VARIATIONS IN ABUNDANCES AMONG MAIN SEQUENCE STARS IN M71 *

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Abstract: CH and CN variations are definitely present among the main sequence stars in a narrow range of luminosity just below the turnoff in the globular cluster stars. We show that the same set of C, N and O abundances that are used to fit the CN band in the CN-strong and CN-weak giants and subgiants in this cluster also successfully reproduce the behavior of the CH and CN molecular bands seen in the main sequence sample. This strongly suggests that the variations seen in M71 are primordial in origin. A hint of variation in the strength of the NaD lines is also seen in the main sequence sample. A range in Na abundance of about a factor of 3 is required to explain this. Strong Na among the main sequence stars appears to be correlated with strong CN, which is also characteristic of Na variations among red giants in globular clusters.

1 Introduction

The work of many people, pioneered by Suntzeff (1981) and reviewed in the literature by Kraft (1994), McWilliam (1997), and Pinnsoneault (1997), and so eloquently by Chris Sneden at this meeting, has clearly demonstrated that there exist large variations in the C and N abundances among giants within a particular galactic globular cluster. In addition, smaller variations, but still well established as real, are seen for Na and Al. Ignoring the anomalous globular cluster ω Cen throughout, no variations are seen within a particular globular cluster among elements heavier than Mg. This suite of phenomena is seen among the red giants in essentially all globular clusters studied to date in sufficient detail.

It is generally believed that these variations represent the result of mixing of nuclear processed material to the surface of red giants. Initially nuclear burning codes, combined with stellar evolutionary models and models for mixing, were successful in reproducing the behavior of the CNO elements, but failed to reproduce the observed behavior of Na and Al, being unable to produce any these heavier elements in such cool low mass stars at such an early stage in their evolution. Subsequently Denisenkov & Denisenkova (1990) demonstrated that instead of neutron captures on Ne^{22}, proton captures on Ne^{22} could produce Na and Al enhancements

*Based in large part on observations obtained at the W.M. Keck Observatory (Mauna Kea, Hawaii), which is operated jointly by the California Institute of Technology and the University of California.

Since there is no source of free neutrons in globular cluster red giants, the former cannot occur in H-burning stars, while the latter can, and apparently does, occur.

As observational capabilities have improved, with the new generation of telescopes and detectors it is now possible to reach the main sequence in the nearer galactic globular clusters with spectra of sufficient resolution and SNR to address these issues among the completely unevolved main sequence stars. The limited work to date, which is concentrated on the very nearby globular cluster 47 Tuc, is reviewed by Briley et al (1994). The sample of stars in 47 Tuc is now sufficiently large that CH and CN variations appear to be well established among stars at the level of the main sequence turnoff, with CH and CN anti-correlated, i.e. stars with srong CN bands show weak CH bands and vice versa (Cannon et al 1998).

This is extremely surprising, and implies either that our understanding of stellar evolution, nuclear burning and mixing is still missing one or more key processes, or that primordial variations are being seen that are inherent in the gas from which the the globular cluster stars we observe today were formed.

2 Observations

We have begun a major project to explore these issues at the Keck Observatory with the Low Resolution Imaging Spectrograph (Oke etal 1995). Our initial reconnaissance of the problem focuses on the globular clusters M13 and M71. Large samples of stars have been observed using the multi-slit capability of LRIS. Cohen (1999a, b) clearly demonstrates that within M71 both the G band of CH and the uv CN band show strong variations from star to star at a given luminosity on the upper main sequence, and that these variations are anti-correlated. This behavior appears to be identical to that shown by the red giants. The situation in M13 is more complex as the cluster metallicity is lower, the molecular bands are weaker, the observational errors become larger compared to the predicted variation in band strength, and the behavior is much less clear.

Briley, Smith & Claver (1999) have sampled the red giants in M71 using DDO photometry. They have used isochrones to determine stellar model atmosphere parameters, then predicted the strength of the DDO CN index. They have established a set of C, N and O abundances that can successfully reproduce the behavior of the CN index in the CN-strong and in the CN-weak giants in M71. Briley & Cohen (1999) have applied similar spectral synthesis techniques to predict the strength of the CH and uv CN bands for the LRIS observations of main sequence stars in M71. This pair of C, N, and O abundances for the CN-strong and for the CN-weak red giants also produces a reasonable match to the molecular band indices seen in this large (~75 stars) sample of M71 main sequence stars, as is shown in Figure 1 for the G band of CH and in Figure 2 for the uv CN band. (Note that the instrumental uvCN indices of Cohen (1999b) have been corrected for the use of a single side band redward of the molecular feature to determine the continuum.)

Thus Briley & Cohen (1999) have demonstrated that the detailed variation among the CNO elements seen in the main sequence stars in M71 is identical to that seen in the red giants in that globular cluster. This makes the determination of the origin of these variations even more critical. If they do result from mixing of nuclear processed material, no theoretical scenario exists to produce such nuclear burning and mixing to the surface of the processed material for main sequence stars, and our understanding of stellar evolution must be seriously flawed if they are caused by mixing.

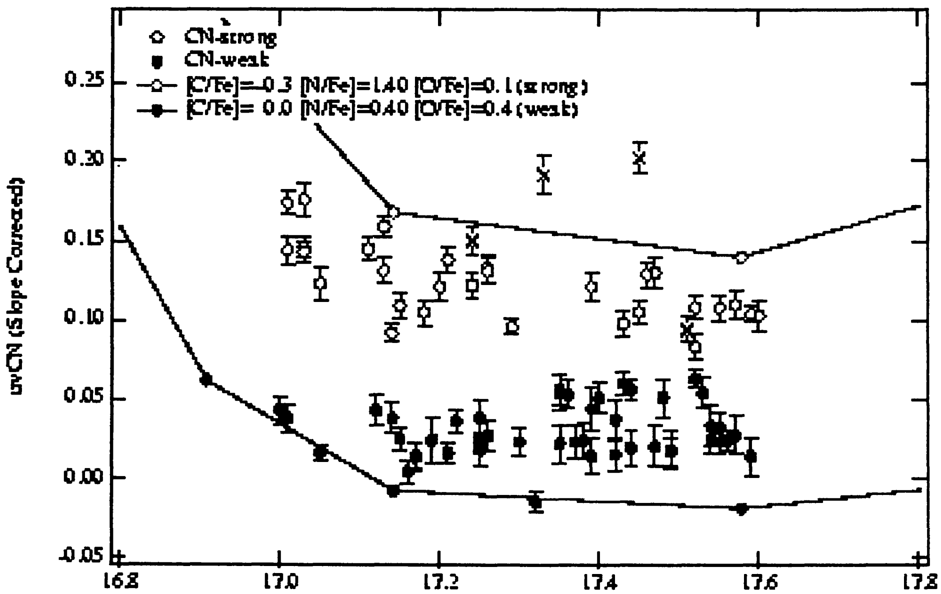

Figure 1: The strength of the uv CN band is shown as a function of R mag for upper main sequence stars in M71. Filled circles denote stars with weak CN, open circles denote stars with strong CN. Several probable field stars are indicated by the symbol "X". The observational indices of Cohen (1999b) have been corrected to remove the continuum slope. The predicted molecular band strength based on spectral synthesis applied to model isochrones is shown by the solid curves. In the upper curve, representing the CN-strong stars, N is strongly enhanced, C is slightly depleted, and O is almost normal for the metallicity of the cluster. In the lower curve, representing the CN-weak case, C/Fe is normal, N/Fe is slightly enhanced, and O/Fe is enhanced by the same factor. The adopted values for [C,N,O/Fe] for each case are indicated on the figure.

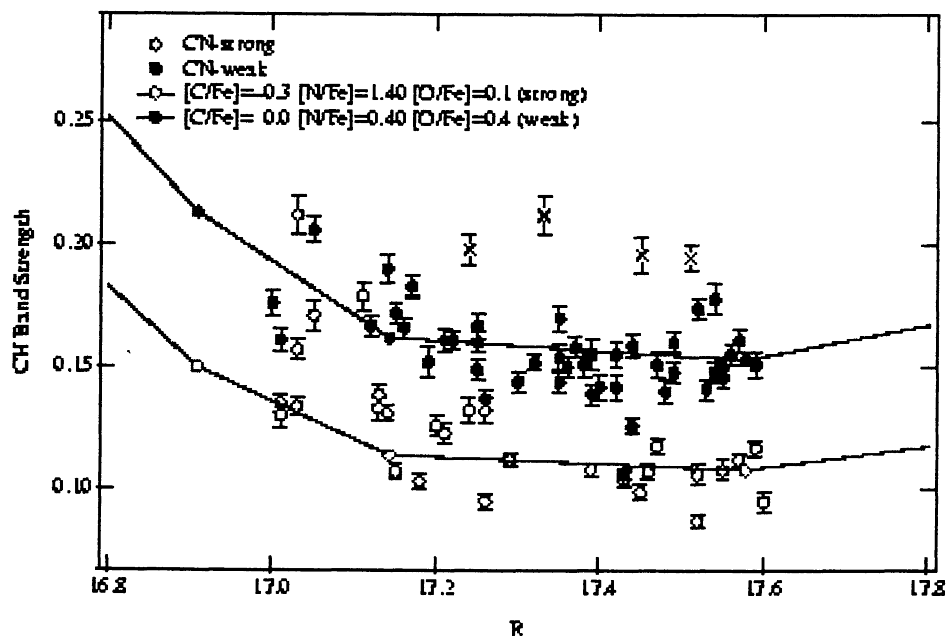

Figure 2: The strength of the 4300 Å G band of CH is shown as a function of R mag for stars just below the turnoff in M71. The symbols are the same as in Figure 1. The two curves represent the behavior of the CN-strong and CN-weak stars and have the same adopted C, N and O abundances as in Figure 1.

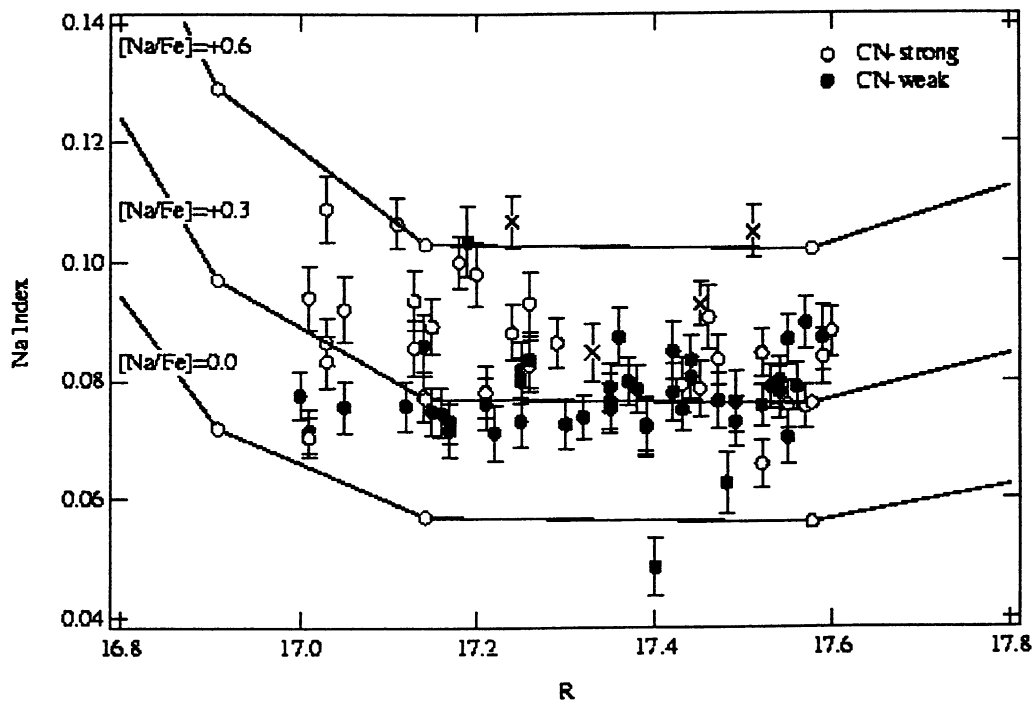

Figure 3: The strength of the NaD lines is shown as a function of R mag for stars just below the turnoff in M71. Filled circles denote stars with weak CN, open circles denote stars with strong CN. Several probable field stars are indicated by the symbol "X". The predicted strength of these strong Na lines based on spectral synthesis applied to model isochrones is shown by the solid curves. In the upper curve, Na is enhanced with respect to that expected for a globular cluster of this metallicity by a factor of four. In the next lower curve, Na is enhanced by a factor of 2, and in the lowest curve, Na is normal ([Na/Fe] = 0).

We are currently working on the variation of the NaD lines among the main sequence sample in M71. The preliminary result, shown in Figure 3, suggests Na/Fe variations of about a factor of 2 among the M71 main sequence, with a hint of a correlation such that increased Na is associated with increased CN. This is suggestive but there is the issue of variations in reddening, and in the strength of the interstellar contribution to the NaD lines. So far, all we can say is that there is no correlation of Na line strength with spatial position on the sky.

At this point, it does appear that primordial variations are the dominant effect at all luminosities from the main sequence to the red giants in M71. Metal rich globular clusters presumably had more first generation supernovae to produce the heavy elements we observe in their stars today, while metal poor ones had very few. If Gaussian statistics are taken as a guide, one would expect the largest variations in abundances of elements produced in these supernovae (i.e. primordial variations) to be more prominent in metal poor clusters. This appears to be wrong. The supernovae ejecta in the gas cloud at the time of the formation of most stars in the metal rich clusters, at least in the case of M71 and of 47 Tuc, appear not to have been well mixed with the bulk of the proto-cluster gas.

We are working hard on the M13 sample now, as that will provide a different perspective on this problem.

The verbal presentation concluded with an advertisement by J.Cohen for the work of her graduate student Brad Behr on gravitational settling, radiative levitation and rotation among BHB stars in M13 (Behr et al 1999a, b). As both of these papers are now published, details are omitted here.

Acknowledgements

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DISCUSSION

R. Peterson: Have you attempted to account for the interstellar absorption in your NaD measurements of M71 stars ?

J. Cohen: I have worried about this, and constructed the spatial position in the cluster vs Na line strength indices plot and there is no correlation. However it is a fact that I have made no correction for interstellar Na absorption. I plan to evaluate this, at least in some cases, with higher dispersion spectra.

R. Kraft [comment]: M71 giants don't show much evidence in favor of abundance variations either. Maybe all clusters show primordial variations, with superimposed deep mixing in more metal poor clusters.

H. Maitzen: In your fascinating paper on the photospheric abundance anomalies in BHB stars of M13 (Behr et al. 1999), photographic B–V data had to be used for some stars not measured by the HST. Is this the actual state of photometry in M13 ?

J. Cohen: I felt that Brad Behr had such an interesting result that we needed to publish something quickly. I recognize that there are some problems in the photometry, but the results are so striking that fixing this will not perturb the results much. Strömgren photometry is in hand and there will be a proper analysis for $T_{\rm eff}$ & g in Behr's thesis and in the resulting publication.