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CARBON ISOTOPE RATIOS IN GIANT STARS OF THE OLD GALACTIC CLUSTER NGC 7789

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ABSTRACT

Carbon isotope ratios have been derived for seven giant stars in the old open cluster NGC 7789. High-resolution, high signal-to-noise spectra of the CN red system bands in these stars were obtained with the KPNO 4 m Cassegrain echelle spectrograph and a CCD camera. ^{13}CN features were detected easily in all cluster stars, and isotope ratios in the range $^{12}C/^{13}C = 10–30$ were derived. The isotope ratios of most stars are normal for K giants possessing convective envelopes and show no correlations with effective temperatures and with lithium abundances. However, one cluster star has both very high lithium and the lowest carbon isotope ratio. We speculate that this star either is an asymptotic giant branch star or a weak G-band star.

Subject headings: clusters: open — stars: abundances — stars: late-type

I. INTRODUCTION

The recent surprising discovery of large lithium abundances in some giant stars of the old galactic cluster NGC 7789 provides a new test case for our understanding of stellar evolution. During the course of a high-resolution spectroscopic metallicity study of NGC 7789 (Pilachowski, 1985), the investigators noticed the great strength of the 6707 Å lithium resonance doublet in several stars. A subsequent detailed abundance analysis showed that lithium approaches its cosmic value [log ϵ(Li) $\approx$ 3] in some NGC 7789 giants (Pilachowski, Mould, and Siegel 1984).

The vast majority of normal field giant stars exhibit surface lithium abundances far below the cosmic value because of the internal destruction and dilution of this fragile element during the normal course of stellar evolution (see Boesgaard 1976 or Lambert, Dominy, and Sivertsen 1980). A very small fraction of giants do possess very large lithium abundances [log ϵ(Li) > 1.5; Wallerstein and Sneden 1982; Sneden *et al.* 1984]. These abundances are not explained easily by standard stellar evolution theory (e.g., see Iben 1967). Therefore, the existence of large lithium contents in some giants in NGC 7789 immediately prompts further questions about formation and evolution of stars in this cluster. What lithium abundance characterized the protocluster NGC 7789? Have the giants of this cluster experienced convective mixing of their envelopes? Do the lithium abundances in these stars correlate with any other evolutionary-sensitive abundances?

Pilachowski (1984) recently has completed a high-resolution spectroscopic study of four stars at the main-sequence turnoff in NGC 7789. The lithium abundances in these stars range from log ϵ(Li) $\approx$ 2.4–3.3, consistent with the hypothesis that the initial lithium contents of all cluster stars were identical to the cosmic abundance. This result rules out the possibility that the large lithium abundances in the NGC 7789 giants simply are remnants of extremely large primordial cluster lithium contents. Explanations for the anomalous giant stars therefore must concentrate on the internal evolutions of the stars themselves.

In order to determine the extent of convective mixing in the envelopes of NGC 7789 giant stars we have determined carbon isotope ratios for seven cluster members. Theoretical and observational studies of single Population I stars agree that during the first ascent of the giant branch, a normal star's surface content of the CNO elements is altered by the effects of mixing of CN-cycle products. In this process, ^{12}C is depleted and ^{13}C and N are enhanced. A typical giant will show a carbon abundance about a factor 2 less than, and a nitrogen abundance a factor of 2.5 times greater than, an unevolved star and will have a $^{12}C/^{13}C$ ratio of $\sim$20, down from an initial value of greater than 50. A more extensive discussion of CNO in field giants may be found in Lambert and Ries (1981). The carbon isotope ratio is by far the easiest of these evolutionary signatures to detect spectroscopically and to determine with accuracy. In the following sections of this paper we report the use of the red system of the CN molecule to determine $^{12}C/^{13}C$ in NGC 7789 giants.

II. OBSERVATIONS AND REDUCTIONS

In 1984 September we obtained high-resolution spectra of the 8000 Å spectral region, employing the Kitt Peak National Observatory 4 m Mayall reflector, Cassegrain echelle spectrograph, and a TI 800 × 800 CCD detector. Spectra were gathered at one grating setting for seven giant stars in NGC 7789, three bright K giants with known $^{12}C/^{13}C$ ratios, and several hot stars with high rotational velocities. The particular cluster stars were chosen to cover a range of 1.1 mag in M_v. The derived lithium contents span three orders of magnitude. The K stars that we observed exhibit a large range in $^{12}C/^{13}C$ ratios. In Table 1 we present details about the program stars and the observational data. Stars selected are all members of NGC 7789, according to the proper motion survey of McNamara and Solomon (1981).

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TABLE 1

PROGRAM STAR DATA

Star[a]	$(B-V)_0$[b]	V[b]	M_v[b]	Exposure[c]	Date (1984)
		Cluster Giants			
72	1.64	10.98	−1.2	120 m (1)	Sep 9
301	1.09	12.08	−0.1	247 m (3)	Sep 7
461	1.38	11.27	−0.9	120 m (1)	Sep 8
501	1.43	11.22	−1.0	90 m (1)	Sep 8
669	1.35	11.46	−0.7	90 m (1)	Sep 8
970	1.27	11.82	−0.4	210 m (2)	Sep 8
971	1.61	10.98	−1.2	60 m (1)	Sep 6
		Field K Giants			
α Boo	1.23	−0.04	+0.3	20 s (1)	Sep 9
α Ser	1.17	2.65	+1.3	20 s (1)	Sep 9
μ Aql	1.17	4.45	+2.1	120 s (1)	Sep 9

[a] Star numbers for NGC 7789 are taken from Kustner 1923.

[b] Colors and magnitudes are taken from Burbidge and Sandage 1958 for NGC 7789. For the field stars, the values in Wilson 1976 and Hoffleit 1982 are quoted.

[c] Total exposure times are listed, with the number of CCD frames employed given in parentheses.

Seven echelle orders, with central wavelengths between 7780 and 8490 Å, appeared on each CCD frame. The frames covered ~45 Å of each order with a 2 pixel resolution of 0.12 Å. Clearly, the spectral coverage was incomplete, so we chose to tilt the echelle grating to be sure to capture the strong triplet of ^{13}CN lines at 8004 Å. The maximum integration times for the CCD frames were held to 2 hr in order to minimize the number of cosmic-ray events per frame; thus, the final spectra of the two faintest cluster stars were formed through the addition of more than one raw spectrum. For each CCD frame, the initial extraction of the echelle orders, including bias subtraction, flat-field correction, and excision of the (few) cosmic-ray events, was accomplished using standard software developed for this purpose at KPNO. Final reduction and analysis of all spectra was carried out with various spectrum computer routines written at the University of Texas.

Telluric water-vapor absorption features abound in the 8000 Å spectral region. In order to remove these lines, we divided all spectra of cluster stars and field K stars by the spectra of the nearly featureless high rotational velocity hot stars. This procedure was performed with an interactive spectrum reduction software package written by Uomoto (1981). In general, it was not possible to observe the program stars and hot stars at exactly identical air masses. Therefore we iterated the division procedure by manually adjusting the depths of the telluric lines until the best cancellation of the telluric features was attained in the program stars. In Figure 1 we show typical spectra of the 8000 Å echelle order for a hot star, a cluster star, and the divided cluster star spectrum. The combination of the cluster heliocentric radial velocity (-54 km s^{-1}; Stryker and Hrivnak 1984) and the Earth's motion during the dates of observation produced a stellar spectrum blueshift of 1.8 Å. Fortunately, this velocity shift moved all prime ^{13}CN features away from any possible telluric line contamination.

The divided echelle spectra were reduced to a linear wavelength scale through spline interpolations between features of known wavelengths, and smoothed by application of appropriate Fourier transform filters. The flat-field corrections in the initial reduction of the CCD frames removed most of the echelle blaze function. The remaining departures from flatness of the continua, caused by slightly different CCD illuminations

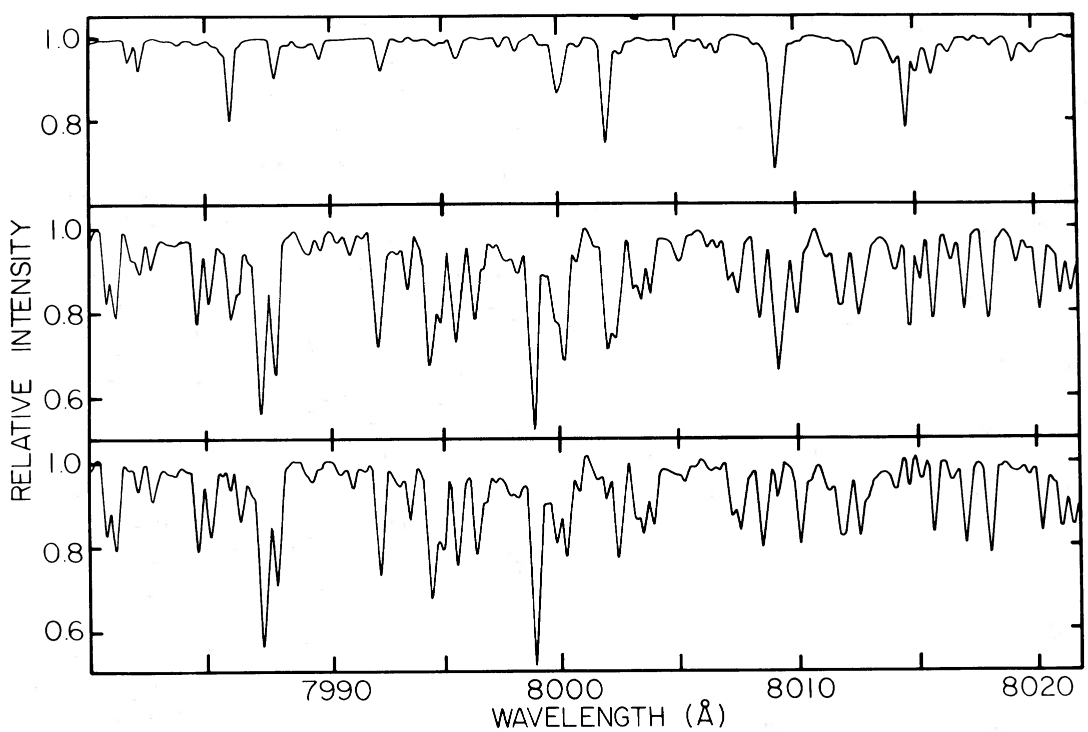

FIG. 1.—Sample observed spectra of part of the 8000 Å echelle order. We show spectra of a bright hot star, a cluster star, and the same cluster star with telluric lines removed by division by the hot star.

by stellar and lamp sources, were eliminated through normalization of each spectrum order to the highest points in the order. The line crowding in this spectral region in K giants is not too severe at our resolution, and the normalization technique proved reliable.

III. DERIVATION OF THE CARBON ISOTOPE RATIOS

We examined all spectral orders carefully to choose the most appropriate ^{12}CN and ^{13}CN lines from the red system $\Delta v = +2$ sequence for the ^{12}C/^{13}C determination. Unless the isotope ratio is near unity, it is difficult to obtain reliable estimates of ^{12}C/^{13}C from the use of normal and isotope molecular transitions with similar vibrational and rotational excitation states. Typically, if the ^{13}CN features may be seen at moderate resolutions in K giant stars, then the ^{12}CN lines of the same band will be saturated. In order to find sufficiently weak lines of both ^{12}CN and ^{13}CN, often it is necessary to compare strong ^{13}CN lines from the (2–0) band with weaker lines from the (3–1) and (4–2) ^{12}CN bands. This comparison introduces a potential error from uncertainties in the vibrational band strengths. Moreover, for the CN red system, both the progression of bands to higher vibrational quantum number and the progression of lines within a band to higher rotational quantum number go toward increasing wavelength. This creates increasing complexity of the CN spectrum at the longer wavelengths and increasing difficulty of finding suitably unblended ^{12}CN features. Since our spectra did not have full wavelength coverage between 7800 and 8500 Å, the adopted primary set of ^{12}CN lines is not large. No unblended single lines of ^{13}CN could be detected in our spectra. The most reliable ^{13}CN feature proved to be, as expected, the isolated triplet of lines at 8004 Å. In Table 2 we list the final set of transitions chosen for the carbon isotope analysis.

The entries in Table 2 show clearly that the 8000 Å spectral region contains the best features for the ^{12}C/^{13}C determination. We chose to synthesize the spectral region from 7980 to 8030 Å, essentially the entire CCD-echelle order containing the 8000 Å features.

We included all ^{12}CN transitions in this spectral region

TABLE 2

CN Red System Features used in Analysis

λ (Å)	Identification
7892.10	^{12}CN (2–0) $Q_2(8)$
7985.11	^{12}CN (2–0) $P_1(18)$
8008.50	^{12}CN (2–0) $Q_2(29)$
8010.06	^{12}CN (2–0) $Q_1(28)$
8015.53	^{12}CN (2–0) $P_1(22)$
8017.04	^{12}CN (2–0) $Q_2(30)$
8023.90	^{12}CN (2–0) $P_1(23)$
8098.66	^{12}CN (2–0) $R_1(46)$
8103.06	^{12}CN (3–1) $R_1(18)$
8123.28	^{12}CN (3–1) $Q_1(13)$
8354.64	^{12}CN (2–0) $P_1(49)$
8359.08	^{12}CN (4–2) $R_2(30)$
8359.89	^{12}CN (4–2) $P_1(13)$
8463.24	^{12}CN (3–1) $P_2(43)$
8469.88	^{12}CN (4–2) $Q_1(33)$
8004.7	^{13}CN (2–0) $Q_2(23)$ ^{13}CN (2–0) $R_2(31)$ ^{13}CN (2–0) $Q_1(21)$
8010.45	^{13}CN (2–0) $Q_1(22)$

listed by Davis and Phillips (1963) and all ^{13}CN lines given by Wyller (1966). The excitation potentials were computed from the formulae and molecular constants of Fay, Marenin, and van Citters (1971), and the rotational Honl-London line strength factors S_L were calculated from formulae given in Schadee (1964). These parameters agree well (when normalized properly) with the more precise values computed by Sneden and Lambert (1982), and we have adopted the band oscillator strengths $f_{v'v''}$ from that study.

The list of atomic contaminating lines came from the solar line identifications of Moore, Minnaert, and Houtgast (1966), and the atomic line compendium of Kurucz and Peytremann (1975). We adjusted the oscillator strengths of these atomic lines to reproduce the spectrum of a standard star. For this application, the solar spectrum, although known in great detail, is useless: the temperature and gravity differences between the Sun and our mid-K giants are so large that undetectable features in the Sun become prominent in our spectra. For example, the Zr I line at 8005.27 Å may be seen easily in our spectra (see Fig. 2), but is not listed by Moore *et al.* (1966) and is not apparent in the Liège solar atlas (Delbouille, Neven, and Roland 1973). Therefore we chose one of our field K giants, μ Aql, as the standard star. μ Aql has a large carbon isotope ratio (^{12}C/^{13}C = 44; Lambert and Ries 1981); thus the ^{13}CN features are extremely weak or absent on our spectra (Fig. 2). We adopted a model atmosphere for μ Aql as described below, then measured the ^{12}CN lines listed in Table 2 for this star, and finally synthesized the stellar spectrum using a standard LTE line analysis code (Sneden 1973). The abundance of the ^{12}CN molecules was set by the requirement that the synthesized and observed CN lines produce the same equivalent widths on average. With the CN features matched, we altered the atomic oscillator strengths until the best complete match was achieved with the observed spectrum of μ Aql.

Model atmosphere parameters for K giants normally must be derived with great care in abundance studies. However, in the present work we desired only isotope ratios, *not* the absolute abundances of any atom. The isotope ratios were derived from a comparison of ^{12}CN and ^{13}CN absorption features. The two molecules are nearly identical, are formed in the same region of a stellar atmosphere, and have nearly the same dependences on atmosphere parameters. Therefore for the ^{12}C/^{13}C ratio most atmosphere uncertainties cancel and more attention may be spent simply on setting a consistent model atmosphere parameter scale. For the NGC 7789 stars, we either adopted the effective temperature and gravity values of Pilachowski *et al.* (1984) or used their methods to compute new values of these parameters. For the field K stars, we derived temperatures from the $B-V$ versus $T_{\rm eff}$ relation of Pilachowski, Sneden, and Wallerstein (1983). Gravities were estimated from the values given by Lambert and Ries (1981) and their prescriptions for the dependence of log (g) values on different $T_{\rm eff}$ choices. We list in Table 3 the adopted model atmosphere parameters for all stars. Model atmospheres conforming to these parameters were interpolated from the cool-star model atmosphere grid of Bell *et al.* (1976).

As mentioned previously, at least part of the ^{12}C/^{13}C ratio must be determined from a comparison of weak ^{13}CN and strong ^{12}CN lines. In principle, then, the derivation of an accurate microturbulent velocity is quite important. The microturbulence values for the field K giants have been taken from Lambert and Ries (1981). For several NGC 7789 giant stars, Pilachowski (1985) finds a turbulent velocity of $v_{\rm mic} \approx 2.5$ km

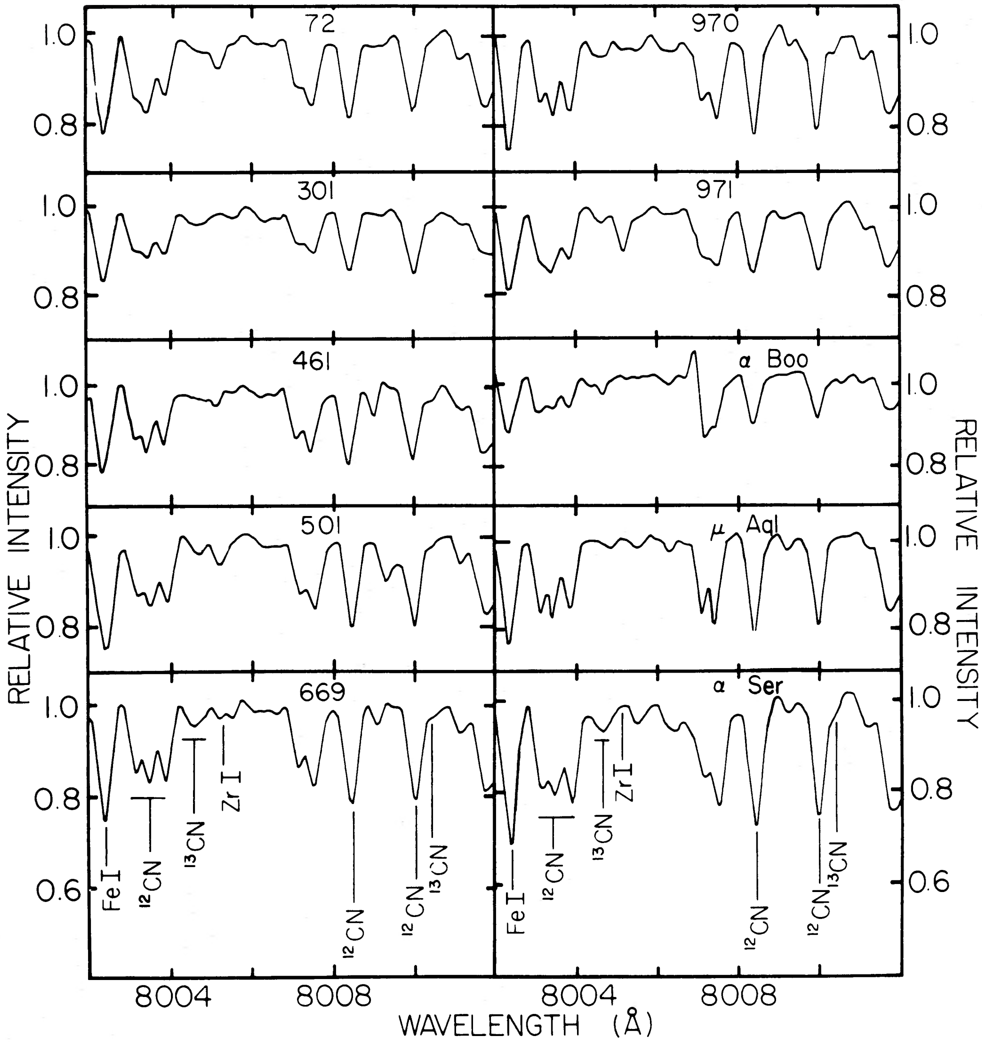

FIG. 2.—Smaller part of the 8000 Å spectrum of the program stars. Note the differences between μ Aql and the cluster stars in the ratios of ^{12}CN and ^{13}CN strengths.

s^{-1}, using photographic Cassegrain echelle spectra with extensive wavelength coverage. This value is slightly larger than typical microtubulent velocities derived for K giants by Lambert and Ries (1981) (admittedly, however, the NGC 7789 giants studied here are higher luminosity stars than most of the ones analyzed in their study, and higher luminosity giants often possess larger microturbulence values). Therefore we used the present ^{12}CN equivalent width measurements to attempt to redetermine each cluster star $v_{\rm mic}$ value. Abundances for each ^{12}CN line were computed for a variety of microturbulent velocities, and we used the value of $v_{\rm mic}$ which produced no trend of abundance with equivalent width. The microturbulent velocities computed in this way are listed in Table 3. We note that the same technique, when applied to the three field K giants, yielded $\langle v_{\rm mic} \rangle \approx 2.5$ km s^{-1}. This derivation of $v_{\rm mic}$ suffers from the use of only a few ^{12}CN transitions, and potential errors are introduced by the use of lines from different vibrational bands. The resulting microturbulence values for the program stars are slightly larger than those of the lower luminosity giants studied by Pilachowski (1985).

TABLE 3

MODEL PARAMETERS AND ABUNDANCES

Star	$T_{\rm eff}$	log (g)	$v_{\rm turb}$	^{12}C/^{13}C	log ϵ(Li)
Cluster Stars					
72	3850	1.2	3.0	20	−0.3
301	4600	2.1	2.0	10	+2.5
461	4200	1.6	3.0	25–30	+0.5
501	4150	1.5	3.5	15–20	+0.5
669	4100	1.6	3.5	15–20	+0.3
970	4200	1.7	3.0	15–20	+0.9
971	3800	1.2	2.0	20	−0.4
Field K Stars					
α Boo	4350	1.5	1.8	10 (7)	< −1.5
α Ser	4400	1.6	2.0	15 (14)	−0.3
μ Aql	4500	2.0	2.0	> 30 (44)	+1.0

With appropriate model atmospheres, an extensive list of atomic and molecular lines, and the measured ^{12}CN equivalent widths, we computed synthetic spectra for each program star. We convolved the computed spectra with a spectrograph slit profile function to compare the synthetic and observed spectra. A preliminary inspection of the 8000 Å spectra region in the program stars suggested immediately that ^{13}CN was present in all NGC 7789 stars of our sample. This is shown in Figure 2, in which we have displayed spectra of all the cluster stars. The detailed synthetic spectra confirmed this initial impression. For example, in Figure 3 we show observed and synthetic spectra for cluster member 301, the warmest star of our sample, along with similar spectra for μ Aql. The greater strength of the ^{13}CN features in the cluster stars is apparent. In Table 3 we give final estimates of ^{12}C/^{13}C for all program stars. We include in Table 3 the lithium abundances from Pilachowski (1986) and from Lambert *et al.* (1980).

From the above discussion it is apparent that the microturbulence errors contribute most to the overall uncertainty in the ^{12}C/^{13}C determinations. However, we will argue here that the maximum uncertainties from this error source cannot negate our basic results. Microturbulence errors affect only the stronger ^{12}CN lines. In the cluster stars the equivalent widths of the ^{12}CN lines range roughly from 10 to 80 mÅ, or log (W/λ) from -5.9 to -5.0. The average equivalent width for a ^{12}CN line typically is log $(W/\lambda) \approx -5.2$. If the true $v_{\rm mic}$ of a NGC 7789 giant is 2.5 ± 0.75 km s^{-1}, then for a line with log $(W/\lambda) = -5.0$, the ^{12}CN abundance is uncertain by $-0.11/+0.21$; for a line with log $(W/\lambda) = -5.2$, the uncertainty is $-0.06/+0.09$; and for a line weaker than log $(W/\lambda) = -5.4$, the error is less than ± 0.04. The smaller abundance uncertainty resulting from a microturbulence *increase* occurs because lines of these strengths virtually are unsaturated for $v_{\rm mic} > 3$ km s^{-1}. These calculations suggest that the uncertainty in ^{12}C/^{13}C from errors in $v_{\rm mic}$ must be of order 20%.

Gustafsson, Kjœrgaard, and Andersen (1974) made a very careful analysis of microturbulence in field giants which have similar parameters to our NGC 7789 stars. They concluded that the mean value of this parameter is ~ 1.7 km s^{-1}, which is at the low end of our estimated range for $v_{\rm mic}$ in the cluster stars. If we were to adopt $v_{\rm mic} = 1.7$ km s^{-1} uniformly for all of our stars, then the derived ^{12}C/^{13}C ratios would increase from ~ 20, on average, to perhaps 25 at most. These adjusted ratios still would remain typical of Population I giant stars. Also, the proposed decrease in $v_{\rm mic}$ would leave the low isotope ratio for star 301 virtually unchanged, since we already have assumed $v_{\rm mic} = 2$ km s^{-1} for this star. Therefore none of the conclusions here would be altered substantially.

IV. DISCUSSION

The basic result of this work is that most giant stars of the old galactic cluster NGC 7789 exhibit carbon isotope ratios which are normal for K giant stars: ^{12}C/^{13}C $\approx$ 15–30. This result is shown in Figure 4, in which we plot the measured isotope ratios for cluster giants and for field giants and supergiants from the samples of Lambert *et al.* (1980) and of Luck (1977). All of the cluster giants appear within the normal distribution of isotope ratios expected from the field stars. The supergiants of Luck (1977) have been included because most of the giants we have observed in NGC 7789 are more luminous and slightly more massive than giants in the field population (Scalo, Dominy, and Pumphrey 1978). Isotopic ratios which are normal for late-type giant stars surely indicate (*a*) the dredge-up of CN-cycle burning products to the surfaces of each NGC 7789 giant and (*b*) the subjection of the envelope material to temperatures in excess of that required to destroy lithium. We note also that, in accord with standard stellar evolution theory (see, for example, Iben 1971), the carbon isotope ratios show no change with luminosity or temperature

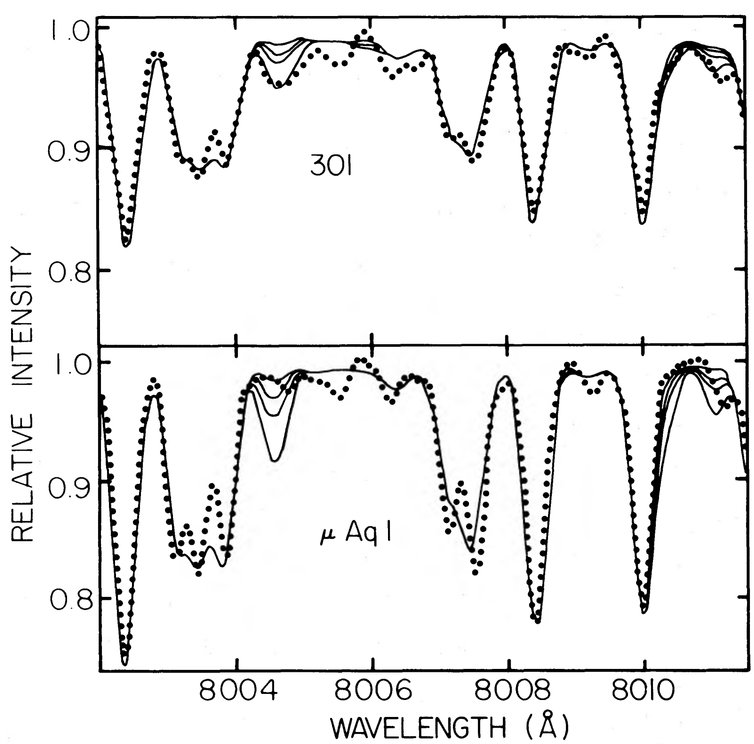

FIG. 3.—Examples of observed and synthetic spectra. For computed spectra, given by solid curves, the abundances of metals and of ^{12}CN were held constant, and the ^{12}C/^{13}C ratios were chosen to be 60, 30, 20, and 10.

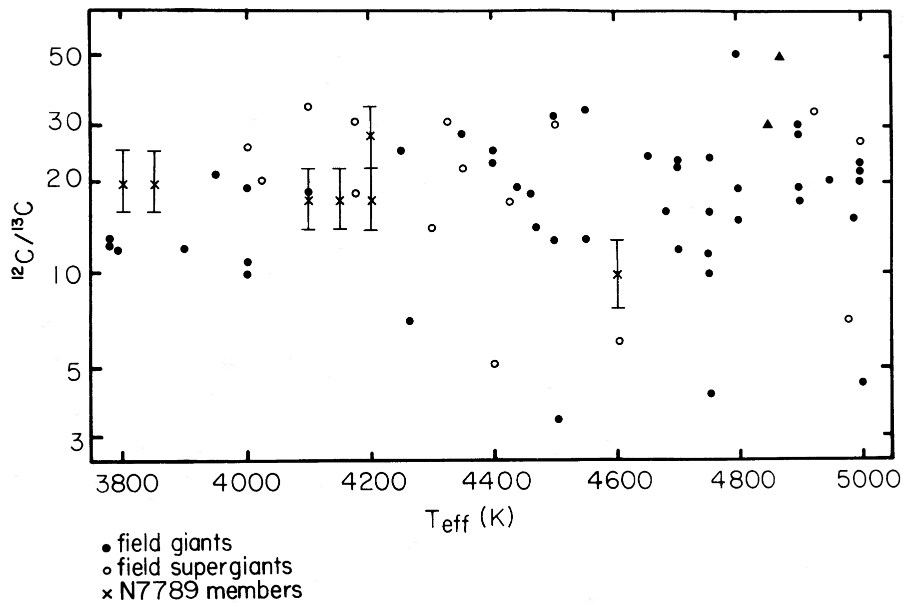

FIG. 4.—Correlation of carbon isotope ratios with effective temperatures for giants in NGC 7789 and for field giants and supergiants

on the giant branch. The gross effects of the first dredge-up have been completed in our stars. However, the present result is curious in light of the high lithium abundances determined by Pilachowski *et al.* (1984) and by Pilachowski (1986) for a few giants of this cluster.

Two promising ideas to explain these anomalously high lithium abundances must be discarded. (1) The stars probably were *not* born with abnormally high lithium abundances, for the main-sequence stars of NGC 7789 do not show lithium contents exceeding the cosmic value (Pilachowski 1984, 1986). (2) The surface lithium in the giants has not survived simply through a lack of convective envelope mixing, for the carbon isotope ratios are too low. If these ideas are untenable, what hypotheses remain?

To begin, let us review the abundances of lithium in giants of NGC 7789. We expect that these stars did not deplete any of their initial surface contents of lithium during their main-sequence evolutions. The present-day NGC 7789 giants originally resided on the upper main sequence. Burbidge and Sandage (1958) first showed that the turnoff of this cluster lies between those of the old cluster M67 and the much younger Hyades. Faulkner and Cannon (1973) then determined a turnoff mass of $\sim 1.6\ M_\odot$, consistent with an age of 1.6 Gyr (Demarque 1980). Stars now on the giant branch were F0 V or earlier. Such stars preserve their surface lithium contents on the main sequence (Boesgaard 1976; Duncan 1981; Soderblom 1983). Although Boesgaard and Tripicco (1984) have shown that stars as early as F3 V may exhibit main-sequence lithium depletion, the precursors of the NGC 7789 giants were even hotter main-sequence stars. Moreover, Pilachowski (1984) has found substantial amounts of lithium in four stars near the present NGC 7789 turnoff. Therefore, with the standard amount of convective dilution on the subgiant and lower giant branches (a factor of 48 depletion; Iben 1967), a typical giant of $\sim 1.5\ M_\odot$ should exhibit $\log \epsilon(\mathrm{Li}) \approx +3.0 - 1.7 = +1.3$.

Ordinary giant stars in fact show a range of lithium abundances ranging from an average of $+1.0$ for the Hyades giants to upper limits of $\log \epsilon(\mathrm{Li}) < -1.0$ for many cool giants (Lambert *et al.* 1980). The average lithium abundance declines for cooler stars among the field population. For field giants with temperatures comparable to our sample of seven stars in NGC 7789, the abundances of lithium typically are $\log \epsilon(\mathrm{Li}) \approx -0.5$, with large scatter, while the lithium abundance for our sample of NGC 7789 giants (omitting the peculiar star 301) is $\log \epsilon(\mathrm{Li}) \approx +0.2$ (Pilachowski 1986). Lambert *et al.* (1980) cite Scalo *et al.* (1978) to argue that the mean mass of their sample of field giants is between 0.8 and 1.2 $M_\odot$, somewhat lower than the 1.6 $M_\odot$ determined as the turnoff mass of NGC 7789 (Demarque 1980). The scatter in the field star measurements is so large, however, that the lithium abundances of the giants in NGC 7789 are within the upper envelope of the field star distribution. The higher mean abundance of lithium in giants of NGC 7789 therefore may be attributed to the higher masses of the cluster giants, leading to less lithium depletion on the main sequence than in most of the precursors to the giants surveyed by Lambert *et al.* (1980). Most giants in NGC 7789 have undergone standard evolutions in accord with theoretical predictions.

This view of NGC 7789 holds that only a small number of stars in the cluster are in any way abnormal. That small number of anomalous stars still must be explained, however. Among our sample, star 301 is especially peculiar. In Figure 5 we plot the measured $^{12}C/^{13}C$ ratios versus the lithium abundances for cluster and field stars, following Lambert *et al.* (1980). The NGC 7789 lithium abundances are taken from Pilachowski (1986). The peculiarity of star 301 is readily apparent. This star has the lowest isotopic ratio of our sample and the highest lithium abundance, so that it is well removed from the normal stellar distribution in Figure 5. Stars located in the upper right corner of Figure 5 all are classified as weak G-band stars, and star 301 shares several characteristics in common with that group. We will explore two hypotheses to explain the unusual chemical composition of star 301: (1) the star could be more evolved than most other giants in NGC 7789 and could

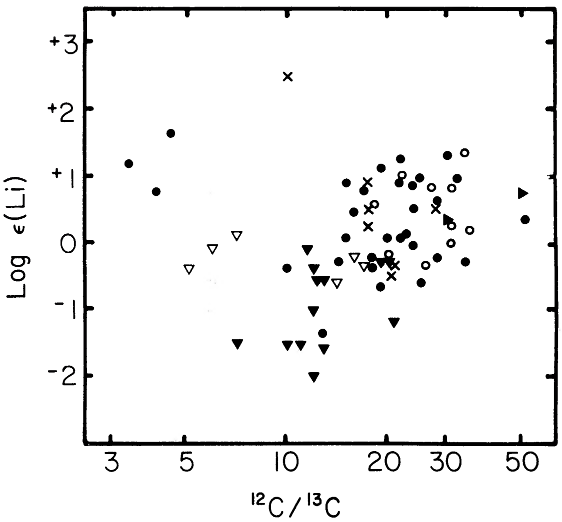

FIG. 5.—Correlation of carbon isotope ratios with lithium abundances for NGC 7789 giants and for giants and supergiants in the field.

have produced additional lithium after depleting its initial supply; and (2) special main-sequence conditions created the large lithium content on the surface of this star.

Is star 301 on the asymptotic giant branch? The location of star 301 in the H-R diagram of NGC 7789 is above the clump and slightly to the blue of the red giant branch. At the luminosity of star 301, stars which have evolved above the helium-burning clump occur slightly to the blue of the first-ascent red giants; at higher luminosity, the first and second giant branches merge together. The position of star 301 is consistent with an evolutionary status as a second ascent giant branch star. The accuracy of existing photometry in the cluster is, however, not sufficient to classify the star unambiguously on its second ascent.

Cameron (1955) and Cameron and Fowler (1971) proposed a mechanism by which low-mass stars could increase significantly their surface abundances of lithium during the double shell-burning phase of stellar evolution. First, ^{7}Be is synthesized from the reaction ^{3}He(α, γ)^{7}Be in the deep interior of a star. Then the ^{7}Be is convected to cooler outer envelope regions where the electron capture reaction ^{7}Be(e^-v) ^{7}Li occurs. If the convection is efficient, the ^{7}Li may be brought to the cool surface layers before it is destroyed in ^{7}Li(p, γ) ^{8}Be(2α) reactions. Sackmann, Smith, and Despain (1974) have argued that this mechanism is plausible for stars undergoing helium shell flashes, but it is difficult to apply to star 301 for two reasons. First, the mechanism is not restricted to produce lithium only up to the cosmic abundance; much higher values could be produced. Second, star 301 is not luminous enough to have achieved a shell flash capable of producing fresh lithium and bringing it to the surface.

Did special main-sequence conditions preserve lithium in star 301? We postulate that special conditions during pre–main-sequence and main-sequence evolution may have preserved the initial lithium on the surface of star 301. This star, and others like it in NGC 7789, may have evolved in a manner similar to the field weak G-band stars. Star 301 resembles a weak G-band star in several important respects. As shown in Figure 5, star 301 displays the high lithium abundance and low carbon isotope ratio common to the weak G-band stars. It also has a similar luminosity. Parthasarathy, Sneden, and Böhm-Vitense (1984) determined absolute V magnitudes of a number of weak G-band stars from several spectroscopic parameters. With a luminosity of $M_v = -0.1$, star 301 is of comparable luminosity, but slightly cooler than most weak G-band stars. The absolute abundances of carbon and nitrogen unfortunately are not known yet, but clearly are needed to confirm an identification of this star as a weak G-band star.

Lambert and Sawyer (1984) have outlined a mechanism which relies on light element diffusion in pre–main-sequence, high-mass stars to produce the observed low-carbon, low ^{12}C/^{13}C, and high lithium in the weak G-band stars. Similar arguments may need to be applied to the rare field giants possessing cosmic lithium abundances. This mechanism invokes diffusion to lift lithium above the region in the interior of a main-sequence star at which the temperature is hot enough to destroy lithium. The lithium is stored and preserved in the cooler upper layers (alas, not necessarily at the surface where it could be accessible spectroscopically!). Carbon atoms, on the other hand, are diffused downward to hotter layers, where extensive CN-cycle burning occurs, to account for the near-equilibrium ratios of CNO atoms and their isotopes in the weak G-band stars. When the outer convective envelope develops as the star leaves the main sequence, the lithium zone is mixed throughout the envelope, leading to lithium abundances as high as the cosmic value on the surfaces of weak G-band giants. Such a mechanism might have been operative in star 301.

The occurrence of a possible weak G-band star in a cluster with a large number of blue stragglers suggests a link between weak G-band stars, the anomalous NGC 7789 giants, and blue stragglers. A connection might be made following the quasi-homogeneous evolution hypothesis of Wheeler (1979) for blue stragglers. Instead of diffusing carbon inward to a region of CN-cycle burning, a star might mix a substantial fraction of its interior through its core. Such mixing would prolong the main-sequence lifetime by bringing fresh fuel into the hydrogen-burning interior and would produce C/N and ^{12}C/^{13}C ratios beneath the visible surface which are similar to the observed characteristics of the weak G-band stars. However, we caution that some limits may need to be placed on the amount of extra burning occurring in the blue straggler precursors of the weak G-band stars. Sneden and Pilachowski (1984) searched without success for abnormally high helium contents in two field-weak G-band stars, placing a limit of $y < 0.3$. If the extra burning in a blue stragglers produces significant amounts of helium, that helium apparently is not brought to the surface of resulting weak G-band star in observable quantities.

The extra mixing hypothesis may be carried a step further by noting that Pendl and Seggewiss (1975), from studies of the spectral types of blue stragglers, have suggested a link between blue stragglers and chemically peculiar stars. Abt (1985) has determined the spectral types of a larger sample of field and cluster blue stragglers and has concluded that an unusually high percentage are chemically peculiar of the Ap(Si) and Ap(Sr, Cr, Eu) types. As Abt points out, such Ap stars often show strong photospheric magnetic fields of order 10^3 gauss (Babcock 1958), and Schussler and Pahler (1978) and Hubbard and Dearborn (1980) have determined that moderate interior magnetic fields (10^5 gauss) will mix the interior of a 2–5 solar mass star in less than its main-sequence lifetime. Abt argues that magnetically induced mixing provides the physical mechanism for Wheeler's (1979) quasi-homogeneous mixing hypothesis to account for the blue stragglers. This hypothesis provides also a natural link to the weak G-band stars.

These tantalizing speculations naturally lead to some observational questions which must be confronted. (1) Can the weak G-band nature of star 301 in NGC 7789 be confirmed? We do not know its absolute CNO abundances, and its $^{12}C/^{13}C$ value is slightly higher than those of the few weak G-band stars analyzed to date. (2) What are the spectral types and magnetic field strengths of the NGC 7789 blue stragglers? (3) Can lithium be detected in the blue stragglers, and is it more abundant than the cosmic limit?

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