Metallicity field and selection effects in spatial distribution of the Galactic globular cluster system

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The prospects for using the present-day data on metallicity of globular clusters (GCs) of the Galaxy to put constraints on the distance to the Galactic center, $R_0$, are considered. We have found that the GCs of the metal-rich and metal-poor subsystems separately form a bar-like structure in metallicity maps whose parameters are very close to those for the Galactic bar. The results indicate the existence of a bar component within both the metal-rich and metal-poor subsystems of GCs. The bar GCs could have formed within the already existing Galactic bar or could have later been locked in resonance with the bar. We conclude that substantial constraints on the $R_0$ value can be obtained only with non-axisymmetric models for the space distribution of GC metallicities with the allowance for the subdivision of GCs into subsystems. We found evidence for a bar extinction component that causes the observational incompleteness of GCs in the far side of the Galactic bar and in the “post-central” region. This selection effect should be taken into account when determining $R_0$ from the spatial distribution of GCs.

1 Introduction

The study of the spatial distribution of metallicity for the Galactic system of globular clusters (GCs) helps to reveal the properties of this system, which are of importance for our understanding of the formation and evolution processes of the system and of the whole Galaxy. In particular, the analysis of this distribution, along with that of kinematics, made it possible to establish the division of GCs into two subsystems: metal-rich disk GCs and metal-poor halo GCs (Zinn 1985). More recently, halo GCs, in turn, were shown to be subdivided into at least two groups based on their horizontal branch morphology, kinematics, and other parameters (Zinn 1993; Da Costa & Armandroff 1995; Borkova & Marsakov 2000; see also Bica et al. 2006 and references therein). In addition, three subsystems were identified among the metal-rich GCs (Burkert & Smith 1997).

Another problem that is discussed extensively is that of the existence of metallicity gradients in the GC (sub)system(s) (e.g., Zinn 1985; Alfaro, Cabrera-Caño & Delgado 1993; Borkova & Marsakov 2000; van den Bergh 2011). This problem, in addition to its importance in itself, is associated with the problem of the determination of the distance to the center of the Galaxy, $R_0$. For one thing, an investigation of the spatial metallicity distribution (as well as merely the spatial distribution) of GCs requires the distance scale for GCs to be compatible with the adopted $R_0$. For another, the existence of a radial gradient, more generally the dependence of [Fe/H] on the distance of the GC from the Galactic axis, $R$, can, in principle, impose constraints on the value of $R_0$.

Surdin (1980) suggested a method of estimating $R_0$ based on the [Fe/H]-$R$ relationship assuming that the GC distribution in the coordinate–metallicity $(X, Y, Z, [m/H])$ space is axisymmetric. However, the $R_0$ values found by Surdin (1980) from all GCs without subdividing them into subsystems, $R_0 = 9.9 \pm 0.3$ kpc and $R_0 = 10.3 \pm 0.6$ kpc for two catalogues of GCs, now appear to be overestimated. This cannot be explained by the evolution of the distance-scale calibration: rescaling to the current calibration

$$M_V(\text{HB}) = 0.165 \text{[Fe/H]} + 0.86,$$  

based on the most direct distance measurements within the Milky Way (see the 2010 edition of the Harris (1996) catalogue), yields $R_0 = 10.8 \pm 0.3$ kpc and $R_0 = 10.1 \pm 0.6$ kpc, respectively. Although the revised $R_0$ estimate found by applying this method to the original version of the Harris (1996) catalogue is $8.6 \pm 1.0$ kpc (Surdin 1999), rescaling it to calibration (1) gives a larger value of $9.0 \pm 1.0$ kpc.

Let us now compare the estimates obtained using Surdin’s method with other $R_0$ estimates based on GC data and with the current best values of $R_0$. Table 1 lists the average $R_0$ values derived by applying the same procedure as used by Nikiforov (2004) to a selection of groups of $R_0$ estimates. We use an updated version of Nikiforov’s (2004) sample of $R_0$ estimates published since 1974. In the case of GC-based estimates, only the result by Bica et al. (2006),

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Table 1  Average $R_0$ values found using different groups of estimates.

| Group of Estimates                                      | $N_{est}$ | $N_{pap}$ | $N_{hg}$ | $\langle R_0 \rangle$ (kpc) |
|--------------------------------------------------------|-----------|-----------|----------|---------------------------|
| Based on GCs, all methods $^a$                          | 19        | 13        | 3        | $7.63 \pm 0.38$ $^b$      |
| Based on GCs, all spatial methods                       | 16        | 10        | 1        | $7.42 \pm 0.23$ $^b$      |
| Based on GCs, Shapley’s method and related spatial methods | 12        | 8         | 1        | $7.36 \pm 0.24$ $^b$      |
| All estimates                                           | 74        | 60        | 18       | $7.91 \pm 0.15$           |

$^a$ Including Surdin’s method with the estimate by Surdin (1999).

$^b$ The quoted error does not include the systematic uncertainty of the adopted distance scale.

$R_0 = 7.2 \pm 0.3$ kpc, was added. All GC-based estimates are rescaled according to calibration [1]. In the table, $N_{est}$ is the number of $R_0$ estimates; $N_{pap}$, the number of papers, and $N_{hg}$, the number of homogeneous groups of $R_0$ estimates, i.e., based on the same class of methods, the same class of reference distances, and the same type of reference objects (see Nikiforov 2004). The uncertainty of the average value, $\langle R_0 \rangle$, listed in Table 1 for groups of GC-based estimates reflects the statistical uncertainty and the systematic uncertainty of the method used to derive the $R_0$ estimate from the adopted reference distances (see Nikiforov 2004), but does not include the systematic uncertainty of the adopted distance scale, because the latter is the same for all GCs’ groups. The uncertainty in value of $\langle R_0 \rangle$ derived from all estimates is a combination of all errors.

The bottom entry in Table 1 shows that the $R_0$ estimates based on the radial metallicity gradient are essentially greater than the mean value of $R_0 = 7.9 \pm 0.2$ kpc averaged over all methods and objects — the so called “best value” for $R_0$; cf. the best estimates of $R_0 = (8.15\pm 8.25)$ \pm (0.14–0.20) kpc by Genzel, Eisenhauer & Gillessen (2010) deduced from 11 recent (2006–2009) $R_0$ estimates. However, the discrepancy between the results obtained by Surdin’s method and those obtained using other GC-based techniques is, on average, even greater (Table 1), although all these $R_0$ estimates were rescaled to the same calibration.

Such discrepancies may be due to incorrect assumptions adopted in Surdin’s method. In particular, the method does not allow for the fact that the GC populations consist of the metal-rich and metal-poor subsystems, that is, it assumes, in fact, the existence of a smooth radial metallicity gradient for the entire system of GCs; however, now we see that this appears not to be the case, rather the gradient is like to a stair-step (e.g., Borkova & Marsakov 2000; van den Bergh 2011). If so, the efficiency and systematics of Surdin’s method depend on the existence of radial gradient in the metal-rich and/or metal-poor subsystems separately. However, radial gradients are found to be insignificant for the most of GCs’ subsystems identified (e.g., Borkova & Marsakov 2000), at least for a fixed value of $R_0$. If there are no radial gradients within the metal-rich and metal-poor subsystems, Surdin’s method reduces to the determination of the centroid of distribution of metal-rich GCs, i.e., becomes akin to Shapley’s method and related ones (see, e.g., Reid 1993; Nikiforov 2004). If so, then it is not clear why $R_0$ estimates found by these two approaches are so different (Table 1)? It is only clear that in this case the allowance for selection effects in the distribution of GCs caused by extinction becomes as important for Surdin’s method as it is for Shepley’s method. In both methods, simulations were performed to estimate the bias (Surdin 1999; e.g., Racine & Harris 1989), but the results of such modelling depend on the assumptions concerning the extinction law. This may be an additional source of systematic error in both methods.

The starting point for this work was to clarify, based on the current knowledge of the Galactic GC system, whether the present-day GC metallicity data can impose (significant) constraints on $R_0$. Pursuing this goal has sent us to evaluate the uncertainty of new metallicity data and study the details of the GC distribution. In this paper we present some of the results obtained.

2 Data on globular clusters

Our GC data is the 2010 December version (hereafter H10) of the Catalog of Parameters for Globular Clusters in the Milky Way by Harris (1996), $N_{tot} = 157$. The catalog presents the distance estimates (for all GCs) calculated using the calibration

$$M_V(HB) = 0.16 [Fe/H] + 0.84,$$

which is based on the most direct distance measurements for objects in the Milky Way and on the distances to GCs in M31 found with an adopted fiducial distance for M31. Thus this calibration is to some extent secondary compared to calibration [1]. The latter is only slightly fainter (0.01–0.02 mag) than calibration [2].

For 152 GCs, the new list provides [Fe/H] values that are on a new metallicity scale based on high dispersion spectroscopy (Carretta et al. 2009). This represents a fundamental change from the older metallicity scale by Zinn & West (1984) used in the 2003 version (hereafter H03) and other previous editions of the catalog. The H10 list also provides weights for [Fe/H], $p$, which are essentially equal to the number of independent [Fe/H] measurements averaged for each GC.

Figure 1(left panel) gives an idea of the systematic differences between the two metallicity scales, i.e., between the metallicities [Fe/H]$_{10}$ and [Fe/H]$_{03}$ in the two versions.
of the catalogue. The vertical chains of data points with large residuals relative to the line of equality at $[\text{Fe}/\text{H}]_{03} = -2.00$ and $-0.50$ suggest that some of these $[\text{Fe}/\text{H}]$ values in H03 were adopted rather than estimated. To evaluate the dependence of uncertainties of $[\text{Fe}/\text{H}]_{10}$ on weights $p$, we computed the variances $\sigma^2_\Delta$ of the differences

$$\Delta = [\text{Fe}/\text{H}]_{10} - [\text{Fe}/\text{H}]_{03}$$

(3)

for common GCs both for $p$-based bins and for all 125 GCs in common. In doing so, we excluded the GCs with $[\text{Fe}/\text{H}]_{03} = -2.00$, $-0.50$ and $[\text{Fe}/\text{H}]_{10} = -1.00$ as “blunders” (see Fig. 1 left panel) as well as GCs with unchanged estimates of $[\text{Fe}/\text{H}]$ ($\Delta = 0.00$). It appears from Fig. 1 (right panel) that the variances $\sigma^2_\Delta$ and weights are very highly correlated, except for one data point in the lowest-weight bin, $p = 1, 2$, because of an overlap between the H03 and H10 source lists for metallicities in this case. Without this point, the linear correlation coefficient for the $\sigma^2_\Delta - p^{-1}$ relation is +0.98, and the weighted least-squares solution for the fit

$$\sigma^2_\Delta = \sigma^2_0(\Delta)/p,$$

(4)

yields $\sigma^2_0(\Delta) = 0.0539 \pm 0.0075$ dex$^2$, i.e., $\sigma_0(\Delta) = 0.232 \pm 0.016$ dex. (The constant term in Eq. 4 is set to zero to avoid formally negative values of variance $\sigma^2_\Delta$ for large $p$.) The resulting variance over all common GCs $\langle \sigma^2_\Delta(\Delta) \rangle = 0.0159 \pm 0.0022$ dex$^2$ and the average $[\text{Fe}/\text{H}]_{03}$ uncertainty of 0.09 dex (see Carretta et al. 2009) give an estimate of the uncertainty of $[\text{Fe}/\text{H}]_{10}$ of $\sqrt{\langle \sigma^2_\Delta(\Delta) \rangle} = 0.092 = 0.088 \pm 0.012$ dex. Thus, the average $[\text{Fe}/\text{H}]$ uncertainties in H03 and H10 may be considered to be the same. We therefore adopted the following formulas for the $[\text{Fe}/\text{H}]_{10}$ uncertainty as a function of $p$:

$$\sigma([\text{Fe}/\text{H}]_{10}) = \sigma_0([\text{Fe}/\text{H}]_{10})/\sqrt{p},$$

(5)

$$\sigma_0([\text{Fe}/\text{H}]_{10}) = \sigma_0(\Delta)/\sqrt{2} = 0.164 \pm 0.011$$

(6)

In particular, $\sigma([\text{Fe}/\text{H}]_{10}) = 0.16, 0.12, 0.046$ dex for $p = 1, 2, 13$, respectively.

The $[\text{Fe}/\text{H}]$ weights adopted in H10 are well correlated with $[\text{Fe}/\text{H}]$ uncertainties and therefore should be allowed for in modelling the spatial metallicity distribution of GCs. The $\sigma([\text{Fe}/\text{H}]_{10})$ values found here can be used as estimates of the absolute values of $[\text{Fe}/\text{H}]$ uncertainty.

Fig. 1  *Left:* Comparison of metallicities $[\text{Fe}/\text{H}]$ from the 2010 (H10) and 2003 (H03) versions of the Harris (1996) catalogue. The solid line corresponds to equal metallicities. The palette represents the H10 metallicity weights, $p = 1, \ldots, 13$. *Right:* The variance of differences between the H10 and H03 metallicities versus the inverse of H10 metallicity weight, $p^{-1}$. The line is the best-fit regression (4) to all data points except that obtained for $p = 1, 2$ (the open circle).
Fig. 3  Metallicity maps for metal-rich (left) and metal-poor (right) subsystems of GCs. The weighted smoothing was performed with the Cauchy kernel ($d = 1$ kpc). The open circles represent individual GCs. The thick solid lines outline the Galactic bar ($a = 3.5$ kpc, $b = 1.4$ kpc, $c = 1.0$ kpc, an angle of $25^\circ$) and the long bar ($a = 3.9$ kpc, $b = 0.6$ kpc, $c = 0.1$ kpc, an angle of $43^\circ$); see Gardner & Flynn (2010). The Sun is at $(X, Y, Z) = (0, 0, 0)$, the Galactic center is at $(X, Y, Z) = (8.10, 0, 0)$.

3 Metallicity distribution and subsystems of globular clusters

From this point on, we shall use only the [Fe/H] estimates from H10.

Figure 2 shows the metallicity distribution for all 152 GCs in H10. The figure shows that the binormal model fits the [Fe/H] data well. The maximum-likelihood fit yields the maxima at $[\text{Fe/H}] = -0.52 \pm 0.06$ and $-0.52 \pm 0.06$ with the standard deviations of $\sigma_{[\text{Fe/H}]} = 0.39 \pm 0.03$ and $0.23 \pm 0.04$ respectively. The metallicity threshold separating metal-poor and metal-rich GCs is found to be $-0.83 \pm 0.11$. Excluding GCs with low weights ($p = 1, 2, 3$) has no significant effect on the results.

Based on our best-fit solutions for the distribution of GC metallicities [Fe/H] (Fig. 2), the [Fe/H] versus $R$ and [Fe/H] versus $Z$ relations ($Z$ is the distance from the Galactic plane), we assume that the boundary between metal-poor and metal-rich GC subsystems is at $[\text{Fe/H}] = -0.8$ in the new metallicity scale of H10.
Our attempts to directly solve the set of equations
\[
[\text{Fe/H}](R) = f_0 + f_1 R,
\]
(7)
\[
R = \sqrt{R_0^2 + r^2 \cos^2 b - 2R_0 r \cos l \cos b},
\]
(8)
(here \(l\) and \(b\) are the Galactic coordinates of the GC and \(r\)
is the heliocentric distance to the GC) for \(R_0, f_1, \) and \(f_0\)
for these two GC subsystems individually failed to produce
well-conditioned results for \(R_0\). This has cast doubt on the
correctness of axisymmetric models like (7) for the spatial
metallicity distribution of GCs.

To analyze the GC metallicity field, i.e., the smoothed
dependence of GC metallicity on spatial coordinates, we
produced metallicity maps in the \(XY\), \(YZ\), \(XZ\) planes for
various subsamples of GCs. All maps presented in this
paper were obtained by the weighted smoothing with the
Cauchy kernel \((d = 1 \text{ kpc})\). For the metal-rich and metal-
poor subsystems of GCs, the \(XY\) metallicity maps, as well
as the space distribution in the \(XY\) plane, indicate a cen-
trally concentrated, bar-like configuration with the param-
ters that agree closely with those of the Galactic bar (Fig. 4
top panels). This “bar component” of GCs, which is more
pronounced for metal-rich GCs, also shows up for metal-
poor GCs. Note that formal metallicity gradient along the
long axis of bar is present in the \(XY\) maps for both GC sub-
systems. However, as is evident from the \((XZ)\) maps (Fig. 4
bottom panels), this gradient is in each case due to the
fact that more metal-rich GCs are always or mostly located
within the near side of the bar (in the far side, GCs are not
visible, probably because of high extinction), and a group of
the more metal-poor GCs is located, judging from their \([Z]\),
the GCs located outside the bar. The open squares and tri-
angles show the GCs located before and behind the bar, re-
spectively.

The bar-like configurations in the \(XY\) metallicity maps
suggest the presence of inclined elongated structures in the
plot of \([\text{Fe/H}]\) versus Galactic longitude. Figure 4 shows
that at least two such structures are actually present, with
\([\text{Fe/H}] \approx -1.4\) and \(-0.5\) at \(l = 0^\circ\) for the metal-poor and
metal-rich subsystems of GCs, respectively. For the metal-
rich GCs, the structure is especially long – it is seen to ex-
tend to \(|l| \approx 30^\circ\), i.e., it goes beyond the bar boundary.
It is not improbable that more structures exist in the GC sys-
tem: (i) a smaller subsystem with \([\text{Fe/H}] \lesssim -1\) at \(l = 0^\circ\),
which forms an individual elongated configuration in Fig. 4
and, maybe, shows up in the \([\text{Fe/H}]\) distribution (Fig. 2);
(ii) possible breakdown of metal-rich subsystem into two
groups with parallel chains of points in Fig. 4.

4 Selection effects in the spatial distribution of
globular clusters

The maps in Fig. 5 suggest that most of GCs at \(|Z| \lesssim 1 \text{ kpc}\)
are not detected behind the Galactic center. This effect is ob-
viously asymmetric with respect to the Galactic center and
therefore is unlikely to be due to dynamic causes. Needless
to say, the deficit of GCs in the “post-central” region of the
Galaxy is more likely due to extinction. In this section, we
try to verify this hypothesis and examine the selection effect
in more detail.

Figure 5 shows the foreground reddening map (top panel), H10 reddening values \(E(B - V)\) indicated for each GC individually (bottom panel) along with the distribution
of GCs in projection on the sky for the Galactic bar re-
region. Hereafter we plot in all figures only the contour of
the Galactic bar, because this bar and the long bar appear to
be parts of the same feature (see Athanassoula 2012). The
filled circles in Fig. 5 and in following figures show the GCs
located inside the Galactic bar, and all open symbols show
the GCs located outside the bar. The open squares and tri-
angles show the GCs located before and behind the bar, re-
spectively.

Figure 5 demonstrates the existence of a post-central re-

dom of avoidance in the system of GCs: there are no GCs
between the chain-dotted lines behind the Galactic bar, al-
though there are GCs in front and inside the bar. This sug-
gests that the absorbing matter concentrates not only in the
Galactic disk, but also in the Galactic bar. The reddening map in Fig. 5 (top panel) is consistent with such specula-
tion.

The reddening map and the spatial distribution of reden-
ing in the \(XY\) plane (top and left bottom panels of Fig. 6
respectively) also indicate the existence of a bar (or at least a
central) component of extinction. Moreover, almost all GCs
inside the bar are distributed within the near side of the bar
with a sudden cutoff along the major axis of the bar in the
first Galactic quadrant and along the \(X = \text{const}\) line in the
fourth quadrant (the same panels of Fig. 6). NGC 6355 at
\((X, Y, Z) = (9.16, -0.07, 0.87)\) kpc is not an exception to
this rule: it is located almost exactly at the boundary of the
bar (Fig. 6 right bottom panel) is just projected onto the
empty region.

We thus conclude that all these results can be explained
only by the existence of a bar extinction component which
produces a sudden GCs’ distribution cutoff in the directions with the strongest extinction. Note that this conclusion does not depend on the adopted parameters of the bar, because the existence of the post-central region of avoidance found does not depend on these parameters.

The distribution of GCs in the $XY$ and $XZ$ planes with individual metallicities $[\text{Fe}/\text{H}]$ indicated for each cluster (Fig. 7) illustrates how the presence of a bar component within both GC subsystems combined with selection due to the concentration of absorbing matter in the Galactic bar produce in metallicity maps (Fig. 5) structures associated with the bar.

The bar GCs differ noticeably from other GCs in terms of iron abundances (Figs. 7 and 8). Figure 8 shows that in the metal-rich subsystem the fraction of GCs with the highest abundances is greater among the bar GCs than among GCs located outside the bar; moreover, the bar component of metal-poor subsystems contains only GCs with $[\text{Fe}/\text{H}] > -1.50$.

## 5 Discussion

The effect of bar-like configurations on GC metallicity maps suggests that the bar GCs formed within the already existing Galactic bar or were later locked in resonance with the bar. In the first case, the implication is that the Galactic bar may have the age of 10 Gyr or more. The presence of parallel elongated structures in the $[\text{Fe}/\text{H}]$ versus $l$ plot (Fig. 4) is rather indicative of bar-induced resonance effects. In any case, these GCs seem to be associated with the Galactic bar.
Fig. 5  Top: Foreground reddening map and location of globular clusters projected on the sky in the Galactic bar region. Bottom: The same as in the top panel, but with the \( E(B-V) \) values shown for each cluster individually. The solid line shows the projection of the boundary of the Galactic bar on the sky. The filled circles show the clusters located inside the Galactic bar. Clusters located outside the bar are plotted as open symbols. The squares and triangles show the clusters located in the foreground and background relative to the bar, respectively. The chain-dotted lines connect clusters located behind the bar. The parameters of the Galactic bar are the same as in Fig. 3.

Note that previously Burkert & Smith (1997) also identified the subsystem of bar clusters, but only among the metal-rich GCs, based on an analysis of the space distribution and kinematics. It is unlikely that this is due to chance.

Regardless of the details of the origin of this effect, it is clear that the spatial distribution of GC metallicities is not axisymmetric. Hence justified and strong constraints on \( R_0 \) can be obtained only in terms of a non-axisymmetric model for this distribution and with the allowance for the fact that the GC population consists of several subsystems. The sizes of bar-like configurations and the number of GCs located inside them lead us to expect statistical uncertainties of 0.4–0.5 kpc for \( R_0 \) estimates based on the metallicity data for each of two main subsystems of GCs. Hence we conclude that this approach appears to be promising.

Observational incompleteness of GCs in the far side of the Galactic bar and in the post-central region shows that the allowance for the selection effect due solely to extinction in the layer of constant scale height (e.g., Racine & Harris 1989; Surdin 1999) seems to be insufficient to eliminate the corresponding systematic errors in \( R_0 \) estimates. This may explain why the GC-based \( R_0 \) estimates are systematically smaller than the best \( R_0 \) values (Table 1).

Fig. 7  The same as in bottom panels of Fig. 6, but for the metallicity of globular clusters.

Fig. 8  A comparison between the metallicity distributions of GCs located inside (solid boxes) and outside (steps) the Galactic bar.

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