A Triple Main Sequence in the Globular Cluster NGC 2808[1]

G. Piotto[1], L. R. Bedin[2], J. Anderson[3], I. R. King [4], S. Cassisi[5], A. P. Milone[1], S. Villanova[1], A. Pietrinferni[5], A. Renzini[6]

ABSTRACT

Accurate photometry with *HST*'s ACS shows that the main sequence of the globular cluster NGC 2808 splits into three separate branches. The three MS branches may be associated with complexities of the cluster's horizontal branch and of its abundance distribution. We attribute the MS branches to successive rounds of star formation, with different helium abundances; we discuss possible sources of helium enrichment. Some other massive globulars also appear to have complex populations; we compare them with NGC 2808.

Subject headings: globular clusters: individual (NGC 2808) — Hertzsprung-Russell diagram

1. Introduction

It had always been considered that the value of studying globular clusters (GCs) is that they host simple, single stellar populations, i.e., that stars of a given cluster are not only

[1]Dipartimento di Astronomia, Università di Padova, Vicolo dell'Osservatorio 3, I-35122 Padua, Italy; giampaolo.piotto, sandro.villanova@unipd.it

[2]European Southern Observatory, Karl-Schwarzschild-Strasse 2, D-85748 Garching, Germany; lbedin@eso.org

[3]Department of Physics and Astronomy, Mail Stop 108, Rice University, 6100 Main Street, Houston, TX 77005; jay@eeyore.rice.edu

[4]Department of Astronomy, University of Washington, Box 351580, Seattle, WA 98195-1580; king@astro.washington.edu

[5]INAF-Osservatorio Astronomico di Collurania, via Mentore Maggini, 64100 Teramo, Italy; cassisi, pietrinferni@oa-teramo.inaf.it

[6]INAF-Osservatorio Astronomico di Padova, Vicolo dell'Osservatorio 5, I-35122 Padua, Italy; arenzini@oapd.inaf.it

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at the same distance, but are also coeval and chemically homogeneous. However, a new set of results has taken the GC population/abundance field in a new and exciting direction. Bedin et al. (2004, B04) have found that for a few magnitudes below the turn-off (TO), the main sequence (MS) of ω Centauri splits in two. The more shocking discovery, however, came from a follow-up spectroscopic analysis that showed that the blue MS has twice the metal abundance of the dominant red branch of the MS (Piotto et al. 2005, P05). The only isochrones that would fit this combination of color and metallicity were greatly enriched in helium ($Y \sim 0.38$) relative to the dominant old-population component, which presumably has primordial helium.

Indeed, the scenario in ω Cen is even more complex. As is already evident in the color-magnitude diagram (CMD) of B04, this object has at least three MSs, which spread into a highly multiple sub-giant branch (SGB) with at least four distinct components characterized by different metallicities and ages (Sollima et al. 2005, Villanova et al. 2007; the latter has a detailed discussion.) These results reinforce the suspicion that the multiple MS of ω Cen could just be an additional peculiarity of an already anomalous object, which might not even be a GC, but a remnant of a dwarf galaxy instead (Villanova et al. 2007).

In order to shed light on the possible presence of multiple MSs in Galactic GCs, we undertook an observational campaign with *HST* this paper 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. 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 3×4 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).

3. 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 ω 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 ~ 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 ω 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 ω Cen, even though both clusters show multiple MSs.

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 3σ 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 $\Delta E(m_{\rm F475W} - m_{\rm F814W}) \sim 0.036$. The MS split at $m_{\rm F814W} = 21.5$ is almost an order of magnitude larger than this. 3) The three distinct sequences can be seen everywhere in the field.

4. 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 ω 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 [O/Fe] at +0.28, but there are two additional groups, which they call O-poor (peak at [O/Fe] $= -0.21$) and super-O-poor (peak at [O/Fe] $= -0.73$). C06 also found a marginal increase in [Fe/H], from -1.113 ± 0.008 for O-normal to -1.079 ± 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 ω 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 [O/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 $[\alpha/\mathrm{Fe}] = +0.4$ 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 ω Cen in having multiple stellar populations that are distinct, but there are two important differences: (1) In ω Cen the He-enhanced MS has an [Fe/H] that is $\sim$0.3 dex larger than that of the main stellar population (P05), whereas in NGC 2808 C06 find very little difference in [Fe/H] ($\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 ω 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 ω 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 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.

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Table 1. The population components of NGC 2808

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

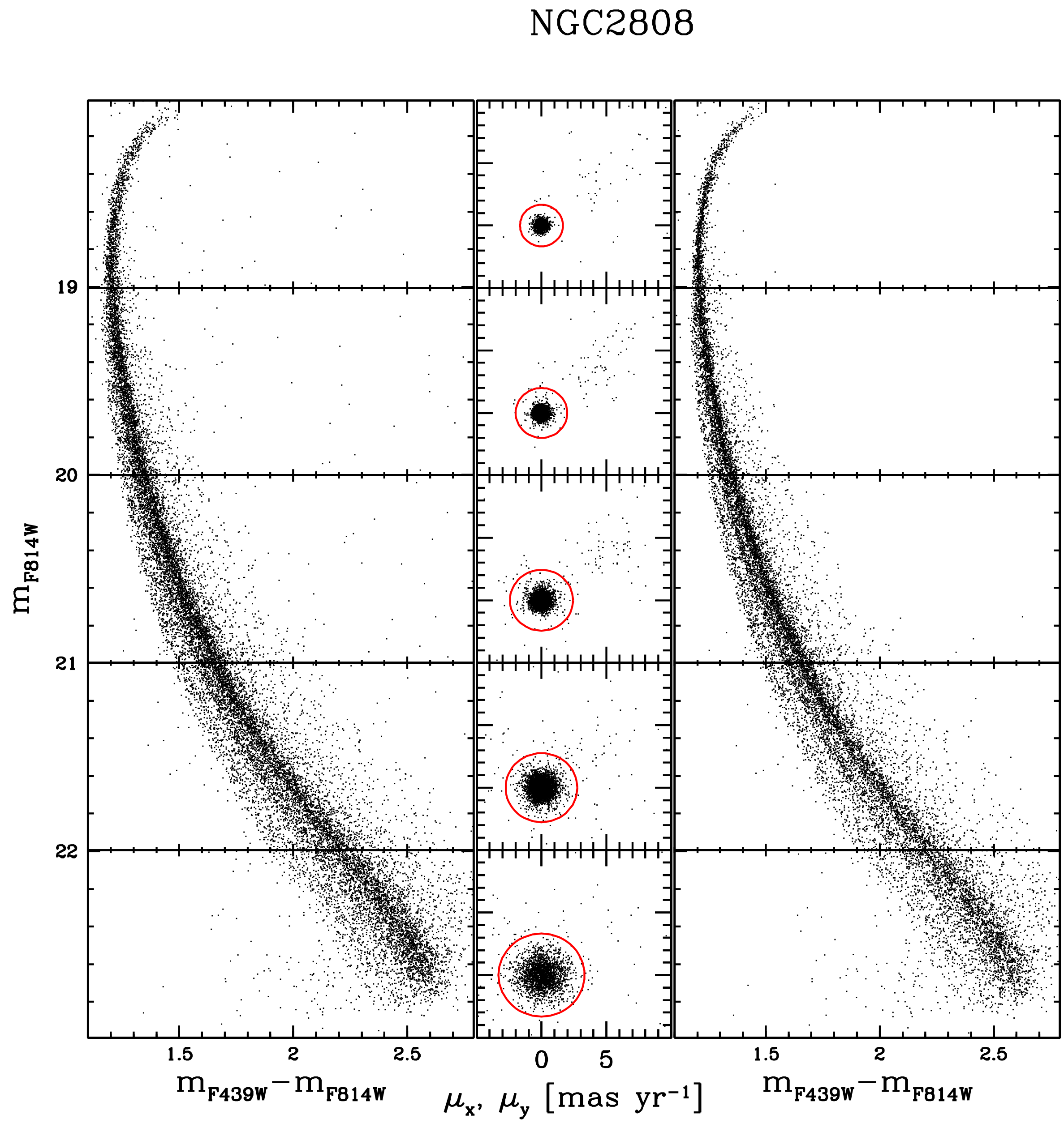

Fig. 1.— Left, the original CMD; middle, the proper-motion distributions in the various magnitude intervals; right, the CMD of the stars whose proper motions lie inside the red circles, with corrections for differential reddening.

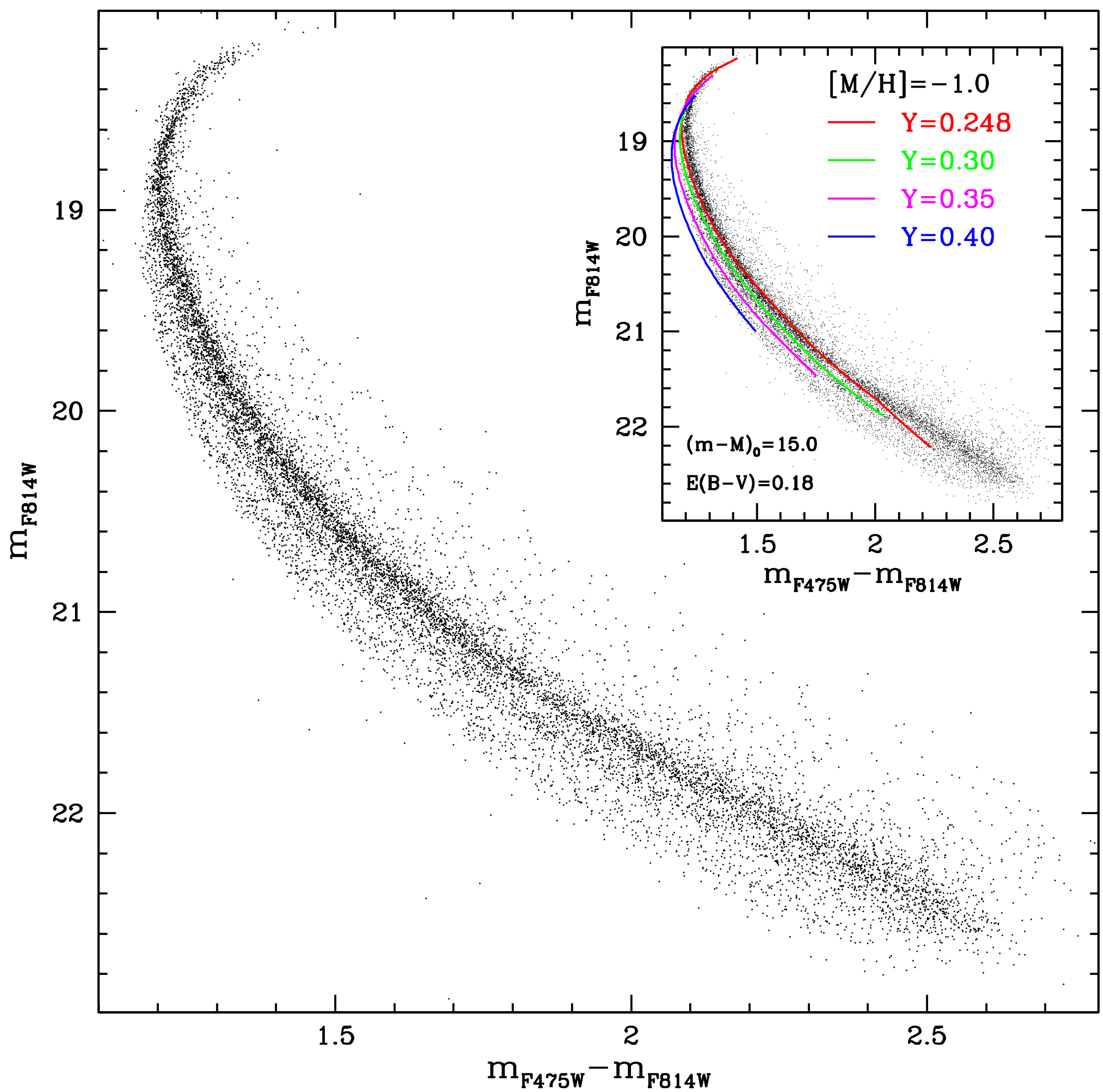

Fig. 2.— A zoom of the proper-motion-selected, differential-reddening-corrected CMD of the right-hand panel of Fig. 1. In the inset the observed CMD is fitted with four 12.5 Gyr isochrones, with different He content.

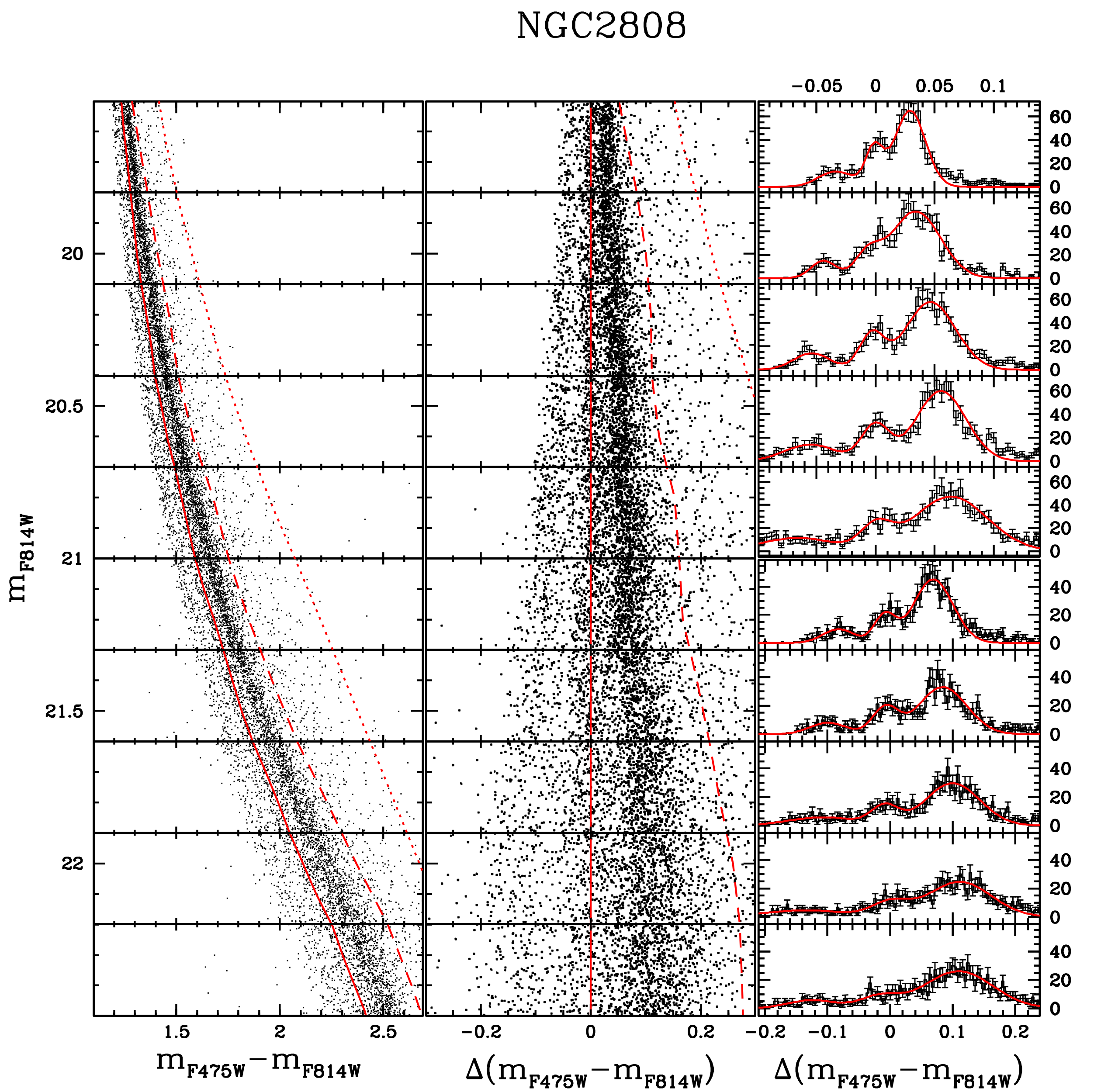

Fig. 3.— Left: The main part of the CMD from Fig. 1. Continuous line is a fiducial line of the mMS, drawn by hand. Dashed line runs 3σ to the red of the rMS. Dotted line marks where equal-mass pairs of rMS stars would lie. Middle: The same CMD, after subtraction of the color of the mMS fiducial line. 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.