CHEMICAL PROPERTIES OF INDIVIDUAL GLOBULAR CLUSTERS

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I. ABUNDANCE CALIBRATION FOR THE METAL RICH GLOBULARS

Rapid improvements in instrumentation over the past few years have made the spectroscopic study of individual globular cluster giants feasable. Three years ago I began a program of high dispersion abundance analyses of such stars to provide a calibration for the many photometric systems used to rank globular clusters in metallicity. The results for four clusters (M92, M15, M13, and M3) of low and intermediate metallicity have already appeared (Cohen, 1978, 1979), and additional detailed analyses of stars in M5 and M13 (Pilachowski, Wallerstein and Leep, 1979) will soon be available. Ignoring the elements C, N, and O, to which we shall return later, these detailed abundance analyses yielded few great surprises; perhaps the metallicity scale that had previously been used was too high by about 0.2 dex, and also it became clear that M3 was a very metal poor cluster. However, the calibration of the metal rich globulars beyond the simple ranking level of Mould, Struthman, and McElroy (1979) had not been attempted.

I have now essentially finished an abundance analysis of four members (A4, 45, 46, and 30) of M71, a metal rich globular, and an identical analysis of three members (224, 231, and 170) of M67 and two giants (stars A and F) which are radial velocity members of NGC 2420. This provides the calibration of the metal rich end of the globular cluster sequence. Although the details will be presented elsewhere, in Table 1 I indicate the mean abundances with respect to the sun averaged over the stars in each cluster; I note that in agreement with my previous results there is no indication of a spread in abundance within any cluster greater than that of the errors. The results for M67 are in reasonable agreement with previous analyses of 2 stars by Griffin (1975, 1979) and with the generally held view that M67 is metal poor by perhaps a factor of 2 compared to the sun. NGC 2420 has a metal abundance only slightly smaller than that of M67

The metallicity of M71 is, however, significantly lower than expected. Iron is down by a factor of approximately 15. I have done everything reasonable that is possible to push the metallicity of M71 higher, including adjusting the reddening of the cluster stars, and am

James E. Hesser (ed.), Star Clusters, 385–400.

https://doi.org/10.1017/S0074180900092214 Published online by Cambridge University Press

TABLE 1

Mean Abundances in M71, M67, and NGC 2420 with Respect to the Sun

Element	M71 (4 stars)	M67 (3 stars)	NGC 2420 (2 stars)
O	-0.71	-0.23	-0.13
Na	-0.74	-0.11	-0.32
Mg	-1.24	-0.69	-0.85
Si	-0.48	+0.31	-0.44
Ca	-0.53	+0.03	-0.02
Sc	-0.80	-0.05	-0.52
Ti	-0.70	-0.15	-0.32
V	-0.85	-0.20	-0.44
Cr	-1.49	-0.28	-0.53
Mn	-1.39	-0.52	-0.85
Fe	-1.22	-0.34	-0.52
Co	-1.20	-0.31	-0.72
Ni	-1.22	-0.33	-0.63
Cu	-1.02	+0.20	-0.24
Zr	-0.96	-0.27	-0.45
Mo	-1.18	-0.39	-0.82
Ba	-1.24	-0.52	-0.29
La	-0.41	+0.18	+0.13
Nd	-0.55	+0.27	-0.06

unable to reach values exceeding those tabulated. I believe the results in Table 1 to be correct, and certainly the relative ratios between the two old open clusters and M71 are correct, as all the stars have been measured and analyzed in an identical manner. It is apparent that the standard calibration of the metal rich globular clusters is greatly in error. The same statement apparently applies to the metallicity of the other standard metal rich globular, 47 Tuc. Dickens, Bell and Gustaffson (1979) have obtained log(Fe/H) = -0.8 and Wallerstein and Pilachowski (1979) also obtain a low value of -1.0.

While these results solve the problem posed by Demarque and McClure (1977) of the relative position of the giant branches of 47 Tuc and NGC 2420, one should try to understand the origin of the commonly held belief that the abundance of M71 is almost solar. Aside from the solar ΔS measurement by Butler (1975) for a single star supposedly in M71 which is not a RR Lyrae variable, the old calibration was based on Hesser, Hartwick and McClure's (1977) metallicities derived from DDO photometry, which is in turn based on δ(U-B) estimates for M71 and NGC 6752. Anyone who goes back through the literature will find cautionary remarks which have been supressed in our collective memory as the years passed regarding possible non-members in clusters with no proper motion studies and at low galactic latitudes, reddening problems, and crowding errors in the photometry, particularly in the U magnitude.

This reduction in the metallicity of the more metal rich end of the globular cluster sequence implies that the most recent set of rankings (e.g. that of Zinn 1979 and of Harris and Canterna 1979) in the mean agree well with the spectroscopic determinations, with a difference of less than 0.15 dex, for metallicities of M5 or lower, i.e. less than -1.4. Above that, globulars are assigned metallicities up to approximately 0.6 dex too high. The most metal rich globulars, which in Zinn's (1979) ranking have metallicities above solar, are at least a factor of two below solar and probably are not more metal rich than the oldest open clusters. The mean metallicity of the globular cluster system in our galaxy and the form of the distribution of globulars over metal abundance are questions which must be re-examined. Also the metallicity calibration of broad band colors derived by Aaronson, Cohen, Mould and Malkan (1978) is affected in a manner currently under study. With the increased reddening for M71 beyond that used by Frogel, Persson, and Cohen (1979), the location of the globular cluster giant branch sequences in the theoretical H-R diagram from the work of Frogel, Persson and myself (including a giant branch for 47 Tuc which will be published shortly), together with the spectroscopic metallicities, gives differences in log Te at fixed luminosity as a function of Z in reasonable agreement with the recent Yale calculations, except near the tip of the giant branch. This will be discussed at length in the forthcoming publication on the 47 Tuc giant branch.

II. PRIMORDIAL VARIATION OF THE HEAVY ELEMENTS

I do not believe that there is any evidence for primordial variations of the heavy elements in any globular cluster with the exception of ω Cen. (We shall ignore the existence of ω Cen for the remainder of this section.) All the detailed spectroscopic analyses show good agreement among the stars within a particular globular cluster. The problem of a scatter for the lighter elements in M3 (Cohen 1978) was most likely due to small temperature errors and to the fact that these are the faintest stars I have tried to observe at such high dispersion.

The main sequence widths, in the very few cases where they are available, (Sandage and Katem, 1977) support this contention. Also one should note where membership has been well established the tight giant branches, both as determined from visual and from near infrared photometry, which are in no case wider than the observational uncertainties. As many theoreticians have stated, and as the series of papers by Persson, Frogel and myself has demonstrated, the giant branch morphology is controlled by the heavy elements. Ranges in heavy element abundances of ±0.3 dex within a cluster with small reddening (so that differential reddening across the cluster is not a problem) would produce a noticeable spread in the color of the giant branch. Smaller ranges in heavy element abundance cannot easily be detected by photometric studies.

https://doi.org/10.1017/S0074180900092214 Published online by Cambridge University Press

III. Pal 12

Before proceeding to the Medusa that is ω Cen, I should like to mention the preliminary result of a study of the giants in Pal 12 by J. Frogel, E. Persson, R. Zinn, and myself. We have obtained moderate dispersion spectra and in some cases broad and narrow band infrared photometry for all the stars studied by Canterna and Schommer (1978). The figure shows my data based on moderate dispersion spectra obtained with the 5m SIT, and shows immediately that Pal 12 is quite metal rich for a distant globular. On the basis of the strengths of spectral lines in the visual region and the CO indices, we conclude that Pal 12 is a high metallicity cluster, that the red horizontal branch is not an anomaly for its metallicity, and that Pal 12 is probably the most metal rich cluster in the outer galactic halo. The details will appear in a forthcoming publication.

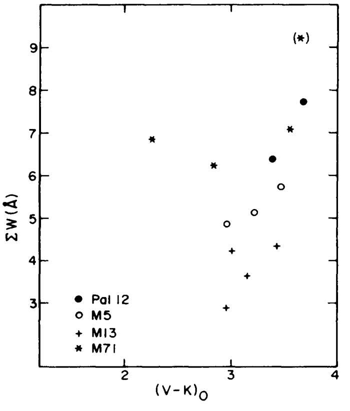

Figure 1. Sums of equivalent widths of several absorption lines plotted against unreddened V-K color for stars in Pal 12 and in other globulars.

IV. THE HEAVY ELEMENTS IN ω CEN GIANTS

A detailed abundance analysis based on high dispersion echelle spectra for several ω Cen giants is now approaching completion, and I present some preliminary results of this work. In Table 2 I list the mean of the abundances derived for two giants on the blue side of the giant branch, ROA 58 and ROA 102. A few abundances which are particularly uncertain are denoted in parethesis. I also list the derived abundances for ROA 253, a star approximately 0.2 mag redder in V-K than stars on the blue edge of the ω Cen distribution at that luminosity. Analysis of stars even further to the red is unfortunately not yet completed.

One first notes that the blue edge of the ω Cen giant branch corresponds to stars slightly more metal rich than those of M92. A clear enhancement of most heavy elements is seen in ROA 253 compared to the two blue edge ω Cen stars. However, there does not appear to be any increase in the Na or Mg abundance between these stars. I have calculated the number of atoms produced of each element, denoted P(A), relative to the number of silicon atoms produced between the time of formation of the two metal poor stars and that when ROA 253 was formed, and the results are shown in the third column. The production ratios

https://doi.org/10.1017/S0074180900092214 Published online by Cambridge University Press

TABLE 2

ω Cen Abundances Relative to the Sun

Mean ROA 58 and ROA 102	$\log(N_A/N_A^{\odot})$	ROA 253	$\log(P(A)/P(Si))$	$\log(N(A)/N(Si)(\odot))$
O	-1.61	≤1.32	≤0.9	+1.4
Na	-1.43	≤-1.33	≤-2.08	-1.3
Mg	-1.83	≤-1.73	≤-1.2	+0.0
Si	-1.94	-1.12	0	0
Ca	-1.46	-0.68	-0.8	-1.3
Sc	-1.77	-0.77	-4.2	-4.6
Ti	-1.47	-1.13	-2.9	-2.7
V	-1.84	-1.39	-4.1	-3.7
Cr	-2.11	(≤-2.01)	(≤-3.6)	-2.1
Mn	-2.26	-1.81	-3.2	-2.4
Fe	-2.16	-1.66	-0.7	-0.0
Co	-2.03	(-1.5)	(-3.2)	-2.8
Ni	-2.03	-1.60	-2.2	-1.5
Cu	-2.70	-2.25	-4.1	-2.8
Zr	-1.44	(-0.66)	(-4.6)	-5.1
Mo	-1.28	(-0.50)	(-4.9)	-5.6
Ba	-2.22	-1.11	-5.3	-5.4
La	-1.71	-0.82	-5.8	-6.1
Nd	-1.15	-0.54	-5.4	-6.0

are compared to the solar composition normalized to silicon, which is in the last column. It is immediately apparent that most elements are produced in ratios indistinguishable from solar at this stage in the analysis, with the exception of Na, Mg and Cu which are significantly underproduced. When such calculations are carried out for more metal rich stars in ω Cen, if these trends are maintained, we will have a very exciting result - the specific production ratios, element by element, for the one or more supernovae that exploded during that time interval in the protoglobular cluster, assuming segregation by atomic weight in the mixing of the ejecta within the cluster does not occur. (With analyses of enough stars, the validity of this assumption about mixing in the protoglobular cluster can be tested by comparing the derived production ratios for stars in widely separated parts of the ω Cen.)

I rule out incomplete mixing throughout the cluster volume of the ejecta from a number of supernovae as the cause of the primordial abundance range seen in the ω Cen giants. As I mentioned earlier, such mixing occurred very efficiently in all other globulars. Furthermore, the range of abundances seen in ω Cen is so large that it seems implausible that the only slightly larger mass of ω Cen would have such a great effect on mixing in the protoglobular. Instead, apparently star formation continued long enough for additional supernovae to have occurred during that time period.

The pattern of production ratios tends to suggests a supernova without carbon burning, but with explosive oxygen, silicon, and s process nucleosynthesis. One should note, however, that for clusters with detailed abundance determinations the general pattern between globular clusters as a whole is that more metal rich ones do have more Na and Mg, with the possible exception of M3 as compared to M13. Until more stars are analyzed in detail, I hesitate to indulge in any further speculation.

V. CNO ELEMENTS

When the metallicities for globular clusters obtained from detailed abundance analyses were combined with narrow band photometry in the region of the 2.2μ Co band (Cohen, Frogel, and Persson, 1978, Pilachowski, 1978), anomalies in the CNO elements became apparent. The cluster M3 is more metal poor than M13, yet all the M3 giants observed show stronger CO absorption than do the M13 stars. M5 may also have a high ratio of CNO elements to the heavier elements. In these cases the variation in CO/Fe (the N abundance doesn't significantly affect the strength of the CO bands) is seen in all the stars within a given cluster that have been observed, so that these effects could arise from primordial variations in abundance ratios between clusters. Such a scenario is made plausible by the realization that O may be largely produced in supernovae of a higher mass than those which produced the heavy elements (Arnett, 1978). Thus a range in mass function, or perhaps stochastic effects due to statistical fluctuations around a mean mass function, in the early stages of formation of globulars may be adequate to produce the effects seen in M3, M13, and M5.

The next stage in the development of this problem was the careful analysis of optical photometry and spectra of stars in M92 and NGC 6397 by Bell, Dickens, and Gustafsson (1979). They suggested via spectral synthesis using model atmospheres that a carbon depletion exists for all of the most luminous stars ($M_V < -0.7$) in these clusters. An earlier preliminary discussion of the CNO abundances in M92 (Carbon, Butler, Kraft, and Nocar, 1977) found moderate C depletions for stars $M_V \approx +1.0$ on the giant branch and even larger C depletions for asymptotic giant branch stars. Strong N enhancements were found in some, but not all, of the stars with depleted C. These results have been interpreted as clear evidence for mixing of CN process materials, as one therefore expects C to be burned and N synthesized. The physical cause of the mixing is not clearly identified, but the luminosity cutoff below which such effects were not seen ($M_V = 0 \pm 1$) is in qualitative agreement with that calculated by Sweigart and Mengel (1979) for meridional circulation. We note, however, that the high internal rotations required for this mechanism have not been observed for such low mass stars. Furthermore in these cases the range in CO strength within such a globular cluster is a smooth function of luminosity and such effects cannot be detected from CO photometry alone without a good calibration of the CO index as a function of effective temperature, abundances, and luminosity.

A recent spate of preprints has added new twists to the problem. Evidence is accumulating that these anomalies in C and/or N continue to lower luminosities, well below the horizontal branch (Hesser, 1978 for 47 Tuc; Hesser and Harris, 1979 for M22). In addition, in some cases, the anomalies in CN strength are found to occur only in a fraction of the giants at each luminosity (e.g. Norris and Freeman, 1979 for 47 Tuc; DaCosta and Cottrell, 1979 for NGC 6752), presumably not corresponding to just the asymptotic giant branch stars as compared to the first ascent red giants. Such distributions have been called "bimodal" by several authors and have led to renewed claims of primordial abundance variations for stars within a given globular cluster.

My view on this situation is rather conservative. I believe there is still no compelling evidence in favor of abundance variations of any element within a given globular cluster, except ω Cen. Norris and Cottrell (1979) have analyzed two stars in 47 Tuc, and found that C is depleted and N enhanced in the CN strong star. Thus the bimodal CN distribution is reminiscent of CN cycle mixing. A strong suggestion that this is the case is provided by comparing the CO and CN strengths. In Figure 2 I show from unpublished observations of J. Frogel the CO index as a function of temperature for CN strong and CN weak stars in 47 Tuc. The anticorrelation of strong CO with weak CN and vice versa is well established. Thus the CN anomalies in this cluster are completely consistent with CN cycle mixing as seen in other globular clusters and in field giants.

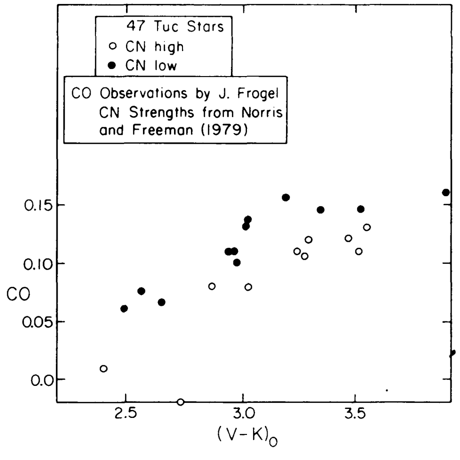

Figure 2. The CO strengths for CN strong and CN weak stars in 47 Tuc plotted against V-K color.

https://doi.org/10.1017/S0074180900092214 Published online by Cambridge University Press

Therefore I believe the mixing mechanism we are searching for must be extremely sensitive to as yet undetermined properties of the globular cluster giants. It must be highly variable from star to star and from cluster to cluster. In some clusters, all giants of a given luminosity mix; in others, only some giants mix. This process must be able to occur at lower luminosities than were required in the past. It is even conceivable that the M3-M13 problem could be due to a complete lack of mixing among the M3 giants, while all those of M13 have mixed, although admittedly this is an extreme view.

Thus at this point I dump the problem of understanding the diversity in globular cluster giants of the phenomenon I believe to be mixing back upon the theoreticians. I would like to remind the skeptics who do not believe in mixing on the main sequence that the apparent progressive decline of surface lithium content between T Tauri stars, G dwarfs in the Pleides, and those in the Hyades implies that depletion of lithium occurs even after stars have reached the main sequence (Wallerstein and Conti 1969). G dwarf models do not have convection zones deep enough to burn lithium.

VI. THE CO STRENGTHS OF THE ω CEN STARS

Given the wide range in heavy element abundance now known to exist in ω Cen, it behooves us to consider the behavior of the CNO elements there in the hope of obtaining clues toward understanding other, hopefully simpler, globular clusters. A determination from the CO indices that C, N, O/Fe were a singly valued function in ω Cen would be very useful in principle, as would a comparison of this function with the C, N, O/Fe ratios seen in other globulars. However, we shall see that situation is more complicated.

Preliminary results of infrared observations of giants in ω Cen were given at the NATO Advanced Study Institute on Globular Clusters last summer by S.E. Persson and J.A. Frogel. The final discussion of this data will be published in the Astrophysical Journal (Persson, Frogel, Cohen,Aaronson, and Matthews, 1980). In Figure 3 is shown a diagram from this paper, where a measure of excess CO, defined with respect to a black body which matches the infrared colors, is plotted against excess V-K denoted R(V-K), normalized to the M92 locus. R(V-K) is thus basically a measure of metallicity ranging from zero (at that of M92) to unity at that of M67 or the mean field. These definitions, arbitrary as they may seem, give unique values for all other globulars studied to date, as the crosses in the figure represent other globulars and are centered on the median values, while the arms of the crosses extend to the quartiles of these distributions.

If the light elements in ω Cen increased monotonically as Fe increased and mixing was not important, this figure should have only one locus of points, with of course some observational scatter. One possible interpretation is that the well populated vertical sequence

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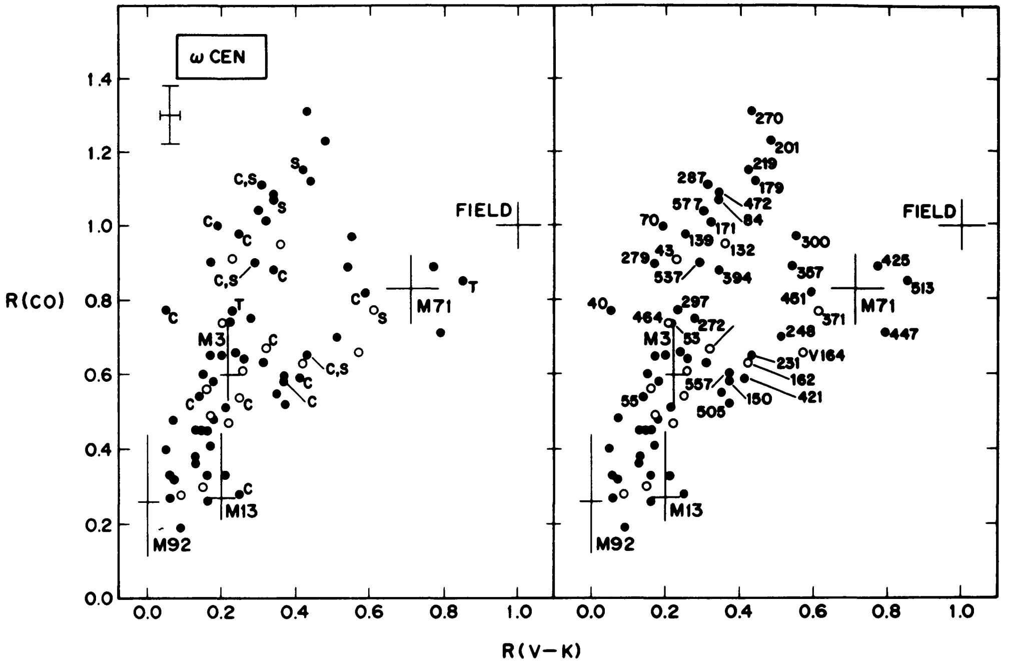

Figure 3. The parameter R(CO) versus metallicity parameter R(V-K) for giants in ω Cen. See the text for details.

represents the unmixed stars, and the more horizontal sequence is composed of the mixed stars with C depleted. If this is true, we again require a highly selective mixing mechanism, which only operates in some fraction of stars at a given luminosity. We also note that most of the stars belong to the sequence with much stronger CO at a given R(V-K) (or metallicity) than are found in the sequence of globulars M92-M13-M71-M67 and field. Whether this is related to mixing differences between these clusters or to real differences in C, N, O/Fe cannot be determined at this time. A more complete discussion can be found in Persson et al., (1980).

VII. SUMMARY

I have presented a new determination of the abundances in the metal rich globular M71 which strongly suggests that the previously accepted calibration of abundances is much too high at the metal rich end. It may well be that there are no globulars with metallicities exceeding the oldest open clusters. Also of interest is that Pal 12 has been definitely established as a metal rich globular. It is the most metal rich globular known in the outer halo.

The basic framework advocated here for interpreting the properties of light elements in globulars is (excepting ω Cen) that stars within a particular globular are to a first approximation chemically homogenous for all elements. All observed ranges (in CO, CN, etc.) can be viewed as differing degrees of mixing. The mixing process must be highly variable in efficiency from star-to-star and from cluster-to-cluster, and must function at a luminosity reaching almost to the main sequence. It cannot be a simple function of luminosity alone.

The situation in this area is changing rapidly. At the present time I find the hypothesis of complete chemical uniformity within globulars still tenable, but I admit the possibility that new evidence to be found in the near future will prove me wrong. This will be the challenge for the next few years of globular cluster abundance research.

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DISCUSSION

KING: Thank you for a provacative talk, and for being extremely thoughtful and using less than your alloted time, so that we have plenty of time for discussion.
JANES: I'm a little bit concerned by the numbers you had for M67: you make M67 somewhat metal weak compared to what my thought of what it was. I mean, most people seem to say that it's about solar, and you have it about half solar.
COHEN: Mrs. Griffin also got the same answer. Now, I'm not claiming that my scale is right. In other words, I'm not really willing to stand up here and swear and say that M67 is below solar, although I bet it is. But I am claiming that my relative scale is right, and that M71 is far more metal poor than M67 or NGC 2420. I don't think my absolute scale can be bad by a lot, but I'm willing to give you 0.2 dex on my absolute scale.
KING: Could I ask a question of a non-expert in this field? Why were the line indices fooling us so much?
COHEN: Well, first of all I think there's no question but that the relative rankings which everybody has come up with are probably correct, with very few exceptions, like Pal 12, for which the data are very bad. Beginning at the metallicities characteristic of M71 or 47 Tuc you suddenly get large numbers of M stars for the first time. And it may well be that in the integrated spectrum these effects pile up and you see the spectral type changing very rapidly even though the actual metallicity is not changing all that rapidly. The other point is that I don't believe that - that's enough. I'll stop there.
WALLERSTEIN: Another contributing factor is that if the star is moderately metal poor, the C and N are not as deficient as the metals; then you get a considerable amount of CN contributing to the blanketing, somewhat in the *B* band and very strongly in the *U* band, because of the band at 3883 Å which contributes or, rather, actually subtracts light from the *U* band.
KING: Is this the Strom-Peterson argument that you get a different boundary temperature and therefore enhance the . . .
COHEN: No, no, this is a different abundance that . . .
KING: Actually a different abundance?
WALLERSTEIN: There's a difference in abundance of C and N. One sees it in O more clearly than in C and N, because you can get to the OI lines which are fairly clear. You see it also in CO, which isn't blended with a lot of other things, either.
BONFONTI: In your second slide, you showed equivalent widths of various stars; I was wondering what the significance of the highest point up there in brackets for M71 was?
COHEN: Well, I'm not sure that star is a member, but there was one star that came out very high. This was a random selection of

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stars observed on the 5-m and there was one star which came out very high.

BONFONTI: Was this one that was in your table, there, averaged in?

COHEN: No, no, those were picked to cover a range in colour, rather than being the brightest ones.

KING: I'd like to hear Kyle Cudworth say he's doing a proper motion study of M71. Is that right?

CUDWORTH: That's part of what I was going to say. We're working on it. The other part of what I was going to say is that there is a rather poor proper-motion study done of M71 in the literature - have you checked against that?

COHEN: I checked the ones which I did high dispersion analysis of. I haven't checked the ones that I did from Palomar. I should. I did check the one star that Dennis Butler measured and, unfortunately, it doesn't go faint enough to cover that star at 14 - it's only really the brightest stars.

CUDWORTH: The new study will go significantly fainter.

RENZINI: What are the effective temperatures and gravities of the two samples? Say, the sample in M71 compared to M67?

COHEN: The difference in gravity is very small, < 0.5 dex. The difference in temperature is about 300^{o} because there aren't all that many members of M67 that are very cool.

RENZINI: The difference in luminosity is quite big, actually.

COHEN: Yeah, but it's a large difference in luminosity and a small difference in the usual parameter, which is just the log of the surface gravity and it's not enough to make a big difference. The mean temperature difference is more worrisome, but I don't think it's enough, either.

CAYREL: Na is not varying with Fe in M71, because the 0.5 dex is significant, no?

COHEN: I think in general the lighter elements tend to be above the iron.

CAYREL: I just mean the difference is within 0.5 dex - have you any explanation for this?

COHEN: No, but I think its a general phenomenon that is true in all metal poor clusters, although maybe Ruth Peterson will disagree.

FREEMAN: I just want to make one comment about CN and mixing and that concerns the internal structure of at least two of the clusters, 47 Tuc and ω Cen. Both of these clusters showed a big range in CN and the thing I want to emphasize is that in both of these clusters the mean CN strength decreases rapidly with increasing radius from the centre of the cluster. It is very marked. It was pointed out in that Norris and Freeman paper that Judy quoted. It's just as strong for ω Cen. So if you want to have mixing being the prime agent for the CN spread, then whatever it is that drives the mixing has got to vary radially inside an individual globular cluster.

COHEN: I admit that things are looking poor, or the more evidence there is,the poorer it might look; but I still am not convinced, primarily because of the anti-correlation of CN and CO.

KRAFT: I would just like to say that it seems to me that mixing vs. primordial abundance variations probably is not an "either/or" situation. I think it's a "both/and". I don't think that there's any doubt that the mixing takes place, given all that evidence, and I think there's evidence very strongly along those lines. But at the same time, I think that in the CN and O groups there is also strong evidence for primordial variations. Ken just mentioned one. Another one is the relationship between the Ca strength and CN that Norris and others found, which I presume is still valid. It's hard to see how that can be entirely a result of mixing. Again, in M92 and M15, we find from stars that are *very* close together on the HR diagram, even stars that are down on the subgiant branch, that the total number of C + N atoms is not constant from one star to another. Since, if C is destroyed it can only go to N, I don't see how that can happen except to have a different number of atoms to begin with.

COHEN: I wish you would hurry up and publish that! (Laughter).

KRAFT: Well, that was stated, in fact, in our review article in the Audouze volume.

COHEN: I think that's the only way to go at this point, given that . . .

KRAFT: You see, what I'm saying is that I'm not disagreeing that there's mixing. No one would do that. But what I'm saying is that I think there are primordial variations superimposed on top of mixing.

COHEN: Well, perhaps I should say that I stand with the faction that believes that mixing is the dominant mechanism, at least in so far as what we see today. It remains to be seen how much actual primordial variation there is.

WALLERSTEIN: Regarding Pal 12, I notice that in M71 Mg is very substantially enhanced over Fe. Since the main feature that was measured in Pal 12 was the Mg band it may not be indicative, which is rather unfortunate because the Mg band is one of the easiest things to measure. It's one of the strongest features in these stars.

COHEN: That was my data alone. The data which will be published is a combination of the infra-red photometry which tells us that the CO is very strong in Pal 12: it is essentially that of M71, or closer to the field of reticon spectra of all four of the stars which are basically blue spectra and show very strong absorption lines, so it's not just the Mg.

SCHOMMER: Searle and Zinn propose from studies of individual stars, a very high metal abundance for M71, -0.2 or something. Is that just a calibration error?

https://doi.org/10.1017/S0074180900092214 Published online by Cambridge University Press

COHEN: Yes, I think that's just a calibration error. Their scale was set based on some of the DDO work and the result that the CO is strong. It was not based on anything I told them.

KRAFT: The scale is calibrated entirely from the RR Lyraes and may have been influenced by that one star in M71 which Dennis Butler measured. You see, they never actually modeled the radiation field. They simply correlated it with the [Fe/H] values determined from the RR Lyrae stars. That's the basic calibration. If that one star proved not to be a member, I suppose that could have a rather strong effect, but of course there are other clusters involved in that calibration besides just the one.

CACCIARI: In all the stars you've measured, the Ca abundance is higher than the Fe abundance by at least 0.5 dex. Does that mean that there is a kind of alpha enrichment, as has been suggested for ω Cen?

COHEN: I ascribed it to that, because I'm not the only person that sees that. All of the classical analyses show that, both in metal poor field stars and in stars in clusters, and I can't believe that we all could be making the same mistake over such a large range in temperature that has been done to date.

KING: Could I ask a question that has bothered me ever since I heard these things last year in Cambridge. If you believe the differences between ω Centauri stars are primordial, would you not predict much wider horizontal branch morphology than ω Centauri shows, and would you not also predict a spreading of the main sequence and the main sequence turnoff?

COHEN: Yes, I do expect there to be a spread in the main sequence and I don't think it's well enough determined to date. The limits are not the greatest. The other point about the horizontal branch is that I think the absence of red horizontal branch stars in ω Cen indicates that it's not the CNO abundance which controls the distribution of horizontal branch stars. That's a very tricky point, wriggling out of the horizontal branch problem.

KING: There must be some information that's telling us something there, if only we knew what it was. I think that maybe Ken Freeman thinks he knows what it is.

FREEMAN: This is actually a question too, concerning particularly the main sequence; and this is probably just to start with, as we will hear from Russell Cannon, as well. The faint photometry is done in the outer parts of ω Cen. In the outer parts of ω Cen the whole abundance range is collapsed to about a third of what one sees in the cluster as a whole.

KING: I notice Russell Cannon has a poster paper on the turnoff of ω Cen, and I can't read it from here. I wonder if he would remind us of what's in it.

https://doi.org/10.1017/S0074180900092214 Published online by Cambridge University Press

CANNON: Do I have to identify myself? (Laughter). The results are somewhat inconclusive, unfortunately. What we did was get the most accurate internal measurement errors that we could down to about 19th magnitude, in the hope that we will be able to say something significant about the spread of *B-V* to stars in that region. The result is that the spread we see gets smaller each time we measure better plates. For most of the stars the scatter is about the size of our measuring errors, but there is a tail towards the red side of the distribution. My best guess at the moment is that there is a primordial abundance range among the main sequence stars, with the majority of the stars being metal poor but with a small portion of relatively metal-rich stars (see paper elsewhere in this volume).

PETERSON: Is it still possible that this distribution is bimodal and therefore that the horizontal branch could be just a result of one of the two subsets?

COHEN: No, it's not. It may be that there are peaks in the distribution, but it's certainly not bimodal unless the width of the gaussians that describe the peaks are large. The colour-luminosity plot that you saw appears to give very good definitions of metallicity and there are no peaks in it. It's a more or less continuous population of stars from the blue edge right through.

KRAFT: I'd like to direct this to Ken and Russell. As you go out to the outer regions of ω Cen, where also the RR Lyrae stars were done, I seem to remember that the metal rich RR Lyraes constitute a significantly smaller fraction of the population than the metal poor ones. Does that also apply to the general population, so that the number of metal rich stars in that region would only be a small fraction? In other words, is the contamination of the main sequence turnoff of metal rich stars in this more metal-poor cluster just a small fraction and so you'd only get a few stars?

CANNON: If I could answer that one. Ken really already said this, but essentially the faint photometry is well out of the cluster at a fairly small range of radius and it's quite possible that we have there something like 5 or 10% of metal rich stars and 90% metal poor. But that may not be true at other radii.

KRAFT: Ok, you do have a very much smaller proportion of metal rich stars?

CANNON: Well, if you put Ken's data together with ours, yes, that is at least a self-consistent picture.

SHAWL: I'd like to add something that may help to confuse things a little bit. I've been doing some work with George Coyne and Ray White. We've been doing polarimetry of some giants in M3 and M13, and in M3 there appears to be 1 out of about 24 sampled

https://doi.org/10.1017/S0074180900092214 Published online by Cambridge University Press

stars that seem to have a statistically significant polarization, and about 4 out of 25 in M13. Of course, the big question is, "what is it due to?"; and one likes to say "dust". You don't know what the formation mechanism is of dust or where the atoms would come from to form it, but this is something that we're working on and may again confuse the problem a little bit.

COHEN: Jay has a program to measure 10μ colours of giants.

LODEN: Could you give an example of the individual values behind the mean values in Table 1?

COHEN: I don't have that with me, but the scatter is quite small. The dispersion in the Fe abundance for the four stars can't be from more than -1.4 to -1.0 for M71. The range is very small. Its equivalent to the errors.

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