Globular Cluster observations with HST

Giampaolo Piotto

Dipartimento di Astronomia
Università’ di Padova
HST has wonderful astrometric capabilities

On well exposed stars, astrometric precision on single images is of ~0.01 pixels, which implies:

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Precision</th>
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<tbody>
<tr>
<td>WFPC2</td>
<td>1.00 mas</td>
</tr>
<tr>
<td>PC</td>
<td>0.50 mas</td>
</tr>
<tr>
<td>HRC/ACS</td>
<td>0.25 mas</td>
</tr>
<tr>
<td>WFC3</td>
<td>0.30 mas</td>
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</tbody>
</table>

But you can use many images, and reach higher precision in relative stellar positions, with local transformations (J. Anderson great idea!)
HST high astrometric precision implies high precision proper motions

1) Bulk motions:
   membership: fast evolving stars, WDs, binaries, exotics like CVs, blue stragglers, etc.

2) Absolute motions:
   clusters, field stars, rotations

3) Internal motions:
   Internal dynamics, IMBH?, absolute distances
Ivan King and the faint stars in NGC 6397
End of sequence lost in field stars
How to identify the members?

Proper motions!!
NGC6397 II: pushing HST to the limits

- Richer et al. (2005) observed NGC6397 with 126 orbits
  - Discoveries
    - End of WD cooling sequence
    - Blue hook at the WDCS bottom!
    - End of MS?
  - Again: limitations: field stars and galaxies!
Proper motion cleaning, 5 years baseline

NGC6397

BLINK

PI-Rich, UCLA
Pushing HST to the limits, sometimes you may get... surprises:
The double peaked WD cooling sequence in NGC 6791

Bedin et al. 2005, 2008a, 2008b
NGC 6397 III: Richer's 126 HST orbits, 398 bk galaxies

250µas astrometric precision on single brightest galaxies; 10yr baseline, 40µas/yr in absolute proper motion error!

The “problem” with proper motions is that... they become better and better with time!
3D absolute motions: the orbits of NGC 6397

Proper motion

Background galaxies

Field stars

NGC6397

Radial velocity

Cluster orbit


d = 2000 pc

d = 2200 pc

d = 2400 pc
Field stars may be as useful as cluster stars!!!!

Measurement of the Galactic constant:

\[(A-B)_{\text{Oort}} = \frac{\Theta_0}{R_0} = 27.6 \pm 1.7 \text{ km/s/Kpc}\]
Geometrical distance of ωCen

2-dimensional proper motion dispersion:

\[ \sigma_x = 833 \pm 59 \text{ \( \mu \)as/yr} \]
\[ \sigma_y = 835 \pm 71 \text{ \( \mu \)as/yr} \]

Comparing proper motion dispersion (an angular) quantity with the radial velocity dispersion (a linear quantity), we get the distance:

\[ D = 4.70 \pm 0.06 \text{ kpc} \]

Anderson and van der Marel (2010)
Van der Marel and Andersono (2010)
Geometrical distance of ωCen

2-dimensional proper motion dispersion:

\[ \sigma_x = 833 \pm 59 \, \mu\text{as/yr} \]
\[ \sigma_y = 835 \pm 71 \, \mu\text{as/yr} \]

4 year time baseline

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\[ D = 4.70 \pm 0.06 \, \text{kpc} \]

Anderson and van der Marel (2010)
Van der Marel and Andersono (2010)
High precision astrometry means high precision PSFs and therefore:

**High precision photometry**

**First photometric survey**

**HST SNAPSHOT PROJECT:**

- 74 GC cores observed with the WFPC2 in the F439W and F555W band [all clusters with (m-M)B<18];
- More than 150 papers based on this data base;
- 1st epoch for proper motion measurements;
The most surprising discovery from the HST WFPC2 snapshot survey

Blue horizontal branches in metal rich globular clusters

Rich et al. 1997

NGC 6441
$E(B-V) = 0.44$
$[Fe/H] = -0.53$

NGC 6388
$E(B-V) = 0.40$
$[Fe/H] = -0.60$
Globular Cluster Treasury project PI: A. Sarajedini

ACS/HST survey of 66 Galactic Globular Clusters

Target: down to 0.2 solar masses with S/N>10; highest S/N at the TO

Data available on: http://www.astro.ufl.edu/~ata/public_hstgc/databases.html
Globular Cluster relative ages

Marin-French et al. 2009
Photometric binaries in 54 Globular Clusters.
Milone et al. 2010, in prep.

Significant anti-correlation between the fraction of binaries in a cluster and its absolute luminosity (mass)
Blue stragglers frequency anticorrelates with cluster total luminosity (total mass). This fact has been interpreted as an evidence of the dynamical evolution of binaries.

Moretti et al. (2008), Davies et al. (2005), Piotto et al. (2004),

From HST snapshot survey
UV sensitivity, high resolution

systematic studies of hot SPs in the core of high density GGCs

Courtesy of F. Ferraro
The BSS radial distribution in 47 Tuc is quite similar to that observed in M3

Mapelli et al. (2004)
Globular Clusters as Simple Stellar Populations?

“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....”

For this reason, star clusters have been - so far - a fundamental benchmark for testing stellar evolution models and for Population Synthesis Models.
The scenario abruptly changed “special” case: Omega Centauri

Most massive Galactic “globular cluster” (present day mass: ~4 million solar masses).

Well known (since the ’70s) spread in metallicity among RGB stars.

A new era in globular cluster research opened.
The most surprising discovery

The bluer sequence is **MORE METAL RICH**

BlueMS: [Fe/H]=-1.27

RedMS: [Fe/H]=-1.56

17x12=204 hours of VLT integration time

Apparently, only an overabundance of Helium (Y~0.40) can reproduce both the photometric and spectroscopic observations

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
The complexity increases!

New spectacular UV data from the new WFC3 camera onboard HST

Amazing perspectives with WFC3!!!
NGC 6715 (M54)

Multiple MSs, SGBs, RGBs ....
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.
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 into three separate branches.

Overabundances of helium ($Y\sim0.30$, $Y\sim0.40$) 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.

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).
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).

<table>
<thead>
<tr>
<th>The Population Components of NGC 2808</th>
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<tr>
<td><strong>MS</strong></td>
</tr>
<tr>
<td>---------------</td>
</tr>
<tr>
<td>rMS</td>
</tr>
<tr>
<td>63% ± 5</td>
</tr>
<tr>
<td>( \Gamma = 0.248 )</td>
</tr>
<tr>
<td>mMS</td>
</tr>
<tr>
<td>15% ± 5</td>
</tr>
<tr>
<td>( \Gamma = 0.30 )</td>
</tr>
<tr>
<td>bMS</td>
</tr>
<tr>
<td>13% ± 5</td>
</tr>
<tr>
<td>( \Gamma = 0.37 )</td>
</tr>
<tr>
<td>Binaries</td>
</tr>
<tr>
<td>9% ± 5</td>
</tr>
</tbody>
</table>

1.4x10^4 and 2.7x10^4 solar masses of fresh Helium are embedded in the 2\textsuperscript{nd} and 3\textsuperscript{rd} generations of stars.

Observations properly fit a scenario in which a 2\textsuperscript{nd} and 3\textsuperscript{rd} stellar generations formed from material polluted by intermediate mass AGB stars of a 1\textsuperscript{st} generation.
NGC 6752: very extended EHB, but with a mass of $1.6 \times 10^5 M_\odot$
Example of a not massive cluster showing clear evidence of multiple populations

...47Tuc MS is also intrinsically spreaded

If the spread in color is due to a spread in Fe, it implies a $\Delta ([\mathrm{Fe/H}]) = 0.001$; if it is helium, it implies $\Delta Y = 0.03$
A problem: star to star variations of light elements are present in all GCs

Carretta et al. 2010

Most clusters have constant [Fe/H], but large star to star variations in light elements. Some elements define correlations like the NaO anticorrelation, or the MgAl anticorrelation. These anticorrelations are present in all clusters analyzed so far.
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.
Radial distribution of the two SGBs in NGC 1851

The double SGB is present all over the cluster, also in the envelope

There is no radial gradient

Log $t_{rh} = 8.9$

Milone et al. (2009) in prep
Cassisi et al. (2007, 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 CNONa enhanced population.

In such hypothesis, the age difference between the two groups may be very small \((10^7 - 10^8\) years). But....

NGC 6656 (M22) double SGB

Piotto et al. (2009), in preparation
Double SGBs are present in many Globular Clusters: e.g. NGC 6388

New WFC3 data acquired; reduction in progress
In order to reproduce the anomalous HB, Caloi and D’Antona (2007) propose an even more complicated scenario with 3 distinct populations:

1. a normal population ($Y \approx 0.25$);
2. a polluted pop. ($0.27 < Y < 0.33$);
3. A strongly He enhanced pop. ($Y \approx 0.4$)

Three He populations in NGC 6388 and NGC 6441, as in NGC 2808 and perhaps ωCen?
We used ACS/HST archive data to construct the CMDs of 46 LMC clusters. We investigated the CMD morphology of 16 intermediate age clusters, with ages between 1 and 3 Gyr.
Eleven out of 16 (2/3) of the intermediate age clusters show either a double or an extended TO! (Milone et al 2009, A&A, 497, 755).
47 Tucanae shows a spreaded SGB, plus a secondary SGB

Example of cluster with not extended HB showing evidence of multiple populations

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Multipopulation zoo

1. Multipopulations may be ubiquitous: NaO anticorrelation found in all clusters searched so far.
2. Clusters with discrete multiple main sequences, apparently implying extreme He enrichment, up to Y=0.40 (e.g., ω Centauri, NGC2808)
3. Clusters with broadened or splitted MS (as NGC6752 and 47Tuc)
4. Complex objects like M54 (= Omega Cen?)
5. Intermediate objects like Ter 5, M22 (=M54, ω Cen?)
6. Clusters with double SGB or RGB (e.g., NGC 1851, NGC6388, NGC 5286, M4, and many others)
7. The LMC/SMC intermediate age clusters with double TO/SGB.
8. Young massive clusters in external galaxies.

Are all of them part of the same story?
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.
Conclusions

Thanks to HST we are now looking at globular cluster (and cluster in general) stellar populations with new eyes. De facto, a new era on globular cluster research is started:

1) Multiple stellar generations seems ubiquitous. Many serious problems remain unsolved, and we still have a rather incoherent picture. The new WFC3/HST will play a major role. In helping us understanding their origin.

2) For the first time, we might have the key to solve a number of problems, like the abundance “anomalies” and possibly the second parameter problem (which have been there for decades), as well as the newly discovered multiple sequences in the CMD.

3) Finally, we should never forget that what we will learn on the origin and on the properties of multiple populations in star clusters has a deep impact on our understanding of the early phases of the photometric and chemical evolution of galaxies.