Observed HR diagrams and stellar evolution
ASP Conference Series, Vol. 274, 2002
Thibault Lejeune and João Fernandes, eds.

A new, cleaner colour-magnitude diagram for the metal-rich globular cluster NGC 6528 and the velocity dispersion in the Galactic Bulge

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Abstract. Using two epochs of observations with HST/WFPC2 we obtain the stellar proper motions for all stars in the field. The proper motion are used to separate the bulge from the cluster stars. The stellar sequences in the resulting colour-magnitude diagram (CMD) are better defined than in any previously published CMD. Using α-enhanced stellar isochrones we find NGC 6528 to have a probable age of 11 ± 2 Gyrs, this is the first attempt to establish the absolute age of NGC 6528. Previous studies have only compared the fiducial ridge line for the cluster to that of other globular clusters of similar metallicities. Mainly the comparisons have been with regards to NGC 6553 and 47 Tuc. With the new metallicity determinations for individual stars in both NGC 6553 and NGC 6528 it is now clear that 47 Tuc (at -0.71 dex) has a significantly lower metallicity than NGC 6528 and NGC 6553 and is thus not a suitable comparison cluster as regards differential age determinations. A comparison with the fiducial line for NGC 6553 confirms results in earlier studies, e.g. Ortolani et al. (1995), that the two clusters indeed have very similar ages. From the measured velocities both the proper motion of the cluster and the velocity dispersion in the Galactic Bulge are found. NGC 6528 is found to have a proper motion relative to the Galactic Bulge of $<\mu_l> = 0.006$ and $<\mu_b> = 0.044$ arcsec per century. Using stars with $\sim 14 < V_{555} < 19$ (i.e. the red giant branch and horizontal branch) we find, for the Galactic Bulge, $\sigma_l = 0.33 \pm 0.03$ and $\sigma_b = 0.25 \pm 0.02$ arcsec per century. This give $\sigma_l/\sigma_b = 1.32 \pm 0.16$, consistent both with previous proper motion studies of K giants in the Galactic bulge as well as with predictions by models of the kinematics of bulge stars.

1. Introduction

NGC 6528 is perhaps *the* most metal-rich globular cluster known, e.g. Carretta et al. (2001). It has also been used as a "reference" cluster in studies of other clusters, e.g. Davidge (2000). NGC 6528 is situated at $(l, b) = (1.14, -4.12)$, i.e. in the plane of the Galactic disk and towards the Galactic bulge. The first

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effect of this is that it is heavily reddened by foreground dust, e.g. Richtler et al. (1998), Heitsch & Richtler (1999). Most recent distance estimates put the cluster within less than 1 kpc from the Galactic centre (e.g. Richtler et al. 1998). The close proximity to bulge stars further complicates the interpretation of the colour-magnitude diagram (CMD). Since the bulge stars and the cluster stars have roughly the same distance modulus they are superimposed in the CMD. This effect has been noted to be particularly pronounced on the red giant branch (Richtler et al. 1998).

In a pre-study we noted in particular that the colour-magnitude diagram of the globular cluster NGC 6528 closely resembled that of NGC 5927 *if* the latter was superimposed on the colour-magnitude diagram of Baade's window (for a set of representative CMDs see Feltzing & Gilmore 2000). This is consistent with the cluster being virtually inside the Galactic bulge and thus having a large contribution of bulge stars in its CMD. Moreover, if the cluster is as metal-rich as indicated in previous studies (and now confirmed by Carretta et al. 2001) then the red-giant branch as well as both the turn-off and the horizontal branch of the bulge and globular cluster will appear at virtually the same magnitudes and colours. The bulge stars will be more spread out in the CMD than those in the cluster, due to the large range of metallicities and ages present in the bulge (e.g. McWilliam & Rich 1994, Feltzing & Gilmore 2000). Thus the only way to obtain a clean CMD for the cluster is to obtain proper motions of the cluster stars relative to the bulge stars and separate the two populations using their proper motions.

This conclusion prompted us to apply for HST time to obtain a second epoch of observations of NGC 6528 with WFPC2 in order to derive the relative proper motion of the cluster as compared to that of the Galactic bulge. We here report on the first results from this proper motion study.

2. Data

The data consist of two sets of observations, one from the HST archive and observed in 1994 (GO 5436) and the other our new data for the same field (GO 8696, PI Feltzing). Stellar photometry was done inside the DIGIPHOT.DAOPHOT package in IRAF following standard routines, see e.g. Feltzing & Gilmore (2000). Details of the photometry can be found in Feltzing & Johnson (2001, A&A submitted). There we also describe the routines we adopt to find the individual proper motions of the stars.

In an ideal scenario, where the globular cluster has an appreciable motion in relation to the bulge stellar population, the bulge and cluster stars will form two distinct distributions in the proper motion diagram. See for example the recent results by Zoccali et al. (2001) for NGC 6553, King et al. (1998) for NGC 6739 or Bedin et al. (2001) for M4 for good illustrations of this effect.

In our case the proper motions shows that the motion of the globular cluster in relation to the Galactic bulge is very small. This is as expected since the heliocentric radial velocity relative to the local standard of rest for NGC 6528 is high (184.9 ± 3.8 km s^{-1} (Harris 1996), $\simeq$210 km s^{-1} (Carretta et al. 2001)), which suggests that NGC 6528 is on a mostly radial orbit away from us. However, we note that the histograms for the velocities in the l and b coordinates

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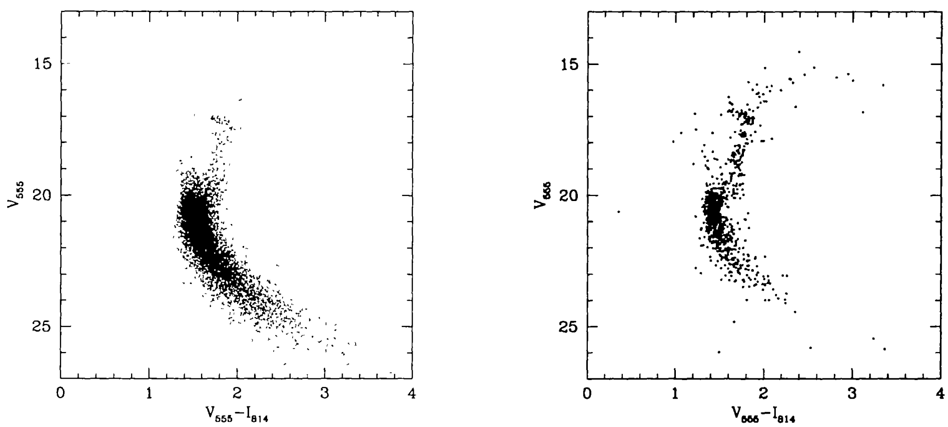

Figure 1. **Left panel:** The CMD for NGC 6528 based on all stars observed in the three WFs. **Right panel:** Final cleaned CMD. This data has also been corrected for differential reddening within the field.

have broad wings. To separate the bulge and cluster stars using the measured proper motions, we divide the stars into different magnitude ranges and find the best fitting Gaussians to the proper motion histograms. We found that two Gaussians were required to fit the data well, indicating that, as expected, we have (at least) two stellar populations with different velocity dispersions. Based on previous measurements of bulge and cluster velocity dispersions, we associate the narrow Gaussian with NGC 6528 and the broad Gaussian with the bulge stars. (For a full discussion of the analysis of the proper motion histograms the reader is referred to Feltzing & Johnson 2001 submitted).

3. The cleaned CMD

We use our Gaussian fits to the different regions of the CMD to estimate the proper motion cuts which maximize the number of cluster stars relative to the number of bulge stars, whilst still allowing enough cluster stars to make a good cluster CMD. Using different proper motion cuts in different regions of the CMD will affect the relative numbers of cluster stars in each region but this does not matter for comparison of the observed CMD with other globular clusters and with isochrones, where all we use is the position of the cluster stars in the CMD and not their number density.

Our cleaned CMD, Fig. 1, is finally obtained by imposing the following cuts: $\sqrt{\mu_l^2 + \mu_b^2} < 0.18$ for star with $V_{555} < 19$ and $\sqrt{\mu_l^2 + \mu_b^2} < 0.09$ for the fainter stars. We also find some differential reddening over the field of view of WFPC2. Our final CMD is corrected for differential reddening.

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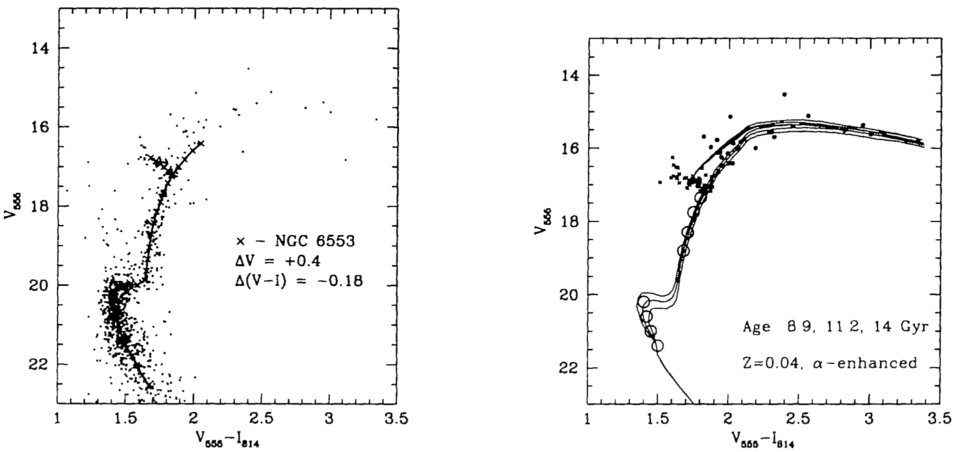

Figure 2. **Left panel:** The CMD for NGC 6528 with ridge line for NGC 6553 from Zoccali et al. (2001) over plotted. **Right panel:** Fiducial points for NGC 6528 main-sequence and stars on the RGB together with the data for AGB and HB. α-enhanced isochrones from Salasnich et al. (2000).

4. Age from fitting stellar isochrones

Since NGC 6528 is found to be enhanced, at least in some, $\alpha-$elements we compare our fiducial points with that of theoretical stellar isochrones from Salasnich et al. (2000) in which α-enhancement has been included. To facilitate the comparison with the stellar isochrones we define a set of fiducial points.

In the case of $Z = 0.019$ we moved the isochrones by $\Delta(V_{555}) = 15.95$ and $\Delta(V_{555} - I_{814}) = +0.63$. The turn-off is well represented by the 11 Gyr isochrone and the horizontal branch is well matched too. However, all the isochrones are brighter than the AGB. In order for $Z = 0.019$ isochrones to fit our data on the AGB we would need to increase the distance modulus and the best fitting isochrone would then be very young, younger than 9 Gyr. The horizontal branch would not be well fitted either. Thus it appears unlikely that our data could be well fitted with α-enhanced isochrones with $Z = 0.019$.

For the $Z = 0.40$ isochrones we moved them with the following amount $\Delta(V_{555}) = 15.95$ and $\Delta(V_{555} - I_{814}) = +0.655$, see Fig. 2. Here the AGB is much better reproduced and both turn-off and horizontal branch can be well fitted simultaneously. The 11 Gyr isochrone appears to fit best. However as this fit cannot be rigorous due to the limitations in the data the estimated error bar on this must be rather large, perhaps up to 2 Gyr.

5. The velocity dispersion in the bulge

From the proper motions and the fitting of the proper motion histograms we find that the velocity dispersion for in cluster is 0.08 arcsec per century. This translates to 24-30 km s^{-1} for the upper and lower distance limits to NGC6528 of 6.5 kpc and 8 kpc (Richtler et al. 1998).

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Globular clusters in the Galaxy have measured velocity dispersions that range from a few km s^{-1} to $\sim$ 20 km s^{-1}, see Pryor & Meylan (1993) and Dubath et al. (1997). In M 31 at least two globular clusters have measured velocity dispersions > 20 km s^{-1}, Dubath & Grillmar (1997). Zoccali et al. (2001) found σ=28 km s^{-1} for NGC6553. This result is very similar to ours. Since most globular clusters in the Galaxy have significantly lower velocity dispersion they concluded that their measured $\sigma_{cluster}$ was dominated by measurement error. This is most likely also the case for NGC6528.

Assuming the cluster velocity dispersion in NGC 6528 is dominated by errors, we deconvolve this from the measured velocity dispersion for the bulge to find the true bulge velocity dispersion. Using the data for the bright red sample we get $\sigma_{l\ bulge} = 0.33 \pm 0.03$ and $\sigma_{b\ bulge} = 0.25 \pm 0.02$ arcsec per century. These numbers are in good agreement with the results for bulge giants found by Spaenhauer et al. (1992), $\sigma_{l\ bulge} = 0.32 \pm 0.01$ and $\sigma_{b\ bulge} = 0.28 \pm 0.01$ arcsec per century for their full sample of 429 stars.

These numbers give a $\sigma_l/\sigma_b = 1.32 \pm 0.16$, which is identical, within the error estimates, to the 1.33 predicted for the coordinates of NGC 6528 by the model of kinematics in the Galactic bulge in Zhao (1996).

In their study of NGC 6553 Zoccali et al. (2001) derived $\sigma_{l\ bulge} = 0.26 \pm 0.03$ and $\sigma_{b\ bulge} = 0.21 \pm 0.02$ arcsec per century giving $\sigma_l/\sigma_b = 1.24 \pm 0.17$. These values are lower than found here, however, NGC 6553 is situated further out from the Galactic centre than NGC 6528 and we should thus expect $\sigma_{l\ bulge}$ to be a factor $\sim$ 0.86 lower than for the coordinates of NGC 6528, see Zhao (1996) Table 6. $\sigma_{b\ bulge}$ should remain roughly the same. Specifically the model of Zhao (1996) predicts a $\sigma_l/\sigma_b = 1.32$ at $l = 1$, $b = -4$ and $\sigma_l/\sigma_b = 1.09$ at $l = 5$, $b = -3$, which is consistent, within the errors, to the values found here and in Zoccali et al. (2001) for the bulge stars observed in the fields of NGC 6528 and NGC 6553 (which are situated close to the coordinates for which Zhao's model makes its predictions).

We may thus conclude that these two new studies of the proper motions of Galactic bulge stars confirm the predictions by models of the kinematics in the Galactic bulge. To our knowledge the current work and that of Zoccali et al. (2001) are the first studies to address the velocity dispersion, measured by proper motions, of bulge stars below the horizontal branch.

6. Summary

CMDs of the metal-rich globular cluster NGC 6528 are notoriously difficult to analyze. This is due to the fact the cluster is situated in the Galactic bulge and thus the fields stars belonging to the bulge have the same magnitudes as the stars in NGC 6528.

Using two epochs of observations with HST/WFPC2 we obtain the stellar proper motions for all stars in the field. The proper motions are used to separate the bulge from the cluster stars. The stellar sequences in the resulting CMD are better defined than in any previously published CMD.

Using α-enhanced stellar isochrones we find NGC 6528 to have a probable age of 11 $\pm$ 2 Gyrs, this is the first attempt to establish the absolute age of NGC 6528. Previous studies have only compared the fiducial ridge line for the

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cluster to that of other globular clusters of similar metallicities. Mainly the comparisons have been with regards to NGC 6553 and 47 Tuc. With the new metallicity determinations for individual stars in both NGC 6553 and NGC 6528 it is now clear that 47 Tuc (at −0.71 dex) has a significantly lower metallicity than NGC 6528 and NGC 6553 and is thus not a suitable comparison cluster as regards differential age determinations (see e.g. Stetson et al. 1996 and references therein).

A comparison with the fiducial line for NGC 6553 confirms results in earlier studies, e.g. Ortolani et al. (1995), that the two clusters indeed have very similar ages.

The stellar proper motion also provide velocity dispersions for both the cluster and field stars. The velocity dispersion of the cluster is most likely dominated by measurement errors. The bulge dispersion can thus be found by deconvolution. The resulting dispersions are consistent with what has previously (Spaenhauer et al. 1992) been found for Bulge giants. Moreover, combining our results with those by Zoccali et al. (2001) we are able to confirm the difference in σ_l at two positions in the bulge as predicted by the model in Zhao (1996).

To our knowledge, our and Zoccali et al.'s study are the first to address the proper motions amongst bulge horizontal branch and fainter stars.

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