# CHEMICAL GRADIENTS IN GLOBULAR CLUSTERS

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## INTRODUCTION

First I will describe briefly some older work on chemical gradients in globular clusters.  Then I will discuss some more recent data on the chemical and kinematical properties of 47 Tuc and Omega Cen, that leave us in little doubt about the reality of such chemical gradients.

## REVIEW OF OLDER WORK

Many years ago, Martin (1937) demonstrated that the radial distributions of RR Lyrae stars and red giants in Omega Cen are clearly different: the RR Lyrae stars are less centrally concentrated.  This was originally believed to result from dynamical relaxation, because the masses of the RR Lyrae stars are less than those of the red giants. However we now know that the relaxation time at the center of this cluster is significantly longer than the total lifetime on the giant branch and the horizontal branch, so this explanation seems unlikely. Another possibility suggested by this observation is that the cluster has a radial gradient of chemical abundance, because the morphology of the horizontal branch is sensitive to abundance.  This suggestion led to much of the recent work on abundance gradients in clusters. We will see later that the direct evidence for a chemical gradient in this cluster is very strong indeed.

In external galaxies, chemical gradients are seen most easily in the form of color gradients.  Such color gradients have also been observed in some globular clusters.  Gascoigne and Burr (1956) first reported the color gradient in 47 Tuc.  This was confirmed by Chun and Freeman (1979); they also made photoelectric UBV concentric aperture of several other clusters, which showed that some clusters have color gradients and some do not.  They noticed that the clusters with color gradients are those whose central relaxation times are longer than about $10^8$ years.  This makes sense if the color gradients are set up early in the life of the clusters; the gradients could then survive to

the present time only in the clusters with relatively long relaxation
times.

In globular clusters, most of the visible light comes from the
giants, so the color gradients must be associated with some change in
the bright end of the color-magnitude diagram or of the luminosity
function. Chun (1976) studied the color-magnitude diagram for 47 Tuc
in several radial zones; he showed that the CMD for the giant branch
is very similar at all radii.  However the bright end of the luminosity
function does change with radius.  There are more bright giants
($M_V$ < -l) per unit luminosity in the inner regions.  A similar radial
change in the luminosity function has been found in Omega Cen (Freeman,
unpublished).  Again, these luminosity function changes are clearly
not dynamical in origin, because the masses of all the giants are
almost the same. Chun was able to show that, for 47 Tuc, the radial
changes in the bright end of the luminosity function are sufficient to
produce the observed color gradient.

It seems, then, that the color gradients are associated with
luminosity function gradients.  However the reason for these gradients
is not yet understood. Probably, it has to do with chemical gradients
(Freeman, 1978; d'Antona et al, 1984) or possibly with radial changes
in some other quantity, like stellar rotation (Norris, 1981). I have
suggested (Freeman, 1978) that the excess bright giants could be AGB
stars; their numbers are sensitive to the distribution of stars on the
HB, which in turn could be affected by radial changes in abundance. To
get more AGB stars near the tip of the giant branch, towards the cluster
center, we would need a redder HB towards the center.  From Chun's
photometry in 47 Tuc, it seems that the HB is indeed redder in the
inner parts where the excess of bright giants is found.

There is some direct older evidence for chemical gradients in
globular clusters.  Firstly,  many clusters have C and N inhomogeneities
which are seen most readily as star to star variations in the strength
of the CN bands in the stellar spectra. The distribution of CN band
strengths is frequently bimodal (Norris and Smith, 1981).  One such
cluster is 47 Tuc. From a sample of about 140 giants with measured CN
band strengths, Norris and Freeman (1979) found that the relative
strength of the two CN modes changes markedly with radius in the cluster.
(The CN-strong mode is most prominent near the cluster center).  Smith
(1979) has also detected a radial CN gradient from integrated spectra
of the inner parts of 47 Tuc.  In Omega Cen, Norris et al (unpublished)
have a sample of about 200 stars with measured CN strengths, all the
way from the cluster center out to the tidal radius.  This sample shows
a spectacular CN gradient: the inner parts have stars covering a wide
range of CN strengths, while the outer parts have only CN-weak stars
(see Figure 4).  I will discuss the CN gradients in 47 Tuc and Omega
Cen again, later.  However, it should be said here that there is still
disagreement about whether the CN spread (and therefore the CN gradients)
come from mixing processes within these low mass stars, or from accret-
ion of CN-rich material on to the surfaces of these stars early in the

life of the cluster, or from CN inhomogeneities in the gas from which
the cluster formed.  See Freeman and Norris (1981) for a discussion of
this problem.

Secondly, Omega Cen shows star to star inhomogeneities in the heavy
element abundances (see Freeman and Norris 1981). Only Omega Cen and M22
(to a lesser degree) have this property. This inhomogeneity is seen
very well in the sample of 58 RR Lyrae stars with measured [Ca/H] values
(Butler et al, 1978). These RR Lyrae stars show a clear radial gradient
in [Ca/H]; again, the inner stars are more Ca-strong (Freeman, 1978;
Smith, 1981). The heavy element inhomogeneity in Omega Cen is particul-
arly interesting, because these elements cannot be produced in the low
mass stars that we are now observing in this cluster. We do not yet
understand the origin of the heavy element inhomogeneity and radial
gradient in Omega Cen, but it seems very likely that they were establish-
ed early in the life of the cluster.  Maybe they were produced by self-
enrichment at the time of cluster formation, while the massive stars
were evolving, or come from the merger of pre-cluster fragments of
different abundances (Searle and Zinn, 1978).  In Omega Cen, the
relaxation time is so long that a radial abundance gradient would
readily survive to the present time.


THE RADIAL DISTRIBUTION OF CN IN 47 TUC

Figure 1 shows the radial distribution of CN strength for Norris
and Freeman's (1979) sample of giants in 47 Tuc. This sample extends
out from the center of the cluster to about half the tidal radius. The
CN gradient is not immediately obvious, because we see stars with strong
and weak CN over the whole range of radius.  However the gradient is
seen clearly when we compare the frequency distributions of CN strength
at different radii.  Generalised histograms of the CN distribution in
three radial intervals are shown in Figure 2. The relative population
of the two CN modes changes with radius: the inner parts of the cluster
have a much larger proportion of CN-strong stars than do the outer parts.

Da Costa and I have accurate radial velocities for this sample of
stars in 47 Tuc (see our paper in this volume). We have examined this
velocity data, to see whether the CN gradient has any associated
kinematical effects.  For example, the CN-strong stars are more centrally
concentrated, so one might expect that their velocity dispersion would
be smaller, particularly at larger radii.  However, we were unable to
find any significant dependence of velocity dispersion on CN, at any
radius.  The lack of an observable effect probably results from the
limited radial range of our sample (few of the stars have $R > R_t/3$).
We also estimated the mean rotation of the CN-weak and CN-strong sub-
samples: both rotate, but there is again no significant difference.

In summary, 47 Tuc has a well-defined CN gradient. Whatever
produces the two modes in the CN distribution (whether abundance
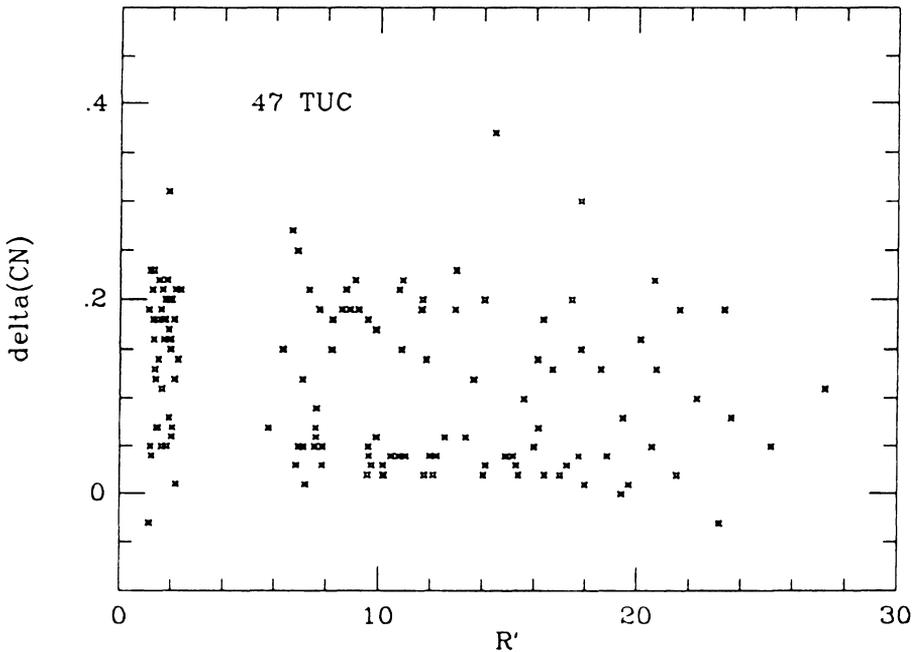bimodality or some mixing process) is itself radially varying.

Figure 1. The radial distribution of CN strength delta(CN) for stars
          in 47 Tuc. High values of delta(CN) correspond to strong CN
          band strengths. Note the wide range of delta(CN) at all radii.


     A comment on the persistence of the CN gradient in 47 Tuc: in the
inner parts of the cluster (R < 2'.5), no gradient is visible (see
Figure 3). In this region, R < $5R_c$, where $R_c$ is the core radius, and
the relaxation time is less than about $10^9$ years. At the next radial
zone shown in Figure 2, where R > 12 $R_c$ and the relaxation time is
longer than the age of the cluster, we see that the CN gradient has
clearly set in.  This is all consistent with the CN gradient having
been established early in the cluster's life and now diffusing away
through dynamical relaxation: the inner parts of the cluster have
already been homogenised by relaxation.  It is unfortunate that there
are no stars in our sample in the radial zone  $5R_c$ < R < $12R_c$, because
in this region we should see the CN gradient gradually appearing.  This
would be a nice test of the above picture.  We will observe a sample of
giants in this region in the coming season.


THE RADIAL CN DISTRIBUTION AND KINEMATICS OF OMEGA CEN

Omega Cen is the chemically inhomogeneous cluster.  It also has a very
long relaxation time, so any initial chemical gradients would have an
excellent chance of surviving to the present time, almost unmodified by
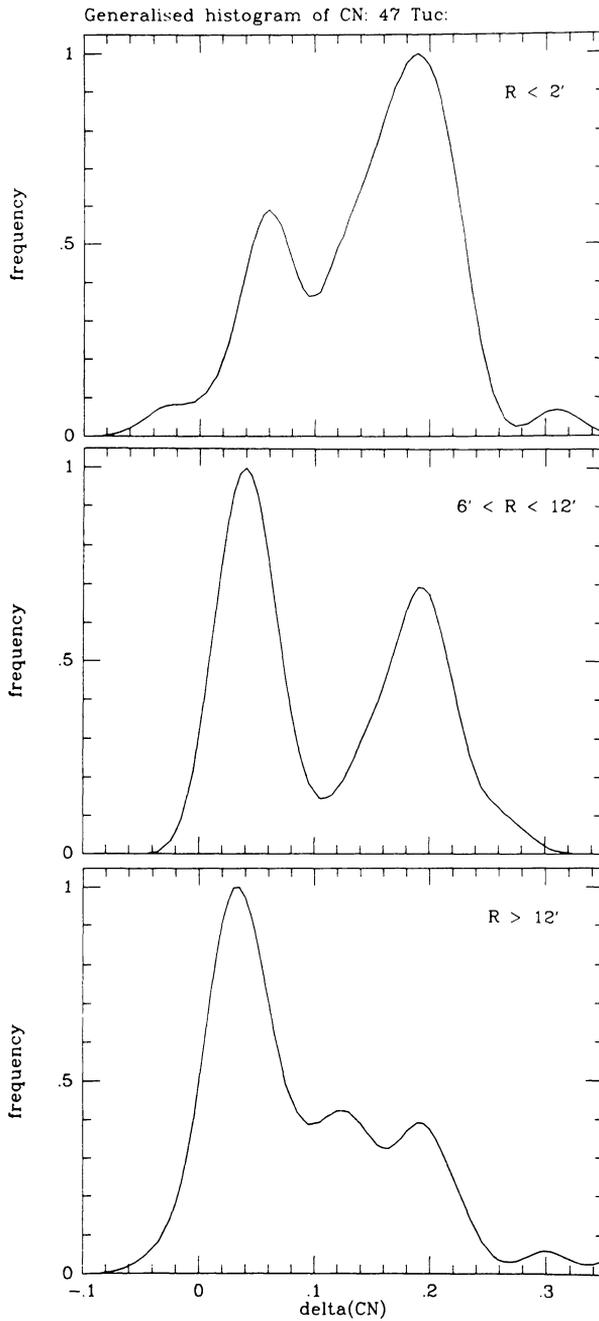
Generalised histogram of CN: 47 Tuc:



Figure 2. Generalised histograms of CN strength for stars in three radial zones in 47 Tuc. Note how the relative strength of the two CN modes changes with radius.
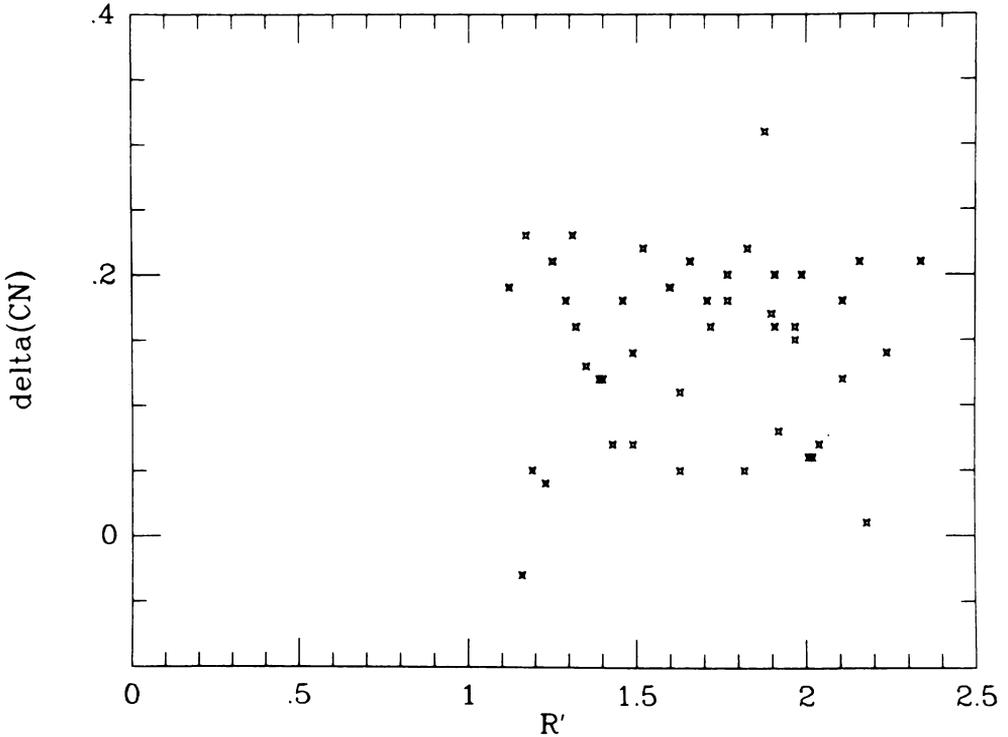
## 47 Tuc: inner region



Figure 3.   The radial distribution of CN strength for stars in the
            inner region of 47 Tuc.  Note the absence of any CN gradient
            in this region.

relaxation effects.   Furthermore, Omega Cen is a very massive and not
very highly concentrated cluster, and it has a large systemic radial
velocity: together, these properties make it relatively easy to find
member stars in the outermost parts of the cluster. Following a program
by Seitzer and Freeman to find such stars, we now have a sample of 115
red giants, with measured CN strengths and accurate radial velocities,
from the cluster center out to the tidal radius.

        Figure 4 shows the CN-radius diagram for these stars.   The CN
gradient in the outer half of the cluster is unmistakable.   The outer
parts of the cluster are CN-weak, while the inner parts have stars with
a wide range of CN strengths. Such an obvious CN gradient should have
a kinematical counterpart.   This is seen in the velocity dispersion-
radius relation for stars with weak, intermediate and strong CN, shown
in Figure 5.   The CN-strong stars are found only in the inner half of
the cluster.   Near the maximum radius at which these stars are found,
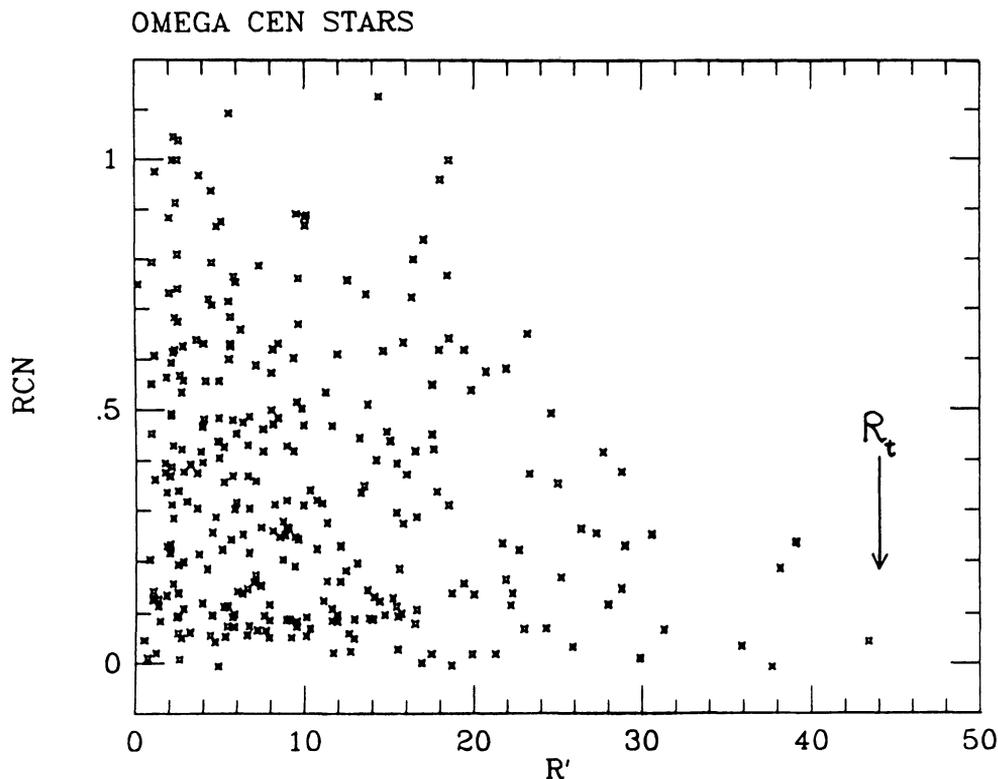
OMEGA CEN STARS



Figure 4. Radial distribution of the CN strength RCN  (RCN increases
with increasing CN strength) for stars in Omega Cen. The
CN gradient is obvious.  The arrow marked $R_t$ is at the
tidal radius.

their velocity dispersion becomes low.  The stars near this maximum
radius are the most energetic stars of their CN class, seen now near
their maximum distance from the cluster center and therefore with low
velocities.  Similarly, the velocity dispersion of the intermediate
and weak CN subsamples becomes low towards the maximum radius at which
such stars are found.  So, in Omega Cen, the kinematics and the radial
distribution of CN give us a consistent picture of the chemical gradient,
in which the CN-strong stars are the ones most bound to the cluster
center.

Omega Cen is a relatively flattened cluster.Analysis of the
stellar velocities shows that the cluster is rotating. The position
angle of the kinematic major axis agrees very well with that for the
major axis determined from the star count distribution. In the
$(V/\sigma)-\epsilon$ plane (V is the maximum rotational velocity, $\sigma$ is the central
velocity dispersion, and $\epsilon = 1 - b/a$, where a and b are the apparent
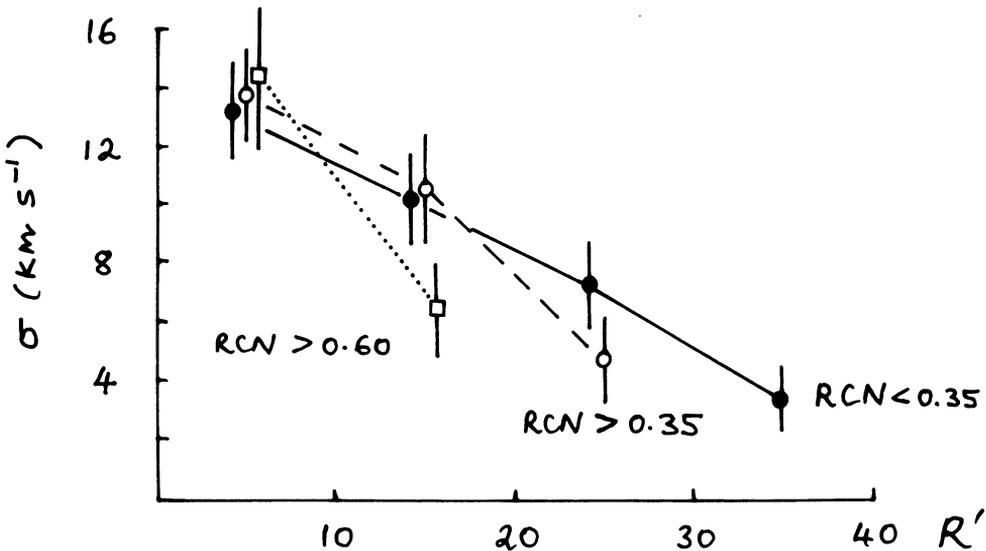
Figure 5. The radial variation of stellar velocity dispersion in Omega
Cen, for the three CN-strength subsamples shown by the labels.
The velocity dispersion decreases most rapidly with radius
for the CN-strongest subsample, which is the most concentrated
to the cluster center.

major and minor axes of the star count distribution at the count level
corresponding to the maximum observed flattening), the cluster lies
close to the oblate isotropic line (see Seitzer et al, 1984) so it seems
very likely that Omega Cen is flattened by its rotation.

It seemed worth comparing the rotation for the CN-weak (RCN < 0.35)
and CN-strong (RCN > 0.35) stars in Omega Cen.  From our sample, it
appears that the subsystem of CN-weak stars is rotating significantly
more rapidly than the CN-strong subsystem. This result is somewhat
unexpected, and more stars with good velocities and CN measures are
needed in the inner parts of the cluster to check its validity. We know
that, in galaxies, the dependence of rotation on chemical abundance is
the other way around: the metal rich component is the more dissipated
and rapidly rotating.  However Omega Cen is unique among the clusters
with its heavy element inhomogeneity.  If this inhomogeneity results
from the coalescence of two or more fragments of different abundance,
then the chemical gradient and the difference in rotation of the CN-weak
and CN-strong components probably reflects the different dynamical
properties of these fragments before coalescence.  On the other hand,
if self pollution produces the inhomogeneity and the chemical gradient,
then the rapid rotation of the CN-weak component becomes an interesting
part of the formation picture.  We recall again that the relaxation
time in Omega Cen is very long, so the dynamical properties of the
cluster are probably much as they were immediately after the time of
formation.

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## DISCUSSION

KING: Most of these abundance gradients are mystifying, but one result is quite astounding. Your high-CN stars have just as great a velocity dispersion at the center, but both their density distribution and their velocity dispersion drop off much faster. Is there any rational model that will fit this?

FREEMAN: Yes. If we write your lowered Maxwellian as $f(E) \approx (e^{-E/\sigma^2} - e^{-E_0/\sigma^2})$, then the CN-rich stars would need a somewhat higher value of the scale dispersion $\sigma$ and a somewhat more bound value of the cutoff energy $E_0$ to produce the observed density and velocity dispersion behavior.

LARSON: Does any of the evidence rule out the possibility that $\omega$ Cen is just a superposition of two clusters, a metal-rich one and a metal-poor one, that merged, and that all of the observed radial trends just represent varying relative proportions of the two populations of stars?

FREEMAN: The CN-distribution in $\omega$ Cen is not bimodal, as it is in many other clusters. It is a broad and fairly continuous distribution, which would argue against your suggestion.

HANES: How strictly correlated, star-by-star, are the CN and Ca variations? Obviously, if the Ca bimodality is primordial, its correlation with CN tells you something about the origin of variations in the latter.

FREEMAN: The correlation is indeed fairly well defined, which does support a primordial origin for the chemical inhomogeneities, as you suggest.

OSTRIKER: A variety of calculations has shown that angular momentum diffuses outwards in related systems. Thus the metal rich components would be expected to "spin down" somewhat. Can this effect quantitatively account for a lower rotational velocity of the CN rich component in $\omega$ Cen?

FREEMAN: It seems unlikely, unfortunately. In $\omega$ Cen, the relaxation time is close to the Hubble time, even in the center of the cluster.

LACHIEZE-REY: A correlation also exists between color gradient and rotation in elliptical galaxies. As a result of a multicolor CCD photometry of elliptical galaxies we found that color (B-R) gradients exist which cannot be reduced to metallicity gradients and that they correlate well to the quantities $(v/\sigma)$ or $(v/\sigma)*$.