Inhomogeneities in Globular Clusters

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Abstract: Inhomogeneities in globular clusters are reviewed with the observational evidence for chemical abundance variations from star to star in individual clusters and the large-scale structural variation of clusters. The reality of the radial colour gradient is tested in 47 Tuc (NGC 104). The result shows that the observed radial colour gradient comes from the integration of the calculated colours of individual stars. The cause of this radial colour variation is the result of the concentration of evolved stars and the reddening of the main sequence in the central region. We propose that the CNO abundance gradient in the early stage of a cluster's formation is the interpretation of the observed radial colour gradient.

1. Introduction
Globular clusters are probably the oldest objects in the Galaxy with an age of \(\sim 10^{10}\) years. To define the dynamical structure of globular clusters, stellar encounters are important. Their central relaxation times are in the range of \(10^7\) to \(10^9\) years, which is less than their lifetime (\(\sim 10^{10}\) yr). Their characteristic dynamical times are typically \(10^6\) years. They are, therefore, relaxed and dynamically well mixed. This means that a cluster is close to a steady state, in which its distribution function tends towards a Maxwellian.

King (1966) made a one-parameter sequence of stationary self-consistent models for spherical globular clusters which come from the steady state solution of the Fokker Planck equation, and their distribution function. In these models, all stars have the same mass, and the velocity distribution is isotropic. The models have two lengthscales. One is the tidal radius \(r_t\), associated with the cut-off energy \(E_o\). The other is the core radius \(r_c\). The surface density profiles derived from these models are an excellent fit to the observed radial surface brightness and star count distributions in globular clusters, and also to the surface brightness distributions in elliptical galaxies (King 1966).

For the chemical abundance, globular clusters are usually believed to be chemically homogeneous with abundances that reflect those of the gas from which they formed. It is possible to regard globular clusters as the homogeneous aggregates of metal-weak stars. However, this belief may be wrong. There is now evidence that some clusters are inhomogeneous. In this review I will describe observational evidence for chemical abundance variations from star to star in individual clusters, and then the inhomogeneities in the large-scale structure of clusters.

2. Chemical Inhomogeneities
(a) CH stars
The CH stars are defined as giants in which the surface abundance of Carbon exceeds that of Oxygen. These stars are found in M22 (McCulc and Norris 1977), M55 (Smith and Norris 1982), M2 (Zinn 1981) and \(\omega\) Cen (Cohen and Bell 1986). The detection of CH stars in M12 makes it difficult for the hypothesised relation between low-concentration and CH star existence (McCulc and Norris 1977).

The existence of CH stars was interpreted as an internal mixing hypothesis (Smith and Demarque 1980), chemical enrichment of different mass stars (Norris and Freeman 1983) and a separate mixing event from N-enriched giants (Cohen and Bell 1986).

(b) Weak G-band stars
The weak G-band stars are mostly found in the metal poor clusters and most of them are AGB stars (Zinn 1973; Norris and Zinn 1977). Among 20 giants in M92, Zinn (1973) found that most weak G-band stars are asymptotic giant branch stars. He interpreted this phenomenon as the result of stellar evolution which may come from the low abundance of CH and the diffusion of carbon during the blue horizontal branch phase.

In M13, M92, NGC 6397 and M15, all the observed weak G-band stars are asymptotic giant branch stars. This result may come from the mixing of CNO processed material to the surface (Norris and Zinn 1977). Mallia (1978) found weak G-band stars in NGC 6397 and NGC 6752, and interpreted this as the mixing of CNO processed material.

(c) CN bimodality
Norris and Freeman (1979) observed 142 red giants in 47 Tuc and they found CN bimodality. These phenomena were also found in NGC 6752 (Norris et al. 1981), M71 (Smith and Norris 1982a; Smith and Penny 1989), M5 (Smith and Norris 1983), NGC 6934 (Smith and Bell 1986) and NGC 6637 (Smith 1989).

Hartwick and McCulc (1980) assumed that primordial N abundance was lower in the gas which formed in the inner halo stars than it was in the disk. They argued that the bimodal CN distribution of 47 Tuc may be present in other stellar populations in varying degrees, and this bimodality is a normal aspect of stellar evolution.

For the interpretation of the observed CN bimodality of 47 Tuc and NGC 6752, Smith and Norris (1982b) made a hypothesis that there are two generations of stars in clusters, one having been enriched by the ejecta from the other.

Smith (1986) suggested the abundance inhomogeneity in \(\omega\) Cen was the result of the supernovae explosions in the early time of the cluster. On the other hand the systematic radial colour gradient and CN bimodality in 47 Tuc were assumed to be the result of the interior stellar mixing or stellar wind enrichment of massive stars.

Briley et al. (1988) assumed that the bimodality in 3383\(^{ACN}\) in 47 Tuc may be due to a difference in the \(^{12}\text{C}/^{13}\text{C}\) ratios of the two groups. Smith and Penny (1989) found a 3383\(^{ACN}\) bimodality and an anti-correlation between CN 3383\(^{A}\) and the G-band 4300\(^{A}\) among HB stars in M71. They explained these phenomena as a result of mixing CNO material, rather than an evolutionary result.

(d) CN variation
CN abundance variations among stars in \(\omega\) Cen, M22, 47 Tuc, NGC 6352, NGC 6397, NGC 6752, M15 and M4 have been reported by many authors (Hesser et al. 1976; Mallia 1978; Mallia and Pagel 1981; Norris and Freeman 1983; Bell et al. 1983; Trefzger et al. 1983; Smith and Suntzeff 1989). These variations have been explained by Sweigart and Mengel (1979) as the meridional circulation due to the internal rotation of a star, which will lead to the mixing of CNO processed material from the vicinity of the H-shell into the envelope of red giants.

From the spectra of 8 giants in \(\omega\) Cen, Mallia and Pagel (1981) found N/H variations among giant stars. They assumed that this
chemical inhomogeneity comes from supernovae ejecta and a colour gradient was set up therein by the inhomogeneous collapse. Da Costa and Demarque (1982) questioned the observed N variation as a result of the deep mixing within a star. They argued that although significant N-enrichments can be produced by the mixing, the star evolves only as a blue straggler but does not become a red giant. So the primordial origin from the protocloud state is more reasonable than mixing to explain the N-enrichment.

(e) Other element variations
In 47 Tuc and NGC 6752, Na and Al abundance variations among giant stars were interpreted according to the primordial hypothesis. In M22, CN/CaII H and K anticorrelation, CH G-band variation, C overabundance and Al, Ca variation were assumed due to the chemical enrichment of different mass stars (Norris and Freeman 1983).

3. Radial Color Gradients
(a) Observational evidence
The integrated colours of globular clusters measured by Stebbins (1950) showed that the inner regions are redder in some systems by up to 0.17 mag in $V-I$. Gascoigne and Burr's (1956) surface photometry of 47 Tuc showed a similar effect with amplitude 0.13 mag in $B-V$.

The radial distributions for RR Lyrae in some clusters show a smaller central concentration than for the giant stars (M3, M5, M15 and $\omega$ Cen by Oort and van Herk 1939; $\omega$ Cen by Woolley and Dickens 1967), and the blue and red horizontal branch stars in M3 have different radial distributions (Wolf 1964). Lloyd Evans (1974) showed that red giants are more concentrated to the centre than the integrated light of 47 Tuc from star counts.

From integrated spectra of 47 Tuc, Smith (1979) showed there were enhanced absorption features in the core region. Chun and Freeman (1979) reported a radial colour gradient in the sense of reddening in the central regions for 8 out of 24 observed globular clusters. The integrated colours of $\omega$ Cen showed that the core region is bluer in $U-B$ and redder in $B-V$ and $R-I$ colours (Scaria 1982). Bendinelli et al. (1983) reported that the centre of NGC 362 is redder than the outer region by about 0.1 mag in $U-B$ and $B-V$. Integrated radial $B-V$ and $c(\lambda 45-48)$ gradients were found in $\omega$ Cen and M30 (Pastoriza et al. 1986), and a significant radial colour gradient, in the sense of reddening with radius, was observed in M30 by Piotto, King and Djorgovski (1988). Bailyn et al. (1989) reported that the area within 6.6 arcsec of the cluster centre of M15 is bluer than the surrounding region.

However, there are several arguments against the radial colour gradients in globular clusters. Among them, Buonanno et al. (1981) have reported that the colour gradient of NGC 5904 observed by Chun and Freeman (1979) is due to the position and size of the measured aperture with respect to those of a few bright giants. Hanes and Brodie (1985) think that most of the observed colour variations come from the miscentering effect. Peterson (1986) observed 101 globular clusters using a concentric aperture. Among them 19 clusters appear to be redder and 10 are bluer in the centre. However, he assumed that the observed colour gradient comes from the random presence of one or a few bright stars. Auriere and Ortolani (1988) investigated the radial colour gradient within a 0.2'-region in 47 Tuc. They could not find any significant colour gradient and concluded that the observed colour gradient comes from the miscentering effect.

(b) Interpretations
(i) Internal effects
Large-scale radial inhomogeneities have usually been interpreted dynamically in terms of mass segregation. Wolf (1964) explained the different radial distributions for RR Lyrae and horizontal branch stars as the consequent segregation by mass through encounters. This mass segregation idea was supported by Lloyd Evans (1974) to explain the red giant distribution in 47 Tuc. Scarl (1982) interpreted the radial integrated colour gradient in $\omega$ Cen as the result of mass segregation, in which AGB stars are more concentrated to the cluster centre than red giants.

However, there are many cautious warnings that the statistical effect of the distribution of stars is such that the radial colour gradient is due to observational error (King 1966; Da Costa 1979; Hanes and Brodie 1985; Peterson 1986) and the radial metal gradient in clusters (Angeletti et al. 1981a, b). Norris (1981) suggested that the distribution of chemical peculiarities is dependent on the initial velocity distribution, which will determine the meridional mixing for each star. The radial variation of the ratio of BHB stars to RGB stars was suggested as the cause of the radial colour gradient in M30 (Piotto, King and Djorgovski 1988). Bailyn et al. (1989) interpreted the radial colour variation in M15 as a population gradient, in which the number of faint blue stars is greater in the core than elsewhere. This tendency is consistent with the post-core-collapse model which predicts a centrally condensed distribution of cataclysmic variables. They suggested that other candidates for this gradient are blue stragglers and blue HB stars.

(ii) External effects
Chun and Freeman (1979) suggested that the observed radial colour gradients are not due to mass segregation through encounters but rather to processes that occurred early in the cluster’s life. That means that the colour gradients could reflect a radial gradient of the inhomogeneities set up at the time of the cluster’s formation. If the proto-globular cluster cloud passed the galactic plane or galactic bulge before the chemically evolved matter is not uniformly mixed, then one can expect an abundance gradient in globular clusters (Iben 1980). Protocluster merging is another explanation for the radial colour gradient. Norris et al. (1981) assumed that some globular clusters may have been the result of the merging of two or more protoclusters of different metallicities within a turbulent proto-Galactic halo. This protocluster merging hypothesis was invoked by Icke and Alcaino (1988) for the study of $\omega$ Cen.

The radial colour gradient in 47 Tuc was explained as the result of the interior stellar mixing or stellar wind enrichment of massive stars (Smith 1986), while Da Costa and Demarque (1982) proposed a primordial origin since the protocluster stage. Bhatt (1988) also proposed the primordial hypothesis where dust segregation in globular cluster protoclusters is considered as a possible mechanism for the colour gradient. He insists that if the globular cluster has a longer relaxation time, the radial gradient may survive to the present time.

There is clear evidence for radial inhomogeneities in some globular clusters, although it is not clear whether they are chemical in origin. There is no unambiguous evidence yet that the observed chemical inhomogeneities are really the result of inhomogeneities set up at the time of the cluster’s formation, rather than by internal mixing in the stars themselves.

How can we prove the existence of radial colour gradients in globular clusters? What is the main cause of these gradients? To
Most of the recent CCD observations of globular clusters have in \( B - V \) one-arcmin annular bins. After dividing the region, we added region. Among many C-M diagrams, we chose 47 Tuc to test made it possible to get C-M diagrams quite close to the central region is redder than the outer one. This difference seen in spot measurements by Chun and Freeman (1979) reported a radial colour change of about 0.1 mag in \( B - V \). This difference is similar to the results of spot measurements, where Chun and Freeman (1979) reported a radial colour change of about 0.1 mag in \( B - V \).

The number ratios of each group of stars were calculated and are displayed in Table 2 and Figure 2. Here we see that the number of giants and horizontal branch stars are more concentrated in the central regions, while main sequence stars are less concentrated. This result is contrary to the general mass segregation hypothesis to explain the radial colour gradient in globular clusters.

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The local C-M diagrams in each region show that the mean main sequence in the central region is redder than the outer one. However, the evolved sequence (giant and horizontal branch) does not show any radial variation (see Figure 11, Hesser et al. 1987).

4. Evidence for a Radial Color Gradient in 47 Tuc

Most of the recent CCD observations of globular clusters have made it possible to get C-M diagrams quite close to the central region. Among many C-M diagrams, we chose 47 Tuc to test the reality of the radial colour gradient. We divided all stars into one-arcmin annular bins. After dividing the region, we added all stars in each region to get the integrated colours.

The F3 and F4 field regions observed by Hesser et al. (1987) have more than 6000 stars and these fields cover from 1 to 7 arcmin from the cluster centre. These fields are good enough to test the radial colour gradient (see Table 1) which was observed using spot measurements by Chun and Freeman (1979). The integrated colours for each region were calculated from stars brighter than \( V = 18 \) mag to reduce the completeness problem.

Figure 1 shows the calculated colours as a function of radius in 47 Tuc. From the figure it is clear that the integrated colour in 47 Tuc becomes redder in the central region than the outer ones with a difference in \( B - V \) of about 0.12. This difference is similar to the results of spot measurements, where Chun and Freeman (1979) reported a radial colour change of about 0.1 mag in \( B - V \).

The reality of the radial colour variation was tested for 47 Tuc from its individual stars for each radial region. The results show that the calculated colour in each radial region has a gradient of as much as 0.1 mag in \( B - V \), which is the same colour difference seen in spot measurements by Chun and Freeman (1979). This radial colour gradient comes from a more centrally concentrated distribution of the evolved stars (giant and horizontal branch stars) and a less concentrated distribution of main sequence stars. At the same time, the mean points of the main sequence become redder in the central region while the giant branch does not show any variation with radial distance. All these observational results indicate that there were CNO radial abundance gradients in the early stages of cluster formation (Renzini 1977).

5. Conclusion

There seems clear evidence that globular clusters are not homogeneous objects. These inhomogeneities can be attributed to the chemical abundance variations from star to star in individual clusters or a gradient in the large-scale structure of the clusters. Among these inhomogeneities the radial colour gradients are worthy of careful study because these phenomena are connected with the dynamical structure and formation of globular clusters.

Table 1. Radial Colour Gradient in 47 Tuc

<table>
<thead>
<tr>
<th>RADIUS (ARCMIN)</th>
<th>1-2</th>
<th>2-3</th>
<th>3-4</th>
<th>4-5</th>
<th>5-6</th>
<th>6-7</th>
</tr>
</thead>
<tbody>
<tr>
<td>( B - V ) (TOTAL)</td>
<td>1.008</td>
<td>0.977</td>
<td>0.937</td>
<td>0.878</td>
<td>0.914</td>
<td>1.043</td>
</tr>
</tbody>
</table>

Table 2. Number Ratios in 47 Tuc

<table>
<thead>
<tr>
<th>RADIUS (ARCMIN)</th>
<th>1-2</th>
<th>2-3</th>
<th>3-4</th>
<th>4-5</th>
<th>5-6</th>
<th>6-7</th>
</tr>
</thead>
<tbody>
<tr>
<td>GB/TOTAL</td>
<td>0.6</td>
<td>0.37</td>
<td>0.26</td>
<td>0.22</td>
<td>0.23</td>
<td>0.24</td>
</tr>
<tr>
<td>HB/TOTAL</td>
<td>0.082</td>
<td>0.036</td>
<td>0.047</td>
<td>0.024</td>
<td>0.029</td>
<td>0</td>
</tr>
<tr>
<td>MS/TOTAL</td>
<td>0.315</td>
<td>0.596</td>
<td>0.686</td>
<td>0.752</td>
<td>0.740</td>
<td>0.761</td>
</tr>
</tbody>
</table>

Figure 1 - The calculated colours of each radial region in 47 Tuc shows a clear radial colour gradient by about 0.12 mag in \( B - V \). This difference in \( B - V \) is similar to the observed spot measurements by Chun and Freeman (1979).

Figure 2 - The number ratio of giant branch stars shows a central concentration in (a), with a similar tendency for horizontal branch stars in (b). However, main sequence branch stars are less concentrated than the evolved stars (c). These different distributions produce a radial colour gradient.
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