a Reticon tube to enable this abundance to be determined more accurately; (2) determining CNO abundances in more metal-poor giant stars; and (3) analyzing the CH bands in other metal-poor stars to derive more data on the $^{12}C/^{13}C$ ratio. Such data should bring important new constraints to bear on theoretical stellar evolutionary models.

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