Multiple Stellar Populations in Globular Clusters

Ten Years of Fascinating Discoveries for Photometrists

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Where everything started

Cambridge (UK) August 2001, Omega Centauri Workshop
Cover of the Proceedings of the Omega Centauri meeting in Cambridge (UK)

Note that we knew about this “anomaly” since 1995 (see Jay Anderson PhD thesis)
Ivan King to Jay Anderson: “Now you had better be right!”

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...and indeed there were many reasons to have doubts....

Note that we knew about this “anomaly” since 1995 (see Jay Anderson PhD thesis)
In 2012, the “definitive” answer:

_Hubble Space Telescope_ Observations of an Outer Field in Omega Centauri: A Definitive Helium Abundance\(^1\)

I. R. King\(^1\), L. R. Bedin\(^2,6\), S. Cassisi\(^3\), A. P. Milone\(^4\), A. Bellini\(^2\) G. Piotto\(^5\), J. Anderson\(^2\), A. Pietrinferni\(^3\), and D. Cordier\(^7\)

**ABSTRACT**

We revisit the problem of the split main sequence (MS) of the globular cluster ω Centauri, and report the results of two-epoch _Hubble Space Telescope_ observations of an outer field, for which proper motions give us a pure sample of cluster members, and an improved separation of the two branches of the main sequence. Using a new set of stellar models covering a grid of values of helium and metallicity, we find that the best possible estimate of the helium abundance of the bluer branch of the MS is \(Y = 0.39 \pm 0.02\).
The typical CMD of a globular cluster all of us wanted to see in the 90’s. Indeed, the narrowness of the sequences was considered the best possible indicator of a good photometry.
A Simple Stellar Population (SSP) is defined as an assembly of coeval, initially chemically homogeneous, single stars. Four main parameters are required to describe a SSP, namely its age, composition (\(Y, Z\)) and initial mass function. In nature, the best examples of SSP’s are the star clusters....” Renzini and Buzzoni (1986)

For this reason, for decades, star clusters have been a fundamental benchmark for testing stellar evolution models and for Population Synthesis Models.
A naive idea? GCs are NOT so simple. A complex chemistry

The 1\textsuperscript{st} evidence: Cohen (1978) – Na scatter in RGB stars (M3, M13);

The 2\textsuperscript{nd} evidence: Peterson (1980) – 1 order of magnitude scatter in Na abundance in RGB stars (M13);

The 3\textsuperscript{rd} evidence: Norris (1981) – Al scatter in RGB stars (NGC6752);

Many GCs show CN bimodality in the RGB;

C and N abundances of GC stars are very different from field stars: the environment must play a role;

Abundance anomalies (?) are present also among MS stars: they must be primordial;

For a complete review see Gratton, Sneden & Carretta 2004, AARA
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Omega Centaury was known as the cluster including all these anomalies, with an additional spread in [Fe/H].

The first evidence for a metallicity spread:

- Freeman & Rodgers (1976) - $-1.6 \leq [\text{Ca/H}] \leq -0.6$ from 25 RRLyr.
- Butler et al. (1978) - $-1.9 \leq [\text{Ca/H}] \leq -0.9$ from 50 RR Lyrae.
- … Rey et al. (2000) – confirmed from 131 RR Lyrae.

Circumstantial evidence from RGB stars:

- The first hint - Norris & Bessel (1975-77).
- Accurate spectroscopic survey from:
  - Suntzeff & Kraft (1996)
  - Norris et al (1997) results:
    ✓ no very metal-poor stars
    ✓ a sharp peak at $[\text{Fe/H}] \approx -1.6$
    ✓ a wide tail extending to high metallicity
First results from accurate, wide field photometry

Because of the complex metallicity distribution, it came not as a surprise the discovery of a multiple RGB in Omega Centauri (Lee et al. 1999. Pancino et al. 2000)

Pancino et al. (2000)
...but with HST, the complexity increased

What makes this discovery quite impressive is the relative number of stars in the two main sequences
VLT@ESO data: Sollima et al. (2005)

<table>
<thead>
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<th>sub-population</th>
<th>$&lt;[M/H]&gt;$</th>
<th>%</th>
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<tr>
<td>RGB-MP</td>
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</tr>
<tr>
<td>RGB-Mint 1</td>
<td>-1.2</td>
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<tr>
<td>RGB-Mint 2</td>
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<td>17</td>
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<td>8</td>
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<tr>
<td>RGB-α</td>
<td>-0.5</td>
<td>5</td>
</tr>
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</table>
The most surprising discovery

RedMS:
Rad. Vel.: $235 \pm 11\text{km/s}$
$[\text{Fe/H}]=-1.56$

BlueMS:
Rad. Vel.: $232 \pm 6\text{km/s}$
$[\text{Fe/H}]=-1.27$

It is more metal rich!

17x12=204 hours i.t.

Apparently, only an overabundance of helium ($Y \approx 0.40$) can reproduce the observed blue main sequence.

The definitive value:
Y \approx 0.39 \pm 0.02

1.4 \times 10^5 \text{ solar masses of fresh helium are embedded in the second generation of stars}


\[ m_{F606W} - m_{FB14W} \]
Spectacular CMD of Omega Centauri from WFC3 data

Bellini et al., 2010, AJ, 140, 631

$m_{F275W} - m_{F814W}$
Omega Centauri: Radial distribution of main sequence stars


The double MS is present all over the cluster, from the inner core to the outer envelope, but... 

...the two MSs have different radial distributions: the blue, more metal rich MS is more concentrated

(IRK co-author)
NGC 6715 (M54)

Multiple MSs, SGBs, RGBs ....

Siegel et al. (2007)

(IRK co-author)
M54 coincides with the nucleus of the Sagittarius dwarf galaxy. It might be born in the nucleus or, more likely, it might be ended into the nucleus via dynamical friction (see, Bellazzini et al. 2008), but the important fact is that, today:

The massive globular cluster M54 is part of the nucleus of a disaggregating dwarf galaxy.
M54

The CMDs of M54 and Omega Centauri are astonishingly similar!

It is very likely that M54 and the Sagittarius nucleus show us what Omega Centauri was a few billion years ago: the central part of a dwarf galaxy, now disrupted by the Galactic tidal field. But, where is the tidal tail of Omega Centauri (see Da Costa et al. 2008)? Is this true for all globular clusters?
The triple main sequence in NGC 2808

The MS of NGC 2808 splits in three separate branches.

Overabundances of helium (Y~0.30, Y~0.40) can reproduce the two bluest main sequences.

The TO-SGB regions are so narrow that any difference in age between the three groups must be significantly smaller than 1 Gyr.


(IRK co-author)
NGC 2808
Extended horizontal branch, with a multimodal stellar distribution

Sosin et al. (1997)

(IRK co-author)
Helium enrichment:
model predictions

$\delta M_V(\text{HB}) = -0.13$

$\delta M_V(\text{TO}) = +0.05$

$\Delta M_V(\text{MS}) = +0.12$

Higher $Y \rightarrow$ brighter HB

Higher $Y \rightarrow$ bluer HB

(also needs higher mass loss along the RGB, but not as extreme as in the case of primordial He content)

D'Antona et al. (2002)
A MS broadening in NGC2808 was already seen by D’Antona et al. (2005). D’Antona et al. (2005) linked the MS broadening to the HB morphology, and proposed that three stellar populations, with three different He enhancements, could reproduce the complicate HB. We found them in the form of three main sequences!!!
Na-O anti-correlation indicates the presence of proton capture processes, which transform Ne into Na, and Mg into Al.

These anticorrelations are present in all clusters so far analyzed.

Carretta et al. 2010
A clear NaO anticorrelation has been identified by Carretta et al. (2006, A&A, 450, 523) in NGC 2808. Besides a bulk of O-normal stars with the typical composition of field halo stars, NGC2808 seems to host two other groups of O-poor and super O-poor stars.

NGC2808 has a very complex and very extended HB (as ω Cen). The distribution of stars along the HB is multimodal, with at least three significant gaps and four HB groups (Sosin et al 1997, Bedin et al 2000)

Observations properly fit the intermediate mass AGB pollution scenario.
In summary, in NGC 2808, it is tempting to link together: 

the multiple MS, 
the multiple HB, 
and the three oxygen groups, 
as indicated in the table below 
(see Piotto et al. 2007 for details).

1.4x10⁴ and 2.7x10⁴ solar masses of fresh Helium are embedded in the 2nd and 3rd generations of stars

NGC 2808 represents another, direct evidence of multiple stellar populations in a globular cluster.
Bragaglia et al. (2011 ApJ, 720, L41) analyzed features of NH, CH, Na, Mg, Al, and Fe. While Fe, Ca, and other elements have the same abundances in the two stars, the bMS star shows a huge enhancement of N, a depletion of C, an enhancement of Na and Al, and small depletion of Mg with respect to the rMS star.

This is exactly what is expected if stars on the bMS formed from the ejecta produced by an earlier stellar generation in the complete CNO and MgAl cycles whose main product is helium. The elemental abundance pattern differences in these two stars are consistent with the differences in helium content suggested by the color-magnitude diagram positions of the stars.
ΔY > 0.17 between two RGB stars in NGC 2808 with different Na and O abundances (Pasquini et al. 2011, arXiv1105.4306)

Y = 0.39, [Na/Fe] = 0.64, [O/Fe] = -0.07

Y = 0.22, [Na/Fe] = 0.12, [O/Fe] = +0.23
The Double Subgiant Branch of NGC 1851

The SGB of NGC 1851 splits into two well defined sequences.

If interpreted only in terms of an age spread, the split implies an age difference of about 1Gyr.

Cassisi et al. (2008, ApJ, 672, 115, Ventura et al. 2009) suggested that the two SGBs can be reproduced by assuming that the fainter SGB is populated by a strongly CNNa enhanced population. In such hypothesis, the age difference between the two groups may be very small ($10^7$–$10^8$ years). But....

New spectacular UV data from the new WFC3 camera onboard HST.
Try to count the single SGBs. We see at least 11 SGBs!

Amazing perspectives with WFC3
47 Tucanae: new results

WFC3 + ACS data
9 photometric bands
MSa (magenta) corresponds to a first stellar generation, with primordial He, and O-rich/N-poor stars, whereas MSb (green) corresponds to a population that is enriched in He and N but depleted in O. This need for differences in both helium and CNO to account for all the color differences fits quite well with nucleosynthesis expectations, as helium-enriched stellar regions are also inevitably oxygen-depleted and nitrogen-enriched.

<table>
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<tr>
<th>MS (Option)</th>
<th>$T_{\text{eff}}$</th>
<th>$\log g$</th>
<th>$Y$</th>
<th>$[\text{C/Fe}]$</th>
<th>$[\text{N/Fe}]$</th>
<th>$[\text{O/Fe}]$</th>
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</thead>
<tbody>
<tr>
<td>MSa (all)</td>
<td>5663</td>
<td>5.42</td>
<td>0.248</td>
<td>0.06</td>
<td>0.20</td>
<td>0.40</td>
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<tr>
<td>MSb (I)</td>
<td>5749</td>
<td>5.41</td>
<td>0.280</td>
<td>0.06</td>
<td>0.20</td>
<td>0.40</td>
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<tr>
<td>MSb (II)</td>
<td>5695</td>
<td>5.42</td>
<td>0.248</td>
<td>-0.15</td>
<td>1.05</td>
<td>-0.10</td>
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<tr>
<td>MSb (III)</td>
<td>5749</td>
<td>5.41</td>
<td>0.265</td>
<td>-0.15</td>
<td>1.05</td>
<td>-0.10</td>
</tr>
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</table>
MS color is a complex mixture of effects:

1. Atmospheric spectra: MSa (magenta) corresponds to a first stellar generation, with primordial He, and O-rich/N-poor stars, whereas MSb (green) corresponds to a population that is enriched in He and N but depleted in O.

2. Stellar temperature Enhanced He makes temperatures higher.
The complex SGB of 47Tuc
Different photometric bands provide us with different evidence of population multiplicity.
Multiple RGBs
In 47Tuc
For the first time, we can follow the evolutionary path of two stellar generations in the same cluster all along the CMD.

Milone et al. 2012
(IRK co-author)
Once upon the time….we were thinking that…
Indeed, we have superb examples of globular clusters in which hydrogen burning stars, in the stellar core or in a shell typically behave as “standard” stellar evolution models predict.

And we have CMDs which, apparently, show that globular clusters are typically populated by stars with homogeneous composition and born at the same time (same age).

OLD TALE!!!
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**OLD TALE!!!**
however HST UV photometry shows....

NGC 6397

The MSa corresponds to the 1st stellar generation with primordial He, and O-rich/N-poor stars, while the MSb would be made of stars enriched in He and N but depleted in O.
# Advances in Understanding Multiple Stellar Generations in Globular Clusters

**Principal Investigator:** Prof. Giampaolo Piotto  
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**Electronic Mail:** giampaolo.piotto@unipd.it  
**Scientific Category:** RESOLVED STELLAR POPULATIONS  
**Scientific Keywords:** Astrometry, Globular Clusters, UV-Bright Stars  
**Instruments:** WFC3, ACS  
**Proprietary Period:** 12

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<tr>
<td>M-15</td>
<td>21 29 58.3800</td>
<td>+12 10 0.60</td>
<td></td>
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</table>
A WFC3 UV Survey of Galactic Globular Clusters

Principal Investigator: Prof. Giampaolo Piotto
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Scientific Category: RESOLVED STELLAR POPULATIONS
Scientific Keywords: Astrometry, Galaxy Formation And Evolution, Globular Clusters, Resolved Stellar Populations, Survey
Instruments: WFC3, ACS

Proprietary Period: 0

Orbit Request: Cycle 20
Prime: 121
Parallel: 121

Cycle 20

46 clusters
Ivan R. King Co-I
A WFC3 UV Survey of Galactic Globular Clusters

Principal Investigator: Prof. Giampaolo Piotto
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Scientific Keywords: Astrometry, Galaxy Formation And Evolution, Globular Clusters, Resolved Stellar Populations, Survey
Instruments: WFC3, ACS
Proprietary Period: 0
Treasury: Yes

Orbit Request
Cycle 20
Time 121
Parallel 121
Thank you Ivan for having been such a wonderful maestro and, overall, for your friendship
Ejecta (10-20 km/s) from intermediate mass AGB stars (4-6 solar masses) could produce the observed abundance spread (D’Antona et al. 2002, A&A, 395, 69). These ejecta must also be He, Na, CN, Mg) rich, and could explain the NaO and MgAl anticorrelations, the CN anomalies, and the He enhancement.

Globular cluster stars with He enhancement could help explaining the anomalous multiple MSs, and the extended horizontal branches.
Alternative explanation (2)


The material ejected in the disk has two important properties:

1) It is rich in CNO cycle products, transported to the surface by the rotational mixing, and therefore it can explain the abundance anomalies;

2) It is released into the circumstellar environment with a very low velocity, and therefore it can be easily retained by the shallow potential well of the globular clusters.