THE CHEMICAL INHOMOGENEITY WITHIN GLOBULAR CLUSTERS

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1. INTRODUCTION

Twenty years ago it was believed by most astronomers that globular clusters were chemically homogeneous - where by homogeneous one means that the outer layers of all stars within a given cluster are the same to within a few tens of percent. Today it is possible to defend the case that no Galactic globular cluster has this characteristic. The reason that this phenomenon has exercised the minds of so many groups in the past 15 years is exciting and obvious: if one can ascertain which are the relevant physical processes in operation, one stands to gain significant insight into both the way in which globular clusters formed and/or the way in which individual low mass stars evolve and mix the products of their nucleosynthesis into their outer layers. A second important driver at the back of the minds of workers in this field is the possible ramifications of an understanding of the phenomenon; for example, if one concludes that the abundance anomalies are being driven today by some particular effect (angular momentum, magnetic fields, interactions within binary systems, stellar collisions - or whatever) this may lead to insight into other important globular cluster phenomena (eg bimodal horizontal branches, gaps at the base of the giant branch, horizontal branch rotation, etc.)

The purpose of the present review is twofold. First, an effort is made to summarize the systematic trends which have been deduced from the wealth of observational material. Second, the constraints which this imposes on the physical processes at work are discussed at some length.

2. CANONICAL WISDOM

The basic ideas which shaped the early expectations of chemical homogeneity are best illustrated by consideration of globular cluster color-magnitude diagrams. The first important point is that the small color spread seen on the giant branch of most systems indicates that there can be little range in the abundance of elements such as Si, Mg, and Fe which play an important role in determining the opacity in the outer layers of red giants. For most objects this sets the limit $\Delta[Fe/H] < 0.15$. The second point is that standard stellar evolution theory (see Iben 1967, 1974) explains the principle sequences in color-magnitude diagrams very well, suggesting that only minor modifications in surface abundances are to be expected during evolution.

J. E. Grindlay and A. G. Davis Philip (eds.),
The Harlow-Shapley Symposium on Globular Cluster Systems in Galaxies, 93–106.

The basic concepts are as follows. First one has the long-lived (15 Gyr) main sequence phase of hydrogen burning. After core hydrogen exhaustion a star leaves the main sequence (burning hydrogen in a shell) and evolves relatively quickly to the base of the giant branch. At this point, according to standard theory, the convective envelope reaches its greatest inward extent and actually mixes up material which has undergone CNO processing into the outer layers of the star. The basic difference between prediction and observation is one of considerable degree - for while the models predict changes in C and N of order a few tens of percent (Faulkner and Iben 1967; Da Costa and Demarque 1982) observation requires modifications by factors of up to 10-50. More of this later. The star now proceeds up the giant branch until the electron degeneracy of its helium core is lifted by the ignition of helium at the tip of the giant branch. Most theoreticians report no upheaval of the surface layers at this point, though the recent work of Deupree and Cole (1983a,b), which includes hydrodynamical effects, suggests the potential for considerable rearrangement. After some 100 Myr of core helium burning on the horizontal branch, the star retraces its steps up the asymptotic giant branch (AGB), where it undergoes helium shell flashes until it finally exhausts its supply of hydrogen and evolves to higher temperature on a short timescale on its way to becoming a white dwarf. The important fact about all standard stellar evolution calculations of the phases after the helium flash is that no prediction of major surface abundance rearrangement has been made.

3. THE REAL WORLD

Life is not that simple. Figure 1 shows spectra in the wavelength range λλ3800 - 4500A for 4 stars of comparable brightness in the remarkable cluster ω Centauri. This object possesses giants with enormous carbon enhancements (CH stars), with carbon deficiences (weak-G-band stars), and large CN enhancements (CN-strong stars) as shown here. ω Cen also exhibits an anomalously wide upper giant branch (Woolley et al, 1966; Cannon and Stobie 1973) indicative of a spread in heavy element abundance, together with a large range in Ca II H and K line strengths found by Freeman and Rodgers (1975) among the RR Lyrae variables.

Fortunately ω Cen (along with M22 to a lesser extent) is unique. Most clusters are much simpler, exhibiting little variation in heavy element abundance, and to some extent insight into the basic problem has come from investigations of the more homogeneous systems. We shall confine our attention initially to these more homogeneous clusters (Section 3.1) and then return to ω Cen in Section 3.2.

The present review makes no attempt to cover the early observational material on the problem. The reader is referred to the Annual Reviews articles by Kraft (1979) and Freeman and Norris (1981), and that of McClure (1979) for a comprehensive set of basic references on the topic. (During this conference the author was presented with a preprint by G.H. Smith entitled 'The Chemical Inhomogeneity of Globular Clusters' which will appear in P.A.S.P. This is the most detailed and

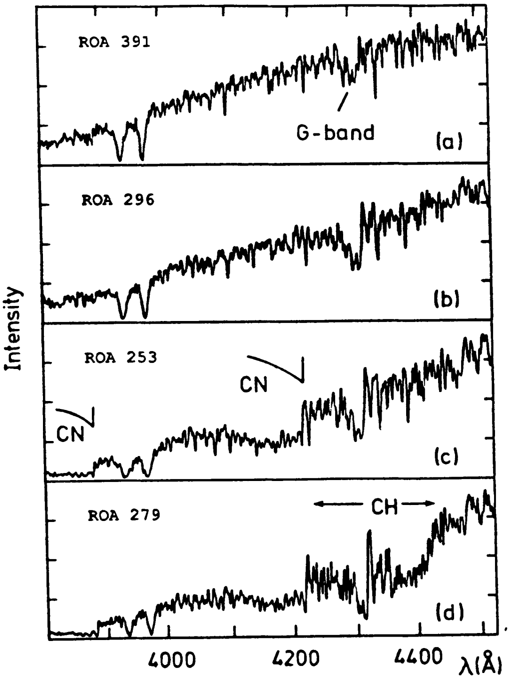

Fig 1. Spectra of 4 giants of similar luminosity in ω Cen. (a) ROA 391 is an example of a weak-G-band star, (b) ROA 296 is a 'normal' star having no carbon or nitrogen anomaly, (c) ROA 253 is a classic CN-strong star, and (d) ROA 279 is an example of a relatively hot CH star.

comprehensive discussion of the topic yet seen by the author and is recommended to any researcher interested in the subject.) Suffice it here to say that it was Harding (1962), Osborn (1971), and Zinn (1973), respectively, who first drew attention to the fact that CH and CN enhancements, together with CH depletions, exist in globular clusters. Subsequent investigations have provided a massive data bank on clusters of all abundances, and for stars at all phases of evolution subsequent to the main sequence. The only phase of evolution where systematic observational material does not exist is that of the main sequence. The aim of the present work is to describe the systematic abundance patterns which have emerged from these efforts with a view to constraining the possible origin of the observed anomalies.

Space precludes detailed description of techniques. Model atmosphere spectrum synthesis analysis (see eg Bell, Dickens, and Gustafsson 1979) of the features of molecules containing C, N, and O have played the major role, with the relevant species determined in large degree by the overall abundance of the cluster. Thus, for [Fe/H] < -1.8, the G band (CH) and the NH features at λλ3350-3360A are the main features analyzed. In the range -1.8 < [Fe/H] < -1.0 the violet CN bands degrading blueward of λ3883Å supplement CH and NH, while at higher abundances the blue CN bands near λ4216Å are adopted in preference to the (by this time) very strong violet bands. For oxygen one is faced with the basic problem that the available features (OI lines near λ6300Å) are extremely weak (~ 30 mÅ), while the CO bands near 2.4 μm are observed only with difficulty.

3.1 Clusters Other Than ω Cen and M22

For convenience we split the discussion into three parts - first comes C and N, then O, and finally the behavior of Na and Al, which seems inextricably connected with that of the CNO group.

3.1.1 Carbon and Nitrogen

3.1.1.1 The Dependence on Cluster [Fe/H]

Bell and Dickens (1980) first pointed out that the level of carbon depletion on the upper giant branch is greatest in clusters of lowest abundance. This remarkable effect is shown in Figure 2. One is thus seeking a process which operates most efficiently in a low abundance environment. As these authors point out, this phenomenon is just what might be expected from the meridional mixing model of Sweigart and Mengel (1979, hereafter SM). For giant branch stars SM examined the mass extent of the regions just outside the hydrogen burning shell in which CN and ON nuclear processing has occurred, and noted that for stars of lower heavy element abundance these regions become larger and further removed from that in which hydrogen has been substantially converted into helium. They argue that mixing of CNO-cycle processed material to the surface will thus proceed more readily in low abundance stars than in those of higher abundance. It is very instructive to look at their Figures 1-3. Note that this property of the extent of the CN and ON processed zones will assist any mixing process in low abundance stars.

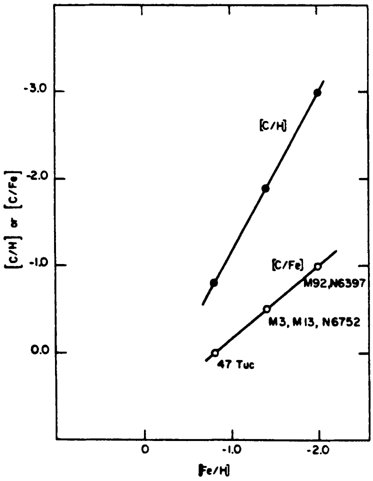

Fig 2. The dependence of [C/H] and [C/Fe] on cluster [Fe/H] (for upper giant branch stars) from Bell and Dickens (1980), showing that carbon depletion is most marked in clusters of lowest heavy element abundance. (Reproduced from Astrophysical Journal.)

3.1.1.2 Dependence on Evolutionary Status

It was evident from the very first that carbon depletion in the most metal weak systems ([Fe/H] ~ -2.0) is in some way connected with evolutionary status. The AGB of M92 was the site where Zinn (1973) identified the weak-G-band phenomenon; Bell, Dickens, and Gustafsson (1979), using the power of spectrum synthesis, next showed that the effect was marked at the tip of the giant branch in the most metal weak clusters; and finally Carbon et al. (1982) and Langer et al. (1986) have shown a pattern of increasing carbon depletion with increasing brightness along the red giant branch of M92, as reproduced in Figure 3.

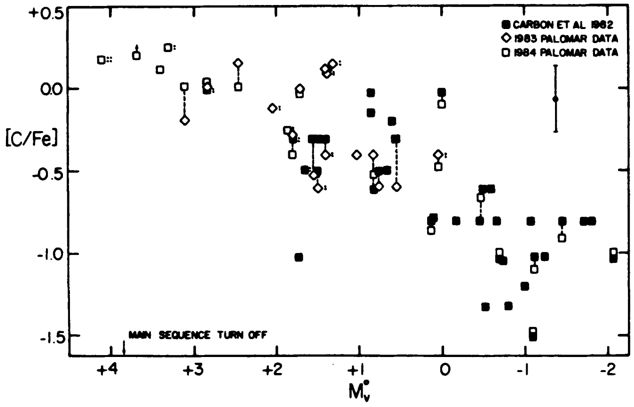

Fig 3. The dependence of [C/Fe] on M_V on the giant branch of M92, from Langer et al. (1986). (Reproduced from Astronomical Journal.)

Clearly this result receives a most natural explanation in terms of CN processing and mixing on the giant branch. It should be noted for completeness that some of the nitrogen overabundances found higher on the giant branch by Carbon et al. (1982) are so large (of order 20-30) as to require (i) additional processing in the ON cycle (which requires more extreme conditions) followed by mixing (SM), or (ii) primordial variations in C followed by CN processing and mixing (Carbon et al. 1982), or (iii) primordial variations in N (Norris and Pilachowski 1985). Unfortunately we know nothing of the behavior of C and N at the base of the giant branch of M92, because of the difficulty in making the necessary observations.

For the more metal rich clusters the situation appears somewhat different. In 47 Tucanae, with [Fe/H] = -0.7, Bell, Hesser, and Cannon (1983) have demonstrated the existence of CN anomalies right down to the main sequence turnoff, consistent with nitrogen abundance variations of order 5. They also find no evidence for a difference in the abundance ranges of C and N from the turnoff to the tip of the giant branch. As demonstrated by Da Costa and Demarque (1982), who considered several ad hoc main sequence mixing possibilities, the existence of a range in nitrogen abundance at the main sequence turnoff is more suggestive of a primordial origin than of a mixing process.

It should also be noted that the observations of C and N variations low on the giant branches of M92 and 47 Tuc are in disagreement with the meridional mixing model of SM. These authors predict that no mixing should occur until much higher on the giant branch when the hydrogen burning shell has moved out through the composition discontinuity left in the stellar envelope by the convective envelope at its deepest penetration on the lower giant branch. This disagreement between observation and the meridional mixing model is found in all clusters where the test has been made (Norris and Smith 1984, and references therein).

3.1.1.3 Systematics at a Given Point on the Giant Branch

Another approach to the problem has been to investigate a relatively large number of stars at roughly the same phase of evolution in a number of clusters. The results for the systematics of violet CN on the giant branch for 12 clusters with $-1.9 < [Fe/H] < -1.3$ are shown in Figure 4, which presents generalized histograms of the cyanogen excess of individual red giants, δCN, from Norris (1987). Note the large range of morphologies exhibited and the propensity towards bimodality. The latter effect is an interesting phenomenon, being suggestive of two populations. This is, however, not necessarily so. Suntzeff (1981), Langer (1985), and Smith and Bell (1986) have suggested that this results from saturation effects in the violet CN bands as N is enhanced by the mixing to the surface of the products of the CN cycle. In principle this works, though it remains somewhat of a challenge to explain the degree on CN enhancement. If, for example, one compares the results for M4 ($[Fe/H] = -1.3$) with the spectrum synthesis calculations of Smith and Bell (1986) for $[Fe/H] = -1.0$ one finds that in M4 the difference in the cyanogen index between the CN-strong and CN-weak stars is ~ 0.4 (see Figure 4), while that predicted from CN processing is only ~ 0.2 (Smith and Bell 1986). A couple of points should be made here. First, similar spectrum synthesis calculations by the author suggest

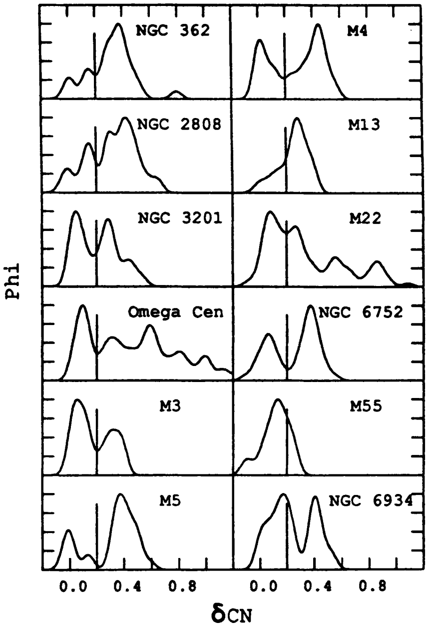

Fig 4. The generalized histograms of CN-excess, δCN, for 12 clusters. Note the large range in morphology of the distributions and the high incidence of bimodality. The vertical lines at δCN = 0.20 are used to separate CN-strong and CN-weak stars to define the parameter r = number of CN-strong stars/ number of CN-weak stars for use in Figure 7.

that the difference of Δ[Fe/H] ~ 0.3 between the observations and calculations will have little effect on the comparison. Second, it might be fruitful to consider the role of ON processing in this problem.

A further important result that has come from this type of investigation is that in many clusters there is an anticorrelation between the behavior of the CN bands and that of the CH features (Norris, Freeman and Da Costa 1984, and references therein). The simplest explanation of this phenomenon clearly lies in the operation of the CN cycle - with the most favored site being the interior of the star itself. It is extremely difficult to explain within a primordial framework (Smith and Norris 1981b), and by any postulated accretion mechanism such as that of D'Antona, Gratton, Chieffi (1983). (See Norris, Freeman, and Da Costa 1984). The anticorrelation seems to hold in clusters with [Fe/H] > -1.8, with ω Cen and M22 being the exceptions.

3.1.2 Oxygen

It seems reasonable to suggest that the systematics of oxygen are not yet understood. This results from the weakness of the available spectroscopic features at optical wavelengths. The severity of the problem of the weakness of the OI lines is nicely illustrated by the work of Leep, Wallerstein and Oke (1986, Figure 1). The CO bands in the infrared have not yet been utilized in a definitive way to attack this problem. See Bell and Dickens (1980) for an example of the problems encountered.

Several comments may be made on the available data. First, such is the observational difficulty of the problem that most investigations are aimed at determining the mean oxygen abundance of clusters (see ,eg, Pilachowski, Wallerstein, and Leep 1980). Second, in an effort to see if oxygen was correlated with C and N, Cottrell and Da Costa (1981) reported that to within 0.1 dex there is no difference in the oxygen abundance of the CN-weak and CN-strong groups in 47 Tuc. Finally, Leep, Wallerstein, and Oke (1986) report that one out of five giants studied in M13 has an oxygen underabandance of a factor of at least 5 relative to the other four. (We note for future reference that the oxygen deficient star in question is II-67, the very object for which Peterson (1980) reported an <u>overabundance</u> of sodium of 0.7 dex. It is also CN-strong (Norris and Pilachowski 1985), while of the other four objects one (II-76) is known to be CN-weak.) Clearly much effort needs to be expended before a clear picture on this problem will emerge.

3.1.3 The Heavier Elements (In Particular Na and Al)

It has become evident that in almost all cases where one finds nitrogen enhancements the features of Al and Na are also enhanced. (See Norris and Smith 1983; Norris and Pilachowski 1985; and references therein.) The effect for Al is shown in Figure 5, which presents spectra of a CN-strong, CN-weak pair of stars in NGC 6752. It is immediately obvious that the mixing of CN-processed material cannot directly produce overabundances of this type. Cottrell and Da Costa

(1981) sought an explanation in terms of primordial production in the first generation 5-10 $M_\odot$ AGB stars, based on the stellar evolution calculations of Iben (1975, 1976).

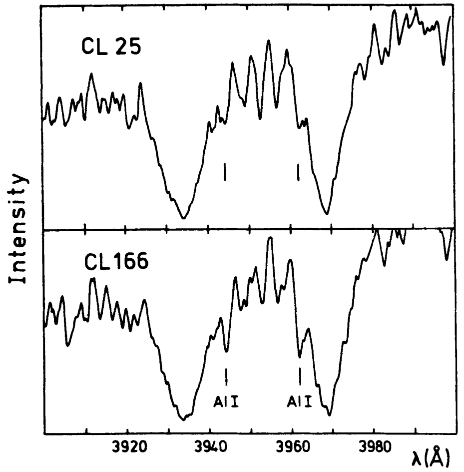

Fig 5. Comparison of the spectra of two red giants in NGC 6752 having similar effective temperature and gravity in the region of the Al I lines at λλ3944 and 3961Å. CL25 is CN-weak while CL166 is CN-strong. See Norris et al. (1981) for details. (Reproduced form Astrophysical Journal.)

3.2 ω Centauri

ω Cen is the most massive of the Galactic globular clusters, and shows the most extreme chemical inhomogeneity. Its color-magnitude diagram clearly indicates that it differs basically from most other Galactic globular clusters. On the giant branch one sees a spread in color of Δ(B-V) ~ 0.4 (Woolley et al. 1966; Cannon and Stobie 1973) in comparison with much smaller ranges (< 0.03) seen in other systems. As noted earlier, the origin of this spread lies in a range of heavy element abundance. The red giants exhibit a large range in the strengths of the molecules formed from C and N (Harding 1962; Norris and Bessell 1975,1977; Dickens and Bell 1976; and Bessell and Norris 1976). Dickens and Bell (1976) also recognized the existence of stars with anomalously strong features of the s-process elements Sr and Ba, while Lloyd Evans (1977a,b) catalogued the coolest stars which exhibit TiO and enhanced Ba. Cohen (1981) and Gratton (1982) reported a large and complex range of heavy element abundances from model atmosphere analysis of high dispersion spectra. The light elements and the rare earths (plus Ba) appear enhanced relative to the iron peak elements in the more metal-rich ω Cen stars.

Two schools of thought developed to explain these observations. On the one hand the variations of Ca are difficult to understand except as the result of primordial effects, since this element is not synthesized in low mass stars. On the other hand anomalies involving C, N, Sr, and Ba are usually associated with mixing phenomema. This was complicated by the observation that at a given luminosity there is a direct correlation between the behavior of CN and Ca (Norris and Bessell 1977; Norris and Freeman 1983, Figure 7). It is important to note, however, that the observations still permit considerable spread in CN at a given Ca line strength.

Another important constraint on the problem is given by the work of Persson et al. (1980) who demonstrated a dichotomous behavior of the infrared bands of CO, suggestive of two distinct phenomena at work. This was followed up by Cohen and Bell (1986, hereafter CB) who analyzed complementary low resolution optical spectra of most of the Persson et al. sample. From spectrum synthesis analysis of the available material, CB conclude that there are three groups of stars in the cluster. First there are the well known carbon stars. Second there is a group of objects in which nitrogen is enhanced by factors of 5-15 and in which carbon and oxygen may be depleted by factors of as much as 10. The third group comprises objects in which C and N are normal to within a factor 2. There is a wide range in heavy element abundance in groups 2 and 3.

The author suggests that this classification is a considerable oversimplification brought about by the large selection effects inherent in the Persson et al. sample. It is his belief that while the nitrogen rich group may have the properties suggested by CB, it is at the extreme of a (probably) continuous distribution. This is best illustrated by the statement that of the 72 stars analyzed by CB only two of the N rich group were chosen in an unbiased manner.

This criticism having been made, it should also be stated that work by Paltoglou and Norris (1987) supports the result of CB that the nitrogen rich stars are oxygen deficient. Figure 6 shows spectra near λ6300 of the normal stars ROA 43 and 53 and the nitrogen rich objects ROA 100 and 150. The four objects have similar T_{eff} and log g, while [Fe/H] varies by ~ 0.2 within the group. Despite this, the OI line is clearly seen in ROA 43 and 53 but not in ROA 100 and 150. These data support the suggestion of CB that not only CN but also ON cycling has acted in the stars having extreme nitrogen enhancements in ω Cen. The preliminary analysis of Paltoglou and Norris finds a strong anticorrelation between oxygen and nitrogen for a sample of 12 stars.

We complete the discussion with one further interesting fact. The nitrogen rich stars exhibit large enhancements of Na and Al relative to iron. Cohen (1981) reports [Na/Fe] = 0.8 and [Al/Fe] = 1.4 for ROA 253, a classic nitrogen enriched object. This is exactly the same result noted in the more normal clusters. In ω Cen there is one further important piece of information. As noted above, oxygen appears anticorrelated with nitrogen. The preliminary results of Paltoglou and Norris (1987) also show the positive correlation between Na and N, and by implication an anticorrelation of oxygen and Na. It should also be recalled that a similar effect exists for II-67 in M13 (see Section 3.1.2.). The obvious conclusion is that, if these results stand, Na (and presumably Al) are in some way enhanced in the mixing process which leads to oxygen depletion, or at the very least the spectral features of Na and Al are modified by phenomena associated with the results of that mixing process.

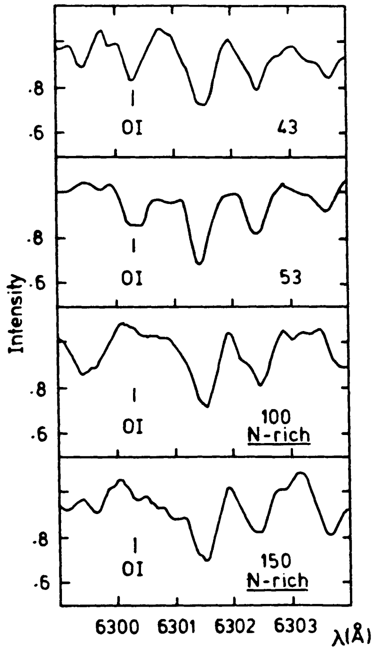

Fig 6. The behavior of OI line strength in four giants of different nitrogen abundance in ω Cen, from the work of Paltoglou and Norris (1987). (The number to the right is the ROA designation.) Note that the OI line is not detected in the N-rich stars, in support of the suggestion of Cohen and Bell (1986) that ON-cycle processing and subsequent mixing has occurred in these objects.

4 DEPENDENCE ON GLOBAL CLUSTER PROPERTIES

The author knows of no cluster in which the necessary observations have been made that does not exhibit C and/or N variations at least (roughly) the factor of 2 level. Investigations aimed at correlating cluster abundance 'anomalies' with global cluster properties such as mass, central density, etc have not been particularly successful. Smith and Norris (1981a, Figure 13) show that a range in CN strengths occurs for all present-day cluster masses. Anomalies exist at all cluster central densities. Even the ghostly Palomar 5 has roughly equal numbers of CN-strong and CN-weak stars (Smith 1985).

While searching for such correlations the author (Norris 1987) found a possible connection between the degree of CN enhancement and apparent cluster flattening, for clusters in which sufficient violet CN data were available. Figure 7 shows the result, where r is defined as the ratio of CN-strong to CN-weak stars in a given cluster, and ε is the apparent flattening of the system. (The adopted dividing line between CN-weak and CN-strong stars is shown in Figure 4.) It was suggested that angular momentum is the driver producing both the flattening of the clusters and, via internal rotation in individual stars, the greater degree of CN enhancement in the more flattened systems.

5 ORIGIN OF THE ANOMALIES

It should be evident from the above that at least two

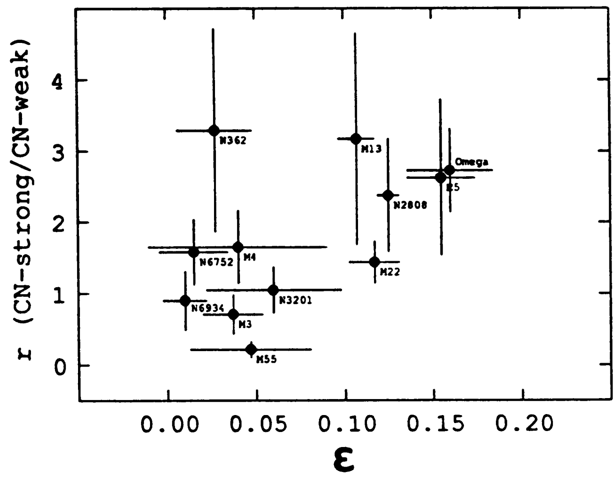

Fig 7. The dependence of the degree of cyanogen enrichment, r, on cluster flattening, ε. This diagram leads to the suggestion that angular momentum may play a role in driving abundance anomalies. (From Norris 1987.)

fundamentally different processes have operated to produce the phenomena described above. In ω Cen there can be little doubt that primordial abundance variations existed 10 Gyr ago. It is the author's opinion that no amount of invention can explain the calcium variations seen in the RR Lyrae stars in that system in any other way. At the other extreme there can be no explanation other than mixing processes for the steady downward march of carbon abundance as one proceeds up the giant branch of M92. It is thus not a question of either/or, but of how much of each.

The simplest picture which suggests itself at the present stage is the following. Some agency causes the stars in globular clusters to supermix (a word borrowed from Iben to denote mixing more extreme than that predicted by standard stellar evolution theory). That agency is not determined, but the number one suspect is angular momentum in stellar interiors. Here is a problem crying for a theoretical solution. The observations of M92 suggest that the process becomes important in clusters of lowest abundance by the time the stars reach $M_V = 2$ on the giant branch. What remains unclear is whether such a process can operate with the required efficiency to produce N anomalies at the main sequence turnoff as is indicated by the observations of 47 Tuc. This remains one of the unanswered questions concerning the evolution of low mass stars at this time.

On the other side of the coin there are some clusters, the clearest cases of which are ω Cen and M22, in which primordial variations also exist. In these objects the situation is complicated by the fact that one observes, for the red giants, not only the primordial variations but also the superposition upon them of mixing effects.

Several problematic observations remain. Foremost is the positive correlation of nitrogen on the one hand with Na and Al on the other. This phenomenon appears to exist in all clusters. Four possible explanations may be suggested. First, complicated primordial variations involving some or all of C, N, Na, and Al exist in most clusters. In principle at least, this could perhaps be solved by future observation of main sequence stars. The second possibility is that non standard evolution at the helium core flash might explain the result. Deupree and Cole (1983a,b) have suggested that during this event Na and Al might be produced within certain bubbles deep within the envelope of the star. Difficulties with this explanation have been described by Norris and Pilachowski (1985) and will not be repeated here. Third, it is not impossible that atmospheric effects related to the mixing status of a star (eg non-LTE effects, boundary-temperature differences induced by different molecular densities, different turbulence, magnetic fields, different rotation, etc.) may lead to spurious strengthening of Na and Al in stars which appear to have enhanced nitrogen. Finally, the preliminary result, noted above, of an oxygen, Na anticorrelation by Paltoglou and Norris (1987) for the giants in ω Cen is certainly suggestive of a causal relationship between the behavior of Na and phenomena associated with mixing. Since s-process element enhancement is also seen in the nitrogen enriched stars one must now address the possibility that neutron addition processes, similar to those described by Iben (1975, 1976) in the context of intermediate mass AGB stars, may be responsible for some of the anomalies.

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DISCUSSION

NEMEC: The recent finding by Nemec, Nemec and Norris (1986 Astron. J. 92), and others, that double-mode RR Lyrae stars are not found in the highly flattened globular cluster ω Cen, despite the apparent similarity of the primary periods of these stars to the primary (first overtone) periods of the double-mode RR Lyrae stars in M 15, seems to us might also be caused by star-to-star angular momentum differences.

BELL: Have you considered the possibility of CH lines blending with the Al lines in the H and K wavelength region?

NORRIS: There are two points. First, since one sees an anticorrelation of CN and CH, the effect of CH blending would be to decrease the Al line strengths in CN strong objects - just the opposite of the positive CN, Al correlation which is observed. Second, in her high dispersion analysis of the CN strong star ROA 253 in ω Cen, Cohen showed a positive CN, Al correlation based on Al lines in the red region of the spectrum.

DEMARQUE: I have two comments. First I would not give up too soon on the Sweigart Mengel mechanism to explain the progressive enrichment of N along the giant branch. Rotation could be responsible for internal mixing in many ways other than meridional circulation, which should occur at a lower luminosity. Second, in reference to N variations found in stars on the turnoff in 47 Tuc, there is, I believe, some recent work by Spite and Spite which shows that N-rich halo stars near the main sequence have the same Li abundance as N-poor stars. In my mind, these observations show unequivocally that mixing must be responsible for the N variations near the main sequence of 47 Tuc.

NORRIS: 1. I did not mean to imply that I think that the SM mechanism should be discarded completely. Rather, I would hope that the dependence of the degree of cyanogen enrichment on cluster flattening might spur the theoreticians, such as yourself, to renew their efforts in tackling the difficult problem of stellar rotation. 2. I think you are comparing two different phenomena. The stars studied by the Spites have [Fe/H] ≃ -2.0, and represent only a few percent of a complete sample (see Bessell and Norris 1982, Astrophys. J. Letters 263, L29.). In 47 Tuc roughly half of the stars are CN strong. I think we are talking about apples and oranges.