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CN AND CH BAND STRENGTH VARIATIONS IN M71 GIANTS

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ABSTRACT

CN and CH band strengths for fourteen bright giants in the globular cluster M71 have been measured from archival spectra obtained with the Multiple Mirror Telescope. Adding the collected data from the literature we confirm a bimodality of CN distribution on the red giant branch and the horizontal branch, and CN-CH anti-correlations on the lower giant branch and horizontal branch. However a CN-CH anti-correlation on the upper red giant branch is not quite clear as those of other branches. The small number of statistics could not be excluded as a possible cause. To confirm this, a greater number of sample stars are needed. We also confirm that the ratio of CN-strong to CN-weak stars is quite different from that in 47 Tuc, although the anti-correlation between CN and CH bands, the bimodality of the CN distribution, and the spatial distribution of CN stars in M71 are found to be similar to those in 47 Tuc.

Key words : globular clusters: individual(M71) — stars: late-type — stars: Population II

I. INTRODUCTION

The large scatter of the abundances of C, N, O, Na, Mg, and Al among globular cluster red giants has tantalized researchers for more than three decades. It has been found that most clusters (except ω Cen and M22) show negligible internal variations in the abundance of iron group elements, but there are wide variations within the CNO group and among light elements Na, Mg, and Al. The observed abundance variations among cluster giants are far different from those predicted from the classical stellar evolution models and larger than those observed in field giants of similar metallicity. Classical evolution theory (Iben 1964) predicts modest alternations of the surface abundances due to the first dredge-up during the RGB phase. For a solar metallicity star, a factor of two depletion of C^{12} with a lowering of the C^{12}/C^{13} ratio from 90 ~ 100 to about 20 ~ 30 and an increase of N^{14} by a corresponding amount are expected (Iben & Renzini 1984). In fact, field halo giants of lower RGB stars are found to have abundances of light elements in agreement with predictions from classical evolutionary models. Therefore, the larger-than modest variations among red giants in globular clusters could have originated from either processed materials dredged up to the surface by extra mixing during RGB evolution or primordial and/or accreted and/or polluted inhomogeneous materials.

Although some observational data of evolved red giant stars in the most metal-poor globular clusters M92 (Carbon et al. 1982), M15 (Trefzger et al. 1983), and NGC 6397 (Briley et al. 1990), hint at the deep mixing episode caused by meridional circulation which was proposed early by Sweigart & Mengel (1979). However, the picture for higher metallicity globular clusters is not so clear. It seems that the processes altering CNO abundance during RGB evolution are sensitive to overall metallicity. The surface abundances of globular cluster RGB stars have revealed a more complex phenomenology. This is likely due to the fact that the surface abundances of these stars are significantly affected by several major factors: deep mixing within individual stars, primordial inhomogeneities within clusters and perhaps accretion and pollution of processed material during the early phases of the cluster evolution.

Some abundance variations found in Turn-Off (TO) and early subgiants, and main-sequence stars in globular clusters are mainly due to the primordial origin and/or accretion and pollution. Especially a CN-CH anti-correlation found in main-sequence stars of NGC 6752 (Suntzeff & Smith 1991), 47 Tuc (Briley 1997; Cannon et al. 1998; Harbeck et al. 2003) and M71 (Cohen 1999; Briley et al. 2001; Briley & Cohen 2001) and a O-Na anti-correlation found in unevolved stars of NGC 6752 (Grattton et al. 2000) and 47 Tuc (Harbeck et al. 2003) could not be explained by an extra deep mixing since main-sequence stars do not have a deep convective envelope down to the burning region. Therefore, if any mixing takes place during red giant branch ascent in M71 it is little and a substantial component of the C and N abundance inhomogeneities is in place before the main sequence turn-off (Briley & Cohen 2001).

M71 is one of the most metal-rich clusters ([Fe/H] ~ -0.79, Sneden et al. 1994) among the Galactic globular clusters. Both CN-strong and CN-weak stars at the same apparent magnitude among M71 giants with luminosities exceeding those of HB stars were discovered by Smith & Norris (1982). It was found that the CN strengths were anti-correlated with the strengths of the CO near-IR bands, but a positive correlation between CN and Na line strengths was shown. Penny et al. (1992) found a bimodal CN-band strength distribution and anti-correlated CN and CH inhomogeneities among lower RGB stars in M71, and a similar pattern was found by Smith & Penny(1989) among the red horizontal branch (RHB) stars of this cluster.

Recent spectroscopic study of main sequence stars in M71 (Cohen 1999) showed significant variations in the strength of the CN band and the CH band among stars at fixed luminosity in the main sequence of M71. Both CH and CN indices appear to be bimodal and they are anti-correlated. These results of M71 are similar to 47 Tuc (Cannon et al. 1998). Both clusters are similar not only in their CN distribution, but also in that they possess a CO/CN anti-correlation, and a positive Na/CN correlation. Moreover C^{12}/C^{13} ratios of the M71 red giants are found to be low and these ratios are correlated with CN band strengths such that CN-strong stars have a lower C^{12}/C^{13} ratio (Briley et al. 1994, 1997).

The bimodality in the CN band strengths on the giant branch and on the main sequence in 47 Tuc (Norris & Freeman 1979; Freeman 1985; Paltoglou 1990; Briley 1997; Cannon et al. 1998) has been found from the large sample of stars: the ratio of CN-strong to CN-weak stars is about 2 while the ratio decreases to lower values toward the outer part of the cluster. For M71, Briley et al. (2001) confirmed the bimodal distribution of CN band strengths as DDO C(41-42) color from the sample of 75 red giants down to Mv=+2. The ratio of CN-strong and CN-weak stars on the main sequence is found to be around 1 in M71 (Cohen 1999). Therefore it is of interest to see whether the spatial trends can also be found in M71 and to find the ratio of CN-strong and CN-weak stars for the giant stars in M71. The main object of this study is to add the new data of CN and CH band strengths of giants in M71 from archival spectra obtained with the Multiple Mirror Telescope to increase the sample stars with CN and CH band strengths in M71. Then we collect the published CN and CH band strengths to transform them to one index system to check the anti-correlation between two bands and to find the bimodality distribution of CN band strengths and their spatial distribution. In section 2 measurements of CN and CH band strengths from the archival data of the MMT are described; in section 3 the anti-correlation between two bands and the spatial variations of CN in M71 are presented; in section 4 results are discussed and summarized.

II. CN AND CH BAND STRENGTH

We have analyzed archival spectra for fourteen M71 giants to measure the CN and CH band strengths. The original spectra were obtained with the Multiple Mirror Telescope for a study of "Distant Halo" (Croswell 1990). The spectra were taken with the blue channel of the MMT spectrograph with an 832 l/mm grating blazed at 4300 Å to second order. The resolution was 1 Å with 5 pixels per resolution element, and the wavelength coverage ranged from 3600 Å to 4400 Å. The observed spectra were reduced using the standard NOVA package at the CfA (Center for Astrophysics). The wavelength-calibrated spectra were used for this study.

We measured indices $CN_{(3883)}$, $CN_{(4215)}$, and CH(G) for the sample stars from these spectra. The definitions of the $CN_{(3883)}$, $CN_{(4215)}$, and CH(G) indices are the same as Lee (1999, 2000)'s studies of M3 and M15. These indices are sensitive to the strength of the CN and CH bands. The CN indices are the same as those in Smith et al. (1996, 1997) and the CH index is almost the same as the CH index in Smith et al. (1996, 1997) except for the continuum part of it. An additional $< CN >$ index was defined as an average of the $CN_{(3883)}$ index and twice the $CN_{(4215)}$ index in Lee (1999). This implies that in M3 the two indices are strongly correlated in such a way that the $CN_{(4215)}$ index has a value of one-half the $CN_{(3883)}$ index.

However in M71 which is a more metal-rich globular cluster than M3, the correlation between $CN_{(3883)}$ and $CN_{(4215)}$ indices which is obtained is approximately $CN_{(3883)} = \sim 2.0 \times CN_{(4215)} + \sim 0.10$ and the slope is approximately the same as in the case of M3, but overall the $CN_{(3883)}$ index is shifted to slightly higher than 0.1. In the derivation of this relation, HB stars, red giants fainter than HB, and I-53 are excluded. I-53 shows either exceptionally strong $CN_{(4215)}$ compared with other stars of similar $CN_{(3883)}$ strengths or exceptionally weak $CN_{(3883)}$ compared with others of similar $CN_{(4215)}$ strengths. However no proper reason of this is found, leaving open the possibility of a flaw in the original spectrum. So we excluded I-53 for the derivation of the relation between two CN indices.

A similar correlation is found in M15 stars except for the overall shift of the $CN_{(3883)}$ index by 0.08 to a lower value (Lee 2000). Although the zero point of the $CN_{(3883)}$ index for a given $CN_{(4215)}$ index seems to vary in each globular cluster, the overall shift has a small effect on the $< CN >$ index (a shift of $\sim$ 0.05 to a higher index value for each star systematically in the case of M71) and does not affect a study of comparisons of $< CN >$ indices in a globular cluster. Therefore for the consistency of the index definition, we use the $< CN >$ index as defined in Lee (1999). However in the case of the study of several globular clusters of different metallicites, the zero point of the $CN_{(3883)}$ index in each globular cluster should be taken into account for the comparison between CN indices of red giants in globular clusters, especially for the case of comparing indices with abundance. The zero point shift seems due to the different abundance effects on $CN_{(3883)}$ and $CN_{(4215)}$ indices. As the metallicity of the globular cluster increases, the $CN_{(3883)}$ index becomes larger for a given $CN_{(4215)}$ index, while the $CN_{(4215)}$ index becomes weaker for a given $CN_{(3883)}$ index. Therefore, even in a globular cluster, if carbon and nitrogen abundances of a star are out of the abundances range of a certain group of stars, the star would not

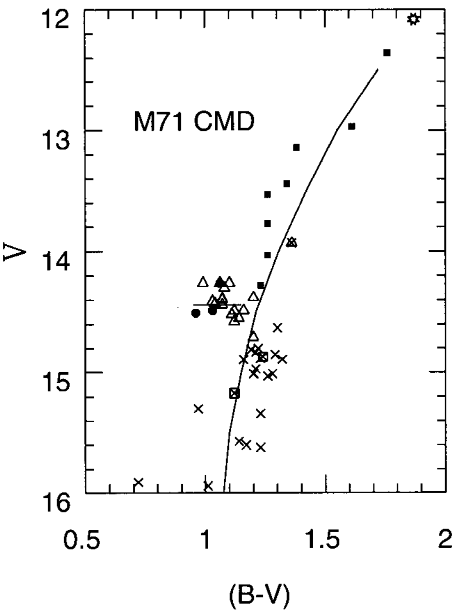

Fig. 1.— V vs. $B-V$ color-magnitude diagram of the globular M71. Fiducial line of giant branch is taken from Hodder et al. (1992). Filled squares, filled circles, and open squares are RGB brighter than HB, HB, and RGB fainter than HB stars of original program stars. Variable V2 is star marked. Open triangles and crosses are stars from Smith & Penny (1989) and Penny et al. (1992).

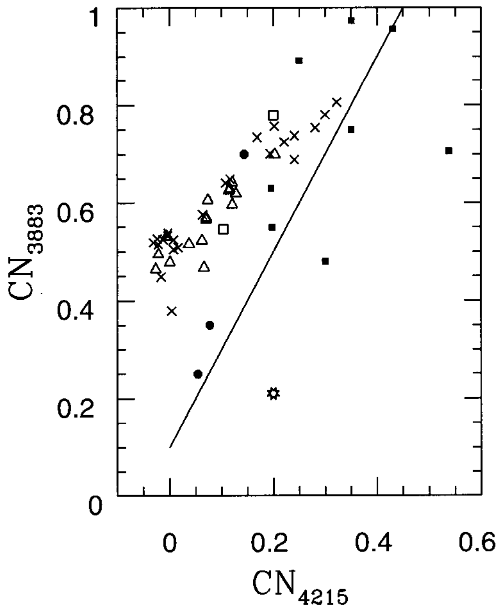

Fig. 2.— Plot of the $CN_{(3883)}$ index vs. the $CN_{(4215)}$ index for all stars listed in Table 1. The correlation between two indices for RGB stars shows quite a similar slope to that found in the previous study of M3 (Lee 1999). However there is some amount of shift and also some scatter found for stars collected from the literature, which are HB and lower RGB stars. Symbols used are the same as for Fig.1.

satisfy the correlation between the $CN_{(3883)}$ index and the $CN_{(4215)}$ index found for that group of stars. Such stars are found in M15, but not in M71. Nevertheless, we used the same definition of $< CN >$, as an average of $CN_{(3883)}$ and two times $CN_{(4215)}$ for M71 stars. Each index for original program stars was measured five times and the error of each index is less than 0.01.

The bright fourteen stars of M71 are listed in Table 1 with collected stars from the literature described in section III. Their designations in column 1 are taken from Arp & Hartwick (1971) and the star number with prefix KC is from Cudworth (1985). Columns 2 and 3 list the V and $(B-V)$ values of Cudworth (1985). The absolute magnitudes and intrinsic colors are also listed, which were obtained from the previously published values of the distance modulus to M71 and the interstellar reddening toward it. Since the values are quite varied across the literature, we adopted a reddening $E(B-V) = 0.27$ and a distance modulus $(m-M)_{v_o} = 12.80$ (Cudworth 1985). Four indices are listed in the following columns with a final column of remarks.

Among fourteen program stars, I-43, I-54, and I-94 are horizontal branch stars (HB), and the rest of the stars are red giants (RGB) according to their positions in the color-magnitude diagram, but I-109 and KC202 are fainter than HB and are in about right position of the RGB bump(Cho & Lee 2002). HB, RGB, and the rest of the stars are represented as filled circles, filled squares, and open squares respectively in Figure 1.

III. CN AND CH BAND STRENGTH VARIATIONS

(a) Anti-Correlation of CN and CH Band Strengths

From literature searches, we could increase the number of stars with CN and CH band strengths up to 50, by transforming indices of other studies to our band index system. Smith & Penny (1989) and Penny et al. (1992) obtained a set of indices qualifying the strengths of the λ 3883 and λ 4215 CN bands, the λ 4300 CH band, and the Ca II H and K lines for 16 red horizontal branch stars and for 23 lower giant stars with magnitudes in the range $+0.8 < M_v < 2.41$ in M71.

We have found one star, I-43 in Smith & Penny (1989) and two stars, I-109, KC-202 in Penny et al. (1992) overlap with our program stars. Since they both used the same index system, we assumed the indices in the two studies are consistent. So with these three stars, we can transform their indices S(3839), S(4142), m_{CH} to our system indices, $CN_{(3883)}$, $CN_{(4215)}$, CH(G), and $< CN >$. They are listed in the lower part of Table 1. Actually the indices for KC-22 were measured in their studies, with differences, -0.055 in S(3839), 0.007 in S(4142), and -0.032 in m_{CH} in the sense of Smith & Penny's (1989) measurements minus Penny et

Table 1
Data for Bright Gaints in M71

Star ID	V	$(B-V)$	M_v	$(B-V)_o$	$\mathrm{CN}_{(3883)}$	$\mathrm{CN}_{(4215)}$	$<CN>$	$CH(G)$	*Remark*
1-1	14.03	1.26	0.43	0.99	0.974	0.350	0.837	0.210	RGB, ST-CN
1-14	13.77	1.26	0.17	0.99	0.630	0.196	0.511	0.280	RGB, WK-CN
1-43	14.26	1.06	0.66	0.79	0.700	0.144	0.494	0.170	HB, ST-CN
1-44	13.44	1.34	-0.16	1.07	0.550	0.198	0.473	0.240	RGB, WK-CN
1-45	12.36	1.76	-1.24	1.49	0.480	0.300	0.540	0.240	RGB, WK-CN
1-53	12.97	1.61	-0.63	1.34	0.706	0.538	0.891	0.280	RGB, ST-CN
1-54	14.49	1.03	0.89	0.76	0.350	0.078	0.253	0.220	HB, WK-CN
1-56	13.14	1.38	-0.46	1.11	0.956	0.430	0.908	0.250	RGB, ST-CN
1-63	13.53	1.26	-0.07	0.99	0.750	0.350	0.725	0.240	RGB,ST-CN
1-67	14.28	1.23	0.68	0.96	0.892	0.250	0.696	0.240	RGB, ST-CN
1-94	14.51	0.96	0.91	0.69	0.250	0.055	0.180	0.190	HB, WK-CN
1-109	14.87	1.24	1.27	0.97	0.546	0.104	0.377	0.220	lower RGB, WK-CN
KC-202	15.17	1.12	1.57	0.85	0.780	0.200	0.590	0.190	lower RGB, ST-CN
V2	12.08	1.87	-1.52	1.60	0.210	0.200	0.305	0.250	variable, WK-CN
1-3	14.38	1.20	0.78	0.93	0.570	0.071	0.356	0.209	RGB, WK-CN
1-11	14.81	1.19	1.21	0.92	0.533	-0.003	0.264	0.213	lower RGB, WK-CN
1-28	14.97	1.21	1.37	0.94	0.449	-0.016	0.209	0.208	lower RGB, WK-CN
1-48	14.39	1.07	0.79	0.80	0.606	0.074	0.377	0.189	HB, ST-CN
1-55	14.26	1.10	0.66	0.83	0.524	-0.116	0.246	0.205	HB, WK-CN
1-58	14.88	1.23	1.28	0.96	0.738	0.241	0.610	0.202	lower RGB, ST-CN
1-59	14.63	1.30	1.03	1.03	0.576	0.064	0.352	0.217	lower RGB, WK-CN
1-61	14.58	1.12	0.98	0.85	0.495	-0.021	0.227	0.202	HB, WK-CN
1-62	14.49	1.12	0.89	0.85	0.523	0.063	0.325	0.203	HB, WK-CN
1-75	14.85	1.29	1.25	1.02	0.781	0.300	0.691	0.198	lower RGB, ST-CN
1-88	14.26	0.99	0.66	0.72	0.597	0.121	0.420	0.177	HB, ST-CN
1-111	14.89	1.32	1.29	1.05	0.689	0.241	0.586	0.222	lower RGB, ST-CN
KC-22	13.93	1.36	0.33	1.10	0.625	0.115	0.428	0.213	RGB, WK-CN
KC-118	14.55	1.14	0.95	0.87	0.479	0.001	0.241	0.197	HB, WK-CN
KC-119	14.52	1.11	0.92	0.84	0.531	-0.005	0.261	0.200	HB, WK-CN
KC-126	14.71	1.20	1.19	0.93	0.566	0.071	0.354	0.209	lower RGB, WK-CN
KC-127	14.44	1.07	0.84	0.80	0.630	0.116	0.431	0.178	HB, ST-CN
KC-130	15.01	1.28	1.41	1.01	0.509	0.017	0.272	0.211	lower RGB, WK-CN
KC-136	14.80	1.22	1.20	0.95	0.806	0.322	0.725	0.197	lower RGB, ST-CN
KC-137	15.91	0.72	2.31	0.45	0.379	0.004	0.194	0.170	WK-CN
KC-141	15.34	1.23	1.74	0.96	0.505	0.008	0.261	0.211	lower RGB, WK-CN
KC-152	15.03	1.26	1.43	0.99	0.527	-0.023	0.241	0.221	lower RGB, WK-CN
KC-155	14.89	1.16	1.29	0.89	0.754	0.281	0.658	0.198	lower RGB, ST-CN
KC-169	14.30	1.08	0.70	0.81	0.699	0.203	0.553	0.178	HB, ST-CN
KC-170	15.57	1.14	1.97	0.87	0.515	-0.021	0.237	0.209	lower RGB, WK-CN
KC-183	15.57	1.14	1.97	0.87	0.725	0.221	0.584	0.193	lower RGB, ST-CN
KC-191	15.01	1.20	1.41	0.93	0.525	-0.012	0.251	0.216	lower RGB, WK-CN
KC-196	15.60	1.17	2.00	0.90	0.701	0.194	0.545	0.199	lower RGB, ST-CN
KC-215	15.30	0.97	1.70	0.70	0.519	-0.030	0.230	0.205	lower RGB, WK-CN
KC-302	15.62	1.23	2.02	0.96	0.525	0.008	0.271	0.213	lower RGB, WK-CN
A3	14.43	1.04	0.83	0.77	0.468	0.067	0.301	0.207	HB, WK-CN
C	14.49	1.16	0.89	0.89	0.516	0.038	0.296	0.214	HB, WK-CN
D	15.94	1.01	2.34	0.74	0.735	0.169	0.537	0.197	lower RGB, ST-CN
K	14.83	1.21	1.23	0.94	0.538	-0.003	0.239	0.213	lower RGB, WK-CN
L	14.41	1.03	0.81	0.76	0.465	-0.026	0.207	0.197	HB, WK-CN
X	14.40	1.07	0.80	0.80	0.642	0.121	0.442	0.187	HB, ST-CN

al.'s (1992) measurements. Therefore we expect those amount of uncertainty for their indices. We use the average values for KC-22.

Figure 1 is the color-magnitude diagram of M71 with the giant branch fiducial line taken from Table 3 of Hodder et al. (1992). The original program stars are represented as filled circles, filled squares, and open squares for HB stars, bright RGB stars, and RGB stars fainter than HB respectively. V2 is represented as a starred mark. Stars from Smith & Penny (1989), mostly HB stars, are represented as open triangles, while those of Penny et al. (1992), all fainter than HB, as crosses.

Although the plot of $\mathrm{CN}_{(3883)}$ versus $\mathrm{CN}_{(4215)}$ for 50 sample stars in Figure 2 shows the zero points and the slope of the relation between two indices are slightly different from those obtained only from bright giants of original program stars, we took the $< CN >$ index as an average of $\mathrm{CN}_{(3883)}$ index and two times the $\mathrm{CN}_{(4215)}$ index as in the previous section for consistency. Since the stars used for index transformation are not all bright giants, it is difficult to correct the different effects of temperature and luminosity on both bands. Since we intend to estimate the deviation from the average strength of CN for a given temperature and luminosity, the $< CN >$ index used in this study would not affect the results of the following analysis.

The $< CN >$ versus M_v and $(B-V)$ behaviors are plotted in Figures 3-a and 3-b, respectively, and the corresponding results for the CH(G) indices in Figures 3-c and 3-d. The same symbols are used in the figures as in Figure 1.

There are luminosity dependencies and strong hints of bimodality of CN strength in Figure 3-a with the separation between the "normal" and "enhanced" CN stars as shown in the [C(41-42), V] diagram in Figure 11 of Smith & Norris (1982), and also a strong color dependence is found in Figure 3-b if we ignore the reddest two stars. The CH(G) index also shows some dependence on luminosity and color as is seen in Figures 3-c and 3-d.

A plot of the the $< CN >$ index against the CH(G) index in Figure 4-a shows two parallel trends. This figure is similar to Figures 3 and 4 of Cannon et al. (1998) for 47 Tuc stars. As they did, we divide stars empirically into two classes using Fig. 4-b. The stars lower right parts are labelled CN-strong and the upper left CN-weak. Cannon et al. (1998) showed that decreasing the carbon or increasing the nitrogen abundance moves points towards the lower right-hand corner, and *vice versa* for synthetic spectra. The results of the classification of the sample stars are listed in the last remark column of Table 1 and are illustrated in Figure 4-b with filled circles representing the CN-strong stars and open circles the CN-weak stars. The empirical line dividing the two classes is also plotted in Figure 4-a.

In the above method, I-45 is grouped with the CN-weak stars. However it was classified as a CN-strong star in Briley et al. (1994, 1997). Recently Ramirez & Cohen (2002) deduced high C abundances for I-45 and I-66 from the analysis of spectra of high dispersion (R=35,000), obtained with HIRES at the Keck Observatory with suspecting their results due to the fact that the CI lines used for their analysis, may be blended with or completely dominated by lines from the red system of CN in stars with $T_{eff} <\sim 4200$ K. However Briley et al. (1994) found that good fits to the observed spectra of I-45 can be obtained with the O abundances from Sneden et al. (1994) and a larger N abundance for arbitrarily low values of [C/Fe] = –0.6. I-45 has the lowest value of [O/Fe] = +0.13 and has the second highest value of [Na/Fe] = +0.49 among the stars, in the abundance study of M71 giants by Sneden et al. (1994). However we found I-45 is well suited as a CN-weak star in the following $< CN >$ index versus magnitude diagram, but not well suited in the CH(G) versus magnitude diagram. That means our CH(G) index is not as large as that expected for a CN-weak star if it follows the CN-CH anti-correlation. Therefore if the high C abundance result of Ramirez & Cohen (2002) is valid, the large N abundance of Briley et al. (1994) and our low value of CH(G) index for I-45 need to be checked. If our low CH(G) index is due to its low temperature, and the large N abundance of Briley et al. (1994) is due to adopting arbitrarily low values of the C abundance, we could not exclude the possibility that I-45 is a low N and high C abundance star of low temperature, although it requires a more detailed high resolution spectroscopic study for confirmation of it's N and C abundances.

Since these two indices, $< CN >$ and CH(G) depend on temperature and luminosity as well as on the relevant abundances, we plot the index-magnitude diagrams for the M71 stars in Figures 5-a and 5-b. In each panel, the same symbols are used as in Fig. 4-b to distingush between the CN-strong and CN-weak stars. These panels resemble conventional CMDs, only with index replacing color as abscissa, showing that both indices are dependent on both temperature and luminosity. Especially, the CN index versus Mv diagram of Fig. 5-a does show a clear dichotomy with surprisingly clear and separate HB and RGB for each class. Although this result is somehow expected since the primary selection criterion for defining the two classes is the $< CN >$ index, it strongly confirms that two classes exist in the lower RGB all the way to the bright RGB as well as in HB with an approximately equal amount of difference in the $< CN >$ index along the RGB and a somewhat smaller amount of it in HB.

The amount of the $< CN >$ difference between the two classes is 0.357 for RGB stars with a dispersion of 0.043 for weak-CN RGB stars and 0.042 for strong-CN RGB stars, and 0.183 for HB stars with a dispersion of 0.053 for weak-CN HB stars and 0.056 for strong-CN HB stars. In this analysis, we exclude a variable star, V2, and KC-137. V2 is not only variable but also the brightest and reddest star among the M71 stars, so it's

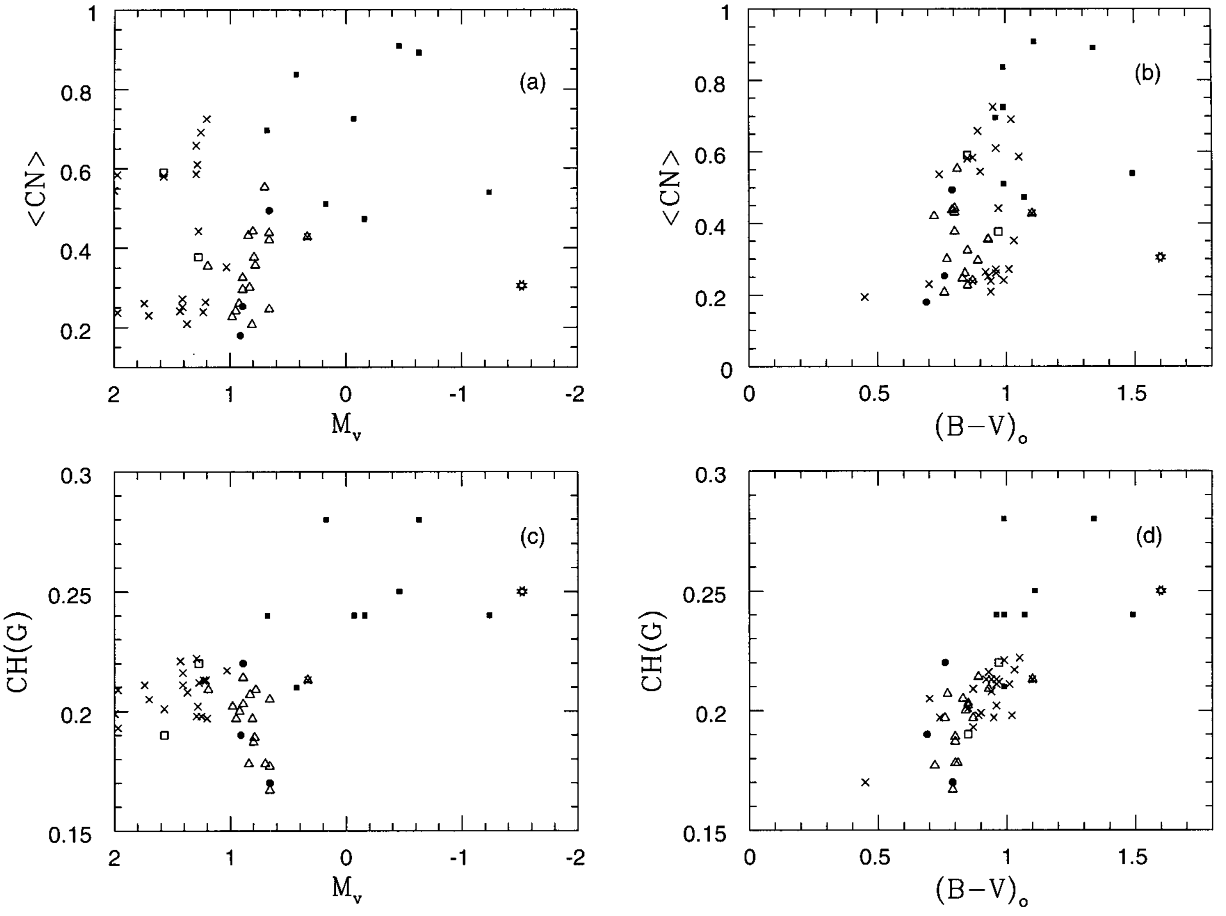

Fig. 3.— $< CN >$ and CH(G) indices are plotted as a function of absolute magnitude and (B-V) color for all stars listed in Table 1. Symbols used are the same as for Fig. 1.

CN and CH band strengths may be affected more by extremely low temperature and gravity. On the other hand, KC-137 has color $(B-V)_o = 0.45$ and an absolute magnitude $M_V = 2.31$, which is too blue to be a RGB star and too faint to be a HB star. In addition to that, the membership probability of 67 % (Cudworth 1985) is lower than any other sample star. Even if KC-137 is a member of M71, it is too blue to have accurate measurements of CN and CH band strengths. So we exclude these two stars in estimating the index difference between two groups. However the varying differences between two groups for RGB stars and HB stars do not directly imply the differences in nitrogen abundance between two classes in the HB stars are smaller than in RGB stars since CN band strengths are related in a complicated way with the CNO abundances as well as with the temperature and luminosity. Elucidation requires detailed synthetic spectrum analysis with stellar model atmospheres.

In the corresponding plot for the CH index of Fig. 5-b, we also found clear and separate branches, in the HB and the lower RGB for the weak-CN stars and strong-CN stars but with a somewhat unclear separation in the brighter part of the RGB. In comparison with Fig.5-a we confirm a strong anti-correlation between the two indices in HB and the lower RGB with one exception star, I-111, but the trend appears not to be confirmed in the upper RGB. The average CH(G) index for weak-CN stars in HB is 0.204 with a dispersion of 0.008, while that for strong-CN stars is 0.180 with a dispersion of 0.006. Therefore the difference between the average indices of the two groups in HB is 0.024, which is more than 3 sigmas for each group. For the fainter part of the RGB, the average index for weak-CN stars is 0.212 with a dispersion of 0.004 and that for strong-CN stars (excluding I-111) is 0.197 with a dispersion of 0.003. We also found a difference of 0.015, which is also more than 3 sigmas for each group. Star I-111 is a strong-CN star, but has a strong CH(G) index too. However the original indices for the CN and CH band are collected from Table 1 of Penney et al. (1992). Their values of S(3839) and S(4142) for CN bands as well as values of δ S(3839) and δS(4142) indicate it is a CN-strong star, which is also seen in their Figure 4. However the value of m_{CH} for the CH band was listed as 0.290 in their Table 1, which value is very large for a CN-strong star.

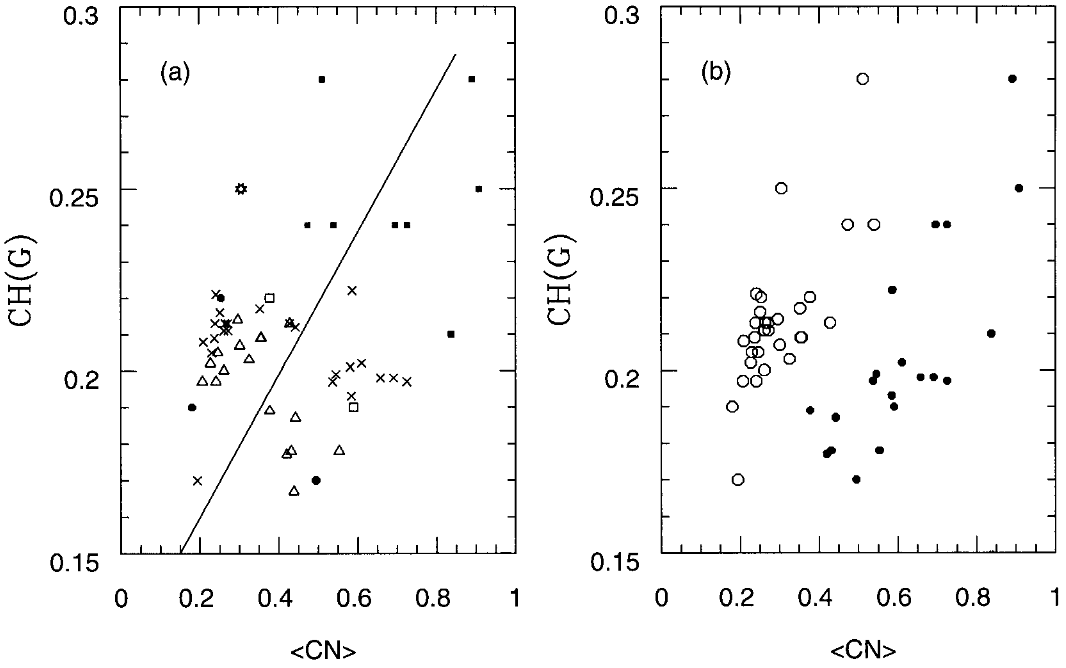

Fig. 4.— a) The $< CN >$ index plotted against the CH(G) index for all stars listed in Table 1. The solid line separated the CN-weak and CN-strong stars. This emprical division of the two classes is based on the study of Cannon et al. (1998). Stars in the lower left are CN-strong, while those in the upper right are CN-weak. They are plotted in Figure 4-b) with symbols of filled circles and open circles respectively. Symbols used in Figure 4-a) are the same as for Fig.1.

But in their Figure 5, no CN-strong star was marked at the position of I-111, which should be at V = 14.89 and m_{CH} = 0.290. However at the position of V $\sim$ 14.90 and m_{CH} $\sim$ 0.210, two CN-strong stars seem to overlap. Therefore it is more likely that the value of m_{CH} for star I-111 in their Table 1 was misprinted. If we assume the value of m_{CH} of the star I-111 is 0.210, then without exception, there are anti-correlations in the lower RGB and HB.

However for the brighter part of the RGB, the average CH(G) index of weak-CN stars is 0.243 with a large scatter of 0.024 and that of strong-CN stars is 0.246 with a dispersion of 0.023. In this part, the index difference between the two groups is too small to conclude any difference, and also it is in the reversed sense of anti-correlation, that is the average CH index for CN-weak stars is smaller than that for CN-strong stars which is reversed from what is expected from anti-correlation between the two indices. However this could result from the small number of statistics.

Therefore we can conclude that there are two classes, weak-CN stars and strong-CN stars, from the faint RGB all the way to the bright RGB and also in the HB. However the anti-correlation of the CN and CH band strengths is found in the HB and the fainter part of the RGB, with the situation not clear in the brighter part of the RGB.

(b) Spatial Distribution of CN Variations

Among our sample of 50 stars in M71 which is rather a small sample for statistical purposes, we found 20 CN-strong stars and 30 CN-weak stars. And the ratio of CN-strong to CN-weak stars is found to be 0.82 within 2 minutes of arc from the cluster center, while beyond that it decreases to 0.65. This result is consistent with those of Cohen (1999), and Briley & Cohen (2001). Cohen (1999) found that there are approximately equal numbers of CN-weak/CH-strong and CN-strong/CH-weak main-sequence stars in M71. Briley & Cohen (2001) also found remarkably similar numbers of CN-weak and -strong stars and a bimodal distribution of CN strengths with a pronounced CN/CH anti-correlation among M71 giants and main-sequence stars.

It is known that M71 and 47 Tuc have not only a similar metallicity but also similar overall patterns of CN strengths with a bimodal distribution and a CN-CH anti-correlation among giants (Briley et al. 2001, Briley 1997, Cannon et al. 1998). However as far as the ratio of CN-strong stars to CN-weak stars is concerned, the two clusters are quite different. In 47 Tuc (Briley 1997) there are much more CN-strong stars than CN-weak stars in RGB and near main-sequence, giving a ratio of 1.8 and the ratio is relatively constant within 10 arc minutes of the cluster center, decreasing to 0.5 at a radius of 16 arc minutes.

Our study also confirms that there are more CN-

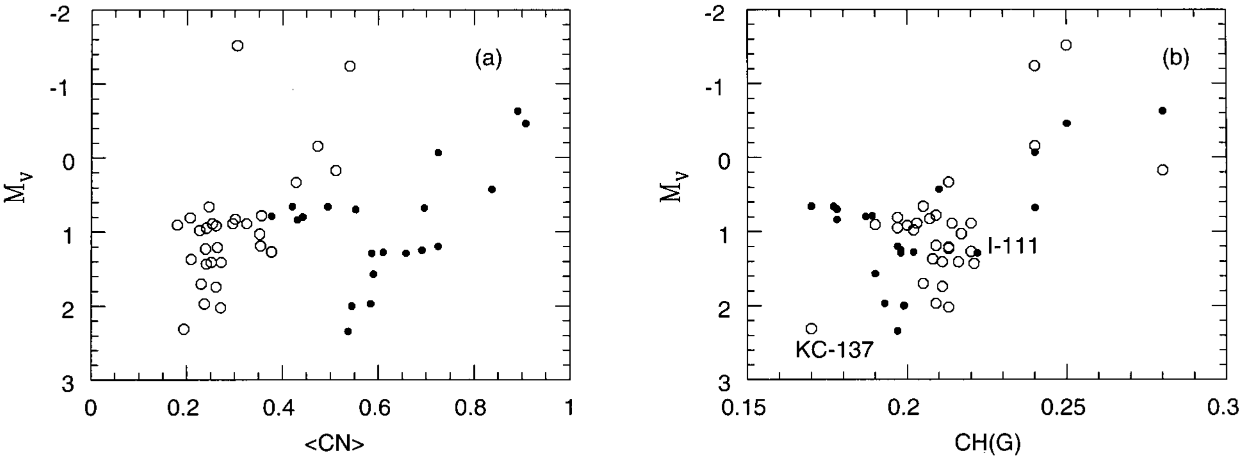

Fig. 5.— Plots of the $< CN >$ index and the CH(G) index against the absolute magnitude for the stars in M71. The same symbols are used as in Figure 4-b), to denote CN-strong (filled circles) and CN-weak (open circles) stars.

weak stars than CN-strong stars in M71 and the ratio of CN-strong to CN-weak stars decreases to 0.65 in the outer region from 0.82 in the central 2 minutes of arc of M71.

IV. DISCUSSION AND CONCLUSION

In this study, we have newly obtained CN and CH indices for fourteen M71 giants from the archival spectra. Adding published indices for CN and CH bands of stars in the M71 cluster, we have reconfirmed that there is a bimodal distribution of CN band strengths among stars from the lower RGB all the way to the upper RGB and in the HB. However CN-CH anti-correlations are found in lower RGB stars and HB stars, but are not clearly shown among upper RGB stars, which fact may be partly due to small size of the statistical sample, but is worth checking with more sample stars. We have classified CN-weak stars and CN-strong stars using the plot of $< CN >$ versus CH(G) as in Cannon et al. (1998). The ratio of CN-strong to CN-weak stars is 0.82 in the central 2 minutes of arc region and decreases outward to 0.65. Overall the r value is 0.71, excluding the variable V2 and a probable non-member KC-137. For each branch of stars, we have found the ratio is 0.69 for the lower RGB, 0.80 for the upper RGB, and 0.60 for the HB. For the upper RGB we exclude the variable star V2. Therefore there seems no evidence that the ratio has been changed according to the evolutionary state.

The observed CN and CH band strength for 77 M71 main-sequence stars (Cohen 1999) showed also a bimodal distribution with a pronounced CN/CH anticorrelation. This pattern was also found in the more luminouse giants by Briley & Cohen (2001). The ratio r was found to be 0.63 for bright giants and 0.70 for main-sequence stars. Recently Smith (2002) confirmed a correlation between the ratio r of CN-strong to CN-weak stars and the ellipticity ϵ of clusters, which was found by Norris (1987). It explains that the low value of r in M71 compared with that in 47 Tuc is because the ellipticity of M71 is zero, while that of 47 Tuc is 0.100 (Norris 1987). However main-sequence stars in 47 Tuc (Da Costa et al. 2004) found a ratio of 0.85 ± 0.10 which is similar to the ratio of 0.77 ± 0.11 far from the center of 47 Tuc (Paltoglou 1989), although the r ratio of the central region of 47 Tuc for the main sequence is 1.8 (Briley 1997). Therefore, the r ratios only in the central regions of M71 and 47 Tuc are different. This implies that whatever the cause is, the CN enhancement of stars in the clusters are related with their central environments.

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