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ISOTOPIC CARBON ABUNDANCES IN M71

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ABSTRACT

High resolution echelle spectra of the 8005 Å CN bands are presented for five bright giants in the globular cluster M71 (C1951 +186, NGC 6838). An analysis of the $^{13}\text{C/N}$ feature included in this region confirms the results of Briley *et al.* [ApJ, 429, L119 (1994)]; that the M71 red giants evince low $^{12}\text{C}/^{13}\text{C}$ ratios and that these ratios are correlated with CN band strengths (CN-strong stars having lower $^{12}\text{C}/^{13}\text{C}$ ratios). This finding is consistent with the theory that the star-to-star CN band strength variations, as well as the oxygen and possibly sodium differences observed in M71, are related to the CN(O)-cycle of hydrogen burning. (One asymptotic giant branch candidate is also included in the present sample, which exhibits both weak-CN band strength and a low $^{12}\text{C}/^{13}\text{C}$ ratio.) Examination of published data on CN band strengths and $^{12}\text{C}/^{13}\text{C}$ ratios among the more metal-poor clusters implies a metallicity dependence in the efficiency of the underlying mechanism responsible for the low $^{12}\text{C}/^{13}\text{C}$ ratios. A likely candidate appears to be the mixing of CN(O)-processed material into the stellar atmospheres, although a primordial source of CN-processing cannot be ruled out. © 1997 American Astronomical Society. [S0004-6256(97)03401-8]

1. INTRODUCTION

Critical to our use of the chemical makeup of stars as probes of Galactic history is an understanding of the underlying processes responsible for the abundance patterns we observe. An excellent example of this can be found in the galactic globular clusters, where star-to-star differences in atmospheric abundances of C, N, O, and often Na and Al have been found within every cluster studied to date. This is in stark contrast to the abundances of other elements such as Fe and Ca, which are almost indistinguishable among most stars within a given cluster (with two notable exceptions: M22 and ω Cen).

Two explanations have been entertained for the star-to-star abundance differences: 1) the gas from which the stars formed was not thoroughly mixed, and 2) deep mixing within the stars has brought differing degrees of freshly synthesized products to the surface from layers that experienced the H-burning CNO-cycles and associated reactions. The extent to which either or both of these processes have contributed to the chemical makeup of present day cluster stars is uncertain, despite a considerable body of research (see Suntzeff 1993; Briley *et al.* 1994a; Kraft 1994 for recent reviews). An understanding of these process is important. The existence of a mixing process would imply that the bright red cluster giants from which the overall cluster abundances are often determined no longer reflect the original composition of the clusters and their lower mass members, e.g., the ratio of O to Fe and other heavy elements may be different between the cluster giants and dwarfs, which in turn

may affect cluster ages as determined from comparisons between main sequence turn-off and horizontal branch morphologies.

One test for the presence of material which has been exposed to the CN-cycle of H-burning is the $^{12}\text{C}/^{13}\text{C}$ ratio. The equilibrium $^{12}\text{C}/^{13}\text{C}$ value for the CN-cycle is 3.5, while the ratio found in the solar atmosphere is almost 90. Standard models of the mixing occurring as stars first ascend the giant branch predict a decrease of the $^{12}\text{C}/^{13}\text{C}$ ratio from an assumed ratio of 90 to about 20 (see Iben 1964; Sneden *et al.* 1986; Charbonnel 1994). Measurements of the $^{12}\text{C}/^{13}\text{C}$ ratio in low mass metal-poor field and cluster giants show $^{12}\text{C}/^{13}\text{C}$ generally much lower than the predicted value (Sneden *et al.* 1986; Gilroy 1989; Smith & Suntzeff 1989; Brown & Wallerstein 1989; Bell *et al.* 1990; Suntzeff & Smith 1991; Brown *et al.* 1991; and others). This discrepancy most likely cannot be attributed to a low initial isotope ratio (cf. Sneden *et al.* 1986; Gilroy & Brown 1991), and is often cited as evidence of a deep mixing process.

Recently, the nearby metal-rich ([Fe/H] = -0.8) globular cluster M71 was found by Sneden *et al.* (1994) to show evidence of star-to-star differences in O (and to some extent Na) abundances, although to a much smaller degree than is seen in the more metal-poor clusters M13, M3, M5, and M10 (Kraft *et al.* 1992; Sneden *et al.* 1992; Kraft *et al.* 1993, 1995). One interpretation of these results is that some form of deep mixing or diffusion has made material which has been processed through the CN and possibly ON branches of the CNO-cycle above the H-burning shell accessible to the convective envelope. Such matter will be C and O-poor and

TABLE 1. M71 program star data.

Star ^a	<i>V</i> ^b	<i>T</i> _{eff} ^c	log <i>g</i> ^c	[<i>Fe</i> / <i>H</i>] ^c	[<i>O</i> / <i>Fe</i>] ^c	¹² <i>C</i>	¹⁴ <i>N</i>	¹⁶ <i>O</i>	ε(<i>CNO</i>)	¹² <i>C</i> / ¹³ <i>C</i>	error
CN-weak stars:											
A4	12.20	4100	0.80	−0.76	0.37	7.30	7.90	8.54	8.65	8.5	1.4
I-46 ^d	12.29	4000	0.80	−0.79	0.38	7.25	7.80	8.54	8.63	8.9	1.8
I-113	12.43	3950	0.70	−0.81	0.33	7.15	8.18	8.45	8.65	8.1	1.2
I-77	12.65	4100	0.95	−0.76	0.38	7.30	7.92	8.55	8.66	7.5	1.7
A9 ^d	12.94	4200	1.20	−0.84	0.41	7.40	7.85	8.49	8.61	8.8	1.5
CN-strong stars:											
I-45 ^d	12.36	4050	0.80	−0.78	0.13	7.20	8.30	8.30	8.62	6.2	1.8
S ^d	12.94	4300	1.25	−0.72	0.17	7.40	8.23	8.38	8.65	4.9	0.9
I-53 ^d	12.97	4300	1.40	−0.82	0.27	7.40	8.30	8.41	8.68	6.4	1.4
I-66	13.01	4350	1.45	−0.80	0.19	7.26	8.34	8.32	8.65	6.5	0.6
AGB member:											
I	12.42	4200	1.00	−0.89	0.37	6.97	8.26	8.41	8.65	5.3	0.8

Notes to TABLE 1

^aStar identifications from Arp & Hartwick (1966).
^bPhotometry from Cudworth (1985).
^cParameters from Sneden *et al.* (1994), with the exception of I-66.
^dObserved by Briley *et al.* (1994b).

N-rich and possibly also enriched in *Na* and *Al* (through proton captures on *Ne* and *Mg*: see Denisenkov & Denisenkova 1990; Langer *et al.* 1993; Langer & Hoffman 1995; Cavallo *et al.* 1996). Thus, the *Na* and *Al* intracluster abundance variations (e.g., Cohen 1978; Peterson 1980; Cotrell & Da Costa 1981; Pilachowski *et al.* 1983; Norris & Pilachowski 1985; Lehnert *et al.* 1991; Suntzeff & Smith 1991; Drake *et al.* 1992), which have been traditionally cited as evidence for a primordial origin to the cluster light element variations (e.g., see Cotrell & Da Costa 1981) may well also be the result of mixing.

A subsequent study of five of these bright M71 giants by Briley *et al.* (1994b) demonstrated that all five of the stars have very low ¹²*C*/¹³*C* ratios. Moreover, the stars with the strongest CN bands also possessed the lowest ¹²*C*/¹³*C* ratios. A plot of the ¹²*C*/¹³*C* ratios for other clusters of lower metallicity (see their Fig. 2) suggested a trend of decreasing ¹²*C*/¹³*C* ratios with decreasing [Fe/H] although the sample size was admittedly small.

The purpose of this paper is to double the number of M71 stars for which ¹²*C*/¹³*C* ratios have been determined. Three of the program stars are CN-weak, one is CN-strong, and the fifth is a possible asymptotic giant branch member.

2. OBSERVATIONS

roughly *R* = 60,000. The slit width was 1.2 × 8.2 arcsec and seeing was generally better than 1.5 arcsec throughout the course of the observations.

Exposures of hot, rapidly rotating stars at similar air-masses to the cluster stars were interspersed with repeated observations of the program stars. Integration times for the M71 stars ranged from 1800 to 3600 s and at no point were the sky conditions photometric. Multiple observations of the same M71 stars were corrected for scattered light, cleaned of cosmic rays by hand, divided by the spectra of the hot stars (to remove telluric features), and averaged. The resulting spectra have S/N ratios of roughly 100.

The final spectra for the five M71 bright giants are presented in Fig. 1. The CN features of interest are located around 8002–8005 Å, with the ¹³CN feature at 8004.7 Å. Other significant atomic lines in this region include *Fe* at 7999.0, *Ti* at 8005.2, and *Al* at 8003.2 Å (from Kurucz & Peytremann 1975).

3. ANALYSIS

FIG. 1. Observed spectra of the M71 giants listed in Table 1 are plotted along with their corresponding synthetic spectra computed for a variety of $^{12}\text{C}/^{13}\text{C}$ ratios. The ^{12}CN features are at 8002.5, 8003.2, 8003.5, and 8003.8 Å. The ^{13}CN absorption is at 8004.5 Å. Note that the 8003.2 Å feature contains an Al line.

a temperature of 4400 K using the Bell & Gustafsson (1989) model IR colors. As discussed by Briley *et al.* (1994b), the CN features of interest lie within $0.0 < \chi < 0.3$ eV and are therefore largely insensitive to small errors in the choice of T_{eff} . The model parameters appropriate to our program stars are listed in Table 1. Note that all of the program stars appear to be first ascent giants, with the exception of star I, which is likely on the asymptotic giant branch (AGB).

The line list used in the synthesis of this region was taken from the open cluster $^{12}\text{C}/^{13}\text{C}$ studies by Gilroy (1989) and Gilroy & Brown (1991). The wavelengths for ^{12}CN are from Davis & Phillips (1963) and the ^{13}CN wavelengths are from Wyller (1966). The absolute f -value of the 2-0 CN band is based upon the analysis of solar CN lines by Sneden & Lambert (1982). The parameters of the few atomic lines in this region were taken from the list of Kurucz & Peytremann (1975).

In computing the synthetic spectra, abundances of elements which affect the lines in this region (specifically Fe, O and Ti) were taken from Sneden *et al.* (1994). Abundances of the elements C and N were allowed to vary in the initial modeling phase, subject to the (arbitrary) constraint that the total number of C + N + O atoms remains constant. The value of this constant was based on the assumption that initially $[C/\text{Fe}] = [N/\text{Fe}] = 0.0$ and $[O/\text{Fe}] = +0.39$ (from the measurements of O abundances in the CN-weak stars by Sneden *et al.*), or $\epsilon(C+N+O) = 8.65$. The final abundances of C and N which produced the best fits to the ^{12}CN features at 8000, 8002, 8003–8003.75 Å are presented in Table 1. Note that the actual abundances are not critical to extracting the isotope ratios, as long as the observed band strengths are adequately reproduced (i.e., we are comparing

FIG. 2. Resulting $^{12}\text{C}/^{13}\text{C}$ ratios have been plotted against O abundances from Sneden *et al.* (1994). Note the trend of lower $^{12}\text{C}/^{13}\text{C}$ ratios among the O deficient stars as might be expected if the origin of the O variations was tied to the CNO-cycle of H-burning.

relative strengths on the linear portion of the curves of growth). In the case of star I-66 an $[O/\text{Fe}]$ of 0.19 (the average O abundance of the CN strong stars in Sneden *et al.*) was used. It is worth noting that the atomic Al feature in this region (at 8003.2 Å) was best fit by a mild overabundance (of order 0.4 dex), although blending with the CN lines made this determination suspect.

The final C, N, and O abundances from Table 1 were used to generate synthetic spectra for each star with $^{12}\text{C}/^{13}\text{C}$ ratios of 4, 6, 8, and 10. The strengths of the observed ^{13}CN absorption feature at 8004.7 Å was then compared with the models over the wavelength range from 8004.45 to 8004.85 Å and averaged. The resulting $^{12}\text{C}/^{13}\text{C}$ ratios are given in Table 1.

4. RESULTS AND DISCUSSION

The present paper has increased the number of M71 stars with a measured $^{12}\text{C}/^{13}\text{C}$ ratio from 2 to 5 for the CN-weak stars, and from 3 to 4 for the CN-strong stars. An additional star (I) appears to be on the AGB. The ratios are low (< 10). This is not surprising as every study of giants in globular clusters has obtained the same general result (cf. Smith & Suntzeff 1989; Brown & Wallerstein 1989; Bell *et al.* 1990; Suntzeff & Smith 1991; Brown *et al.* 1991). The new results confirm our earlier result that the $^{12}\text{C}/^{13}\text{C}$ ratio is lower for the CN-strong stars: the mean value is $^{12}\text{C}/^{13}\text{C} = 8.3$ (from 7.5 to 8.9) and 6.0 (from 4.9 to 6.5) for the CN-strong stars. This correlation is qualitatively consistent with an increasing level of mixing of the envelope with severely CN-cycled material that is C-poor, N-rich, with a $^{12}\text{C}/^{13}\text{C}$ ratio close to the equilibrium value. Light exposures to the CN-cycle reduce the $^{12}\text{C}/^{13}\text{C}$ ratio to near the equilibrium value before effecting a significant conversion of C to N.

A new correlation emerges from the larger sample now available. The $^{12}\text{C}/^{13}\text{C}$ ratio appears to be correlated with the oxygen abundance as determined by Sneden *et al.* (1994). Figure 2 suggests the $^{12}\text{C}/^{13}\text{C}$ ratio is lower in the O-poor

giants. This implies that ON-cycled H-burning products are increasingly present in the atmosphere of the most ^{13}C -rich stars. Since the ON-cycled material should be very C-poor (and correspondingly N-rich with $^{12}\text{C}/^{13}\text{C} = 3.5$) in contrast to the (partially) CN-cycled material, it should be possible through a full C, N, and O abundance analysis to estimate the relative fractions of CN- and ON-cycled material present in the atmospheres.

One possible source of CN(O)-processed material lies within the cluster giants themselves. Yet, the observed isotope ratios are *not consistent* with the predictions of standard first dredge-up (e.g., Iben 1967) in that they are too low by at least a factor of two. When combined with the implied presence of CN(O)-processed material in virtually every globular cluster giant studied to date (via star-to-star CN and CH band strength differences), the decreasing C abundances with increasing luminosity (advancing evolutionary state) on the red giant branches (RGB's) of the metal-poor globular clusters (Suntzeff 1981; Carbon *et al.* 1982; Trefzger *et al.* 1983; Langer *et al.* 1986; Briley *et al.* 1990), and the observations of $^{12}\text{C}/^{13}\text{C}$ ratios in M67 by Gilroy & Brown (1991), the operation of some additional and possibly continuous (at least in the case of the metal-poor stars) "extra-mixing" process in these low-mass stars is implied. Suggestions presented in the literature include the meridional circulation mechanism described by Sweigart & Mengel (1979), the "cool bottom processing" of Wasserburg *et al.* (1995), and the rotation-induced turbulent diffusion of Charbonnel (1995).

An observable aspect of these types of "extra-mixing," in addition to very low isotopic ratios, is that the efficiency of such processes should be a function of overall metallicity: as one looks to progressively more metal-poor stars, the lower opacities result in higher pressures and temperatures at any given depth. In the more metal-poor stars, this causes an outward shift of the regions of CN and ON-cycling and therefore the location of the ^{13}C peak away from the principally H-burning shell and the corresponding molecular weight gradient. Thus, the overall effect of decreasing metallicity is to increase the amount of material exposed to the CN and possibly ON-cycle that may be circulated to the surface (Sweigart & Mengel 1979; Charbonnel 1994, and others).

There is evidence that this prediction is recognized by stars. Measurements of the $^{12}\text{C}/^{13}\text{C}$ ratios in red giants from globular clusters of various metallicities are assembled in Fig. 3. Giants from the more metal-poor clusters ($[\text{Fe}/\text{H}] < -1.0$) show a low $^{12}\text{C}/^{13}\text{C}$ ratio irrespective of the CN band strength. The $^{12}\text{C}/^{13}\text{C}$ ratios are close to the equilibrium ratio for the CN-cycle: the mean for NGC 6752 and M4 is 4.6 and 4.9, respectively. For the two metal-rich clusters — 47 Tuc and M71, there is a clear difference between the $^{12}\text{C}/^{13}\text{C}$ ratios of CN-weak and CN-strong giants. This difference for 47 Tuc was noted by Bell *et al.* (1990) from an analysis of four giants. The difference for M71 noted by Briley *et al.* (1994b) is confirmed by this present study of additional giants. That Bell *et al.* obtained similar results with IR ^{13}CO band strengths rather than CN implies this effect is not an artifact of the present technique, but

FIG. 3. Observed $^{12}\text{C}/^{13}\text{C}$ ratios for stars with known CN-band strengths (CN-weak = filled markers, CN-strong = open). Among the more metal-rich cluster giants (47 Tuc and M71) there is a noticeable separation in $^{12}\text{C}/^{13}\text{C}$ ratios between the CN-strong and weak stars, implying a link between the C/N inhomogeneities and the CN(O)-cycle. Moreover, the trend of increasing $^{12}\text{C}/^{13}\text{C}$ ratios with $[\text{Fe}/\text{H}]$ implies a metallicity sensitivity to the efficiency with which CN(O)-processed material may be brought to the stellar surface.

rather a general property of the behavior of CN band strengths and isotopic carbon abundances in the more metal-rich clusters. In the case of these clusters, the relation between $^{12}\text{C}/^{13}\text{C}$ and CN band strength is perhaps the strongest link yet between these CN inhomogeneities and the CN-cycle. It should be emphasized that, although metallicity may play a role in determining the extent of the dredge-up of CN-cycled material to the surface, the differences between CN-strong and CN-weak stars are unlikely to be solely due to metallicity: neighboring stars on a red giant branch may be identical in this regard except for their CN band strengths (and related differences).

Star I, the AGB candidate, is a CN-weak star with a low $^{12}\text{C}/^{13}\text{C}$ ratio in contrast to the first ascent CN-weak red giants with "high" $^{12}\text{C}/^{13}\text{C}$ ratios. Perhaps, the He-core flash that terminates the first ascent provided additional mixing of CN-cycled material to the surface. Analysis of elemental C, N, and O abundances may shed light on the origins of the apparent differences between the AGB star and the less evolved giants. Our calculations show that the CN bands of star I are well fit if the C abundance is slightly less than that of the other stars.

We note however that although the present data imply a relation between the CN-cycle and CN(O) abundance variations, in no way do they identify the location of this process, i.e., whether the abundance variations are indeed the result of some "extra" mixing process, or whether they are the result of CN(O) processing in some still unidentified primordial source. Given the observations of CN band strength variations on the main sequences of two of the clusters in Fig. 3 (NGC 6752, Suntzeff 1989; Suntzeff & Smith 1991; and in 47 Tucanae by Hesser 1978; Hesser & Bell 1980; Bell *et al.* 1983; Briley *et al.* 1991, 1994c,), it is quite likely that there is a primordial component to these inhomogeneities. Thus it is possible that some degree of dredge-up has taken place in the M71 RGB stars, but not to the extent that primordial

C, N, and/or O abundances have been significantly modified (as the higher metallicity of M71 limits the efficiency of the dredge-up mechanism). If this is indeed the case, then the correlation between CN-band strengths and isotopic carbon ratios further suggests that either the efficiency of dredge-up is also sensitive to CN-band strength (an unlikely prospect) or that the CN(O)-cycle operating in some other site (not the current cluster giants) is the underlying source of the present abundance variations.

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