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MULTIPLE STELLAR  
POPULATIONS IN GLOBULAR  
CLUSTERS

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Antonino





# Riassunto

Le recenti osservazioni condotte da HST negli ultimi anni hanno portato a uno dei piu' eccitanti e sorprendenti sviluppi negli studi sulle popolazioni stellari: la scoperta di generazioni multiple di stelle in molti ammassi globulari.

La prima di queste scoperte fu la sequenza principale di Omega Centauri che si divide in due distinti rami al livello di varie magnitudini. Poiche', inaspettatamente e' stato trovato che il ramo blu ha metallicita' maggiore (Piotto et al. 2005), le sole isocrone in grado di riprodurre questa combinazione di colore e metallicita', sono arricchite in elio ( $Y \sim 0.38$ ) rispetto alla popolazione dominante che si suppone avere elio primordiale.

Durante la mia tesi di dottorato, ho contribuito a una serie di queste scoperte, principalmente basate su dati HST di incomparabile precisione fotometrica, che hanno mostrato che Omega Centauri non e' cosi' peculiare tra gli ammassi globulari. Sono stati trovati molti altri ammassi globulari che mostrano evidenze, nel loro diagramma colore magnitudine, della presenza di diverse popolazioni di stelle. Il primo di questa serie di globulari e' stato NGC 2808 che manifesta la presenza di diverse popolazioni stellari con una separazione della sequenza principale in tre sequenze ben definite, anche se il ramo delle sub giganti e' molto stretto, e non ci sono evidenze per una dispersione nell'abbondanza degli elementi pesanti. Evidenze di popolazioni multiple sono state trovate anche in NGC 1851 (Milone et al. 2008), questa volta nella forma di una separazione nella regione del ramo delle sub giganti. Inoltre, la presenza di un gruppo di giganti rosse sovrabbondanti in Sr e Ba e caratterizzate da bande del CN forti, e la presenza di un ramo orizzontale bimodale, sono in accordo con l'ipotesi di due generazioni stellari come indicato dalla bimodalita' del ramo delle sub-giganti.

Inoltre altri ammassi molto massivi mostrano una separazione sul ramo delle sub-giganti: NGC 6388, NGC 6715 (M54), NGC 6656 (M22), NGC 5286, NGC 7089 e NGC 362. In particolare, questi ammassi mostrano differenze nel

diagramma colore magnitudine e nelle loro proprietà chimiche. Particolarmente interessante il caso di M22 in cui sono stati trovati due gruppi di stelle, lungo il ramo delle giganti rosse, caratterizzati da un differente contenuto di elementi  $s$  con una piccola differenza in ferro (Marino et al. in preparazione), e nella stessa percentuale dei due gruppi osservati sul ramo delle sub giganti.

L'elevata precisione della fotometria ACS ha inoltre rivelato che il fenomeno delle popolazioni multiple non è confinato solo agli ammassi globulari della nostra Galassia. Mackey & Broby Nielsen (2007) suggeriscono la presenza di due popolazioni nell'ammasso NGC 1846 nella Grande Nube di Magellano. Inoltre, dallo studio di un elevato numero di ammassi ad et intermedia nella Grande Nube, abbiamo trovato che il  $\sim 70\%$  del campione analizzato ospita popolazioni multiple.

Tutte queste scoperte stanno affermando l'affascinante idea per cui la presenza di diverse popolazioni stellari sia una caratteristica comune tra gli ammassi globulari, abbattendo il paradigma per cui questi oggetti ospiterebbero un'unica popolazione di stelle. In questa Tesi discuter le nostre scoperte osservative, nel contesto delle popolazioni multiple in ammassi globulari, trovate durante il mio dottorato e le loro implicazioni sui modelli teorici di formazione e l'evoluzione di questi oggetti.

# Abstract

Over the last few years HST observations have resulted in one of the most exciting and unexpected developments in stellar population studies: the photometric discovery of multiple generations of stars in several globular clusters (GC).

It began with the discovery that the main sequence (MS) of Omega Centauri splits for several magnitudes into two distinct branches (Anderson 1997, Bedin et al. 2004) . Since, surprisingly the blue branch was found to have higher metallicity (Piotto et al. 2005), the only isochrones that are able to fit this combination of color and metallicity are highly enriched in helium ( $Y \sim 0.38$ ), relative to the dominant population that is presumed to have near primordial helium.

During my PhD, I contributed to a series of discoveries, mainly based on HST data of unparalleled photometric accuracy, that demonstrated that Omega Centauri is far to be unique among globular clusters. Many other GCs were found to have features in their colour-magnitude diagram indicating the presence of multiple stellar populations. The first of this series of globulars was NGC 2808 that manifests the presence of different populations of stars with a split of the MS into three well defined sequences, even though its sub-giant branch (SGB) is very narrow, with no dispersion in the abundance of iron-peak elements (Chapter 2, Piotto et al. 2007). Evidence of multiple populations has been found also in NGC 1851 (Milone et al. 2008), this time in the form of a split in the SGB region. Moreover, the presence of a group of RGB stars with enhanced Sr and Ba and strong CN bands (Yong & Grundahl 2008),

and the presence of a bimodal horizontal branch, agrees with the hypothesis of two stellar generations inferred by the observed SGB split.

In addition, several other massive globulars have splitted SGB: NGC 6388, NGC 6715 (M54), NGC 6656 (M22), NGC 5286, NGC 7089 and NGC 362. Notably, each of these clusters has a different color magnitude diagram and

chemical properties. Interestingly enough, in M22, two groups of stars, characterized by different  $s$ -element and slightly different iron content (Marino et al. in preparation), were found along the RGB, in the same percentage of the two groups observed on the SGB.

The high accuracy ACS photometry has also revealed that the multiple stellar population phenomenon is not confined only to Galactic GCs. Mackey & Broby Nielsen (2007) suggest the presence of two populations in Large Magellanic Cloud (LMC) globular NGC 1846. Moreover, by studying a large number of intermediate-age clusters in the LMC, we found that  $\sim 70\%$  of the entire analyzed sample hosts multiple stellar populations.

All these findings are introducing the intriguing idea that the multiple stellar populations are a common feature among GCs, challenging the paradigm of globulars hosting a unique population of stars. In this Thesis I will discuss our observational findings in the context of multiple populations in GCs found during my PhD and their implications in the theoretical models on the formation and evolution of these objects.

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# **I. MULTIPLE STELLAR POPULATION IN GLOBULAR CLUSTERS**



# 1

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## Introduction

### 1.1 The scientific framework

GCs have always represented an ideal laboratory for testing and calibrating stellar evolutionary models. Since they are regarded as consisting of coeval and chemically homogeneous stars, they have been considered as the prototype of Simple Stellar Populations (SSP). In consequence, GCs have been employed as an ideal template for checking the accuracy and reliability of the population synthesis tools that are used to retrieve the properties of unresolved stellar populations. As the oldest population II objects for which accurate ages can be inferred, they place an important constraint on the age of the Universe and, in turn, on cosmology. In addition, the analysis of the chronology of the Galactic GC system can provide fundamental information on the formation process of the Galaxy.

For half a century, the SSP model for GCs constituted an astronomical doctrine. This idea of GCs consisting of stars born at the same time out of the same material, bore reach results. Indeed, the deepest GC HST observations so far have revealed astonishingly narrow sequences in the colour-magnitude diagram (CMD) of NGC 6397 (Richer et al. 2007).

However, in the last decades, several empirical findings were collected that are demolishing this traditional picture.

First of all, many GCs exhibit a very peculiar HB that cannot be reproduced by any combination of metallicity and age in standard stellar-structure calculations. In some cases, there is an extended blue tail (Recio-Blanco et al. 2006), and /or a clumpy distribution of stars with one or more gaps (Ferraro et al. 1998, Piotto et al. 1999). These anomalies are known as 'second parameter' problem and have not yet fully understood.

In addition, it is well known, since the 1980s that GCs show abundance variations for several light elements. While part of them (Li, C, N) show the same behavior in field stars, some others (O, Na, Mg, Al) follow a pattern typical of GCs. In particular all GCs studied so far show anticorrelations between O and Na, Al and Mg which are present not only in evolved RGB stars but also in unevolved MS stars (Gratton et al. 2001, Ramirez & Cohen 2002, Carretta et al. 2004). Since MS stars are unable to activate the required nucleosynthetic chains, the observed anticorrelations should be imprinted in the gas by a previous generation, therefore we are observing a second stellar population in these GCs (see Carretta et al. 2008 and references within).

Despite these observations, up until a few years, the view of GCs as SSP was supported by the interpretation of the available CMDs in the framework of theoretical stellar evolution (see, for instance, King et al., 1998). In the last years, however, a series of photometric observations of multiple stellar populations, has shattered this paradigm, and the study of the GC populations has acquired a new life that is now moving it in new directions. A lot of such discoveries has been obtained by our group during my PhD and are widely discussed in this thesis. The following section is a summary of the observational scenario.

## 1.2 Observational evidence for Multiple Populations in GCs

The Milky Way GCs in which multiple populations have been identified, are: Omega Centauri (Anderson 1997, Lee et al. 1999, Bedin et al. 2004), NGC 2808 (D’Antona et al. 2005, Piotto et al. 2007), NGC 1851 (Milone et al. 2008b), NGC 6121 (M4, Marino et al. 2008). In this thesis we present direct evidence for multiple stellar population in other six globulars: NGC 6715 (M54), NGC 5286, NGC 6656 (M22), NGC 6388, NGC 306 and NGC 7089 (M2).

Multiple stellar population have been identified also in intermediate-age clusters in the Large and Small Magellanic clouds (Mackey & Broby Nielsen 2007, Mackey et al. 2008, Milone et al. 2008c, Goudfrooij et al. 2008). Particularly, we found that 11 globulars on a sample of 16 studied in the LMC, possess MS Turn Off (MSTOs) which are not consistent with being SSP (Milone et al. 2008c).

All these results suggest that, contrary to expectation, multiple stellar population may be a common feature among intermediate-age LMC clusters and, possibly, Milky Way globulars.

### **Omega Centauri**

Omega Centauri is the most massive GC in the Milky Way ( $\log(M)=6.6$ )

and the most peculiar in terms of structure, kinematic and stellar content. Much observational and theoretical effort has been dedicated to this cluster, since the discovery that it spans a wide range of metallicities (Cannon & Stobie 1973; Freeman & Roger 1975). Over the last years it has been source of great interest, starting with the identification of several distinct branches in the RGB (Lee et al. 1999, Pancino et al. 2000). Then come the evidence that, below the turn-off, the main sequence of this cluster splits for several magnitudes into two parallel branches (Anderson et al. 1997, Bedin et al. 2004). Accurate observational analysis has shown that significant differences do exist among the spatial distribution of the red and the blue MS stars being the blue population more centrally concentrated with respect to the red one (Sollima et al. 2008, Bellini et al. in preparation). However, the most intriguing discovery on the multiple population in Omega Centauri comes from the spectroscopic analysis by Piotto et al. (2005). They have carefully combined VLT's GIRAFFE spectra of seventeen stars on each sequence into a single spectrum, with adequate signal-to-noise ratio, to show clearly that, instead of a higher metal abundance, the stars of the blue main sequence are less metal-poor by 0.3 dex than those of the dominant red one. The only isochrones that are able to appropriately fit the metal rich blue sequence are extremely helium rich ( $Y \sim 0.38$ ) respect to the dominant metal poor component, which, possibly, has primordial helium.

The scenario in Omega Centauri is even more complex. Bedin et al. (2004) identified three MSs which spread into at least four SGB (Sollima et al. 2005). The most complete analysis to date on this cluster comes from Villanova et al. (2007). On the bases on HST photometry of the central field and of VLT high-resolution spectroscopic of eighty SGB stars, they identified at least four distinct SGB sequences that correspond to four stellar populations with distinct age and metallicity.

- An old metal poor population ( $[\text{Fe}/\text{H}] \sim -1.7$ ), coeval to the oldest GCs of the Milky Way. This group primarily populates the SGB group C and contains about one third of the metal poor population of the cluster.
- A second metal poor group including the remaining two thirds of the metal-poor SGB population. It is about 3-4 Gyr younger than the previous group. Because of their metallicity, these two groups may be connected to the red MS.
- A young intermediate-metallicity group ( $[\text{Fe}/\text{H}] \sim -1.4$ ) coeval with the young metal-poor component. This group seems to populate the SGB Group B and may be connected with the blue MS. In this case it should

be also He-enriched and contains about one-third of the SGB stars in the central region

- An old metal-rich group ( $[\text{Fe}/\text{H}] \sim -1.1$ ) coeval with the old metal-poor group. It populates the SGB Group D and is connected to the RGB-a segment of Pancino et al. (2000), and to the MS-a component (Villanova et al. 2007). It contains about the 10 % of stars in the central region of the cluster.

A careful correction of the HST CMD analysed by Villanova et al. (2005) allowed us to identify a fifth SGB branch that is clearly visible in Fig. 1.1. Unfortunately, no spectroscopic informations are available for their stars. Fig. 1.2 is a zoom of the previous CMD around the MSs region. The complex system of multiple populations of Omega Centauri reinforces the idea that this anomalous object might not even be a GC, but the remnant of a tidally disrupted dwarf galaxy.

### NGC 2808

This massive GC possesses a well-populated bimodal HB with a red clump, almost no RR Lyrae, and an extended blue HB. There is a huge literature which has defined and attempt to correctly interpretate the three gaps discovered by Sosin et al. (1997) and Bedin et al. (2000) along the HB of this cluster. The first of these gaps is located at the colour of the RR Lyrae instability strip while the other two are on the blue extension of the HB and delimit three distinct segments. According to Bedin et al. (2000) they are: the EBT1 placed on the blue of the instability strip, the EBT2 which contains the extreme HB (D'Cruz et al. 2000), and the EBT3 which hosts the still misterious 'blue hook' stars (Moehler et al. 2004). These gaps on the blue side of the HB can be interpreted with discontinuities in the helium content (Lee et al. 2005, D'Antona et al. 2005).

Carretta et al. (2006) analysed spectra of 122 RGB stars and found an extended Na-O anticorrelation in NGC 2808. They found that most of the stars are O-normal, ( $[\text{O}/\text{Fe}] \sim 0.28$ ), but there are two additional groups, which they named O-poor ( $[\text{O}/\text{Fe}] \sim -0.21$ ) and super O-poor ( $[\text{O}/\text{Fe}] \sim -0.73$ ). They found a marginal increase of  $\Delta[\text{Fe}/\text{H}] = 0.034 \pm 0.016$  dex between O-normal and super O-poor. Since helium enrichment makes the metal lines stronger (Bohm-Vitense 1979), they interpreted this as an evidence of an increased He.

However, the most amazing results comes from the analysis of deep HST images. It began with the discovery of D'Antona et al. (2005) that the MS of NGC 2808 has an anomalous blueward extension that contain about the 20 % of the stars. By means of high accuracy photometry with HST's ACS, we have demonstrated not only that this feature is real but that, surprisingly, the MS of

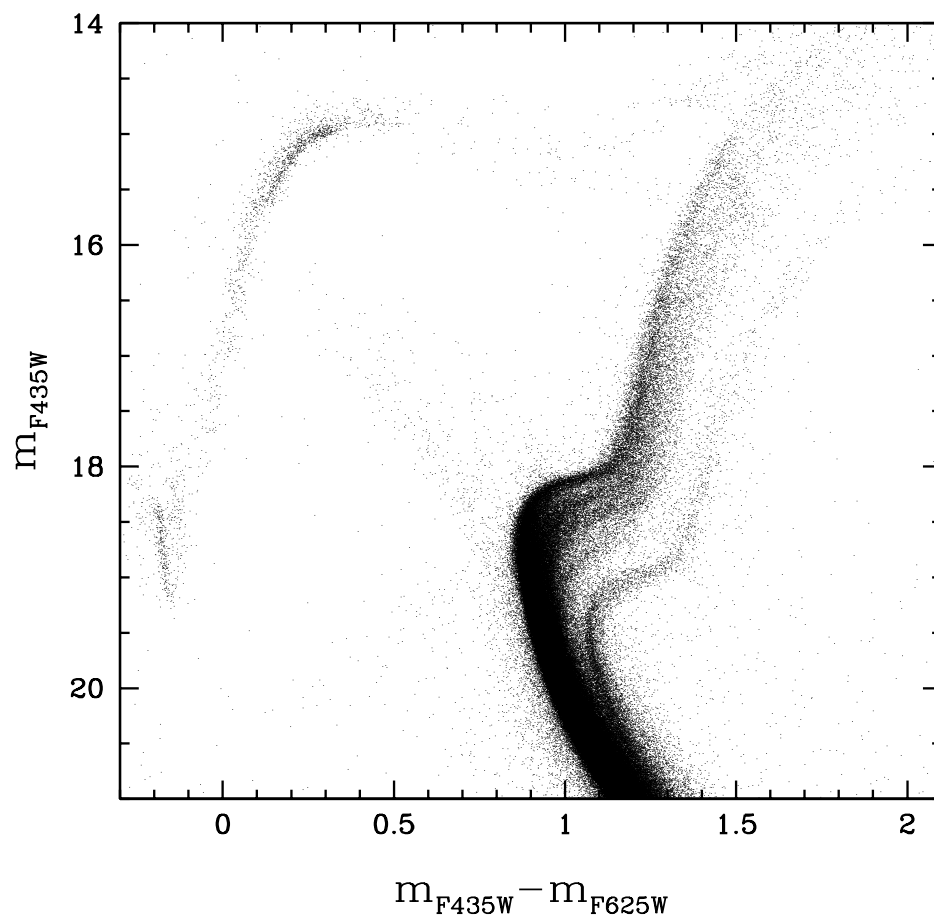


FIGURE 1.1— CMD of Omega Centauri from ACS/HST data corrected for differential reddening.

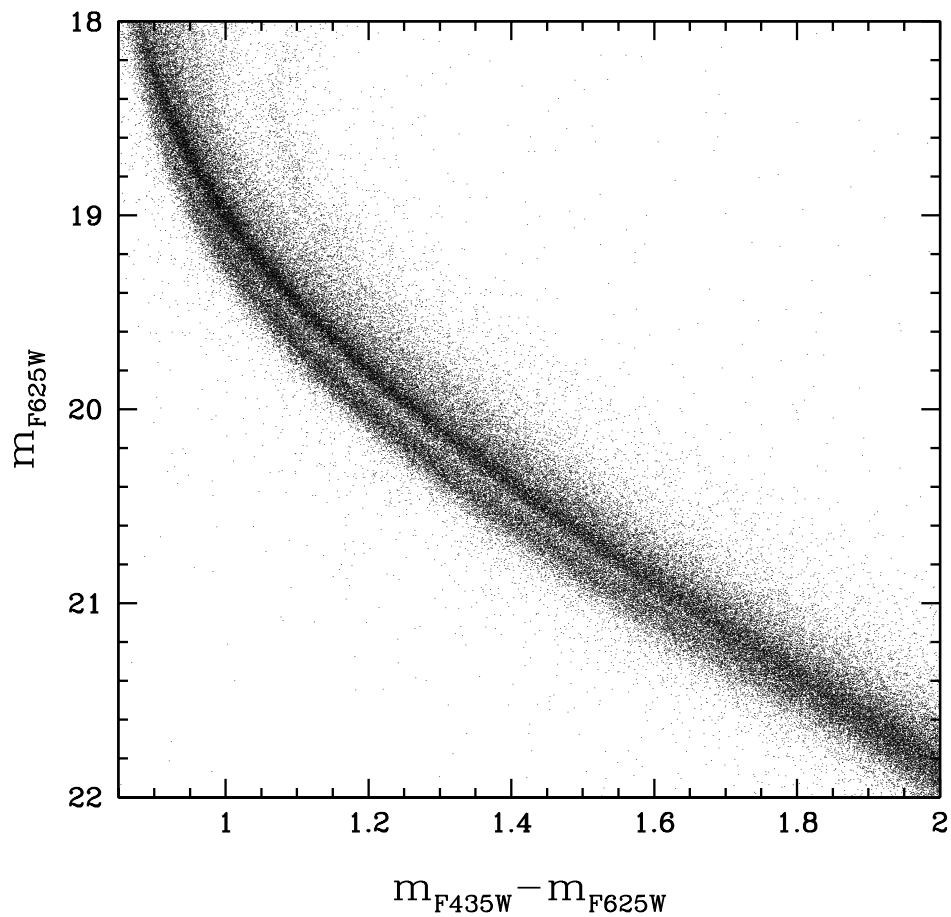


FIGURE 1.2— Zoom of the CMD of Fig. 1.1 around the three MSs of Omega Centauri. The bMS is clearly separated from the rMS in a range of  $\sim 2.5$  magnitudes in the F625W band and merges with the rMS around  $m_{F625W} = 21.5$ .



NGC 2808 is formed by three discrete branches as shown in Fig. 1.3 (Piotto et al. 2007). Our observations suggest the presence of three stellar groups with  $\sim 63\%$  of the stars having primordial helium abundance ( $Y=0.25$ ),  $\sim 15\%$  having helium enhanced to  $Y \sim 0.30$  and about  $13\%$  being up to  $Y \sim 0.38$ .

These groups may be associated to the three groups with different oxygen abundance identified by Carretta et al. (2006). Our results are also consistent with the HB morphology as discussed by D’Antona & Caloi (2004). Finally, we noted that the narrowness of the TO region suggests that the three stellar populations of NGC 2808 must have a small age dispersion, much less than 1 Gyr.

### NGC 1851

Accurate Hubble Space Telescope (HST) photometry allowed us to discover that NGC 1851 hosts two distinct sub-populations (Milone et al. 2008, chapter 4) as indicated by the clear splitting in the sub giant branch (SGB) region in its colour magnitude diagram (CMD) shown in Fig. 1.4. This discovery has brought new interest on this cluster accompanied by numerous efforts aimed to better understand how this cluster formed and evolved.

We noted that, if the double SGB is only due to an age difference, the two star formation episodes should have occurred with a time delay of about one Gyr (Milone et al. 2008). As an alternative scenario, Cassisi et al. (2008) showed that two stellar populations, one with a normal  $\alpha$ -enhanced heavy element distribution, and one characterised by a strong CNONa anticorrelation pattern, could respectively account for the observed bright and faint SGB (hereafter bSGB and fSGB), without requiring any significant age difference.

Interestingly, this working scenario seems to be supported by spectroscopic measurements (Hesser et al. 1982) indicating the presence of two groups of CN-strong and CN-weak stars and by the work of Calamida et al. (2007) who showed that, in the Strömgren ( $m_1, u-y$ ) CMD, the red giant branch (RGB) of NGC 1851 splits into two sequences possibly related to two populations with different CN abundance. A more recent spectroscopic investigation comes from Yong & Grundahl (2008) who determined the chemical composition for eight bright giants in NGC 1851. Their analysis revealed large star-to-star abundance variations of the elements Zr and La. These  $s$ -process elements are correlated with Al and anticorrelated with O. Furthermore, the Zr and La abundances appear to cluster around two distinct values. Unfortunately, their sample is too small to determine with some significance whether the measured O abundances are bimodal or not.

NGC 1851 is considered a sort of prototype of bimodal HB clusters. Milone et al. (2008) noted that the fraction of fainter/brighter SGB stars is remarkably similar to the fraction of bluer/redder HB stars. Therefore it is tempting to

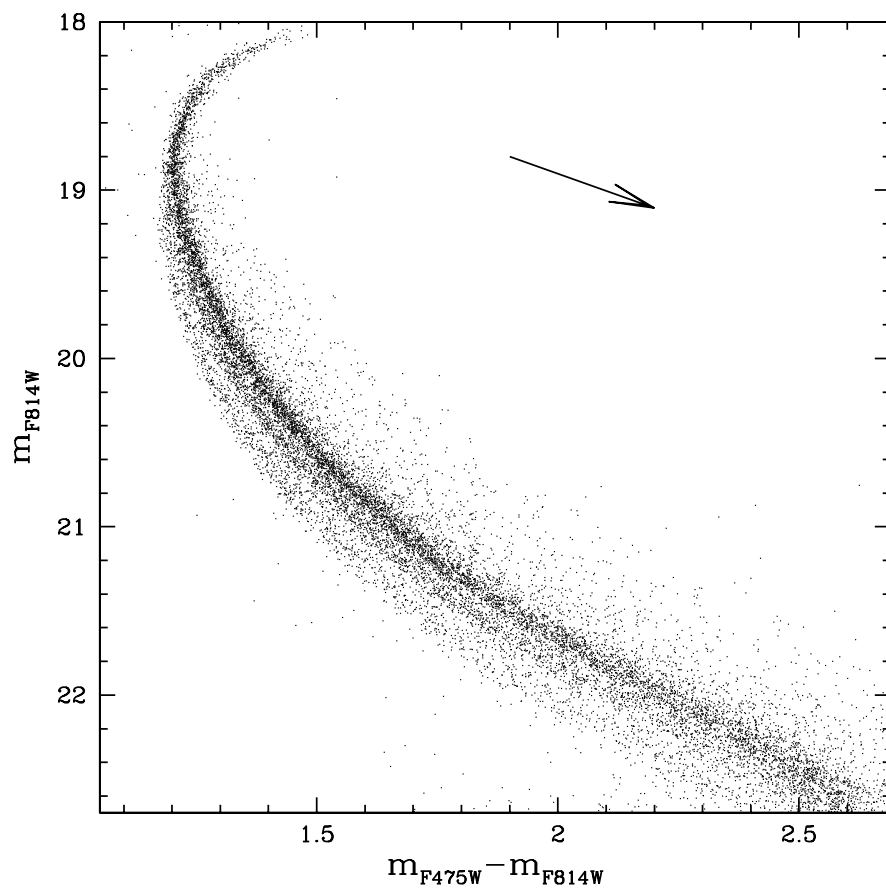


FIGURE 1.3— CMD of NGC 2808 corrected for differential reddening.

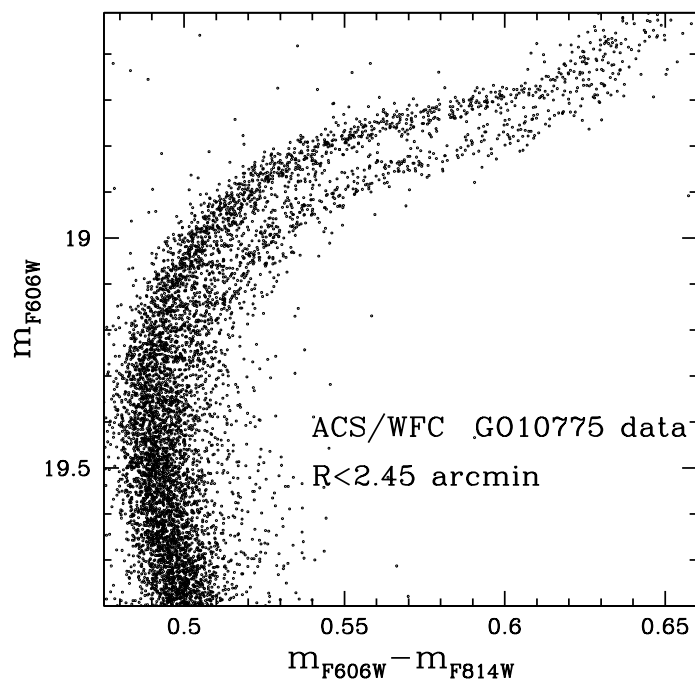


FIGURE 1.4— The double SGB of NGC 1851

associate the brighter SGB stars to the CN normal, *s*-process element normal stars and to the red HB, while the fainter SGB should be populated by CN-strong, *s*-process element enhanced stars which should evolve into the blue HB. This scenario requires that fSGB stars are the younger population and comes from processed material.

In Milone et al. (2008) we studied a CMD containing stars with radial distances smaller than  $\sim 2.4$  arcmin. In chapter 3 (Milone et al. 2009), we extend the photometric analysis up to the outermost region of the cluster. Our radial extension analysis covers the whole cluster from the center up to the tidal radius ( $r_{\text{tidal}}=11.70$  arcmin, Harris 1996, 2003). To this aim we combined data from three different instruments: the Advanced Camera for Survey (ACS) and the Wide Field Planetary Camera 2 (WFPC2) on board on HST and the Wide-Field Imager of the Max-Planck-Institute Telescope (WFI@ESO2.2m). We detected a split SGB at all radial distances and trace the radial distribution of NGC 1851 stars both in the HB and in the SGB. We found that stars in the two SGB branches have the same radial distribution.

### NGC 6656 (M22)

High accuracy WFPC2 and ACS photometry, that we present in chapter 4, show that the SGB of NGC 6656 splits into two separate branches with resemblance to NGC 1851.

The most surprising result however, comes from our spectroscopic analysis for a sample of seventeen RGB stars from UVES spectra (Marino et al. 2009, Chapter 4). We find a strong dichotomy in the distribution of the *s*-process elements barium, yttrium and zirconium. Most importantly, we find that the abundance of these elements is correlated with the iron abundance. Stars enriched in *s*-process elements also show larger values of  $[\text{Fe}/\text{H}]$ , by  $\sim 0.13$  dex. The *s*-process elements abundance correlates with calcium, and calcium with iron. These results prove once and for all that the longly debated (e.g. Ivans et al. 2004) metallicity spread of NGC 6656 is real and make NGC 6656 the only known genuine GC showing a clear bimodal iron content.

Interestingly, the fraction of stars on the bSGB corresponds to  $62\% \pm 5\%$  of the total SGB population, while the fSGB includes the remaining  $38\% \pm 5\%$  of the SGB stars (Chapter 4). In the stellar sample of the present work, the fraction of Ba-strong, Y-strong, Zr-strong stars is  $\sim 41\%$ . It is therefore tempting to connect the *s*-process element poor sample to the bright SGB stars, while the faint SGB stars could be the ones with enhanced *s*-process elements. The correct reproduction of the two SGBs needs an accurate determination of the NaCNO abundances, as shown by Cassisi et al. (2008) for the analogous case of NGC 1851. Also an He variations between the two populations can affect the SGB morphology.

**NGC 6388**

Located in the Galactic Bulge, NGC 6388 is a metal-rich GC with  $[\text{Fe}/\text{H}]=-0.60$  (Harris 1996, 2003). A great interest has been dedicated to this cluster, since the discovery that its HB exhibits a blue tail (Rich et al. 1997). The fact that it shows not only the typical red HB but also an extended blue extension, demonstrates that the second parameter is also at work in old, metal rich stellar systems. Together with the twiny cluster NGC 6441, is the only GC containing a number of RR Lirae with an average period as long as 0.75 days, making it a third Oosterhoff type (Pritzl et al. 2000).

Based on an ultraviolet WFPC2/HST CMD, Busso et al. (2007) emphasized the similitude between its blue HB and those of  $\omega$  Centauri and NGC 2808. They suggested that the HB of NGC 6388 can be interpreted by assuming that about the 10-20 % of the stellar population of NGC 6388 is strongly helium enriched ( $Y \geq 0.40$ ). This cluster has been also studied by Caloi & D'Antona (2007) who showed that three stellar population are necessary to reproduce the HB: a first He-normal population contains the 38 % of stars, a second He enriched ( $0.27 \leq Y \leq 0.35$ ) generation with the 48 % of stars and the 14 % of very helium rich stars ( $Y \geq 0.40$ ). They assumed that helium rich stars populate also the red clump, indeed He core burning stars having high  $Y$  and  $Z$  make long loops from the red to the blue in HB (Sweigart & Gross 1976). Their analysis explains not only the anomalous periods of the RR Lyrae but also the extension in magnitude of the red clump and hot blue tail of the HB.

Unfortunately, available data do not allow us to study the MS of this cluster, searching for a MS split as we could expect if the interpretation of the HB is correct. As a further complication, given its low galactic latitude, NGC 6388 is affected by high reddening and, as a consequence, by high differential reddening. The latter tends to randomly broaden the CMD features making hard any search for multiple sequences in its CMD.

However, after a careful correction of the differential reddening from several WFPC2 and ACS/WFC CMDs, we identified a double SGB also in NGC 6388 (chapter 4). Interestingly, the ratio of faint and bright SGB star is similar to the ratio of blue and red HB suggesting that bSGB is related to the red HB while the fSGB stars could be the progenie of the blue HB.

**NGC 6121 (M4)**

With an accurate spectroscopic analysis of more than 100 UVES spectra, we have provided the evidence that NGC 6121 shows the classical Na-O anticorrelation, and hosts two groups of stars with significantly different Na and O (Marino et al. 2008). In addition, we have observed a tight correlation between the Na and CN. The coupling of spectroscopic data with accurate photometry has also shown that the two subpopulations with different Na content populate distinct

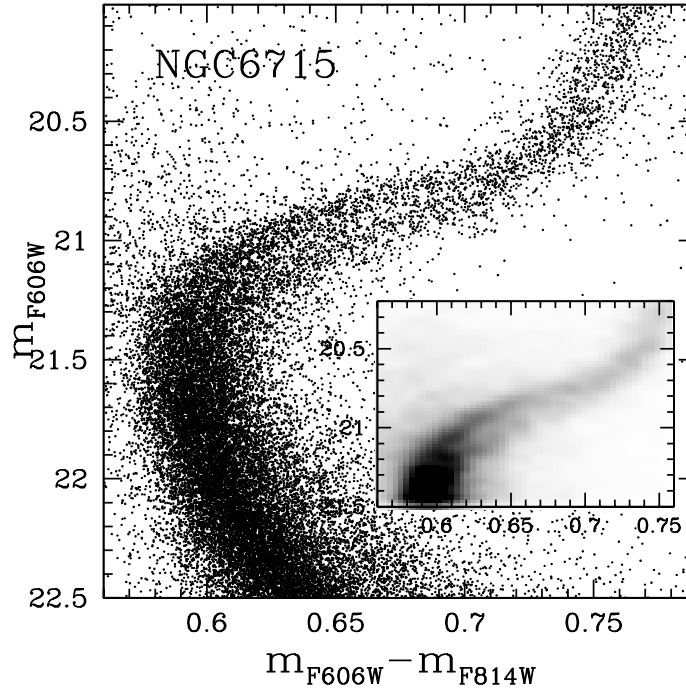


FIGURE 1.5— The double SGB of NGC 6715.

branches along the RGB when the U band is included. This is possibly related to the presence of NH and CN bands. Interestingly, the mass of this cluster is at least an order of magnitude smaller than that of any other cluster hosting multiple stellar population.

#### NGC 6715 (M54)

This massive cluster is superposed on the core of the tidally disrupted Sagittarius dSph galaxy. The observed CMD is extremely complex due to the multiple sequences related to the presence of several stellar populations of the Sagittarius galaxy (see Siegel et al. 2007 and references within). In this work we show that NGC 6715 possess a splitted SGB demonstrating the presence of a double stellar population in the cluster itself (Fig. 1.5).

#### NGC 5286, NGC 7089 (M2), and NGC 362

The discovery of a second, fainter SGB in the CMD of these GCs joins them in the intriguing family of clusters hosting multiple stellar populations. In all the case the fSGB is poorly populated with less than  $\sim 15\%$  of the total number of SGB stars.

It is also worth noting that almost all the Milky Way clusters that host multiple stellar populations are among the most massive cluster in the Galaxy. One may expect that massive clusters are able to better retain the ejecta from first stellar generation from which the second further stellar generations form. However it is not clear if the apparent relation between the cluster mass and the multiple stellar populations is real or it an observational bias. A second stellar population containing a few percent of the total number of stars, like the one we observe in some clusters cannot be easily distinguished in the poorly populated CMD of a small mass cluster. The scenario becomes even more puzzling when consider the case of NGC 6121, which is a small mass cluster. Possibly the mass of at least some GCs is only a fraction of the initial total mass, as a consequence of tidal shocks with the Milky Way.

### Magellanic Clouds

In an old population of a typical MW GC, a difference in age of few Myrs corresponds to a difference of a few hundredths of a magnitude at the level of the MS turn-off (TO) and SGB. At the moment, it is not possible to firmly establish a spread in a cluster's MSTO with this amplitude, given the presence of differential reddening and difficulties in doing systematically accurate crowded-field photometry at this level of precision.

The families of young and intermediate-age massive clusters that populate the Large and the Small Magellanic Clouds offer us precious opportunities for photometrically searching for multiple stellar populations because, in the CMD of a 1-3 Gyr old cluster, an age interval of 200-300 Myr corresponds to a magnitude difference of a few tenths of a magnitude. Two populations with such a difference could be distinguished easily even at the distance of the Magellanic Clouds (MC).

Indeed, recent photometric studies of LMC clusters have demonstrated that the presence of multiple stellar populations is not a peculiarity of the most massive Galactic GGCs. Bertelli et al. (2003) compare a CMD of NGC 2173 from FORS/VLT data with Padova models and suggest for this LMC cluster a prolonged star-formation episode spanning a period of about 300Myr. In a recent paper, M08 find that the main-sequence turn off (MSTO) for NGC 1783 reveals a much spread in colour wider than can be explained by photometric errors. Both M07 and M08 also reveal the presence of a double MSTO in the rich intermediate-age clusters NGC 1846 and NGC 1806 of the LMC, and suggest that their CMDs unveil two populations with an age difference of  $\sim 300$  Myr.

Driven by these results on Galactic and LMC clusters, we undertook an analysis of archival *HST* images of LMC and SMC clusters with the purpose of measuring the frequency of clusters with evidence of multiple or prolonged star formation. The clusters that have been analysed cover a wide range of ages,

from  $\sim 10^6$  to  $\sim 10^{10}$  yr. Since the search of multiple populations is carried out through analysis of CMDs, the study of clusters with different ages requires a different sort of analysis.

In this work we show our entire sample of ACS/WFC CMDs for forty-seven LMC and SMC stellar clusters and present a detailed study of sixteen intermediate-age LMC clusters (between  $\sim 1$  and  $\sim 3$  Gyr).

We confirm that two clusters (NGC 1806 [Fig. 1.6] and NGC 1846) clearly exhibit two distinct MSTOs and observe, for the first time, a double MSTO in NGC 1751. In these three clusters, the population corresponding to the brighter MSTO includes more than two-thirds of the cluster stellar population. We confirm the presence of multiple stellar populations in NGC 1783. Our photometry strongly suggests that the MSTO of this cluster is formed by two distinct branches. In seven clusters (ESO057-SC075, HODGE7, NGC 1852, NGC 1917, NGC 1987, NGC 2108, and NGC 2154), we observed an intrinsic broadening of the MSTO that may suggest that these clusters have experienced a prolonged period of star formation that spans a period between 150 and 250 Myr. The CMDs of IC 2146, NGC 1644, NGC 1652, NGC 1795, and NGC 1978 show no evidence of spread or bimodality within our photometric precision. In summary,  $70 \pm 25\%$  of our sample are not consistent with the simple, single stellar population hypothesis.



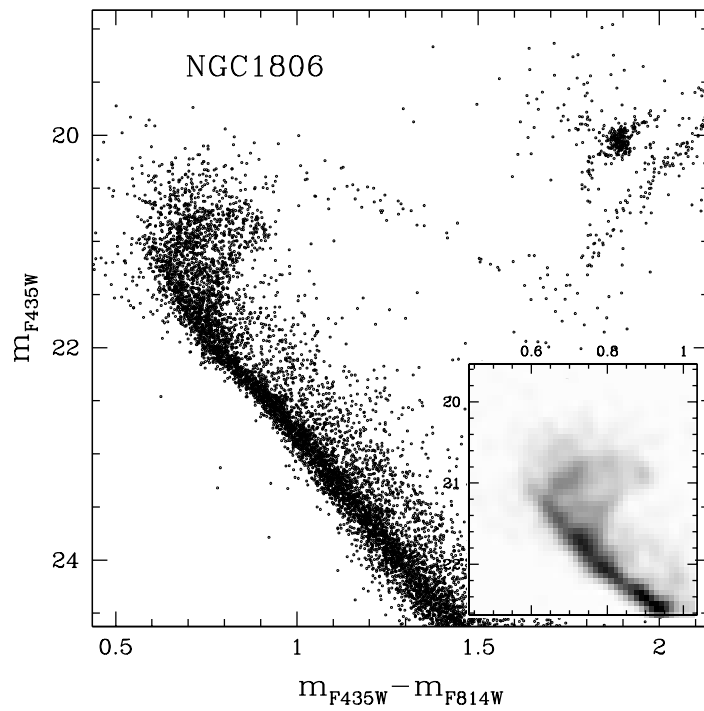


FIGURE 1.6— The double SGB of NGC 1806.



# 2

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## The triple Main Sequence of NGC 2808.

In order to shed light on the possible presence of multiple MSs in Galactic GCs, we undertook an observational campaign with HST this work we present the first results, on NGC 2808. D’Antona et al. (2005) had suggested that the MS of this cluster has an anomalous blueward extension that involves  $\sim 20\%$  of the stars. Here we will demonstrate that the blueward extension is indeed real, and that, surprisingly, it is due to the presence of at least three distinct MSs. We will take advantage of multi-epoch observations to verify, through proper motions, that these stars are really cluster members, and we will discuss the implications of this strange population.

### 2.1 Observations and Measurements

For this project we used *HST* WFC/ACS images from GO-9899 and GO-10922 (P.I. Piotto), taken at three epochs:

|           |                             |
|-----------|-----------------------------|
| May 2005  | 6×340s F475W                |
| Aug. 2006 | 2×350s F475W + 3×350s F814W |
| Nov. 2006 | 2×360s F475W + 3×360s F814W |

The reductions were done with the algorithms described by Anderson & King (2006), with one important change: whereas they used a perturbation PSF that is constant across the WFC detector, we found here that the focus during the 2006 observations was so far off nominal that a  $3\times 4$  array of perturbation PSFs produced better results.

The photometry was put into the WFC/ACS Vega-mag system according to the procedure given in Bedin et al. (2005), and using the encircled energy

and zero points given by Sirianni et al. (2005). No CTE corrections have been made, since they would not affect the present photometric results. The proper motions were derived as in Bedin et al. (2006).

## 2.2 The Color-Magnitude Diagram

The left panel of Fig. 1 shows our CMD. The most surprising result is clearly visible: the MS of NGC 2808 is split into at least three sequences. Thanks to our longer color baseline, the split is even more evident than the one that B04 showed in  $\omega$  Centauri. The MS complexity is quite different in the two cases, however. Omega Cen has, in addition to its principal MS, a less-populated branch on the blue side and another on the red side, the latter joining to the anomalous red giant branch, the RGB-a of Pancino et al. (2000). NGC 2808 has neither RGB-a nor a redward branching of its MS; instead it has *two* extra sequences on the blue side of its MS. Extending from the dense red part of the MS is only a sprinkling of stars, in the region where we expect to see MS-MS binaries.

Since NGC 2808 is projected on a rich Galactic field, it is important to verify that the stars on the additional MSs are really cluster members. The middle panel of Fig. 1 shows the proper-motion distribution, over the 18-month baseline that our data sets span. Cluster members furnish the zero point of the motions. A few stars have a motion that is clearly different; they must be the foreground/background objects. We make a conservative selection of cluster members with the red circles in Fig. 1.

As shown by Bedin et al. (2000, B00), NGC 2808 is affected by a small amount of differential reddening. The CMD of the right-hand panel of Fig. 1 shows the proper-motion-selected cluster members, corrected for differential reddening with the procedure described in Sarajedini et al. (2007). A zoomed version of the same CMD is shown in Fig. 2. An excess of stars on the blue side of the MS is already evident just below the TO, while a sequence between the bluest sequence and the reddest, most populated one starts to be visible at  $F814W \sim 20$ . We will refer to these sequences as bMS, mMS, and rMS, respectively, from left to right. It is noteworthy that the three sequences merge close to the TO, and that for brighter magnitudes the CMD remains narrow, no wider than expected from the observational errors. Thus the morphology of the SGB of NGC 2808 is quite different from that of  $\omega$  Cen, where the multiple SGBs have a vertical extent of more than 1.2 magnitudes (see B04, Sollima et al. 2005, and Villanova et al. 2007). This difference is important, as it implies for NGC 2808 a star-formation history that is significantly different from that of  $\omega$  Cen, even though both clusters show multiple MSs.

NGC2808

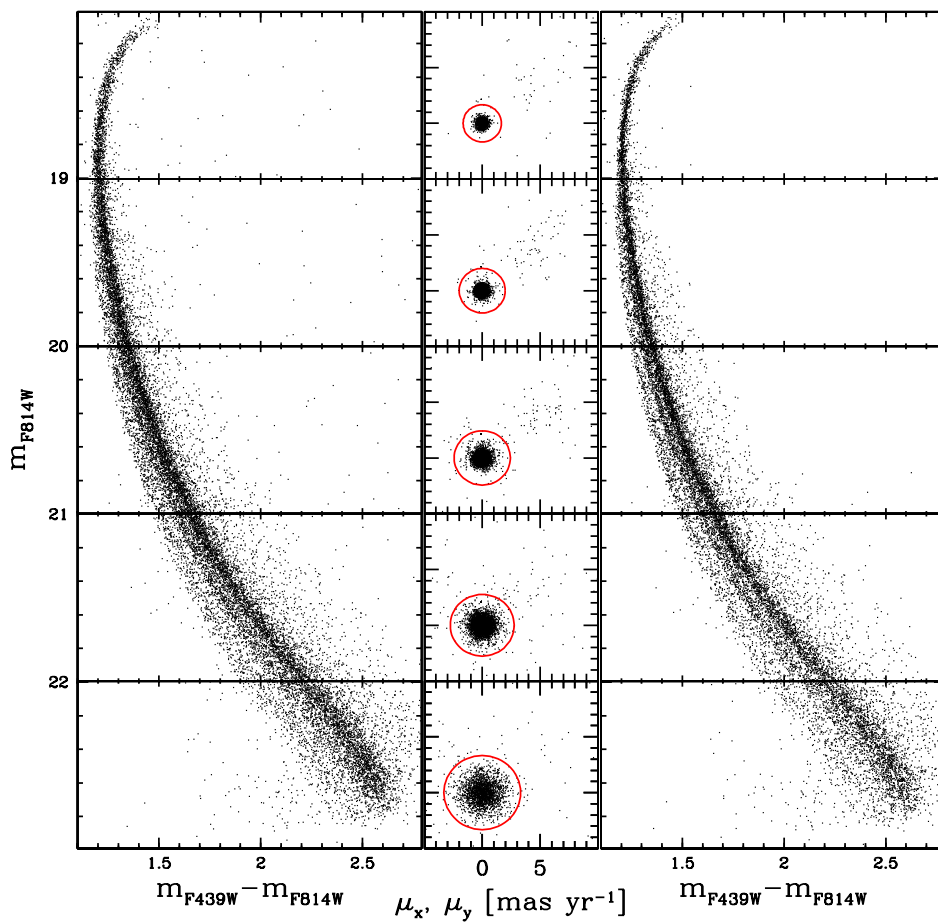


FIGURE 2.1— Left, the original CMD; middle, the proper-motion distributions in the various magnitude intervals; right, the CMD of the stars whose proper motions lie inside the red circles, with corrections for differential reddening.

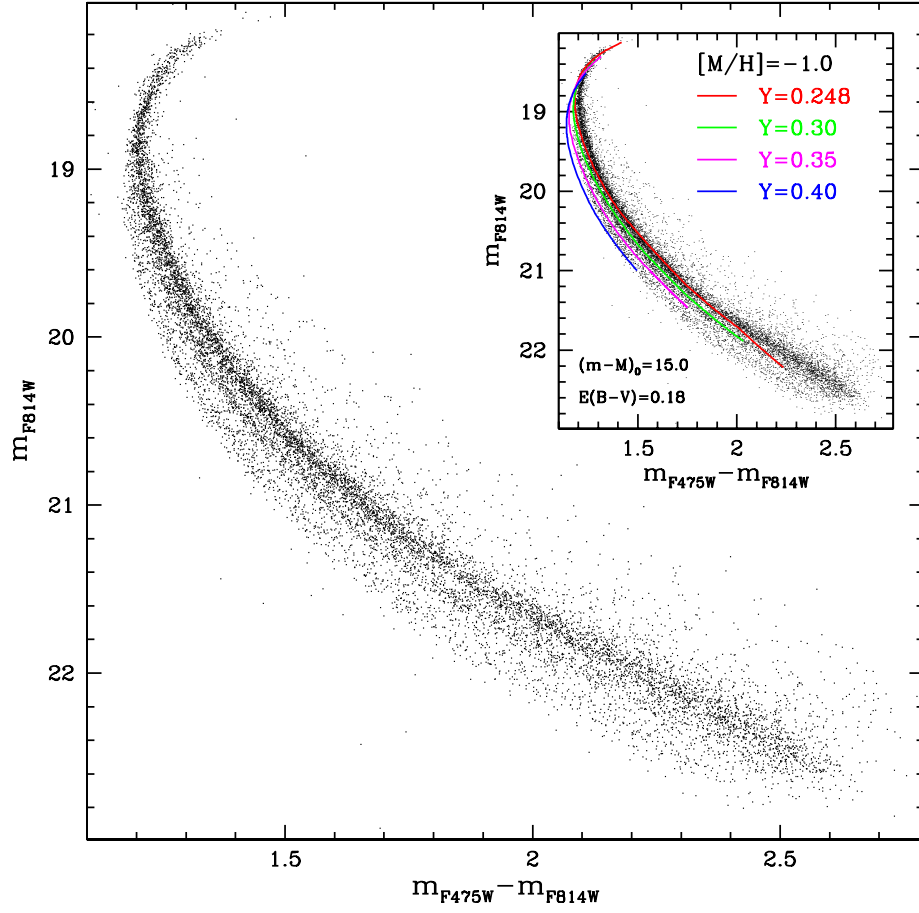


FIGURE 2.2— A zoom of the proper-motion-selected, differential-reddening-corrected CMD of the right-hand panel of Fig. 1. In the inset the observed CMD is fitted with four 12.5 Gyr isochrones, with different He content.

## NGC2808

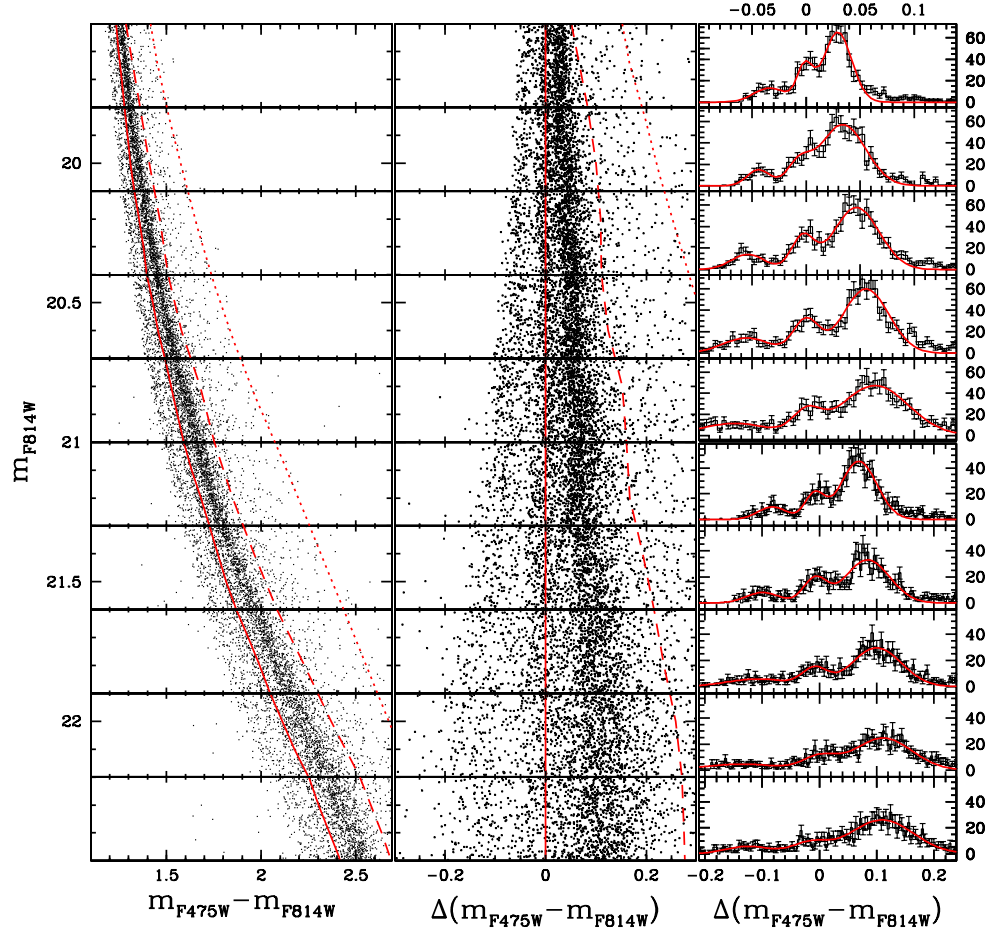


FIGURE 2.3— Left: The main part of the CMD from Fig. 1. Continuous line is a fiducial line of the mMS, drawn by hand. Dashed line runs  $3\sigma$  to the red of the RMS. Dotted line marks where equal-mass pairs of RMS stars would lie. Middle: The same CMD, after subtraction of the color of the mMS fiducial line. Right: The color distribution of the points in the middle panel. Note that the color scale is different for the upper half and the lower half. The continuous red lines are fits by a sum of three Gaussians.

The splitting of the MS in NGC 2808 is shown quantitatively in Fig. 3. The left-hand panel shows a part of the right-hand panel of Fig. 1; in the central panel we have subtracted from the color of the MS the color of a fiducial line of the mMS, drawn by hand (the continuous line in Fig. 3). The right-hand panel shows the color distribution of the points in the middle panel; the distributions have three clear peaks.

In order to estimate the fraction of stars in each of the MSs, we began by fitting each of the histograms with three least-squares Gaussians, independently in each 0.3-magnitude interval from F814W 19.5 to 22.5. We then iterated as follows. We drew the lines that are shown; the dashed line runs  $3\sigma$  on the red side of the rMS, while the dotted line farther to the right is the locus of equal-mass binaries made of rMS stars. We then did a new fit of the Gaussians, but this time we excluded from the fit all stars to the red of the dashed line, because all those stars are likely to be binaries, or else field stars that accidentally are close to the cluster motion. (The continuous red lines show the fits.) Adding up the areas under the 10 Gaussians for each sequence, we found that  $13 \pm 5\%$  of the stars belong to the bMS,  $15 \pm 5\%$  to the mMS, and  $63 \pm 5\%$  to the rMS. The remaining 9% of the stars are binaries or unremoved field stars.

We have corrected our CMD as well as we can for differential reddening. There are at least three reasons for excluding the possibility that the multiple MSs of NGC 2808 could be a consequence of remaining spatial variations of the reddening: 1) Differential-reddening effects would also be evident at the level of the TO, where the sequence is almost perpendicular to the reddening direction, but Fig. 1 shows that in that region the color distribution of the stars is narrowest. (We believe that this is the strongest evidence for the reality of the MS splitting.) 2) B00 have estimated that the differential reddening is of the order of  $\Delta E(B - V) = 0.02$ , corresponding to  $\Delta E(m_{F475W} - m_{F814W}) \sim 0.036$ . The MS split at  $m_{F814W} = 21.5$  is almost an order of magnitude larger than this. 3) The three distinct sequences can be seen everywhere in the field.

### 2.3 Discussion

Before discussing the implications of the triple MS, we need to recall two additional sets of observed facts about this cluster:

1) NGC 2808 has a very complex HB. First, it is greatly extended; among Galactic GCs only  $\omega$  Cen and M54 have HBs that go so far to the blue. Second, the distribution of stars along the HB is multimodal, with at least three significant gaps (Sosin et al. 1997; B00), one of these gaps being at the color of the RR Lyrae instability strip. In fact, even though the HB is well populated both to the blue and to the red of the instability strip, very few RR Lyraes have



been identified in NGC 2808. The other two gaps are on the blue extension of the HB, and delimit three distinct segments, which B00 called EBT1, EBT2, and EBT3. B00 found that  $46 \pm 10\%$  of the HB stars belong to the red part of the HB, while  $35 \pm 10\%$  are in EBT1,  $10 \pm 5\%$  in EBT2, and  $9 \pm 5\%$  in EBT3. D’Antona and Caloi (2004) have suggested that the HB multimodality could be due to a multimodal distribution of helium abundances.

2) From an analysis of medium-high-resolution spectra of 122 red-giant-branch (RGB) stars, Carretta et al. (2006, C06) have found a significant Na-O anticorrelation in NGC 2808. The bulk of the stars are O-normal, with a peak in  $[\text{O}/\text{Fe}]$  at  $+0.28$ , but there are two additional groups, which they call O-poor (peak at  $[\text{O}/\text{Fe}] = -0.21$ ) and super-O-poor (peak at  $[\text{O}/\text{Fe}] = -0.73$ ). C06 also found a marginal increase in  $[\text{Fe}/\text{H}]$ , from  $-1.113 \pm 0.008$  for O-normal to  $-1.079 \pm 0.014$  for super-O-poor. They interpret this as evidence of increased helium; as discussed by Böhm-Vitense (1979), helium enrichment makes the metal lines look stronger.

Thus three pieces of observational evidence (photometry of the HB, photometry of the MS, and spectroscopy of the RGB) all seem to point in the same direction: NGC 2808 contains at least three different groups of stars, with little or no dispersion in iron abundance, but with different ratios of other metals, and different photometric properties. As all cluster stars have basically the same iron content, differences in He abundance seem to be the only way to account for the triple MS. In the case of the MS splitting in  $\omega$  Cen, no alternative to the He explanation has been proposed so far, and therefore we explore this possibility further. Note that the CNO-Na variations, indicated by the presence of the three  $[\text{O}/\text{Fe}]$  groups, cannot produce the MS split, as isochrones computed adopting canonical heavy-element proportions or a mixture mimicking an extreme CNO-Na anticorrelation perfectly overlap on both the MS and the RGB (Salaris et al. 2006). The MS split occurs only if the CNO-Na anticorrelation is accompanied by an increase of He content.

In order to test this hypothesis, we computed stellar models for a metallicity suitable for this cluster,  $Z = 0.002$ , with  $[\alpha/\text{Fe}] = +0.4$  and with various values of the He content (see Pietrinferni et al. [2006].) We adopted a distance modulus  $(m - M)_0 = 15.0$  and an  $E(B - V) = 0.18$ . In the inset of Fig. 2 we compare our data with isochrones for age 12.5 Gyr, with  $Y = 0.248, 0.30, 0.35$ , and  $0.40$ . The location of the rMS fits the isochrone for the canonical He content of  $Y = 0.248$ , while the mMS is well matched by the  $Y = 0.30$  isochrone. The bMS falls between the  $Y = 0.35$  and  $Y = 0.40$  isochrones. Note that the 12.5 Gyr isochrones give a good fit of the turnoff/subgiant part of the CMD, which is quite narrow, leaving no room for any appreciable age difference between the various subpopulations. The less satisfactory fit at the faintest magnitudes

of the  $Y = 0.248$  isochrone is a known problem for GCs of this metallicity (see Bedin et al. 2001), and is due to the less than optimal color-temperature transformations for low-mass stars.

NGC 2808 is similar to  $\omega$  Cen in having multiple stellar populations that are distinct, but there are two important differences: (1) In  $\omega$  Cen the He-enhanced MS has an  $[\text{Fe}/\text{H}]$  that is  $\sim 0.3$  dex larger than that of the main stellar population (P05), whereas in NGC 2808 C06 find very little difference in  $[\text{Fe}/\text{H}]$  ( $\sim 0.03$  dex) between the two extreme RGB populations, O-normal, and super-O-poor. (2) The MS of NGC 2808 suggests three different He values, whereas only two appear to be necessary in  $\omega$  Cen (P05, Villanova et al. 2007).

What can we say about connections among the various groups of MS, RGB, and HB stars? We know that there are three MSs, plus a well-populated binary sequence, three groups of RGB stars characterized by different O content, and four distinct HB sections. Since the rMS component includes the majority of MS stars, their progeny must also remain dominant on the RGB and HB, indicating a connection between the rMS, the O-normal RGB, and the red part of the HB. Then, since one expects O depletion to go hand in hand with He enhancement, it is natural to connect the mMS to the O-poor RGB, and the bMS to the super-O-poor RGB. Indeed, to get any significant O depletion, CNO cycling at high temperature must operate, and the product of CNO cycling is He. The connections with the other HB segments are less obvious, however, as their locations depend on the unknown amount of mass loss that the stars in each group suffered when they were on the RGB. In any case, higher He implies a bluer HB location and hence tentative connection of the O-poor and super-O-poor groups to EBT1 and EBT2, respectively.

But this still leaves us with the fourth HB group, EBT3. These high-temperature stars must either have extremely high He, or else very thin envelopes, after extreme mass loss along the RGB. Therefore, one would be strongly tempted to connect the EBT3 stars to the MS binaries, given that each represents  $\sim 9\%$  of the stars in that part of the CMD. Binaries can indeed experience enhanced mass loss on the RGB, e.g. due to Roche-lobe mass transfer, and this might help to populate EBT3. After all, it has been demonstrated (Maxted et al. 2001) that a large fraction of hot field sdB stars formed in binaries that went through a mass-transfer phase. However, only a fraction of MS binaries will undergo excess RGB mass loss and land at the blue end of the HB; others will merge to become blue stragglers. Moreover, other clusters with a similar population of MS binaries do not exhibit an extremely hot HB similar to EBT3. Thus it may be that binaries help to populate EBT3, but they cannot be the whole story, so basically we remain without a satisfactory connection of EBT3 to other parts of the CMD.

These tentative connections between the various groups of MS, RGB and HB stars are summarized in Table 1. The columns correspond to regions in the HR diagram of the cluster and the rows to population components; the connections go across the rows. The percentages in each column add to 100%. The errors come from Poisson statistics. If the connections are correct, the percentages should be nearly constant across each row. They are reasonably so, when allowance is made for Poisson statistics and for the fact that the HB lifetime should be  $\sim 10\%$  shorter for stars with the primordial He value than for those with the highest He abundance (Renzini 1977).

NGC 2808 and  $\omega$  Cen are among the seven Galactic GCs in the compilation of Pryor & Meylan (1993) that have masses greater than  $10^6 M_\odot$ . Two other GCs in this heavyweight group, NGC 6388 and NGC 6441, also show evidence of multiple stellar populations on the HB (Rich et al. 1997), possibly associated with strong He enhancements (Sweigart & Catelan 1998, Raimondo et al. 2002, Caloi & D’Antona 2007). It is therefore tempting to speculate that multiple stellar generations and the super-He phenomenon are more likely to appear among the most massive clusters, whose deep potential wells favor the retention of gas from low-velocity stellar winds. This fits with the oft-proposed scenario that the He-rich populations may have formed out of the He-rich ejecta from intermediate-mass AGB stars,  $10^8$ – $10^9$  yr after the first generation of star birth (see Ventura et al. 2001). Note that the presence in NGC 2808 of two groups of stars that are strongly depleted in O relative to normal GC stars indicates a very efficient CNO process, which would further support the idea of stars formed from material ejected by intermediate-mass AGB stars.

In the uppermost three intervals of Fig. 3, the Gaussians that best fit the color distributions of the bMS and the mMS have sigmas of 0.01 mag, consistent with the width that would come from photometric errors alone. The sigma of the rMS is twice as large; but since it is contaminated by binaries, it is hard to say whether there is a real spread. Thus there is no clear evidence for a spread in He content within each of the sequences. This makes it more likely that He accumulation in the interstellar matter and star formation have been *sequential* events, whereas a spread would have indicated He accumulation and star formation as *concurrent* events. Even if this scenario is qualitatively very attractive, it has some serious quantitative problems. In some cases a very high He abundance is required, and AGB stars could not produce it (Karakas et al. 2006). Also, the large mass fraction of the He-enriched population relative to the enriching one would require an extremely flat IMF (see D’Antona & Caloi 2004). Alternative sources of He, such as massive rotating stars (Maeder & Meynet 2006) can lead to higher He yields, but their high-velocity winds would be much harder to retain within a GC. Moreover, such massive stars

| MS                          | RGB                   | HB                    |
|-----------------------------|-----------------------|-----------------------|
| rMS<br>63%±5<br>$Y = 0.248$ | O-normal<br>61%±7     | red segment<br>46%±10 |
| mMS<br>15%±5<br>$Y = 0.30$  | O-poor<br>22%±4       | EBT1<br>35%± 10       |
| bMS<br>13%±5<br>$Y = 0.37$  | super O-poor<br>17%±4 | EBT2<br>10%±5         |
| binaries<br>9%±5            | ?                     | EBT3?<br>9%±5         |

TABLE 2.1— The population components of NGC 2808

would explode as SNe, ejecting gas rather than holding it, and increasing the metallicity beyond what is observed in NGC 2808.

We conclude that the existence of multiple stellar populations within some of the most massive GCs is now a well-established fact. Apparently, the only way we have of interpreting this observational evidence is to assume that a fraction of GC stars have sizable helium enhancements over the primordial value. What remains to be understood, however, is the sequence of events that could have led to the formation of such populations, along with the source of the helium enrichment itself.

# 3

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## The Double Subgiant Branch of NGC 1851

### 3.1 Introduction

Although NGC 1851 is a massive GC with a prototypical bimodal HB, not much attention has been devoted to the study of its stellar population. The most complete photometric investigation of this cluster is by Saviane et al. (1998), and the most extended spectroscopic analysis was done over 25 years ago, by Hesser et al. (1982). Saviane et al. (1998) confirmed the bimodal nature of the HB of NGC 1851, but did not find any other anomaly in its CMD. Hesser et al. (1982) found that three out of eight bright red giant branch (RGB) stars have extremely strong CN bands. The present work is based on new photometry of NGC 1851, from HST Advanced Camera for Surveys (ACS) imaging and from archival Wide Field and Planetary Camera 2 (WFPC2) images. Section 2 describes the data sets, and Section 3 presents the CMD from the ACS data, with a split in the SGB clearly visible. In Section 4 we use the WFPC2 data, both for proper-motion elimination of field stars and to construct a CMD with a broader wavelength baseline, which we use to set a severe upper limit on any spread in the MS. Section 5 discusses the properties of the SGB and of the HB, and shows that the two parts of each have the same spatial distribution. Section 6 considers the ages of the two populations, and Section 7 is a discussion and summary.

| DATE           | EXPOSURES  | FILT  | PROGRAM |
|----------------|------------|-------|---------|
| WFPC2          |            |       |         |
| April 10, 1996 | 4×900s     | F336W | 5696    |
| ACS/WFC        |            |       |         |
| July 1, 2006   | 20s+5×350s | F606W | 10775   |
| July 1, 2006   | 20s+5×350s | F814W | 10775   |

TABLE 3.1— Description of the data sets used in this work.

### 3.2 Observations and Measurements

The main database used in this work comes from *HST* ACS/WFC images in the F606W and F814W bands, taken for GO-10775 (P.I. Sarajedini). In addition, we use *HST* WFPC2 archive data from GO-05696 (P.I. Bohlin) to extend the wavelength range to the blue, as well as to obtain proper motions. The data sets are summarized in Table 1.

The photometric and astrometric measurements were made for both WFPC2 and ACS using the algorithms described by Anderson & King (2000, 2006). Each image was reduced independently, with the observations averaged to produce a single flux for each star in each filter. We put the WFC photometry into the Vega-mag system following the procedures in Bedin et al. (2005) and adopting the encircled energy and zero points as given by Sirianni et al. (2005). WFPC2 data were photometrically calibrated following Holtzman et al. (1995). The proper motions were derived as in Bedin et al. (2006).

Breathing can change the focus of the telescope, which can result in small spatial variations of the PSF relative to the library PSF, and consequently in small spatial variations of the photometric zero point. In order to deal with any residual PSF variation, we used a method similar to the one described in Sarajedini et al. (2007) to perform a spatial fit to the color residuals relative to the main-sequence ridge line, and remove them. In this case, however, the corrections were made only to colors, rather than along a reddening line, because, as noted in Section 3, the reddening of NGC 1851 is so small that what we are correcting is surely differences between the spatial variations of the PSF in the two filters, rather than differential reddening. The spatially dependent correction was at the level of  $\sim 0.01$  magnitude, and merely sharpens the sequences a little.

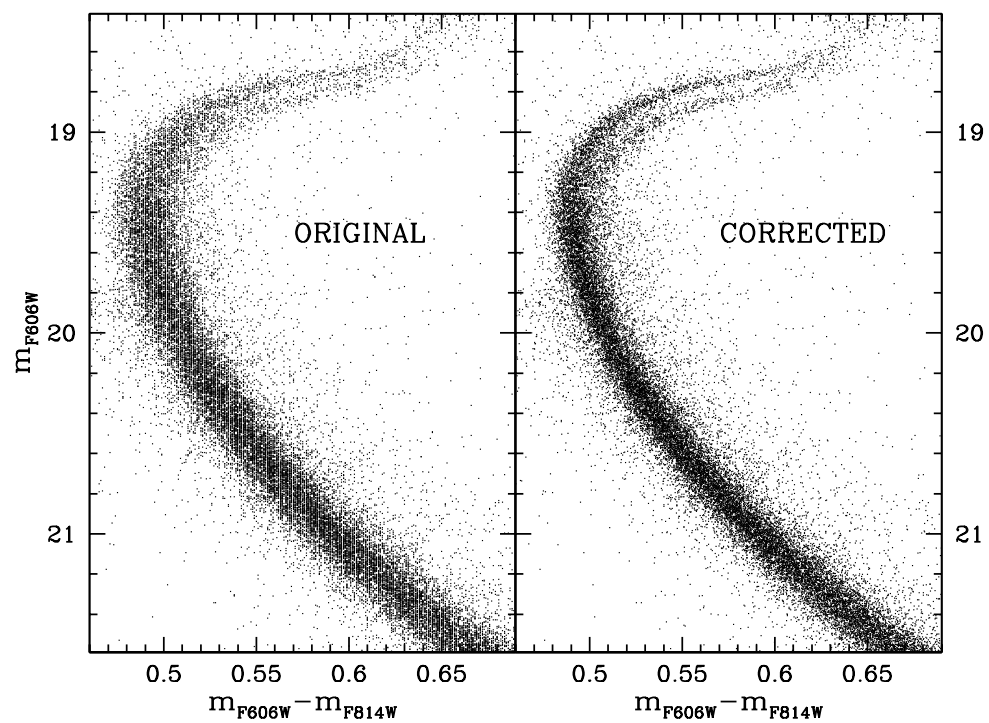


FIGURE 3.1— *Left:* Original CMD. *Right:* CMD corrected for spatial variation of the photometric zero point of color.

### 3.3 The ACS/WFC Color-Magnitude Diagram

In Figure 6.7 we show the color-magnitude diagram for the ACS/WFC photometry. The left panel shows the original CMD. The main result is already evident: the subgiant branch (SGB) is split into two distinct branches. The right panel shows the CMD after the correction for the spatial variation of the color zero point. The SGB split is still there, and there are clearly two sequences down to the cluster TO. No separation is evident in the main sequence. It must be immediately noted that because of the narrowness of MS below the TO, the SGB broadness can be due neither to any residual spatial variation of the zero point nor to any differential reddening, which is expected to be negligible because of the low reddening of NGC 1851 [ $E(B - V) = 0.02$ , Harris 1996].

The two SGBs remain separated by  $\sim 0.1$  mag in the magnitude interval  $18.0 < m_{F606W} < 19.0$ , over the color interval  $0.5 < m_{F606W} - m_{F814W} < 0.6$ . Hereafter we will refer to the two SGBs as bSGB and fSGB, where b stands for brighter and f stands for fainter.

Omega Cen and NGC 2808 also show evidence of multiple populations, but we note that the split in the SGB of NGC 1851 is quite different from what we found in the former two cases. In NGC 2808, the main sequence splits into three distinct sequences a couple of magnitudes below the turnoff, but the SGB shows no evidence of splitting. In Omega Cen, both the SGB and the MS show evidence of splitting. Here, it is only the SGB that is split. We will see that the main sequence of NGC1851 appears consistent with a single population.

### 3.4 The WFPC2 Data

#### 3.4.1 Proper motions for field decontamination

We used the archival WFPC2 images as a first epoch to determine proper motions. WFPC2 has a field of view that is only  $\sim 50\%$  of the ACS field, and the crowding prevented us from measuring good WFPC2 positions for stars within 500 ACS/WFC pixels of the cluster center. This somewhat reduces the size of our sample.

In the left panel of Fig. 3.2 we show the CMD, using the F336W magnitudes from the WFPC2 images and the F814W magnitudes from the ACS images. The second column of panels shows the proper-motion diagrams of the stars for four different magnitude intervals. It should be noted that we measure proper motions relative to a reference frame made up of only cluster members, so that the zero point of our motions is the mean motion of the cluster. In the third column the magnitudes of the proper motion vectors are plotted against stellar magnitude. The errors clearly increase toward fainter magnitudes. The line



was drawn in order to isolate the stars that have member-like motions, and was derived as follows. First, we note that in our study of SGB stars it is more important to have a pure cluster sample than a complete one, so we make a conservative choice. Taking each interval of 1 magnitude in F336W, we begin by estimating the sigma of the member-like motions. To do this we find the size of proper motion that includes 70% of the stars; for a bivariate Gaussian this radius should lie at  $1.552\sigma$ , where  $\sigma$  refers to each dimension. We then plot a point at  $2.448\sigma$ , which is the size that should include 95% of the cluster stars. We use spline interpolation to draw a line through these points, and choose all the stars to the left of the line. By giving up 5% of the cluster stars we effectively exclude nearly all of the field stars. The rightmost panel shows the CMD of our chosen cluster stars.

In Fig. 5.24 we summarize the results. The top left panel shows a zoomed CMD around the SGB for the stars in our proper-motion-selected sample. Stars marked in red are bSGB stars (119 objects), and the ones in blue are fSGB stars (88 objects). In the bottom right panel is the vector point diagram for the same stars. The two SGBs seem to have the same proper motion distribution. To show this more clearly, in the adjacent panels we plot normalized histograms of the separate components of the proper motions, for the stars of the three groups separately. Gaussian fits are also shown.

A side-benefit of proper-motion cleaning is that it also removes from the CMD stars that did not have well-measured positions. These stars tend to have poor photometry as well, so removing them naturally improves the quality of the CMD.

### 3.4.2 Wide color baseline

The second benefit of the WFPC2 data is that it provides a much better color baseline than the ACS data alone; our study of NGC 2808 (P07) showed that a wider color baseline yields a more significant splitting of the main sequence. The CMD in Figure 3.2 shows F336W vs. the F336W – F814W color. The SGB split is even more clear in this figure than in the  $V - I$  CMD of Figure 6.7 from the ACS data alone — but what is more important is that we now have a better opportunity to study any possible color spread in the main sequence. Any limits on the intrinsic width of the main sequence will translate directly into upper limits on spreads in the helium and heavy-element abundances, since age differences have little effect below the turnoff. (We note, however, the possibility that simultaneous changes in He and heavy elements could have effects that offset each other.)

Fig. 3.4 shows the color distribution of the MS stars. The left panel repeats

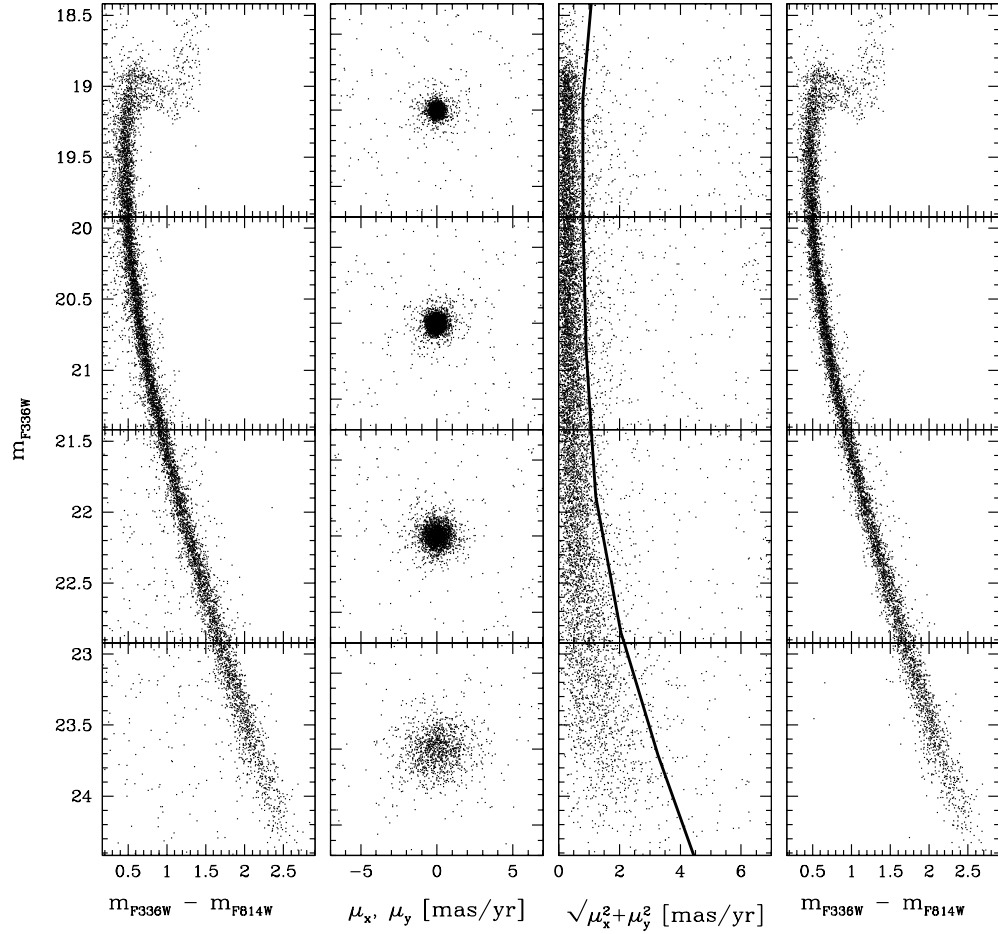


FIGURE 3.2— *Left:* F336W vs. F336W – F814W CMD for all stars. *Second column:* Proper-motion diagram of the stars in the left panel, in intervals of 1.5 magnitudes. *Third column:* The total proper motion relative to the cluster mean proper motion. *Right:* The proper-motion-selected CMD.

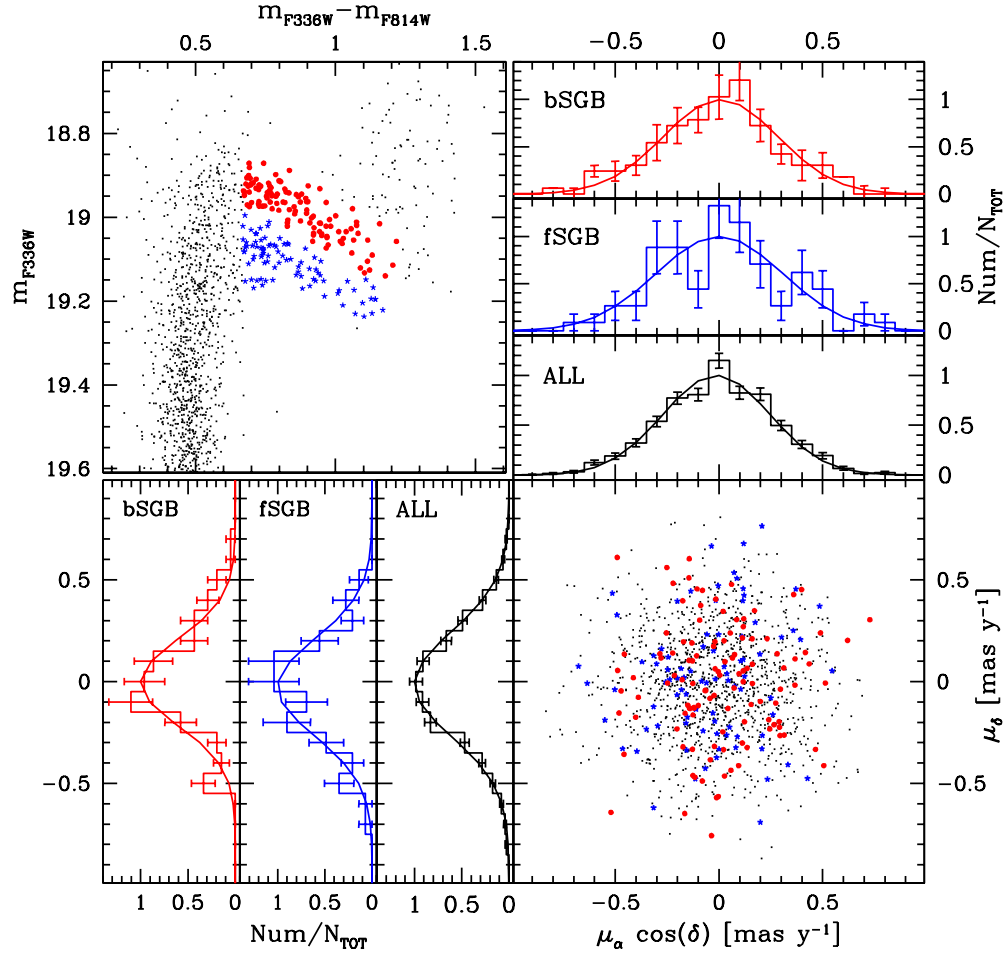


FIGURE 3.3— *Top left:* The same CMD as in Fig. 3.2, zoomed around the SGB, bSGB stars in red, fSGB stars in blue. *Bottom right:* proper motions, with same color coding. The other two panels show histograms of the individual components of proper motion.

a part of the proper-motion-selected CMD that we showed in Fig. 3.2. In order to derive the main sequence ridge line (MSRL) we divided the CMD into intervals of 0.2 mag in the F336W band and computed the median color in each interval. By fitting these median points with a spline, we obtained a raw fiducial line. Then for each star we calculated the difference in color with respect to the fiducial, and took as the  $\sigma$  the location of the 68th percentile of the absolute values of the color differences. All stars with a color distance from the MSRL greater than  $4\sigma$  were rejected, and the median points and the  $\sigma$  were redetermined. The middle panel of Fig. 3.4 shows the same CMD as the left panel, but after subtracting from each star the MSRL color appropriate for its F336W magnitude. Finally, the right panel shows the histograms of the color distributions in five different magnitude intervals.

The color distribution is fairly well reproduced by a Gaussian, and there is no evidence of a split of the MS, such as observed in  $\omega$  Cen or NGC 2808. Since most of the error in color will come from the WFPC2 photometry, which will at best have an error of 0.02 mag (Anderson & King 2000), a 0.01 mag color error in the WFC (Anderson & King 2006) will give us an expected color error of 0.025 mags from measuring error alone. As Fig. 3.4 shows that the MS broadening can be represented with a Gaussian with  $\sigma \sim 0.05$ , we obtain an upper limit for the intrinsic color dispersion of the MS of NGC 1851 of  $\sigma_{MS} = 0.04$ .

### 3.5 Two Stellar populations in NGC 1851

In this section we will derive the basic properties of the two SGBs, and consider whether other features in the CMD may indicate the presence of two stellar populations in NGC 1851.

#### 3.5.1 SGB population ratios

Figure 3.5 shows how we fitted Gaussians to the magnitude distributions of the bSGB and fSGB stars to estimate their number ratio. The top panel of the figure is a blow-up of the part of the SGB where the split occurs. The red line is a fiducial line through the bSGB. We drew it by marking the middle magnitude level of bSGB at four equally spaced points and drawing a line through them by means of a spline fit. In the middle panel the magnitude of each star has had subtracted from it the magnitude of this fiducial line at the color of the star. For the analysis that was to follow, we divided the color range into four sections, as shown.

In each color section we estimated the fraction of stars in each of the SGBs, as follows. Our aim was to fit the magnitude distributions in the two branches

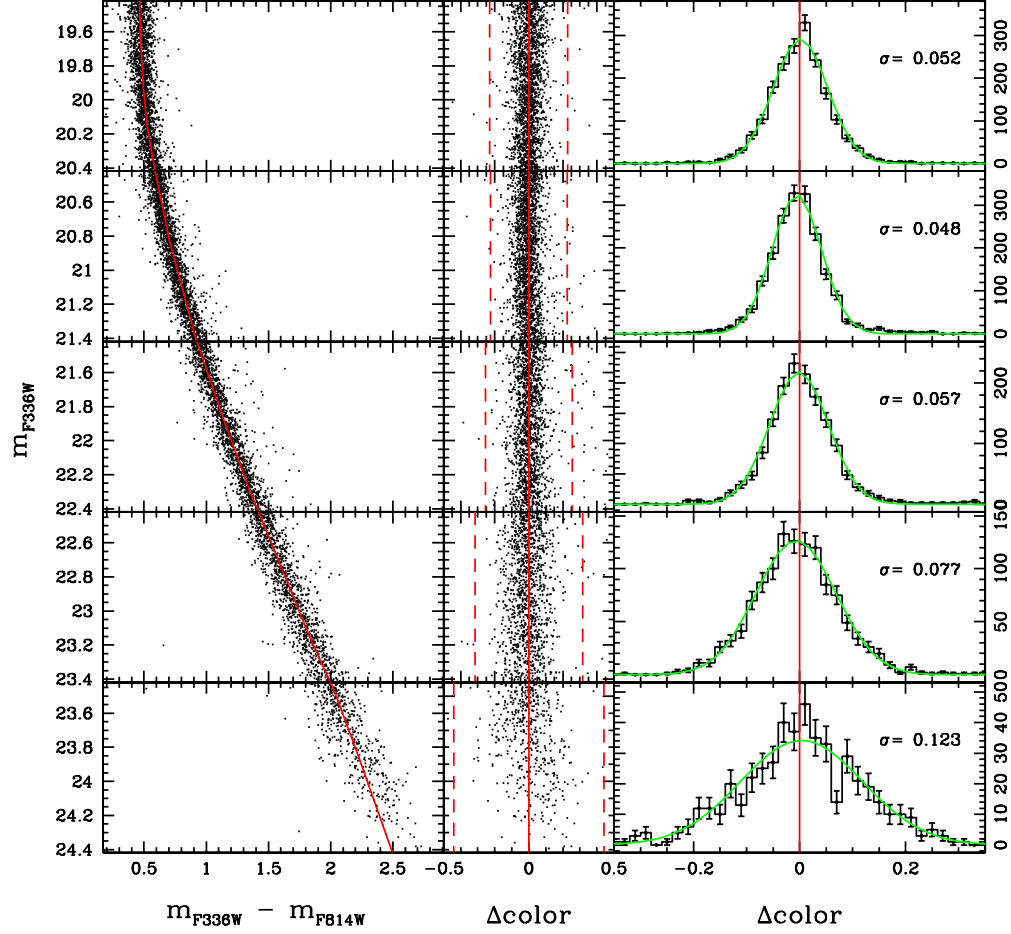


FIGURE 3.4— *Left*: The same CMD as shown in the right-hand panel of Fig. 3.2, with our MSRL overplotted; *Middle*: The CMD, rectified by subtraction of the MSRL; *Right*: Color distribution of the rectified CMD. The  $\sigma$  in the inset are those of the best-fitting Gaussians.

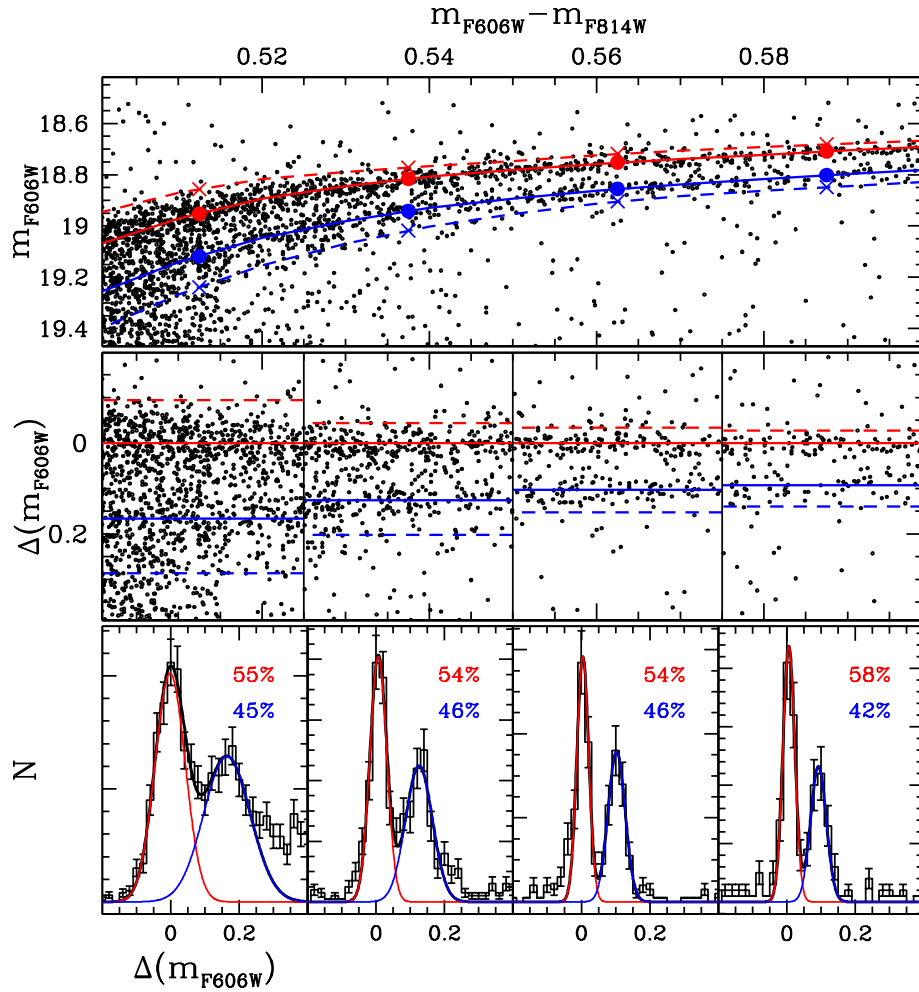


FIGURE 3.5— *Top:*  $F606W$  vs.  $F606W - F814W$  diagram zoomed around the SGB. The red continuous lines show the adopted fiducial line for the bSGB; the other lines are explained in the text. *Middle:* The same diagram, after subtraction of the bSGB fiducial line. The lines are explained in the text. *Bottom:* Distribution in magnitude of the bSGB stars (red) and fSGB (blue). The numbers indicate the fraction of stars in each SGB, as the area of the best-fitting Gaussians, shown in the plot. (See the text for more details.)

by a pair of overlapping Gaussians, but we felt the need to eliminate outliers, especially in the bluest color section. This we did by making a preliminary least-squares fit of the Gaussians, using all of the stars. We then repeated the solution, but omitting the stars that lay more than  $2\sigma$  above the midpoint of the Gaussian for bSGB or more than  $2\sigma$  below the midpoint of the Gaussian for fSGB (using in each case the sigma of the corresponding Gaussian). In the middle panel of Fig. 3.5 the horizontal lines show the midpoint of the final Gaussians. The red dashed line runs  $2\sigma_b$  on the bright side of the bSGB, and the blue dashed line runs  $2\sigma_f$  on the faint side of the fSGB (where the  $\sigma$ 's are those of the best-fitting Gaussians in each color section, fitted to the distributions of the bSGB and fSGB stars, respectively). The stars rejected consist of field stars, objects with poor photometry, or binaries (brighter than the bSGB). We have also marked, in the top panel of Fig. 3.5, the values of the Gaussian centers of bSGB with large dots and the spline through them with continuous lines. The crosses are the Gaussian centers of fSGB lowered by  $2\sigma_f$ , and the dashed lines are a spline fitted through the crosses.

The bottom section of Fig. 3.5 shows the histogram of the magnitude distribution in each color section of the middle panel, and the best-fitting Gaussians. The numbers reported in the figures give the percentage of total area under each of the two Gaussians, i.e., the percentage of bSGB (red) and fSGB (blue) in each interval.

When we added up, for each SGB, the areas under the four Gaussians fitted to the separate color sections, we found that 55% of the stars belong to the bSGB, and 45% to the fSGB. Although the expected sigma of samplings from a binomial distribution of more than 1000 stars, with a probability of 0.55, is less than 2%, we estimate that our observed 55/45 split really has an uncertainty that is more like 5%. This estimate is based on the differing results of several different ways of fitting the Gaussians (e.g., as simple a thing as changing the bin-width of the histograms).

As for the intrinsic width of each SGB, the dispersions in magnitude of the two Gaussians in the color sections where the two SGBs are well separated are of the order of 0.02 mag, consistent with the uncertainties in our corrections for spatial variation of the PSF. (Paradoxically, WFC colors are more accurate than WFC magnitudes, because these corrections are what limits the accuracy of high-S/N photometry, and in the case of colors the corrections are only for the difference in behavior of the PSF through two different filters.)

### 3.5.2 Spatial distribution of the SGB stars

Figure 3.6 shows the spatial distributions of the two SGB components. We select the two SGB subsamples as shown in the bottom-right panel, and plot the spatial distributions in the bottom-left panel. Stars from both groups have similar spatial distributions. This is also confirmed by the cumulative radial distributions shown in the top panel. The Kolmogorov-Smirnov statistic shows that in random samplings from the same distribution a difference this large would occur 11% of the time, which is very reasonable for the hypothesis that the two SGBs have the same distribution.

### 3.5.3 The horizontal branch stars

Since the WFC data set included short exposures, we can also examine the horizontal branch (HB) population. Figure 3.7 shows the upper part of the F606W vs. F606W – F814W CMD. The NGC 1851 HB is clearly bimodal. Interestingly enough, the red HB contains  $63 \pm 7\%$  of the total red + blue HB stars (242 stars), and the blue part contains  $37 \pm 9\%$  of the red + blue HB stars (143 stars). Note that some stars populate the RR Lyrae gap. It is difficult to extract RR Lyrae variables from the small number of exposures that went into Fig. 3.7, with each star caught at random phases in each color band. In any case, the contribution of the RR Lyraes to the total population of the HB stars is  $<10\%$  (see Saviane et al. 1998 and Walker 1992). As in the case of the bSGB and fSGB, stars from the red and blue HB groups have similar spatial distributions (see top right panel of Fig. 3.7). This is also confirmed by the cumulative radial distributions shown in the bottom panel. The Kolmogorov-Smirnov statistic shows that in random samplings from the same distribution a difference this large would occur 17% of the time, so here too there is no significant indication of a difference in their radial distribution.

Neither for the SGB stars nor for the HB stars is the distribution of the two samples significantly different. It would obviously be desirable to strengthen the statistics by combining the two sets of counts, but unfortunately this is not possible, because the incompletenesses in star counts at the HB and at the SGB level are different.

On the basis of the relative numbers of red to blue HB stars and of bSGB to fSGB populations, it is very tempting to connect the bSGB (which includes 55% of the SGB stars) with the red HB, and the fSGB (45% of the SGB stars) with the blue HB stars.



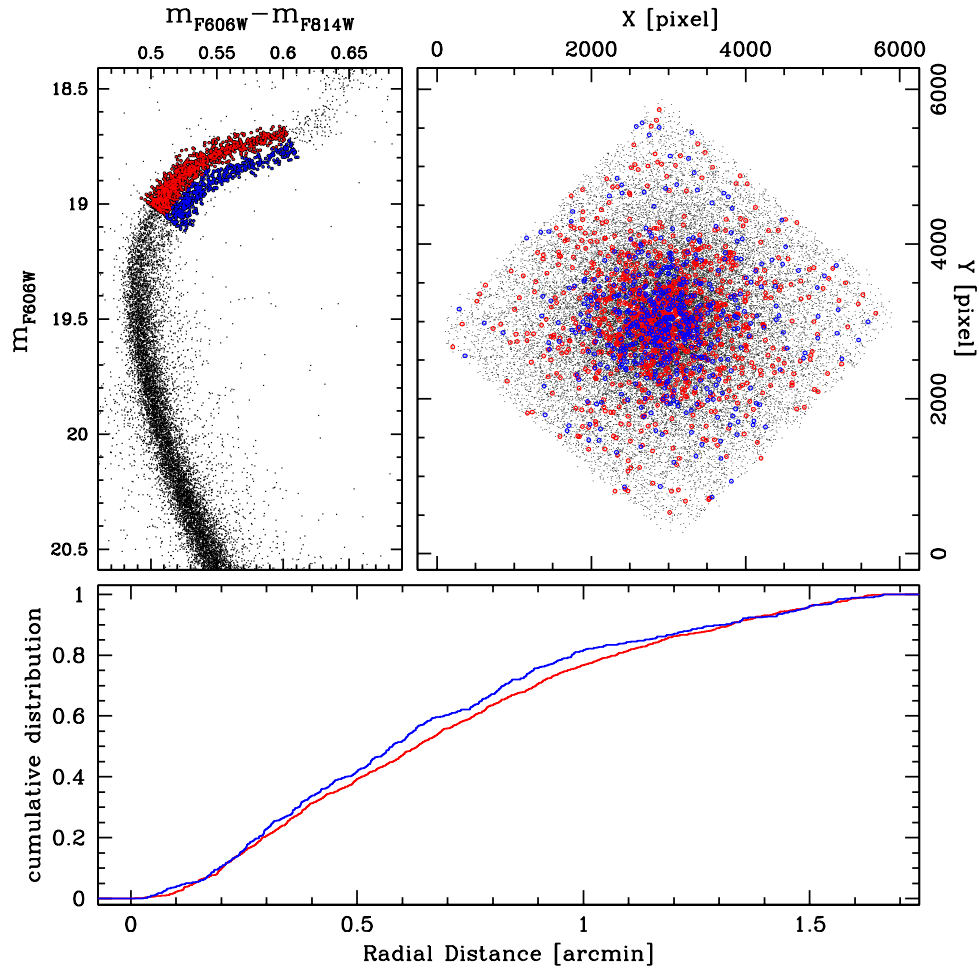


FIGURE 3.6— *Lower right*: Selection of the bSGB stars (red dots) and fSGB stars (blue dots). *Lower Left*: Spatial distribution of the bSGB and fSGB stars. *Top*: Cumulative radial distributions of the bSGB and fSGB stars.

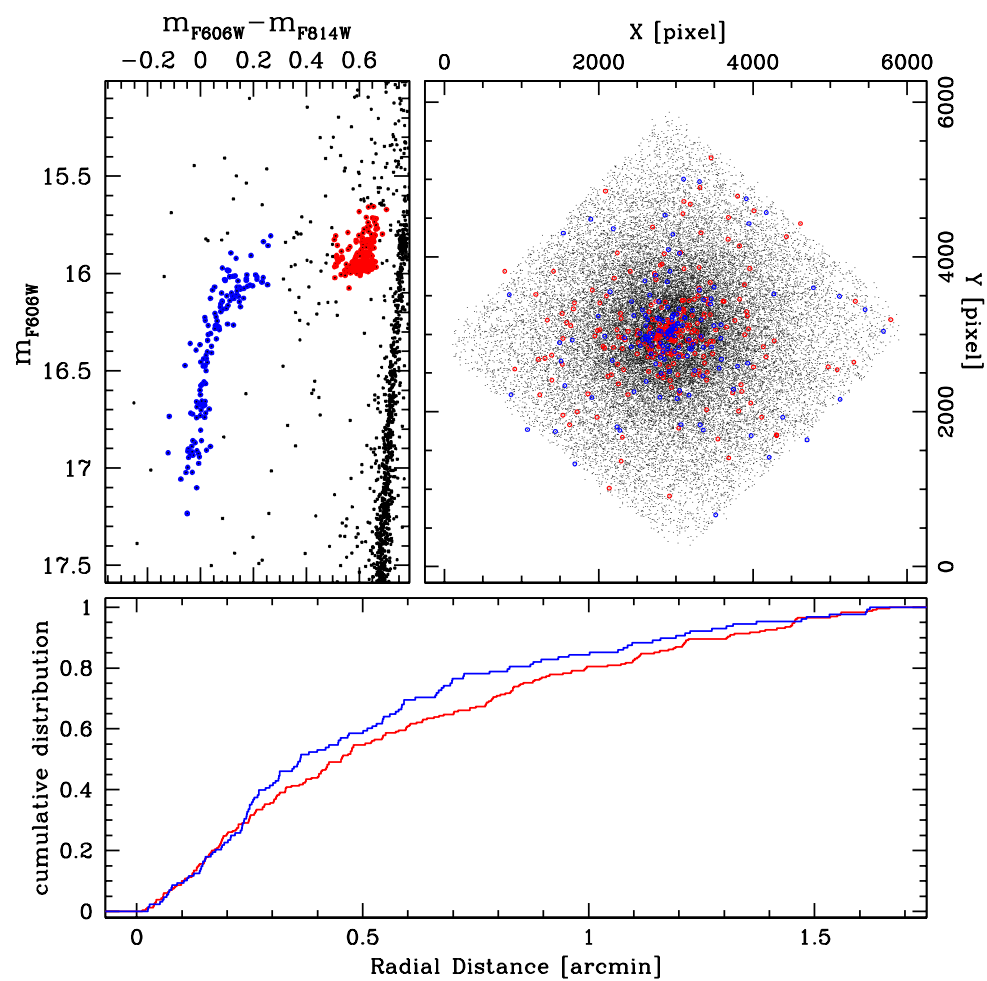


FIGURE 3.7— As in Fig. 3.6, but for the HB.

### 3.6 The ages of the two populations

The dispersion in the MS in  $F336W - F814W$  is less than 0.04 mag. Such a narrow main sequence implies that either the two SGB populations have the same metallicities and the same helium abundances or some fortuitous combination of abundances that results in no MS split. Comparison with the theoretical models of Dotter et al. (2007) provides an upper limit to a possible dispersion in  $[\text{Fe}/\text{H}]$  of 0.1 dex or in helium abundance of  $\Delta Y = 0.026$ , if each of the two is assumed to act alone. We are not suggesting that such spreads exist; we merely state upper limits to what might be present.

We note that if we just increase the He abundance, there will be no appreciable effect on the SGB luminosity. Helium alone cannot explain the observed SGB split. On the other hand, a population 0.2 dex more metal rich would have an SGB that is fainter by  $\sim 0.12$  magnitude, and therefore it would be able to explain the SGB split. However, such a high difference in  $[\text{Fe}/\text{H}]$  is ruled out by the narrowness of the MS. We have also looked at the color distribution of the red giant branch (RGB) and found no evidence of a split, and found an RGB color dispersion consistent with the photometric error, confirming that any dispersion in  $[\text{Fe}/\text{H}]$  alone must be much smaller than 0.2 dex.

Note, however, that increasing  $[\text{Fe}/\text{H}]$  makes the MS redder, while increasing helium makes the MS bluer. Thus if, as a mere working hypothesis, one increases  $[\text{Fe}/\text{H}]$  by 0.2 dex (enough to explain the SGB split), while changing  $Y$  from 0.247 to 0.30, then the two effects cancel each other out, and the MS would have the same color. The same would happen on the RGB: an  $[\text{Fe}/\text{H}]$  content 0.2 dex higher would move the RGB to the red, but the RGB would be moved to the original color in the presence of a He content  $Y \sim 0.30$ . In this way we would be able to reconcile the SGB split with the low dispersions in the MS and RGB. (Clearly, this kind of conspiracy cannot be ruled out till we have high-resolution spectra to measure the metal content of the NGC 1851 stars.) However, there is additional observational evidence which seems to rule out such an unlikely coincidence. A change in  $[\text{Fe}/\text{H}]$  of +0.2 dex would imply an HB 0.03–0.04 magnitude fainter, while the suggested  $Y$  enhancement would end with a bluer HB that is  $\sim 0.2$  magnitude brighter. The resulting sloping of the horizontal branch is not observed in Fig. 3.7.

The only remaining possibility of explaining the SGB split is therefore to assume that in NGC 1851 there are two stellar populations with similar metallicity and He content, but with different ages. Figure 3.5 shows that the two SGBs are separated vertically by  $\sim 0.1$  magnitude in  $F606W$ . Comparison with the theoretical models of Dotter et al. (2007) shows that this separation corresponds to an age difference of  $\sim 1$  Gyr, with the fSGB older than the bSGB.

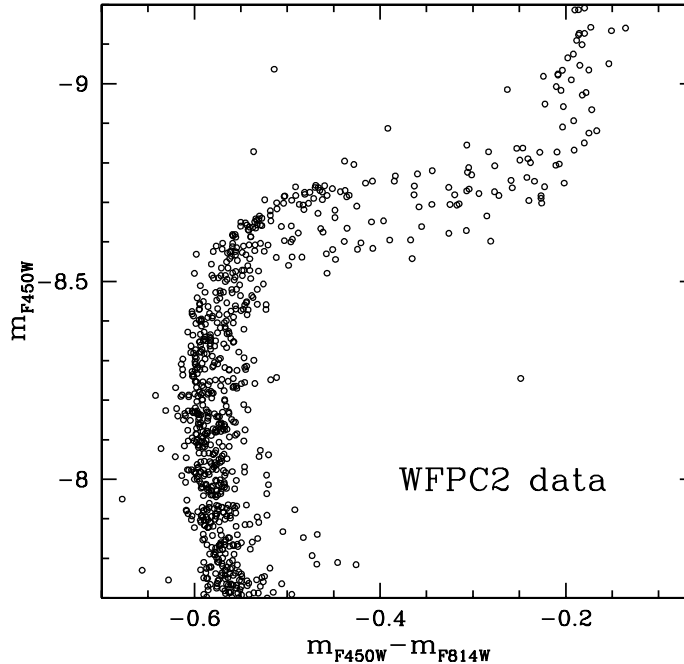


FIGURE 3.8— CMD of NGC 1851 from WFPC2/HST data.

### 3.7 Detection of the SGB split in the external field

In this work, we extend the photometric analysis up to the outermost region of the cluster. Our radial extension analysis covers the whole cluster from the center up to the tidal radius ( $r_{\text{tidal}}=11.70$  arcmin, Harris 1996, 2003). To this aim we combined data from three different instruments: the Advanced Camera for Survey (ACS) and the Wide Field Planetary Camera 2 (WFPC2) on board on HST and the Wide-Field Imager of the Max-Planck-Institute Telescope (WFI@ESO2.2m). Fig. 3.8 is a zoom of the CMD from WFPC2/HST data from GO11233 (PI Piotto). This WFPC2 field has an average radial distance of  $\sim 1.5$  arcmin. The CMD from ground based photometry is shown in Fig. 3.9 for stars with radial distance greater than two arcmins. We detected a split SGB at all radial distances and trace the radial distribution of NGC 1851 stars both in the SGB. We found that stars in the two SGB branches have the same radial distribution. By using the method described in Milone et al. 2008c, we have determined the fraction of bSGB and fSGB at several ra-

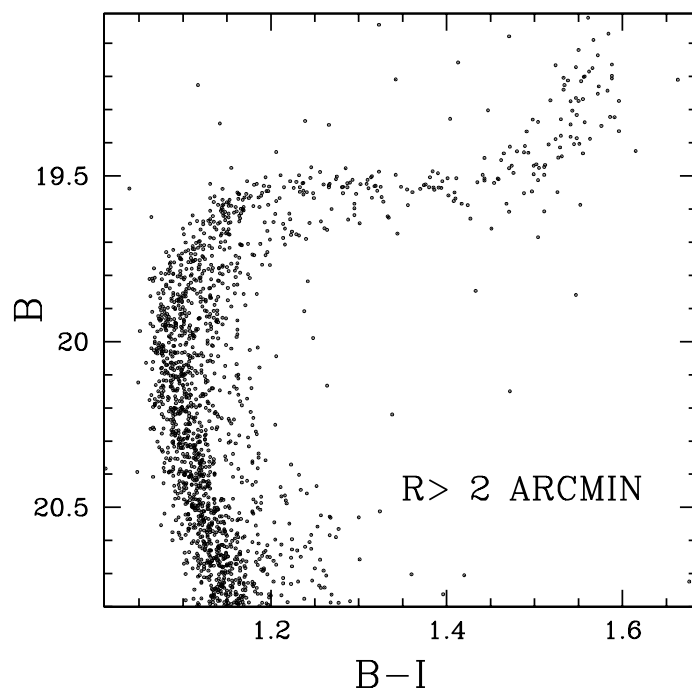


FIGURE 3.9— CMD of NGC 1851 from WFI photometry.

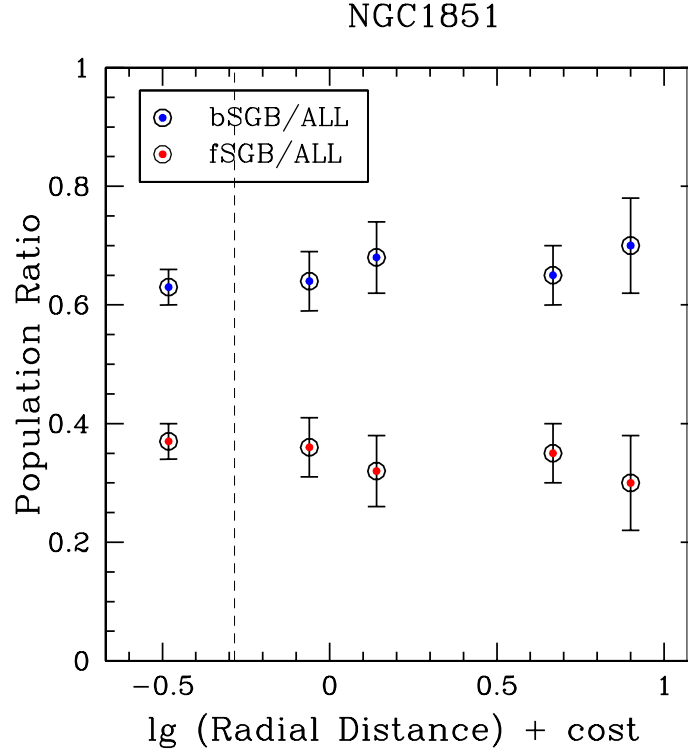


FIGURE 3.10— fraction of bSGB and fSGB stars as a function of the radial distance

dial distances. We found that the two stellar population have almost the same concentration over the entire field

are illustrated in Fig. 6.20

### 3.8 Discussion

In this work we have shown that the SGB of the Galactic GC NGC 1851 is split into two distinct branches. If the split is interpreted in terms of age, its width implies that the two populations were formed at epochs separated by  $\sim 1$  Gyr. As discussed in the previous section, the age difference seems a possible explanation for the peculiar SGB.

The SGB split is not the only observational evidence of the presence of more than one population in NGC 1851, though it is probably the clearest one. We have already noted that NGC 1851 has a bimodal HB, and that there might be a connection between the two SGBs and the two HB sections. The relative frequency of stars in the different branches implies that the progeny of the bSGB

are in the red part of the HB, while the progeny of the fSGB are on the blue side of the instability strip. This is what one would expect qualitatively from stellar evolution models, though an age difference of only 1 Gyr is not enough to move stars from the red to the blue side of the HB. Our models indicate that to move stars from the red to the blue side of the RR Lyrae gap would require an age difference of  $\sim 2\text{--}3$  Gyr. Some additional parameter, or combination of parameters, must be at work in order to explain the morphology of the HB of NGC 1851.

There is another relevant observational fact that must be mentioned. Hesser et al. (1982) found that three out of eight of their bright RGB stars show “extraordinarily strong” CN bands. These stars also show enhanced Sr II and Ba II lines, and lie systematically on the red side of the RGB. In other words,  $\sim 40\%$  of their sample of bright RGB stars contains CNO-processed material. This material could come from the interior of these stars through mixing processes, but after what we have learned from  $\omega$  Cen and NGC 2808 we cannot exclude the possibility that this processed material comes from a first generation of stars that polluted the gas from which the CN-strong stars have formed. This hypothesis would be further supported if Sr and Ba are also confirmed to be enhanced (as the spectra of Hesser et al. [1982] seem to imply), as these elements cannot be produced in the low-mass stars presently on the RGB of NGC 1851.

Unfortunately, the results by Hesser et al. (1982) are based on a very limited sample of stars; a more extended spectroscopic investigation is clearly needed. Meanwhile, it is rather instructive to look at the CMD published by Grundahl et al. (1999), based on Strömgren photometry. Among the 15 CMDs in their Fig. 1, NGC 1851 shows by far the broadest RGB, with some hint of a bimodality. This bimodality is not visible in our narrow-color-baseline F606W vs. F606W – 814W CMD, but the capability of Strömgren photometry to distinguish stellar populations with different metal content (in particular CN content) is well known, and the CMD of Grundahl et al. (1999) tends to confirm the results of Hesser et al. (1982). We have investigated the possibility that an enhancement of C or N, or of both elements, can be the cause of the observed SGB split. Hesser et al. (1982) found that model spectra with  $[C/A] = +0.2$  and  $[N/A] = +0.5$  (where they define  $[A/H]$  as the logarithmic relative abundance of all heavy elements in the theoretical models), or else model spectra with  $[C/A] = 0$  and  $[N/A] = +1.0$  could fit the observed spectra equally well. A detailed analysis of the effect of C and N overabundances is beyond the scope of the present work. Furthermore, before such an analysis is justified we will need better abundance constraints, which would require fitting a larger sample of stellar spectra with modern atmospheric models.

Here we note that one possible consequence for a second generation of stars is indeed an increased CNO abundance from mass lost after the third dredge-up in intermediate-mass AGB stars from an earlier generation (see discussion in Ventura & D’Antona 2005 and Karakas et al. 2006). The spectroscopic results of Hesser et al. (1982) suggest enhanced levels of C and N but do not include an analysis of the oxygen abundance, due to a lack of measurable features in the spectra. (This further underlines the need for a new study.) It is however possible that the C + N + O amount is enhanced to some extent, though at the moment we cannot quantify this enhancement. The CNO enhancement is an important observational input, as the level of enhancement would allow us to better identify the possible polluters from the first generation of stars.

The presence of CNO enhancement would affect the age difference between the two populations. A CNO enhancement of +0.3 dex would reduce the age difference between the two SGBs to 300–500 Myr. Under this hypothesis, we estimate a gap in the SGB of  $\sim 0.07$  magnitude due to the composition alone, and an additional 0.03–0.05 mag displacement due to the age difference, fully accounting for the observed magnitude difference between the two SGBs.

Larger CNO enhancements would further reduce the age gap between the two generations of stars, down to a few hundred Myr, as expected in the intermediate-mass-AGB-star pollution scenario (Ventura et al. 2002). We note that if the CNO enhancement in second-generation stars of NGC 1851 is confirmed, NGC 1851 might differ from other globular clusters, in which the sum of CNO elements for normal and self-enriched stars seems to be constant (Cohen & Melendez 2005). New spectroscopy of stars in NGC 1851, along with the photometry presented in this work and detailed modeling, can significantly improve our understanding of this intriguing situation.



# 4

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## A double SGB in six Globular Clusters

### 4.1 introduction

In this chapter, we increase by six the number of objects with photometric evidence of a split of the SGB, and so of with multiple populations. These namely are: NGC 6388, NGC 6715 (M 54), NGC 6656 (M 22), NGC 5286, NGC 362, and NGC 7089 whose CMDs reveal a double sub-giant branch (SGB). This chapter is organized as follow. In the next section we describe the data set, the photometric reduction, and the calibrations. In section 3 we present our correction for differential reddening and spatial dependent zero point variations, and present the detection of the SGB-split in the homogeneous GO-10775 data set for : NGC 6388, NGC 6715 (M 54), NGC 6656 (M 22) and NGC 5286. In section 4 we describe how we used property and archival material: *(i)* to derive proper motions to exclude field objects as responsible for the split, and *(ii)* to have confirmation of the SGB-split from totally independent data-set, and *(iii)* to obtain the largest possible color base-line in order to put an upper limit to the intrinsic split of the Main Sequence due to a different chemical composition. In section 5 we used isochrones to better characterize the main properties of the clusters and of the multiple stellar population that they host. In Section 6, for each cluster, carefull analysis are done to determine the fraction of stars in the two branches of the SGB. The double SGB of NGC 362 and NGC 7089 are presented in Section 7, while Section 8 is a short summary of our spectroscopic study on seventeen RGB stars in NGC 6656 where we demonstrate that this clusters hosts two well defined group of stars with a different abundance of iron

and  $s$ -process elements (Marino et al. 2009) .

## 4.2 Observations and data reduction

The principal data sets used in this work are from the HST programs GO-10922 and GO-11233 (PI: Piotto) which are specifically dedicated to photometric detection of multiple populations, and from the HST Treasury program GO-10775 (PI: Sarajedini). In addition to these data sets, a huge number of images were retrieved and reduced from the STSCI archive. In Table 5.2 we give a summary of all the images used in the present photometric and astrometric study, indicating: the cluster ID, the epoch of the observation, the number and the duration of the single exposures, the filters, the program ID, and the PI.

The astrometry and photometry of WFPC2 images have been carried out for each chip, filter and epoch independently, by adopting the method described by Anderson & King (2000) based on the effective-point-spread function fitting. We corrected for the 34<sup>th</sup> row error in HST's WFPC2 cameras (see Anderson & King 1999 for details) and used the best available distortion solution available given by Anderson & King (2003). Photometric calibration has been done according to the Holtzman et al. (1995) Vega-mag flight system for the WFPC2 camera.

The astro-photometric reduction of ACS/WFC data was done with the software tools described in great details by Anderson et al. (2008). It consists in a package that analyses all the exposures of each cluster simultaneously in order to generate a single list of stars for each field. Stars are measured using the perturbed best available PSF models from Anderson & King (2006). This routine was designed to work well in both crowded and uncrowded fields and it is able to detect almost every star that can be detected by eye. It takes advantage of the many independent dithered pointings of each image and the knowledge of the PSF to avoid including artifacts in the list. Calibration of ACS photometry into the Vega-mag system has been performed following recipes in Bedin et al. (2005) and using the zero points given in Sirianni et al. (2005). For ACS/WFC coming from the GC Treasury program GO-10775 (PI: Sarajedini) we simply used the calibrated catalogs produced by Anderson et al. (2008, see also Sarajedini et al. 2007) using the same procedures.

## 4.3 CMDs from GO10775 ACS/WFC data

### 4.3.1 Selection of the Star Sample

Stars on the ACS images may be poorly measured for several reasons: crowding by nearby neighbors, contamination by cosmic rays, or image artifacts, such bad

| ID       | DATE                      | N×EXPTIME       | FILT   | INSTRUMENT | PROGRAM | PI         |
|----------|---------------------------|-----------------|--------|------------|---------|------------|
| NGC 6656 | Jun 06 2000               | 12×26s          | F555W  | WFPC2      | 8174    | van Altena |
|          | Jun 06 2000               | 11×26s          | F785LP | WFPC2      | 8174    | van Altena |
|          | Apr 01 2006               | 3s+4×55s        | F606W  | ACS/WFC    | 10775   | Sarajedini |
|          | Apr 01 2006               | 3s+4×65s        | F814W  | ACS/WFC    | 10775   | Sarajedini |
|          | Apr 29 2008               | 9×350s          | F450W  | WFPC2      | 11233   | Piotto     |
|          | Apr 29 2008               | 9×100s          | F814W  | WFPC2      | 11233   | Piotto     |
| NGC 6388 | Sep 04 2003 - Jun 26 2004 | 6×11s           | F435W  | ACS/WFC    | 9821    | Pritzl     |
|          | Sep 02 2003 - Jun 23 2004 | 6×7s            | F555W  | ACS/WFC    | 9821    | Pritzl     |
|          | Oct 02 2003 - Jun 23 2004 | 6×3s            | F814W  | ACS/WFC    | 9821    | Pritzl     |
|          | Apr 06 2006               | 40s+5×340s      | F606W  | ACS/WFC    | 10775   | Sarajedini |
|          | Apr 06 2006               | 40s+5×350s      | F814W  | ACS/WFC    | 10775   | Sarajedini |
|          | Apr 22-23 and May 17 2008 | 11×700s+11×800s | F450W  | WFPC2      | 11233   | Piotto     |
|          | Apr 22-23 and May 17 2008 | 11×500s         | F814W  | WFPC2      | 11233   | Piotto     |
|          |                           |                 |        |            |         |            |
| NGC 5286 | Nov 07 1997               | 10s+4×140s      | F555W  | WFPC2      | 6779    | Gebhardt   |
|          | Nov 07 1997               | 7s+3×140s       | F814W  | WFPC2      | 6779    | Gebhardt   |
|          | Mar 03 2006               | 30s+5×350s      | F606W  | ACS/WFC    | 10775   | Sarajedini |
|          | Mar 03 2006               | 30s+5×360s      | F814W  | ACS/WFC    | 10775   | Sarajedini |
| NGC 6715 | Maj 25 2006               | 2×30s+10×340s   | F606W  | ACS/WFC    | 10775   | Sarajedini |
|          | Maj 25 2006               | 2×30s+10×350s   | F814W  | ACS/WFC    | 10775   | Sarajedini |
|          | Jun 20-22-24 2007         | 9×700s+9×800s   | F450W  | WFPC2      | 10922   | Piotto     |
|          | Jun 20-22-24 2007         | 9×500s          | F814W  | WFPC2      | 10922   | Piotto     |

TABLE 4.1— Description of the HST archive data sets used in this chapter.

pixels, or diffraction spikes. The goal of the present work is to clearly identify multi-populations. For this purpose we need to select the best-measured stars in the field (i.e., those with the lowest random and systematic errors), but we also need to have a large enough statistical sample to be able to identify secondary sequences that may have many fewer members than the primary ones.

The software developed by Anderson et al. (2008) provides very valuable tools to reach this goal. In addition to the stellar fluxes and positions it generates a number of parameters that can be used as diagnostics of the reliability of photometric measurements. These include a parameter,  $q$ , related to the quality of the fit of the PSF model to the real stars, the rms of the position measured in different exposures transformed in a common distortion-free reference frame,  $rms_{X,Y}$ , the  $rms$  of magnitudes measured in different exposures,  $rms_{mag}$ , and a parameter,  $o$ , which quantifies how a star is contaminated from neighbouring stars flux. (see Anderson et al. 2008 for the details).

To select the sample of stars with the best photometry, we adopted the following procedure which is described in more details in the Sect. 2.1 of Milone et al 2008b. Since the  $q$  and the  $rms$  parameters exhibit a trend with the magnitude, we divided all the star into bins of 0.04 magnitude and calculated for each bin the median  $rms$  ( $q$ ) and the 68.27<sup>th</sup> percentile (hereafter  $\sigma$ ), by using the iterative procedure explained in Milone et al 2008b. Then we added to the median of each bin four times  $\sigma$  and interpolated these points with a

spline. All the stars that lie below the spline were flagged as well-measured.

The  $o$  parameter does not show a clear trend with magnitude, so we considered all the stars with  $o < 5$  as well-measured.

#### 4.3.2 Correction for differential reddening, and zero point spatial variations

The foreground reddening of the GCs studied in this chapter goes from 0.15 (NGC 6715) to 0.37 (NGC 6388, Harris 1996), therefore, relatively large variations of reddening are expected within the field of view. Indeed, the CMDs in all clusters reveal that all MSs are significantly broader than what expected from our photometric precision, even taking into account the small unmodelable PSF spatial changes which cause photometric zero points variations of the order of 0.01-0.02 magnitudes (see Anderson et al. 2008 for details).

Correcting for both differential reddening and the residual spatial variations of the photometric zero point represents a necessary step towards an accurate analysis of the cluster sequences. For an accurate estimate of these corrections, we applied the method described in Sarajadeni et al. (2007).

In Figs. 4.1- 4.4 we show a CMD before and after our differential reddening and zero point corrections for the four clusters considered in this work.

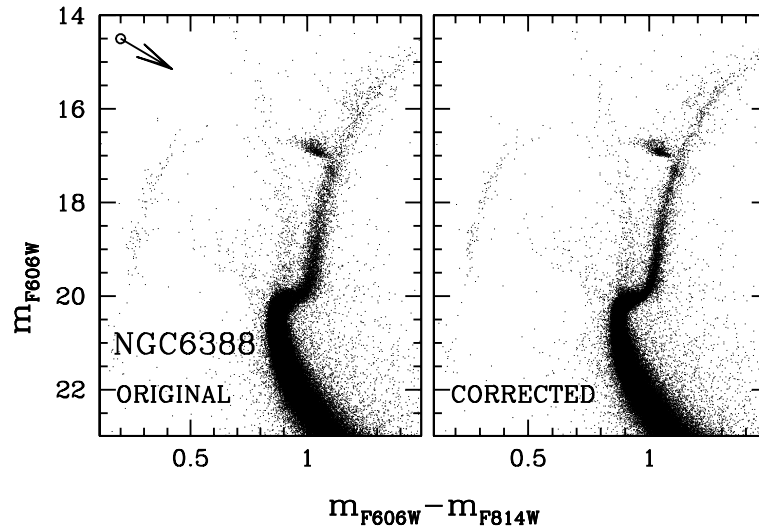


FIGURE 4.1— Comparison between the original (*left*) and the corrected CMD (*right*) of NGC 6388.

In Figs. 4.5- 4.8 we show a zoom of the CMDs around the MS turn off (MSTO) and SGB region in the observational plane  $m_{F606W}$  vs.  $m_{F606W} -$

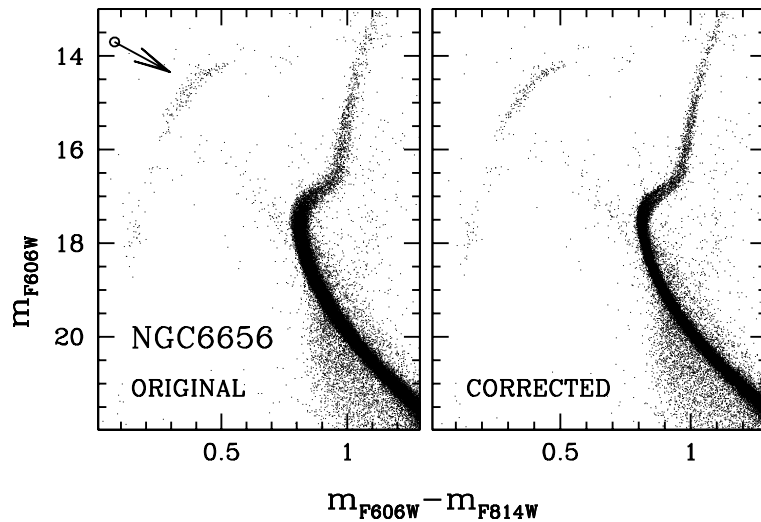


FIGURE 4.2— As in Fig. 4.1 for NGC 6656.

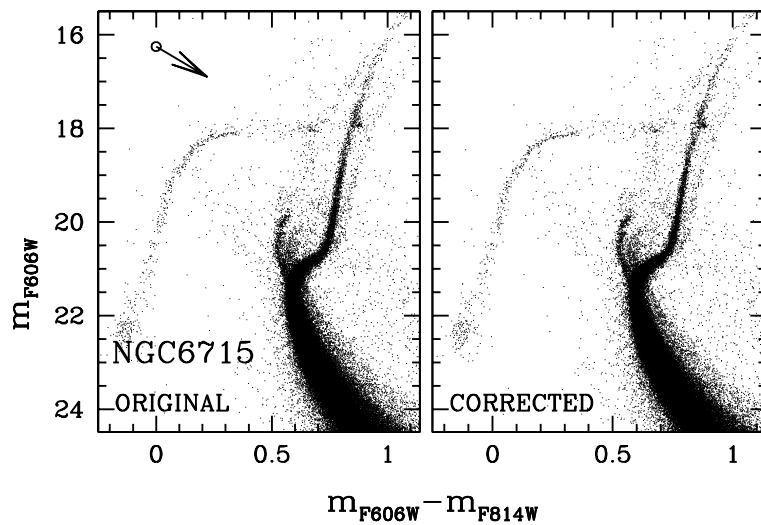


FIGURE 4.3— As in Fig. 4.1 for NGC 6715.

$m_{F814W}$ , for the four GCs: NGC 6388, NGC 6656, NGC 6715 and NGC 5286. All CMDs come from ACS/HST GO10775 data, and are corrected for differential reddening. Only stars that successfully passed our criteria of selection have been plotted.

The most interesting feature in all zoomed CMDs of Figs. 4.5- 4.8 is that

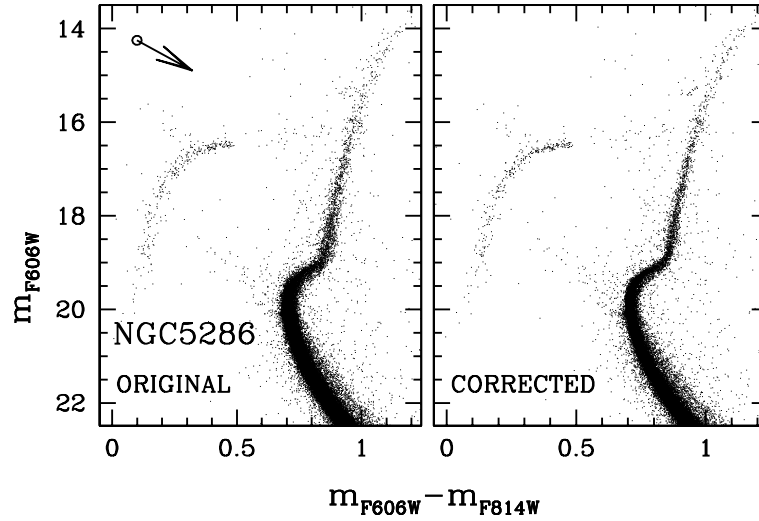


FIGURE 4.4— As in Fig. 4.1 for NGC 5286.

the SGB is cases clearly splitted in two branches. In some cases, this split is quite evident. This is exalted by the Hess diagram in the inset of each figure. These features are very similar to the SGBs observed in NGC 1851 (Milone et al. 2008), and much broader than expected on the basis of our photometric precision, which, for these selected star CMDs, is smaller than 0.01 magnitudes, even in the cluster center, as confirmed by the artificial star tests (see description of artificial star tests in Anderson et al. 2008). Note that the fraction of the stars Note also that the section of the HB running parallel to the SGB do not show any broadening or split, confirming that this feature is not due either to the differential reddening or to the residual zero point spatial variation.

#### 4.4 Proper motions and field-star decontamination

One of the most obvious advantages of having more than one epoch observations is the possibility to measure the proper motions of stars. Internal motions in all our clusters, with the precision provided by the existing data-sets, are negligible, so we can refer our motions to the cluster members.

The method that we have used to determine proper motions has been widely described in many other papers (e.g. see Bedin et al. 2008 and references within). For each cluster, we have adopted the reference frame defined by Anderson et al. (2008) with the abscissa and the ordinate increasing from east to west and from south to north respectively. To measure proper motions relatively to the bulk cluster motion, we started by identifying all the stars that,

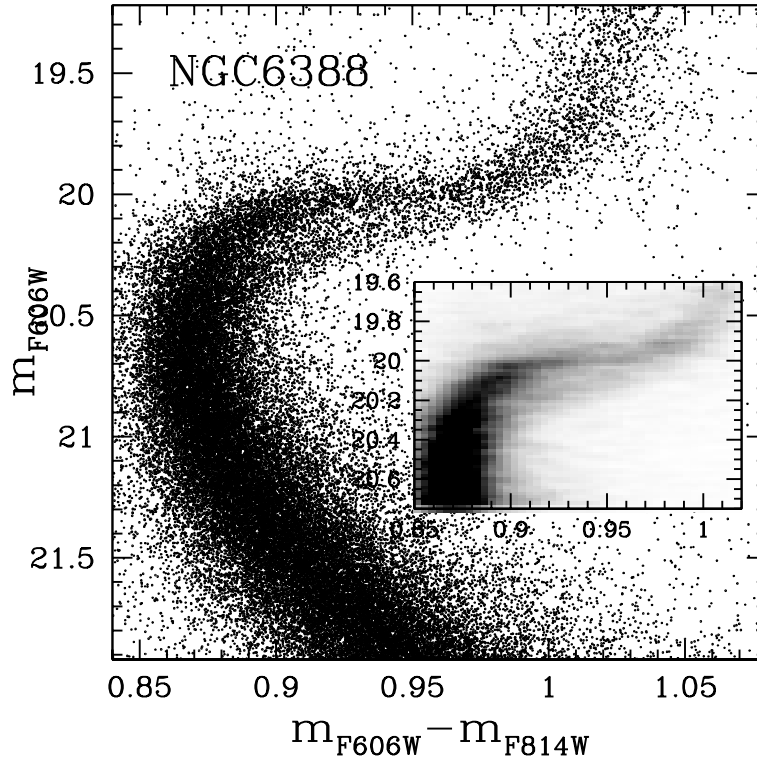


FIGURE 4.5— CMD of NGC 6388, from GO 10775 data corrected for differential reddening. Only stars that successfully passed all the selection criteria have been plotted. In the inset we show the Hess diagram for the CMD region around the SGB.

on the basis of their position in the CMD, are probable cluster members and obtained a raw proper motion estimate by using a global transformation based on this sample. Then we have iteratively excluded from this list all the stars that have not cluster like proper motion, even though they are placed near the cluster sequences. This ensures that the relative motions of cluster stars should be zero to within the measurement errors. Finally, we have minimized the effect of any residual distortion on transformations into reference frame, by using local transformations based on a sample of  $N$  closest stars, with  $N$  ranging from 35 to 75.

The result is shown in Figures 4.9- 4.12 where we show for each of the four clusters, the CMD of the stars for which we have an estimate of the proper motions (on the left), the vector point diagram at different magnitude levels (middle), and the proper motion cleaned CMD. The distinction between member and non-member was done following the procedures described in Piotto et

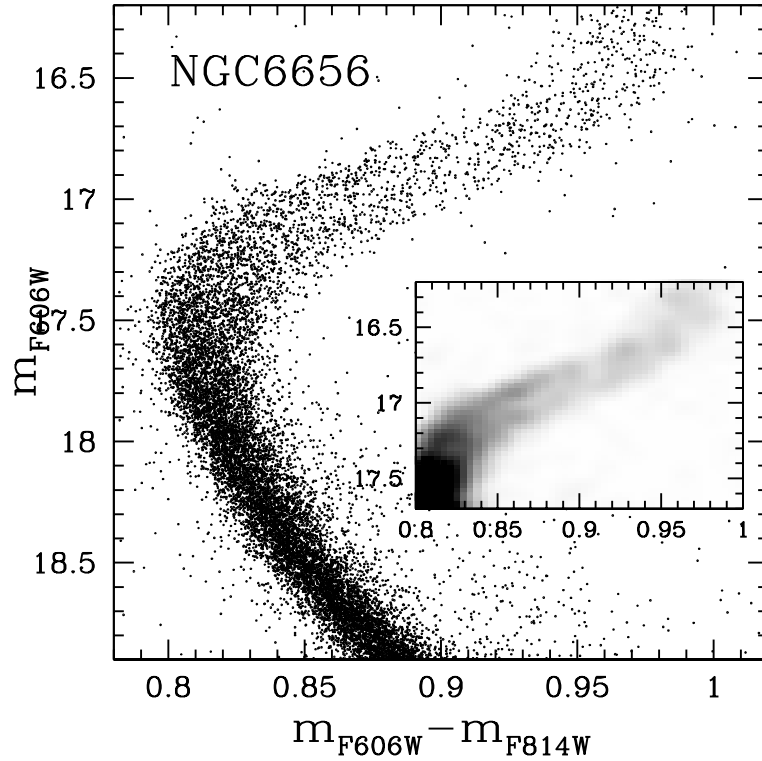


FIGURE 4.6— As in Fig. 4.5 for NGC 6656.

al. (2007).

#### 4.4.1 Independent confirmation of the SGB split

In this section we used the photometry from all of the other WFPC2 and ACS independent data sets to confirm the split that we found in the CMD from the homogeneous GO10775 data. We note that the new images have been collected with different cameras, filters, orientations. The only draw-back is that WFPC2 data overlap the GO10775 field of view only partially, reducing significantly the SGB star count statistics.

The strategy we adopted to perform our consistency test is rather simple. First of all, we arbitrarily separated on the GO-10775 CMDs the stars on the faint (fSGB) and on the bright (bSGB) section of the SGB, and then selected (on the basis of their position on the images) the same stars on the independent data sets, and plotted the corresponding CMDs. Only proper motion selected cluster members have been plotted. The independent CMDs from all the data



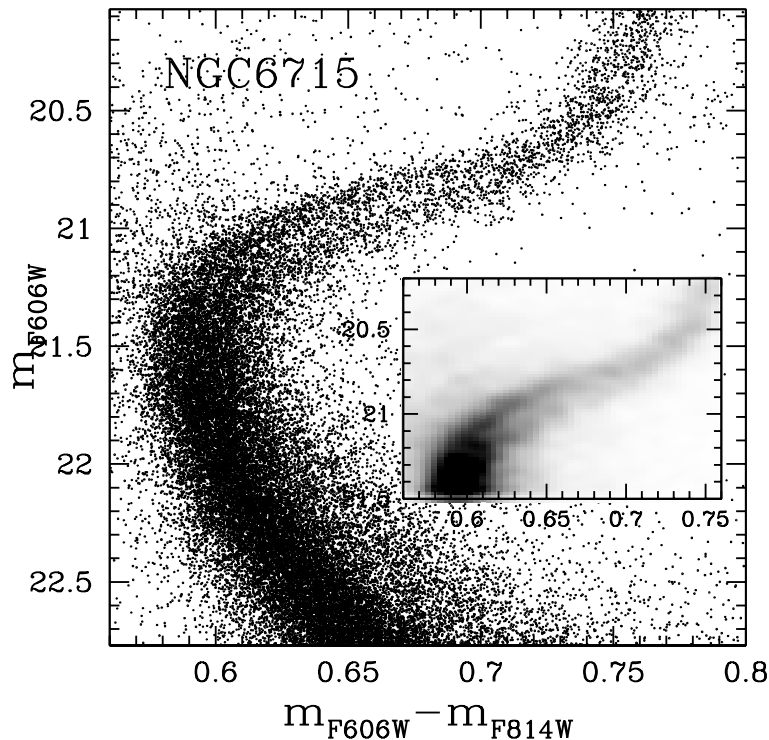


FIGURE 4.7— As in Fig. 4.5 for NGC 6715.

sets are shown in Fig ?? . Note that in all the CMDs we have plotted only stars that are also present in the GO10775 CMD. Two CMDs, from two independent data sets are shown for M22 (top-row), and NGC 6388 (middle-row), and one for each of NGC 5286 (bottom-left) and NGC 6715 (bottom-right). The inset of each panel, shows the GO 10775 CMDs for the stars in common between the two data-sets. The fSGB stars are plotted in blue, while the bSGB ones are in red. In all panels we used the same color code to identify the same stars. It is clear that, in all four clusters, all the stars that were on the bSGB in the GO10775 CMDs are also in the bSGB in the other independent CMDs. No random or systematic errors can explain the fact that the two distribution remain confirmed in independent data-set.

Figures 4.14- 4.19 further confirms that NGC 6388, NGC 6656, NGC 5286 and NGC 6715 posses indeed a double SGB, possibly similar to the one previously identified in NGC 1851 by Milone et al. (2008a).

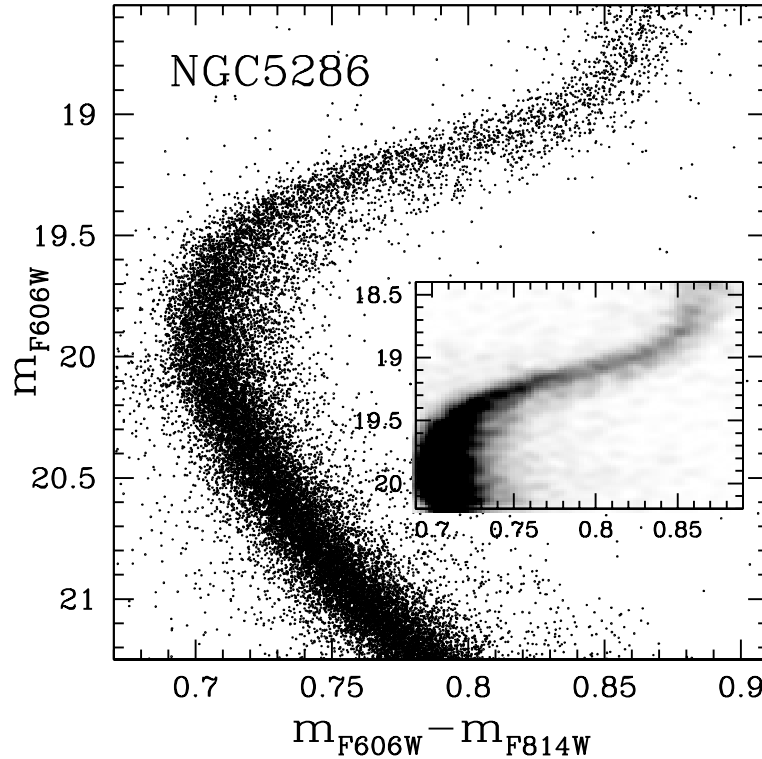


FIGURE 4.8— As in Fig. 4.5 for NGC 5286.

#### 4.5 Theoretical isochrones

A simple way of explaining the SGB split is to assume that in each cluster there are two stellar populations with different ages and similar chemical composition. In the left panels of Figs. 4.20-4.23 we overplotted to the observed CMDs theoretical isochrones from Pietrinferni et al. (2004) with the same chemical composition.

Cassisi et al (2008) demonstrated that the SGB and HB morphology of NGC 1851 can be reproduced by assuming the existence of two stellar groups: a normal  $\alpha$  enhanced population corresponding to the bSGB, and one, that is characterized by a CNONa anticorrelations, with an increased CNO abundance and corresponds to the fSGB. Here we applied a similar approach to our clusters. The comparison between theoretical models and observed data is shown in the right panels of Figs. 4.20-4.23. We found that, in all the clusters, the age difference between the bSGB and the fSGB should be negligible in full agreement with the result of Cassisi et al. (2008) on NGC 1851.

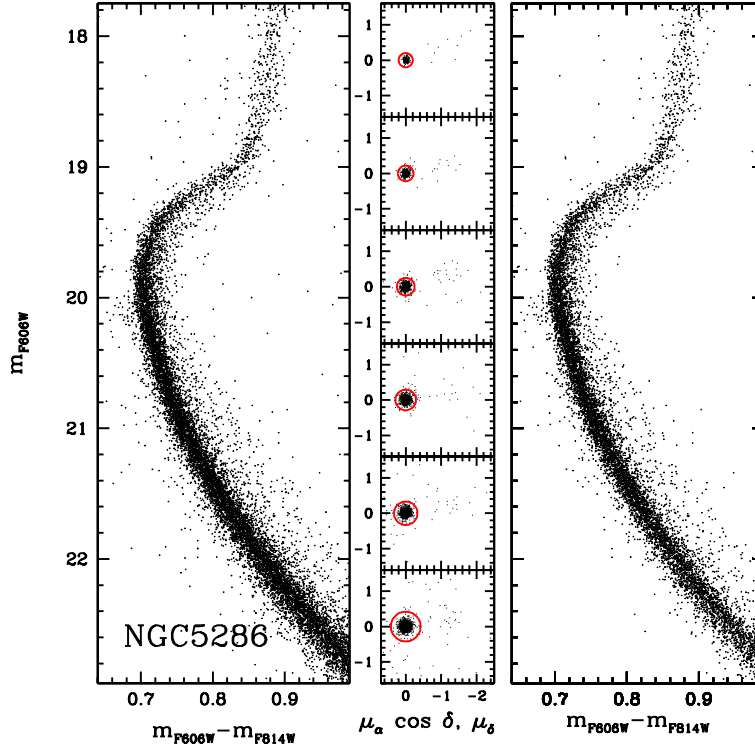


FIGURE 4.9— *Left* the original CMD of NGC 5286 from G010775 photometry, only stars with available proper motions have been plotted; *center* proper motion diagram in different magnitude intervals; *right*: The CMD of stars whose proper motion lie in the red circles.

The best fitting distance modulus, average reddening, and ages are listed in Table 4.5. We accounted for the reddening variation as a function of the magnitude by using the relations from Girardi et al. (2002). The last column indicates the age difference between the two stellar populations,  $\Delta_{\text{age}}$ , that we obtain assuming age as the only responsible of the SGB split.

## 4.6 Population ratio

In this section, we take advantage of the high photometric quality of our CMDs from GO 10775 data to homogeneously measure the fraction of stars belonging to each SGB.

We have followed the method adopted by Milone et al. (2008b) to determine the population ratio in LMC clusters. In this case, we limited the analysis to the SGB region only. The main steps of our procedure are illustrated in Fig. 4.24 for the case of NGC 6656. We began by finding the isochrones that best fit the

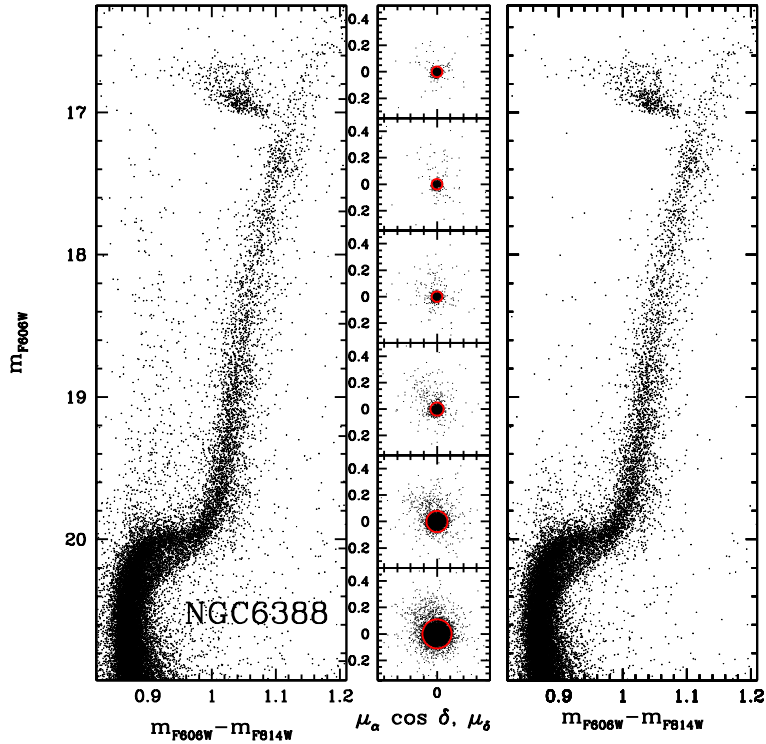


FIGURE 4.10— As in fig. 4.9 for NGC6388.

two SGBs, represented by the red and the blue lines. We then defined by hand two pairs of reference points:  $P_{1,f}$  and  $P_{2,f}$  on the fSGB isochrone and  $P_{1,b}$  and  $P_{2,b}$  on the bSGB isochrone. The two pairs of points have been chosen with the criterion of delimiting the region of the CMD where the split is more evident and have been used to draw the gray lines in panel (a). Only stars contained in the region between these lines have been used for the following analysis.

In panel (b), we have shifted and rotated the reference frame such that the new origin corresponds to  $P_{1,b}$  and the abscissa goes from  $P_{1,b}$  to  $P_{1,f}$ . For simplicity, in the following, we will refer to the abscissa and ordinate in this

| ID       | $(m - M)_0$ | $E(B - V)$ | Ages from 'normal' isocrones | Ages from 'extreme' isocrones |
|----------|-------------|------------|------------------------------|-------------------------------|
| NGC 6388 | 15.30       | 0.35       | 10,12 Gyr                    | 10,12 Gyr                     |
| NGC 6656 | 12.60       | 0.36       | 12,14 Gyr                    | 10.5,12 Gyr                   |
| NGC 6715 | 17.10       | 0.25       | 11,13 Gyr                    | 10,11 Gyr                     |
| NGC 5286 | 15.20       | 0.25       | 12,14 Gyr                    | 10.5,12 Gyr                   |

TABLE 4.2— Best fitting distance modulus, average reddening, and ages

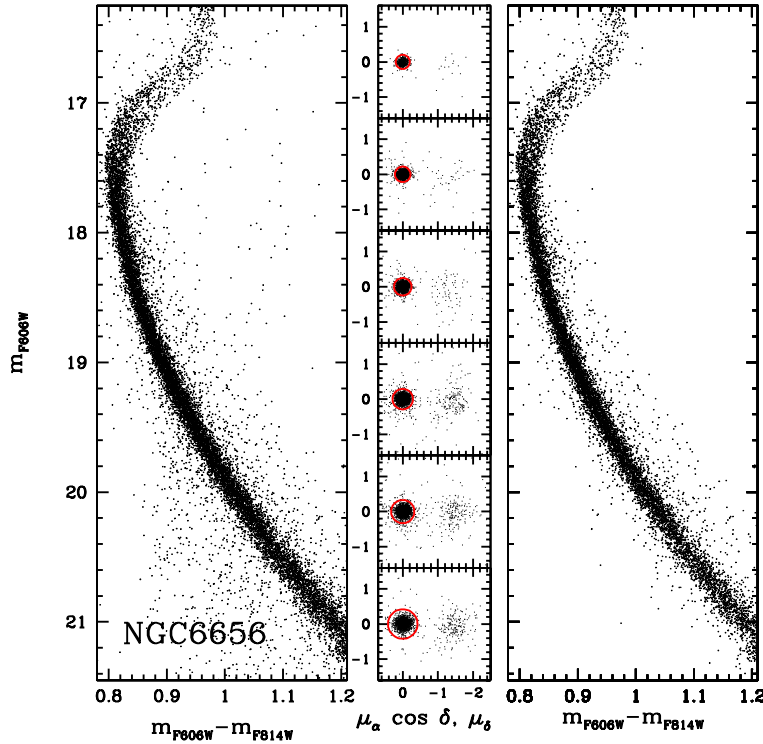


FIGURE 4.11 — As in fig. 4.9 for NGC6656.

plane as 'color' and 'magnitude'. The red dashed line is a fiducial line through the region close to the fSGB. We drew it by marking on the region close to the fSGB four points, equally spaced in 'magnitude' and drawing, a line through them by means of a spline fit.

In panel (c) the 'color' of this line has been subtracted from the color of each star, and the 'magnitude' of each star has been divided by the 'magnitude' of a stars with the same 'color' that lie on the line that goes from  $P_{2,f}$  to  $P_{2,b}$ .

For the analysis that follows, we have divided the  $\Delta$ 'magnitude' range into four bins. In each of them, we have determined the fraction of stars belonging to each SGB as follows. We assumed to be able to model the  $\Delta$ 'color' distribution by fitting the sum of two partially overlapping Gaussian, but we need to reduce the influence of outliers (such as stars with poor photometry, residual field stars and binaries). To this end, we did a preliminary fit of the Gaussian using all available stars, then we rejected all the stars distant more than two  $\sigma_b$  from the bSGB and less than  $2 \sigma_f$  from the fSGB (where the  $\sigma$ 's are those of the best fitting Gaussian in each  $\Delta$ 'magnitude' bin fitted to the fSGB and bSGB

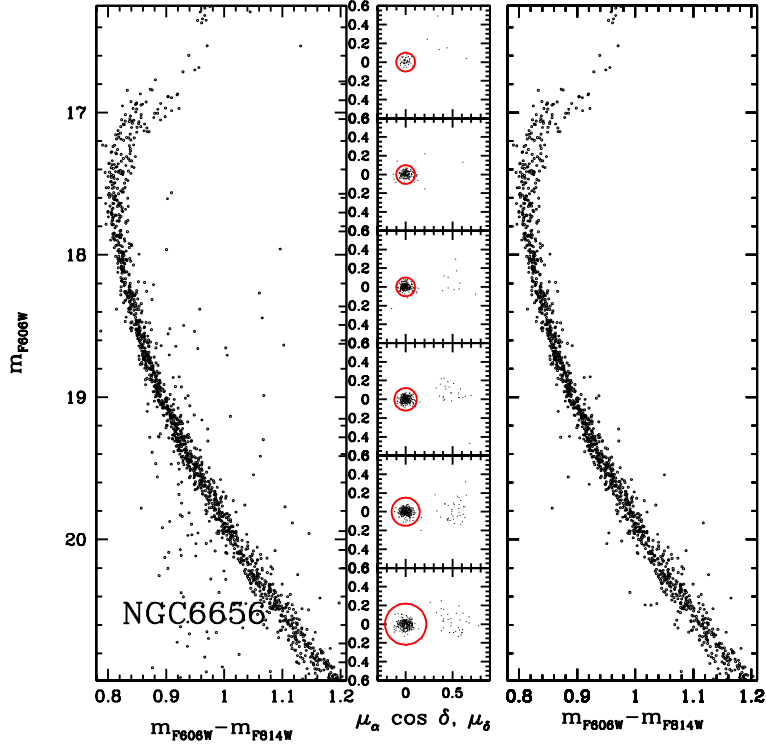


FIGURE 4.12— As in fig. 4.9 for NGC6656.

respectively), and repeated the fit.

The continuous vertical lines show the centers of the best-fitting Gaussian in each  $\Delta$ 'magnitude' interval. The red dashed line is located two  $\sigma_f$  on the "blue" side of the fSGB and the blue line runs two  $\sigma_b$  on the "red" side of the bSGB.

Note that, to each point  $(P_{1,f(b)}, P_{2,f(b)})$  that we have arbitrarily selected on the two isochrones with the only purpose of disentangle the two SGBs, corresponds a mass  $(\mathcal{M}_{P_{1f(b)}}, \mathcal{M}_{P_{2f(b)}})$ . In order to obtain a more correct measure of the fraction of stars in each of the two population ( $f_{bSGB}, f_{fSGB}$ ) it must be noted that we are dealing with two different mass intervals ( $\mathcal{M}_{P_{2f}} - \mathcal{M}_{P_{1f}} \neq \mathcal{M}_{P_{2b}} - \mathcal{M}_{P_{1b}}$ ) and we have to compensate for two facts: first, more massive stars are more rare, and second, more massive stars evolve faster.

We calculated the fraction of stars in each branch as:

$$f_{bSGB} = \frac{\frac{A_b}{N_b/N_f}}{A_f + \frac{A_b}{N_b/N_f}}$$

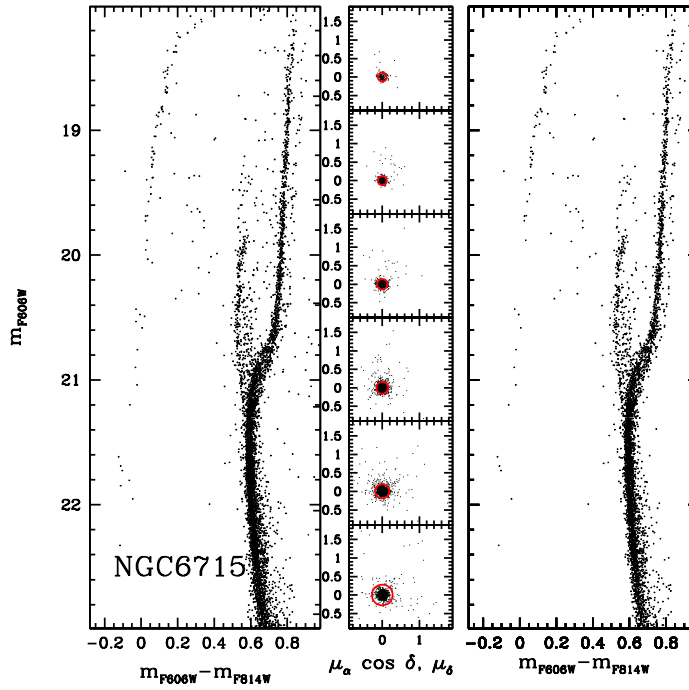


FIGURE 4.13— As in fig. 4.9 for NGC6715.

$$f_{fSGB} = \frac{A_f}{A_f + \frac{A_b}{N_b/N_f}}$$

where  $A_b$  and  $A_f$  are the area of the Gaussian that best fit the bSGB and the fSGB, and  $N_{f(b)} = \int_{P_{1,f(b)}}^{P_{2,F(b)}} \phi(\mathcal{M}) d\mathcal{M}$ , being adopting for  $\phi(\mathcal{M})$  the Salpeter (1955) IMF.

The results are summarized in Table 4.6.

Clearly, the two SGB groups include significantly different fractions of the total SGB stars in the different clusters. Interestingly, in all the cases, the maximum separation between the bSGB and the fSGB is about 0.15 magnitudes.

#### 4.6.1 The Horizontal-Branch stars

Since the GO10775 data set included short exposure images, our CMDs include also the horizontal branch (HB). All clusters analyzed in the present chapter have a bimodal HB: most of HB stars in NGC 6388 are in the red side (with respect to the RR Lyrae gap) of the HB. In the other three clusters, the main

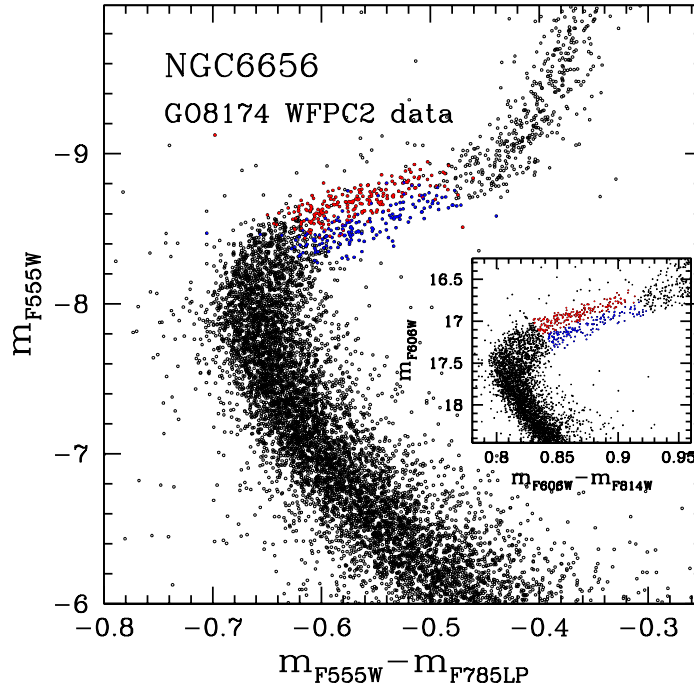


FIGURE 4.14— CMDs of NGC 6656 from ACS and WFPC2 data sets. Only stars that match the WFC/ACS GO10775 field of view have been plotted. The insets show a the CMD from GO10775 around the SGB for stars in common and have been used to select two groups of stars in the bSGB and fSGB. These stars are marked with the same colors in the main CMD.

HB population belongs to the blue HB. The fraction of the red/(blue+red) HB stars is reported in Table 4.6. On the basis of the relative numbers of red to blue HB stars and bSGB to fSGB populations in NGC 1851, Milone et al. (2008b) made the hypothesis that the red HB stars could be the progenie of the bSGB ones, and that the blue HB comes from fSGB stars. In Fig. 4.32 we have plotted the relative numbers of red HB stars with respect to the total red + blue HB stars as a function of the fraction of bSGB to the total SGB populations for the four clusters studied in this chapter (black points) and for NGC 1851 (red point, from Milone et al 2008). Only in two cases NGC 6388 and NGC 6715 the relative numbers of red to blue HB stars and bSGB to fSGB populations are similar.



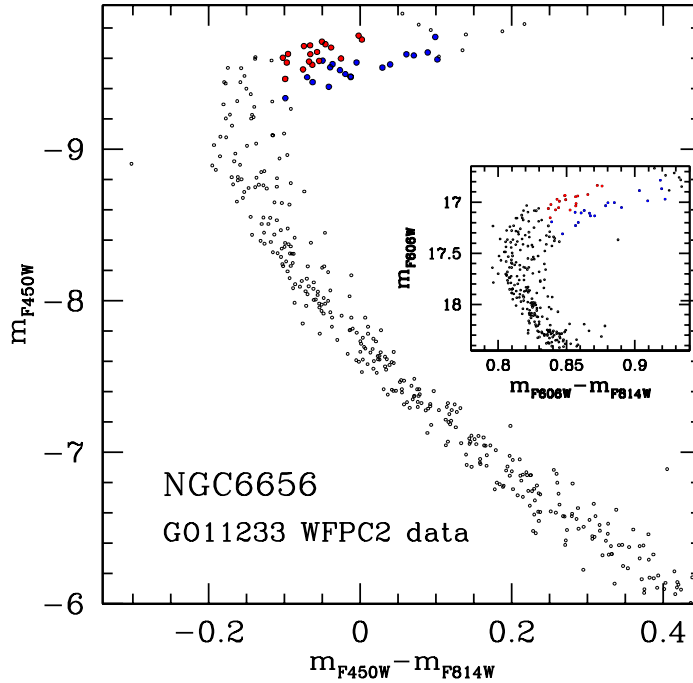


FIGURE 4.15 — As in Fig. 4.14 for NGC6656

#### 4.6.2 An upper limit to the intrinsic width of the MS

The position on the CMD of a stars in the lower part of the MS, after  $\sim 10$  Gyr, can be considered age independent. An intrinsic color spread in the MS can only be due to a star to star variations of the chemical composition. A wide color base-line it is a convenient way to study any possible MS spread, as demonstrated by Piotto et al. (2007) who showed that in the  $m_{F814W}$  vs.  $m_{F475W} - m_{F814W}$  CMD the split of the MS in NGC 2808 becomes very prominent. For these reasons, our GO10922 and GO11233 programs were designed to have the largest color base-line made reasonably be possible by the WFPC2 performances, still allowing for a  $S/N \sim 100$  for stars 1.5 mag fainter than the MSTO.

In order to check for any possible spread in the MS in NGC 6388, NGC 6656, and NGC 6715, we built CMDs using the  $m_{F814W}$  ACS/WFC photometry from GO10775 and the  $m_{F450W}$  WFPC2 photometry from GO10922 and GO-11233. In the case of NGC 5286, a cluster that was not observed within GO10922

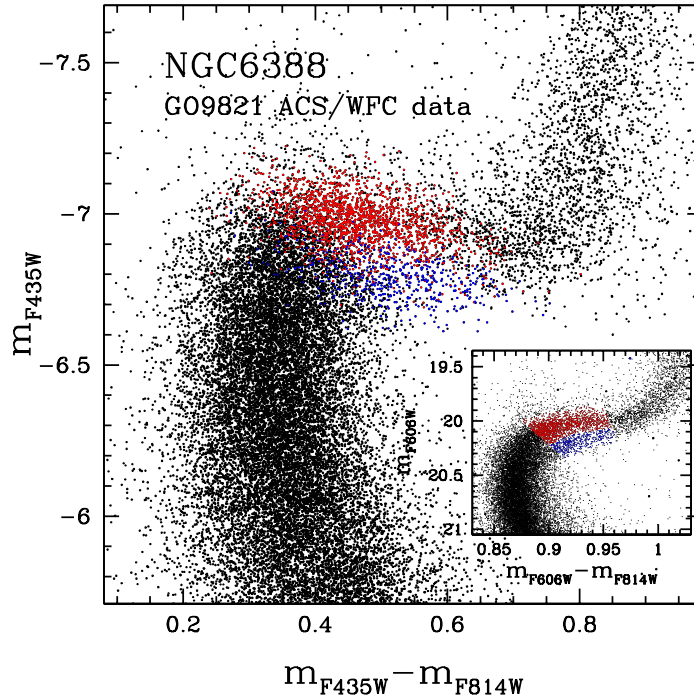


FIGURE 4.16— As in Fig. 4.14 for NGC6388

or GO-11233, we have been limited to the shorter color base-line ( $m_{F606W} - m_{F814W}$ ) provided by GO-10775 ACS/WFC observations.

The procedure that we have adopted to measure the MS spread is illustrated in Fig. ??, and described in great details in Milone et al. (2008c). The left panel shows the CMD. In order to derive the MS fiducial ridge-line we have divided the CMD in intervals of twelve magnitude bins in F814W band, computed the median color and magnitude in each bin and derived a raw fiducial line by fitting these points with a spline. Then we derived for each star the absolute value of the difference between its color and the color of the fiducial line, and calculated the  $\sigma$  as the 68.27<sup>th</sup> percentile. All the stars with distances larger than  $N \sigma$  from the fiducial were rejected and the survivors used to redetermine the median color, magnitude and  $\sigma$ . We iterated this procedure five times with  $N$  going from 6 to 2 (integer numbers).

In all the cases, the observed color dispersion is nearly consistent with the one due to photometric errors, therefore we have no evidence for an intrinsic

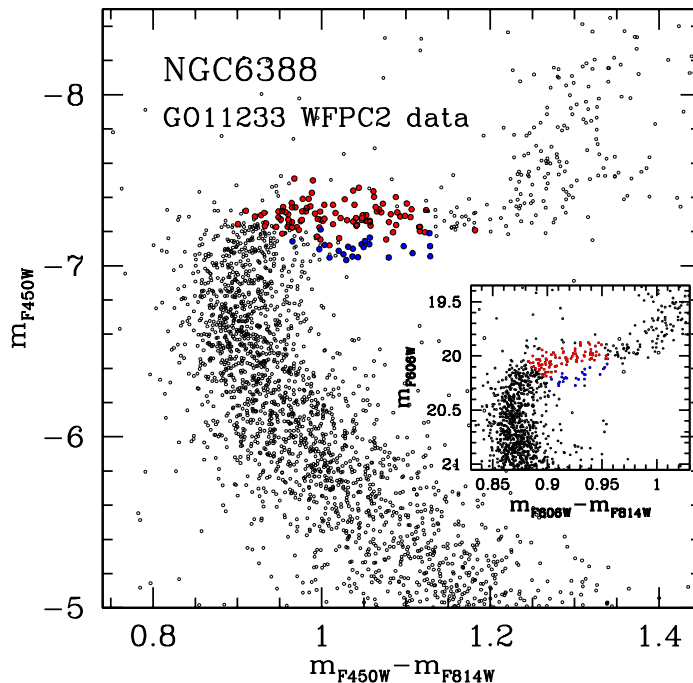


FIGURE 4.17— As in Fig. 4.14 for NGC6388

spreaded or a splitted MS.

#### 4.7 The double fSGB of NGC 7089 (M2) and NGC 362.

In this section we present preliminary results from our study on the anomalous SGB of NGC 7089 (M2) and NGC 362. An accurate comparison of several high accuracy HST CMDs in different photometric bands demonstrates that both these GCs hosts a splitted SGB. Other than the main bright SGB component, they show a second fainter and poorly populated SGB.

In the top-left panel of Fig. 4.33 CMD we show the CMD from GO10005 data, on which we selected by hand a sample of stars that apparently belong to the fSGB and marked them with red circles. In the other CMDs we show for the same stars the CMD from several different ACS/WFC datasets. When we plot on this CMD the stars classified as fSGB with the same symbols, we can clearly see that fSGB stars are sistematically fainter than the bulk of SGB stars. We note that our CMDs contain only stars that, on the basis of their

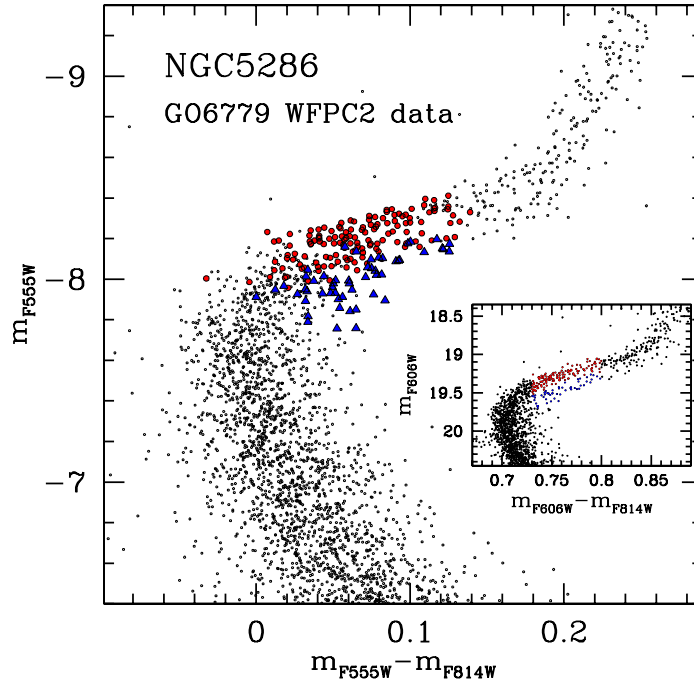


FIGURE 4.18 — As in Fig. 4.14 for NGC5286

proper motion, are cluster members. In addition, this cluster suffer by a small average reddening ( $E(B-V)=0.05$ ) and therefore differential reddening should be negligible. This is confirmed by the fact that fSGB stars are located averywhere in the field of view. In spite of this, we have corrected our photometry for any spatially dependent variation of the photometric zero point. Therefore the NGC 362 shows a split similar to that found in other cluster. In this case, however the fSGB component should contain a small percentage of SGB stars.

Also NGC 7089 posses a second poorly populated fSGB as shown in the  $m_{F606W}$  vs  $m_{F606W} - m_{F814W}$  CMD of Fig. 4.34 In Figs. 4.35 and 4.36 we have shown that stars identified as fSGB members in the CMD of Fig. 4.34 are sistematically fainter than the bulk of SGB stars. Since this cluster is not effected by significant variation of reddening ( $E(B-V)=0.06$ , Harris 1996, 2003) and only stars with cluster-like proper motion have been plotted, this further confirms that NGC 7089 the fSGB is a real.

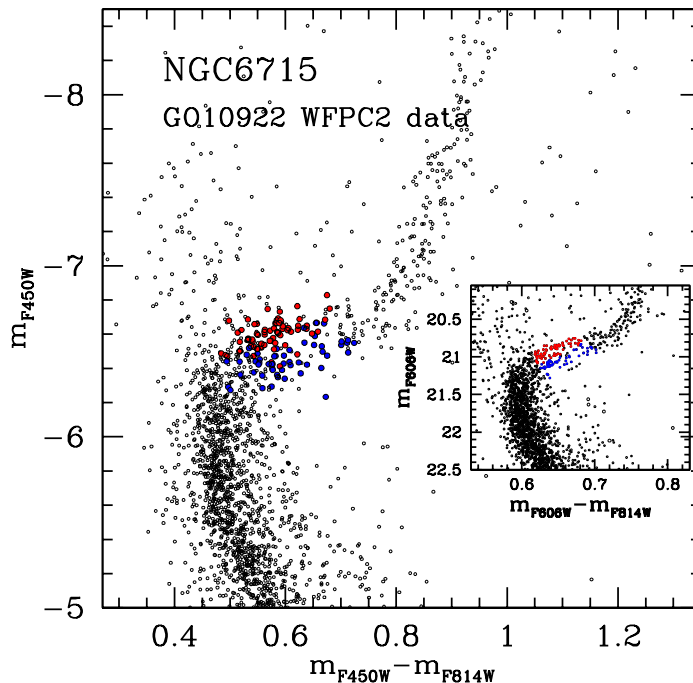


FIGURE 4.19 — As in Fig. 4.14 for NGC6715

#### 4.8 The bimodality in $s$ process elements and $[\text{Fe}/\text{H}]$ in M22

The most intriguing result comes from the recent paper by Marino et al. (2009), where we present high resolution spectroscopic analysis for a sample of seventeen RGB stars in the GC NGC 6656 from UVES and FLAMES+UVES data.

We confirm that NGC 6656 is a metal poor GC, with a mean iron-content  $[\text{Fe}/\text{H}] = -1.76 \pm 0.02$  and a mean  $\alpha$ -enhancement  $[\alpha/\text{Fe}] = +0.36 \pm 0.04$ . Sodium and oxygen follow the well known anti-correlation, while no evidence for an Mg-Al anticorrelation was revealed. A clear correlation was found between Na and Al.

We find a strong dichotomy in the distribution of the  $s$ -process elements barium, yttrium and zirconium as shown in Fig. 4.37.

Most importantly, we find that the abundance of these elements is correlated with the iron abundance. Stars enriched in  $s$ -process elements also show larger values of  $[\text{Fe}/\text{H}]$ , by  $\sim 0.13$  dex (Figs. 4.38 and 4.39, right panel). The  $s$ -process elements abundance correlates with calcium, and calcium with iron (Fig. 4.39,

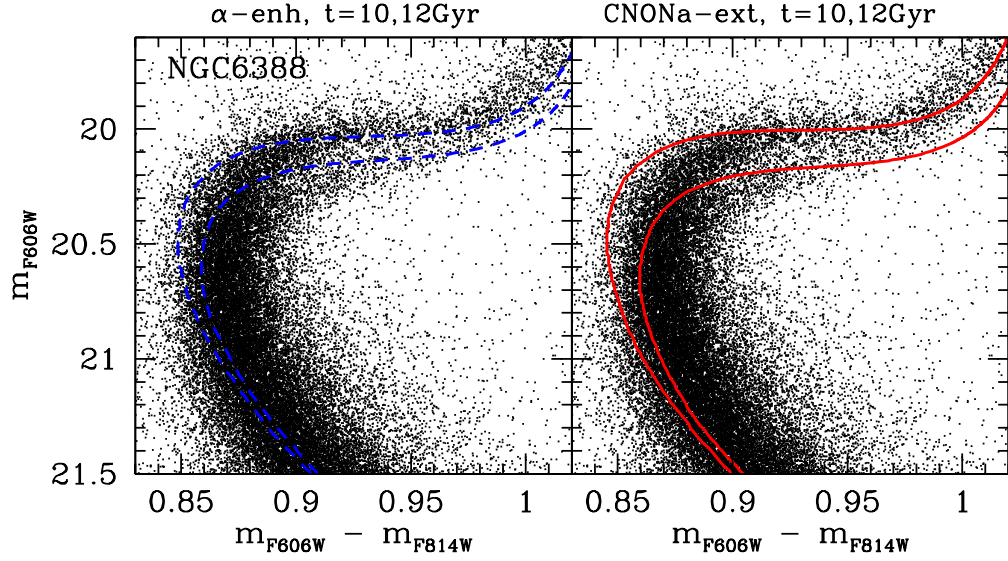


FIGURE 4.20—  $m_{F606W}$  vs.  $(m_{F606W} - m_{F814W})$  diagram of NGC 6388 from GO 10775 zoomed around the SGB. The dashed lines are isochrones for the normal population. The solid lines represent the isochrones for the extreme population.

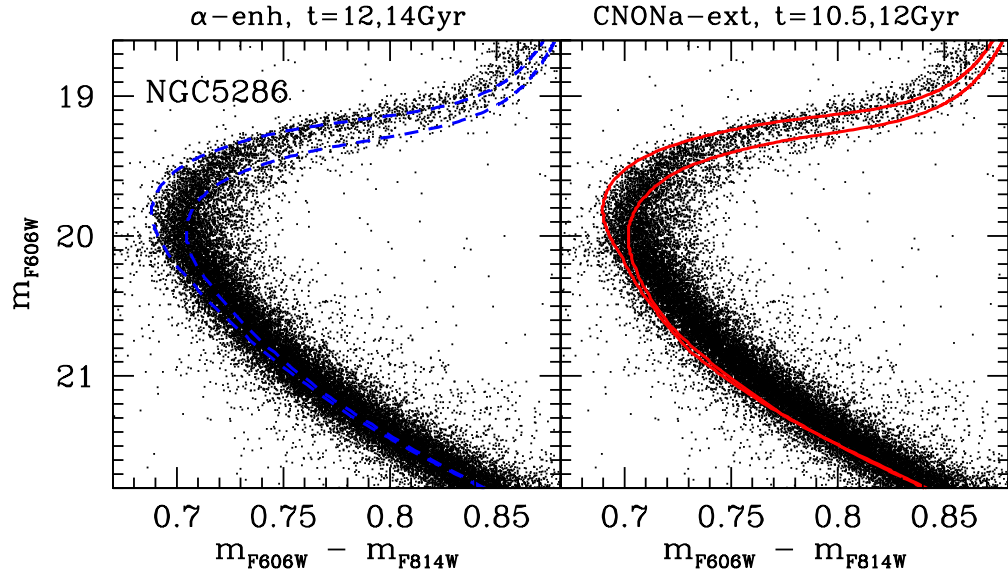


FIGURE 4.21— As in Fig. 4.20 for NGC 5286.

right panel). No clear correlation is present between the  $s$ -process elements and

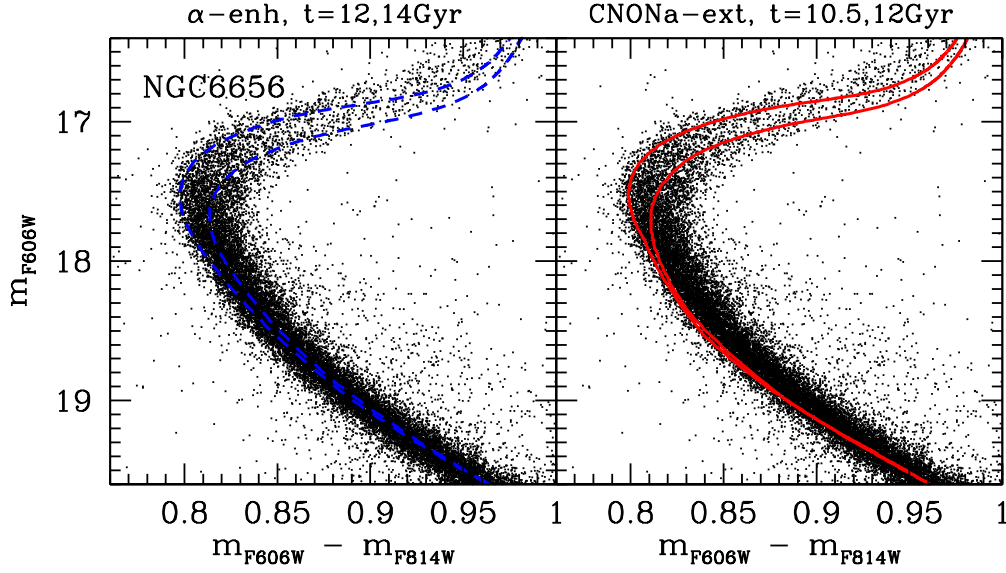


FIGURE 4.22— As in Fig. 4.20 for NGC 6656.

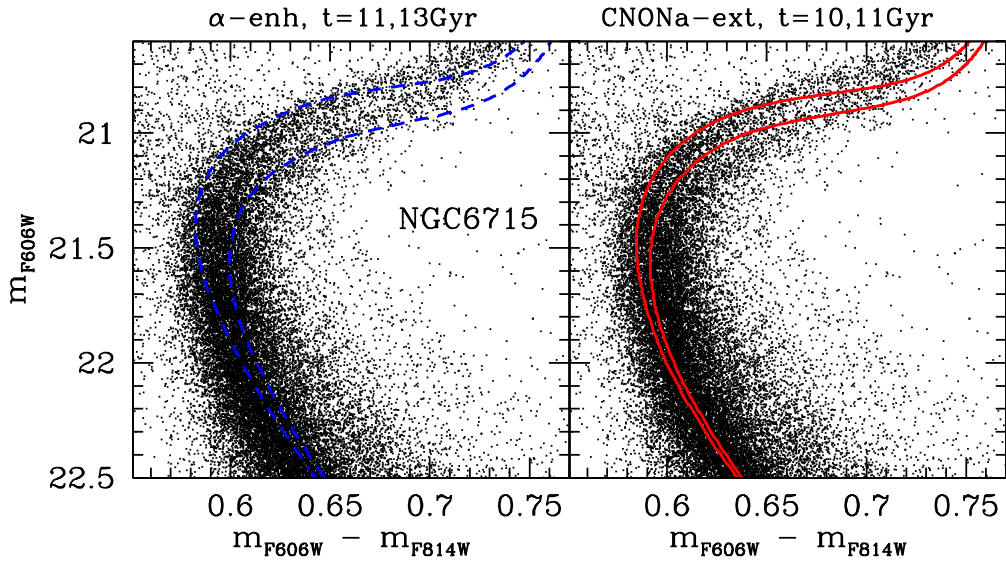


FIGURE 4.23— As in Fig. 4.20 for NGC 6715.

sodium, and between iron and sodium, but we noted that the  $s$ -element enriched stars show larger values of sodium. These stars show also an overabundance of magnesium and silicon. The correlation between  $s$ -process elements, and Ca



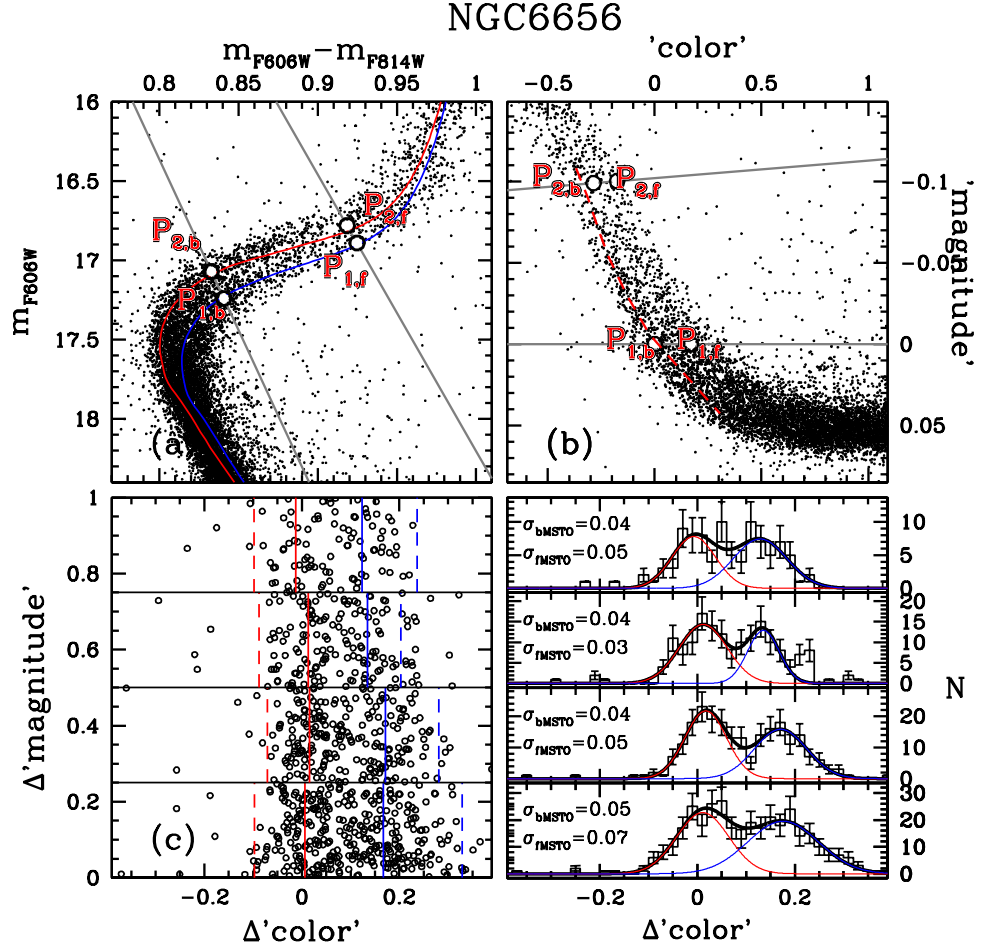


FIGURE 4.24— Procedure adopted to measure the fraction of stars belonging to the bSGB and fSGB in NGC 6656. Panel (a) shows a zoom of the CMD from Fig. ?? with the isochrones that best fits the fSGB and the bSGB overimposed. The grey lines delimit the portion of the CMD where the split is more evident. Only stars from this region are used to measure the population ratio. In Panel (b) we shifted and rotated the reference frame of Panel (a). Red dashed line is the fiducial of the region around the bSGB. In Panel (c) we plotted stars of the region around between the grey lines but after the subtraction of the  $'color'$  of each star from the  $'color'$  of each star and the division of the  $'magnitude'$  of each star by the  $'magnitude'$  of the upper grey line. The four right bottom panels show the  $\Delta'color'$  distribution for stars in four  $\Delta'magnitude'$  bins. The solid lines represent a bigaussian fit. For each bin, the dispersions of the best fitting gaussians are indicated.



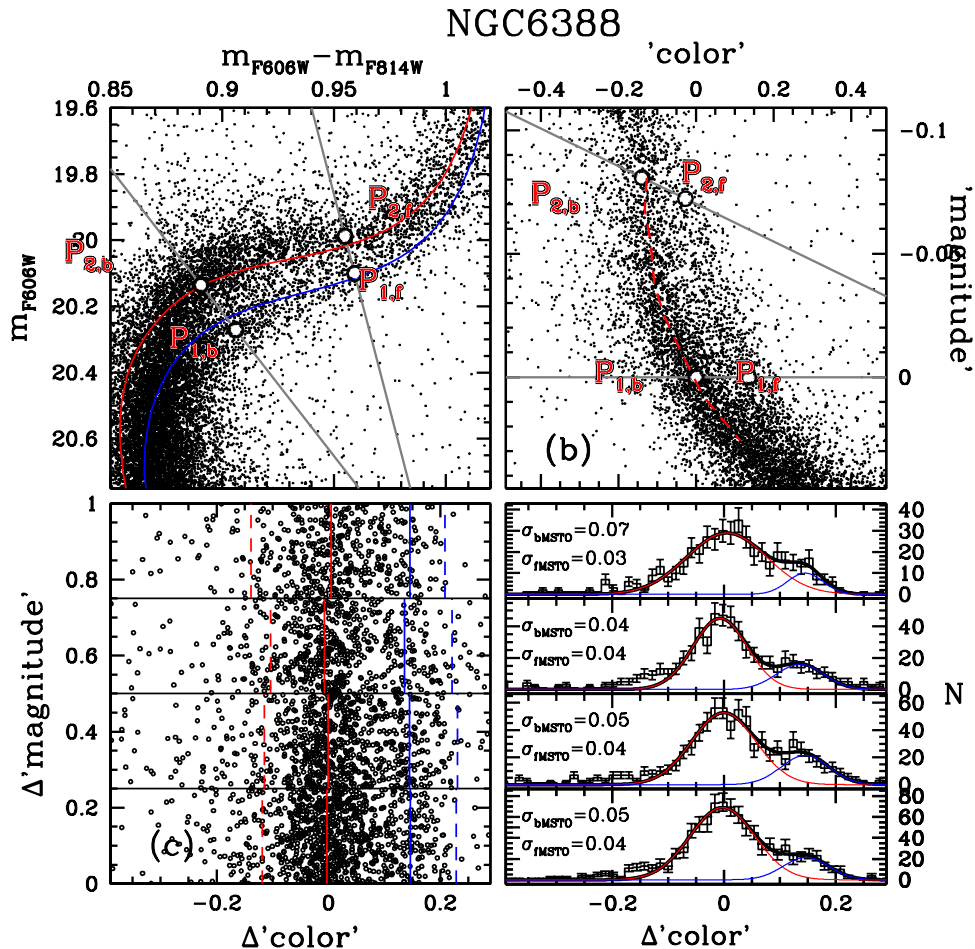


FIGURE 4.25— As in Fig. 4.24 for NGC 6388.

abundances, with  $[\text{Fe}/\text{H}]$  is the strongest argument in favour of the presence of an intrinsic spread in  $[\text{Fe}/\text{H}]$  in M 22. All these results have been confirmed by a sample of fourteen lower resolution GIRAFFE spectra, which allowed us to double the original UVES sample.

According to most recent theoretical models by Pietrinferni et al. (2004), a difference in metallicity of 0.13 dex should cause a difference of  $\sim 0.10$  mag in the F606W ACS/WFC band at the level of the SGB. Piotto et al. (2009) have indeed found that the SGB of M 22 is separated into two, distinct branches. However, the average separation in F606W band is of 0.17 magnitudes: The

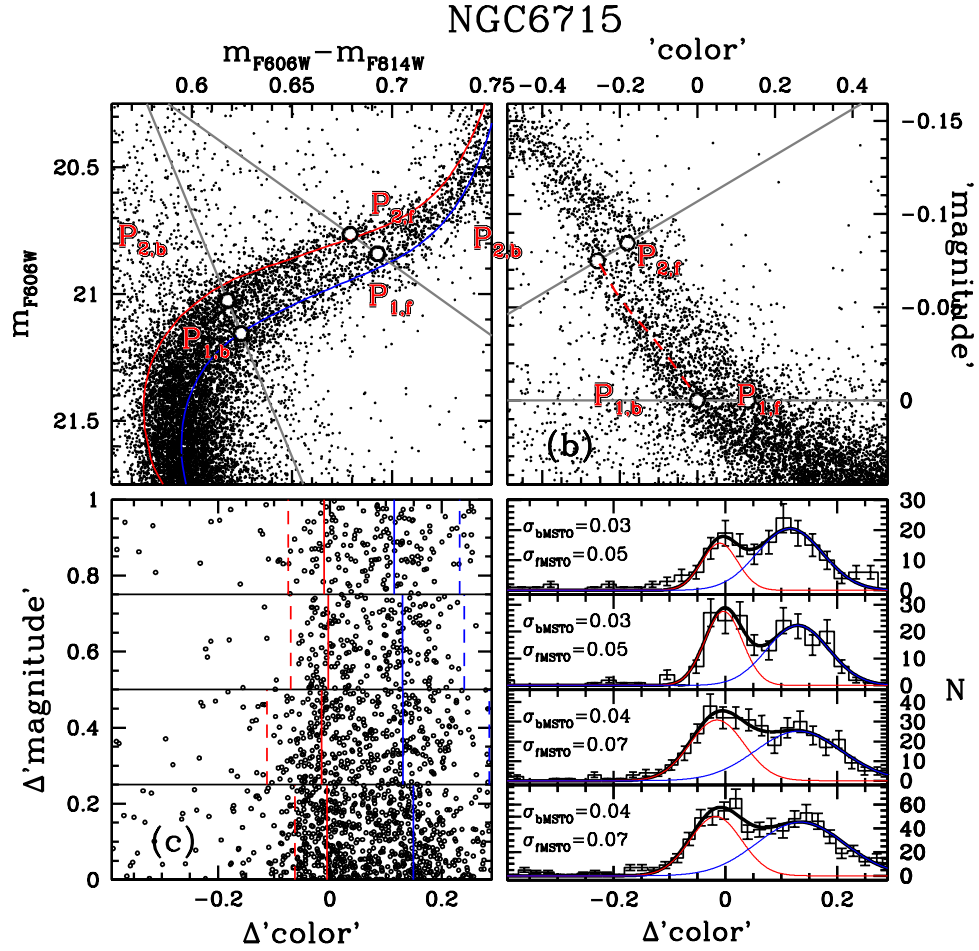


FIGURE 4.26— As in Fig. 4.24 for NGC 6715.

SGB split can not be attributed to a difference in  $[\text{Fe}/\text{H}]$  alone.

The fraction of stars on the bright SGB (bSGB) corresponds to  $60\% \pm 5\%$  of the total SGB population, while the faint SGB (fSGB) includes the remaining  $40\% \pm 5\%$  of the SGB stars. In the stellar sample of the present section, the fraction of Ba-strong, Y-strong, Zr-strong stars is  $\sim 41\%$ . It is therefore tempting to connect the  $s$ -process element poor sample to the bright SGB stars, while the faint SGB stars could be the ones with enhanced  $s$ -process elements. The correct reproduction of the two SGBs needs an accurate determination of the NaCNO abundances, as shown by Cassisi et al. (2008) for the analogous case

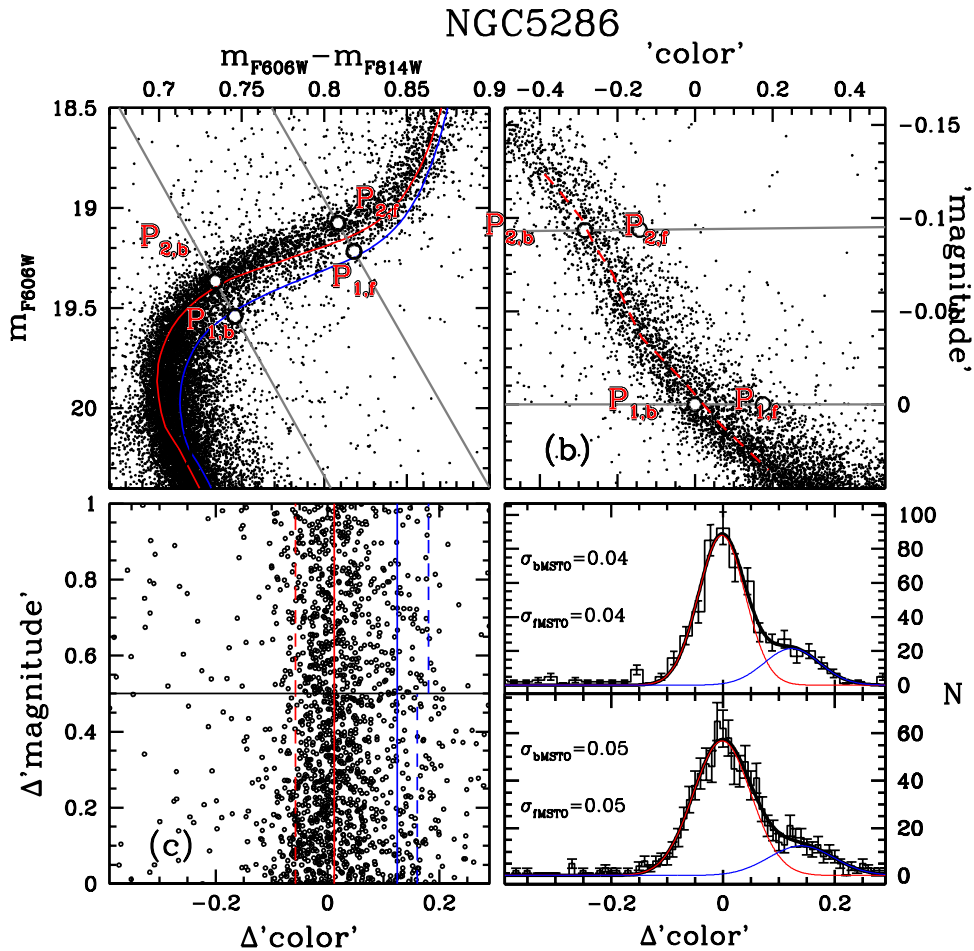


FIGURE 4.27— As in Fig. 4.24 for NGC 5286.

of NGC 1851. Also an He variations between the two populations can affect the SGB morphology. Indeed, we note that M 22 shares many similitudes with  $\omega$  Centauri and NGC 1851: these clusters, where multiple stellar populations have been photometrically identified along the SGB, exhibit a large range, not only in C, N, O, Na, Al, but also in  $s$ -process element abundance.  $\omega$  Centauri and M 22 are the only globulars where an intrinsic spread in  $[\text{Fe}/\text{H}]$  has been confirmed, though some hints (even if very uncertain due to the low number statistics of the analyzed sample) for a some iron spread in NGC 1851 was suggested by Yong & Grundahl (2008). NGC 1851,  $\omega$  Centauri, and M 22 show

| ID       | $\frac{bSGB}{ALL}$ | $\frac{fSGB}{ALL}$ | $\frac{rHB}{bHB+rHB}$ |
|----------|--------------------|--------------------|-----------------------|
| NGC 6388 | $0.91 \pm 0.02$    | $0.09 \pm 0.02$    | $0.83 \pm 0.05$       |
| NGC 6656 | $0.60 \pm 0.04$    | $0.40 \pm 0.04$    | $0.04 \pm 0.02$       |
| NGC 5286 | $0.84 \pm 0.03$    | $0.16 \pm 0.03$    | $0.04 \pm 0.01$       |
| NGC 6715 | $0.37 \pm 0.04$    | $0.73 \pm 0.04$    | $0.19 \pm 0.02$       |

TABLE 4.3— Ratio between bSGB and fSGB and the total number of SGB stars, and fraction of blue HB stars.

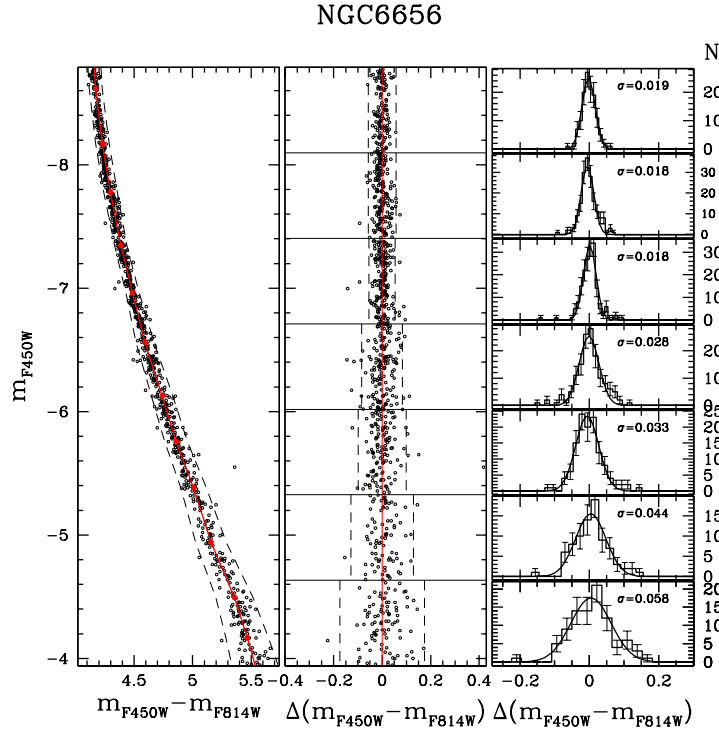


FIGURE 4.28— *Left* : CMD of NGC 6656 with the MSRL overplotted; *Middle* : The CMD rectified by subtraction of the MSRL; *Right* : Color distribution of the rectified CMD. The  $\sigma$  in the inset are those of the best-fitting gaussians.

a large variation in the Strömgren index, traditionally used as a metallicity indicator. All of these three GCs have a splitted SGB.

From our observations, it is tempting to speculate that the SGB split could be related to the presence of two groups of stars with different *s*-process element content and a difference, albeit low, in iron. According with this scenario

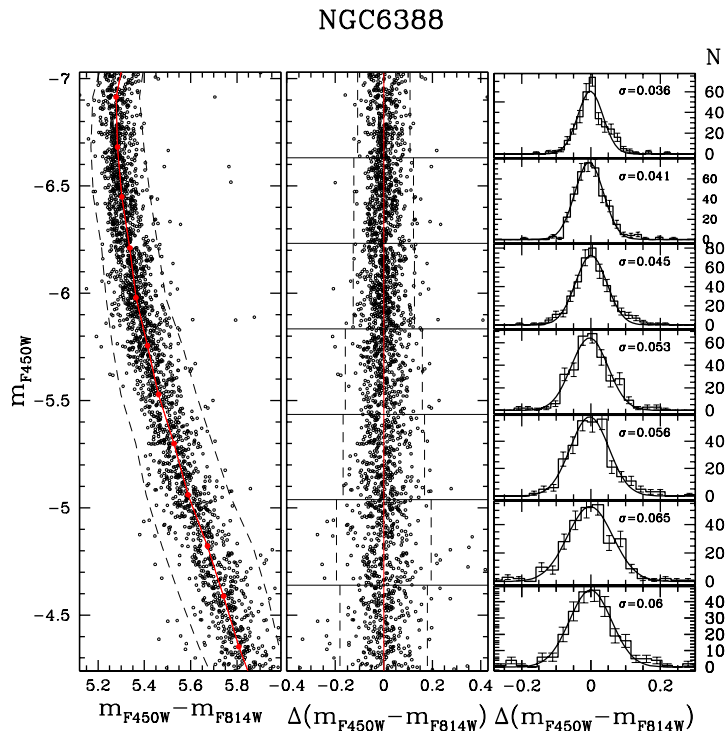


FIGURE 4.29— As in Fig. 4.28 for NGC 6388.

$s$ -process element poor stars are those populating brighter SGB stars and constitute the first M 22 population. The second stellar generation should have been formed after that the AGB winds of this first stellar generation have polluted the protocluster interstellar medium with  $s$ -process elements. This second generation, may have formed from material which was also enriched by core-collapse supernovae ejecta, as indicated by the larger iron, magnesium, and silicon content, and the lack of correlation of the iron content with a pure  $r$ -process element (Eu). In this scenario, the fainter SGB (and TO) of this second generation of stars can not be (of course) attributed to age, but their different chemical mixture. A detailed analysis of the C, N, O abundances of the SGB stars in M22 is strongly needed in order to properly settle this problem.

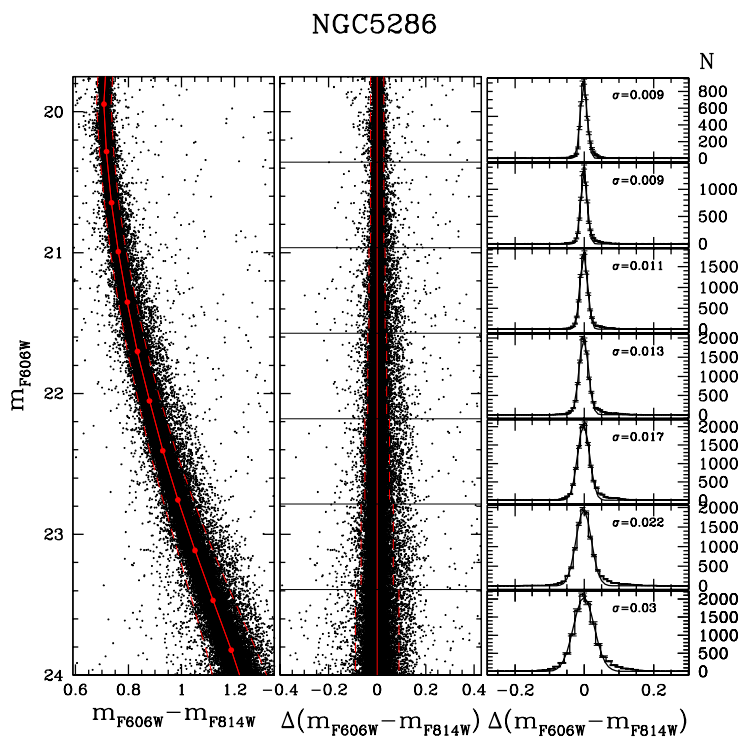


FIGURE 4.30— As in Fig. 4.28 for NGC 5286.

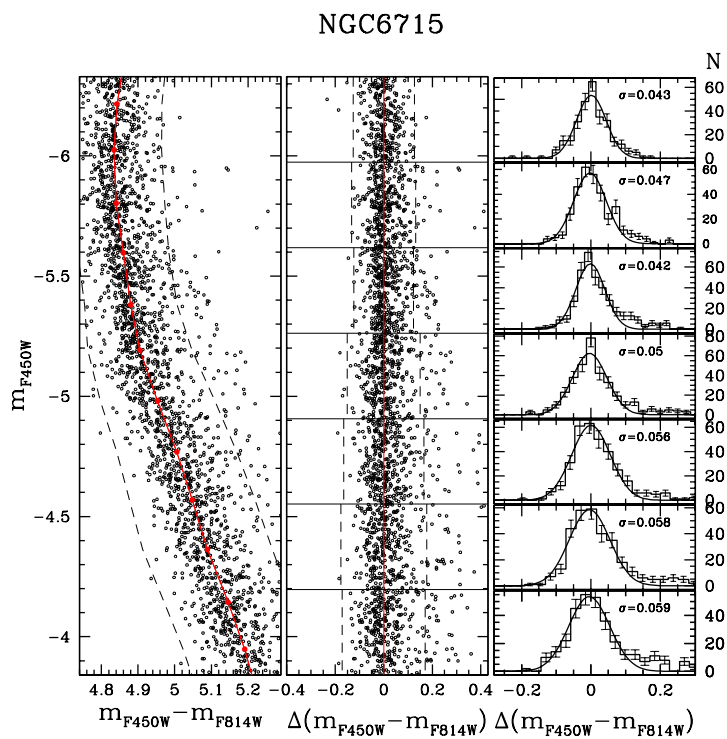


FIGURE 4.31— As in Fig. 4.28 for NGC 6715.

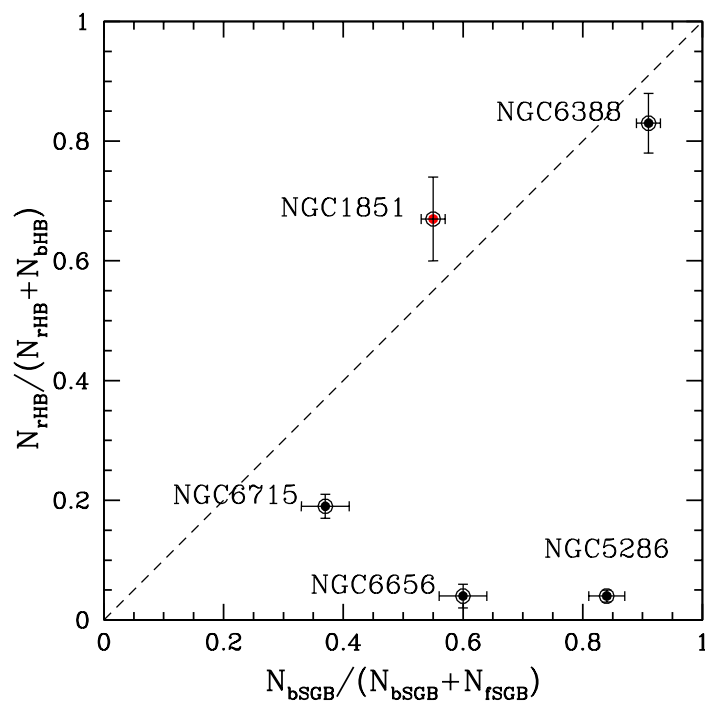


FIGURE 4.32— Fraction of rHB stars as a function of the fraction of bSGB for five MW GCs with double SGB.



NGC362

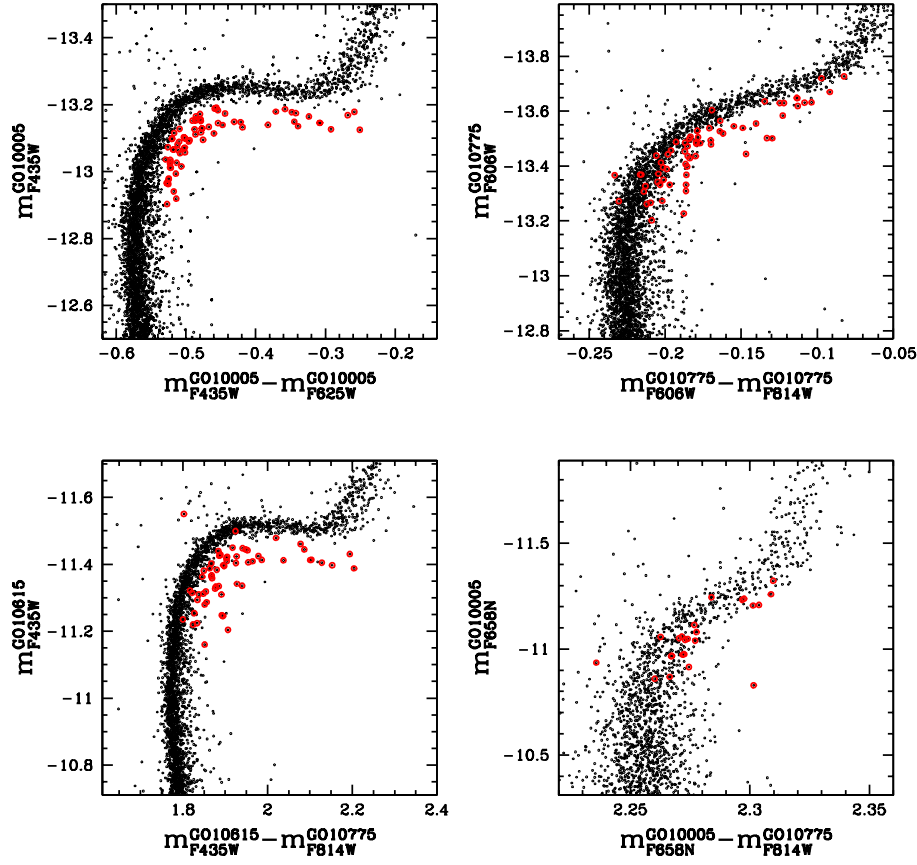


FIGURE 4.33— ACS/WFC CMDs of NGC 362 from several distinct dataset.

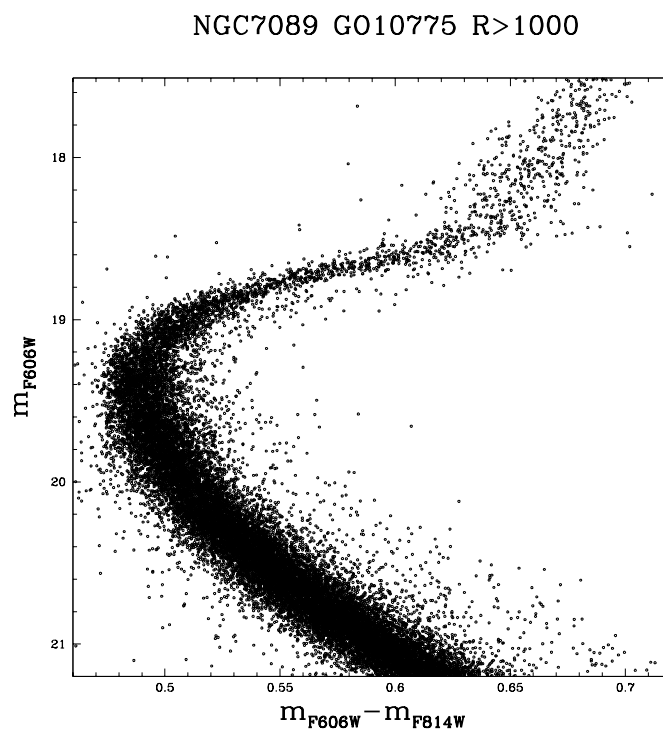


FIGURE 4.34— ACS/WFC CMDs of NGC 7089 from GO10775 data.

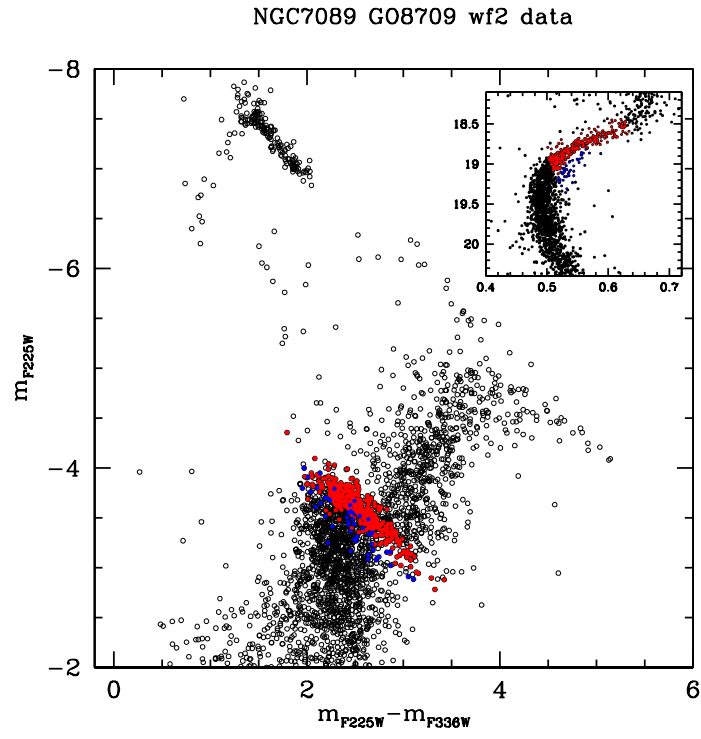


FIGURE 4.35— WFPC2/WFC CMDs of NGC 7089 from G08709 data.

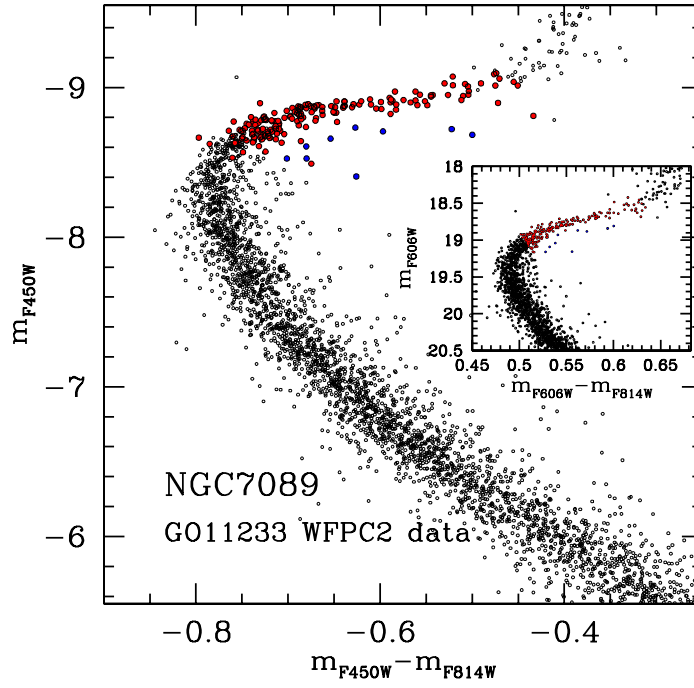
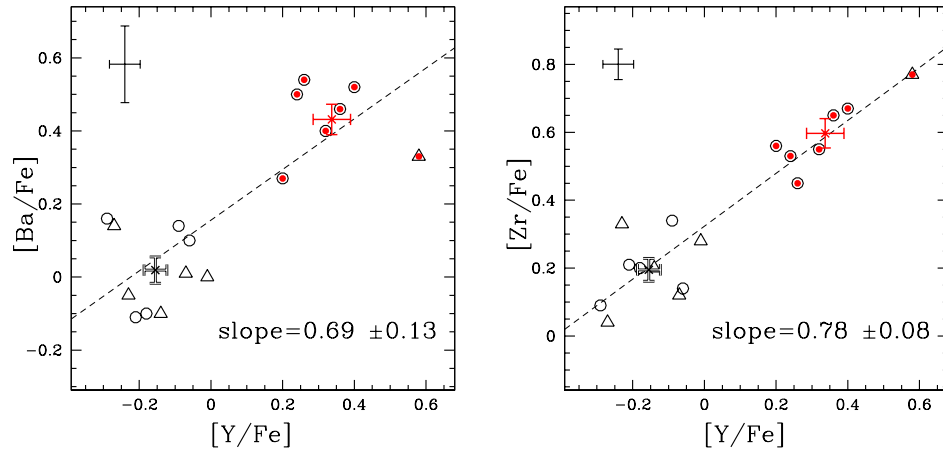
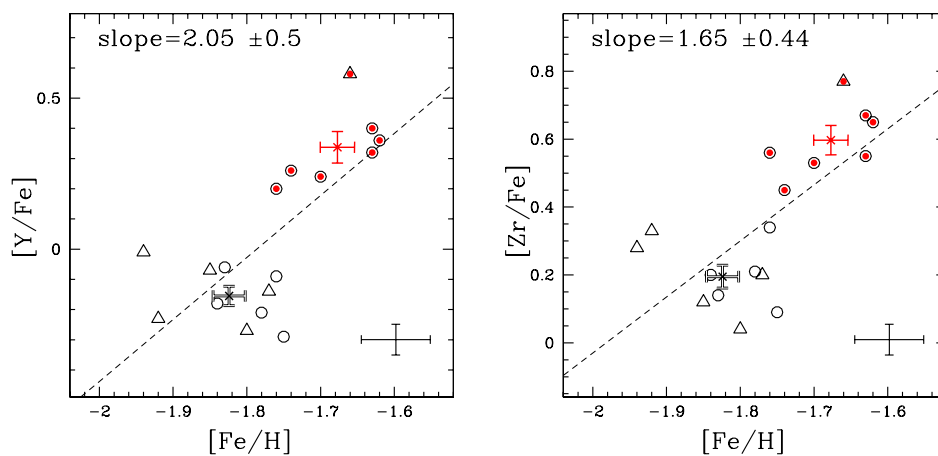
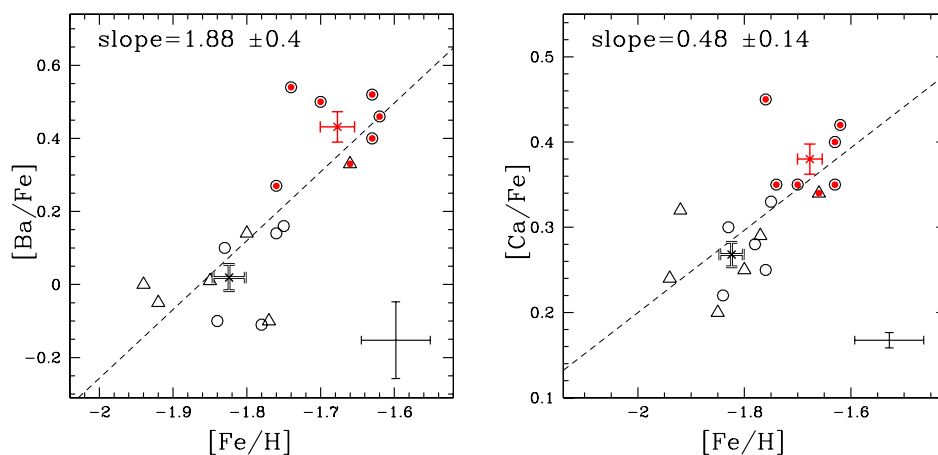


FIGURE 4.36— WFPC2/WFC CMDs of NGC 7089 from GO11233 data.

FIGURE 4.37—  $[Ba/Fe]$  (left) and  $[Zr/Fe]$  (right) as a function of  $[Y/Fe]$  for seventeen RGB stars of NGC 6656.

FIGURE 4.38—  $[\text{Fe}/\text{H}]$  as a function of  $[\text{Y}/\text{Fe}]$  (*left*) and  $[\text{Zr}/\text{Fe}]$  (*right*).FIGURE 4.39—  $[\text{Fe}/\text{H}]$  as a function of  $[\text{Ba}/\text{Fe}]$  (*left*) and  $[\text{Ca}/\text{Fe}]$  (*right*).



# 5

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## Multiple population in LMC stellar clusters.

### 5.1 Introduction

Nearly all the clusters that have been resolved into individual stars exhibit a colour-magnitude diagram (CMD) consistent with the stars belonging to a single, simple stellar population. In recent years, however, thanks to the improving precision of instruments and techniques (mainly from space), the discovery of multiple populations of stars in stellar clusters is challenging this traditional picture and has led to new views on how clusters form and evolve.

Thus far, photometry has revealed multiple stellar populations in a few Galactic globular clusters (GGCs) i. e. Omega Centauri (Anderson 1997, Bedin et al. 2004, Piotto et al. 2005, Sollima et al. 2007, Villanova et al. 2007), NGC 2808 (D’Antona et al. 2005, Piotto et al. 2007), NGC 1851 (Milone et al. 2008), and NGC 6388 (Piotto 2008), also in some intermediate-age Large Magellanic Cloud (LMC) clusters (Bertelli et al. 2003, Mackey & Broby Nielsen 2007 [M07], Mackey et al. 2008 [M08]) and in the Small Magellanic Cloud (SMC) cluster NGC 419 (Glatt et al. 2008a). Each of the above clusters exhibits a different pattern of age spread and/or chemical enrichment. It is clear that the star-formation history differs from cluster to cluster (see Piotto 2008 for a review).

There is additional photometric evidence that other clusters exhibit some kind of population multiplicity. Marino et al. (2008) find photometric evidence of two distinct stellar populations among the red giant branch (RGB) stars of M4. Yong et al. (2008) find abundance variations in NGC 6752 that correlate

with the Strömgren *cy* index and show eight other clusters that present a similar *cy* spread in their giant branches.

In addition, many GGCs, including those with no photometric evidence for multiple populations, exhibit large star-to-star variations in their chemical abundances (see Gratton et al. 2004 for a review). Almost all GGCs have homogeneous Fe-peak-element abundances (with the only exception being Omega Centauri, hereafter  $\omega$  Cen), but they show a significant dispersion in CNO, Na, Mg, Al, and *s*-process elements. The pattern of chemical abundances in GGCs must be primordial as it is observed not only among RGB or asymptotic giant branch (AGB) stars, but also among the sub giant branch (SGB), and most importantly among unevolved stars on the MS (Gratton et al. 2001, 2004). The presence of a well-defined pattern among Na, O, Mg, and Al suggests that most of the GGCs may have hosted multiple episodes of star formation separated by a few hundred Myrs (D’Antona & Caloi, 2008).

Unfortunately, in an old population, such a difference in age corresponds to a difference of a few hundredths of a magnitude at the level of the MS turn-off (TO) and SGB. At the moment, it is not possible to firmly establish a spread in a cluster’s MSTO with this amplitude, given the presence of differential reddening and difficulties in doing systematically accurate crowded-field photometry at this level of precision.

The families of young and intermediate-age massive clusters that populate the Large and the Small Magellanic Clouds offer us precious opportunities for photometrically searching for multiple stellar populations because, in the CMD of a 1-3 Gyr old cluster, an age interval of 200-300 Myr corresponds to a magnitude difference of a few tenths of a magnitude. Two populations with such a difference could be distinguished easily even at the distance of the Magellanic Clouds (MC).

Indeed, recent photometric studies of LMC clusters have demonstrated that the presence of multiple stellar populations is not a peculiarity of the most massive Galactic GGCs. Bertelli et al. (2003) compare a CMD of NGC 2173 from FORS/VLT data with Padova models and suggest for this LMC cluster a prolonged star-formation episode spanning a period of about 300Myr. In a recent paper, M08 find that the main-sequence turn off (MSTO) for NGC 1783 reveals a much spread in colour wider than can be explained by photometric errors. Both M07 and M08 also reveal the presence of a double MSTO in the rich intermediate-age clusters NGC 1846 and NGC 1806 of the LMC, and suggest that their CMDs unveil two populations with an age difference of  $\sim 300$  Myr.

Driven by these results on Galactic and LMC clusters, we undertook an analysis of archival *HST* images of LMC and SMC clusters with the purpose of measuring the frequency of clusters with evidence of multiple or prolonged star



formation. The clusters that have been analysed cover a wide range of ages, from  $\sim 10^6$  to  $\sim 10^{10}$  yr. Since the search of multiple populations is carried out through analysis of CMDs, the study of clusters with different ages requires a different sort of analysis.

In this work, which is the first of a series, we show our entire sample of ACS/WFC CMDs for forty-seven LMC and SMC stellar clusters and present a detailed study of sixteen intermediate-age LMC clusters (between  $\sim 1$  and  $\sim 3$  Gyr). The work is organised as follow. Section 5.2 describes the data and the data reduction techniques. In Section 5.3 we present the CMDs of the sixteen intermediate-age clusters. In Section 4, we confirm the split of the MSTO of NGC 1806 and NGC 1846 and observe, for the first time, two distinct MSTOs in NGC 1751. We analyse the CMD of these clusters in detail and measure the fraction of stars belonging to each of their MSTO populations. We confirm the presence of multiple stellar populations in NGC 1783 and suggest that the MSTO of this cluster should be formed by two distinct branches. In Section 5 we note an anomalous spread around the MSTO of seven clusters: ESO057-SC075, HODGE 7, NGC 1852, NGC 1917, NGC 1987, NGC 2108, and NGC 2154. In Section 6 we demonstrate that the observed spread in the MSTO region of these clusters must be real, since it cannot stem from differential reddening, field contamination, photometric errors, or binary stars. In Section 5.7 we determine the cluster ages and the age differences among different stellar populations in the same cluster through isochrone fitting. Finally, Section 5.8 includes a short summary of our results.

## 5.2 Observation and data reduction

To investigate the presence of multiple stellar populations in Magellanic Cloud clusters we searched the MAST STScI-archive for *HST* images collected with the Wide Field Channel (WFC) of the Advanced Camera for Surveys (hereafter ACS/WFC). We found useful images for 53 clusters from GO 9891 (PI: G. F. Gilmore), GO 10395 (PI: J. S. Gallagher) and GO 10595 (PI: P. Goudfrooij). The result of this search is presented in Table 1 for 47 clusters from GO 9891 and GO 10595, while the GO 10396 data set described in Table 1 of Glatt et al. (2008b) (which includes six SMC clusters) will be used in a future work focused on SMC.

The photometric reduction of the ACS/WFC data was carried out using the software presented and described in detail in Anderson et al. (2008). It consists in a package that analyses all the exposures of each cluster simultaneously to generate a single list of stars for each field. Stars are measured independently in each image by using the best available PSF models from Anderson & King

(2006).

This routine was designed to work well in both crowded and uncrowded fields, and it is able to detect almost every star that can be detected by eye. It takes advantage of the many independent dithered pointings of each scene and the knowledge of the PSF to avoid including artifacts in the list. Calibration of ACS photometry into the Vega-mag system was performed following recipes in Bedin et al. (2005) and using the zero points given in Sirianni et al. (2005).

### 5.2.1 Selection of the star sample

Stars can be poorly measured for several reasons: crowding by nearby neighbours, contamination by cosmic-rays (CRs), or image artifacts such as hot pixels or diffraction spikes. The goal of the present work is to clearly identify multi-populations. For this purpose we need to select the best-measured stars in the field (i.e., those with the lowest random and systematic errors), but we also need to have a large enough statistical sample to be able to identify secondary sequences that may have many fewer members than the primary ones.

The software presented by Anderson et al. (2008) provides very valuable tools for reaching this goal. In addition to the stellar fluxes and positions it provides a number of parameters that can be used as diagnostics of the reliability of photometric measurements. Specifically, these are,

- the rms of the magnitudes measured in different exposures ( $rms_{m_{F435W}}$ ,  $rms_{m_{F555W}}$ , and  $rms_{m_{F814W}}$ , available only for clusters with more than one exposure in the same filter, cfr. Table 1);
- the rms of the positions measured in different exposures transformed in a common distortion-free reference frames ( $rms_X$ , and  $rms_Y$ );
- the residuals to the PSF fit for each star ( $q_{m_{F435W}}$ ,  $q_{m_{F555W}}$ , and  $q_{m_{F814W}}$ ; what Anderson et al. 2008 define as *quality fit*);
- the ratio between the estimated flux of the star in a 0.5 arcsec aperture, and the flux from neighbouring stars within the same aperture ( $o_{m_{F435W}}$ ,  $o_{m_{F555W}}$ , and  $o_{m_{F814W}}$ , again see Anderson et al. 2008 for details).

We used these parameters to select a sub sample of stars with the best photometry.

In the five left hand panels of Fig. 6.1, we show the criteria we used to select the sample of stars with the best photometry in the F435W band for NGC 1806. The photometric system at this stage is kept in instrumental magnitudes,  $-2.5\log_{10}(\text{flux})$ , where the flux is expressed in photo-electrons recorded in the reference exposure.

We note a clear trend in the quality-fit and *rms* parameters as a function of the magnitude due to the decreasing signal-to-noise ratio (S/N). To select well-measured stars at different S/N we adopted the following procedure. We began by dividing all the stars into magnitude bins. The size of each bin varied from one cluster to another depending on the number of stars; for each of them, we computed the median *rms* ( $q$ ) and the 68.27<sup>th</sup> percentile (hereafter  $\sigma$ ). The median was derived recursively: after each computation, all stars exceeding four times  $\sigma$  were provisionally rejected until the next iteration and the median was recomputed. This procedure was repeated until two subsequent measures of the median differ by less than the 1% of the value.

Finally, we arrived at the red line of Fig. 6.1 by adding to the median of each bin  $N$  times  $\sigma$ . This gave us the red circles, which we then fitted with a spline. All stars below the red line in each plot were flagged as well-measured. The factor  $N$  ranges from 5 to 6, and was chosen to draw the boundaries that follow the bulk of the distribution of each parameter value.

The neighbour-contamination parameters do not show a clear trend with magnitude, so we simply flagged all the stars with  $o_{m_{\text{F435W}}, \text{F555W}, \text{F814W}}} < 5$  as well-measured.

Obviously, the *rms* of the magnitudes was not available in the case of clusters with only one image per band (HODGE 7, IC 2146, NGC 1644, NGC 1652, NGC 1795, NGC 1852, NGC 1917, NGC 1978, and NGC 2154). In such cases those selections were not applied. In the right panels of Fig. 6.1 we show the CMD of all the measured stars of NGC 1806 (top) and of stars that pass all the selection criteria (bottom).

### 5.2.2 Artificial-star tests

The artificial-star (AS) experiments used in this work were run following the procedures described in Anderson et al. (2008). First of all, for each cluster, we produced an input list with about  $10^5$  stars located on the entire ACS field of view. It includes the coordinates of the stars ( $X_{\text{in}}, Y_{\text{in}}$ ) in the reference frame, and the magnitudes in the F435W (or F555W) and F814W bands ( $mv_{\text{in}}, mi_{\text{in}}$ ). We generated the artificial stars with a flat luminosity function in the F814W band and with instrumental magnitudes from  $-5$  to  $-14$ . We placed artificial stars fainter than the MSTO on the MS ridge line that is determined as described in Sect. 5.6.2 and added artificial stars brighter than the MSTO along the isochrone that fits the observed CMD best (see Sect. 5.7).

The program described in Anderson et al. (2008) allows artificial-star tests to be performed for one star at a time and entirely in software guaranteeing that artificial stars will never interfere with each other, no matter how many tests

## NGC1806

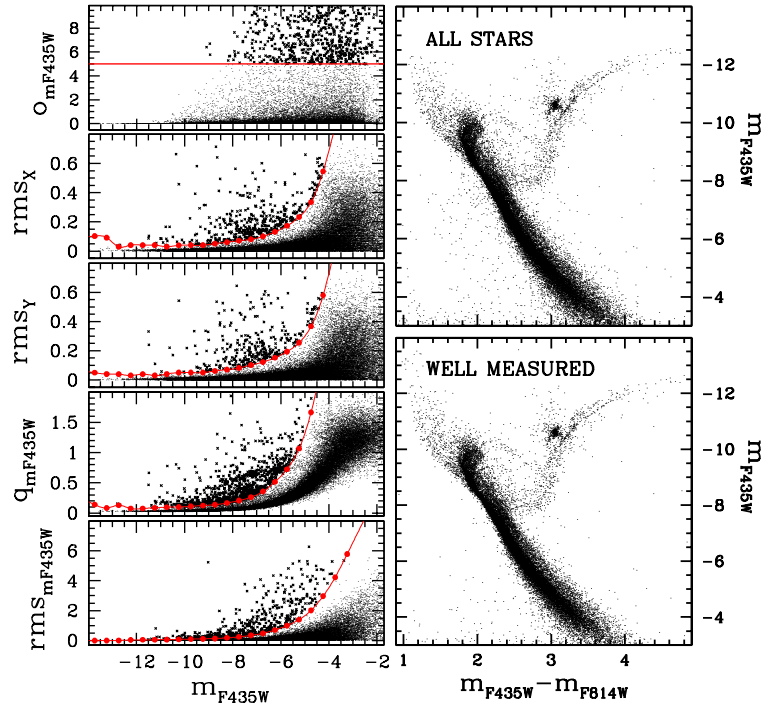


FIGURE 5.1— Diagnostic parameters used to select the stars with the best photometry are plotted as a function of  $m_{F435W}$  for NGC 1806. Red lines separate the well-measured stars (thin points) from those that are more likely to have a poorer photometry (thick points). On the right we compare the CMD of all the measured stars (top) and of stars that pass our criteria of selection (bottom).

are done. Therefore it makes it very simple to do artificial star tests because it is not necessary to add an array of non-interfering stars on the images, reducing all the images each time. For each star in the input list, the routine adds the star to each exposure at the appropriate place with the appropriate flux, and measures the images in the same manner as real stars, producing the same output parameters as in Sect. 5.2.1. If the input and the output positions differ by less than 0.5 pixel and the fluxes differ by less than 0.75 magnitudes, then the artificial star is considered as found.

Artificial stars played a crucial role in this analysis by allowing us to determine the completeness level of our sample and to measure the fraction of chance-superposition “binaries”. The completeness depends on the crowding conditions, as well as on stellar luminosity. Our procedures account for both

of these. Our goal in the AS tests is to probe how incompleteness and photometric errors vary with crowding or brightness. As a result, we generated a list of artificial stars that had colours that placed them on the average cluster sequence and positions drawn from the overall cluster radial distribution.

We divided the ACS/WFC field for each cluster into 5 concentric annuli centred on the cluster centre, and within each annulus we examined the AS results in eight magnitude bins, from  $-14$  to  $-5$ . For each of these  $5 \times 8$  grid points, we then determined the average completeness by taking the ratio of the recovered to input artificial stars within that bin. This grid then allowed us to estimate the completeness for any star at any position within the cluster. As an example, the left panel of Fig. 6.2 shows the completeness as a function of the instrumental  $m_{F814W}$  magnitude in each of the five annuli used to divide the field of NGC 1806. Finally, we interpolated the grid points and derived the completeness value associated with each star. The right panel of Fig. 6.2 shows the completeness contours in the radius versus  $m_{F814W}$  magnitude plane. Continuous lines correspond to completeness levels of 0.25, 0.50, and 0.75. Dotted lines indicate differences of completeness of 0.05.

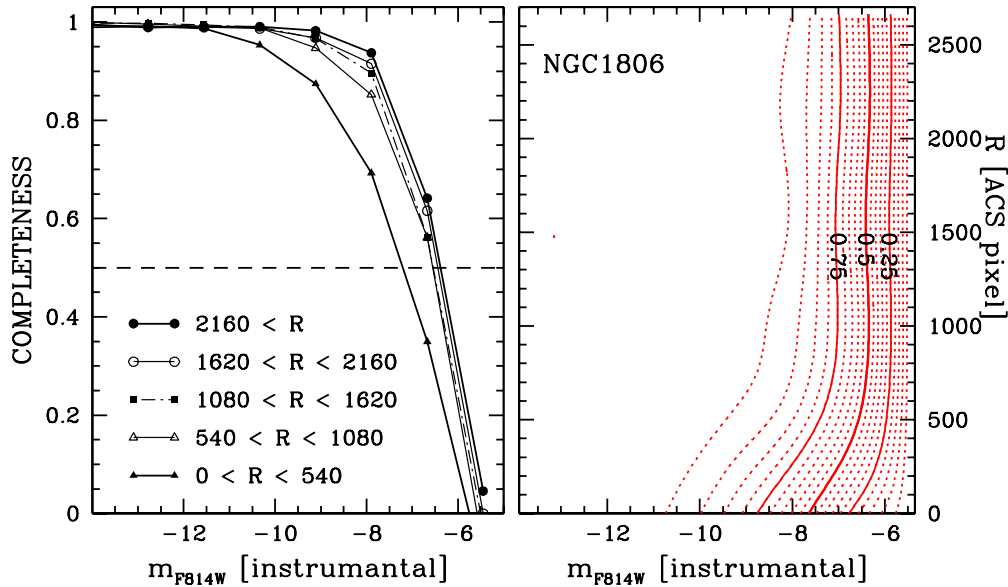


FIGURE 5.2— Left: Completeness as a function of the  $m_{F814W}$  magnitude in five annuli. Right: Completeness contours in the radial distance versus  $m_{F814W}$  magnitude plane.

### 5.3 The cluster CMDs

In Fig. 5.3 we show the instrumental  $m_{F555W}$  versus  $m_{F555W} - m_{F814W}$  CMDs of all the 47 clusters from GO 9891 and GO 10595 presented in Sect. 5.2. It is clear from this figure that our sample contains clusters at many different stages of evolution. This work will deal with the CMDs of the sixteen intermediate-age clusters (from  $\sim 1$  to  $\sim 3$  Gyr). The other clusters will be covered in forthcoming papers. All selected intermediate age clusters are LMC members.

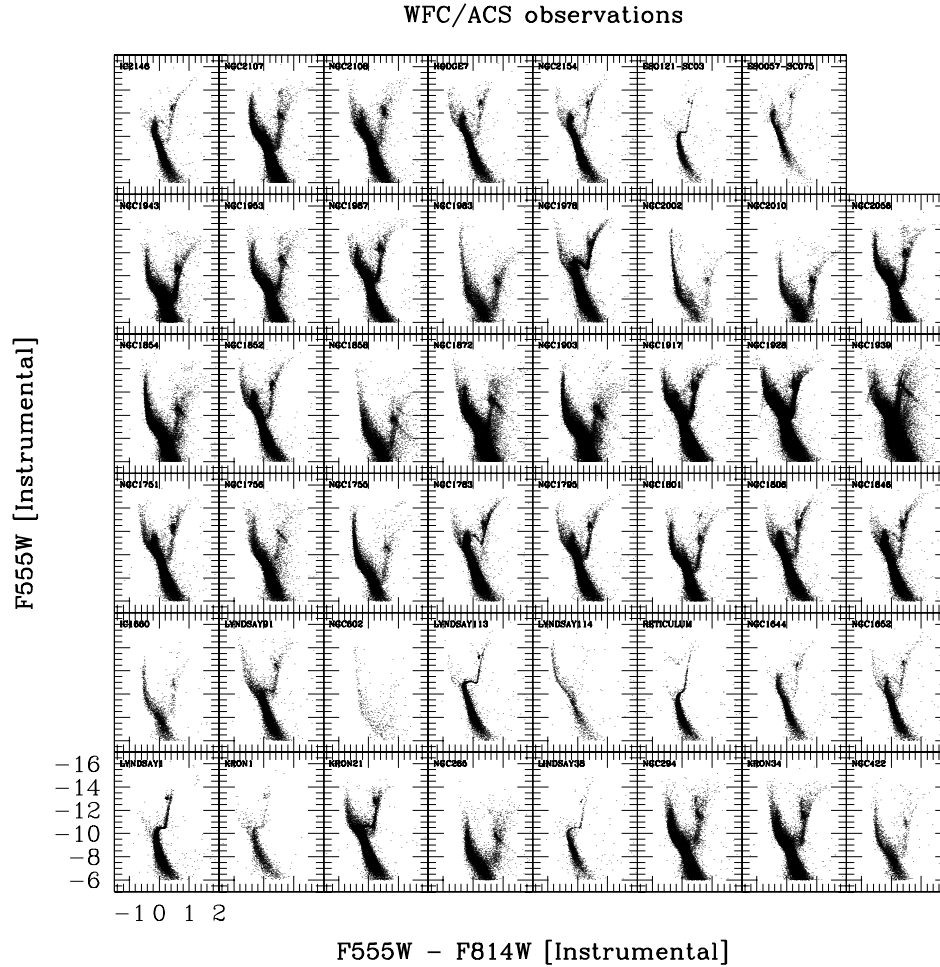


FIGURE 5.3— Instrumental  $m_{F555W}$  vs.  $m_{F555W} - m_{F814W}$  for 47 MCs clusters.

Most of the CMDs plotted in Fig. 5.3 show considerable evidence of con-

tamination, mainly due to MC field stars. For the purposes of this work, it is crucial to determine the stellar distribution in the field-star CMD as well as possible, since without such attention, field sequences could be erroneously attributed to the cluster and interpreted as an additional population.

Since most of the clusters of our sample cover a small portion of the ACS/WFC field of view, we can easily isolate a CMD that is representative of the field population surrounding the cluster by selecting the portion of the ACS/WFC image that is farthest from the cluster centre, so that the contamination of cluster members should be negligible and, in many cases, almost absent.

To minimize the fraction of field stars in the cluster CMD, we selected two regions with the same area. The first region, which below we call the ‘cluster field’, is centred on the cluster and includes the region with the highest density of cluster members (with NGC 1978 the only exception, where we chose an annulus around the cluster centre to exclude the crowded cluster core). The second region is far enough from the cluster center that very few cluster stars would be expected to be present there. We will call this field ‘reference field’ and its stars should be representative of the typical population in front of and behind the cluster. Since cluster stars in the vicinity of the MSTO are the main targets of the present study, we defined the area of these regions such that the density of stars within a magnitude from the TO, namely with  $m_{F814W} < (m_{F814W}^{TO} + 1)$ , in the cluster field would be at least a fixed number ( $N$ ) of times that of the reference field. In most cases we could set  $N = 5$ , which would mean that, even without field correction, we have at most a 20% contamination. An exception is NGC 1917, which is projected upon a densely populated region of the LMC. In this case we used  $N = 3$ . For the most populated clusters (IC 2146, NGC 1806, NGC 1846, and NGC 1978), we adopted  $N = 10$ .

In Fig. 5.4, we compare the CMDs of the cluster and reference fields for the sixteen intermediate age clusters that have been studied in this work. All the reference-field CMDs selected with this criterion share a broadened, young main sequence and a 5-6 Gyr old stellar population that departs from the MS at around  $m_{F555W} = 22.5$  and populates the evolved portions of the CMD. In Sect. 5.6.1 we use the CMDs of the reference field to decontaminate the CMD of the cluster.

### 5.3.1 Differential reddening

It is well known that differential reddening causes a shift in all the CMD features parallel to the reddening line and tends to randomly broaden them. A quick look at the CMDs presented in this work shows that most of the RGBs and AGBs are narrow and well defined, and that the HB red clump is compact.

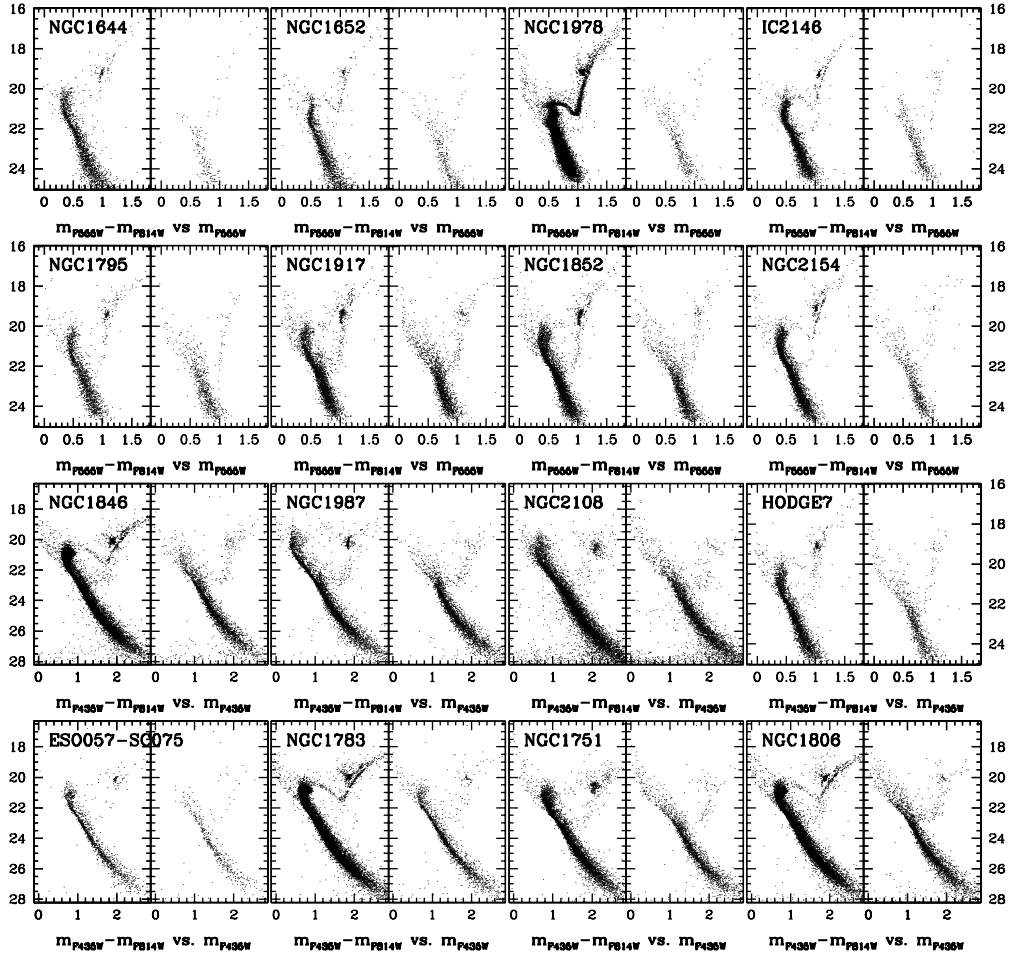


FIGURE 5.4— Comparison of the CMD of cluster and reference fields for the 16 selected intermediate-age clusters.

Moreover, we have divided the cluster field into many subregions (the exact number varies from one cluster to another, depending on the number of stars) and compared the CMDs of stars located in each of them. In most cases, we found no evidence of any offset among the CMDs, and so, any variations in reddening should be negligible.

Two exceptions to this reddening-free rule are NGC 1751 and NGC 2108. We show their CMD in Figs. 5.5 and 5.6. The confused shape of the HB red clumps and of other primary features suggests differential reddening. Since differential reddening acts along the direction of the reddening arrow shown at



the lower left, sequences (such as the SGB) that are aligned perpendicular to the reddening line are most affected.

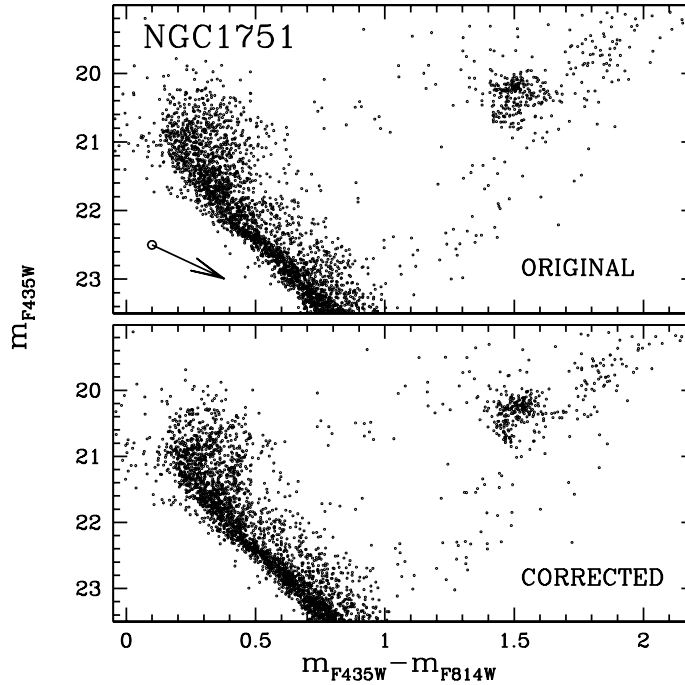


FIGURE 5.5— Comparison between the CMD of NGC 1751 before (top panel) and after (bottom panel) the correction for differential reddening. The arrow indicates the reddening direction.

For this reason, a search for a possible split or a spread around the MSTO requires an accurate correction of the effects produced by differential reddening on the observed CMD. To correct for differential reddening, we used the procedure described in Sarajedini et al. (2007). Briefly, we define the fiducial main sequence for the cluster and tabulate, with a grid of points across the field, how the observed stars in the vicinity of each grid point may systematically lie to the red or the blue of the fiducial sequence; this systematic colour offset is indicative of the local differential reddening.

In the lower panel of Fig. 5.5, we show the corrected CMD of NGC 1751. It should be noted how, after the correction has been applied, all the main features of the CMD become narrower and clearly defined, confirming that most of the effects of differential reddening have been removed. The improvement of the

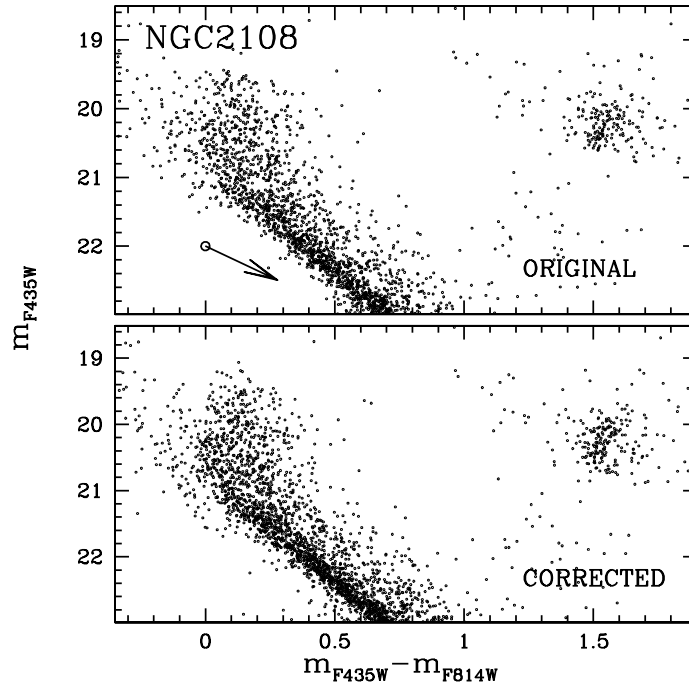


FIGURE 5.6— As in Fig. 5.5 for NGC 2108.

CMD is particularly evident for the stars of the HB red clump; the tightness along the reddening line of this clump means that the spread (or split) we see in the MSTO cannot be due to differential reddening. Figure 5.6 illustrates the effects of the reddening correction in NGC 2108. The total amount of differential reddening within the cluster region is  $\Delta E(F435W-F814W)=0.10$  for NGC 1751 and  $\Delta E(F435W-F814W)=0.08$  for NGC 2108.

The two clusters that suffer from sizable differential reddening are not at any particular angular distance from the centre of the LMC or with respect to the Milky Way, compared to the other fourteen clusters. They might just fall in some poorly known gas-dust complex structure, and/or with a limited spatial extension.

#### 5.4 Clusters with a double MSTO: NGC 1806, NGC 1846, and NGC 1751

At least three clusters of our sample clearly show two distinct MSTOs: NGC 1846, NGC 1806, and NGC 1751. The split is evident in the CMDs of the cluster fields that are shown in Figs. 5.7, 5.8, and 5.9, and is exalted by the Hess diagram in the inset. The presence of two, distinct TOs in NGC 1806 and NGC 1846 was discovered by M07 and M08, who also found no difference in the spatial distribution between the stars in the brighter and fainter MSTOs (hereafter bMSTO and fMSTO). In this work, we take advantage of the high

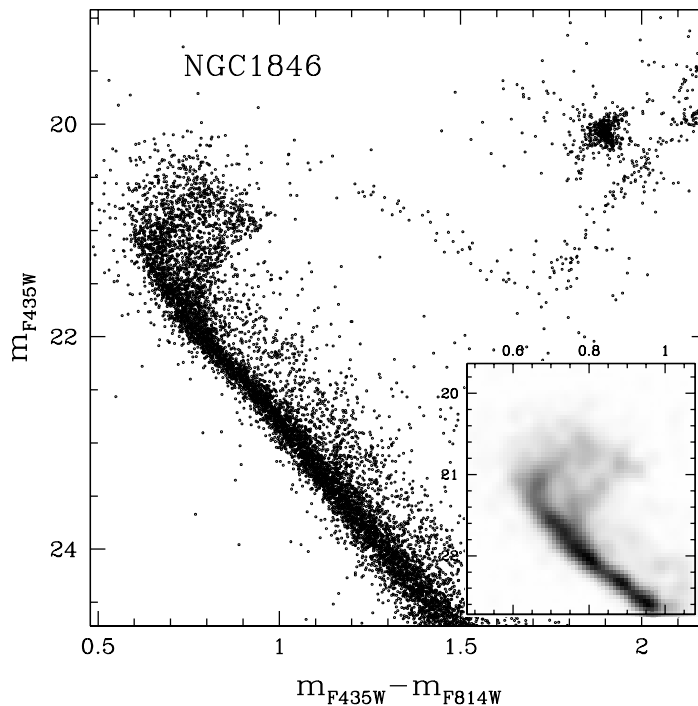


FIGURE 5.7— CMD of NGC 1846. All detected sources in the inner field that successfully passed all the selection criteria have been plotted. In the inset we show the Hess diagram for the CMD region around the MSTO.

photometric quality of our CMDs to measure the fraction of stars belonging to each turnoff population. To do this, it is necessary to select and compare the two groups of bMSTO and fMSTO.

This procedure is illustrated in Fig. 5.10 for NGC 1806. We used the CMD of the cluster field, with foreground/background contamination removed as de-

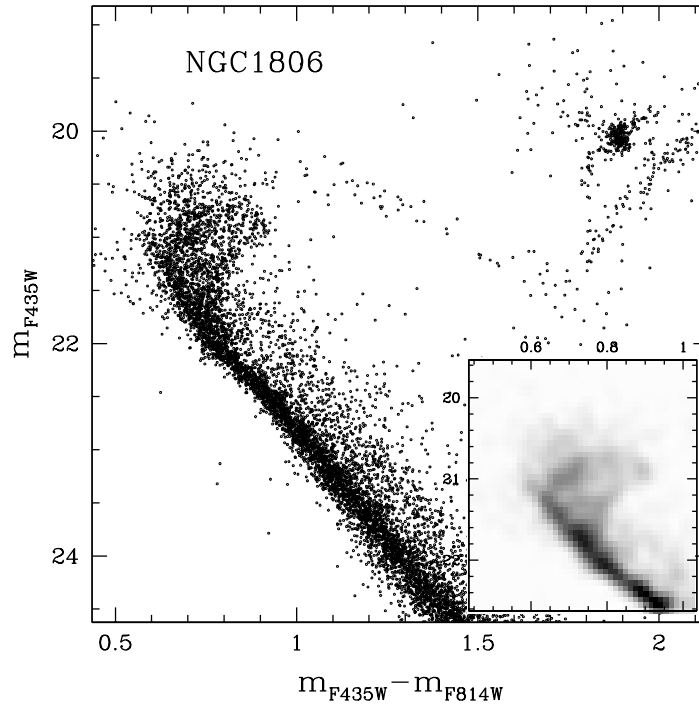


FIGURE 5.8— As in Fig. 5.7 for NGC 1806.

scribed in Sect. 6.1. We began by finding the isochrones that went through the two sequences and the giant branch (as will be described in detail in Sect. 5.7). These are the red and blue lines. We then defined by hand two pairs of reference points:  $P_{1,f}$  and  $P_{2,f}$  on the fMSTO isochrone and  $P_{1,b}$  and  $P_{2,b}$  on the bMSTO isochrone. The two pairs of points were chosen with the criterion of delimiting the region of the CMD where the split is more evident and were used to draw the grey lines in panel (a). Only stars contained in the region between these lines have been used for the following analysis.

In panel (b), we shifted and rotated the reference frame such that the new origin corresponds to  $P_{1,f}$  and the abscissa goes from  $P_{1,b}$  to  $P_{1,f}$ . For simplicity, in the following, we refer to the abscissa and ordinate of this reference frame as ‘colour’ and ‘magnitude’. The red dashed line is a fiducial line through the region close to the fMSTO. We drew it by marking four points on the region close to the fMSTO, equally spaced in ‘magnitude’ and drawing a line through them by means of a spline fit.

In panel (c) the ‘colour’ of this line was subtracted from the colour of each

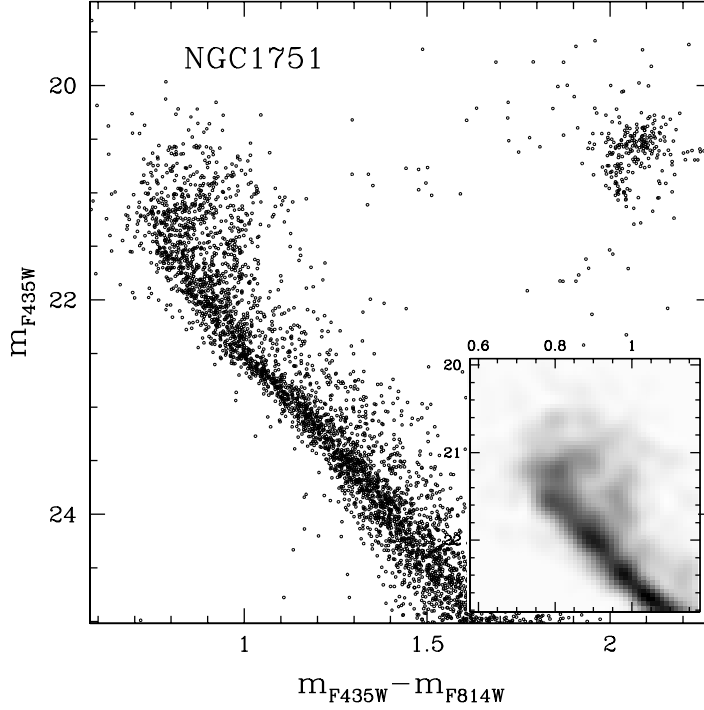


FIGURE 5.9— As in Fig. 5.7 for NGC 1751.

star, and the 'magnitude' of each star has been divided by the 'magnitude' of a stars with the same 'colour' that lies on the line that goes from  $P_{2,f}$  to  $P_{2,b}$ .

For the analysis that follows, we have divided the  $\Delta$ 'magnitude' range into  $N$  bins. We used  $N = 4$  for NGC 1806 and NGC 1846 and  $N = 2$  for the less populated NGC 1751. In each of them, we determined the fraction of stars belonging to each MSTO as follows. Our aim was to model the  $\Delta$ 'colour' distribution by fitting the sum of two partially overlapping Gaussians, but we need to reduce the influence of outliers (such as stars with poor photometry, residual field stars, and binaries). To this end, we did a preliminary fit of the Gaussians using all available stars, then we rejected all the stars more than two  $\sigma_b$  distant and less than  $2\sigma_f$  from the fMSTO and repeated the fit (where the  $\sigma$ 's are those of the best fitting Gaussians in each  $\Delta$ 'magnitude' bin fitted to the fMSTO and bMSTO respectively).

The continuous vertical lines show the centres of the best-fitting Gaussians in each  $\Delta$ 'magnitude' interval. The red dashed line is located two  $\sigma_f$  on the

”blue” side of the fMSTO and the blue line runs two  $\sigma_b$  on the ”red” side of the bMSTO.

It is important to notice here that, to each point  $(P_{1,f(b)}, P_{2,f(b)})$  that we have arbitrarily selected on the two isochrones with the only purpose to disentangle the two SGBs, corresponds to a mass  $(\mathcal{M}_{P_{1f(b)}}, \mathcal{M}_{P_{2f(b)}})$ . To obtain a more correct measure of the fraction of stars in each of the two populations ( $f_{bMSTO}, f_{fMSTO}$ ) it must be noted that we are dealing with two different mass intervals  $(\mathcal{M}_{P_{2f}} - \mathcal{M}_{P_{1f}} \neq \mathcal{M}_{P_{2b}} - \mathcal{M}_{P_{1b}})$  and we have to compensate for two facts: first, more massive stars are rarer, and second, more massive stars evolve faster.

We calculated the fraction of stars in each branch as,

$$f_{bMSTO} = \frac{\frac{A_b}{N_b/N_f}}{A_f + \frac{A_b}{N_b/N_f}}$$

$$f_{fMSTO} = \frac{\frac{A_f}{N_b/N_f}}{A_f + \frac{A_b}{N_b/N_f}}$$

where  $A_b$  and  $A_f$  are the area of the Gaussians that best fit the bMSTO and the fMSTO, and  $N_{f(b)} = \int_{P_{1,f(b)}}^{P_{2,f(b)}} \phi(\mathcal{M}) d\mathcal{M}$ , being adopting for  $\phi(\mathcal{M})$  the Salpeter (1955) IMF.

We find that  $74 \pm 4$  % of stars of NGC 1806 belong to the bMSTO and  $26 \pm 4$  % to the fMSTO. In the case of NGC 1846, we have  $75 \pm 3$  % of stars in the bMSTO and  $25 \pm 3$  % in the fMSTO. Finally,  $69 \pm 4$  % of the NGC 1751 stars belong to the bMSTO and the  $31 \pm 4$  % to the fMSTO. Interestingly enough, a similar population ratio between the bright and the faint SGB ratios has been found in the Galactic globular clusters NGC 1851 (Milone et al. 2008) and NGC 6388 (Piotto et al, in preparation). We note here that D’Antona and Coloi (2008) predict that more than 50% of the cluster stars must be coming from the second (younger) population in their intermediate mass AGB ejecta pollution scenario proposed to explain multiple populations in star clusters.

#### 5.4.1 The (double ?) MSTO of NGC 1783.

A spread in colour around the MSTO of NGC 1783 was first noted by Mucciarelli et al. (2007). Unfortunately their  $m_{F555W}$  versus  $m_{F555W} - m_{F814W}$  CMD had low photometric accuracy, because it was obtained from the GO 9891 images alone. Therefore, they were unable to distinguish between the intrinsic spread in colour and the broadening expected by photometric uncertainties. M08 obtained a CMD for this cluster from data with higher S/N (using both GO 10595 and GO 9891 images) and demonstrated that NGC 1783 shows a

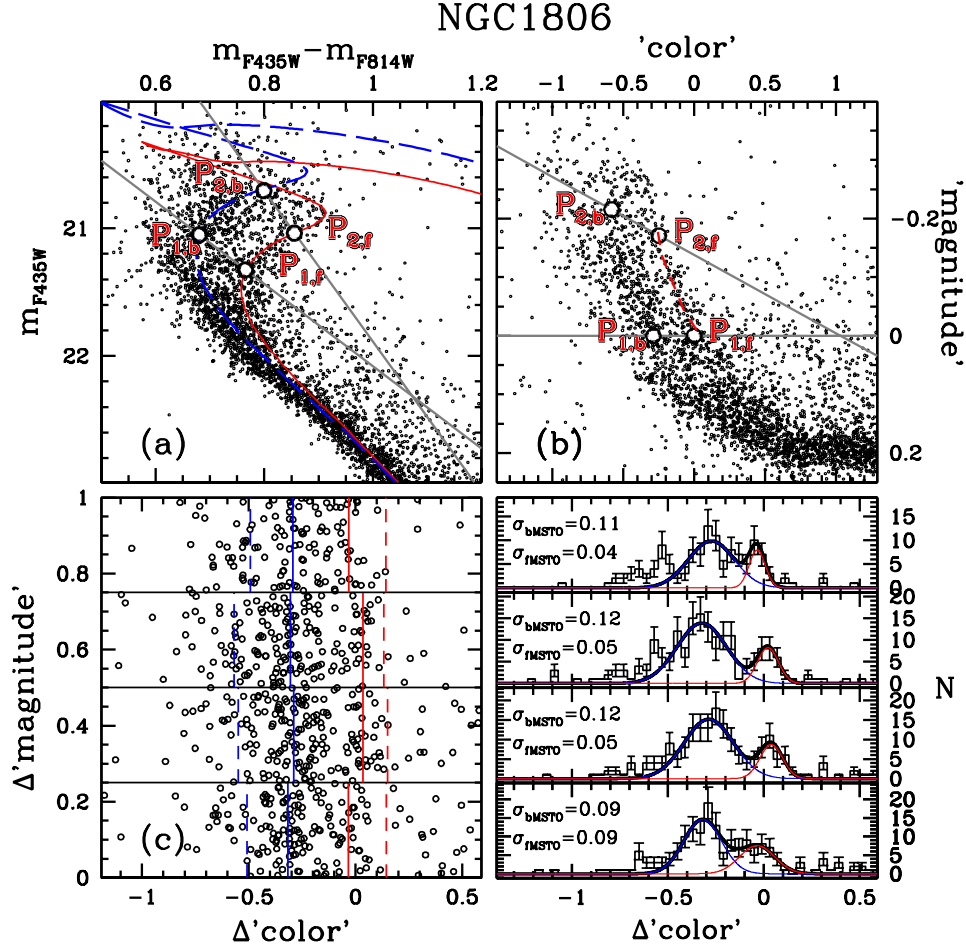


FIGURE 5.10— This figure illustrates the procedure adopted to measure the fraction of stars belonging to the bMSTO and fMSTO in NGC 1806. Panel (a) shows a zoom of the CMD from Fig. 5.8 with the isochrones that best fits the fMSTO and the bMSTO overimposed. The grey lines delimit the portion of the CMD where the split is more evident. Only stars from this region are used to measure the population ratio. In Panel (b) we shifted and rotated the reference frame of Panel (a). Red dashed line is the fiducial of the region around the fMSTO. In Panel (c) we plotted stars between the grey lines but after the subtraction of the 'color' of the region around the fMSTO fiducial from the 'color' of each star and the division of the 'magnitude' of each star by the 'magnitude' of the upper grey line. The four right bottom panels show the  $\Delta'color'$  distribution for stars in four  $\Delta'magnitude'$  bins. The solid lines represent a bigaussian fit. For each bin, the dispersions of the best fitting Gaussians are indicated.

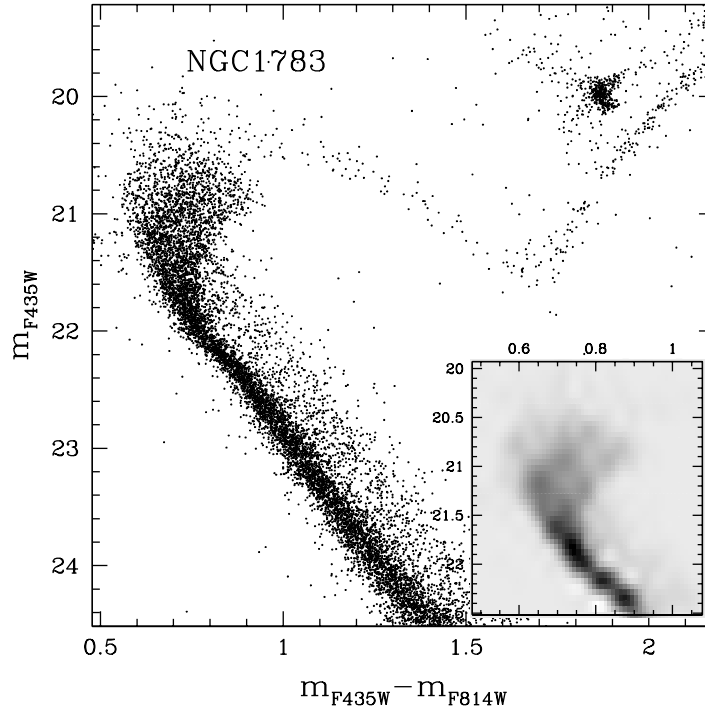


FIGURE 5.11— As in Fig. 5.7 for NGC 1783.

much wider spread in color than what would be expected by photometric errors alone.

Our CMD of NGC 1783 is shown in Fig. 5.11 and clearly confirms the anomalous spread around the MSTO. In addition, the Hess diagram in the inset reveals a split MSTO and strongly suggests that the apparent spread could be attributed to two distinct branches that are closely spaced and poorly resolved by the observations.

### 5.5 Possible evidence of prolonged star formation

The CMDs around the MSTO loci for the remaining twelve intermediate-age clusters that have been studied in this work are presented in Figs. 5.12 - 5.23. Unfortunately, being this an archive project, the photometric data set available for these twelve clusters is not homogeneous. One short and two deep images for each of the three filters: F435W, F555W, and F814W, were collected within program GO 10595, while one single deep image in both F555W



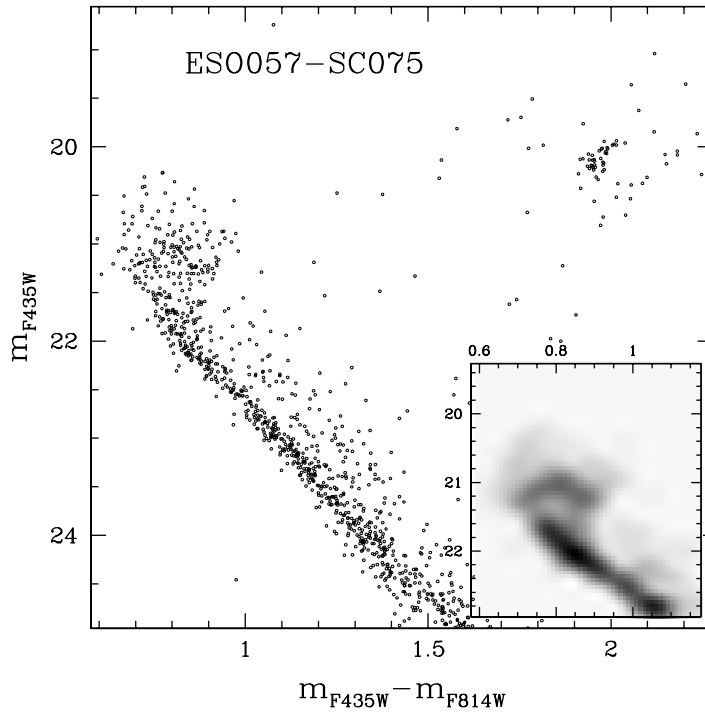


FIGURE 5.12— As in Fig. 5.7 for ESO057-SC075.

and F814W bands were collected within the snap-shot program GO 9891. Only two clusters were observed by both programs (NGC 1987 and NGC 2108), one cluster (ESO057-SC075) only in GO-10595, and the remaining nine (HODGE 7, IC 2146, NGC 1644, NGC 1652, NGC 1795, NGC 1852, NGC 1917, NGC 1978, and NGC 2154) were observed within GO 9891 only (see Table 1 for more details).

We find that seven of these clusters show hints of an intrinsic spread around the MSTO: ESO057-SC075, HODGE 7, NGC 1852, NGC 1917, NGC 1987, NGC 2108, and NGC 2154. The CMDs of IC 2146, NGC 1644, NGC 1652, NGC 1795, and NGC 1978 show no evidence of such a spread and are all consistent with hosting stars with the same age and chemical composition, within our photometric precisions. When simulated CMDs are introduced, we will give a more objective criterion for distinguishing clusters with an intrinsic spread around the MSTO (at the end of Sect. 6.2.2).

It must be noted that, apart from the broadened MSTO region, the other

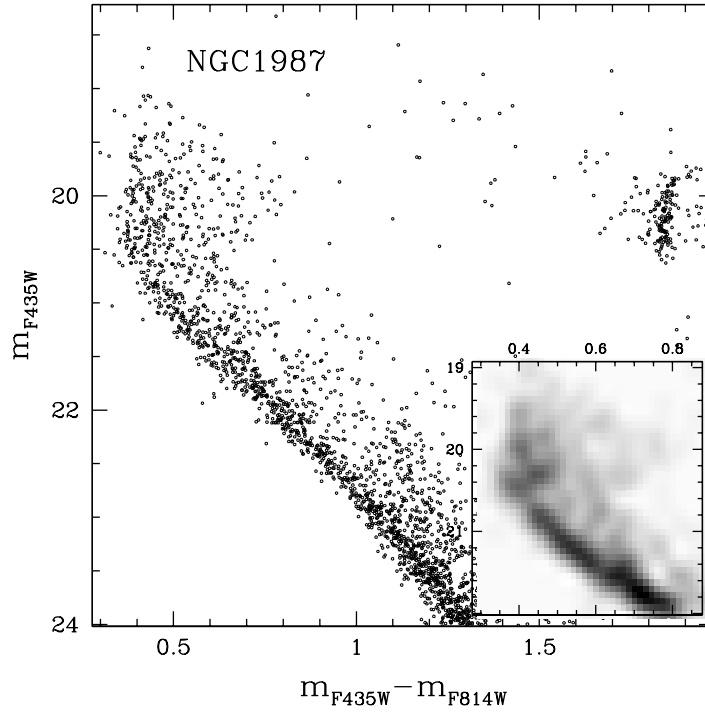


FIGURE 5.13— As in Fig. 5.7 for NGC 1987.

primary features of the CMDs of these clusters (MS, RGB, and AGB) are narrow, and the HB red-clump is well-defined, thus the spread cannot be an artifact produced by differential reddening or variations in photometric zero points along the ACS field.

The limited statistic and photometric resolution do not allow us to establish whether these spreads are just unresolved splits -like those identified in the more populous clusters described in Sect. 4- or not.

In the following section, we show that the spread around the MSTO of the clusters mentioned above must be intrinsic. To do this, we demonstrate that the broadening we see cannot be explained by any combination of photometric errors, field-star contamination, or unresolved photometric binaries.

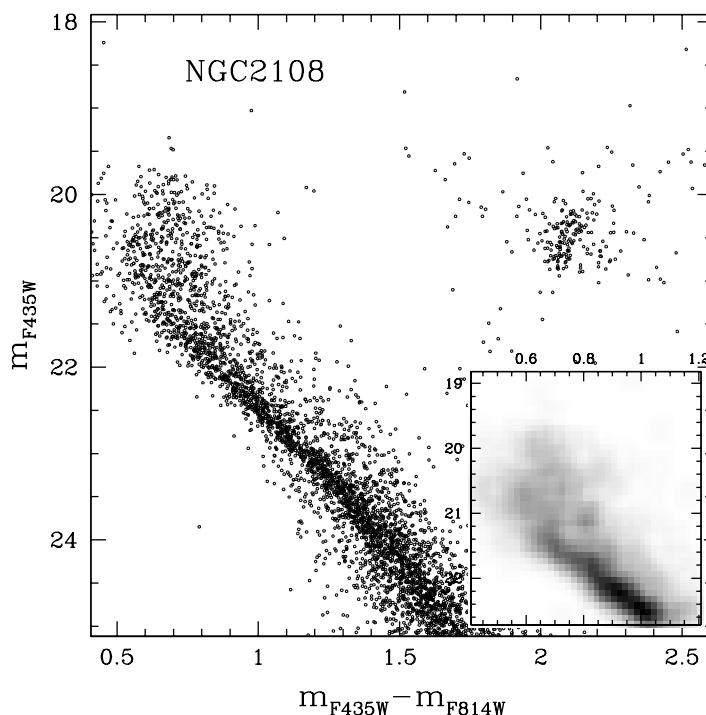


FIGURE 5.14— As in Fig. 5.7 for NGC 2108.

## 5.6 Does the spread MSTO reflect the presence of multiple stellar populations?

Globular-cluster systems with multiple populations manifest themselves in many different photometric ways. In  $\omega$  Cen we (Anderson 1997, Bedin et al. 2004) detected a split of the MS, which can only be explained by two stellar groups with different He content and metallicity (Piotto et al. 2005), and also at least four distinct SGBs (which may indicate age differences greater than 1 Gyr, see Villanova et al. 2007 and references within). In NGC 2808 we inferred the existence of three distinct stellar populations from the three MSs (which is most easily explained by three groups of stars with different helium content, see Piotto et al. 2007). In the case of NGC 1851, two populations of stars are inferred from the fact that the SGB splitting into two branches. This feature can be explained either by two distinct bursts of star formation with a time separation of about 1 Gyr or by two stellar populations with distinct initial chemical composition and a much smaller age difference (Milone et al. 2008, Cassisi et

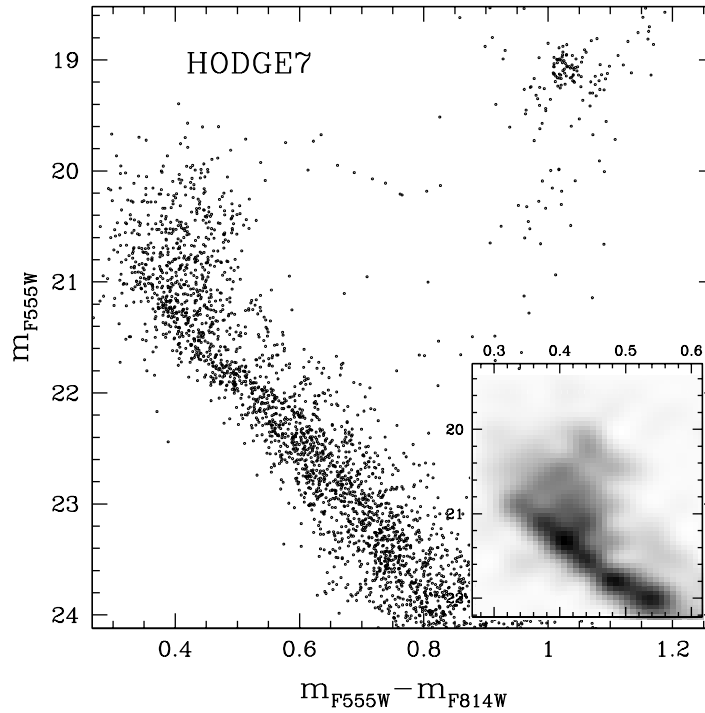


FIGURE 5.15— As in Fig. 5.7 for HODGE 7.

al. 2008). A split in the SGB has also been observed in NGC 6388 (Piotto 2008) demonstrating that this massive GC hosts two distinct stellar groups. In a spectro-photometric study of M4, Marino et al. (2008) detect a bimodal RGBs, and demonstrate that it is due to a bimodal distribution of CN, Na, O, also indicating that this relatively-small cluster contains multiple populations.

The Galactic clusters cited above variously exhibit broadening or bifurcation of the RGB, SGB, and lower MS populations. In the case of the intermediate-age LMC clusters we studied here, we detected both splits of the MSTO, as in NGC 1846 and NGC 1806 (Sect. 5.4, M07 and M08), in NGC 1751 and possibly NGC 1783 (Sect. 5.4), and a broadening of the MSTO as the clusters in Figs. 5.12 - 5.14 and NGC 2173 (Bertelli et al 2003). The low numbers of stars on the RGB make it difficult to assess the presence of a split or anomalous broadening along this evolutionary sequence, and the distance of the LMC makes it impossible to detect splits in the lower MS population with the presently available data.

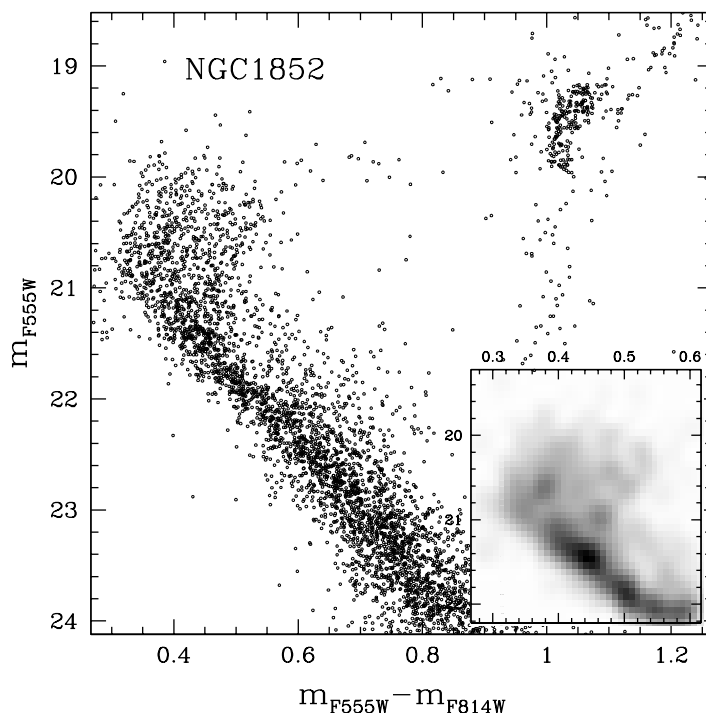


FIGURE 5.16— As in Fig. 5.7 for NGC 1852.

While the splits and broadening we have shown above look quite convincing, it is important to consider the possibility that photometric errors or other effects can generate anomalous spreads and bifurcations, which could be confused with differences in age and/or chemical composition. In addition, it is also important to consider that both binaries and field stars contaminate the CMD region around the MSTO where we are most sensitive to the presence of multiple stellar populations.

In Sect. 5.6.1, we demonstrate that the MSTO broadening visible in Figs. 5.12-5.14 is not due to field-star contamination by statistically subtracting field stars from the cluster CMD. In Sect. 5.6.2, we consider the influence that binary stars could have on the spread of the MSTO. To do this, we use of artificial stars to simulate the CMD of a single population plus a population of binaries such that visible in the lower main sequence. We then present the decontaminated cluster CMD and compare it with the simulated one that includes both realistic errors and binaries to show that the observed MSTO broadening cannot be explained

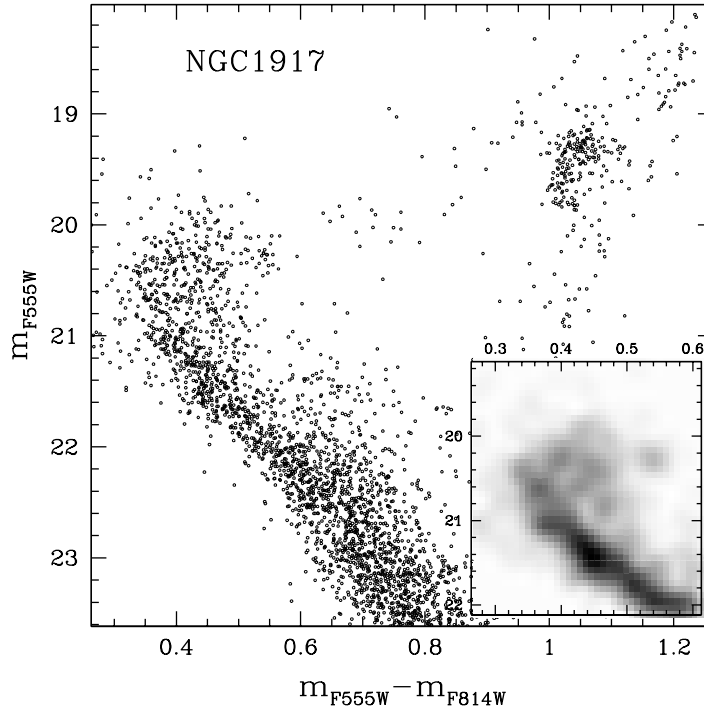


FIGURE 5.17— As in Fig. 5.7 for NGC 1917.

by a single population.

### 5.6.1 A method to decontaminate the cluster CMD from field stars

We began our analysis looking at the original CMD from stars near the cluster centre, where we estimated that the contamination by field stars is at most at the level of  $\sim 20\%$  (see Sect. 5.3).

However, it is possible to reduce this contamination even further by a statistical subtraction of those stars that are most likely to be field stars. We used the following approach which is based on the assumption that the distribution of field stars in the CMD of the cluster and reference field is nearly the same. For each star in the reference field CMD, we calculated the distance to all the cluster field stars:  $d = \sqrt{(\Delta(m_{F435W} - m_{F814W}))^2 + (\Delta m_{F435W})^2}$  (or  $d = \sqrt{(\Delta(m_{F555W} - m_{F814W}))^2 + (\Delta m_{F555W})^2}$ ). We then flagged the closest cluster field star as a candidate to be subtracted. We remind the reader that cluster and reference fields cover the same area.

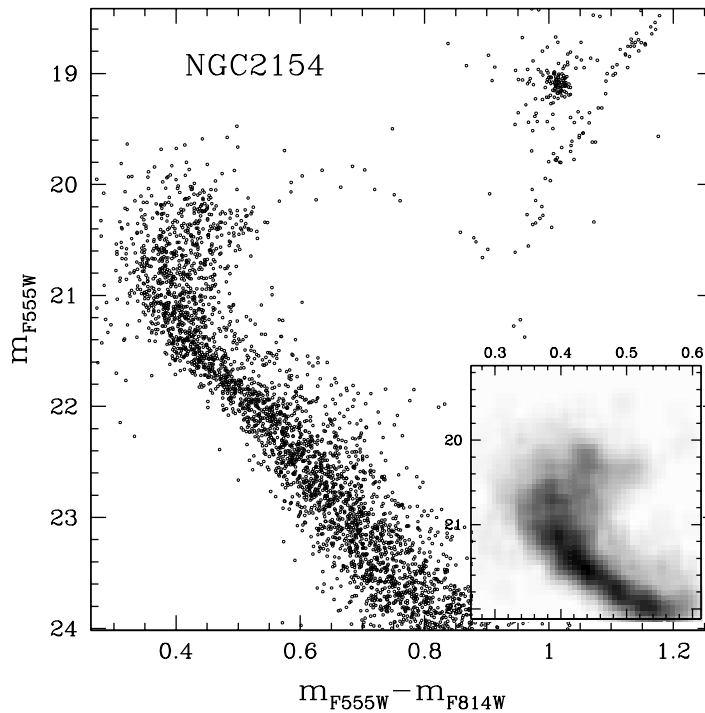


FIGURE 5.18— As in Fig. 5.7 for NGC 2154.

We determined the ratio  $r$  between the completeness of this stars and the completeness of the reference field star. This ratio is always  $r < 1.0$ . To avoid over-subtracting field stars, we generated a random number between 0 and 1, and removed the star from the cluster CMD whenever this random number was less than the ratio of the completenesses.

The main steps in this procedure are illustrated in Fig. 5.24 for NGC 1806. The upper panels show the CMD of stars in the reference (left) and cluster (right) field, the bottom ones the CMD of subtracted stars (left), and the decontaminated CMD (right). The statistical subtraction of field stars was not applied to the most populated clusters (NGC 1978, NGC 1783), which occupy most of the field of view and have the highest ratio of cluster to reference field stars. We note that there is an additional young stellar cluster within the ACS images of NGC 1852, so we were careful to select a reference field that was as far as possible from both clusters.

Obviously, small variations in the distribution of stars in the reference field

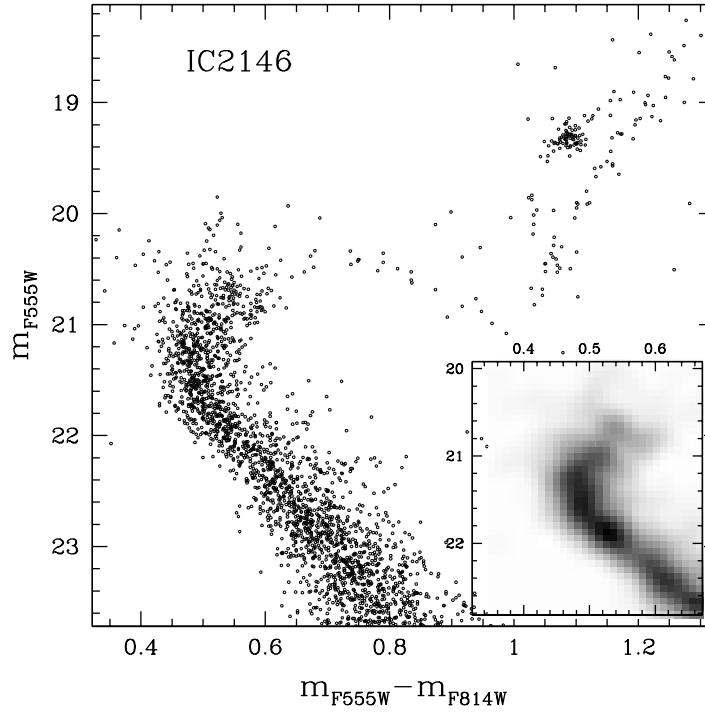


FIGURE 5.19— As in Fig. 5.7 for IC 2146.

are expected even within the small WFC/ACS field of view. To check whether the reference field star distribution can be reasonably assumed uniform, we defined four regions with the same area of the cluster field and the largest possible distance from the cluster centre. We extracted the CMD of each region and compared it with that of the cluster field. A typical example of this procedure is shown in Fig. 5.25 for NGC 1987. In particular, we compared the number of stars (corrected for completeness) in the boxed region around the MSTO. We found that, in most cases, the variation in the number of stars in this region is smaller than about 30%. Obviously, this procedure has been applied only to clusters that cover a sufficiently small fraction of the ACS field of view. We cannot exclude the possibility that the variation of the number of stars in reference field regions could be (partially) due to contamination of cluster members. However, we note that oversubtracting the cluster members does not affect our results for the morphology of the MSTO.



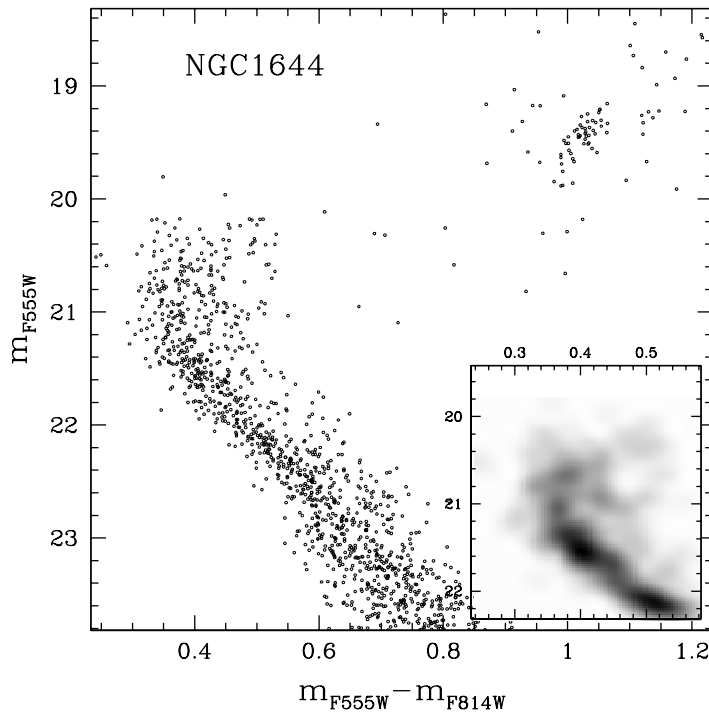


FIGURE 5.20— As in Fig. 5.7 for NGC 1644.

### 5.6.2 The synthetic CMD

The main goal of this section is to generate a synthetic CMD of a cluster with the same characteristics as the observed one, but hosting a single stellar population. This is a necessary step for demonstrating whether the observed spread in color around the MSTO is an intrinsic feature due to the multiple stellar populations or is an artifact produced by unresolved binaries or photometric errors.

To simulate a CMD that reproduces the main properties of the observed one well enough we must ensure that:

- the mass function of the synthetic CMD is as similar as possible to the observed one;
- simulated and observed stars have the same radial distribution, completeness, and photometric errors;
- the fraction and the mass ratio distribution of simulated photometric binaries are as close as possible to the real ones.

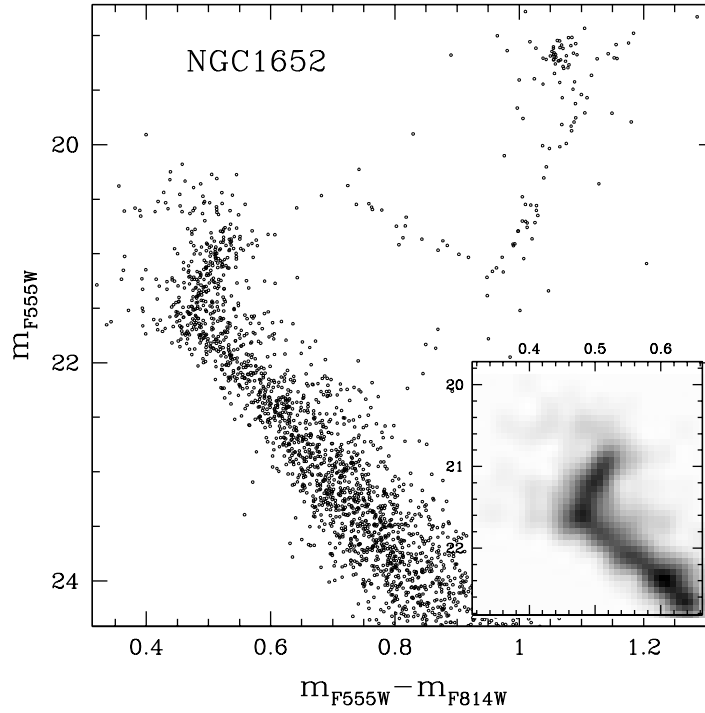


FIGURE 5.21— As in Fig. 5.7 for NGC 1652.

In the following we describe the procedure used to generate a synthetic CMD with these requirements. It consists of two main steps: in the first one we generate single stars; in the second one we measure the fraction of photometric binaries in the observed CMD and add the corresponding number of binary systems to the simulated CMD.

*Step one: simulation of single stars*

We separately simulated MS and evolved stars.

**UNEVOLVED STARS:** To generate single MS stars we started by selecting a subsample of artificial stars with the following criterion. For each star in the cluster field that survived to the statistical subtraction of reference field stars of Sect. 5.6.1, we have assigned a subsample of the artificial stars and randomly extracted a star from it (see Sect. 5.2.2 for a description of how AS were generated). The artificial-star subsample consists of all the artificial stars

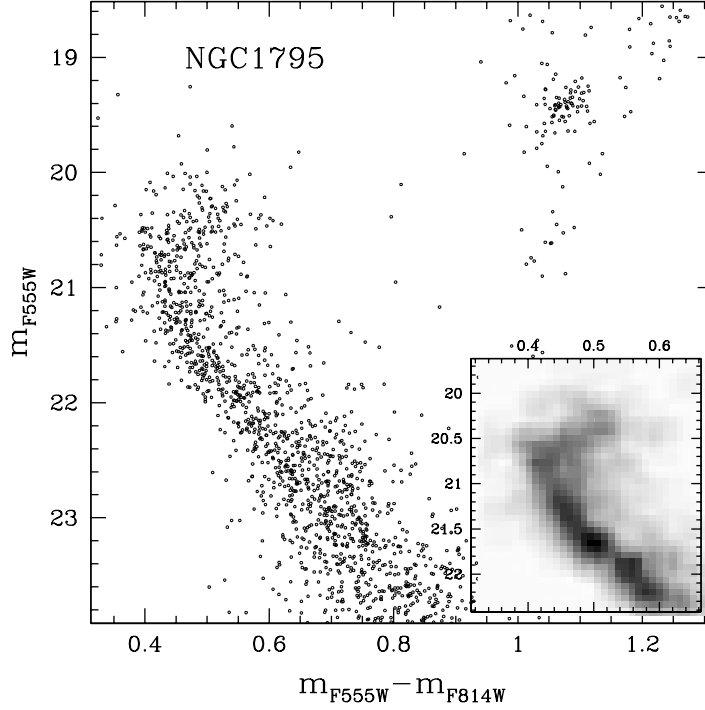


FIGURE 5.22— As in Fig. 5.7 for NGC 1795.

with similar magnitudes (within 0.1  $m_{F814W}$  mag) and radial distances (less than 50 pixel from the observed star). This method produces a catalogue of simulated stars with almost the same luminosity, and radial distribution of the observed catalogue. This procedure has been applied only to MS stars.

**EVOLVED STARS:** Things become more complicated for stars brighter than the MSTO where the complex shape of the CMD makes it harder to associate a star with the CMD sequence that corresponds to its evolutionary phase. For this reason, a different approach was used to simulate evolved stars (i.e. stars brighter than the MSTO).

First of all, we counted the number of MS stars (corrected for completeness) with  $m_{F814W}^{TO} < m_{F814W} < m_{F814W}^{TO} + 0.5$  and calculated the average number of stars per unit mass  $N_M$  in this range of luminosity. Next, we obtained  $N_M$  for stars brighter than the MSTO by using a Salpeter (1955) IMF and associated these stars to each portion of the CMD according to the Pietrinferni et al. (2004) models.

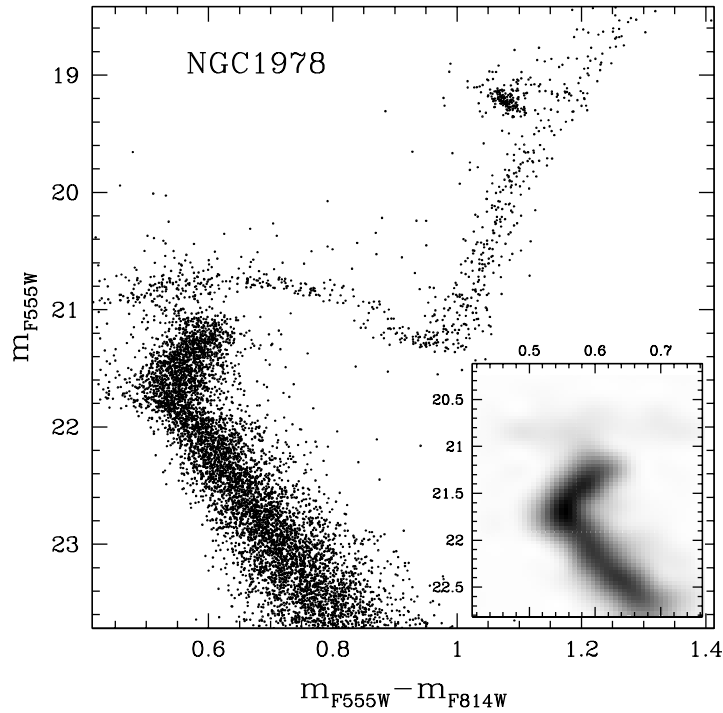


FIGURE 5.23— As in Fig. 5.7 for NGC 1978.

Since evolved stars should all have nearly the same mass, we would expect them to also have the same radial distribution. For this reason, we randomly associated the radial distance of an observed star brighter than the MSTO to each simulated evolved star. Finally, for each simulated star, we selected the sample of artificial stars with almost the same magnitude, colour and distance from the cluster centre (we imposed that both input  $m_{F814W}$  magnitude and colour must differ by less than 0.01 mag and radial distance by less than 50 pixels) and randomly extracted a star from it.

It must be noted that the simulated CMDs have photometric errors that are slightly smaller than the errors of real stars. This reflects a fundamental limitation of artificial-star tests. An artificial star is measured by using the same PSF as was used to generate it, while for the real stars we necessarily have an imperfect PSF. The PSF is constructed to fit the real stars as closely as possible, but there will invariably be errors in the PSF model for the real stars, which will not be present for the artificial stars. [However, it must be

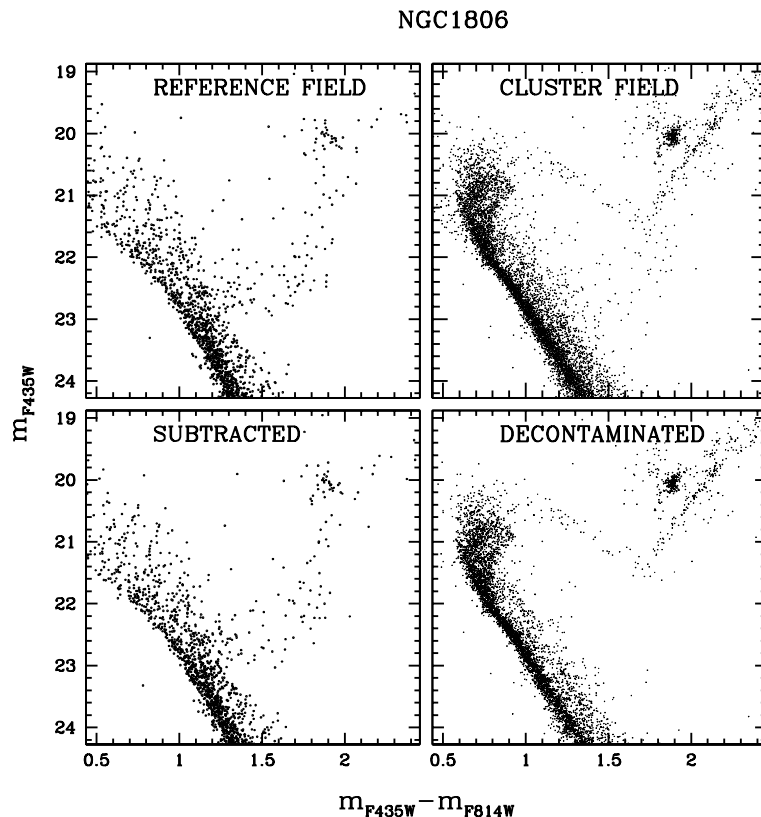


FIGURE 5.24— Statistical decontamination from field stars of the CMD of NGC 1806. Upper panels: CMD extracted from the reference (left), and cluster fields (right). Bottom panels: CMD of all the stars that have been subtracted from the reference field (left) and decontaminated cluster CMD (right).

clearly stated that these differences are appreciable only for the stars with the highest S/N ratio].

Below, we describe the method we used to estimate the difference between the photometric errors of real and artificial stars. This allows us to introduce an additional error component in to the artificial-star photometry so that the real and artificial sequences can be directly compared. We illustrate the procedure for the case of NGC 1806. The same procedure was applied for all clusters.

To determine how much artificial broadening of the error distribution is necessary, we compare the color distribution of the observed and simulated MS stars. Figure 5.26 shows the colour distribution of MS stars for NGC 1806: the left panel contains the CMD of all the stars contained in the cluster field after the subtraction of the reference field stars. The red fiducial line (MSRL) is

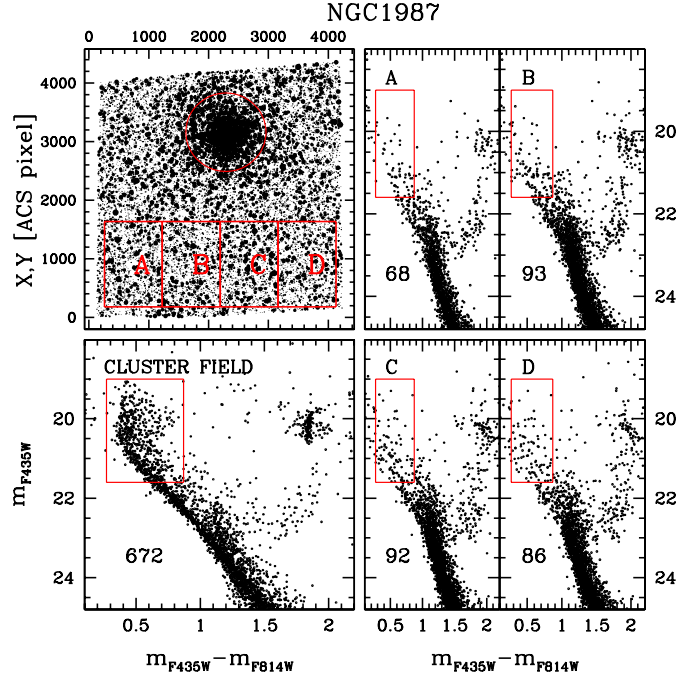


FIGURE 5.25— Comparison of the CMD of the cluster field and those of four external reference regions (*A*, *B*, *C* and *D*) for NGC 1987. The values given in the bottom left corner of each CMD are the number of stars (corrected for incompleteness) in the box around the cluster MSTO.

computed by using the following procedure. We started by dividing the CMD into bins of magnitude in the F814W band and, for each bin, we calculated the median colour and magnitude and obtained a raw fiducial line by fitting these points with a spline. Then for each star we derived the absolute value of the difference between its colour and the colour of the fiducial line, and calculated the  $\sigma$  as the 68.27<sup>th</sup> percentile. All the stars with distances greater than  $N \sigma$  from the fiducial were rejected and the survivors used to redetermine the median colour, magnitude, and  $\sigma$ . We iterated this procedure five times with  $N$  going from 6 to 2 (integer numbers).

In the middle panel we show the straightened CMD obtained by subtracting the color of the fiducial line from the color of each star. In the right panel we show the histograms of the color distribution in eight  $m_{F814W}$  magnitude intervals. The distribution in color is reproduced well by a Gaussian plus a tail on the red side due to the conspicuous number of photometric binaries and blends.

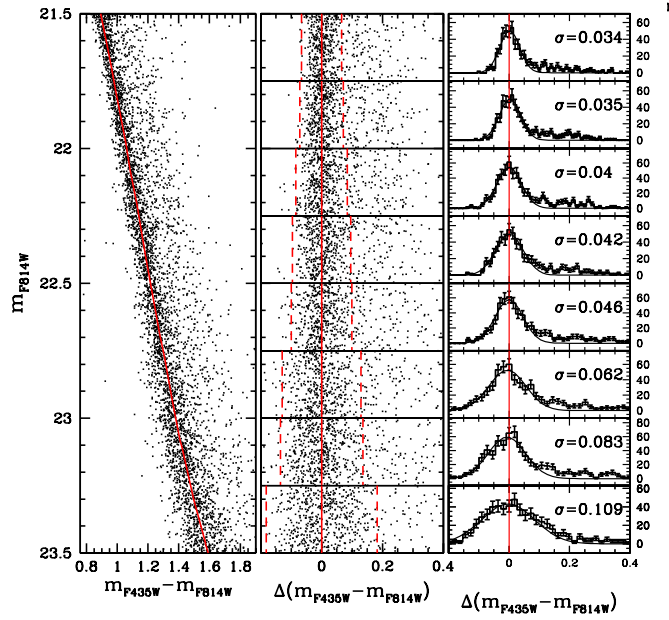


FIGURE 5.26— *Left* : CMD of NGC 1806 with the MSRL overplotted; *Middle* : The CMD rectified by subtraction of the MSRL; *Right* : Color distribution of the rectified CMD. The  $\sigma$  in the inset are those of the best-fitting gaussians.

In Fig. 5.27 we also reproduce the distribution in colour for the artificial star MS. As expected, the spread of the latter is slightly less than that of the observed MS. We note that this additional dispersion does not allow us to exclude intrinsic dispersion of the MSs smaller than 0.03 mag in color, which might result from dispersion of Z, Y, or a combination of the two (see discussion in Milone et al. 2008). In Fig. 5.28 we compare the dispersions of the observed MS ( $\sigma_{\text{OBS}}$ , circles) and for artificial stars ( $\sigma_{\text{ART}}$ , triangles) as a function of the  $m_{\text{F814W}}$  magnitude. The continuous lines are the best-fitting fourth-order polynomials ( $P_{\text{OBS}}$  and  $P_{\text{ART}}$ ). Finally, we added to the color of each star of the artificial-star CMD an error randomly extracted from a Gaussian distribution with dispersion:  $P_{\text{DIF}} = \sqrt{P_{\text{OBS}}^2 - P_{\text{ART}}^2}$ .

#### Step two: simulation of binary systems

It is clear from the excess of stars on the red side of the main sequence that many of these clusters have sizeable binary populations (compare Fig. 26 with Fig. 27). We expect that this binary population can have some effect on the distribution

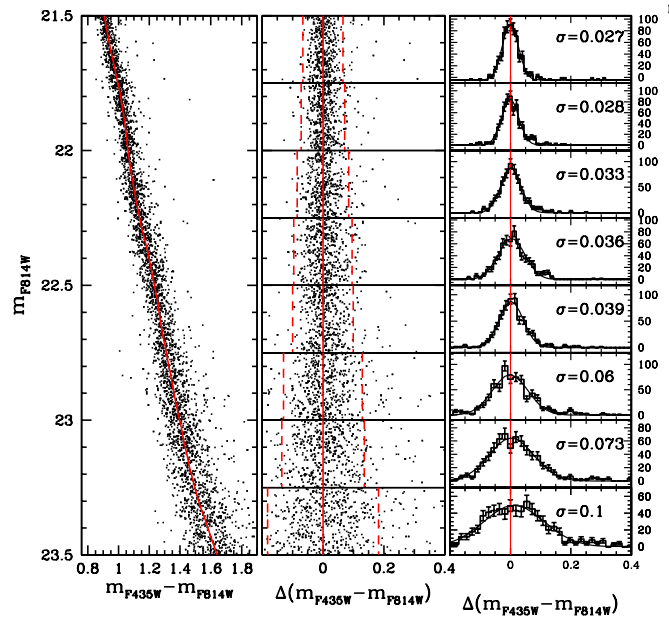
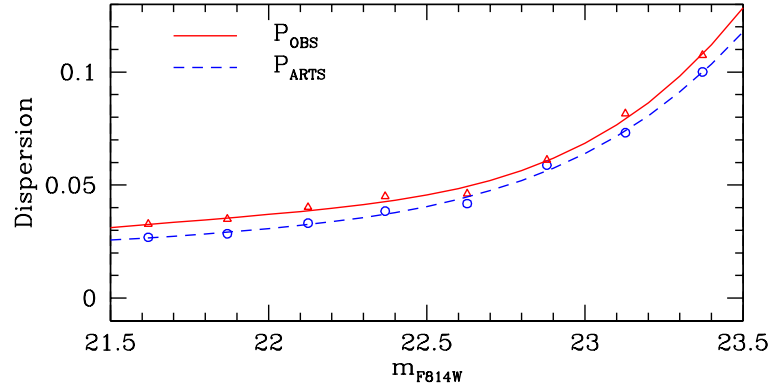


FIGURE 5.27— As in Fig. 5.26 but for artificial stars

FIGURE 5.28— Comparison of the  $\sigma$  of gaussians that best fit the color distributions of MS stars in the observed (red triangles) and artificial stars (blue circles) CMD as a function of the  $m_{F814W}$  magnitude. Continuous and dashed lines are the best fitting fourth order polynomials.

of stars around the turnoff, so we estimate the binary-contamination effect. Binary stars of LMC clusters will be unresolved even with *HST*, but the light



from each star will combine and the binary system will appear as a single point-source object. These binaries can be discerned photometrically from the single stars along the MS as they are located brightward and to the red of the sequence. The position of the binary systems formed by two MS stars (MS-MS binaries) with different mass ratios in a typical CMD of an intermediate age LMC clusters are illustrated in Fig. 5.29.

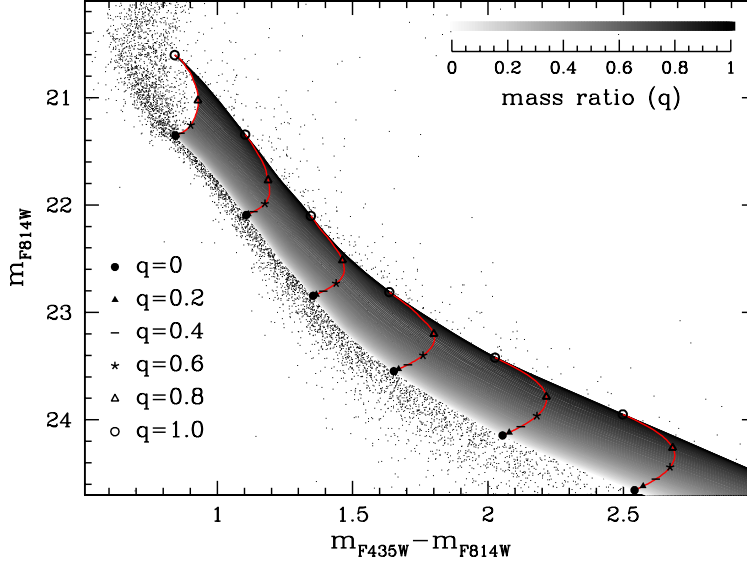


FIGURE 5.29— Grey area highlight the loci populated by MS-MS binaries. The levels of grey are proportional to the mass ratio. Red lines indicate the position of a MS-MS binary for six fixed values of the mass of the primary star ( $m_1$ ) and  $q$  ranging from 0 to 1.

In the same region of the CMD, in addition to the true physically associated binaries, we also expect a few chance superpositions (blends). The artificial-star tests (see Fig. 27) show that this is a very weak effect.

It is important to note here that measuring the fraction of binaries is not the goal of this work. Instead, our aim here is to estimate their fraction so that we can determine how much of the spread of the MSTO region can reasonably be attributed to them.

Binaries can be parametrized by their mass ratio,  $q = m_1/m_2$ , where  $m_1 < m_2$ . To estimate the fraction of MS-MS photometric binaries with a mass ratio greater than a threshold value (hereafter  $q_{\text{th}}$ , see Table 2 for the adopted  $q_{\text{th}}$  for each cluster), we applied the methods described in Milone et al. (2008) and Bedin et al. (2008). We divided the CMD into two regions: the first one (A) contains all the single MS stars and binaries with a primary star with

$(m_{\text{F814W}}^{\text{MSTO}} + 0.4) < m_{\text{F814W}} < (m_{\text{F814W}}^{\text{MSTO}} + 2.4)$  (where  $m_{\text{F814W}}^{\text{MSTO}}$  is the magnitude of the MSTO in the F814W band). It corresponds to the light and dark grey areas of Fig. 5.30. The second region (*B*) is the part of *A* that contains MS-MS binaries with  $q > q_{\text{th}}$ , and corresponds to the dark grey area of Fig. 5.30. We adopted  $q_{\text{th}} = 0.6$  or  $q_{\text{th}} = 0.7$ , as indicated in Table 2, depending on the photometric quality of the data. The fraction of binaries with  $q > q_{\text{th}}$  has been evaluated as

$$f_{\text{BIN}}^{q > q_{\text{th}}} = \frac{N_{\text{CLUSTER}}^{\text{B}} - N_{\text{REFERENCE}}^{\text{B}}}{N_{\text{CLUSTER}}^{\text{A}} - N_{\text{REFERENCE}}^{\text{A}}} - \frac{N_{\text{ARTS}}^{\text{B}}}{N_{\text{ARTS}}^{\text{A}}}$$

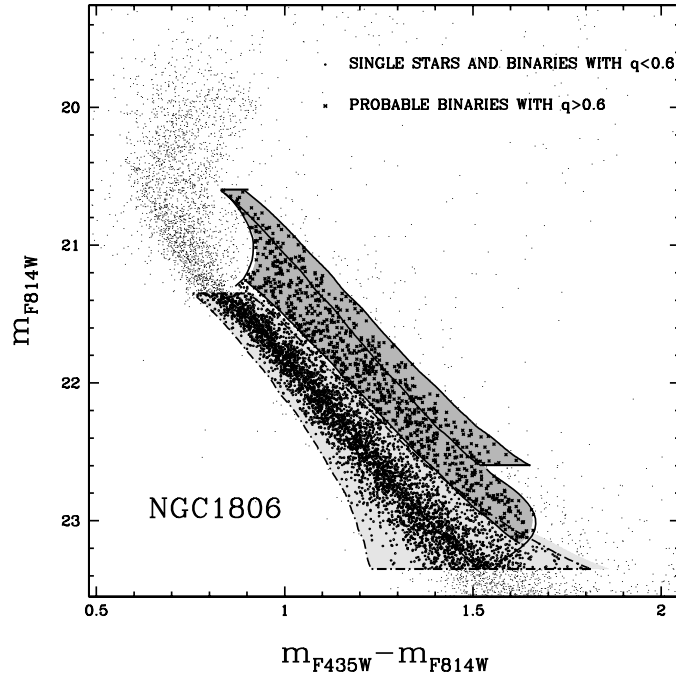


FIGURE 5.30— The MS of NGC 1806 with the candidate binaries with mass ratio  $q > 0.6$  plotted as crosses.

where  $N_{\text{CLUSTER}}^{\text{A(B)}}$  is the number of stars (corrected for completeness) observed in the region A (B) of the CMD extracted from the cluster field,  $N_{\text{REFERENCE}}^{\text{A(B)}}$  are the corresponding numbers of stars in the CMD of the reference field and account for the field contamination and  $N_{\text{ARTS}}^{\text{A(B)}}$  refers to artificial stars: their ratio indicates the fraction of blends. Finally, we calculated the global fraction of binaries by interpolation, assuming a flat mass-ratio distribution. The only

differences from Milone et al. (2008) and Bedin et al. (2008) is that in this work we removed the contribution from field stars by using the CMD observed in the reference region, rather than by using a Galactic model or proper motions. The measured fraction of binaries in each cluster are in Table 2.

We tried very hard to get a reliable binary fraction for those clusters, but unfortunately, they are just too big on ACS/WFC FOV. If we take the outskirts as representative of the field, we would end up subtracting cluster members from clusters, and since energy equipartition makes the binary sink into the cluster core, this could potentially generate dangerous biases in the relative fraction of a single to binary system. We avoid on purpose to giving numbers in Table 1 for those clusters, to avoid contamination of the literature with unreliable values of the binary fraction for those objects.

To simulate binary stars to be added to the simulated CMD described in Sect. 5.6.2 we adopted the following procedure:

- We selected a fraction  $F_{\text{BIN}}$  of single stars equal to the measured fraction of binaries and derived their masses by using the Pietrinferni et al. (2004) mass-luminosity relation. For the clusters where the measure of the binary fraction is not available, we assumed the average value of  $F_{\text{BIN}} = 0.33$ .
- For each of them, we calculated the mass  $\mathcal{M}_2 = q \times \mathcal{M}_1$  of the secondary star and obtained the corresponding  $m_{\text{F814W}}$  magnitude. Its colour was derived by the MSRL.
- Finally, we summed up the F435W (or F555W) and F814W fluxes of the two components, calculated the corresponding magnitudes, added the corresponding photometric error, and replaced the original star in the CMD with this binary system.

Figures 5.31, 5.32, 5.33, and 5.34 show the contribution that we would expect from binaries to the broadening of the cluster TOs. It is clear that the double MSTO in NGC 1806, NGC 1846, and NGC 1751, and the extended (broadened) MSTO in ESO057-SC075, HODGE 7, NGC 1783, NGC 1852, NGC 1917, NGC 1987, NGC 2108, and NGC 2154 are intrinsic features of these objects, and cannot be due to field-star contamination, photometric errors, or binaries. In these figures, we show, from the left to the right, a zoom of the original cluster-field CMD around the MSTO, the same portion of the CMD but for stars in the reference field, the CMD after field-star decontamination, and the simulated CMD for these clusters.

Figures 35 and 36 illustrate the same exercise for the clusters with no significant MSTO broadening. Now that we have introduced the simulated CMDs, we

can describe how we distinguish between clusters that show evidence of hosting a multiple population, and those that do not. First, we calculated the dispersion of stars along the same direction perpendicular to the observed spread (on the right of the MSTO) for real ( $\sigma_{SGB}^{OBS}$ ) and artificial stars ( $\sigma_{SGB}^{ART}$ ). Then, we considered a cluster as hosting a multiple population if the dispersion of real stars was more than three times the dispersion of the simulated CMD. This condition is verified for eleven out of the sixteen clusters. Although the exact position of the line along which to measure the spread is not unique, it seemed to us a reasonably solid approach.

### 5.7 Isochrone fitting

Both M07 and M08 propose that the split of the MSTO of NGC 1846 and NGC 1806 is consistent with the presence of two distinct stellar populations with the same chemical composition and a difference in age of about  $\sim 300$  Myr. In addition, M08 suggest that the spread of the MSTO of NGC 1783 can be attributed to a prolonged star formation.

In the previous sections, we demonstrated that eight additional clusters show strong indications of an intrinsic spread or split of the CMD around the MSTO region. The remaining five objects of our sample show no significant evidence of a multiple stellar population within our photometric precision (see Figs. 5.35 and 5.36).

We note that in the clusters where a spread in the MSTO is claimed, the other evolutionary sequences are narrow and well defined, after a correction for differential reddening has been made. The tightness of these other sequences is also a strong indication that there is very little variation in metallicity among the stars.

Therefore, in the absence of any detailed chemical composition analysis, we will assume in what follows that any spread around the MSTO can be attributed to a difference in age alone. We derive the main parameters for each cluster (metallicity, age, and the maximum age spread among the populations) by fitting the data with the isochrones from the BaSTI evolutionary code (Pietrinferni et al. 2004, updated version of August 2008). Each of the isochrones has a solar-scaled distribution of metals and includes convective overshooting.

To determine the isochrone that best matches the observed CMD of our clusters with no evidence of an intrinsic spread around the MSTO, we followed a procedure similar to the one adopted by M07. We generated a grid of isochrones using metallicities of  $Z = 0.008$  and  $0.010$ , sampling an age range between 1.0 and 3.0 Gyrs at intervals of 0.05 Gyr. Then, we defined by hand the magnitude of the MSTO, the color of the RGB at a level intermediate between that of the

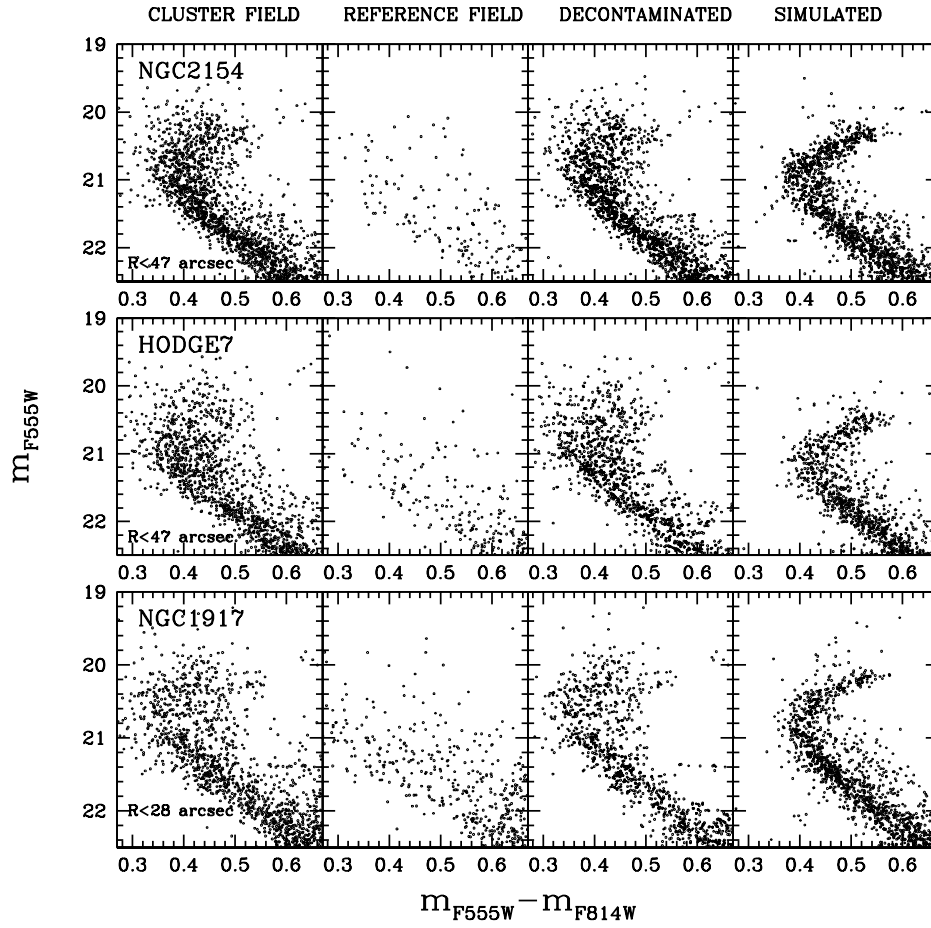


FIGURE 5.31— From the left to the right: CMD of the cluster field for NGC 2154, HODGE 7 and NGC 1917, CMD of the reference field, CMD of the cluster field after that reference field stars have been statistically subtracted, simulated CMD.

red end of the SGB and that of the HB red-clump, and the magnitude of the HB red-clump. In this way we calculated the difference in magnitude between the MSTO and the HB red-clump ( $\Delta_{\text{mag}}$ ) and the difference in color between the MSTO and the fiducial points on the RGB ( $\Delta_{\text{col}}$ ). Then we calculated a value of  $\Delta_{\text{mag}}$  and  $\Delta_{\text{col}}$  for each isochrone in the grid and compared them with the observed ones. Finally, we selected all the isochrones where  $\Delta_{\text{col}}$  and  $\Delta_{\text{mag}}$  differ respectively by less  $\pm 0.25$  and  $\pm 0.03$  magnitudes and fitted them

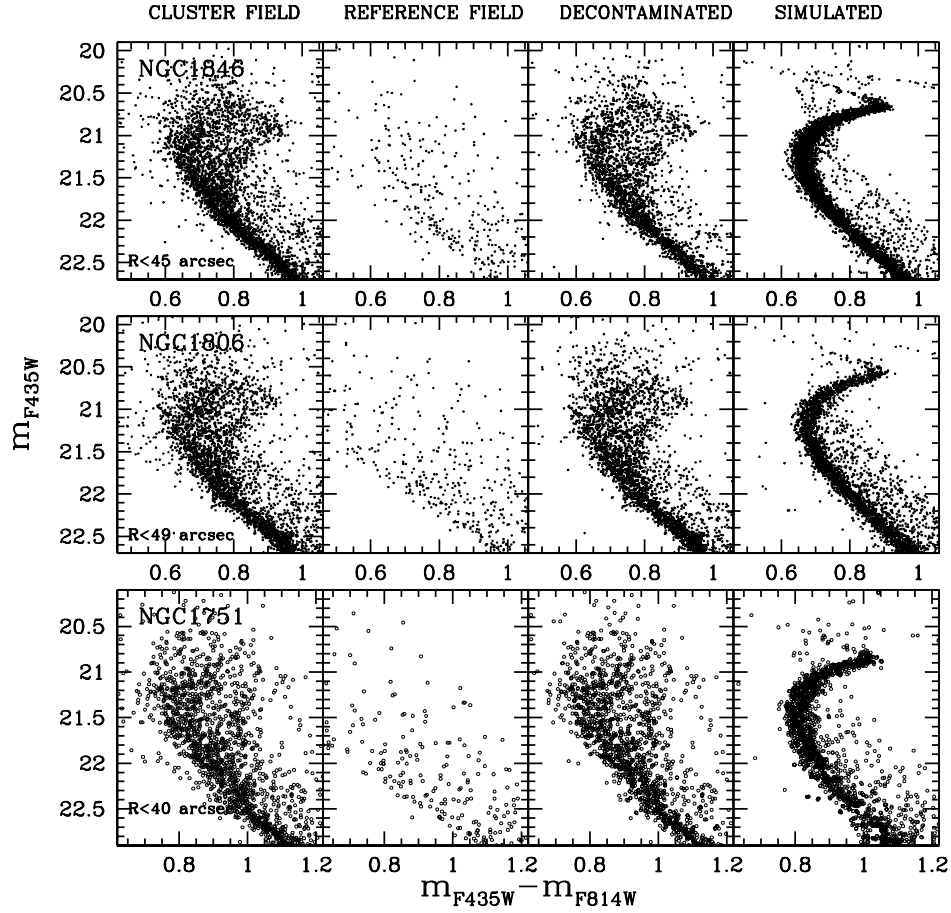


FIGURE 5.32— As in Fig. 5.31 for NGC 1846, NGC 1806 and NGC 1751.

to the CMD by hand. To do this, we varied the distance modulus in the range  $18.30 < (m - M)_0 < 18.70$  and the reddening between 0.00 and 0.30, both in steps of 0.01 mag and searched for the combination that matches the cluster sequences best. For clusters with a double or broadened MSTO, we used a similar approach with the exception that, in this case, we first defined on the observed CMD the magnitude of the MSTO and the values of  $\Delta_{\text{mag}}$  and  $\Delta_{\text{col}}$  for the bMSTO and determined the isochrone that best fits this younger population. Then, we selected all the isochrones with the same metallicity, distance modulus, and reddening, but different ages, and fitted the fMSTO. For

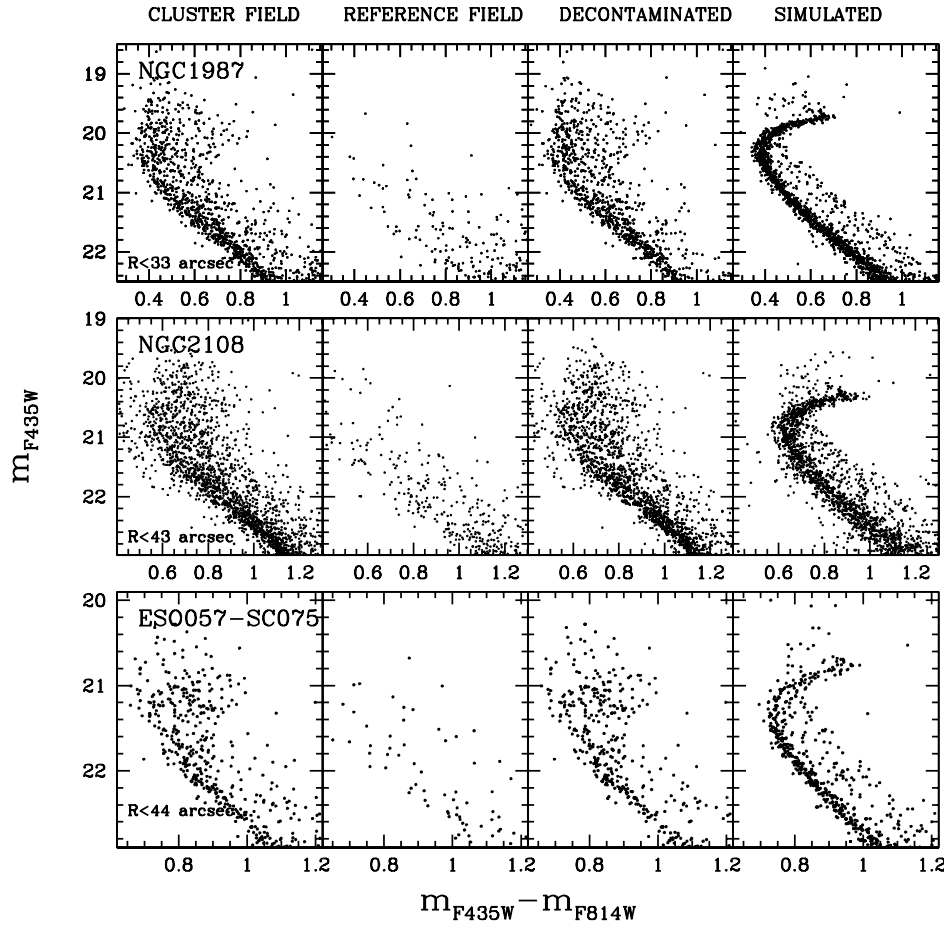


FIGURE 5.33— As in Fig. 5.31 for NGC 1987, NGC 2108 and ESO057-SC075.

clusters with a broadened MSTO, we calculated those values that correspond to the brighter and the fainter region of the MSTO.

The best fitting distance modulus, reddening, metallicity, and age are listed in Table. 3. The last column indicates the maximum age difference,  $\Delta_{\text{age}}$ , for stars in clusters that show possible evidence of multiple or prolonged star formation episodes. In Figs. 5.37, 5.38, and 5.39, we have overplotted the best fitting isochrones to the observed CMDs. Interestingly, the multiple (or prolonged) star-formation episodes seem to lie between 150 and 250 Myr, which is very similar to the time interval between successive star formation episodes

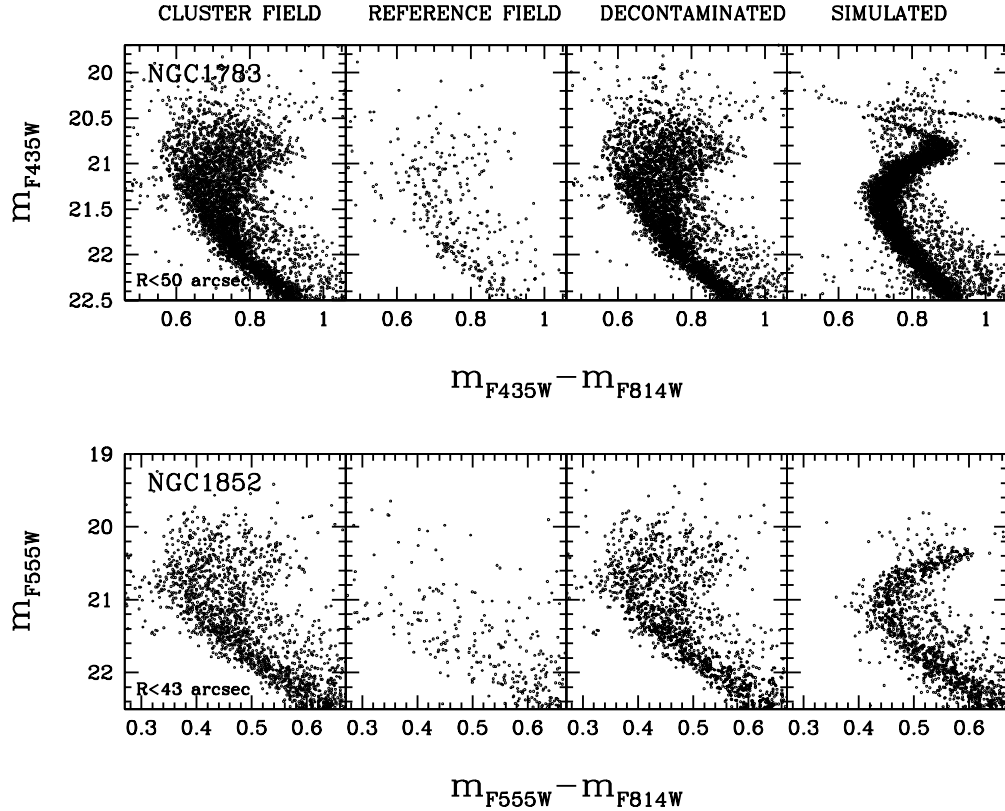


FIGURE 5.34 — As in Fig. 5.31 for NGC 1783 and NGC 1852.

in the intermediate-mass AGB star ejecta pollution depicted by Ventura et al (2001).

## 5.8 Conclusions

High-precision *HST* ACS/*HST* photometry of sixteen intermediate age LMC stellar clusters has revealed that eleven of them (i.e. about the  $70 \pm 25\%$  of the entire sample) host multiple stellar populations.

The CMDs of NGC 1806, NGC 1846, and NGC 1751 exhibit two distinct MSTOs, suggesting that these clusters have experienced (at least) two main episodes of star formation with a temporal separation of 200 - 250 Myr. For these three clusters, the high quality of our photometry enabled us not only to distinguish the two populations, but also to measure the fraction of stars belonging to each of them. In all these cases, the population corresponding to the brighter MSTO (the younger population) is the main population, and it



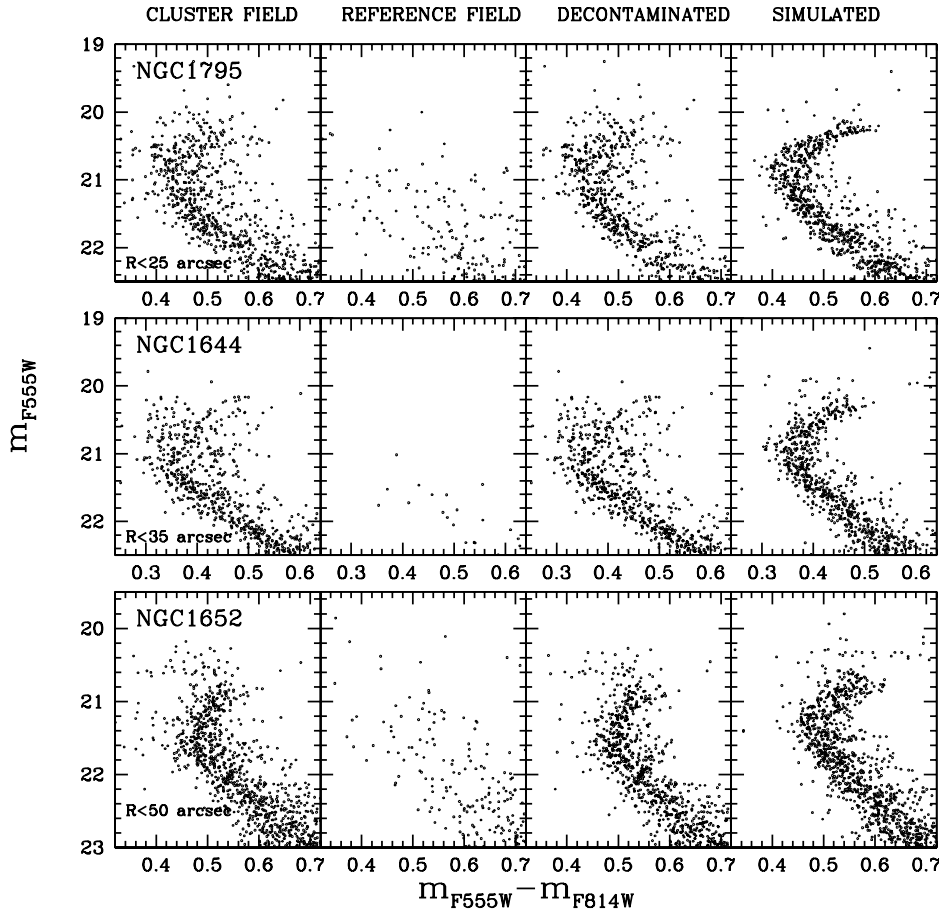


FIGURE 5.35— As in Fig. 5.31 for NGC 1795, NGC 1644 and NGC 1652.

includes more than two-thirds of the cluster stellar population, consistent with the intermediate mass AGB pollution scenario (See D’Antona & Caloi 2008 for a recent review).

Our photometry strongly suggests that the intrinsic broadening of the MSTO of NGC 1783 observed by M08 could be attributed to the presence of two distinct branches that are closely spaced and poorly resolved by the observations.

In seven additional clusters, namely ESO057-SC075, HODGE7, NGC 1852, NGC 1917, NGC 1987, NGC 2108, and NGC 2154, we observed a wide spread in colour for the stars around the MSTO. In spite of this, the other main fea-

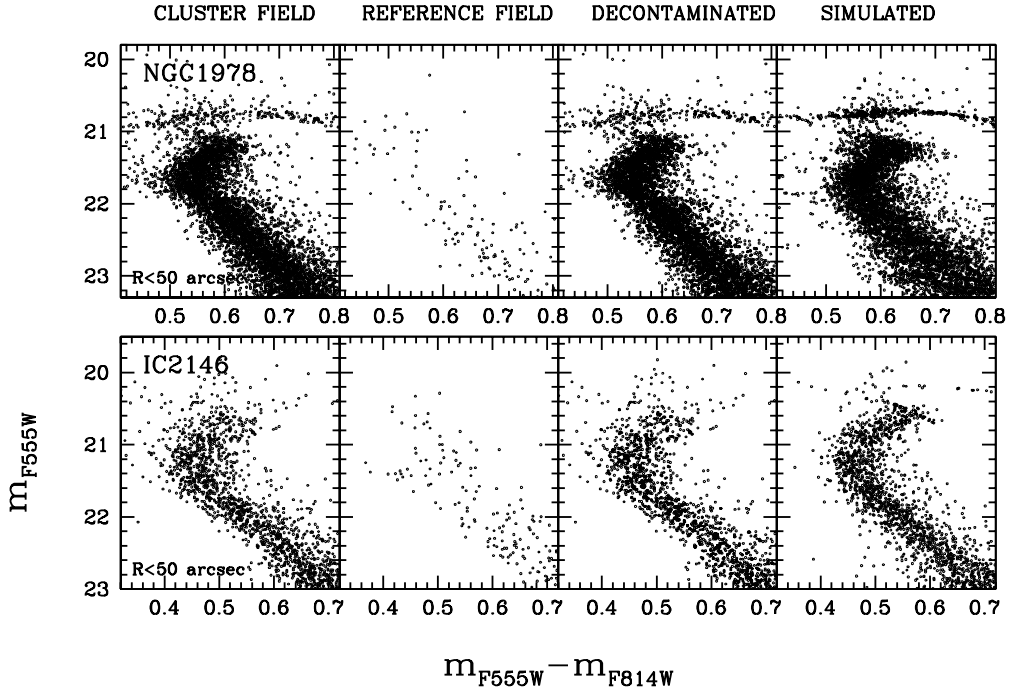


FIGURE 5.36— As in Fig. 5.31 for NGC 1978 and IC 2146.

tures of the CMD are narrow and well-defined, demonstrating that the spread cannot be an artifact produced by differential reddening, by variation in the photometric zero point along the chip, or by a relatively wide spread in metallicity. By using the CMD of the stars in the fields that surround the cluster, we demonstrated that the observed feature is unequivocally associated with the clusters. Finally, artificial stars and simulated CMDs show that the wide spread in colour observed around the MSTO cannot be produced by photometric errors or binaries. It is interesting to note that the age spreads observed in this sample appear to be quite similar, with all between 150 and 250 Myr.

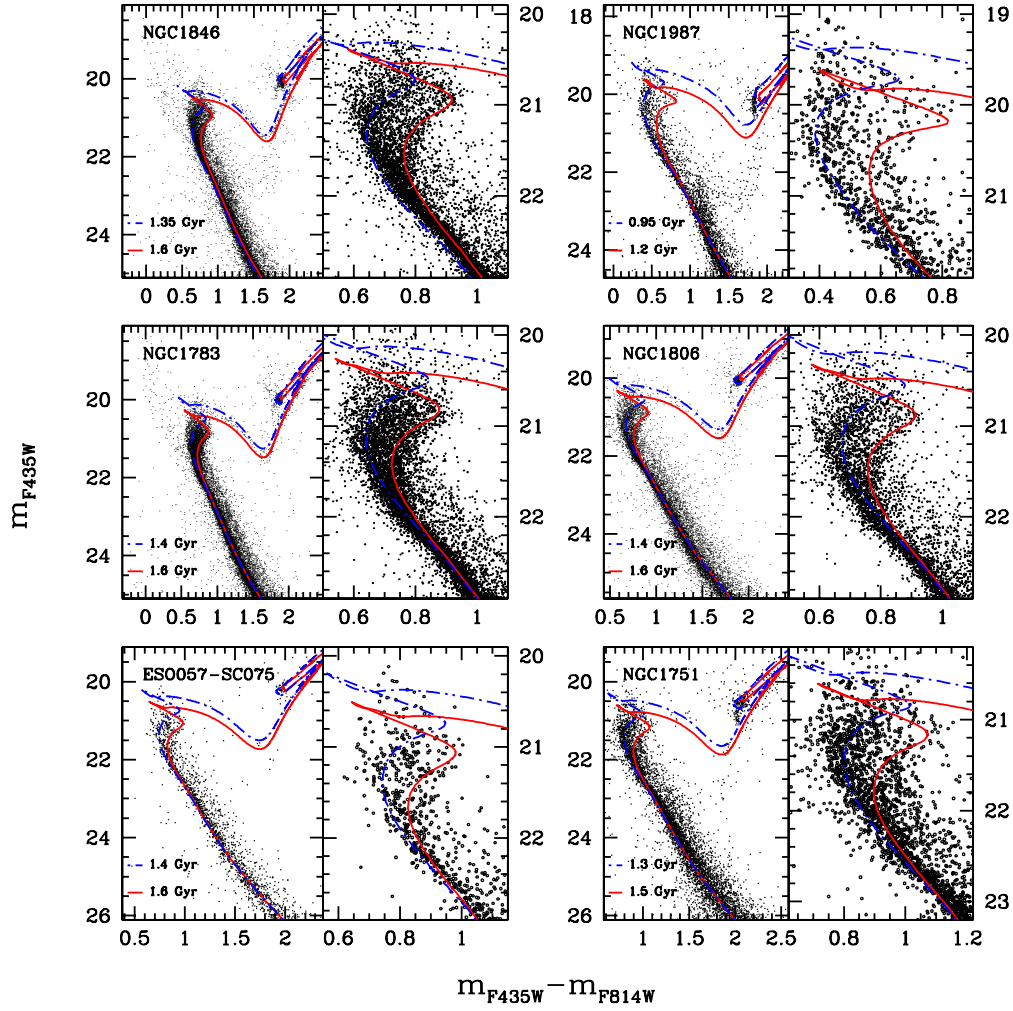


FIGURE 5.37— The best fitting isochrones, obtained by using the distance modulus, reddening, metallicity and age(s) of NGC 1846, NGC 1987, NGC 1783, NGC 1806, ESO057-SC075 and NGC 1751 listed in Table 5.7 are overplotted to the CMD of the cluster field of (left). A zoom of the region around the MSTO is shown on the right.

| ID            | DATE           | EXPOSURES  | FILT  | PROGRAM |
|---------------|----------------|------------|-------|---------|
| ESO 057-SC075 | Nov 05 2006    | 55s+2×340s | F435W | 10595   |
|               | Nov 05 2006    | 25s+2×340s | F555W | 10595   |
|               | Nov 05 2006    | 15s+2×340s | F814W | 10595   |
| ESO 121-SC03  | Oct 07 2003    | 330s       | F555W | 9891    |
|               | Oct 07 2003    | 200s       | F814W | 9891    |
| HODGE 7       | Oct 07 2003    | 330s       | F555W | 9891    |
|               | Oct 07 2003    | 200s       | F814W | 9891    |
| IC 1660       | Aug 13 2003    | 73s        | F555W | 9891    |
|               | Aug 13 2003    | 58s        | F814W | 9891    |
| IC 2146       | Jul 07 2003    | 250s       | F555W | 9891    |
|               | Jul 07 2003    | 170s       | F814W | 9891    |
| KRON 1        | Aug 27 2003    | 480s       | F555W | 9891    |
|               | Aug 27 2003    | 290s       | F814W | 9891    |
| KRON 21       | Aug 22 2003    | 480s       | F555W | 9891    |
|               | Aug 22 2003    | 290s       | F814W | 9891    |
| KRON 34       | Aug 12 2003    | 165s       | F555W | 9891    |
|               | Aug 12 2003    | 130s       | F814W | 9891    |
| LYNDSAY 1     | Jul 11 2003    | 480s       | F555W | 9891    |
|               | Jul 11 2003    | 290s       | F814W | 9891    |
| LYNDSAY 38    | Jun 03 2004    | 480s       | F555W | 9891    |
|               | Jun 03 2004    | 290s       | F814W | 9891    |
| LYNDSAY 91    | Aug 24 2003    | 435s       | F555W | 9891    |
|               | Aug 24 2003    | 290s       | F814W | 9891    |
| LYNDSAY 113   | Jun 03 2004    | 480s       | F555W | 9891    |
|               | Jun 03 2004    | 290s       | F814W | 9891    |
| LYNDSAY 114   | Aug 07 2003    | 480s       | F555W | 9891    |
|               | Aug 07 2003    | 290s       | F814W | 9891    |
| NGC 265       | Aug 24 2003    | 29s        | F555W | 9891    |
|               | Aug 24 2003    | 29s        | F814W | 9891    |
| NGC 294       | Aug 24 2003    | 165s       | F555W | 9891    |
|               | Aug 24 2003    | 130s       | F814W | 9891    |
| NGC 422       | Oct 07 2003    | 73s        | F555W | 9891    |
|               | Oct 07 2003    | 58s        | F814W | 9891    |
| NGC 602       | Aug 16 2003    | 29s        | F555W | 9891    |
|               | Aug 16 2003    | 29s        | F814W | 9891    |
| NGC 1644      | Oct 07 2003    | 250s       | F555W | 9891    |
|               | Oct 07 2003    | 170s       | F814W | 9891    |
| NGC 1652      | Oct 07 2003    | 300s       | F555W | 9891    |
|               | Oct 07 2003    | 200s       | F814W | 9891    |
| NGC 1751      | Oct 07 2003    | 300s       | F555W | 9891    |
|               | Oct 07 2003    | 200s       | F814W | 9891    |
|               | Oct 17-18 2006 | 90s+2×340s | F435W | 10595   |
|               | Oct 17-18 2006 | 40s+2×340s | F555W | 10595   |
|               | Oct 17-18 2006 | 8s+2×340s  | F814W | 10595   |
| NGC 1755      | Aug 23 2003    | 50s        | F555W | 9891    |
|               | Aug 23 2003    | 40s        | F814W | 9891    |
| NGC 1756      | Aug 12 2003    | 170s       | F555W | 9891    |
|               | Aug 12 2003    | 120s       | F814W | 9891    |
| NGC 1783      | Oct 07 2003    | 250s       | F555W | 9891    |
|               | Oct 07 2003    | 170s       | F814W | 9891    |
|               | Jan 01 2006    | 90s+2×340s | F435W | 10595   |
|               | Jan 01 2006    | 40s+2×340s | F555W | 10595   |
|               | Jan 01 2006    | 8s+2×340s  | F814W | 10595   |
| NGC 1795      | Aug 09 2003    | 300s       | F555W | 9891    |
|               | Aug 09 2003    | 200s       | F814W | 9891    |
| NGC 1801      | Oct 08 2003    | 115s       | F555W | 9891    |
|               | Oct 08 2003    | 90s        | F814W | 9891    |
| NGC 1806      | Aug 08 2003    | 300s       | F555W | 9891    |
|               | Aug 08 2003    | 200s       | F814W | 9891    |
|               | Sep 29 2005    | 90s+2×340s | F435W | 10595   |
|               | Sep 29 2005    | 40s+2×340s | F555W | 10595   |
|               | Sep 29 2005    | 8s+2×340s  | F814W | 10595   |

TABLE 5.1— Description of the data sets.

| ID        | DATE        | EXPOSURES  | FILT  | PROGRAM |
|-----------|-------------|------------|-------|---------|
| NGC 1846  | Oct 08 2003 | 300s       | F555W | 9891    |
|           | Oct 08 2003 | 200s       | F814W | 9891    |
|           | Jan 01 2006 | 90s+2×340s | F435W | 10595   |
|           | Jan 01 2006 | 40s+2×340s | F555W | 10595   |
|           | Jan 01 2006 | 8s+2×340s  | F814W | 10595   |
| NGC 1852  | Oct 07 2003 | 330s       | F555W | 9891    |
|           | Oct 07 2003 | 200s       | F814W | 9891    |
| NGC 1854  | Oct 07 2003 | 50s        | F555W | 9891    |
|           | Oct 07 2003 | 40s        | F814W | 9891    |
| NGC 1858  | Oct 08 2003 | 20s        | F555W | 9891    |
|           | Oct 08 2003 | 20s        | F814W | 9891    |
| NGC 1872  | Sep 21 2003 | 115s       | F555W | 9891    |
|           | Sep 21 2003 | 90s        | F814W | 9891    |
| NGC 1903  | Jui 02 2004 | 50s        | F555W | 9891    |
|           | Jui 02 2004 | 40s        | F814W | 9891    |
| NGC 1917  | Oct 07 2003 | 300s       | F555W | 9891    |
|           | Oct 07 2003 | 200s       | F814W | 9891    |
| NGC 1928  | Aug 23 2003 | 330s       | F555W | 9891    |
|           | Aug 23 2003 | 200s       | F814W | 9891    |
| NGC 1939  | Jul 27 2003 | 330s       | F555W | 9891    |
|           | Jul 27 2003 | 200s       | F814W | 9891    |
| NGC 1943  | Oct 07 2003 | 50s        | F555W | 9891    |
|           | Oct 07 2003 | 40s        | F814W | 9891    |
| NGC 1953  | Oct 07 2003 | 115s       | F555W | 9891    |
|           | Oct 07 2003 | 90s        | F814W | 9891    |
| NGC 1978  | Oct 07 2003 | 300s       | F555W | 9891    |
|           | Oct 07 2003 | 200s       | F814W | 9891    |
| NGC 1983  | Oct 07 2003 | 20s        | F555W | 9891    |
|           | Oct 07 2003 | 20s        | F814W | 9891    |
| NGC 1987  | Oct 07 2003 | 250s       | F555W | 9891    |
|           | Oct 07 2003 | 170s       | F814W | 9891    |
|           | Oct 18 2006 | 90s+2×340s | F435W | 10595   |
|           | Oct 18 2006 | 40s+2×340s | F555W | 10595   |
|           | Oct 18 2006 | 8s+2×340s  | F814W | 10595   |
| NGC 2002  | Aug 23 2003 | 20s        | F555W | 9891    |
|           | Aug 23 2003 | 20s        | F814W | 9891    |
| NGC 2010  | Oct 07 2003 | 20s        | F555W | 9891    |
|           | Oct 07 2003 | 20s        | F814W | 9891    |
| NGC 2056  | Aug 08 2003 | 170s       | F555W | 9891    |
|           | Aug 08 2003 | 120s       | F814W | 9891    |
| NGC 2107  | Oct 07 2003 | 170s       | F555W | 9891    |
|           | Oct 07 2003 | 120s       | F814W | 9891    |
| NGC 2108  | Aug 16 2003 | 250s       | F555W | 9891    |
|           | Aug 16 2003 | 170s       | F814W | 9891    |
|           | Aug 22 2006 | 90s+2×340s | F435W | 10595   |
|           | Aug 22 2006 | 40s+2×340s | F555W | 10595   |
|           | Aug 22 2006 | 8s+2×340s  | F814W | 10595   |
| NGC 2154  | Oct 08 2003 | 300s       | F555W | 9891    |
|           | Oct 08 2003 | 200s       | F814W | 9891    |
| RETICULUM | Sep 21 2003 | 330s       | F555W | 9891    |
|           | Sep 21 2003 | 200s       | F814W | 9891    |

TABLE 5.2— Description of the data sets.

| ID           | $q_{\text{th}}$ | $f_{\text{bin}}^{q > q_{\text{th}}}$ | $f_{\text{bin}}^{\text{TOT}}$ |
|--------------|-----------------|--------------------------------------|-------------------------------|
| ESO057-SC075 | 0.6             | $0.17 \pm 0.02$                      | $0.42 \pm 0.05$               |
| HODGE7       | 0.7             | $0.08 \pm 0.01$                      | $0.27 \pm 0.04$               |
| NGC1644      | 0.7             | $0.09 \pm 0.02$                      | $0.29 \pm 0.06$               |
| NGC1652      | 0.7             | $0.06 \pm 0.01$                      | $0.19 \pm 0.04$               |
| NGC1751      | 0.6             | $0.13 \pm 0.01$                      | $0.33 \pm 0.03$               |
| NGC1795      | 0.7             | $0.12 \pm 0.02$                      | $0.39 \pm 0.06$               |
| NGC1806      | 0.6             | $0.13 \pm 0.01$                      | $0.32 \pm 0.03$               |
| NGC1852      | 0.7             | $0.11 \pm 0.02$                      | $0.36 \pm 0.05$               |
| NGC1917      | 0.7             | $0.09 \pm 0.02$                      | $0.31 \pm 0.05$               |
| NGC1987      | 0.6             | $0.12 \pm 0.01$                      | $0.31 \pm 0.03$               |
| NGC2108      | 0.6             | $0.18 \pm 0.01$                      | $0.46 \pm 0.03$               |
| NGC2154      | 0.7             | $0.08 \pm 0.01$                      | $0.28 \pm 0.04$               |

TABLE 5.3— Fraction of photometric binaries with  $q > q_{\text{th}}$  and total fraction of binaries (columns 5 and 6) within the cluster field.

| ID           | $(m - M)_0$ | $E(B - V)$ | Z     | Age (Myr) | $\Delta_{\text{age}}$ |
|--------------|-------------|------------|-------|-----------|-----------------------|
| ESO057-SC075 | 18.46       | 0.14       | 0.008 | 1400-1600 | $200 \pm 50$          |
| HODGE7       | 18.48       | 0.04       | 0.008 | 1400-1550 | $150 \pm 50$          |
| IC2146       | 18.50       | 0.07       | 0.008 | 1550      | $< 50$                |
| NGC1644      | 18.48       | 0.01       | 0.008 | 1550      | $< 50$                |
| NGC1652      | 18.48       | 0.06       | 0.008 | 1700      | $< 50$                |
| NGC1751      | 18.45       | 0.22       | 0.008 | 1300-1500 | $200 \pm 50$          |
| NGC1783      | 18.46       | 0.06       | 0.008 | 1400-1600 | $200 \pm 50$          |
| NGC1795      | 18.45       | 0.10       | 0.008 | 1300      | $< 50$                |
| NGC1806      | 18.44       | 0.09       | 0.008 | 1400-1600 | $200 \pm 50$          |
| NGC1846      | 18.49       | 0.09       | 0.008 | 1350-1600 | $250 \pm 50$          |
| NGC1852      | 18.50       | 0.08       | 0.008 | 1200-1450 | $250 \pm 50$          |
| NGC1917      | 18.48       | 0.08       | 0.008 | 1200-1350 | $150 \pm 50$          |
| NGC1978      | 18.49       | 0.09       | 0.008 | 2000      | $< 100$               |
| NGC1987      | 18.40       | 0.04       | 0.010 | 950-1200  | $250 \pm 50$          |
| NGC2108      | 18.40       | 0.21       | 0.010 | 950-1100  | $150 \pm 50$          |
| NGC2154      | 18.48       | 0.04       | 0.008 | 1350-1500 | $150 \pm 50$          |

TABLE 5.4— Parameters that have been used to obtain the best fit between the observed CMD and the BaSTI isochrones.

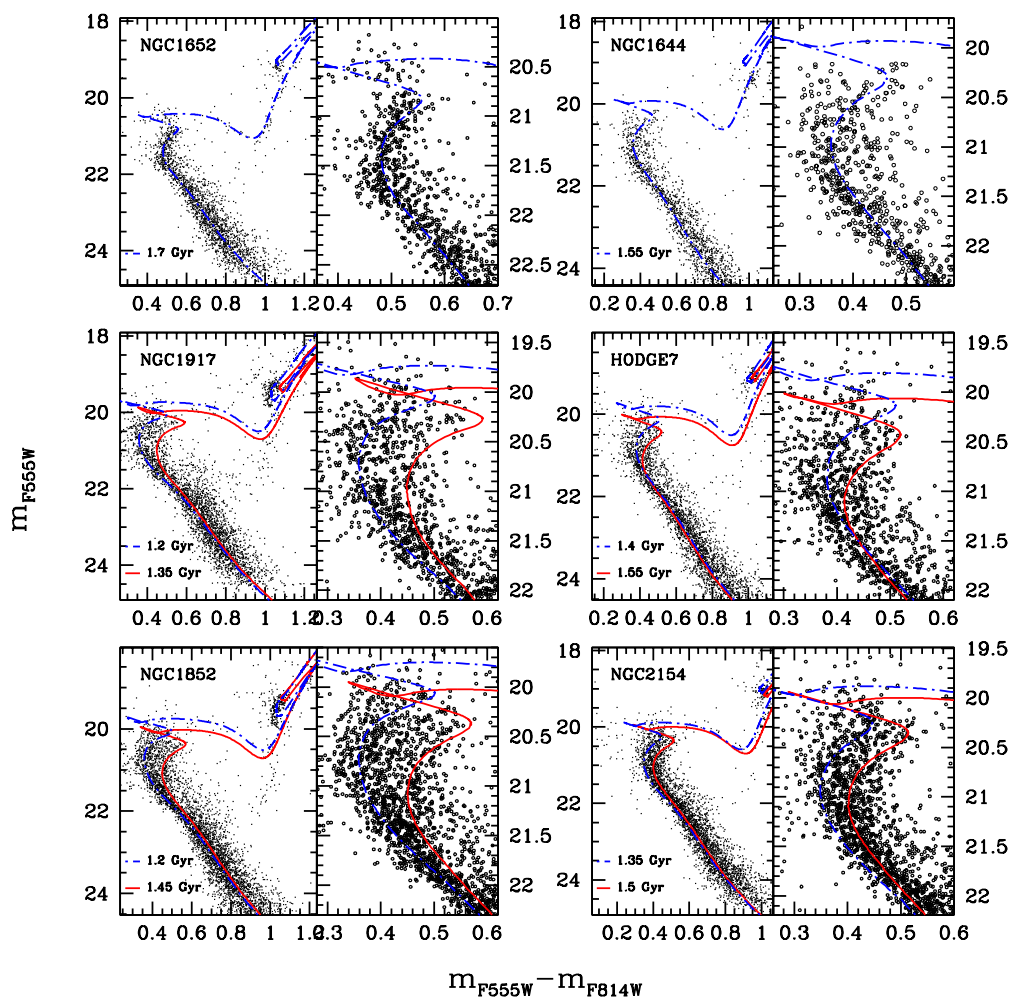


FIGURE 5.38— As in Fig. 5.37 for NGC 1652, NGC 1644, NGC 1917, HODGE7, NGC 1852 and NGC 2154.

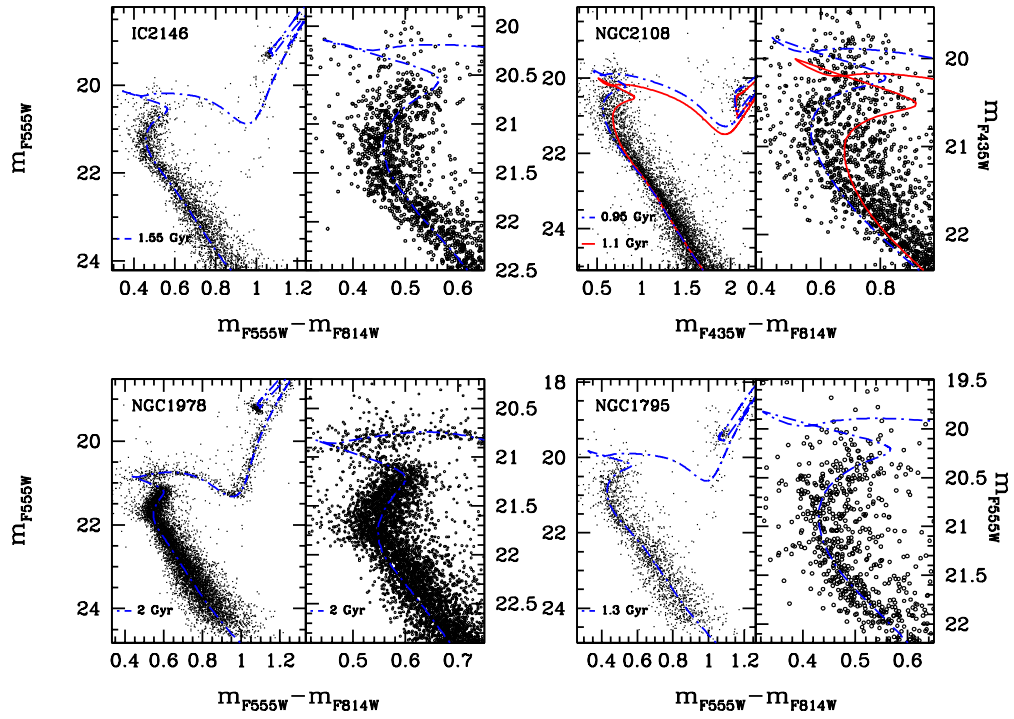


FIGURE 5.39— As in Fig. 5.37 for IC 2146, NGC 2108, NGC 1978 and NGC 1795.



# 6

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## Discussion

Very recently, a spectacular, and somehow unexpected confirmation that, at least in some GCs, the origin of the chemical anomalies must be primordial, came from high precision photometry from Hubble Space Telescope observations.

The first object challenging the paradigm of GCs hosting simple stellar populations was  $\omega$  Cen. As shown by Bedin et al. (2004), the MS of  $\omega$  Cen is split into two sequences. But the most exciting discovery came from the spectroscopic investigation by Piotto et al. (2005), who found that the bluest MS is more metal rich than the redder one. The only way to account for the spectroscopic and photometric properties of the two main sequences is to assume that the bluest sequence is also strongly He enhanced, to an astonishingly high  $Y=0.38$ . More recently, Villanova et al. (2007) showed that the two main sequences split in at least four sub giant branches (SGB) which must be connected in some way to the multiplicity of RGBs identified by Lee et al. (1999). The metal content of the different SGBs measured by Villanova et al. (2007) also implies a large age difference among  $\omega$  Cen stellar populations, larger than 1 Gyr. The exact age dispersion depends on the assumed abundances (including the He content) of the different stellar populations, and it is still controversial (Sollima et al. 2007). Villanova et al. (2007) demonstrated that there is also a third MS, running on the red side of the two main MSs, and likely connected with the anomalous RGB-a of Pancino et al. (2000).

Omega Centauri was well-known since the seventies because of its peculiar metallicity distribution. For a long time it has been considered the only GC showing iron-peak element dispersion (Freeman & Rodgers 1975 and, more recently, Norris et al. 1996, Suntzeff & Kraft 1996). In a sense, the findings by

Pancino et al. (2000), Bedin et al. (2004), Piotto et al. (2005), Villanova et al. (2007) and Sollima et al. (2007) could simply be considered additional evidence that  $\omega$  Cen is so peculiar that it might not be a GC. Perhaps, as suggested by many authors (Freeman 1993, Hughes & Wallerstein 2000), it might simply be the nucleus of a much larger system, likely disrupted by the tidal field of our Galaxy.

In this sense the most recent discovery by Piotto et al. (2007) that the MS of NGC 2808 is split into three, distinct sequences came as a sort of surprise, shaking at its foundation our understanding of GC stellar populations. NGC 2808 has been always considered a GC, with many peculiar properties regarding its metal content and its color-magnitude diagram, but a genuine, massive GC. Still, it hosts multiple stellar populations. Moreover, also in this case, in view of the negligible dispersion in iron-peak elements in NGC 2808, the only way so far available to reproduce the three MSs is to assume that there are three populations, characterized by three different helium contents, up to an (again) astonishingly high  $Y=0.38$ . Interestingly enough, D’Antona et al. (2005) already made the hypothesis of three groups of stars, with three different helium abundances in order to explain the peculiar, multi-modal Horizontal Branch (HB) of NGC 2808 (Sosin et al. 1997, Bedin et al. 2000). Piotto et al. (2007) simply found them in the form of a MS split and also noticed that the different stellar populations in NGC 2808 are consistent with the spectroscopic observations by Carretta et al. (2006), who identified three groups of stars with different Oxygen abundances. The fraction of stars in the three abundance groups is in rough agreement with the fraction of stars in the three MSs.

NGC 2808 and  $\omega$  Cen are, at the moment, the most extreme examples of a rather complex observational scenario. In fact, evidence of multiple populations has been found in other GCs, like NGC 1851 (Milone et al. 2008b), NGC 6388, NGC 6715, NGC 6656, NGC 5286, NGC 306 and NGC 7089 in the form of a split in the SGB.

In NGC 1851 the presence of a group of RGB stars with enhanced Sr and Ba and strong CN bands, among the majority of CN-normal RGB stars (Yong & Grundahl 2008), and the presence of a bimodal HB, agrees with the hypothesis of two stellar generations inferred by the observed SGB split.

The extremely peculiar HB of NGC 6388 (Rich et al. 1997), with the presence of extremely hot HB stars (Busso et al. 2007) was already interpreted in terms of multiple, helium enhanced, population by Sweigart & Catelan (1998), and in the more detailed analysis by Caloi & D’Antona (2007). We showed that this cluster undoubtedly shows a split in the SGB with resemblance with NGC 1851. Interestingly, the fraction of fainter over brighter SGB stars is close to the fraction of blue over red HB, suggesting a connection between the blue

HB and the fSGB.

NGC 6715 has been recognized as the nucleus of the Sagittarius dwarf galaxy (Da Costa & Armandroff 1995; Bassino & Muzzio 1995; Layden & Sarajedini 2000), and it could simply represent what  $\omega$  Cen was long time ago.

Apart from Omega Centauri, NGC 6656 is the only GC with a clear spread in iron content, as revealed by our spectroscopic study based on UVES data. We find a strong bimodality in the distribution of the *s*-process elements with stars enriched in *s*-process elements also showing larger values of [Fe/H]. The similar fraction between the two groups of stars with different *s*-element content and the two populations observed on the SGB, makes tempting to connect the two observed phenomena. Nevertheless, by superposing the theoretical isochrones by Pietrinfermi et al. (2004), we verified that the observed difference in iron, alone, can not account for the SGB split.

In the cases of NGC 5286, NGC 362, and NGC 7089 we observed a fSGB which is poorly populated with less than  $\sim 15$  % of the total number of SGB stars.

It is worth noting that the clusters showing multiplicities in their CMDs are among the most massive GCs of our Galaxy ( $M > 10^6 M_\odot$ ) and all of them have peculiar HBs, as well as peculiar abundances, including Na-O anticorrelations. However, we must also note that much less massive GCs, with no evidence of multiple populations identified so far, show very large star-to-star abundance variations. And, the Na-O anticorrelation has been found in about 20 GCs (see Carretta et al. 2006 for the most updated list).

In summary, it is clear that GCs are not as simple systems as thought in the past. Up to now, we lack a complete explanation for the mechanisms necessary to understand the observational scenario. A systematic study of the chemical abundances of many stars in GCs is needed to better understand the star formation history of these objects. The emerging evidence is that the observational framework is becoming more and more complex with multiple stellar populations revealing themselves in different ways.

Although it is generally accepted that the observed chemical anticorrelations, as well as the multiple sequences in the CMD, are due to the fact that a fraction of stars in GCs have formed from matter that has been polluted with the yields of a previous stellar generation, the debate about the kind of star responsible of this pollution is still open. In the following two sections we summarize the most promising scenarios for the formation and the evolution of GCs in the Milky Way and in Magellanic Clouds. We also briefly discuss both the advantages and disadvantages of the various scenarios. Although new empirical findings are of fundamental importance to shed light on the formation and evolution of GCs, we are perhaps on the right track to compose what has

been for many years a broken puzzle.

### 6.1 MW GCs

The best candidates include AGB stars (Ventura et al. 2001) and fast-rotating massive stars (Maeder & Meynet 2006, Decressin 2007). The two mechanisms act on different timescales of respectively  $10^8$  and  $10^7$  years and both of them present advantages and disadvantages.

**AGB** Since the 1980s, AGB stars have been considered for being responsible for some of the composition anomalies of GC stars (D’Antona, Gratton & Chieffi 1983; Renzini 1983). Indeed, they present a couple of fundamental properties.

- They eject a significant amounts of mass at low velocity (a few tens of Km/sec) which can be easily trapped by the potential hole of the cluster.
- The ejecta are processed through H-burning at high temperature and therefore are enriched in He and N and show the Na-O, Al-O anticorrelations (Voli 1981, D’Antona & Ventura 2007, Karakas & Lattanzio 2007).

The main difficulty of this scenario is that it requires a first stellar population much more massive than that observed in the clusters (e.g. Bekki & Norris 2006, Karakas & Lattanzio 2007). For example, if we assume that the mass of the first stellar population in Omega Centauri is  $2 \times 10^6 M_\odot$ , the quantity of fresh helium produced is only  $\sim 1.6 \times 10^4 M_\odot$ , about a factor 10 less than the observational requirement (Renzini 2008).

Obviously, if we assume that the IMF of GCs was heavily weighted toward massive stars the number of AGB increases. However, this scenario may work only if the IMF of the subsequent stellar generations is much steeper than that of the first one.

A second possibility is that the mass of the protocluster from which the first stellar generation is formed was about 10-20 times larger than the mass that we observe today, so that the ejecta from the first stellar generation provide enough mass to generate the second one. In this case GCs may be formed within a dwarf galaxy environment by mixing of pristine gas with the winds of AGB stars evolving in the field. Later on, the galaxy was tidally disrupted (Bekki & Norris 2006). A possible evidence from this scenario is that NGC 6715, one of the most massive GCs, is indeed associated to the Sagittarius Dwarf Galaxy. Interestingly, this cluster show also a double SGB with similarity to others MW globulars (see Sect. 4).

An alternative scenario was proposed by D’Ercole et al. (2008). They suggested that the second generation is originated in the cluster core where the gas

ejected by the first generation AGB stars collects in a cooling flow. The second generation is initially strongly concentrated in the cluster innermost regions and its structural properties are largely independent of the first generation initial properties. The core is densely populated by high mass stars first generation stars that explode as SNII. Due to the mass loss associated to SNII ejecta, the cluster expands and start losing stars. By means of N-body simulations, D’Ercole et al. (2008) studied the dynamical evolution of each stellar population and found that the cluster mainly loses first generation stars; they also demonstrate possible evolutionary scenarios leading to a cluster dominated by second generation stars. As the cluster evolves and the two populations mix, the local ratio of second to first generation stars tends to a constant value in the inner parts of the cluster.

**Massive rotating stars** Massive rotating stars harbour meridional circulations that bring to the surface the helium produced through hydrogen burning, and eject the helium enriched material in three distinct and physically separated episodes: (1) a slow outflowing equatorial disc whose helium abundance increases as evolution proceeds and is responsible for the production of helium-enriched stars, (2) a fast, regular, radiative wind also enriched in helium in the directions unimpeded by the disc, and (3) a final CCSN explosion. Both radiative winds and SN ejecta run at thousands of km/s, and would not be retained inside the protocluster.

This scenario is able to avoid the mixing of O-poor Na-rich material with the products of SNe. However it suffers from the difficulty of predicting the efficiency of meridional circulations to mix helium into the stellar envelope, and the rate of mass loss via the outflowing disc. Moreover, star formation would have to be confined within the outflowing discs around individual stars (Meynet et al. 2008). It is not clear how the chemically processed material can be retained within the cluster in spite of the fast stellar winds and the SNe explosions.

## 6.2 The case of Magellanic Clouds stellar clusters

As widely discussed in chapter 5, recent studies of intermediate-age star clusters in the Magellanic Clouds, have demonstrated that a significant number of these objects show double or spreaded MSTOs in their CMDs (see Milone et al. 2008c and references within). In spite of this, the other sequences of the CMD (RGB, MS, red clump) are all narrow and well defined demonstrating that the MSTO spread cannot be an artefact due to differential reddening nor to photometric errors. A simple explanation for the origin of these anomalous MSTO is that the clusters contain two different stellar populations with age differences of about

200 Myr.

In the following we discuss the merits of various scenarios for the origin double or spreaded MSTOs.

**Star Cluster Merging** A significant number of stellar clusters in the LMC are in binary or multiple systems (e.g. Bhatia et al. 1991, Diebell et al. 2002) and there are some binary clusters with age difference of about 500 Myrs (Leon et al. 1999). It would be possible that merging of the two components SCs in such systems can happen in LMC. However the merging scenario has difficulties to explain: (1) why the age differences between two merging clusters can be typically about  $\sim 200$  Myr, (2) why the masses of the older component are larger than those of the first stellar population.

**Self pollution from AGB stars** According to the scenario proposed by D’Ercole et al. (2008), stellar ejecta from AGB stars can be accumulated in the inner regions of the clusters and take part in the formation of the second stellar generation. Recent numerical simulations of the formation of multiple stellar populations based on this scenario have demonstrated that the second star formation episode starts soon after the the ejection of chemically processed material from AGB stars and that star formation can gradually continue for a timescale of  $10^8$  years. Therefore this scenario needs to explain: (1) why the observed age difference between the two populations is always similar to 200 Myrs, and why stars of the second stellar generation have a negligible age spread.

**Merging with Giant Molecular Cloud** An interesting alternative scenario is explored in a recent paper by Bekki & Mackey (2008). Based on analytical methods and numerical simulations, they explore a different scenario in which stellar clusters interact and merge with star-forming giant molecular clouds to form new composite stellar clusters with two distinct populations. In this scenario, the possible age differences between the two different stellar populations responsible for the double MSTOs are due largely to secondary star formation within GMCs interacting and merging with already-existing stellar cluster in the LMC disk. The total gas masses that generate the second generation of stars during the interaction and the merging between the giant molecular cloud and the stellar cluster can be comparable to or even larger than the masses of the first generation of stars.

The simulations show that the spatial distributions of the second stellar population are more centrally concentrated than those of stars initially in the cluster.

## II. PHOTOMETRIC BINARIES IN FIFTY GLOBULAR CLUSTERS





### 6.3 Introduction

The knowledge of the binary frequency in Globular Clusters (GCs) is of fundamental importance in many astrophysical studies.

According to the theory of core collapse, binaries play an important role in the dynamical evolution of a clusters. Interactions with hard binaries pump kinetic energy into the cluster core, slowing the core collapse and, eventually, causing the core to reexpand if the number of binaries is large enough.

Exotic stellar objects, like Blue Stragglers, cataclismic variables, millisecond pulsars and low mass X ray binaries are believed to represent late evolutionary stages of close binary systems. The determination of the fraction of binaries plays a fundamental role towards the understanding of the evolution of these peculiar objects.

Furthermore, binary stars introduce systematic errors in the determination of the main sequence (MS) fiducial line as they make it redshifted with respect to its correct position.

Finally, a correct determination of the mass and luminosity functions requires a correct measure of the fraction of binaries.

Up to now, three main techniques have been used to measure the fraction of binaries in GCs (Hut et al. 1992).

The first one identifies binaries by measuring their radial velocity variability (eg. Latham 1996). This method relies with the detection of each individual binary system but, due to actual limits in sensibility of spectroscopy, these studies are possible only for the brightest GCs stars. Moreover it is sensitive to binaries with short orbital periods, and the estimated fraction of binaries depends on eccentricity distribution.

The second technique is based on the search for photometric variables (eg. Mateo 1996). As in the previous case it is possible to infer specific properties of each binary system (like the measure of orbital period, mass ratio, orbital inclination). Unfortunately, their method is biased towards binaries with short periods and large orbital inclination. The estimated fraction of binaries depends on assumed orbital periods, eccentricity and mass ratio distribution.

Both these techniques have a low discovery efficiency and are very expensive in terms of telescope time because of the necessity to repeat measures in different epochs.

A third approach, that is based on the analysis of the number of stars located on the red side of the MS fiducial line may represent a more efficient method to measure the fraction of binaries in a cluster for several reasons:

- availability of a large number (thousands) of stars makes it a statistically robust method;

- it is efficient in terms of observational time: two filters are enough for detecting binaries, and repeated measurements are not needed.
- it is sensitive to binaries with any orbital period and inclination

This approach have been used by many authors (Romani & Weinberg 1991; Bolte 1992; Rubenstein & Baylin 1997; Bellazzini et al. 2002; Clark, Sandquist & Bolte 2004, Richer et al. 2004, Zhao & Baylin 2005, Sollima et al. 2007) to study the populations of binaries in GCs. The relative small number of clusters that have been analyzed is consequence of the intrinsic difficulties of the method:

- high photometric quality is required;
- in some cases, the differential reddening spreads the MS and makes it more difficult to isolate the binary sequence;
- an accurate analysis of photometric errors as well as a correct estimate of field contamination are necessary to disentangle real binaries from bad photometry and field stars.

In this paper, we analyse the HST treasury catalog (Sarajedini et al. 2007, Anderson et al. 2008) which is based on HST ACS/WFC data. We exploited both the homogeneity of this dataset, and the high photometric accuracy of the measures to derive the fraction of binaries in the central regions of fifty GGCs.

## 6.4 Observations and data reduction

Most of the data used in this paper come from HST ACS/WFC images in F606W and F814W bands, taken for GO 10775 (P.I. Sarajedini). In addition we also used archive HST WFPC2 and ACS/WFC images to obtain proper motions. The GO 10775 data set as well as the methods used for its photometric reduction has been presented and largely described in Anderson et al. (2008). The recipes of Anderson et al. (2008) have been further used to reduce the archive ACS/WFC data. The WFPC2 data are analyzed by using the programs and the techniques of Anderson & King (1999, 2000, 2003).

### 6.4.1 Selection of the best measured stars

It is well known that stars can be poorly measured for several reasons like the contamination of light from nearby neighbours, the presence of image artifacts as diffraction spikes or hot pixels and the contamination by cosmic rays. Since we are interested in determining the fraction of photometric binaries of each cluster by analyzing the CMD, we need to select the best measured stars and eliminate any spurious photometric detection that may bias our results.

The software presented by Anderson et al. (2008) provides formidable tools to reach this goal: besides the stellar magnitudes and positions, it provides parameters that can be used as diagnostics of the photometric and astrometric precisions. They are:

- the rms of the magnitudes and position measures made in different exposures  $rms_{m_{F606W}}$ , and  $rms_{m_{F814W}}$ )
- the rms of the positions measured in different exposures and transformed in a common reference frame ( $rms_X$  and  $rms_Y$ )
- the residuals of the PSF fit for each star ( $q_{m_{F606W}}$  and  $q_{m_{F814W}}$ )
- the ratio between the flux in a 0.5 arcsec aperture, and the flux from neighbor stars and the star's own flux ( $o_{m_{F606W}}$  and  $o_{m_{F814W}}$ )

We used these parameters to select a sub-sample of stars with the best photometry. In the five left hand panels of Fig.6.1, we show the criteria that we have used to select the sample of stars with the best photometry in the F606W band for NGC 2298.

We note an evident trend of the quality fit and the  $rms$  parameters as a function of the magnitude. There are however, some outliers for each distribution for all magnitude values that are more likely to be sources with a poorest photometry to be removed before any analysis. Because of this, we adopted the following recursive procedure to select the best measured stars.

We began by dividing all the stars into bins of magnitudes. The size of each bin varies from one cluster to other depending by the number of stars; for each of them, we computed the median  $rms$  ( $q$ ) and the 68.27<sup>th</sup> percentile (hereafter  $\sigma$ ). The median was derived recursively: after each computation, all stars exceeding four times  $\sigma$  were provisionally rejected until the next iteration and the median was recomputed. This procedure was repeated until two subsequent measures of the median differ by less than the 1% of the value.

In order to derive the red line of Fig. 6.1, we added to the median of each bin  $N$  times  $\sigma$ , obtained the red circles and fitted these points with a spline. All stars below the red line have been flagged as well-measured. The factor  $N$  ranges from 4 to 6 and has been chosen in order to draw the boundaries that follow the bulk of the distribution of each parameter value.

The parameters  $o_{m_{F606W}, F814W}$  do not show a clear pattern with the magnitude and we flagged as well-measured stars all the stars with  $o_{m_{F606W}, F814W} < 5$ .

In the right panels of Fig. 6.1 we show the CMD of all the measured stars of NGC 2298 (top) and of stars that pass all the selection criteria (bottom).

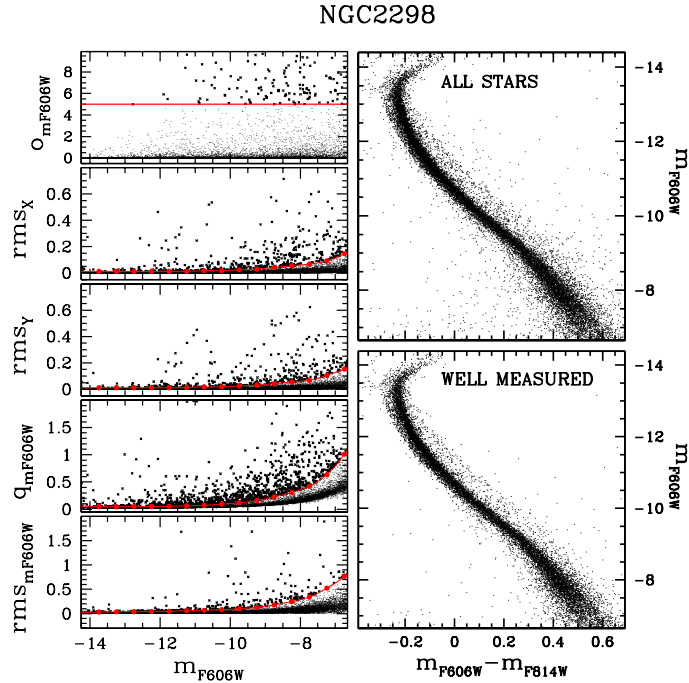


FIGURE 6.1— In the five left hand panels we show the diagnostic parameters that we have used to select the sample of NGC 2298 stars with high quality photometry as a function of the instrumental  $m_{F606W}$  magnitude. Red lines delineate the well-measured stars (thin points) from those that are more likely to have a poorest photometry (thick points). On the right we compare the CMD of all the measured stars (top) and of stars that pass our criteria of selection (bottom).

The sample of stars that have been used in this work to correct the CMDs from differential reddening and variation of the photometric zero point (see Sec. 6.5.1), includes stars flagged as well measured with respect all the parameters that are used as diagnostics of the photometric quality. It must be notice that short period variables binaries might be characterized by large rms of the magnitudes measurements due to the intrinsic variation of their luminosity. In order to avoid the exclusion of this class of binaries, we have not used the  $rms_{F606W}$  and  $rms_{F814W}$  as diagnostics of the photometric quality in the determination of the binary fraction.

#### 6.4.2 Artificial-star tests

The artificial-star (AS) experiments which have been used in this paper are fully described in Anderson et al. (2008). Briefly, for each cluster, we generated a

list of  $10^5$  stars located on the entire ACS field of view, with a density that is flat within the core and decline as  $r^{-1}$  outside of the core. The programs described in Anderson et al. (2008) allow ASs test to be performed for one star at a time and entirely in the software: therefore artificial stars will never interfere with each other. The ASs have a flat luminosity function in F606W, instrumental magnitudes from -5 to -17 and colors that placed them along the observed cluster sequences.

For each star in the input list, the routine adds the star to each exposure with the appropriate position and flux, measures the images with the same procedure used for real stars and produces the same output parameters as in Section 6.4. We considered an artificial star recovered when the input and the output fluxes differ by less than 0.75 magnitudes and the positions by less than 0.5 pixel.

Artificial stars played a fundamental role in this analysis; they allowed us to determine the completeness level of our sample and to measure the fraction of chance-superposition "binaries".

Since completeness depends on crowding as well as on stellar luminosity, we measured it applying a procedure that accounts both for the stellar magnitude and the distance from the cluster center. We divided the ACS field into 5 concentric annulos and, within each of them, we examined AS results in 9 magnitude bins, in the interval  $-14 < m_{F814W} < -5$ . For each of these  $9 \times 5$  grid points we calculated the completeness as the ratio of recovered to added stars within that range of radius and magnitude. This grid allowed us to estimate the completeness associated to any star at any position within the cluster.

As an example, the left panel of Fig. 6.2 shows the completeness as a function of the instrumental  $m_{F814W}$  magnitude in each of the five annuli we used to divide the field of NGC 2298. Finally, we interpolated the grid points and derived the completeness value associated with each star. The right panel of Fig. 6.2 shows the completeness contours in the radius versus  $m_{F814W}$  magnitude plane. Continuous lines correspond to completeness levels of 0.25, 0.50 and 0.75. Dotted lines indicate differences of completeness of 0.05.

## 6.5 Photometric zero point variations

It is well known that the color magnitude diagrams (CMD) of some GCs are broadened by reddening spatial variations. Small unmodelable PSF variations, mainly due to focus changes, further introduce a slight shift in the photometric zero point as a function of the star location in the chip (see Anderson et al. 2008 for details). The trend with position is less than  $\pm 0.02$  magnitudes. In

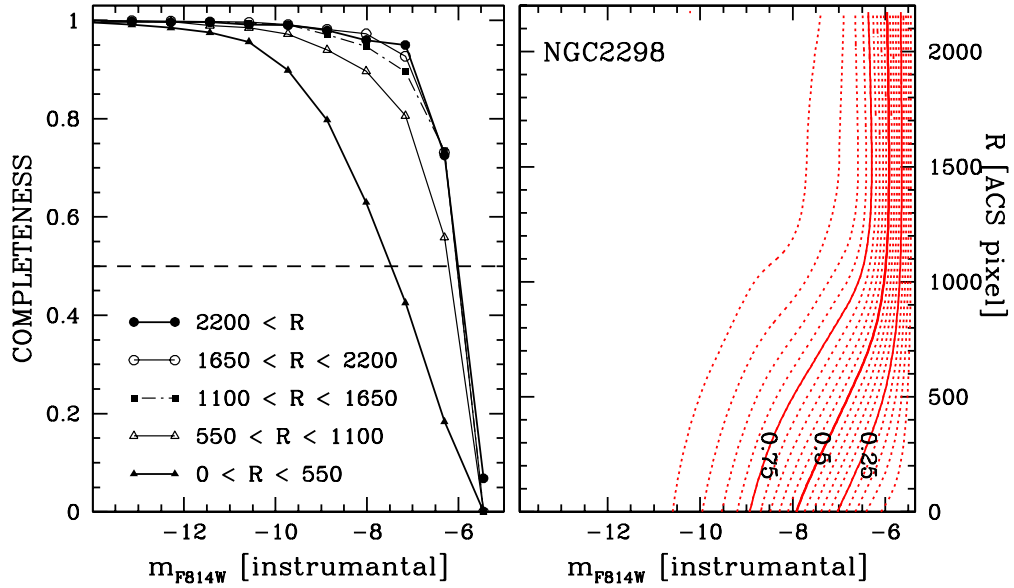


FIGURE 6.2— Left: Completeness as a function of the  $m_{F814W}$  magnitude in five annuli for NGC 2298. Right: Completeness contours in the radial distance versus  $m_{F814W}$  magnitude plane.

some clusters, differential reddening may be much larger. Correcting for these effects represents a fundamental step towards an accurate analysis of the MS and the determination of the photometric binary fraction.

### 6.5.1 Differential reddening

As an example, a visual inspection of the right panels of Fig. 6.1 shows that NGC 2298 has a broadened main sequence. Whether this is due to photometric zero point dispersion or differential reddening does not change the need to sharpen the observed sequence. In the following, we will describe an algorithm specifically devised to reduce the effects of differential reddening. It comes out that the algorithm is also efficient to correct for the spatial variation of the photometric zero point.

In order to correct for differential reddening, we started by defining a reference frame where the abscissa is parallel to the reddening line as shown in Fig. 6.3 for NGC 2298. To do this, we have first arbitrarily defined a point (O) in the left hand CMD, then we have translated the CMD such that origin of the new reference frame corresponds to O, and, finally, we have rotated counterclockwise the CMD by an angle:

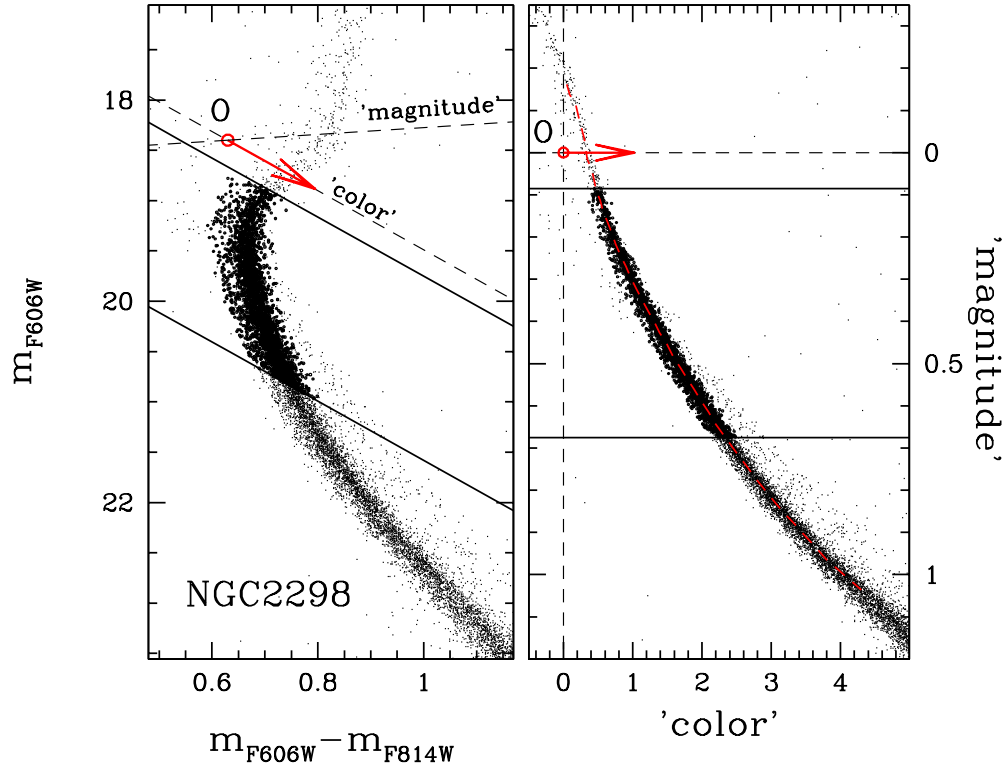


FIGURE 6.3— left: the original CMD of NGC 2298 clearly show a wide spread mainly due to differential reddening, the arrow indicate the reddening direction, dashed lines are the axis of the rotated reference frame; right) rotated CMD with the abscissa parallel to the reddening line. Stars between the continuous lines (thick points) have been considered as reference stars. Red dashed line is fiducial line.

$$\theta = \arctan \frac{A_{F606W}}{A_{F606W} - A_{F814W}}$$

as shown in right panel of Fig. 6.3.  $A_{F606W}$  and  $A_{F814W}$  are the absorption coefficients in the F606W and F814W ACS bands and are given in Table 3 of the Bedin et al (2005) paper for a cool star, while the average reddenings of the clusters that have been used to derive  $A_{F606W}$  and  $A_{F814W}$ , come from

the Harris (1996, 2003) catalog. The value of  $\theta$  weakly depends on the stellar spectral type, but, in any case, this variation can be ignored for our present purposes. Therefore, in the following, we will adopt, for all the stars, the value calculated by using the absorption coefficients that correspond to a cool star. For simplicity, in this section, we will indicate as 'color', the abscissa of the rotated reference frame, and as 'magnitude', its ordinate. The reason for rotating the CMD is that it is much intuitive to determine a reddening difference on the horizontal axis rather than along the oblique reddening line.

At this point, we used an iterative procedure that goes through the following three operations:

- 1) We generate the red fiducial line shown in the right panel of Fig. 6.3. In order to determine the fiducial line, we used only the stars that are more likely to belong to the cluster SGB or MS (thick points) and are not evident photometric binaries. They are selected by hand according to their position on the CMD. We divided this sample of stars in 'magnitude' bins (the exact size of the bin varies from one cluster to the others, depending on the number of stars). For each bin, we calculated the median 'color'. The latter has been associated to the median 'magnitude' of the stars in the bin. The fiducial has been derived by fitting these median points with a spline. It is important to underline here that the use of the median allows us to minimize the influence of the outliers as residual binary stars, field stars or stars with a poorest photometry. At the first iteration, this procedure has been applied to the original CMD, while, in the subsequent iterations, we have used a CMD where we have applied the best available differential reddening correction.
- 2) We select a sample of reference stars that located in the regions of the CMD where the effects of differential reddening are more evident, and calculate, for each of them, the distance from the fiducial line along the reddening direction ( $\Delta \text{color}$ ). Obviously not all the stars provide useful informations for the determination of differential reddening. We accounted for this by assigning to each star a weight:

$$w_i = \left( \frac{\sin \phi}{\Delta \text{magnitude}_i + \Delta \text{color}_i \cos \phi} \right)^2$$

Where  $\Delta \text{color}_i$  and  $\Delta \text{magnitude}_i$  are the photometric errors and  $\phi$  is the angle between the reddening line and the tangent to the fiducial line at  $\text{magnitude}_i$ .  $w_i$  is close to zero for the stars on the faint MS (where the photometric errors are larger and the fiducial is almost parallel to the reddening line) and is maximum for stars in the region between the



MSTO and the SGB. In order to measure the differential reddening, we used the sample of stars placed in the region between the two dashed lines of Fig. 6.3, that are chosen with the criterion that  $w_i$  is larger than 0.5 times the maximum value.

- 3) In principle, we can measure the differential reddening suffered by any single star by comparing the position on the CMD of a sample of reference stars located in a small region around it with respect to the fiducial sequence of the CMD. The size of the comparison region around the target stars is crucial in order to obtain the best possible reddening estimate, and results from a compromise between two conflicting needs. On one hand, we want to use as small as possible cells for the measurement of the displacement from the fiducial sequence in order to increase the spatial resolution of the differential reddening map. On the other hand, we want to use as many stars as possible in order to reduce the error on the determination of the correction factor. As a compromise, for each star, we selected the (usually 30-100) nearest reference stars and calculate the median  $\Delta \text{color}$  that is assumed as the reddening correction for that star. In this way, our differential reddening correction will be done at higher spatial frequencies in the more populated parts of the observed field.

After that the median  $\Delta \text{color}$  have been subtracted by the 'color' of each star in the rotated CMD, the principal sequences of the cluster dramatically narrow and a significant number of binaries outcrops as shown in the bottom right panel of Fig. 6.3. This improved CMD has been used both to obtain a more accurated fiducial line and to exclude from the sample of reference stars those binaries and field stars that were previously mixed to the SGB and MS stars.

This step ends a cycle of the iteration, the convergence typically requires about four iterations. Finally the corrected *magnitude* and *color* of the rotated CMD are converted into  $m_{F606W}$  and  $m_{F814W}$  magnitudes. In Fig. 6.4 we compare the CMD of four clusters: NGC 3201, NGC 2298, NGC 6171 and NGC 288 before and after the correction for differential reddening.

In Fig. 6.5 we display the variations of reddening for all the stars of NGC 2298. The location of each star in the ACS field of view is indicated with a grey square. The levels of grey refer to different amounts of differential reddening.

Since the central regions of same clusters have a poor photometry, we have corrected for differential reddening only stars that lie outside a minimum radius that is fixed by eye. Obviously these stars have been also excluded from the study on photometric binaries due to the low quality of their photometry.

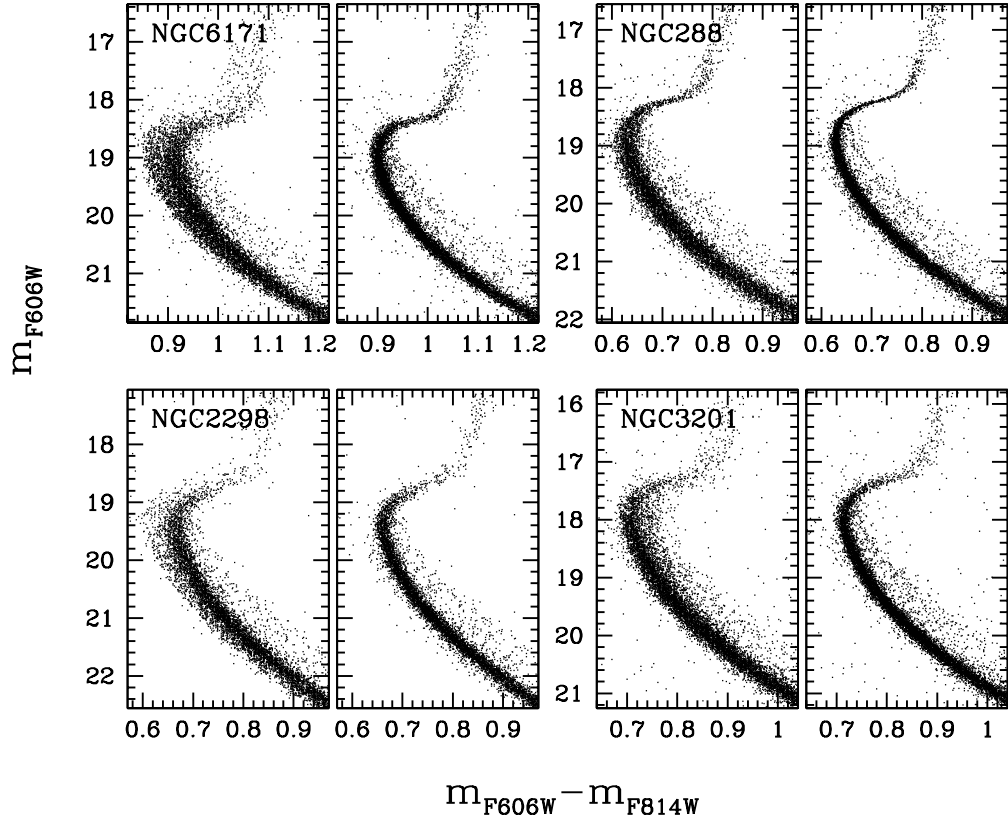


FIGURE 6.4—

### 6.5.2 Unmodelable PSF Variations

Some GCs have a reddening that is close to zero and therefore we aspect negligible variations of reddening within their field of view. In this cases the observed spatial changes of the photometric zero point can be attributed mainly to small unmodelable PSF variations. Usually, these PSF variations affect each filter in a different way, so their most evident manifestation is a slight shift in the color of the cluster sequence as a function of the location in the field (Anderson et al. 2008). For this reason, when the average reddening of the cluster (from Harris 1996, 2003) is lower than 0.05 mag, we corrected the effects the variations of photometric zero point along the chip by using a procedure that slightly differ from the one described in Sec. 6.5.1. This procedure iteratively goes through the following three steps.

- 1) We have used the most probable cluster members stars that are not ev-

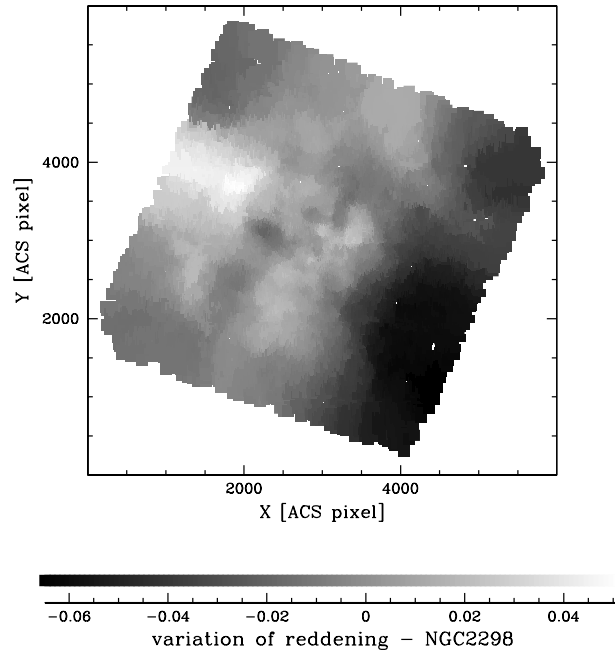


FIGURE 6.5— Map of all the NGC 2298 stars represented as grey squares. The grey level associated to the position of each star corresponds to the magnitude of the variation in local reddening.

ident photometric binaries to determine the red fiducial line overimposed to the CMD of Fig. 6.6. We divided this sample of stars in  $m_{F814W}$  bins (the exact size of the bin varies from one cluster to the others, depending on the number of stars). For each bin, we calculated the median values of  $m_{F606W} - m_{F814W}$  and  $m_{F814W}$  for the stars in the bin. We determined the fiducial by fitting these median points with a spline. At the first iteration, this procedure has been applied to the original CMD, while, in the subsequent iterations, we have used a CMD where we have applied the best available photometric zero points correction.

- 2) We select a sample of reference stars located in the regions of the CMD where the spread due to photometric zero point variations are more evident, and calculate, for each of them, the color difference from the fiducial line ( $\Delta(m_{F606W} - m_{F814W})$ ). Since not all the stars provide useful informations for the determination of the photometric zero point variation, we assigned to each star a weight:

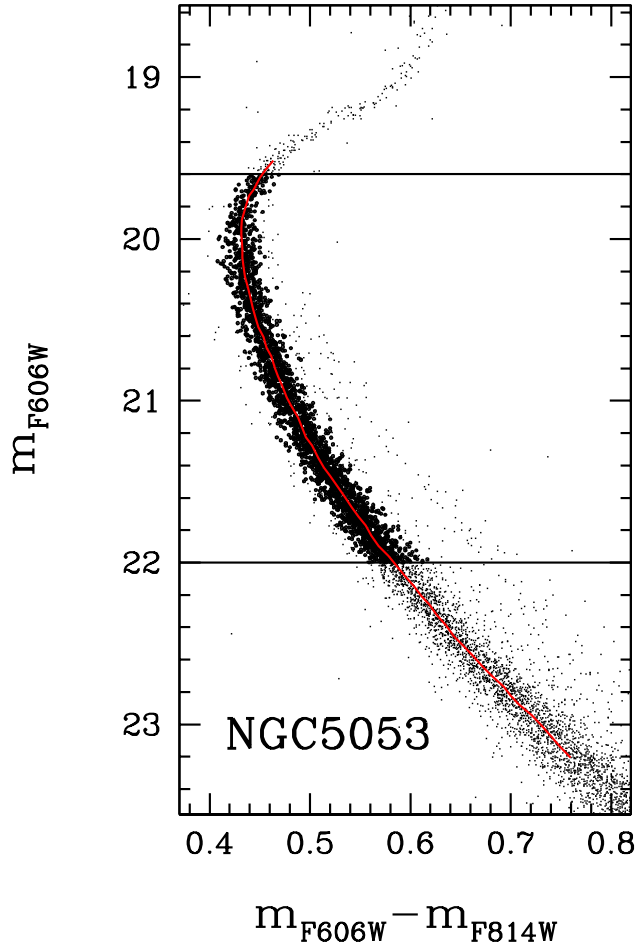


FIGURE 6.6— The CMD of NGC 5053 shows a slight spread partially due to spatially variable zero point variation. Stars between the continuous lines (thick points) have been used as reference stars. Red line is the fiducial line.

$$w_i = \left( \frac{\sin\psi}{\Delta(m_{F814W})_i + \Delta(m_{F606W} - m_{F814W})_i \cos\psi} \right)^2$$

Where  $\Delta(m_{F814W})_i$  and  $\Delta(m_{F606W} - m_{F814W})_i$  are the photometric errors and  $\psi$  is the angle between the color axis and the tangent to the fiducial line at  $(m_{F814W})_i$ .

- 3) For each star, we selected the (usually 30-100) nearest reference stars and calculate the median  $\Delta(m_{F606W} - m_{F814W})_i$  that is assumed as the photometric zero point correction for that star.

Usually, the convergence requires three iterations.

## 6.6 Outliers in Color Magnitude Diagram

Binaries that are able to survive in the dense environment of a globular cluster are so close that even the Hubble Space Telescope (HST) is not able to separate their single components. For this reason, light coming from each star will combine, and the binary system will appear as a single pointlike source.

In this paper we will take advantage from this instrumental limit to search for binaries by analysing their peculiar position in the color-magnitude diagram (CMD).

In the most general case, if we consider two stars in a binary system and we indicate with  $m_1$ ,  $m_2$ ,  $F_1$ , and  $F_2$  their respective magnitudes and fluxes, the binary will appear as a single object with a magnitude:

$$m_{bin} = m_1 - 2.5 \log(1 + \frac{F_1}{F_2})$$

In the case of a binary formed by two MS stars (MS-MS binary) the fluxes are related to the two stellar masses ( $M_1$ ,  $M_2$ ), and its luminosity depends on the mass ratio  $q = M_2/M_1$  (in the following we will assume  $M_2 < M_1$ ,  $q < 1$ ). The binaries formed by an equal mass pair form a sequence parallel to the MS, 0.75 magnitudes brighter. When the masses of the two components are different, the binary will appear redder and brighter than the primary and populate a CMD region on the red side of the MSRL.

In Fig.6.7 we used our empirical MSRL and the mass-luminosity relations of Dotter et al. (2007) to generate sequences of MS-MS binary systems with different mass ratios. In this figure the sequences with constant primary mass are indicated with light continuous lines.

An obvious consequence of this analysis is that our capability in detecting binaries mainly depends on the photometric quality of the data. Binaries with large mass ratios have a large distance from the MSRL and are relatively easy to be detected. On the contrary, a small mass ratio pushes binaries near the MSRL and makes it hard to separate them from single MS stars. Moreover, the poorer photometry of faint stars limits the luminosity (mass) range where binaries can be detected and studied.

In practice, the limited photometric precision makes impossible the direct count of the overall population of binaries. For this reason, in this paper, we do not pretend to measure the global fraction of binaries in a cluster but limit our study to particular groups of them. Each group is formed by objects that share the same properties in terms of luminosity and mass ratio.

In Sec. 6.7 we isolated three different samples of high mass ratio binaries (defined as the binary systems with  $q > 0.5$ , 0.6 and 0.7) and separately studied the properties of each group.

It is important to notice here that the data used in this paper are very homogeneous as they come from the same observing facility (ACS/HST) and have been reduced adopting the same techniques. However, the photometric quality varies from cluster to cluster, mainly because of the different stellar densities.

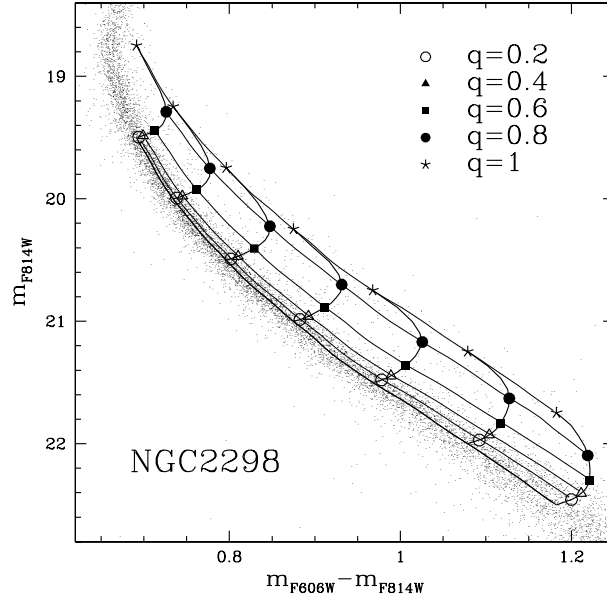


FIGURE 6.7— Model MS-MS binary sequences with different mass ratios for NGC 6809. Dashed lines indicate the sequences of constant  $q$  while the MS ridge line is represented by the continuous line. Dotted lines indicated the ( $3\sigma$ ) dispersion size for the MS stars.

## 6.7 The high mass ratio binary fraction

In each cluster, we estimated the fraction of high  $q$  binary stars from 0.75 (hereafter  $I_{\text{bright}}$  to 3.75 ( $I_{\text{faint}}$ ) magnitudes in the F814W band below the MS turn off (MSTO). The choice of this magnitude interval represents a compromise between the necessity of a large set of stars and the need to not go too faint in order to be able to measure the binary fraction also in clusters with poorer photometry (more crowded).

We started by considering an ideal CMD, formed by a pure population of cluster stars, all of them with the same age and chemical composition. In this hypothesis, if we exclude casual superpositions of physically unrelated stars on the same line of sight, we can assume that the distribution of photometric errors is gaussian and that the single MS stars are symmetrically distributed with respect to the MSRL.

We divided this ideal CMD in two regions (see Fig.6.8):

A region ( $A$ ) that includes all the MS single stars and the binaries with a primary star with  $I_{\text{bright}} < m_{\text{F814W}} < I_{\text{faint}}$ . This region is divided into three subregions. The first one ( $A_1$ ) includes all the MS single stars and MS-MS binaries with small mass ratios; it is limited by the dashed lines in Fig.6.8 and corresponds to the CMD portion with a color distance from the MSRL smaller than three times the MS dispersion. The second subregion ( $A_2$ ) includes all the binary candidates with high mass ratios. In Fig.6.8 it corresponds to the CMD portion on the red side of the  $A_1$  region and is delimited:

- On the top of the CMD, by the track formed by binary systems with a primary star with  $m_{\text{F814W}} = I_{\text{bright}}$  and a mass ratio ranging from 0 to 1;
- On the bottom, by the track defined by binary systems with a primary star of mass corresponding to  $m_{\text{F814W}} = I_{\text{faint}}$ , and mass ratio ranging from 0 to 1;
- On the right side of the CMD, by the ridge line for equal mass binary systems.

The third subregion ( $A_3$ ) contains all the binaries with  $q \sim 1$  that are shifted by photometric errors to the right side of the equal mass binary fiducial line. It is adjacent to the region  $A_2$  and is limited by the ridge line for equal mass binary systems shifted on the blue side and by the same line shifted by three times the MS dispersion to the red (see Fig. 6.8).

The second region  $B$  is defined as the portion of the region ( $A$ ) on the red side of the track formed by a binary star with  $q = q_{th}$ , and it includes all the binaries formed by a primary star with  $I_{\text{bright}} > m_{\text{F814W}} > I_{\text{faint}}$  and mass ratios greater than a threshold value ( $q_{th}$ ). In this section we separately studied the samples of binaries with mass ratios larger than  $q_{th}=0.5, 0.6$  and  $0.7$ .

Unfortunately, in the real CMD, the regions  $A$  and  $B$  are populated also by intruders such as field stars and prospective binaries. In the following two subsections we will describe the methods that we used to estimate their contribution.

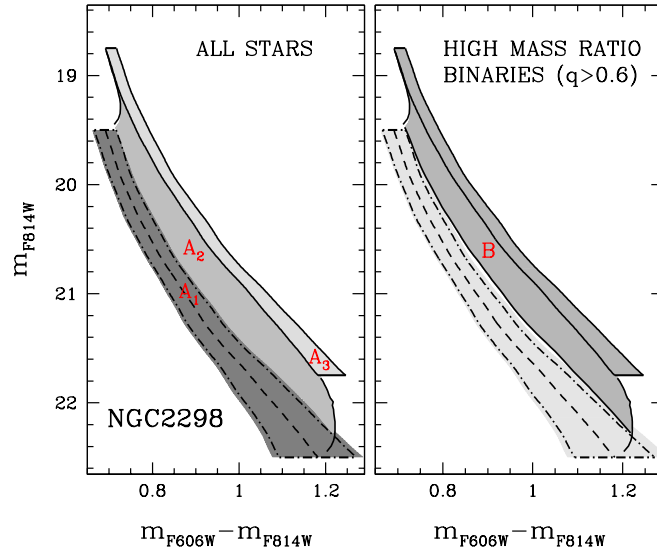


FIGURE 6.8— Grey areas are the regions of the NGC 2298 CMD adopted to select all the (single and binary) cluster stars (right) and the candidate binaries with  $q > 0.6$  (left) in a range of  $3 m_{F814W}$ .

### 6.7.1 Apparent binaries

Chance superpositions of two physically unrelated stars that happen to lie nearly along the line of sight (apparent binaries) and superposition of a star and a positive background fluctuation may reproduce the color and luminosity of a genuine binary system and populate the CMD region associated to binaries. In a crowded stellar field, like the core of a globular cluster, a reliable measure of the binary fraction requires a great accuracy in deriving the number of chance superpositions.

The most favorable case is a not perfect superposition of the two unrelated stars, when the binary system assumes an elongated profile. In such a situation, we can identify and reject (at least a fraction of) these objects by analysing the stellar profile, and the PSF-fit errors. For this reason, in this work, we limited our study to the objects that pass the criteria of selection described in Sec. 6.4.2.

Completely superposed sources on the same line of sight cannot be detected



and a statistical estimate of their distribution in the CMD is necessary. In this paper, we used extensive artificial stars experiments to evaluate directly the effects of blends.

This analysis requires that the artificial star sample that we will compare to observed data reproduces as much as possible all the details of real stars. In particular we need the best possible match between the luminosities, the radial distribution and the photometric errors of observed and simulated stars.

For this reason we generated our artificial star samples by assigning a sample of artificial stars per each real star and randomly extracting one of them. For each star, the corresponding artificial star reference sample consists of all the artificial stars with similar magnitudes (within  $\pm 0.10$  mag) and similar radial distances to the cluster center (within 100 pixel) as the real star.

Anderson et al. (2008) programs provide for artificial stars the same parameters ( $rms_{m_{F606W}, m_{F814W}}, q_{m_{F606W}, m_{F814W}}, o_{m_{F606W}, m_{F814W}}$  and  $rms_{X,Y}$ ) that have been described in Sec.6.4.1 for real stars. As well as we have done for real stars, we have applied to artificial stars photometry exactly the same criteria of selection of Sec.6.4.1 and used for the following analysis only stars that successfully passed through all of them.

This procedure produces a catalog of simulated stars that reproduces both the radial and the luminosity distributions, and have the same completeness as real stars.

The observed broadening of the MS is the product of the combination of several effects. In addition to photon noise, we have the contribution of spatial variations of the PSF, scattered light, possible star-to star metallicity variations and residual differential reddening that is beyond the sensitivity of the method that we used to correct them. However, for the purposes of this work, it is not necessary to distinguish the contributions of the single sources of the broadening we will include them in the photometric errors ( $\sigma$ ).

Since MS-MS binary systems and apparent binaries lie all on the red side of the MS, we can use the MS scatter to the blue side of the MS as an estimate of the photometric error. We note that the blue portion of the MS is contaminated by MS-white dwarf binaries but their influence on  $\sigma$  is expected to be negligible.

In order to estimate  $\sigma$ , we used the following iterative procedure, which has been applied to both the observed and artificial star CMD. First of all we have subtracted the color of the MSRL from the color of each star. Then we have divided this CMD into several intervals of magnitude containing all the same number of stars and calculated the histogram distribution of the color for each of them. The size of each interval is a compromise between two conflicting necessities: on one hand we want large bins, in order to maximize the number of stars and reduce the statistical errors; on the other hand, we want a small

magnitude interval to account for the smallest possible variations of the photometric error as a function of the magnitude. For these reasons, the size of each interval varies from one cluster to another, depending on the sampled number of stars.

We least square fitted each histogram with gaussians; we have left as free fitting parameters the center of the gaussian, its amplitude, and its dispersion ( $\sigma$ ). Then, we rejected all stars whose color is distant more than  $3\sigma$  from the fiducial line, because most of these objects must be field stars or binaries. Finally we used the remaining sample for a new gaussian fit.

All the stars with negative color in the rectified CMD (i. e. all the stars on the blue side of the MS) are used for a new gaussian fit, but, this time, we fixed the center and the amplitude of the gaussian and considered  $\sigma$  as the unique free parameter. The best fitting  $\sigma$  is assumed to be the average photometric error in that magnitude interval. The errors corresponding to each magnitude in the CMD are obtained by interpolations.

However, it is important to notice that, as expected, the artificial star color distribution is narrower than the real star one. We need to properly estimated the difference between the artificial star photometric error and the photometric error of real stars, as, as it will be more clear in next section, we do need an artificial star CMD with the correct photometric error in order to estimate the photometric outliers which contaminates the binary region.

The smaller color dispersion of the artificial star CMD comes from the fact that the measurement errors of artificial stars are smaller than the photometric error of real stars because, in fitting artificial stars, we use exactly the PSF used to originate them, while we cannot expect the same perfect match of the PSF with the real PSF of real stars. Moreover artificial stars photometry is not affected by zero point photometric errors and errors associated to the differential reddening correction. As an example, the difference in color dispersion between the original and the artificial star CMDs of NGC 2298 are shown in Fig. 6.9.

Therefore, in order to compare the real and the artificial star color distribution it is necessary to appropriately correct the latter. To this aim we considered the measured dispersions as a function of the  $m_{F814W}$  magnitude for both observed and simulated MSs and calculated by least squares the 6<sup>th</sup> order polynomials ( $P_{REAL}$  and  $P_{ARTS}$ ) that best fit each of them. As an example, Fig.6.11 shows the measured dispersions and best the fitting functions for the case of NGC 2298. In this paper, we considered the spread of the MS stars as a reliable indicator of the photometric errors to be associated to color measures. We believe that it represents a much more accurate estimate for the photometric error than the one given by the rms value obtained from magnitude measures of the single stars. Infact it also account for residuals photometric zero point

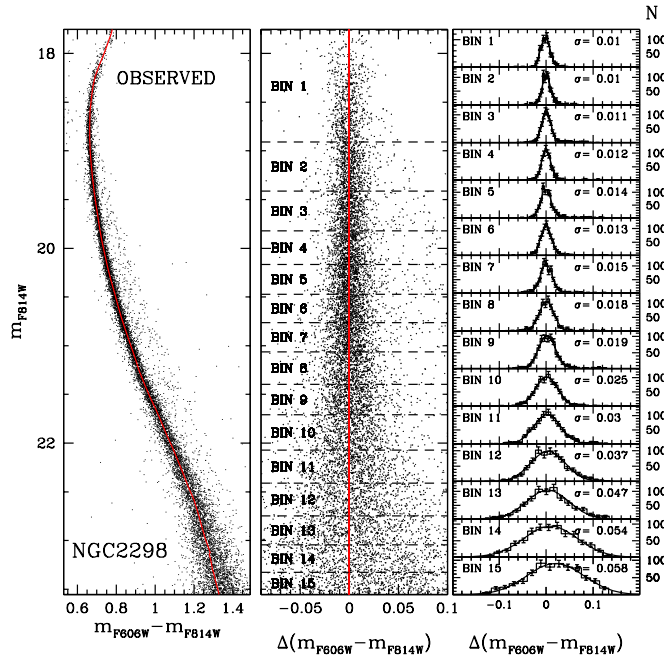


FIGURE 6.9— *Left*: CMD of NGC 2298 with the fiducial line overplotted; *Middle*: The CMD rectified by subtraction of the fiducial; *Right*: Color distribution of the rectified CMD. The  $\sigma$  in the inset are those of the best-fitting gaussians

errors and errors associated to the reddening correction method.

The difference between the observed and simulated MS dispersion is expressed as:  $\Delta\sigma_{VI} = \sqrt{P_{REAL}^2 - P_{ARTS}^2}$ . Assuming that any spread of MS stars around the MS fiducial line comes only from photometric errors,  $\Delta\sigma_{VI}$  indicates how the artificial stars error in color underestimate the our real star photometric errors. As a final, fundamental step for the following discussion, we made the artificial stars CMD similar to the observed one by adding to each artificial star additional random noise in color, extracted from a gaussian distribution with dispersion  $\Delta\sigma_{VI}$ .

## 6.8 Field stars

We used the theoretical Galactic model described by Girardi et al. (2007/2008). First of all, we generated a syntetic catalog (in the ACS F606W and F814W bands) containing the expected field stars in the cluster area that we are studying. We assumed an homogeneous distribution of field stars in the ACS field,

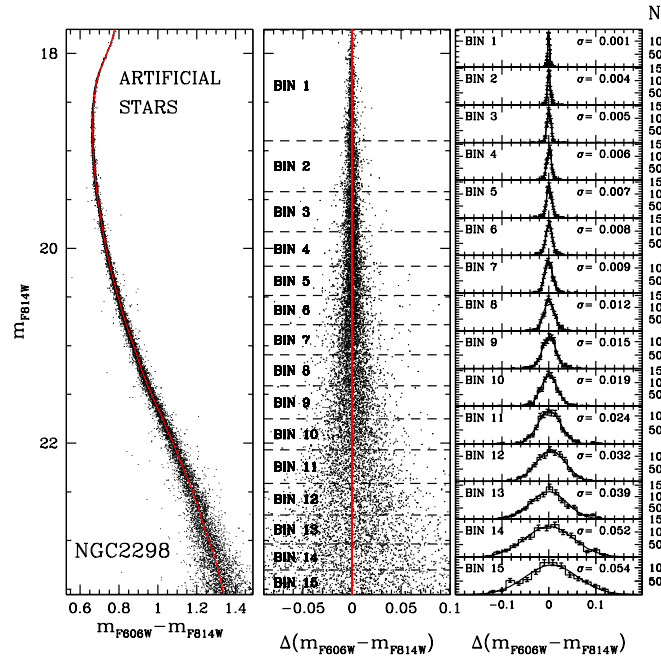


FIGURE 6.10— As in Fig. 6.9 but for artificial stars.

and consequently we randomly attributed to each of them a pair of coordinate within our field.

Then, we associated to each field star an artificial star with similar  $m_{F814W}$  magnitude (within 0.1 mag) and similar distance from the cluster center (within 100 pixel). If the artificial star has been recovered, we added the corresponding errors in magnitude and color. Non recovered stars have been deleted from the catalog.

As for artificial stars this procedure accounts for incompleteness and photometric errors.

## 6.9 Measuring the fraction of binaries with $q > 0.5$

In order to measure the fraction of high mass ratio ( $q > 0.5$ , 0.6 and 0.7) binaries we started by counting the stars in regions  $A$  ( $N_{\text{OBS}}^A$ ) and  $B$  ( $N_{\text{OBS}}^B$ ). Then we evaluated the corresponding numbers of artificial stars ( $N_{\text{ART}}^A$  and  $N_{\text{ART}}^B$ ) and field stars ( $N_{\text{FIELD}}^A$  and  $N_{\text{FIELD}}^B$ ). They are calculated as  $N = \sum 1/c_i$ , where  $c_i$  is the completeness. In order to minimize the error associated to the sample statistics, we simulated 10 different samples of field stars and 3 of artificial stars

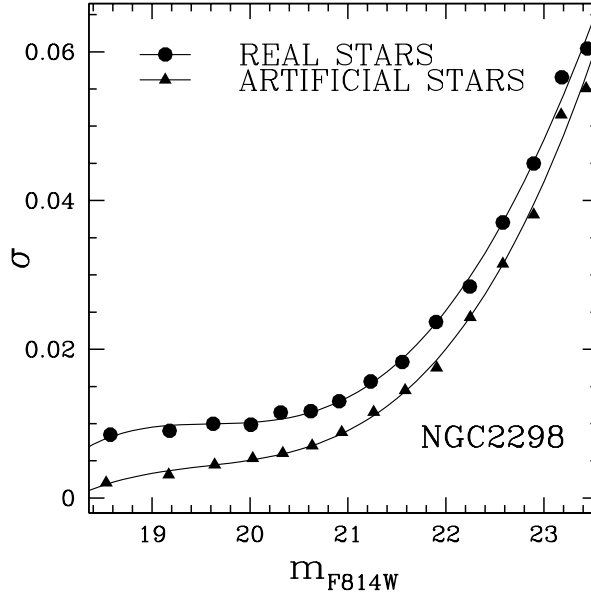


FIGURE 6.11— MS dispersion as a function of  $m_{F814W}$  magnitude for NGC 2298. Triangles and circles correspond to real and simulated stars, the respective best fitting 4<sup>th</sup> order polynomials are represented by continuous and dashed lines.

and calculated the average numbers of stars in each CMD portion.

The high mass binary fraction is calculated as

$$f_{bin} = \frac{N_{OBS}^B - N_{FIELD}^B}{N_{OBS}^A - N_{FIELD}^A} - \frac{N_{ART}^B}{N_{ART}^A}$$

The error associated to this measure is the Poisson error, and therefore it represents a lower estimate of the uncertainty of  $f_{bin}$ . Additional sources of error come from the selection of binaries and MS candidates samples and from the uncertainties in the number of field stars predicted by the adopted Galactic model.

Because of mass segregation, binary radial distribution is different from the distribution of single stars. In order to provide information useful for a dynamical models of our target clusters, we have calculated the binary fraction at different radial distances from the cluster center. More specifically, we defined three different regions:

- a circle with a radius of one core radius ( $I_{CORE}$  sample);
- an annulus between the core and the half-mass radius ( $HM$  sample);

- a region outside the half-mass radius ( $O_{HM}$  sample).

Even if our data are homogeneous, in the sense that they came from the instrument (ACS/HST) and have been reduced adopting the same techniques, their photometric quality (and completeness) vary from cluster to cluster, mainly because of the different stellar densities.

For this reason it was possible to include in the  $I_{CORE}$  sample only 35 out of the original 50 GGCs. In addition, the limited ACS field of view reduced the number of GGCs with  $HM$  and  $O_{HM}$  samples to 46 and 29 clusters, respectively.

## 6.10 Mass ratio distribution for $q > 0.5$

Up to now, there are no observational constraints on the mass ratio distribution ( $f(q)$ ) of the binary population in globular clusters. Fisher et al. (2005) estimated the shape of the mass ratio distribution function  $f(q)$  for the field binaries within 100 parsecs from the Sun. According to Tout (1991), the  $f(q)$  shape can be derived by randomly extracting secondary stars from the observed initial mass function.

In this paper, we provide  $f(q)$  in the range of  $0.5 < q < 1$  for 25 of our target globular clusters. To this aim, we have divided the portion of the CMD populated by binary systems with  $q > 0.5$  into five intervals of mass ratio. We chose the exact size of these intervals in such a way that each of them cover almost the same area in the CMD.

In order to derive the fraction of binaries in each bin we have applied the procedure described in previous Sec.6.9 for each mass ratio bin. The results are shown in Fig.6.12 for binaries within one core radii. In general,  $f(q)$  is flat, with a few relevant exception, for which  $f(q)$  tends to decrease at decreasing  $q$ .

### 6.10.1 Correlation between the binary fraction and the parent cluster parameters

In this section we investigate whether the binaries fraction is correlated with any of the physical and morphological parameters of their host globular clusters. We explored possible relations between the fraction of binaries and the main parameters of their host globular clusters. The cluster parameters, e.g. absolute visual magnitude, metallicity, collisional parameter, core and half mass relaxation time, central density and concentration have been extracted from Harris et al. (1996) compilation and its 2003 updated version. The monovariate correlations with the above mentioned parameters are displayed in Figs. 6.13, 6.14

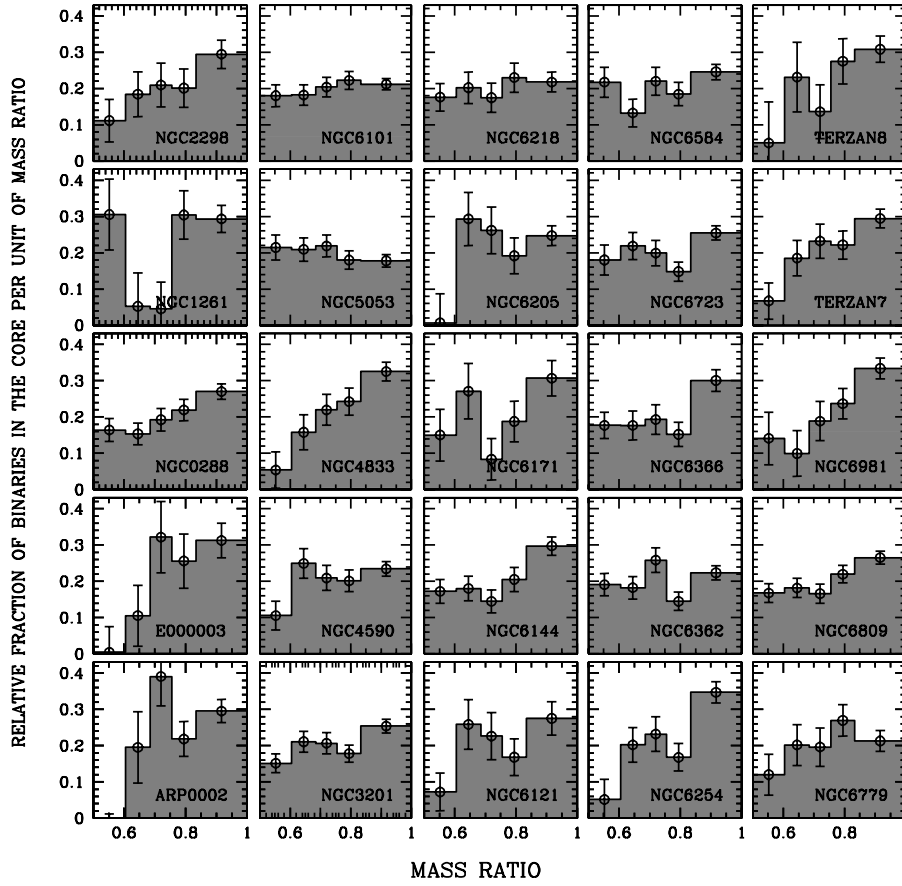


FIGURE 6.12— Mass ratio distribution for the binary population in the cores of 25 globular clusters.

and 6.15.

The most interesting trend is the clear anticorrelation between the cluster binary fraction and its absolute magnitude. In particular, we found that clusters with fainter absolute luminosity (smaller mass) have higher binary fractions. This anticorrelation is present in all of our samples of binaries, i.e. for binaries inside the cluster core (Fig. 6.13) for binaries located between the core and the half mass radius (Figs. 6.14) and for binaries outside the half mass radius (Fig. 6.15), and for binaries with any  $q > 0.5$ .

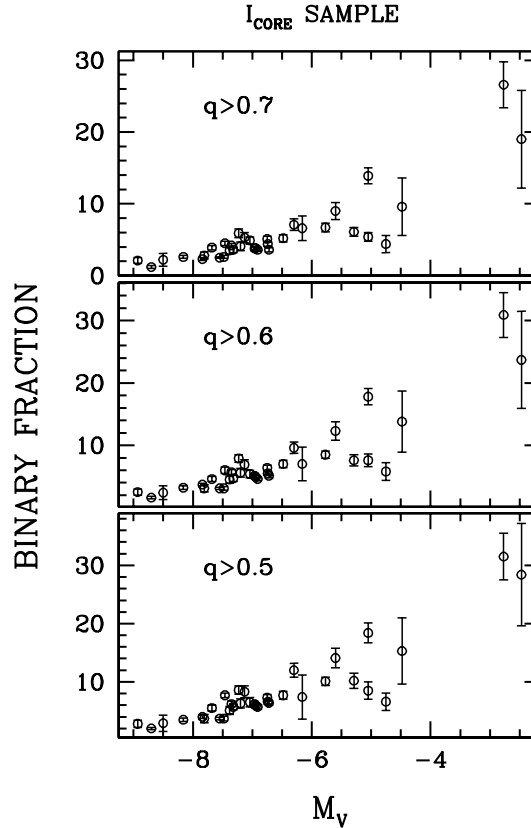


FIGURE 6.13— Fraction of binaries with  $q > q_{th}=0.5$  , 0.6 and 0.7 and global fraction of binaries in the core as a function of the host GCs luminosity.

A similar anticorrelation has been found by Piotto et al (2004) and Moretti et al. (2008) between the frequency of blue stragglers and the absolute luminosity of the parent cluster. It is very tempting to connect BSS and binaries populations in globular clusters, as it has been shown that BSS frequency is related to the evolution of the binary fraction due to encounters, as described by Davies et al. (2004).

A second noteworthy correlation of the binary fraction is with the central velocity dispersion (Fig. 6.17). The central velocity dispersions  $\sigma_0$  come from Meylan (1989) and Gebhardt et al. (1993). Fig.6.17 suggests a possible anticorrelation between the fraction of binaries in the core and the central velocity dispersion of the host clusters. Unfortunately  $\sigma_0$  measures are available only for a restricted fraction of the GCs that are studied in the present work.

Surprisingly enough, we found only a marginal correlation between the bi-



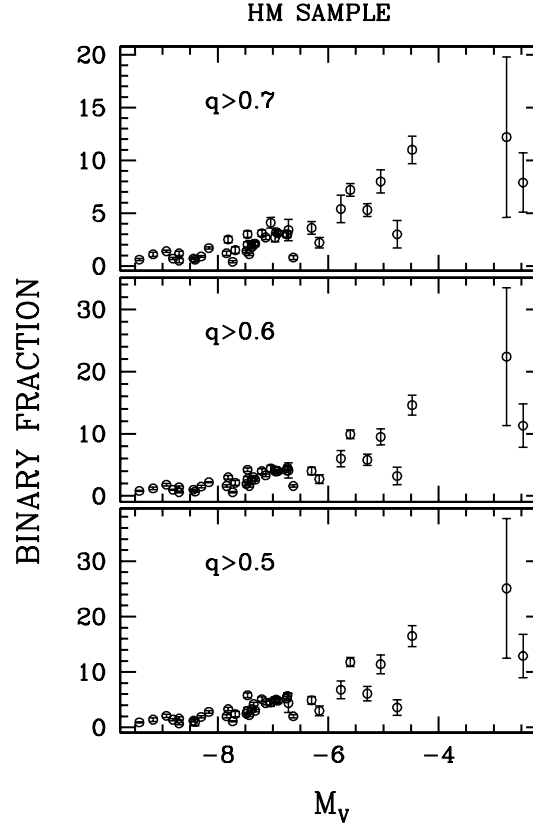


FIGURE 6.14— Fraction of binaries with  $q > q_{th}=0.5$  in the region between core and half mass radius as a function of the host GCs luminosity.

nary fraction and the cluster collisional parameter (See Fig. 6.18). There is no correlation between the binary fraction and the central concentration, the central density, the core relaxation time, and the metal content (Fig. 6.19).

S07 have compared the fraction of binaries they have measured in thirteen clusters, with the cluster age. Ages have been taken from the Salaris & Weiss (2002) paper with the exception of the NGC 6981 one that comes from De Angeli et al. (2005). They found a correlation between age and binary fraction and suggested the age as the dominant parameter that determine the fraction of binaries in a GC.

Marín-Franch et al. (2008) have measured accurate relative ages for all the clusters studied in this paper starting from the same photometric catalogs of Anderson et al. (2008). In Fig.6.16 we plotted the fractions of binaries as a function of their relative ages. Our measures can not confirm S07: There is no

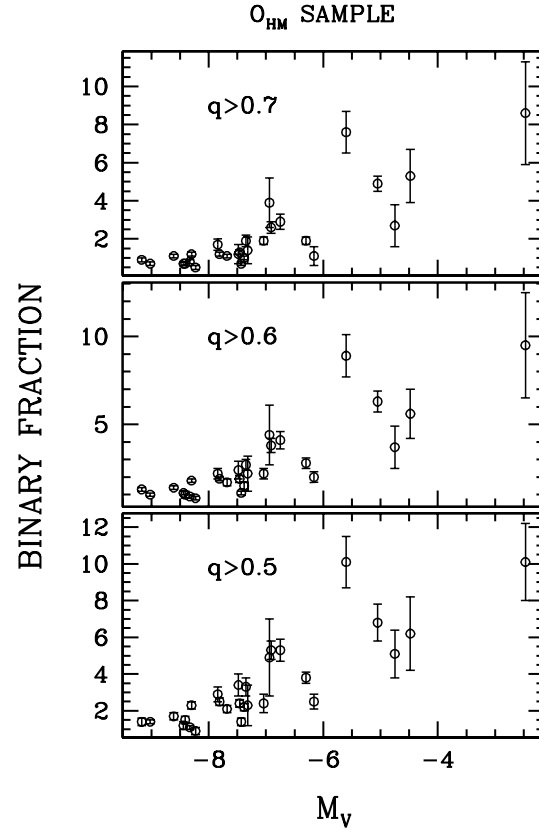


FIGURE 6.15— Fraction of binaries with  $q > q_{th}=0.5$  out the half mass radius

evident trend between ages and binary fraction.

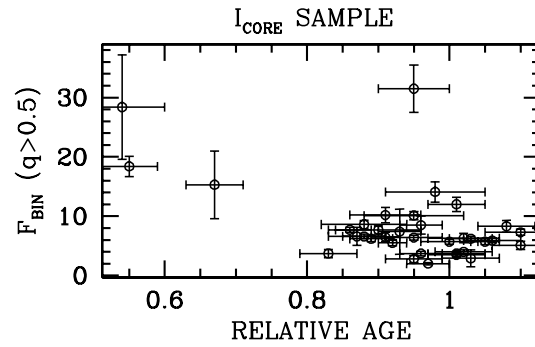


FIGURE 6.16— Fraction of binaries in the core as a function of cluster relative ages from Marín-Franch et al. (2008).

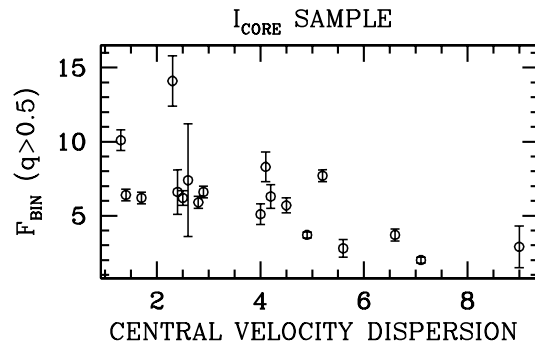


FIGURE 6.17— Fraction of binaries in the core as a function of cluster central velocity dispersion.

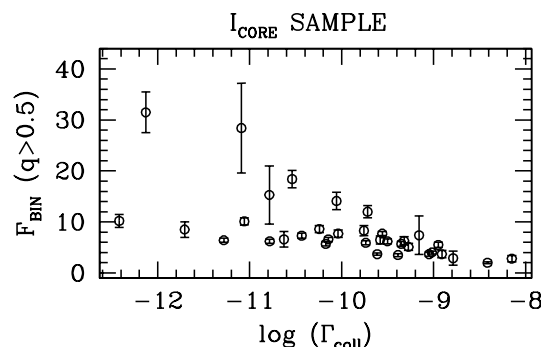


FIGURE 6.18— Fraction of binaries in the core as a function of collisional parameter.

### 6.10.2 High mass ratio binaries radial distribution

In this section we investigated whether the fraction of high mass binaries depends on the radial distance.

To this aim, we divided the ACS field of view into four concentric annuli and calculated the fraction of  $q > 0.5$ , 0.6, 0.7 binaries by using the method described in Sec. 6.9. We chose the size of the annuli such that the number of stars that populate the CMD region *A* is equal in each of them.

Results are shown in Fig. 6.20.

In (at least) the 60% of 37 GCs binaries are significantly more centrally concentrated with respect to the single MS stars. In the other clusters the distribution of binary frequency as a function of the radial distance is consistent with a flat one, probably, as a consequence of the small radial coverage of our images.

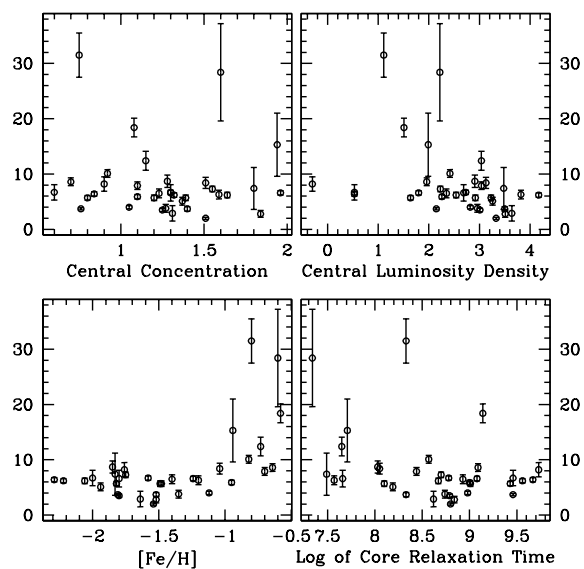


FIGURE 6.19— Clockwise from the upper left panel: fraction of binaries with  $q > q_{th}=0.5$  in the core as a function of central concentration, logarithm of central luminosity density, logarithm of core relaxation time and metallicity.

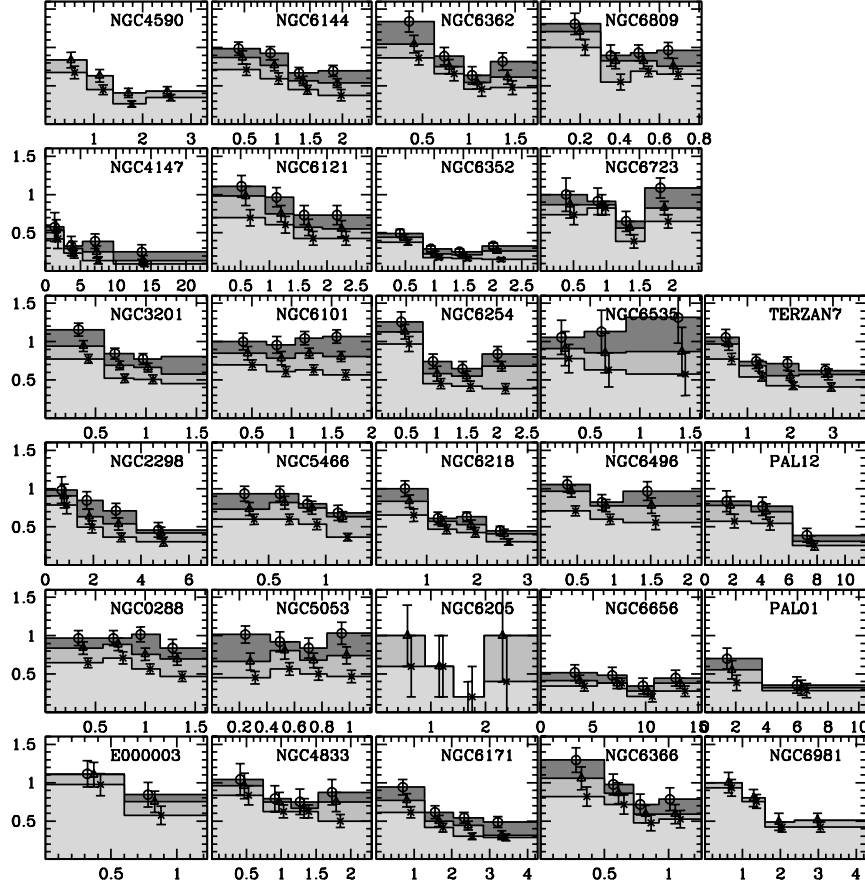


FIGURE 6.20— Fraction of binaries with  $q > q_{th}=0.5$  (circles), 0.6 (triangles) and 0.7 (squares) as a function of the radial distance (in unit of core radii).



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