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ISOTOPIC CARBON RATIOS AMONG M71 BRIGHT RED GIANTS

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ABSTRACT

We present high signal-to-noise, high-resolution spectra of 8005 Å ^{12}CN and ^{13}CN lines in two groups of CN strong/weak M71 (C1951+186, NGC 6838) bright giants chosen for their different [O/Fe] and [Na/Fe] abundances, as well as CN band strengths. These abundance variations in M71, as well as similar star-to-star differences in [O/Fe] and [Na/Fe] seen in other clusters (e.g., M92, M15, M13, M3, and M5), have been suggested to result from differing degrees of deep mixing. Our analysis of the present observations with synthetic spectra yields ^{12}C/^{13}C ratios ranging from 4.9 to 8.9; the CN-strong/O-poor stars exhibit slightly lower ratios. This ^{12}C/^{13}C difference between the two groups may conceivably be the result of differing degrees of the dredge-up.

Subject headings: globular clusters: general — stars: abundances — stars: evolution

1. INTRODUCTION

A remarkable feature of galactic globular clusters is that stars within a single cluster are, with the exception of two clusters (M22 and ω Cen), of a common metallicity. Significantly, this uniformity does not extend to lighter elements such as C, N, O, Na, and Al. Possible explanations typically break down into two scenarios: (1) that the star-to-star abundance differences are due to primordial variations, that is, inhomogeneous pollution by an early generation of massive or intermediate mass stars, or (2) the deep mixing of freshly synthesized nucleosynthetic products to the stellar surface of a giant. The body of previous observations is summarized in the reviews of Smith (1987, 1989) and Suntzeff (1989, 1993).

The recent high-resolution surveys of bright globular cluster giants by Sneden et al. (1991, 1992, 1994) and Kraft et al. (1992, 1993) have brought an interesting trend to light: namely, the anticorrelation of O and Na abundances among highly evolved stars in a number of clusters. This has led Langer, Hoffman, & Sneden (1993) to model the possibility of Na (and Al) production during the ON-cycle of H burning in these low-mass stars. Should this prove correct, the CN versus Na and Al correlations observed in several globulars (first noted by Peterson 1980) and long believed to be only possible by primordial enhancements, as well as the O versus Na anticorrelations, may well be the result of deep mixing—not only of material processed through the CN-cycle, but the ON-cycle as well.

The atmospheric isotopic ratio of ^{12}C/^{13}C is a sensitive probe of the presence of material processed through the CN-cycle. As increasing amounts of CN-processed material are mixed to the surface, the ^{12}C/^{13}C ratio is expected to fall to a value approaching equilibrium and the ^{14}N abundance to saturate close to the sum of the initial ^{12}C, ^{13}C, and ^{14}N abundances (see, e.g., Sneden, Pilachowski, & VandenBerg 1986). Indeed, among low-mass bright (evolved) red giants in the field, open, and globular clusters, ^{12}C/^{13}C ratios from 10 to 3.5 are common (Sneden et al. 1986; Gilroy 1989; Brown & Wallerstein 1989; Bell, Briley, & Smith 1990; Suntzeff & Smith 1991). In this *Letter*, we examine ^{12}C/^{13}C ratios in five bright red giants from the globular cluster M71: two are CN-weak and three are CN-strong.

2. OBSERVATIONS

Two CN-strong/weak pairs of M71 giants with similar color and luminosity (I-45, I-46, I-53, and A9) were observed on the nights of 1993 August 12, 13, and 15 with the McDonald Observatory's 2.7 m telescope, cross-dispersed "2D coudé" echelle spectrograph (Tull et al. 1993), and a Tektronix CCD detector (TK2). The remaining star (S) was observed on the nights of 1993 October 1–4 with the identical setup, except that a Texas Instruments CCD (TI2) was used. A resolution of $R = \lambda/\Delta\lambda$ of 60,000 at 8005 Å was achieved with TK2 and $R \approx 100,000$ with TI2. A slit width of 1".2 was employed throughout, and the seeing varied from 1".0 to 1".5. Exposures of bright, hot, rapidly rotating stars were made at the start and end of each night to aid in the removal of the telluric lines. Spectra were also taken of Arcturus (HR 5340) on the first night for comparison with the analysis of Day, Lambert, & Sneden (1973). The program stars themselves were observed with 1800–3600 s integrations, switching between members of each CN-strong/weak group. Multiple observations of the same star were cleaned of cosmic rays by hand, divided by the spectra of the hot stars to minimize telluric absorption features, and averaged. The resulting spectra are plotted in Figure 1. The primary CN lines of interest are near 8005 Å; the central order covered the interval 7985–8020 Å (TK2) and 7990–8020 Å (TI2). The S/N of the summed spectra at 8005 Å are roughly 200 for TKS and 150 for TI2.

3. ANALYSIS

The principal tool of our analysis is the MOOG spectrum synthesis package developed by Sneden (1973). Model atmospheres were interpolated from the grid of Bell et al. (1976). Our model parameters (Table 1) were taken directly from the high-resolution analysis of Sneden et al. (1994), including their metallicities and microturbulent velocities (ξ).

In order to determine ^{12}C/^{13}C ratios, the region containing both weak ^{12}CN and ^{13}CN lines near 8005 Å was used as the "primary" isotope indicator. As is clear from Figure 1, the 8005 Å region contains five features attributable primarily to CN absorption: four are dominated by ^{12}CN and one blend consists of three ^{13}CN lines. The line list used here was taken from Gilroy (1989) and Gilroy & Brown (1991), who have used

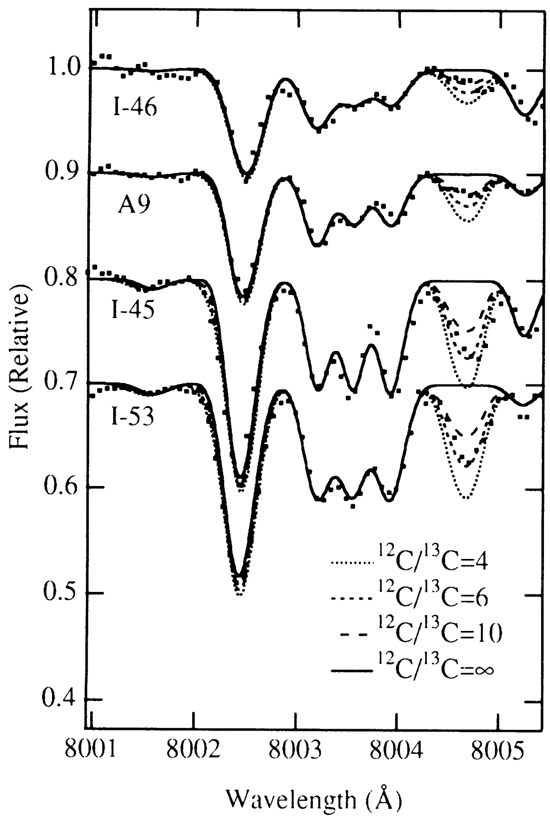

FIG. 1.—Observed spectra of two CN-weak (I-46 and A9) and two CN-strong (I-45 and I-53) M 71 giants are plotted along with their corresponding fits with synthetic spectra.

these features to determine $^{12}C/^{13}C$ ratios in open cluster giants. The CN wavelengths are laboratory measurements from Davis & Phillips (1963) for ^{12}CN, and Wyller (1966) for ^{13}CN, and the absolute *f*-value for the 2–0 band is based upon the solar analysis of the CN lines from Sneden & Lambert (1982). Weak atomic lines in this region have been included using the line list of Kurucz & Peytremann (1975); the only detectable atomic lines are a Ti I line at 8005.223 Å (visible in the cooler stars I-45 and I-46; Fig. 1), and a Ti I line which contaminates slightly the 8003.21 Å ^{12}CN feature.

The excitation potentials of the CN lines used here span the range $\chi = 0.0$ to 0.3 eV, and thus their relative line strengths are insensitive to plausible changes in the effective temperature of the model atmosphere used. Also, as is apparent from Figure 1, these are relatively weak features in these metal-poor giants ($\log W/\lambda < -5.2$ for the CN-strong stars), on the linear portion of the curve of growth. With the ^{13}CN blend rivaling the ^{12}CN in absorption, the derived isotope ratio is therefore effectively independent of the microturbulence used in the spectrum synthesis. These insensitivities to $T_{\rm eff}$ and ξ make these excellent features to use in a determination of $^{12}C/^{13}C$.

In deriving the $^{12}C/^{13}C$ ratios, the choice of C and N abundances is unimportant as long as the synthesis reproduces the observed ^{12}CN and ^{13}CN lines. We suppose that the initial surface abundances of these giants are given by the mean [Fe/H] = −0.78 and [O/Fe] = +0.39 of the CN-weak giants as analyzed by Sneden et al. (1994), and the assumption that [C/Fe] = [N/Fe] = 0.0, that is, $\log \epsilon(X) = 7.82$, 7.22, and 8.54 for X = C, N, and O, respectively. The C, N, and O abundances of the giants are calculated using Sneden et al.'s O abundance and the assumption that the processed material added to the atmosphere redistributed but conserved the total number of CNO nuclei. Adopted values are given in Table 1.

For the CN-weak stars I-46 and A9, good fits to the spectra can be found by simply decreasing the abundance of C and increasing that of N, while holding the total C + N fixed. The somewhat lower oxygen abundances found by Sneden et al. for the CN-strong stars (I-45, I-53, and S) may indicate the mixing of ON-cycle material to the surface here, and, for these stars, we require significantly larger N abundances (for arbitrarily low values of [C/Fe] = −0.6) to fit the CN lines. Good fits to the observed spectra can be obtained with the O abundances from Sneden et al. and increasing N such that total CNO is approximately conserved. Without independent C abundances, we cannot uniquely determine both C and N with our limited spectral coverage; however, our syntheses suggest that it is plausible that the CN line strengths observed in these five stars can be explained by a constant C + N + O abundance.

Our fit to the observed spectrum of Arcturus (α Boo), as computed from the parameters in Table 1, yields $^{12}C/^{13}C = 8.0 \pm 1.5$, in accord with the results of Day et al. (1973). This is reassuring, as Arcturus is similar to our program stars. Figure 1 displays the observed 8005 Å region of four of the M71 stars along with their corresponding synthetic spectra. Immediately evident is the difference in CN band strengths between stars I-45 and I-53 (CN-strong), and I-46 and A9 (CN-weak). The derived $^{12}C/^{13}C$ ratios for all five program stars are listed in Table 1. All of these stars have very low ratios, regardless of CN-band strength, [O/Fe], and [Na/Fe].

As a check on the results obtained using the ^{13}CN feature near 8005 Å, we ran additional spectrum syntheses on two distinct, but weaker features near 8011 Å. In our high-quality spectrum of α Boo, these lines yield $^{12}C/^{13}C$ ratios that are in complete agreement with that derived from the 8005 Å feature: 8.0 ± 1.5. In M71, these ^{13}CN lines are detected in all of the program stars; however, in the CN-weak giants these features are extremely weak (weaker than the 8005 Å feature) and cannot be used to determine very accurate $^{12}C/^{13}C$ ratios.

TABLE 1

PROGRAM STARS, MODEL PARAMETERS, AND RESULTS

Star	CN-type	V^a	$T_{\rm eff}^a$	$\log g^a$	[Fe/H]^a	[O/Fe]^a	[Na/Fe]^a	^{12}C	^{14}N	^{16}O	ΣCNO	$^{12}C/^{13}C$
Arcturus	...	−0.05	4300	1.50	−0.47	+0.27	+0.14	...	...	...	...	8.0 ± 1.5
I-45	Strong	12.36	4050	0.80	−0.78	+0.13	+0.49	7.20	8.30	8.30	8.62	6.2 ± 1.8
I-46	Weak	12.29	4000	0.80	−0.79	+0.38	+0.22	7.25	7.80	8.54	8.63	8.9 ± 1.8
I-53	Strong	12.97	4300	1.40	−0.82	+0.27	+0.53	7.40	8.30	8.41	8.68	6.4 ± 1.4
A9	Weak	12.94	4200	1.20	−0.84	+0.41	+0.20	7.40	7.85	8.49	8.61	8.8 ± 15
S	Strong	12.94	4300	1.25	−0.72	+0.17	+0.19	7.40	8.23	8.38	8.65	4.9 ± 0.9

[a] See Sneden et al. 1994 and references therein.

Using the ratios derived from the 8005 Å feature, however, results in very good fits to the ^{13}CN features near 8011 Å, and, although it is not possible to make definitive tests of $^{12}C/^{13}C = 8$ versus 6, ratios as low as four are ruled out by these ^{13}CN lines. For the CN-strong giants, the 8011 Å lines are strong enough to provide good checks, and for these stars the agreement is very good: differences of less than, or about, 1.0 in the carbon isotope ratio are derived from the 8011 Å lines relative to the 8005 Å feature. These comparisons indicate that the $^{12}C/^{13}C$ ratios derived here for the five M71 stars are of high quality.

4. DISCUSSION

The first dredge-up experienced by stars evolving onto the red giant branch is predicted to bring material mildly exposed to the CN-cycle into the atmosphere such that red giants have reduced abundances of ^{12}C and enhanced levels of ^{13}C and ^{14}N. In common with stars in other globular clusters and similar stars in the field, the observations of RGB stars show that the predictions of the first dredge-up do not account completely for the observed compositions.

The new data provided here are the $^{12}C/^{13}C$ ratios of three CN-strong and two CN-weak giants (Table 1). These results are the first determinations of the $^{12}C/^{13}C$ ratio for M71's red giants. Of especial note are the lower ratios for the CN-strong stars: $^{12}C/^{13}C = 8.9 \pm 1.8$ and 8.8 ± 1.5 for the CN weak stars, but 6.2 ± 1.3, 6.4 ± 1.4, and 4.9 ± 0.9 for the CN-strong stars. This is not a surprising result because the N-rich C-poor material added to make the CN-strong stars presumably had a $^{12}C/^{13}C$ ratio near 3.4, the equilibrium ratio for the CN-cycle. Similar results were obtained from CO 2.3 μm bands for two pairs of CN- weak/strong giants in 47 Tuc by Bell et al. (1990); however, the ^{12}CO bands in their stars were saturated, so the difference in $^{12}C/^{13}C$ between the two groups was uncertain. CO 2.3 μm bands have also been used by Smith & Suntzeff (1989) and Suntzeff & Smith (1991) in M4, NGC 6752, and M22. Successful attempts to extract the $^{12}C/^{13}C$ ratios from the CN 8000 Å lines (e.g., Brown & Wallerstein 1989 for M4, M22, Omega Cen, and 47 Tuc, and Brown; Wallerstein, & Oke 1991 for M13) have covered CN-strong but not CN-weak stars.

The $^{12}C/^{13}C$ ratios of the CN-weak stars are most probably in conflict with predictions of the first dredge-up. Predictions depend on the initial (main-sequence) $^{12}C/^{13}C$ ratio which, in principle, could be so low (say, $^{12}C/^{13}C \approx 10$) that a ratio $^{12}C/^{13}C$ of eight follows then naturally for a red giant. Sneden et al. (1986) and Shetrone, Sneden, & Pilachowski (1993) discuss the low $^{12}C/^{13}C$ ratios of field old disk stars and provide some evidence that their main-sequence progenitors did not have a low $^{12}C/^{13}C$. If the low $^{12}C/^{13}C$ ratios of M71's CN-strong and CN-weak giants are to be ascribed to internal effects, one possibility is that extensive mixing occurred in the progenitors such that material later incorporated into a giant's convective envelope was mildly exposed to the CN-cycle. Lambert & Ries (1981) discuss such a scheme to account for the low $^{12}C/^{13}C$ ratios seen in field G and K giants of near-solar metallicity. If the production of the excess ^{13}C is ascribed to the progenitor, one might expect there to be no trend in the $^{12}C/^{13}C$ ratio with luminosity on the RGB. Sneden et al. (1986) offer evidence that the $^{12}C/^{13}C$ ratio for field old disk giants declines up the RGB. Of more pertinence are observations showing the ^{12}C abundance to decline with luminosity on the RGB of the well-studied globular clusters M92, M15, and NGC 6397 (Carbon et al. 1982; Trefzger et al. 1983; Langer et al. 1986; Briley et al. 1990). A luminosity-dependent change of composition implies that red giants are changing their surface composition as deep mixing and (probably) processing are active in the interior. Sweigart & Mengel (1979) proposed that meridional circulation around a rapidly rotating He-core could lead to continuous exposure of material in the envelope to H-burning reactions. If the bimodal distribution of the CN intensities are to be identified with such processing, it would seem necessary to suppose that there is a sharp threshold for the onset of mixing into the envelope and atmosphere.

Standard predictions for the first dredge-up expect the surface O and Na abundances to be unaffected. As noted earlier, recent studies have shown that giants in globular clusters may show correlated Na (and Al) enrichments and O deficiencies. According to Sneden et al., M71's giants offer no extreme examples of the Na-O anticorrelation but scrutiny of their abundances does suggest that the atmospheres of the CN-strong stars are contaminated with products of the ON-cycles. Sneden et al. analyzed three CN-strong and seven CN-weak giants. A striking presentation of the difference between the two classes is that the [O/Fe] of the three CN-strong stars are 0.13, 0.17, and 0.29, whereas the CN-weak stars have [O/Fe] in the narrow range from 0.33 to 0.44. The lesson seems clear: the N enrichment of the CN-strong stars came from addition to the atmospheres of ON-cycled (O-poor and N-rich) material. Qualitatively, this conclusion is consistent with our result that the CN-strong stars have the lower $^{12}C/^{13}C$ ratios.

Evidence for Na enrichment of the CN-strong stars is not quite so clear-cut as the remarkable O deficiency. Two of the three CN-strong giants have a higher than average Na abundance: [Na/Fe] = 0.49 and 0.53 where the mean for the seven CN-weak giants is 0.15 ± 0.10 ($\sigma = 0.04$). The third CN-strong giant has [Na/Fe] = 0.19 and, at face value, appears to be O-poor but not Na-enriched. Then apart from this CN-strong star, the CN-strong stars in M71, as in other clusters, are O-poor and Na-rich thanks (presumably) to the addition of material exposed to the ON-cycle and associated nuclear reactions. The exception may show that ON cycling conversion of H to He is not always accompanied by the conversion of Ne to Na.

Finally, we remark upon Figure 2 in which $^{12}C/^{13}C$ ratios derived for cluster red giants in 47 Tuc, NGC 6752, M4, and M71 are plotted as a function of [Fe/H]. These stars are all near the RGB tips in their respective clusters (by virtue of the necessary brightness in order to observe the isotopic features), and therefore in similar evolutionary states. While these results come from a variety of authors and sources (both ^{13}CO and ^{13}CN), two interesting trends are apparent. First, among the metal-rich globulars 47 Tuc and M71, all of the CN-weak stars (plotted with open markers) have higher $^{12}C/^{13}C$ ratios. Yet among the more metal-poor clusters, this is not the case. Also, there appears to be a slight trend between [Fe/H] and the $^{12}C/^{13}C$ ratio. This makes sense in terms of the features outlined by Sweigert & Mengel (1979): both the molecular weight (μ) gradient that normally prohibits deep mixing and the thickness of the H-burning shell are sensitive to the overall metallicity. In the more metal-poor stars, the μ gradient is smaller and the shell thinner. Thus in the more metal-poor stars, the mixing mechanism described by Sweigert & Mengel (1979) should be more efficient, leading to lower $^{12}C/^{13}C$ ratios. This may further explain why C depletions with increasing evolu-

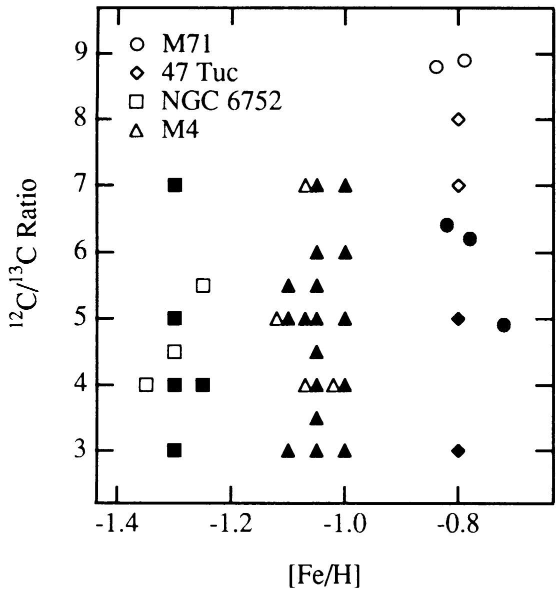

FIG. 2.—$^{12}C/^{13}C$ ratios are plotted as a function of [Fe/H]. CN-weak stars are plotted with open symbols, CN-strong with filled symbols.

tionary state have been observed in many low [Fe/H] clusters (M92, M15, and NGC 6397, Carbon et al. 1982; Trefzger et al. 1983; Langer et al. 1986; Briley et al. 1990), yet not in metal-rich clusters such as 47 Tuc. Moreover, the [O/Fe] versus [Na/Fe] correlation, so pronounced in the more metal-poor clusters (M92, M15, M13, M3, and M5; Sneden et al. 1991, 1992; Kraft et al. 1992), appears weaker among the M71 and M4 red giant branch (RGB) stars (Drake, Smith, & Suntzeff 1992; Sneden et al. 1994). Of course, the chance that a primordial mechanism may have caused these patterns must not be overlooked. Likewise it may be possible that Figure 2 may be explained in terms of slightly differing masses of evolved red giants in the clusters. Both 47 Tuc and M71 are "disk" globular clusters, while M4 and NGC 6752 are considered members of the halo. Should 47 Tuc and M71 be slightly younger than M4 and NGC 6752, the higher masses of the younger bright giants will inhibit mixing.

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