Wide-field photometry of the Galactic globular cluster M22

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ABSTRACT

We present wide-field photometry of the Galactic globular cluster M22 in the B, V and I passbands for more than 186 000 stars. The study is complemented by the photometry in two narrow-band filters centred on Hα and the adjacent continuum, and by infrared J, H and K magnitudes derived from the Two-Micron All-Sky Survey for ~2000 stars. Profiting from this huge data base, we completely characterized the evolved stellar sequences of the cluster by determining a variety of photometric parameters, including new photometric estimates of the mean metallicity, reddening and distance to the cluster. In particular, from our multiwavelength analysis, we re-examined the long-standing metallicity spread problem in M22. According to our data set, we conclude that most of the observed width of the red giant branch must be due to differential reddening, which amounts to a maximum of \(\Delta E(B-V) \simeq 0.06\), although the presence of a small metallicity spread cannot be completely ruled out. More specifically, the maximum metallicity spread allowed by our data is of the order of \(\Delta [\text{Fe}/\text{H}] \simeq 0.1-0.2\) dex, i.e. not much more than that allowed by the photometric errors. Finally, we identified most of the known variable stars and peculiar objects in our field of view. In particular, we have found additional evidence supporting previous optical identifications of the central star of the planetary nebula IRAS 18333−2357, which is associated with M22.

Key words: planetary nebulae: individual: IRAS 18333−2357 – globular clusters: individual: M22.

1 INTRODUCTION

M22 was one of the first Galactic globular clusters (GGCs) to be discovered, in 1665, by Abraham Ihle, and also one of the first to be studied in detail (Shapley 1930; Arp & Melbourne 1959). It soon became the target of a series of studies (starting with Hesser, Hartwick & McClure 1977) because of the large colour spread of its red giant branch (RGB) sequence, similar to that observed in \(\omega\) Centauri (\(\omega\) Cen; Woolley 1966). This suggested the possibility of a metallicity spread in M22, as was demonstrated in the case of \(\omega\) Cen a few years before (Dickens & Woolley 1967).

However, while the presence of significant reddening variations was excluded in the case of \(\omega\) Cen (Cannon 1980), some differential reddening was found in the direction of M22 (see Richter, Hilker & Richtler 1999, and references therein). Of course, the presence of differential reddening does not exclude the presence of some metallicity spread, because the two effects could be both present and responsible for the observed width of the RGB. The photometric studies of M22 by Piotto & Zoccali (1999) and Richter et al. (1999) were able to put upper limits to the amount of differential reddening of \(\sigma_{\Delta E(V-I)} = 0.05\) and \(\Delta E(B-V) = 0.07\), respectively. Interestingly, Richter et al. (1999) demonstrated that part of the spread observed in the Strömgren colours must be due to CH and CN variations, so that the eventual spread in heavy elements should be negligible.

Spectroscopic studies, on the other hand, gave controversial results as far as the heavy element abundances are concerned, while a spread in the CH and CN abundances of RGB stars appears unquestionable (Norris & Freeman 1983).1 For example, some studies reported on metallicity variations of 0.3–0.5 dex in Ca and/or Fe, often correlated with the CH and CN variations (Peterson 1980; Pilachowski et al. 1982; Lehner, Bell & Cohen 1991; Brown & Wallerstein 1992), while other studies found no significant variation in the heavy element content (Manduca & Bell 1978; Cohen 1981; Gratton & Bell 1982; Gratton & Ortolani 1989; Laird, Wilhelm & Peterson 1991).

Concerning this apparent contradiction, Lehner et al. (1991) noted that, because the estimated standard deviation of the abundance variations (~0.2 dex) is close to the typical uncertainty of most spectroscopic analyses, it is very difficult to unequivocally demonstrate the presence of a metallicity spread. This is

\[\text{\footnotesize \cite{Note1}}\]

\footnotetext{\textsuperscript{1}Some marginal evidence for an overabundance of \(s\)-process elements has also been reported by Gratton (1982).}
particularly true if we consider that most of the above studies are only based on a handful of stars (≤10). In the next years, thanks to the new generation of multi-object spectrographs, it will be possible to analyse large samples of stars in a homogeneous way, thus shedding more light on this issue.

M22 is a metal poor ([Fe/H] ≃ −1.62; Harris 1996) and very bright cluster. Considering also its position on the sky, (l, b) = (9.89; −7.55), and its proximity to us (only 3.2 kpc from the Sun\(^2\)), M22 is certainly the ideal target for various studies, ranging from the dynamical modelling of the dense stellar system (Albrow, De Marchi & Sahu 2002) to microlensing studies (Sahu et al. 2001). On the other hand, the characterization of its stellar content is still quite uncertain because it suffers, once again, from the presence of differential reddening along the line of sight. Here we provide a complete and homogeneous photometric characterization of the stellar content of M22.

The paper is organized as follows. In Section 2 we present the observations and data reduction procedures, we compare our results with previous literature and we derive optical and infrared mean ridge lines (MRLs). In Section 3 we deal with the differential reddening and metallicity spread issues. In Section 4 we derive the mean metallicity, reddening and distance along with other photometric parameters of M22. In Section 5 we identify the known variables and peculiar objects, including the central star of the planetary nebula (PN) IRAS 18333−2357. In Section 6 we summarize our main results.

2 OBSERVATIONS AND DATA REDUCTION

Observations were obtained at the 2.2-m European Southern Observatory/Max-Planck Institut (ESO/MP1) telescope at La Silla, Chile, using the Wide Field Imager (WFI), a mosaic of eight 2048 × 4096 pixel CCDs. The instrument scale is 0.238 arcsec pix\(^{-1}\), giving a total field of view of 34 × 33 arcmin\(^2\). A set of B, V and I images were secured during a single observing run on 2000 July 6–7, with exposure times ranging from 5 to 400 s. We also secured a set of exposures in two narrow-band filters, H\(_\alpha\) and [O\(_i\)], centred around the H\(_\alpha\) line (λ\(_\alpha\) ≃ 6580 Å) and on the adjacent continuum (λ\(_\alpha\) ≃ 6650 Å). The uncalibrated H\(_\alpha\) photometry is briefly discussed in Section 5.1. The average seeing during the observations was ≃1 arcsec full width at half-maximum (FWHM).

The raw images were corrected for bias and flat-field using specific IRAF\(^3\) procedures, within the NOAO.MSCRED package. The photometric reduction was carried out using the DAOPHOT II and ALLSTAR packages (Stetson 1987, 1999). Stars were searched independently on each CCD of the WFI mosaic with a 3σ threshold and fitted with a second-order spatially variable point spread function (PSF).

We used standard IRAF routines to obtain aperture photometry for a sample of isolated stars at various positions along the CCD. We derived the optimal radius for the aperture photometry by constructing the curve of growth of each star. We compared the aperture photometry with the DAOPHOT PSF-fitting photometry and we obtained an aperture correction of 0.00 for the V and I filters (with typical errors of 0.02 and 0.01, respectively) and 0.03 for the B filter (with a typical error of 0.02). The aperture corrections do not correlate with the position of the star on the CCD.

Then we corrected our instrumental magnitudes considering the extinction coefficients available for each filter from the ESO webpage\(^4\) and the airmass at the beginning of the observations.

All observations were carried out under photometric conditions. The calibration to the standard Johnson–Cousins photometric system was obtained using two standard fields (namely TPhe and PG 1323; Landolt 1992) observed at different airmasses during the night. The adopted calibrating equations are

\[
B = b + 0.45(b - v) - 0.48
\]

\[
V = v - 0.09(b - v) - 1.03
\]

\[
i = i + 0.12(v - i) - 1.88
\]

where \(b\), \(v\) and \(i\) are the corrected instrumental magnitudes and \(B\), \(V\) and \(I\) the corresponding magnitudes in the Johnson–Cousins photometric system.

The resulting, calibrated colour magnitude diagrams (CMDs) are displayed in Figs 1 and 2 in the \((B - V)\) and \((V - I)\) planes, respectively. As can be seen, the population of M22 dominates the CMD resulting from CCD 2, because the cluster centre has been placed on that chip. The bulge and disc populations dominate instead the CMDs of the outer CCDs, where the contribution by M22 tends to disappear (see, for example, chips 4 and 5). A few bright stars with \(V < 11.3\), \((B - V) = 1.8\) and \((V - I) = 1.9\) are saturated.

Therefore, in the following sections, we will restrict our analysis to stars measured in CCD 2 only, because most of the cluster population lies in that chip, where the contamination by the disc and the bulge is less important and the CMD appears cleaner. This way, we also avoid the propagation of the photometric zero-point differences between different CCDs, which could degrade the overall quality of the photometric catalogue.

Finally, in order to complement the multiwavelength study of M22, we identified approximately 1840 stars in our catalogue having \(J\), \(H\) and \(K_s\) magnitudes measured by the Two-Micron All-Sky Survey (2MASS).\(^5\) An example of the resulting \(K_s\), \((V - K_s)\) and \(K_s\), \((J - K_s)\) CMDs can be seen in Fig. 6, later.

2.1 Online catalogue

Although the following analysis is entirely based on stars belonging to CCD 2, several M22 stars are still present in CCDs 1, 3, 6, 7 and 8 (Figs 1 and 2). Therefore, the full catalogue presented in Table 1 and published electronically contains all the stars detected in these CCDs.

The catalogue contains the \(B\), \(V\) and \(I\) calibrated magnitudes on columns 2, 4 and 6, each followed by the formal DAOPHOT errors (\(\delta B\), \(\delta V\) and \(\delta I\)). Only stars measured both in the \(V\) and \(I\) filters are tabulated while the \(B\) magnitude is provided only when available. A flag ‘0.000’ can be found in columns 2 and 3 if a star is not measured in the \(B\) filter.

Star positions are provided both in the pixel coordinate system of each CCD (columns 7 and 8) and in the equatorial (RA; Dec.) coordinate system (columns 9 and 10). In the first column we provide a sequential identifier for each star.

The coordinates in the J2000.0 absolute astrometric system have been obtained with a procedure already described in other papers (see, for example, Ferraro et al. 2001). The new astrometric Guide Star Catalogue (GSC II) recently released and now available on

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\(^2\) Note that the Galactic bulge is in the background of M22.

\(^3\) IRAF is distributed by the National Optical Astronomy Observatories, which is operated by the association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.

\(^4\) See http://www.eso.org/gen-fac/pubs/astclim/lasilla/index.html; see also http://www.eso.org/lasilla/sciops/2p2/E2p2M/WFI/zeropoints/

\(^5\) See http://www.ipac.caltech.edu/2mass
The Versus \((B-V)\) CMDs obtained for each of the eight chips of the ESO WFI mosaic.

In order to derive an astrometric solution for each WFI CCD, we used a program specifically developed at the Bologna Observatory (Montegriffo et al., in preparation). As a result of the entire procedure, rms residuals of \(\sim 0.2\) arcsec, both in RA and Dec., were obtained. This value can be considered as a representative uncertainty of the astrometric calibration procedure.

The photometry of stars belonging to CCDs 1, 3, 6, 7 and 8 has been shifted to match the photometry of CCD 2, taking into account the different CCD responses. The correction was calculated by fitting the MRLs calculated in Section 2.3 to the CMDs. The correction applied to each of the \(B\), \(V\) and \(I\) magnitudes of the external chips is always \(\leq 0.1\) mag. However, in the CMD of chips 6, 7 and 8, only a handful of cluster stars is present in the main-sequence and turn-off regions and the calculated corrections are correspondingly less certain.

2.2 Literature comparisons

In order to check our calibration, we compared our \(V, (V-I)\) photometry with two catalogues previously published by Piotto & Zoccali (1999) and Rosenberg et al. (2000).

Fig. 3 shows the results of such a comparison. In particular, the photometry by Piotto & Zoccali (1999) appears in good agreement with ours as far as the upper RGB is concerned (left-hand panel of Fig. 3). However, their horizontal branch (HB) appears redder and fainter than ours, by approximately 0.18 dex in magnitude and 0.04 dex in colour. A similar discrepancy can be observed for the lower RGB and the turn-off (TO) regions, pointing towards a possible

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6 See http://www-gss.stsci.edu/gsc/gsc2/GSC2home.htm
residual \((V-I)\) colour term between the two calibrations. On the
other hand, the comparison with Rosenberg et al. (2000) results
again in a discrepancy, but in the opposite sense (right-hand panel
of Fig. 3). Both the RGB and HB appear in fact systematically bluer
and brighter than ours, by roughly 0.1 dex in colour and 0.05 dex
in magnitude. In this case, there appears to be a residual zero-point
difference between the two calibrations.

To further investigate this issue, we compared (Fig. 4) our pho-
tometry with that of three globular clusters having similar metallic-
ities (and thus similar RGB shapes) as M22. More specifically, the
Figure 3. The M22 photometry by Piotto & Zoccali (1999) (left-hand panel) and by Rosenberg et al. (2000) (right-hand panel) is superposed to the CMD obtained in this paper (light grey).

Figure 4. The photometries of NGC 5272 (left-hand panel), NGC 5897 (middle panel) and the RGB MRL of M2 (right-hand panel) are superposed on our M22 CMD (light grey). See the text for references.

Figure 5. The photometries of NGC 5272 (left-hand panel), NGC 5897 (middle panel) and M2 (right-hand panel) are superposed on our M22 CMD (light grey). See the text for references.

The left-hand panel of Fig. 4 shows the comparison of our M22 photometry with that of NGC 5272 (Ferraro, Fusi Pecci & Buonanno 1992), which has [Fe/H]ZW = −1.66 in the Zinn & West (1984) scale. NGC 5272 has been corrected with the reddening and distance tabulated by Ferraro et al. (1999) and with the corresponding values for M22 (see Section 4). The middle panel of Fig. 4 shows the comparison with NGC 5897 (Ferraro et al. 1997), which has [Fe/H]ZW = −1.68 and has been corrected for reddening and distance as above. Finally, the right-hand panel of Fig. 4 shows the comparison of our M22 photometry with the RGB MRL of M2, which has [Fe/H]ZW = −1.62 Harris (1996) and was published by Da Costa & Armandroff (1990) already corrected for reddening and distance. We thus applied the distance modulus and reddening of M22 following Harris (1996), to be consistent with the distance scale of Da Costa & Armandroff (1990).

As can be seen, all three panels of Fig. 4 show an excellent match with the present photometry of M22, thus dispelling any remaining doubt on the adopted absolute V and I calibration.

Unfortunately, among the recent CCD studies of M22, the only available B-band data set is that by Kaluzny & Thompson (2001) and, as the authors explicitly state in their paper, their absolute photometric calibration is not reliable. In Fig. 5 we compare our photometry to that of NGC 5272 and 5897 (Ferraro et al. 1999) and M2 (Lee & Carney 1999) in the V versus B−V plane. The CMDs of NGC 5272 and 5897 have been corrected exactly as in Fig. 4. The M2 CMD has been corrected for the appropriate reddening and distance and the corresponding M22 values tabulated by Harris (1996). We find a reasonable agreement with each of the reference clusters and we conclude also that our B-band calibration can be considered reliable. In particular, a good match is obtained in the case of NGC 5897 and of the RGB of NGC 5272. The NGC 5272 HB is redder than that of M22 even if the mean level appears similar. We also obtain a reasonable agreement in the case of M2, even if its CMD is bluer than that of M22.

2.3 Optical and infrared mean ridge lines

Profiting from this large photometric data base, we have constructed the RGB MRLs for M22, both in the optical and infrared colours. Because the optical photometry is deeper than the infrared 2MASS photometry, we were able to reach down to the main sequence in the V, (V−I) and V, (B−V) planes, while we reach the base of the RGB in the K, (V−K) and K, (J−K) planes (see Fig. 6).
3 DIFFERENTIAL REDDENING AND METALLICITY SPREAD

The most striking characteristic of the CMD of M22 is the large colour spread of the RGB, incompatible with measurement errors. As summarized in Section 1, there is a long-standing debate about a possible metallicity spread in M22, but the well-established presence of some differential reddening (Richter et al. 1999) in the direction of M22 further complicates the analysis, because both mechanisms can contribute to widen the RGB in colour and they are difficult to disentangle.

The presence of differential reddening is easily demonstrated in Fig. 8. As can be seen, stars on the red and blue sides of the MRLs derived in Section 2.3 occupy different spatial positions in the cluster. In particular, stars redder than the MRL tend to populate preferentially the uppermost part of CCD 2 (i.e. north of the cluster centre). The opposite is true for stars bluer than the MRL. Thus, the northern part of the cluster must be more reddened than the southern part. The same type of behaviour can be observed using the HB sequence, which is less sensitive to metallicity than the RGB, confirming that the dominant contribution to the colour spread of both sequences must be due to reddening variations. However, we still cannot exclude the presence of some (small) degree of metallicity
Table 3. Infrared and optical–infrared M22 MRLs.

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<th>$(V-K_S)$</th>
<th>$(J-K_S)$</th>
<th>$K_S$</th>
<th>$(V-K_S)$</th>
<th>$(J-K_S)$</th>
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<tr>
<td>10.10</td>
<td>3.229</td>
<td>0.761</td>
<td>13.61</td>
<td>2.671</td>
<td>0.605</td>
</tr>
<tr>
<td>10.18</td>
<td>3.215</td>
<td>0.757</td>
<td>13.69</td>
<td>2.662</td>
<td>0.603</td>
</tr>
<tr>
<td>10.25</td>
<td>3.202</td>
<td>0.752</td>
<td>13.76</td>
<td>2.653</td>
<td>0.601</td>
</tr>
</tbody>
</table>

spread. From a careful inspection of Fig. 8, it is also evident that differential reddening is present on different scales, ranging from ~100 pix (see the ‘hole’) at $(X, Y) = (600, 1100)$ in the lower left-hand panel) to ~1000 pix (see the lower half of the lower left-hand panel). Therefore, a wide field study is required in order to obtain mean properties that are really representative of M22.

Here, we profited from our multiband photometry to put quantitative constraints to the amount of metallicity spread allowed by the colour spread of the RGB. In particular, we studied the RGB colour distribution of M22 in $(B-V)$, $(V-I)$ and $(V-K_S)$, selecting stars with $V \leq 15$ for $(B-V)$ and $(V-I)$, and stars with $K_S \leq 12$ for $(V-K_S)$. This is necessary to avoid any contamination from the Galactic bulge and to use only measurements with the highest possible signal-to-noise ratio. We then computed the colour difference, at fixed magnitude, between each star and the corresponding MRL (Section 2.3). The histograms of the resulting differences are plotted in Fig. 9 for each colour. A Gaussian curve representing the measurement errors is overplotted on each histogram (dot-dashed curve). A Gaussian fit to the actual colour dispersion is also overplotted (solid curve) on each histogram. The latter Gaussian shows, of course, a larger dispersion than that representing the errors only, therefore, a wide field study is required in order to obtain mean properties that are really representative of M22.

Figure 7. Our M22 infrared MRL (continuous line) is compared with the M22 and M13 normal points by Davidge & Harris (1996) (open squares) and Davidge & Harris (1995) (filled triangles), respectively. We applied horizontal and vertical shifts to align M13 to the M22 normal points at the turn-off and the point 0.05 mag redward of the turn-off, just as done by Davidge & Harris (1996) (see lower panel in their figure 7).

Figure 8. The stars in the M22 RGB are divided into two samples, according to their position with respect to the MRL (upper panels). The stars in the two samples have different spatial distributions (lower panels).
because it contains also the contribution of the intrinsic spread, i.e. the differential reddening plus the eventual metallicity dispersion.\(^7\)

We can then represent the observed colour dispersion, \(\sigma_{(M_1-M_2)_{\text{obs}}}\), as the sum of three terms, one due to photometric errors, \(\sigma_{\delta(M_1-M_2)}\), the second to the differential reddening, \(\sigma_{\Delta E(M_1-M_2)}\), and the third to the intrinsic metallicity spread, \(\sigma_{\Delta[M/H]}\):

\[
\sigma_{(M_1-M_2)_{\text{obs}}}^2 = \sigma_{\delta(M_1-M_2)}^2 + \sigma_{\Delta E(M_1-M_2)}^2 + \sigma_{\Delta[M/H]}^2
\]

Because the observed colour spreads and the photometric errors are

\[
\sigma_{(B-V)_{\text{obs}}} = 0.026; \quad \sigma_{(B-V)} = 0.015
\]

\[
\sigma_{(V-I)_{\text{obs}}} = 0.030; \quad \sigma_{(V-I)} = 0.016
\]

\[
\sigma_{(V-Ks)_{\text{obs}}} = 0.055; \quad \sigma_{(V-Ks)} = 0.030
\]

we can derive the intrinsic colour spreads obtaining

\[
\sigma_{(B-V)_{\text{int}}} = \sqrt{\sigma_{\Delta E(B-V)}^2 + \sigma_{\Delta[M/H]}^2} = 0.02
\]

\[
\sigma_{(V-I)_{\text{int}}} = \sqrt{\sigma_{\Delta E(V-I)}^2 + \sigma_{\Delta[M/H]}^2} = 0.03
\]

\[
\sigma_{(V-Ks)_{\text{int}}} = \sqrt{\sigma_{\Delta E(V-Ks)}^2 + \sigma_{\Delta[M/H]}^2} = 0.05.
\]

\(^7\) We point out the presence of a clump of stars with redder colours in Fig. 9, especially visible in \((B-V)\). If the colours of these stars are due to differential reddening, they could be tracing a denser interstellar matter region, with an \(E(B-V)\) which is \(\sim 0.06\) mag higher than the average cluster reddening.

\(^8\) Photometric errors are computed as the standard deviation of repeated measurements of a star magnitude, available for the \(B\), \(V\) and \(I\) filters. In the case of the \(K_s\) filter, we used errors provided by the 2MASS extraction algorithm. We excluded stars belonging to the inner 1 arcmin around the cluster centre, where crowding effects are most severe.

These values have to be considered as upper limits to the amount of differential reddening needed to explain the RGB width, if we assume zero metallicity spread. The above values are in reasonable agreement with previous determinations. In fact, \(\sigma_{\Delta E(V-I)} = 0.05\), derived by Piotto & Zoccali (1999) using the main sequence, compares reasonably with our \(\sigma_{\Delta E(V-I)} = 0.03\), while \(\Delta E(B-V) = 0.07 \pm 0.08\), derived respectively by Richter et al. (1999) and Anthony-Twarog, Twarog & Craig (1995) from Strömgren photometry, compare very well with our \(\Delta E(B-V) \approx 3\sigma_{\Delta E(B-V)} = 0.06\).

We also note that the intrinsic spread, in the three different colours, changes following the reddening laws (in the following we will always use the reddening laws by Dean, Warren & Cousins 1978 and Savage & Mathis 1979). In fact, assuming \(\sigma_{\Delta E(B-V)} = 0.02\) as above, we obtain \(\sigma_{\Delta E(V-I)}\) and \(\sigma_{\Delta E(V-K_s)}\), which are virtually identical to the values derived above:

\[
\sigma_{\Delta E(V-I)} = 1.34\sigma_{\Delta E(B-V)} = 0.03
\]

\[
\sigma_{\Delta E(V-K_s)} = 2.72\sigma_{\Delta E(B-V)} = 0.06.
\]

Therefore, because the intrinsic width of the RGB scales from the optical plane to the optical--infrared plane exactly as expected from the reddening laws, we have to conclude that the room left for an intrinsic metallicity spread must be very small.

To confirm this conclusion, we made use of two reddening free colour indices

\[
Q_{BV} = (B - V) - \frac{E(B-V)}{E(V-I)}(V - I)
\]

\[
Q_{BVK} = (B - V) - \frac{E(B-V)}{E(V-K_s)}(V - K_s)
\]

and we plotted these in the top panel of Fig. 10. The position of stars in the \((Q_{BV}, Q_{BVK})\) plane should thus depend only on the intrinsic properties of the stars (i.e. temperature and chemical composition). In particular, the spread around the mean locus should depend

\begin{figure}[h]
\centering
\includegraphics[width=0.8\textwidth]{figure9}
\caption{The observed colour difference distribution between stars in the RGB and the corresponding MRL is plotted in \(B-V\) (lower panel), \(V-I\) (middle panel) and \(V-K_s\) (upper panel). Two Gaussian curves representing the fit to the observed distribution (continuous curve) and the distribution expected by photometric errors (dot-dashed curve) are also plotted on each panel.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=0.8\textwidth]{figure10}
\caption{RGB stars in M22 are plotted in the plane of the two reddening free colour indices \(Q_{BV}\) versus \(Q_{BVK}\) (upper panel). The continuous curve is the mean locus of stars in the plane. In the lower panel the observed distribution of the stars distances from the mean locus is plotted (histogram). The two Gaussian curves represent a fit to the observed distribution (continuous curve) and the distribution expected considering the photometric errors (dot-dashed curve).}
\end{figure}
only on the eventual metallicity spread and on the photometric errors, because the $Q$-colour indices are independent on reddening by definition.

Therefore, we derived the MRL of the locus in Fig. 10 (thick line) with the same method used in Section 2.3. We measured the distance of each star from the MRL and we constructed the histogram shown in the bottom panel of Fig. 10. Two Gaussians have been overplotted: the one obtained by propagating the photometric errors to the $(Q_{RV}, Q_{YK})$ plane (dot-dashed line) and the one that best fits the distribution (solid line). As can be seen, the two Gaussians are virtually identical.

Summarizing, the metallicity spread contribution to the intrinsic width of the RGB must be smaller than our typical measurement errors, i.e. of the order of $\sim 0.01$–$0.02$ mag. Using equation (8) in Carretta & Bragaglia (1998) and considering $(V-I)_{0,8} = 0.92$ (see next section), we derive that a colour spread of $\sim 0.01$–$0.02$ corresponds to a metallicity spread of approximately $\Delta [\text{Fe}/\text{H}] \sim 0.1$–$0.2$ dex, which is the maximum metallicity spread allowed by the present photometry. This spread is also of the order of the uncertainty of high-resolution abundance determinations for a single star ($\sim 0.15$ dex). Therefore, such a low metallicity spread, if present, could remain hidden into the instrumental errors even studying a large sample of high-resolution spectra of M22 stars.

4 METALLICITY, REDDENING AND DISTANCE

In this section we characterize the photometric properties of the stellar population in M22 by measuring the complete set of observables for the evolved sequences, with the aim of obtaining modern, CCD-based estimates of the cluster mean metallicity, mean reddening and distance modulus.

The $V_{\text{ZAHB}}$ level was obtained from the comparison of the observed star distribution along the HB with synthetic HB of appropriate metallicity ([M/H] $\sim -1.5$, see below), following the semi-empirical approach described by Ferraro et al. (1999). This method is extremely robust because it allows the direct determination of $V_{\text{ZAHB}}$, instead of relying on the mean HB level as an indicator of the zero-age horizontal branch (ZAHB) level. We obtained

$$V_{\text{ZAHB}} = 14.33 \pm 0.05,$$

about 0.15 mag fainter than that reported by Harris (1996). This is easily understood in view of the fact that the Harris (1996) value is referred to the mean HB level instead of the ZAHB level (see equation 2 in Ferraro et al. 1999).

Rosenberg et al. (2000) derived $V_{\text{ZAHB}} = 14.25$ for M22 and, considering the zero-point difference with our $V$ magnitudes (0.05, see Section 2.2), our $V_{\text{ZAHB}}$ level results to be about 0.03 mag fainter than their value.

Next, we proceeded to the simultaneous determination of the mean metallicity and reddening, using a procedure that was first introduced by Sarajedini (1994). In its original description, the method allowed the derivation of [Fe/H] in the Zinn & West (1984) scale, using $V$, $(V-I)$ photometry and MRLs of the RGB. Later, the procedure was calibrated to the Carretta & Gratton (1997) scale by Carretta & Bragaglia (1998) and extended to the $B$, $(B-V)$ plane by Sarajedini & Layden (1997) and Ferraro et al. (1999).

Using the calibration of Carretta & Bragaglia (1998), we assumed a mean HB level $(V_{\text{HB}}) = 14.15$ (Harris 1996) and used the $V$, $(V-I)$ MRL derived in Section 2.3, obtaining $[\text{Fe}/\text{H}]_{\text{CG}} = -1.63$ and $E(B-V) = 0.36$ (we also derived $(V-I)_{0,8} = 0.92$ and $\Delta V_{1,2} = 2.19$). Using the calibration by Ferraro et al. (1999), we adopted the $V_{\text{ZAHB}}$ just derived and used the $V$, $(B-V)$ MRL, obtaining $[\text{Fe}/\text{H}]_{\text{CG}} = -1.73$ and $E(B-V) = 0.39$ (we also derived $(B-V)_{0,8} = 0.73$ and $\Delta V_{1,2} = 2.68$).

Because the two above reddening determinations are in good agreement with each other, we will adopt their average for the rest of this paper:

$$E(B-V) = 0.38 \pm 0.02.$$

Our determination of the reddening is identical to that by Richter et al. (1999), which is also the most recent determination. Other estimates of the reddening range from $E(B-V) = 0.32$ to 0.42 and can be found in Hesser (1976), Harris & Racine (1979), Harris (1996) and Crocker (1988). These values are in broad agreement with our determination within the errors, if we take into account the presence of a strong differential reddening in direction of M22 (see previous section).

The average metallicity of M22 can also be derived from the optical–infrared CMDs $V$, $(V-K_S)$ and $K_S$, $(J-K_S)$ using the RGB intrinsic colours $(V-K_S)_0$ and $(J-K_S)_0$, measured at different magnitude levels (see the definition of these parameters in Ferraro et al. 2000). We used the calibrations of Valenti, Ferraro & Origlia (in preparation) to yield metallicities in the Carretta & Gratton (1997) scale from the infrared photometry in the 2MASS photometric system. We corrected our optical–infrared CMD using $E(B-V) = 0.38$ and the $(m - M)_0$ derived below. In this way we obtained different photometric metallicity estimates for M22, which produce an average value of $[\text{Fe}/\text{H}]_{\text{CG}} = -1.68$.

Averaging together all the optical and infrared metallicity determinations we obtained

$$[\text{Fe}/\text{H}]_{\text{CG}} = -1.68 \pm 0.15.$$

This value is in agreement, within the errors, with the most recent spectroscopic and photometric works, which provide mean metallicities of $-1.55$ and $-1.48$ (Lehnert et al. 1991 and Carretta & Gratton 1997, respectively) and $-1.62$ (Richter et al. 1999).

An estimate of the global metallicity can be now derived according to the prescription of Salaris, Chieffi & Straniero (1993)

$$[\text{M}/\text{H}] = [\text{Fe}/\text{H}] + \log(0.638 \times 10^{0.68/\text{Fe}} + 0.362) = -1.47$$

by assuming $[\alpha/\text{Fe}] = +0.30$ (Salaris & Cassisi 1996). The distance modulus is derived from the comparison of the observed value of the ZAHB obtained above ($V_{\text{ZAHB}} = 14.33 \pm 0.05$) and the absolute level computed from the Straniero, Chieffi & Limongi (1997) models (see equation 4 by Ferraro et al. 1999). From this relation and the global metallicity computed above ([M/H] = $-1.47$) we obtain $(m - M)_V = 13.74 \pm 0.2$

and finally (using $E(B-V) = 0.38$), an intrinsic distance modulus $(m - M)_0 = 12.56 \pm 0.2$, which corresponds to a distance of $\sim 3.2$ kpc. A conservative uncertainty of 0.2 mag is assumed. Our $(m - M)_V$ is about 0.15 mag fainter than the value reported by Harris (1996). Therefore, the two distance moduli are in agreement within the uncertainties, however a systematic difference between

$^9$ $(V-I)_{0,8}$ and $(B-V)_{0,8}$ are the dereddened RGB colours at the level of the HB, while $\Delta V_{1,2}$ is the difference in $V$ between the HB and the RGB at a dereddened colour 1.2, i.e. $(V-I)_{1.2} = 1.2$ and $(B-V)_{1.2} = 1.2$; see Sarajedini (1994) and Ferraro et al. (1999).
the Harris (1996) distance scale and distances derived by our semi-empirical procedure still remains and is further discussed in Ferraro et al. (1999).

As a consistency check for the parameters derived until now, we derived the putative position of the RGB tip, in the $K$ band. From the relations provided by Ferraro et al. (2000) and assuming the $\text{[Fe/H]}_{\text{CG}}$ just derived, we obtained as absolute magnitude of the RGB tip:

$$M_{K}^{\text{tip}} = -5.93.$$  

Then, using the $(m - M)_0$ and $E(B - V)$ we derived the predicted position for the RGB tip in apparent magnitude:

$$K_{\text{tip}} = 6.77.$$  

In Fig. 11 the $K_s$, $(J - K_s)$ CMD of M22 is plotted. Even if the presented CMD does not possess enough stars in the upper RGB for a safe determination of the RGB tip, it is nevertheless clear that the predicted RGB tip is very similar to the magnitude at which the star counts drop to zero, $K_s \approx 6.74$.

The last important feature that we were able to measure on the RGB of M22 is the so-called RGB bump. This feature was one of the first successful predictions of the stellar evolution theory (Thomas 1967; Iben 1968), identified observationally in 47 Tuc and subsequently in all the properly observed clusters (King, Da Costa & Demarque 1985; Fusi Pecci et al. 1990; Ferraro et al. 1999; Zoccali et al. 1999; Ferraro et al. 2000; Cho & Lee 2002), both in the optical and infrared filters. Recently, the RGB bump was also observed in a few satellites of the Milky Way (Monaco et al. 2002; Bellazzini et al. 2002, and references therein).

As demonstrated by Fusi Pecci et al. (1990), the change in slope of the integrated luminosity function is the safest way to identify the RGB-bump location, because it makes use of stars contained in several magnitude bins. We thus identified the RGB bump of M22 in the $V$ band, as shown in Fig. 12:

$$V_{\text{bump}} = 13.90 \pm 0.05.$$  

We also identified the RGB bump in the $K_s$ band, finding a value in good agreement with Cho & Lee (2002).

In Fig. 13 the difference of $V_{\text{bump}}$ and $V_{\text{ZAHB}}$, $\Delta V_{\text{bd}}$ versus $\text{[Fe/H]}_{\text{CG}}$ plane is plotted for the 42 clusters of Ferraro et al. (1999; small empty squares) and for M22 (big filled circle). As can be seen, M22 matches quite well the empirical calibration of Ferraro et al. (1999).
5 VARIABLE STARS AND PECULIAR OBJECTS

M22 is known to host various types of variable stars, from the RR Lyrae stars typical of globular clusters (Wehlau & Hogg 1978) to rather peculiar or rare objects such as a type II Cepheid, one sdB star (Wehlau & Hogg 1978; Kaluzny & Thompson 2000) and a PN (see next section). A probable dwarf nova in outburst phase has also been recently identified (Anderson, Cool & King 2003) as well as a population of X-ray sources (Webb, Gendre & Barret 2002). In spite of the modest number of blue straggler stars, M22 contains also a significant number of SX Phoenicis variables (Kaluzny & Thompson 2001).

We cross-correlated our catalogue with that of variable stars by Clement et al. (2001), which provides coordinates, classification and other useful information for all the known variable stars in M22. In Fig. 14 we have used various symbols to show the position in the CMD of the various type of variables successfully identified in our photometry. 51 variables over the 79 known in M22 have been identified. Among them, 16 are RR Lyrae stars. Averaging the magnitude is about 0.15 mag brighter than our estimate of \( S_\star \) (small empty circles), \( S_\star \) in the HB phase are plotted as filled triangles.

5.1 Planetary nebula in M22

Together with Pal 6, NGC 6441 and M 15 (Jacoby et al. 1997; Adams et al. 1984), M22 is one of the few GGCs which are known to host a PN. It was first discovered with the IRAS satellite by Gillett et al. (1986) as a point-like source (IRAS 18333–2357) and then identified as a PN (Gillett et al. 1989). The central star of the PN has also been identified (Gillett et al. 1989), as a blue star (the ‘southern component’), hereafter \( S_\star \) belonging to a pair which lies only \( \sim 2 \) arcsec away from the infrared source.

Some of the physical properties of the PN and its central star were derived by Cohen & Gillett (1989). Considering the expansion velocity (11 km s\(^{-1}\)) of the nebula and assuming that its size corresponds to the distance to \( S_\star \), Cohen & Gillett (1989) concluded that the age of the PN appears to be only \( 6000 \) yr. This short time-scale implies that the central star should still be quite bright, with a luminosity comparable to that of the RGB tip. This poses an apparent problem, because \( S_\star \) has a magnitude (and even colours) comparable to that of a slightly evolved HB star, as can be seen in Fig. 14.

To further investigate the photometric properties of \( S_\star \), we constructed the instrumental (non-calibrated) \( H_\alpha \) (\( H_\alpha \) – \( \pi \)) CMD for stars contained in a circle with a radius of 150 pixels, centred on \( S_\star \) (Fig. 15). In this diagram, RGB stars occupy a vertical sequence while genuine HB stars (filled triangles), which have a more pronounced \( H_\alpha \) absorption, tend to have redder (\( H_\alpha \) – \( \pi \)) colours. In the same diagram, \( S_\star \) (large filled square) shows a moderate \( H_\alpha \) excess, with (\( H_\alpha \) – \( \pi \)) slightly bluer than the normal RGB stars and very different from the HB stars. This is in agreement with the substantial amount of hydrogen emission displayed by the spectrum of \( S_\star \) (Harrington & Paltoglou 1993), consistent with that expected if \( S_\star \) is the central star of a new-born PN.

We thus need to explain the unusual position of \( S_\star \) in the \( V, (B-V) \) diagram. An enlargement of the CMD around \( S_\star \) is shown in Fig. 16 (upper panel), where the theoretical isochrone of a post-asymptotic giant branch (post-AGB) star with \( t \approx 12.5 \) Gyr and \( Z = 0.0004 \) has also been overplotted (Bertelli et al. 1994). Clearly, the position of \( S_\star \) (large filled square) is not compatible with the isochrone. However, \( S_\star \) should be surrounded by nebular dust, which causes an excess of reddening of about \( \Delta E(B-V) \approx 0.14 \) (Cudworth 1990; Harrington & Paltoglou 1993). After applying the corresponding correction, the
in the near-infrared by the 2MASS survey, providing calibrated $J$, $H$ and $K_s$ magnitudes in addition to our five optical bands.

We use this catalogue to characterize the evolved stellar sequences in M22, especially the RGB, by deriving MRLs in the optical and infrared colours, and by measuring the $V$ magnitude of the RGB bump, which appears in good agreement with the most recent calibration versus metallicity (Ferraro et al. 1999). We also derived the mean metallicity, reddening and distance moduli, in a self-consistent way. The derived values agree well with previous determinations.

Profiting from our multiband catalogue, we re-examined the problem of the metallicity spread in M22. We demonstrated the presence of differential reddening, confirming earlier findings (Richter et al. 1999, and references therein). We also conclude that, according to our photometric measurements, most of the intrinsic width of the RGB must be due to differential reddening, while the maximum metallicity spread allowed by our data is $\Delta [\text{Fe/H}] \approx 0.1$–0.2 dex, i.e. compatible with the photometric errors.

We finally identified most of the variable stars and peculiar objects known in the observed field of M22. In particular, we provided additional evidence supporting the optical identification of the central star in the PN IRAS 18333$-$2357, one of the few identified in a GGC up to now.

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