The fraction of binary systems in the core of thirteen low-density Galactic globular clusters

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ABSTRACT
We used deep observations collected with ACS@HST to derive the fraction of binary systems in a sample of thirteen low-density Galactic globular clusters. By analysing the color distribution of Main Sequence stars we derived the minimum fraction of binary systems required to reproduce the observed color-magnitude diagram morphologies. We found that all the analysed globular clusters contain a minimum binary fraction larger than 6% within the core radius. The estimated global fractions of binary systems range from 10% to 50% depending on the cluster. A dependence of the relative fraction of binary systems on the cluster age has been detected, suggesting that the binary disruption process within the cluster core is active and can significantly reduce the binary content in time.

Key words: stellar dynamics – methods: observational – techniques: photometric – binaries: general – stars: Population II – globular clusters: general

1 INTRODUCTION
Binary stars provide a unique tool to determine crucial information about a variety of stellar characteristics including mass, radius and luminosity. Fortunately, there are ample opportunity to observe binary star systems: most stars are in fact in binary systems, at least in the solar neighborhood (Duquennoy & Mayor 1991). Since the first decades of the twentieth century, the study of binary star systems provided valuable information about the stellar structure and evolution, such as the mass-luminosity and mass-radius relations (Kuiper 1938; Huang & Struve 1956). Binarity, under particular conditions, induces the onset of nuclear reactions leading to the formation of bright objects like novae and determines the fate of low-mass stars leading to SN Ia explosions.

Binaries play also a key role in the dynamical evolution of stellar systems and stellar populations studies. In collisional systems binaries provide the gravitational fuel that can delay and eventually stop and reverse the process of core collapse in globular clusters (see Hut et al. 1992 and references therein). Furthermore, the evolution of binaries in star clusters can produce peculiar stellar object of astrophysic interest like blue stragglers, cataclysmic variables, low-mass X-ray binaries, millisecond pulsars, etc. (see Bailyn 1995 and reference therein). The binary fraction is a key ingredient in chemical and dynamical models to study the evolution of galaxies and stellar systems in general.

The main techniques used to derive the binary fraction in globular clusters are: i) radial velocity variability surveys (Latham 1996; Albro et al. 2001) ii) searches for eclipsing binaries (Mateo 1996) and iii) searches for secondary main-sequences (MS) in color-magnitude diagrams (CMD, Rubenstein & Bailyn 1997). The first two methods rely on the detection of individual binary systems in a given range of periods and mass-ratios. The studies carried out in the past based on these methods argued for a deficiency of binary stars in globular clusters compared to the field (Pryor et al. 1989; Hut 1992; Cote et al. 1996). However, the nature of these two methods leads to intrinsic observational biases and a low detection efficiency. Conversely, the estimate of the binary fraction on the basis of the analysis of the number of stars displaced in the secondary MS represents a more efficient statistical approach and does not suffer of selection biases. In fact, any binary system in a globular cluster is seen as a single star with a flux equal to the sum of the fluxes of the two components. This effect locates any binary system systematically at brighter magnitudes with respect to single
MS stars, defining a secondary sequence in the CMD running parallel to the cluster MS that allows to distinguish them from other single MS stars. Until now, the binary fraction has been estimated following this approach only in few globular clusters (Romani & Weinberg 1991; Bolte 1992; Rubenstein & Bailyn 1997; Bellazzini et al. 2002; Clark, Sandquist & Bolte 2004; Zhao & Bailyn 2005).

In this paper we present an estimate of the binary fraction in thirteen low-density Galactic globular clusters. We used the photometric survey carried out with the Advanced Camera for Surveys (ACS) on board HST as a part of a Treasury program (Sarajedini et al. 2007).

In §2 we describe the observations, the data reduction techniques and the photometric calibration. In §3 the adopted method to determine the fraction of binary systems is presented. In §4 we derived the minimum binary fractions in our target globular clusters. §5 is devoted to the estimate of the global binary fractions and to the comparison of the measured relative fractions among the different globular clusters of our sample. In §6 the radial distribution of binary systems is analysed. Finally, we summarize and discuss our results in §7.

2 OBSERVATIONS AND DATA REDUCTION

The photometric data-set consists of a set of high-resolution images obtained with the ACS on board HST through the F606W ($V_{606}$) and F814W ($I_{814}$) filters. The target clusters were selected on the basis of the following criteria:

- A high Galactic latitude ($b > 15^\circ$) in order to limit the field contamination;
- A low reddening (E(B-V)<0.1) in order to avoid the occurrence of differential reddening;
- A low apparent central density of stars ($\rho_0 < 5 \, M_\odot \, arcmin^{-2}$) in order to limit the effects of crowding and blending.

Thirteen cluster passed these criteria namely NGC288, NGC4590, NGC5053, NGC5466, NGC5897, NGC6101, NGC6362, NGC6723, NGC6981, M55, Arp 2, Terzan 7 and Palomar 12. In Table 1 the main physical parameters of the above target clusters are listed. The central density $\rho_0$, the core radii $r_c$ and the half-mass relaxation times $t_{r_m}$ are from Djorgovski (1993), the age $t_0$ from Salaris & Weiss (2002) and the global metallicities [M/H] from Ferraro et al. (1999). Note that the analysed sample spans a wide range in age and metallicity containing only low-density ($\rho_0 < 2.75 \, M_\odot \, pc^{-3}$) globular clusters.

1 The apparent central density of stars has been calculated from the central surface density $\rho_{S,0}$ and the cluster distance $d$ (from McLaughlin & Van der Marel 2005) according to the following relation

$$\rho_0 = \rho_{S,0}d^2 \left( \frac{2\pi}{21600} \right)^2$$

2 For the clusters NGC6101, NGC6362, NGC6723 and Palomar 12 not included in the list of Ferraro et al. (1999) we transformed the metallicity [Fe/H] from Zinn & West (1984) into the global metallicity [M/H] following the prescriptions of Ferraro et al. (1999).

For each cluster the ACS field of view was centered on the cluster center. We retrieved all the available exposures from the ESO/ST-ECF Science Archive. The exposure times for each cluster in each filter are listed in Table 2. All images were passed through the standard ACS/WFC reduction pipeline. Data reduction has been performed on the individual pre-reduced images using the SExtractor photometric package (Bertin & Arnouts 1996). The choice of the data-reduction software has been made after several trials using the most popular PSF-fitting softwares. However, the shape of the PSF quickly varies along the ACS chip extension giving trouble to most PSF-fitting algorithms. Conversely, given the small star density in these clusters, crowding does not affect the aperture photometry, allowing to properly estimate the magnitude of stars. This is evident in Fig. 1 where a zoomed portion of the central region of the cluster NGC6723 (the most crowded GC of our sample) is shown. Note that the surface density of stars in this field is $\leq 1.4 \, sarscc^{-2}$. For each star we measured the flux contained within a radius of 0.125" (corresponding to 2.5 pixels ~ FWHM) from the star center. The source detection and the photometric analysis have been performed independently on each image. Only stars detected in three out four frames have been included in the final catalog. The most isolated and brightest stars in the field have been used to link the aperture magnitudes at 0.5" to the instrumental ones, after normalizing for exposure time. Instrumental magnitudes have been transformed into the VEGAMAG system by using the photometric zero-points by Sirianni et al. (2005). Finally, each ACS pointing has been corrected for geometric distortion using the prescriptions by Hack & Cox (2001).

Two globular clusters (NGC5053 and NGC5466) were already analyzed by Sarajedini et al. (2007). Our photometry has been compared with the photometric catalog already published by these authors. The mean magnitude differences found are $\Delta V_{606} = -0.004 \pm 0.012$ and $\Delta I_{814} = 0.004 \pm 0.012$ for NGC5053 and $\Delta V_{606} = -0.031 \pm 0.012$ and $\Delta I_{814} = -0.020 \pm 0.012$ for NGC5466, which are consistent with a small systematic offset in both passbands.

Fig. 2 and 3 show the ($I_{814}, V_{606}$) CMDs of the 13 globular clusters in our sample. The CMDs sample the cluster population from the sub-giant branch down to 5-6 magnitudes below the MS turn-off. In all the target clusters the binary sequence is well defined and distinguishable from the cluster’s MS. In the less dense clusters (e.g. Terzan 7, Pal 12) binary stars appears to populate preferentially a region of the CMD ~0.75 mag brighter than the cluster MS, approaching the equal-mass binary sequence (Eggleton, Mitton & Whelan 1978). In most clusters a number of blue stragglers stars populating the bright part of the CMD is also evident.

3 METHOD

As quoted in §1, any binary system in a globular cluster is seen as a single star with a flux equal to the sum of the fluxes of the two components. This effect produces a systematic overluminosity of these objects and a shift in color depending on the magnitudes of the two components in each passband. In a simple stellar population the luminosity of a
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Figure 2. $I_{814}, V_{606} - I_{814}$ CMDs of the target globular clusters NGC288, NGC4590, NGC5053, NGC5466, NGC5897 and NGC6101.

Figure 1. Zoomed image of the central region of the globular cluster NGC6723, the most crowded cluster of our sample.

Table 1. Main physical parameters of the target globular clusters

| Name       | $\log p_0$ | $r_c$  | $t_0$ | $\log t_{r, rh}$ | $[M/H]$ |
|------------|------------|--------|-------|------------------|---------|
| NGC 288    | 1.80       | 85.20  | 11.3  | 8.99             | -0.85   |
| NGC 4590   | 2.52       | 41.35  | 11.2  | 8.90             | -1.81   |
| NGC 5053   | 0.51       | 134.40 | 10.8  | 9.59             | -2.31   |
| NGC 5466   | 0.68       | 116.50 | 12.2  | 9.37             | -1.94   |
| NGC 5897   | 1.32       | 118.70 | 12.3  | 9.31             | -1.44   |
| NGC 6101   | 1.57       | 69.25  | 10.7  | 9.22             | -1.40   |
| NGC 6362   | 2.23       | 79.15  | 11.0  | 8.83             | -0.72   |
| NGC 6723   | 2.71       | 56.81  | 11.6  | 8.94             | -0.73   |
| NGC 6981   | 2.26       | 32.09  | 9.5*  | 8.93             | -1.10   |
| M55        | 2.12       | 170.8  | 12.3  | 8.89             | -1.41   |
| Arp 2      | -0.35      | 96.03  | 7-11.5| 9.46             | -1.44   |
| Terzan 7   | 1.97       | 36.51  | 7.4   | 9.03             | -0.52   |
| Palomar 12 | 0.68       | 65.83  | 6.4   | 9.03             | -0.76   |

* The age of NGC6981 has been taken from De Angeli et al. (2005) (see §5.3).

MS star is univocally connected with its mass. In particular, stars with smaller masses have fainter magnitudes following a mass-luminosity relation. So, named $M_1$ the mass of the most massive (primary) component in a given binary system and $M_2$ the mass of the less massive (secondary) one, the magnitude of the binary system can be written as:

$$m_{sys} = -2.5 \log(F_{M_1} + F_{M_2}) + c$$
In this formulation the shift in magnitude of the binary system can be viewed as the effect of the secondary star that perturbs the magnitude of the primary. The quantity \( \frac{F_{M_2}}{F_{M_1}} \) depends on the mass ratio of the two component (\( q = \frac{M_2}{M_1} \)). According to the definition of \( M_1 \) and \( M_2 \) given above, the parameter \( q \) is comprised in the range \( 0 < q < 1 \). When \( q=1 \) (equal mass binary) the binary system will appear \(-2.5 \log(2) \sim 0.752 \) mag brighter than the primary component. Conversely, when \( q \) approaches small values the ratio \( \frac{F_{M_2}}{F_{M_1}} \) becomes close to zero, producing a negligible shift in magnitude with respect to the primary component. Following these considerations, binary systems with small values of \( q \) becomes indistinguishable from MS stars when photometric errors are present. Hence, only binary systems with values of \( q \) larger than a minimum value \( q_{\text{min}} \) are unmistakably distinguishable from single MS stars. For this reason, only a lower limit to the binary fraction can be directly derived without assuming a specific distribution of mass-ratios \( f(q) \).

In order to study the relative frequency of binary systems in our target clusters we followed two different approaches:

- We estimated the global binary fraction by assuming a given \( f(q) \) and comparing the simulated CMDs with the observed ones.
- We derived the minimum number of binary systems by considering only the fraction of binary systems with large mass-ratio values \( (q > q_{\text{min}}) \);

A correct binary fraction estimation requires corrections for two important effects: i) blended sources contamination and ii) field stars contamination. In the following sections we describe the adopted procedure to take into account these effects.

3.1 Blended sources

Chance superposition of two stars produces the same magnitude enhancement observed in a binary system. For this reason it is impossible to discern whether a given object is a physical binary or not. However, a statistical estimate of the distribution of blended sources expected to populate the CMD as a function of magnitude and color is possible by means of extensive artificial stars experiments (see Bellazzini et al. 2002).

For each individual cluster the adopted procedure for the artificial star experiments has been performed as follows:

- The cluster mean ridge line has been calculated by averaging the colors of stars in the CMD over 0.2 mag boxes and applying a 2\( \sigma \) clipping algorithm;
- The magnitude of artificial stars has been randomly extracted from a luminosity function (LF) modeled to re-

Figure 3. \( I_{814}, V_{606} - I_{814} \) CMDs of the target globular clusters NGC6362, NGC723, NGC6981, Arp 2, M55, Terzan 7 and Palomar 12.
produce the observed magnitude distribution of bright stars ($F814W < 22$) and to provide large numbers of faint stars down to below the detection limits of the observations ($F814W > 26$). The color of each star has been obtained by deriving, for each extracted $F814W$ magnitude, the corresponding $F606W$ magnitude by interpolating on the cluster ridge line. Thus, all the artificial stars lie on the cluster ridge line in the CMD:

- We divided the frames into grids of cells of known width (30 pixels) and randomly positioned only one artificial star per cell for each run.
- Artificial stars have been simulated using the Tiny Tim model of the ACS PSF (Krist 1995) and added on the original frames including Poisson photon noise. Each star has been added to both $F606W$ and $F814W$ frames. The measurement process has been repeated adopting the same procedure of the original measures and applying the same selection criteria described in Sect. 2.

\begin{itemize}
  \item The results of each single set of simulations have been appended to a file until the desired total number of artificial stars has been reached. The final result for each subfield is a list containing the input and output values of positions and magnitudes.
\end{itemize}

The residuals between the input and output $V_{606}$ and $I_{814}$ magnitudes and the completeness factor as a function of the $I_{814}$ magnitude are shown in Fig. 4 for the target cluster M55. In lower panels the residuals between the input and output $F606W$ and $F814W$ magnitudes of artificial stars are shown.

### 3.2 Field stars

Another potentially important contamination effect is due to the presence of background and foreground field stars that contaminate the binary region of the CMD. To account for this effect, we used the Galaxy model of Robin et al. (2003). A catalog covering an area of 0.5 square degree around each cluster center (from Djorgovski & Meylan 1993) has been retrieved. A sub-sample of stars has been randomly extracted from the entire catalog scaled to the ACS field of view (202” × 202”). The V and I Johnson-Cousin magnitudes were converted into the ACS photometric system by

![Figure 4. Completeness factor c as a function of the F814W magnitude (upper panel) for the target cluster M55. In lower panels the residuals between the input and output F606W and F814W magnitudes of artificial stars are shown.](image-url)
means of the transformations of Sirianni et al. (2005). For each synthetic field star, a star with similar input magnitude ($\Delta I_{814} < 0.1$) has been randomly extracted from the artificial stars catalog. If the artificial star has been recovered in the output catalog the $V_{606}$ and $I_{814}$ magnitude shifts with respect to its input magnitudes have been added. This procedure accounts for the effects of incompleteness, photometric errors and blending.

4 THE MINIMUM BINARY FRACTION

As pointed out in §3 there is a limited range of mass-ratio values ($q > q_{\text{min}}$) where it is possible to clearly distinguish binary systems from single MS stars. The value of $q_{\text{min}}$ depends on the photometric accuracy (i.e. the signal-to-noise $S/N$ ratio) of the data. The approach presented in this section allows to estimate the fraction of binaries with $q > q_{\text{min}}$ that represents a lower limit to the global cluster binary fraction.

In the following we will refer to the binary fraction $\xi$ as the ratio between the number of binary systems whose primary star has a mass comprised in a given mass range ($N_b$) and the number of cluster members in the same mass range ($N_{\text{tot}} = N_{\text{MS}} + N_b$). To derive an accurate estimate of this quantity we adopted the following procedure:

(i) We defined an $I_{814}$ magnitude range that extends from 1 to 4 magnitudes below the cluster turn-off. In that magnitude range the completeness factor is always $\phi > 50\%$;
(ii) We converted the extremes of the adopted magnitude range ($I_{\text{up}}$ and $I_{\text{down}}$) into masses ($M_{\text{up}}$ and $M_{\text{down}}$) using the mass-luminosity relation of Baraffe et al. (1997). To do this, the V and I Johnson-Cousin magnitudes of the Baraffe et al. (1997) models were converted into the ACS photometric system by means of the transformations by Sirianni et al. (2005). For our target clusters we assumed the metallicities listed by Ferraro et al. (1999), the distance moduli and reddening coefficients listed by Harris (1996) and the extinction coefficients $A_{606W} = 2.809\ E(B-V)$ and $A_{814W} = 1.825\ E(B-V)$ (Sirianni et al. 2005). Small shifts in the distance moduli ($\Delta(m-M)_0 < 0.1$) have been applied in order to match the overall MS-TO shape;
(iii) We defined three regions of the CMD (see Fig. 5) as follows:

- A region (A) containing all stars with $I_{\text{down}} < I_{814} < I_{\text{up}}$ and a color difference from the MS mean ridge line smaller then 4 times the photometric error corresponding to their magnitude (dark grey area in Fig. 5). This area contains all the single MS stars in the above magnitude range and binary systems with $q < q_{\text{min}}$;
- We calculated the location in the CMD of a binary system formed by a primary star of mass $M_{\text{up}}$ (and $M_{\text{down}}$ respectively) and different mass-ratios $q$ ranging from 0 to 1. These two tracks connect the MS mean ridge line with the equal mass binary sequence (which is 0.752 mag brighter than the MS ridge line) defining an area ($B_1$) in the CMD. This area contains all the binary systems with $q < 1$ and whose primary component has a mass $M_{\text{down}} < M_1 < M_{\text{up}}$;
- A region ($B_2$) containing all stars with magnitude $I_{\text{down}} - 0.752 < I_{814} < I_{\text{up}} - 0.752$ and whose color difference from the equal mass binary sequence is comprised between zero and 4 times the photometric error corresponding to their magnitude. This area is populated by binary systems with $q \approx 1$ that are shifted to the red side of the equal-mass binary sequences because of photometric errors;

(iv) We considered single MS stars all stars contained in a MS sample, binary stars all stars contained in $B_1$ and $B_2$ but not in A (binary sample, grey area in Fig. 5);
(v) Since the selection boxes defined above cover different regions of the CMD with different completeness levels, we assigned to each star lying in the MS sample and in the binary sample a completeness factor $c_i$ according to its magnitude (Bailyn et al. 1992). Then, the corrected number of stars in each sample ($N_{\text{MS}}^{\text{CMD}}$ and $N_{\text{bin}}^{\text{CMD}}$) has been calculated as

$$N = \sum_i \frac{1}{c_i}$$

(vi) We repeated steps (iv) and (v) for the samples of artificial stars and field stars, obtaining the quantities $N_{\text{art}}^{\text{CMD}}$ for the artificial stars sample and $N_{\text{art}}^{\text{CMD}}$ for the field stars sample;
(vii) We calculated the normalization factor $\eta$ for the artificial stars sample by comparing the number of stars in the MS selection box

$$\eta = \frac{N_{\text{art}}^{\text{CMD}}}{N_{\text{MS}}^{\text{CMD}}}$$

(viii) The minimum binary fraction, corrected for field stars and blended sources, turns out to be

$$\xi_{\text{min}} = \frac{N_{\text{bin}}^{\text{CMD}} - N_{\text{field}}^{\text{CMD}}}{N_{\text{MS}}^{\text{CMD}} - N_{\text{art}}^{\text{CMD}} - \eta N_{\text{art}}^{\text{CMD}}}$$

Since the target clusters in our sample are located at different distances, the ACS field of view covers different fractions of the cluster’s extent. The procedure described above has been conducted considering only cluster stars (and artificial stars) located inside one core radius ($r_c$, adopted from Djorgovski 1993).

The obtained minimum binary fractions $\xi_{\text{min}}$ for the clusters in our sample are listed in Table 3. The typical error (calculated by taking into account of the Poisson statistic and the uncertainties in the completeness corrections) is of the order of 1%. As can be noted, the minimum binary fraction $\xi_{\text{min}}$ is larger than 6% in all the clusters of our sample. Therefore, this value seems to represent a lower limit to the binary fraction at least in low-density ($\log \rho_0 < 2.75 M_\odot pc^{-3}$, see Table 1) globular clusters.

5 THE GLOBAL BINARY FRACTION

The procedure described above allowed us to estimate the minimum binary fraction $\xi_{\text{min}}$ without any (arbitrary) as-
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5.1 \(\xi_{BA}: f(q)\) from random associations

In the case of binary stars formed by random associations between stars of different masses the general scheme adopted for an assumed binary fraction \(\xi\) has been the following:

(i) Artificial star \(I_{814}\) magnitudes have been converted into masses by means of the mass-luminosity relation of Baraffe et al. (1997). Then, a number of \(N'(>\xi \times N)\) artificial stars were extracted from a De Marchi et al. (2005) IMF, where \(N\) is the number of stars in the observed catalog. This sample of stars reproduces the MS population of each cluster taking into account also of blended sources;

(ii) The binary population has been simulated as follows:

\[ a) \text{ A number of } N'(>\xi \times N) \text{ pairs of stars were extracted randomly from a De Marchi et al. (2005) IMF; }
\]

\[ b) \text{ The } V_{606} \text{ and } I_{814} \text{ magnitudes of the two components were derived adopting the mass-luminosity relations of Baraffe et al. (1997) and the corresponding fluxes were summed in order to obtain the } V_{606} \text{ and } I_{814} \text{ magnitudes of the unresolved binary system; }
\]

\[ c) \text{ For each binary system, a star with similar input magnitude (}\Delta I_{814} < 0.1\text{) has been randomly extracted from the artificial stars catalog. If the artificial star has been recovered in the output catalog the } V_{606} \text{ and } I_{814} \text{ magnitude shifts with respect to its input magnitudes have been added. This procedure accounts for the effects of incompleteness, photometric errors and blending; }
\]

\[ d) \text{ The final binary population has been simulated by extracting a number of } \xi N \text{ objects from the entire catalog; }
\]

(iii) The field stars catalog (obtained as described in §3.2) was added to the simulated sample;

(iv) The ratio between the number of objects lying in the selection boxes defined in §4 (\(r_{\text{sim}} = \frac{N'(>\xi \times N)}{N_{MS}}\)) has been calculated and compared to that measured in the observed CMD (\(r_{\text{CMD}} = \frac{N'_{\text{CMD}}}{N_{MS}}\));

(v) Steps from (i) to (iv) have been repeated 100 times.
and a penalty function has been calculated as

\[ \chi^2 = \sum_{i=1}^{100} (r_{\text{sim},i} - r_{\text{CMD}})^2 \]

The whole procedure has been repeated for a wide grid of binary fractions \( \xi \) and a probability distribution as a function of \( \xi \) has been produced. The value of \( \xi \) which minimizes the penalty function \( \chi^2 \) has been adopted as the most probable. The error on the estimated binary fraction has been estimated by estimating the interval where the \( \chi^2 \) account for the 68.2% probability (\( \sim 1\sigma \)) to recover the measured quantity.

A typical iteration of the procedure described above is showed in Fig. 6 where a simulated CMD of M55 is compared with the observed one. In Fig. 6, the distribution of \( \chi^2 \) and the related probability as a function of the assumed value of \( \xi \) is shown.

The global binary fractions \( \xi_{\text{RA}} \) for the target clusters are listed in Table 3. As can be noted, most of the analysed clusters harbour a binary fractions 10% \( < \xi < 20\% \) with the exceptions of four cluster (NGC6981, Arp 2, Terzan 7 and Palomar 12) which show a significantly larger binary fraction. The error on the estimated binary fraction has been estimated by estimating the interval where the \( \chi^2 \) account for the 68.2% probability (\( \sim 1\sigma \)) to recover the measured quantity.

The adopted procedure to derive the binary fraction

\[ \xi_F \] is the same described above but for the simulated binary population (point (ii)a). In this case in fact, a number of \( N' (> \xi N) \) mass-ratios were extracted from the distribution \( f(q) \) shown in Fig. 6 (lower panel). Then, for each of the \( N' \) binary systems the mass of the primary component has been extracted from a De Marchi et al. (2005) IMF and the mass of the secondary component has been calculated. All the other steps of the procedure remain unchanged.

The calculated binary fractions \( \xi_F \) are listed in Table 3. As expected, the values of \( \xi_F \) estimated following the assumption of a Fisher et al. (2005) \( f(q) \) are comprised between the minimum binary fraction \( \xi_{\text{min}} \) and the binary fraction estimated by random associations \( \xi_{\text{RA}} \). Note that neither the ranking nor the relative proportions of the binary fractions estimated among the different clusters of the sample appear to depend on the assumption of the shape of \( f(q) \).

For some clusters of our sample the binary fraction were already estimated in previous works. Bellazzini et al. (2002) and Bolte (1992) estimated a binary fraction comprised in the range 10% \( < \xi < 20\% \) for NGC288 by adopting a technique similar to the one adopted here. These estimates are in good agreement with the result obtained in the present analysis (\( \xi \sim 12\% \)). Yan & Cohen (1996) measured a binary fraction of 21% \( < \xi < 29\% \) in NGC5053 on the basis of a radial velocity survey. Our estimate suggests a slightly smaller binary fraction in this cluster (\( \xi \sim 11\% \)). Note that the estimate by Yan & Cohen (1996) is based on the detection of 6 binary systems in a survey of 66 cluster members in a limited range of periods and mass-ratios. The uncertainty of this approach due to the small statistic is \( \sim 10\% \) and can account for the difference between their estimate and the one obtained in the present analysis.
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Figure 7. Simulated (lower left panel) and observed (lower right panel) CMD of M55. In the upper panels the individual CMDs of the simulated single stars (upper left panel), binaries (upper central panel) and field stars (upper right panel) are shown.

Table 3. Binary fractions estimated for the target globular clusters

| Name      | $\xi_{min}$ | $\xi_F$ | $\xi_{RA}$ | $\sigma_\xi$ |
|-----------|-------------|---------|------------|--------------|
| NGC 288   | 6           | 11.6    | 14.5       | 1.0          |
| NGC 4590  | 9           | 14.2    | 18.6       | 2.5          |
| NGC 5053  | 8           | 11.0    | 12.5       | 0.9          |
| NGC 5466  | 8           | 9.5     | 11.7       | 0.7          |
| NGC 5897  | 7           | 13.2    | 17.1       | 0.8          |
| NGC 6101  | 9           | 15.6    | 21.0       | 1.3          |
| NGC 6302  | 6           | 11.8    | 12.7       | 0.8          |
| NGC 6723  | 6           | 16.1    | 21.8       | 2.0          |
| NGC 6981  | 10          | 28.1    | 39.9       | 1.6          |
| M55       | 6           | 9.6     | 10.8       | 0.6          |
| Arp 2     | 8           | 32.9    | 52.1       | 3.6          |
| Terzan 7  | 21          | 50.9    | 64.9       | 2.9          |
| Palomar 12| 18          | 40.8    | 50.6       | 6.6          |

In the following section we compare the obtained binary fractions among the clusters of our sample as a function of their physical parameters.

5.3 Cluster to cluster comparison

Our sample contains thirteen low-density Galactic globular clusters spanning a large range of metallicity, age and structural parameters (see Table 1). We used the results obtained in the previous section to compare the core binary fraction $\xi$ among the clusters of our sample as a function of their main general and structural parameters in order to study the efficiency of the different processes of formation and destruction of binary systems.

We correlated the core binary fraction derived according to the different assumptions described in the previous sections ($\xi_{min}$, $\xi_F$ and $\xi_{RA}$) with the cluster’s ages ($t_9$, from Salaris & Weiss 2002), global metallicity ([M/H], from Ferraro et al. 1999) central density ($\rho_0$) and half-mass relaxation time ($t_{r,r_h}$, from Djorgovski 1993), destruction rate ($\nu$, from Gnedin & Ostriker 1997) and different structural parameters (mass $M$, concentration $c$, binding energy $E_b$, half-mass radius $r_F$, mass-luminosity ratio $M/L$, velocity dispersion $\sigma_v$ and escape velocity $v_e$) adopted from McLaughlin & Van der Marel (2005). Of course, most of the quantities listed above are correlated.

The ages of two clusters, namely Arp2 and NGC6981, need a comment. According to Salaris & Weiss (2002), the age of Arp 2 is comparable to those of the oldest Galactic globular clusters ($t_9 \sim 11.3$). The same conclusion has been reached by Layden & Sarajedini (2000). Conversely, Buo-
nanno et al. (1995) and Richer et al. (1996) classified it as a young globular cluster with an age comparable within 1 Gyr to those of Terzan 7 and Palomar 12. Given the debated question on the age of this cluster we excluded it from the following analysis. The globular cluster NGC6981 is not included in the list of Salaris & Weiss (2002). An estimate of the age of this globular cluster has been presented by De Angeli et al. (2005). We converted the ages measured by De Angeli et al. (2005) into the Salaris & Weiss (2002) scale. Hence we adopted for this cluster an age of 9.5 Gyr.

In order to estimate the degree of dependence of $\xi$ on the different clusters parameters we applied the Bayesian Information Criterion test (Schwarz 1978) to our dataset. We assumed the binary fraction $\xi$ as a linear combination of a subsample of $p$ parameters ($\lambda_i$) selected among those listed above.

$$\xi_f = \alpha_{p+1} + \sum_{i=1}^{p} \alpha_i \lambda_i$$

Given a value of $p$, for any choice of the $p$ parameters we best-fit our dataset with the above relation and calculated the quantity

$$BIC = \ell_p - \frac{p}{2} \log N$$

where $\ell_p$ is the logarithmic likelihood calculated as

$$\ell_p = \log L_p = \sum_{j=1}^{N} \log P_{R_j,p}$$

$$= \sum_{j=1}^{N} \log \left( \frac{(f_j - \xi_f)^2}{\sigma^2 \xi} \right)$$

Where $N$ is the dimension of our sample (N=13) and $\sigma_\xi$ is the residual of the fit. The $p$ parameters that maximize the quantity BIC are the most probable correlators with $\xi$. The above analysis gives the maximum value of BIC for $p=1$ and $\lambda_p = t_0$. All the higher-order correlations appears as non-significant.

The same result has been obtained considering all the three estimates of $\xi$. A Spearman-rank correlation test gives probabilities > 99% that the variables $\xi$ and $t_0$ are correlated, for all the considered estimates of $\xi$.

In Fig. 9 the core binary fractions $\xi_{min}$, $\xi_F$ and $\xi_{RA}$ are plotted as a function of the clusters age. All the clusters of our sample that present a large core binary fraction ($\xi_F > 25\%$) are systematically younger than the other clusters.

Gaven the large systematic uncertainties involved in the estimate of the global binary fraction the above result can be considered only in a qualitative sense. However, the above analysis indicates that the age seems to be the dominant parameter that determines the binary fraction in globular clusters belonging to this structural class.

## 6 BINARIES RADIAL DISTRIBUTION

Being bound systems, binary stars dynamically behave like a single star with a mass equal to the sum of the masses of the two components. After a time-scale comparable to the cluster relaxation time, binary systems have smaller mean velocities than single less massive stars, populating preferentially the most internal regions of the cluster. Since all the globular clusters in our sample have a central relaxation time shorter than their age, binary stars are expected to be more centrally concentrated with respect to the other cluster stars. In order to test this hypothesis we calculated for each target cluster the binary fraction $\xi$ (following the procedure described in §4 in three annuli of 500 pixels width located at three different distances from the cluster center. We noted that in seven (out of thirteen) globular clusters of our sample (namely NGC4590, NGC6101, NGC6362, NGC6723, NGC6981, Terzan 7 and Palomar 12) there is evidence of radial segregation of binary systems toward the cluster center. In Fig. 10 the binary fractions (in unit of core fraction $\xi$) measured at different distances from the cluster’s centers in these seven clusters are shown. The binary fraction decreases by a factor 2 at two core radii with respect to the core binary fraction. A Kolmogorov-Smirnov test made on the $MS$ sample and binary sample (as defined in §4) yields for these clusters probabilities smaller than 0.05% that the two samples are drawn from the same distribution. Note that in most clusters the radial segregation of binary systems is visible also within the core radius, indicating that mass segregation is a very efficient process in these clusters. In the other six clusters the small number of stars and/or the small radial coverage do not allow to detect a significant difference in the radial distribution of binary stars.
7 DISCUSSION

In this paper we analysed the binary population of thirteen low density Galactic globular clusters with the aim of studying their frequency and distribution.

In all the analysed globular clusters the minimum binary fraction contained within one core radius is greater than 6%. This quantity seems to represent a lower limit to the binary fraction in globular clusters of this structural class. This lower limit poses a firm constraint to the efficiency of the mechanism of binaries disruption. The existing estimates of the binary fraction in low-density globular clusters (Yan & Mateo 1994; Yan & Reid 1996; Yan & Cohen 1996) agree with this lower limit. On the other hand, in high-density clusters the present day binary fraction appears to be smaller (< 4 – 9% see Cool & Bolton 2002 and Romani & Weinberg 1991 for the case of NGC6397, M92 respectively) as expected because of the increasing efficiency of the disruption through close encounters and of stellar evolution (Ivanova et al. 2005). According to the theoretical simulations of Ivanova et al. (2005) the present day binary fraction in a stellar system with a small central density ($10^3 M_\odot pc^{-3}$) should be < 30% of its initial fraction. Following these considerations the initial binary fraction in our target globular clusters could be > 20 – 60%, comparable to that observed in the solar neighborhood (Abt & Levy 1976; Duquennoy & Mayor 1991; Reid & Gizis 1997).

The comparison between the estimated relative binary fractions among the clusters of our sample suggests that the age is the dominant parameter that determines the fraction of surviving binary systems. This result can be interpreted as an indication that the disruption of soft binary systems through close encounters with other single and/or binary stars is still efficient in low density globular clusters also in the last 5 Gyr of evolution. Unfortunately, there are no estimates of the binary fraction in globular clusters younger than 6 Gyr to test the efficiency of the process of binary disruption in the early stages of evolution. Note however that estimates of the binary fraction in open clusters (with ages < 3 Gyr) gives values as high as 30-50% (Bica & Bonatto 2005).

The comparison between the radial distribution of binary systems with respect to MS stars indicates that binary systems are more concentrated toward the central region of most of the clusters of our sample. This evidence, already found in other past works (Yan & Reid 1996; Rubenstein & Baylin 1997; Albrow et al. 2001; Bellazzini et al. 2002; Zhao & Baylin 2005) is the result of the kinetic energy equipartition that lead binary systems to settle in the deepest region of the cluster potential well.

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