MULTIPLE STELLAR POPULATIONS IN 47 TUCANAE (AND NGC 6397)

Antonino P. Milone

Instituto de Astrofisica de Canarias

coworkers:

Anna F. Marino (MPA-Garching, Germany)

G. Piotto, A. Bellini (Univ. of Padova, Italy)

Antonio Aparicio, Matteo Monelli (IAC, Spain)

F. D'Antona, M. Di Criscienzo (INAF, Roma, Italy)

Peter Stetson (Herzberg Inst., Victoria, Canada)

Ivan R. King (Univ. of Washington, USA)

Jay Anderson (STScI, USA)

S. Cassisi, A. Pietrinferni (INAF, TE, Italy)

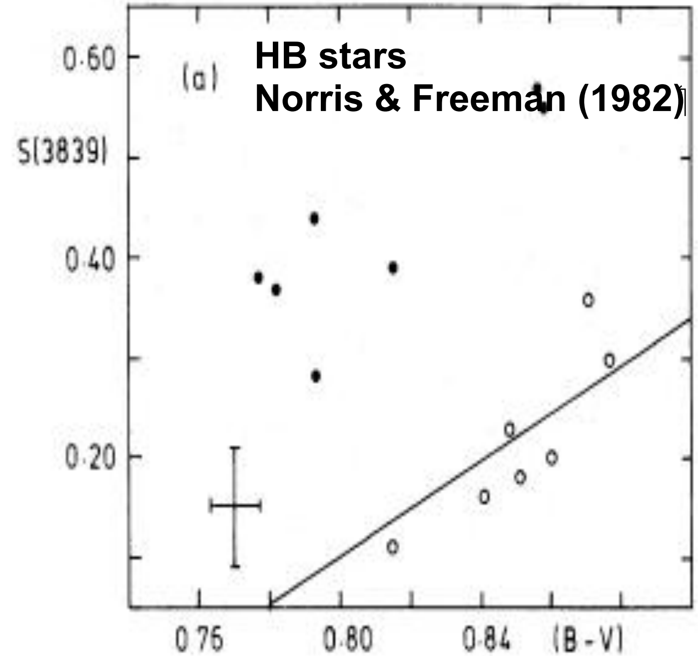
A. Bragaglia, E. Carretta (INAF, BO, Italy)

R. M. Rich (UCLA, USA)

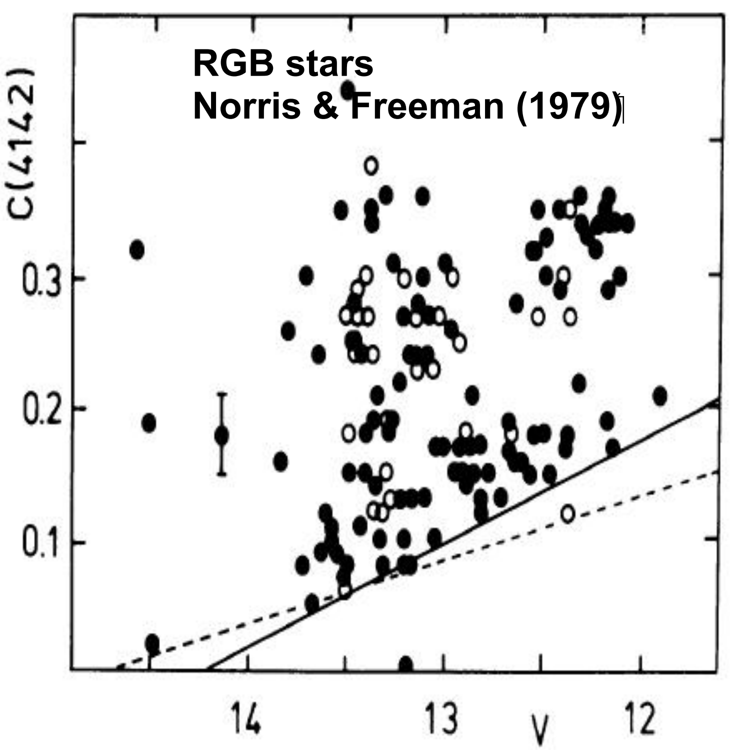
Luigi R. Bedin, Raffaele Gratton, Sara Lucatello, Alvio Renzini (INAF, PD, Italy)

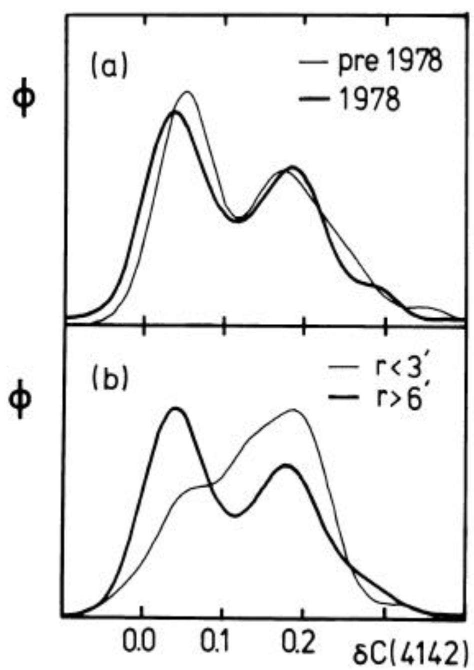
Spectroscopic evidence of multiple populations in 47 Tucanae

Since the early seventies, spectroscopic investigations have shown:



- large star-to-star variations in CN band strength (Mc Clure & Osborn 1974, Bell et al. 1975).
- Two groups of stars showing different CN content (Norris & Freeman 1979, Briley 1997, Cannon 1998, Harbeck et al. 2003).
- The Na-O anticorrelation has been studied by Carretta et al. (2009).

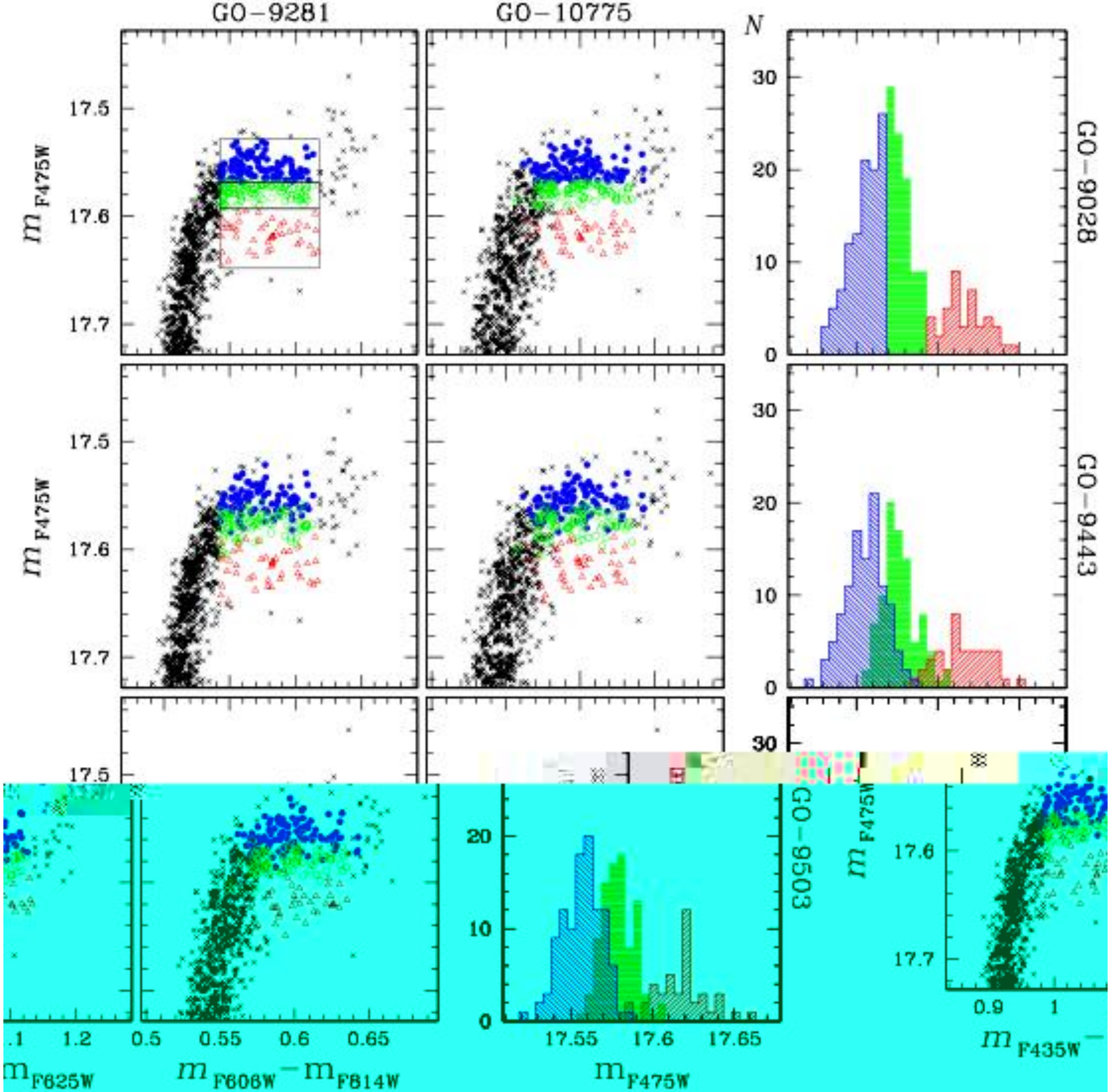




The CN bimodality has been detected also among HB stars (Norris & Freeman 1982)

CN-strong stars are more centrally concentrated (Norris & Freeman 1979, Norris & Smith 1980, Briley 1997).

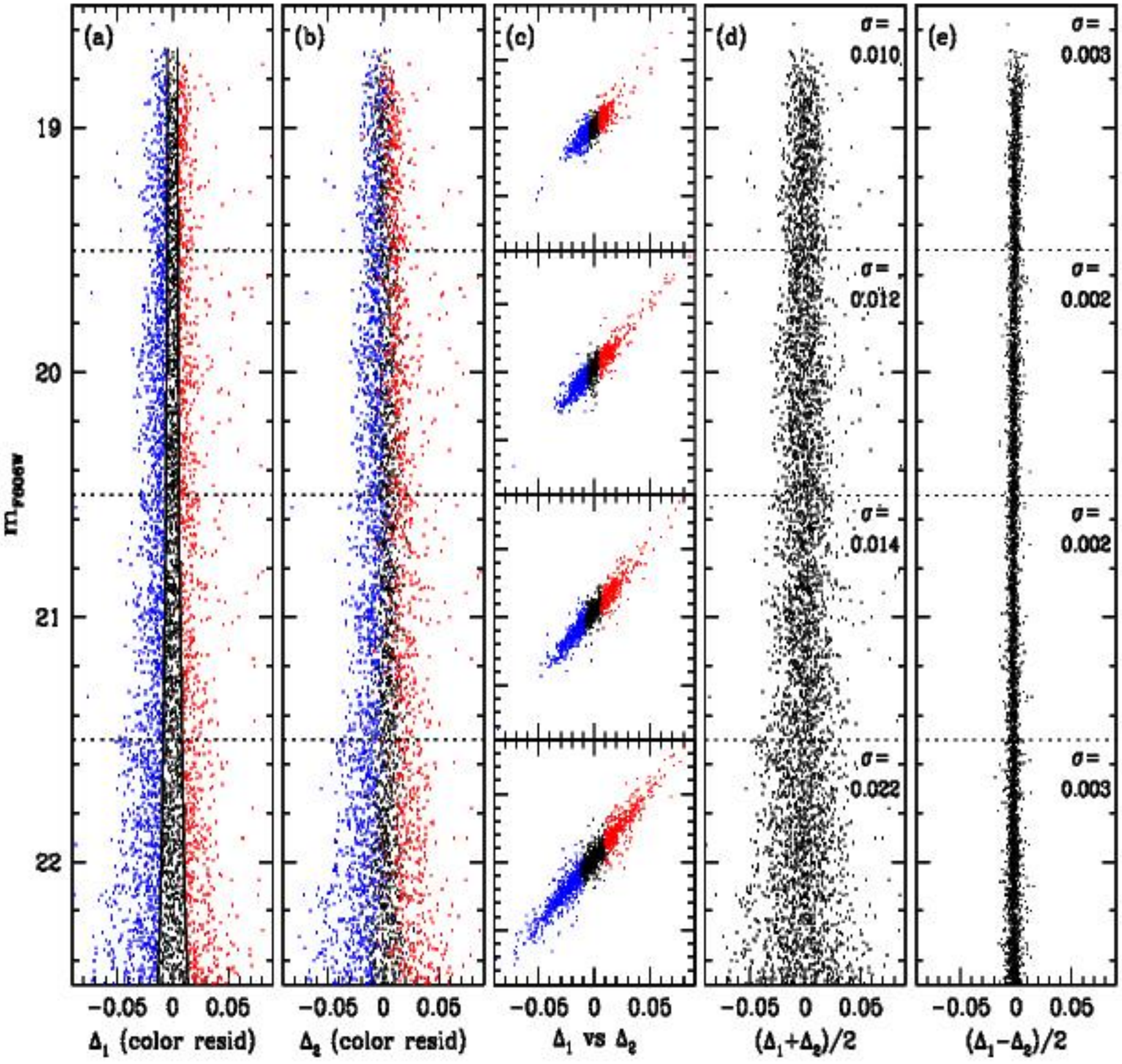
Photometric evidence of multiple populations in 47 Tucanae



Anderson et al. (2009, ApJ, 697, L58) found that, in the cluster core, **the SGB splits into two components**:

- A brighter one with a spread that is real but not bimodal.
- A second one about 0.05 mag fainter, containing a small fraction of stars.

Photometric evidence of multiple populations in 47 Tucanae



Anderson et al. (2009, ApJ, 697, L58) also found that the MS is broadened much more than can be accounted for photometric errors.

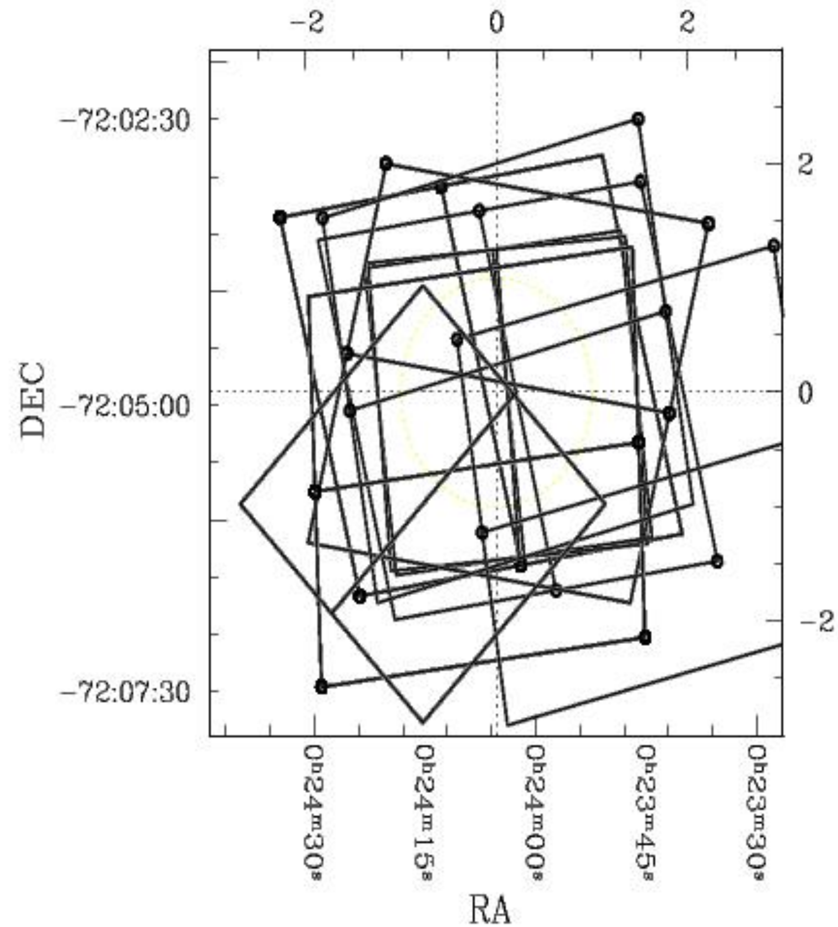
Di Criscienzo et al. (2010, MNRAS, 408, 999) show that the MS colour spread could be due to small helium variations (ΔY~0.02).

The photometric dataset

HST dataset:

~100 ACS/WFC and WFC3/UVIS images in F275W, F336W (~U), F390W, F435W (~B), F475W, F555W, F606W, F625W, F814W (~I). Reduced with the programs described by Anderson et al. (2006, 2008).

INSTR	DATE	N×EXPTIME	FILT	PROGRAM	PI
UVIS/WFC3	Nov 21-22 2011	2×323s+12×348s	F275W	12311	Piotto
UVIS/WFC3	Sep 28 2010	30s+1160s	F336W	11729	Holtzman
UVIS/WFC3	Sep 28 2010	2×10s+2×348s+2×940s	F390W	11664	Brown
ACS/WFC	Sep 30-Oct 11 2002	9×105s	F435W	9281	Grindlay
ACS/WFC	Apr 05 2002	20×60s	F475W	9028	Meurer
ACS/WFC	Jul 07 2002	5×60s	F475W	9443	King
ACS/WFC	Jul 07 2002	1×150s	F555W	9443	King
ACS/WFC	Mar 13 2006	3s+4×50s	F606W	10775	Sarajedini
ACS/WFC	Sep 30-Oct 11 2002	20×65s	F625W	9281	Grindlay
ACS/WFC	Mar 13 2006	3s+4×50s	F814W	10775	Sarajedini



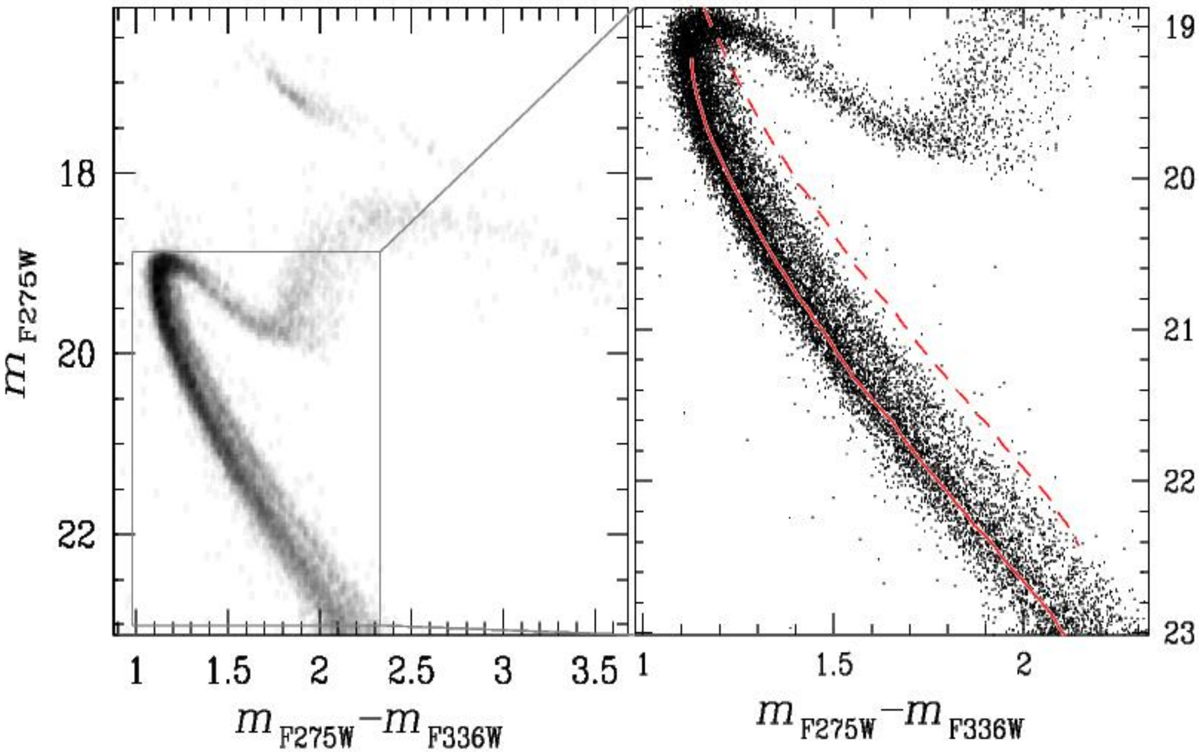
ground-based dataset:

>1500 images mainly from:
the Wide-Field Camera of the MPI 2.2m telescope and the Cerro-Tololo 1.5m telescope.
(data reduced by Peter Stetson, DAOPHOT).

Photometry has been corrected for differential reddening and zero-point photometric errors as in Milone et al. (2009).

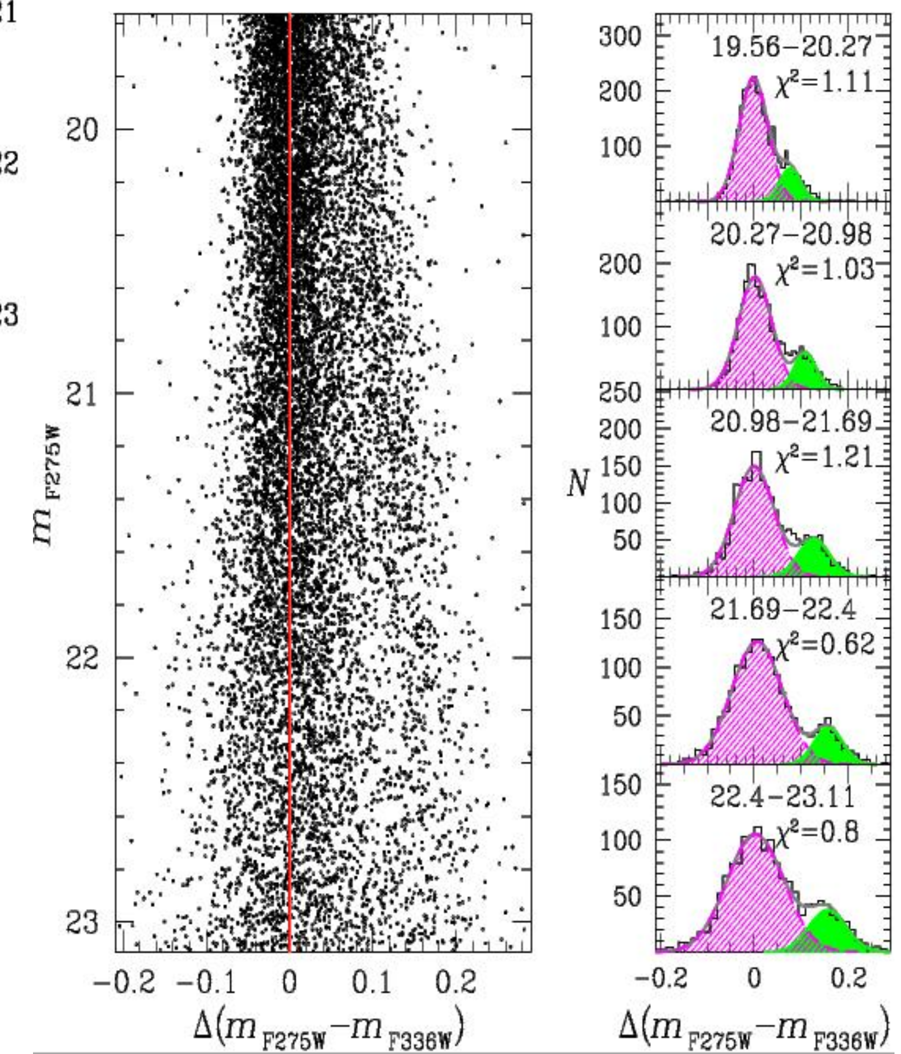
The double MAIN SEQUENCE

High-precision WFC3/UVIS photometry reveals that the main sequence (MS) of 47 Tucanae is bimodal in the F275W vs. F275W-F336W CMD.

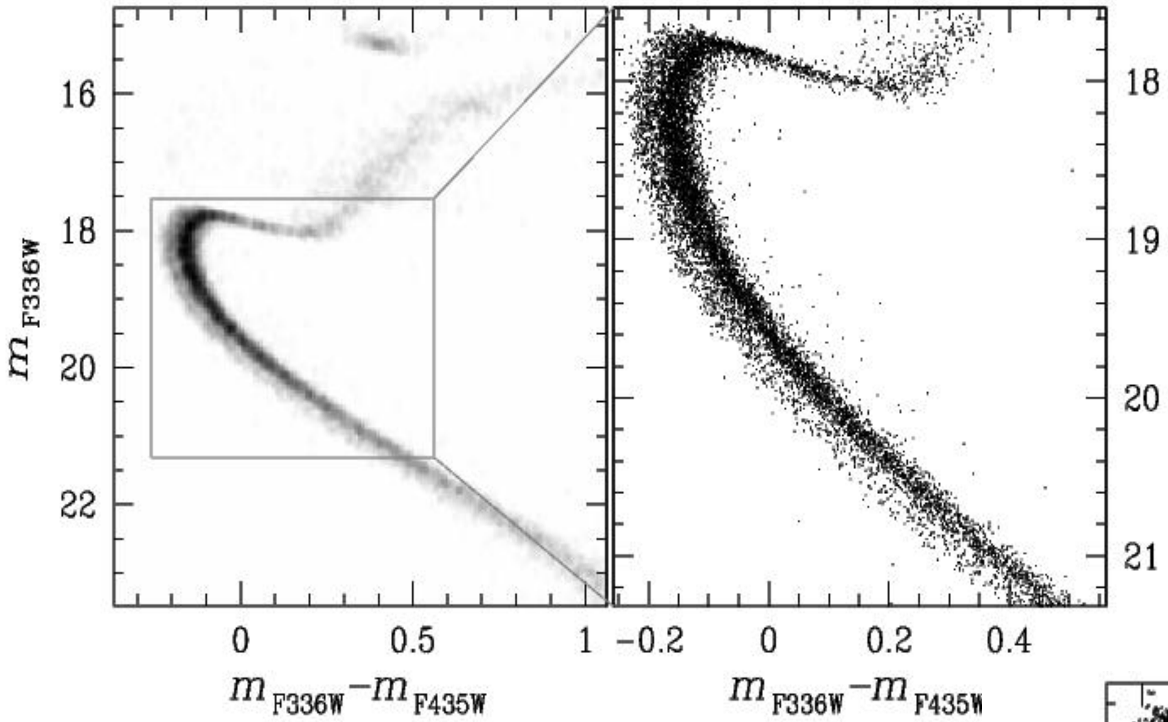


The two MSs merge close to the turn-off but the separation between the two components increases towards fainter magnitudes.

In the cluster centre, about 80% of stars belong to the most-populated component and ~20% to the less-populated MS.



The double MAIN SEQUENCE

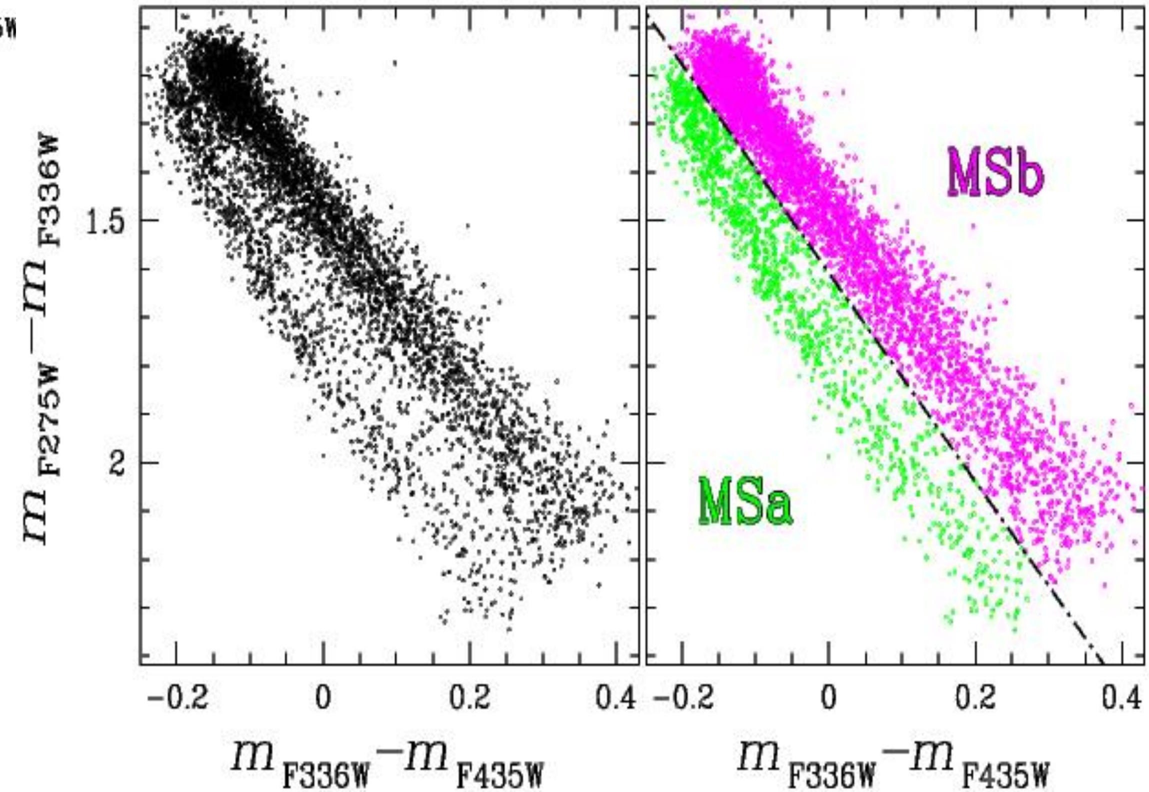


The double MS is evident in CMDs that use different combination of magnitude and colour like F336W vs. F336W-F435W.

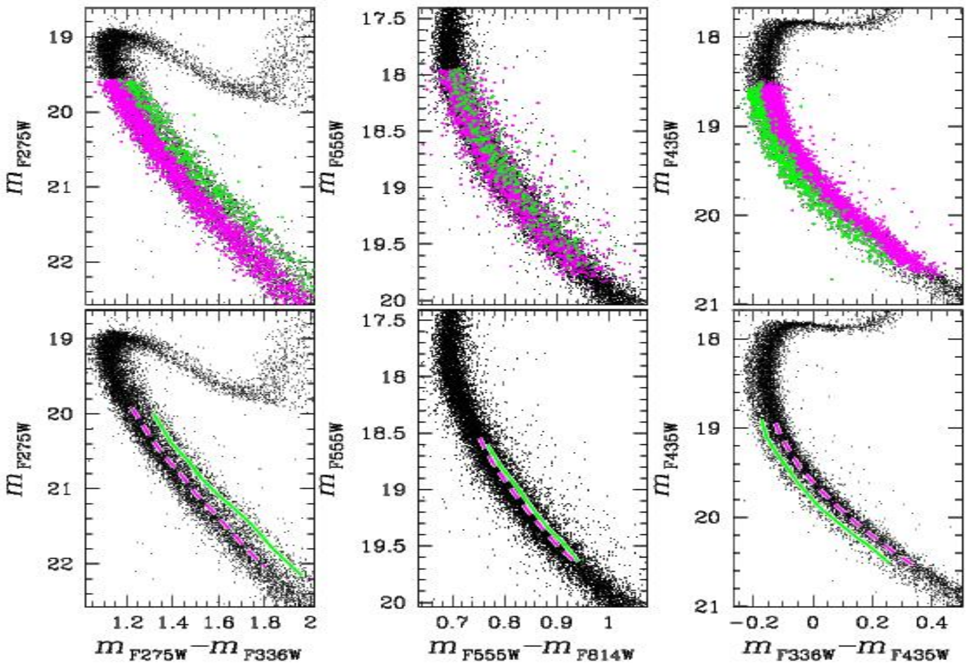
Note that, contrary to its behaviour in the previous CMD, the less-populous MS is bluer than the bulk of MS stars.

Since the two CMDs from the filter set F275W, F336W, F435W behave so different, we construct a F275W-F336W vs. F336W-F435W two-colours diagram.

There is a clear separation between the two populations.



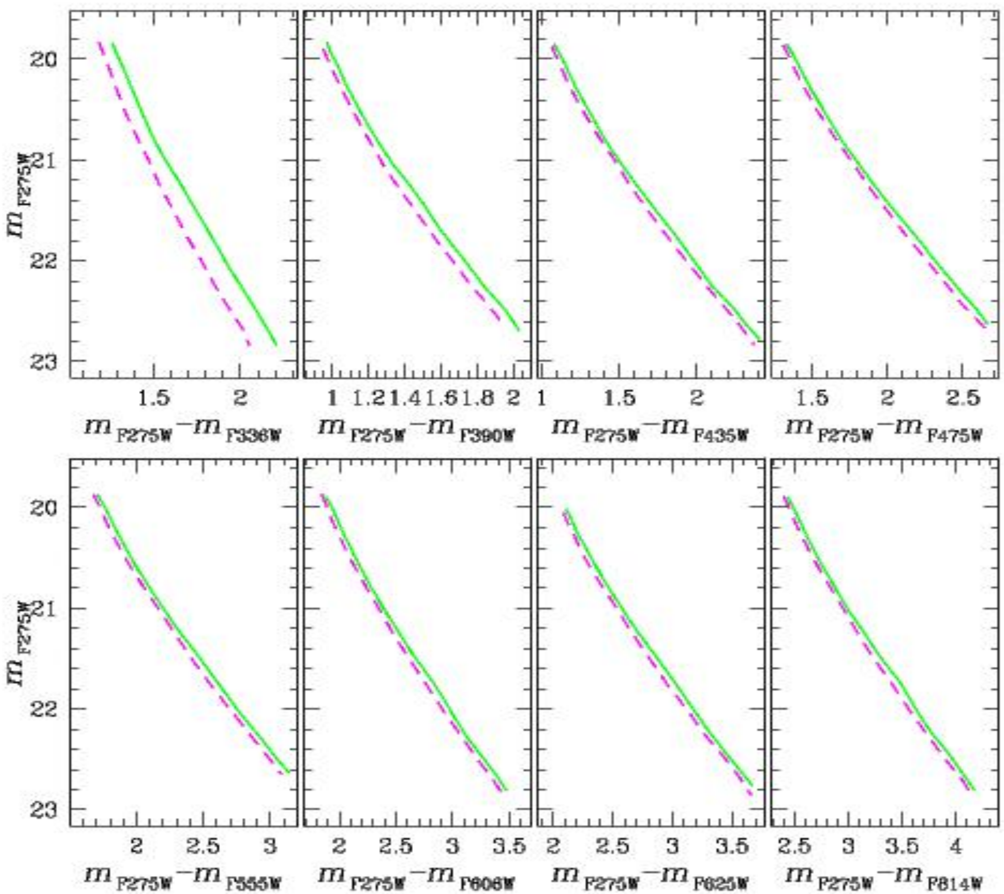
The double MAIN SEQUENCE

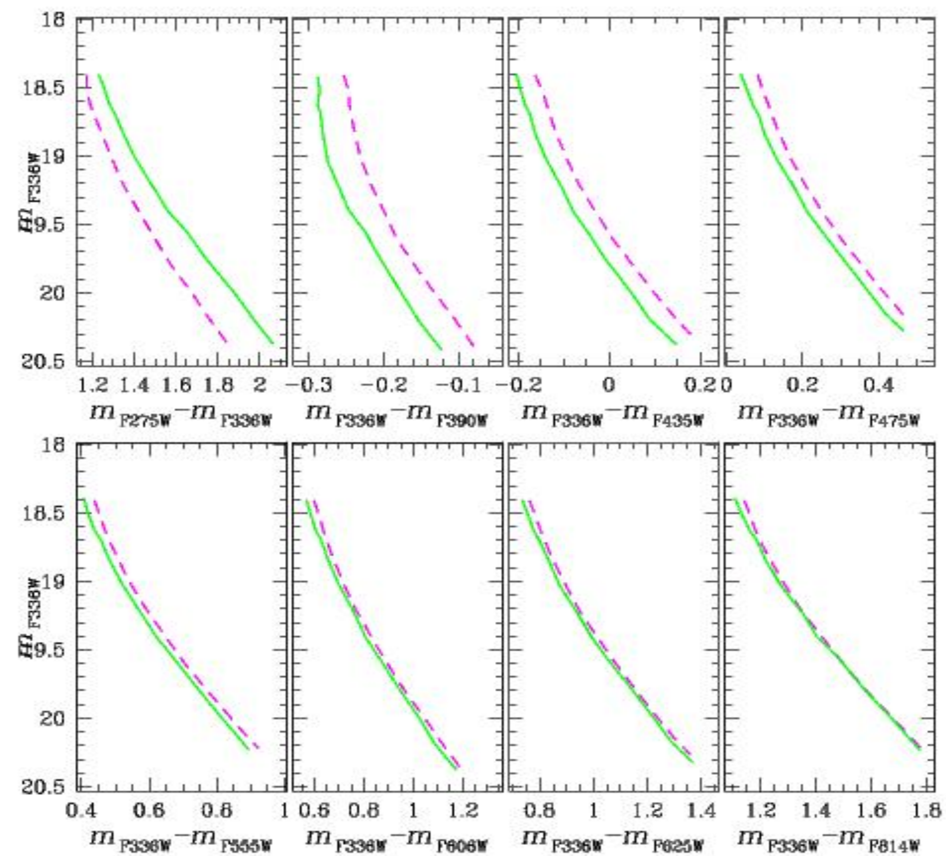


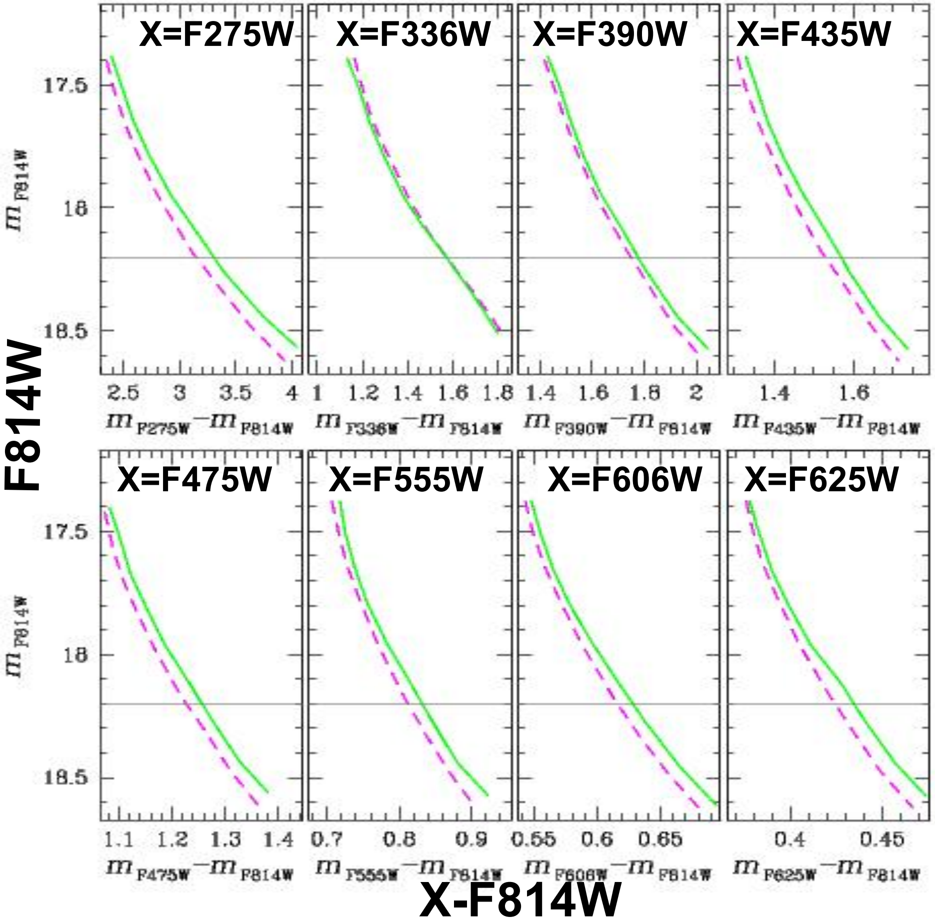
With high-accuracy photometry in 9 bands we are able to construct 36 CMDs.

We determined the fiducial lines of the MSa and the MSb in each CMD.

We note that MSa is redder than the MSb in most of these CMDs but the colour order is otherwise in some of them.



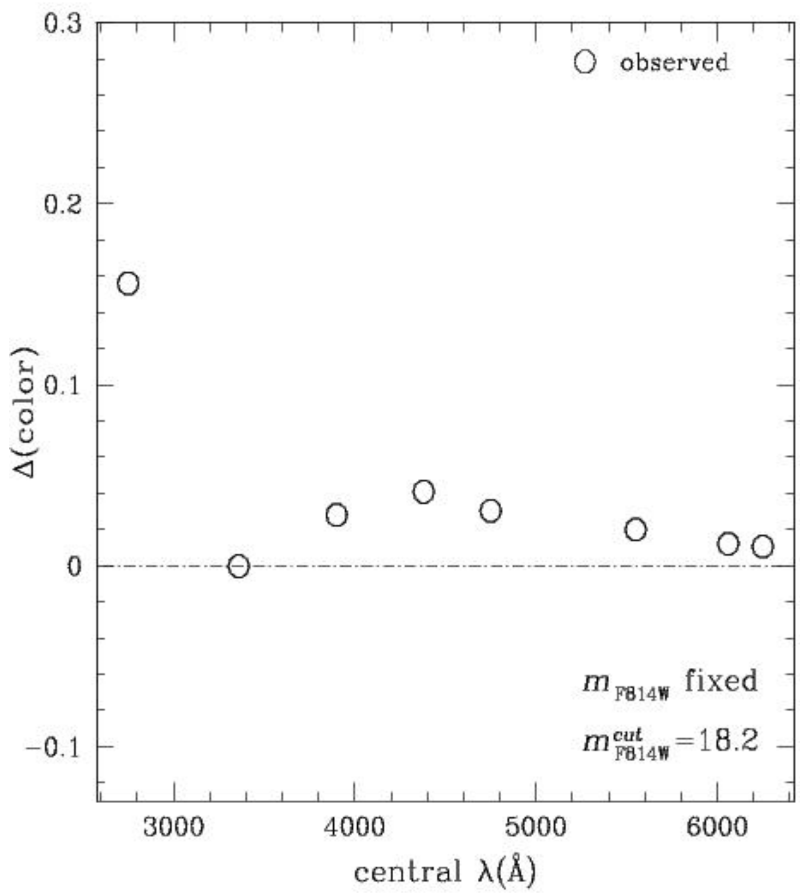




The double MAIN SEQUENCE

On the theoretical side, multiplicity of MSs has been attributed to:

- differences in helium content (e.g. Norris 2004, ApJ, 612, L25)
- difference in light-elements abundance (e.g. Sbordone et al. 2011, arXiv:1103.5836)

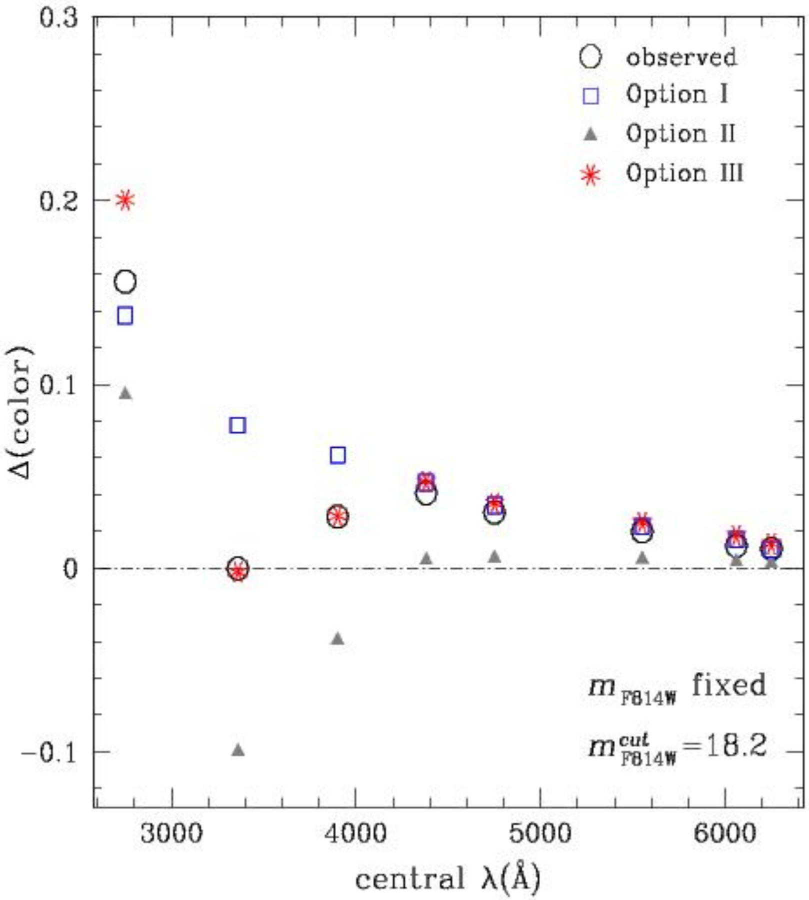


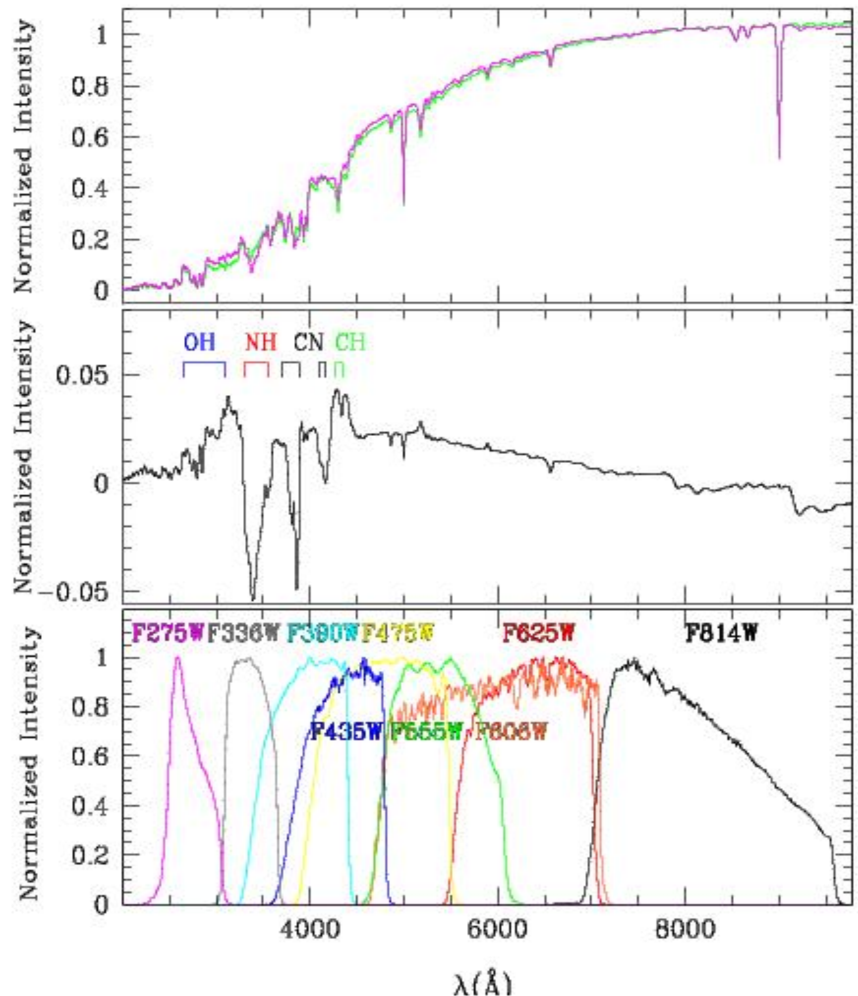
So we explore both these possibilities making different choices for the abundance of He, C, N, and O.

We calculate synthetic colours for MSa and MSb stars for each option, seeking the composition that best reproduces all the observed colour differences between the two MSs.

The double MAIN SEQUENCE

The two MSs are consistent with two stellar populations, one (MSa) with primeval abundance; and another (MSb) with enhanced N and a small helium enhancement, but with depleted C and O.





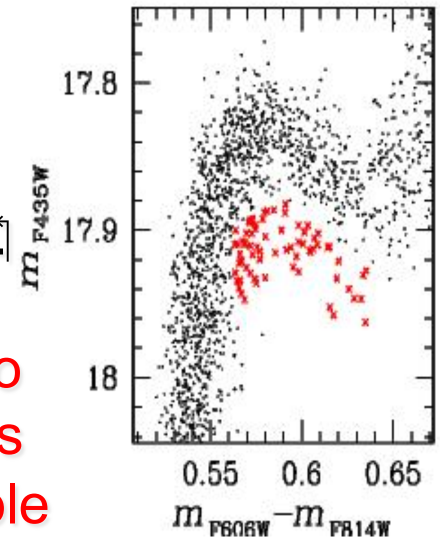
C, N, O abundances from Cannon et al. (1998) and Carretta et al (2009)

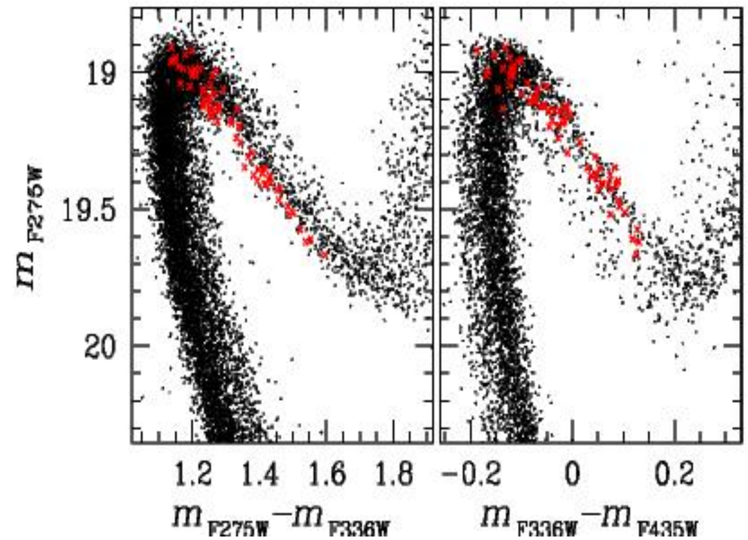
MS (Option)	T_{eff}	log g	Y	[C/Fe]	[N/Fe]	[O/Fe]
MSa (all)	5563	5.42	0.256	0.06	0.20	0.40
MSb (I)	5648	5.41	0.288	0.06	0.20	0.40
MSb (II)	5563	5.42	0.256	-0.15	1.05	-0.10
MSb (III)	5592	5.41	0.272	-0.15	1.05	-0.10

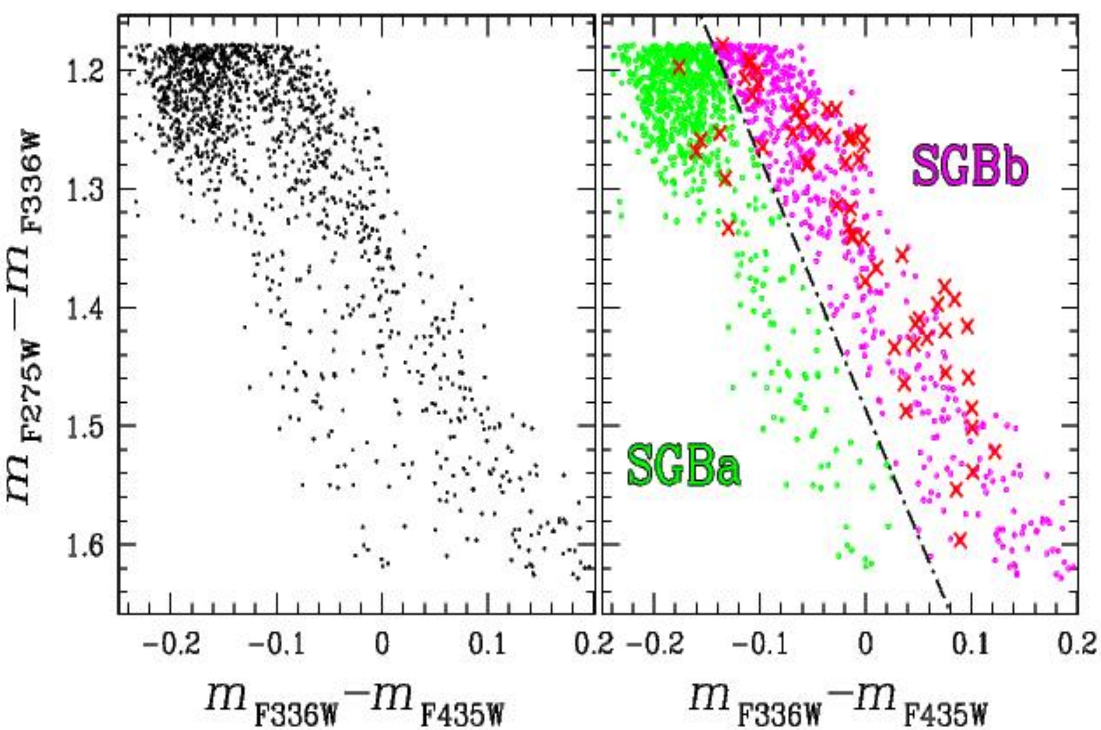
The SUB-GIANT BRANCH

We confirm the presence of the faint SGB discovered by Anderson et al. (2009, ApJ 697, L58).

The dominant SGB sequence also splits into two separate sequences bringing the total to three observable SGBs.



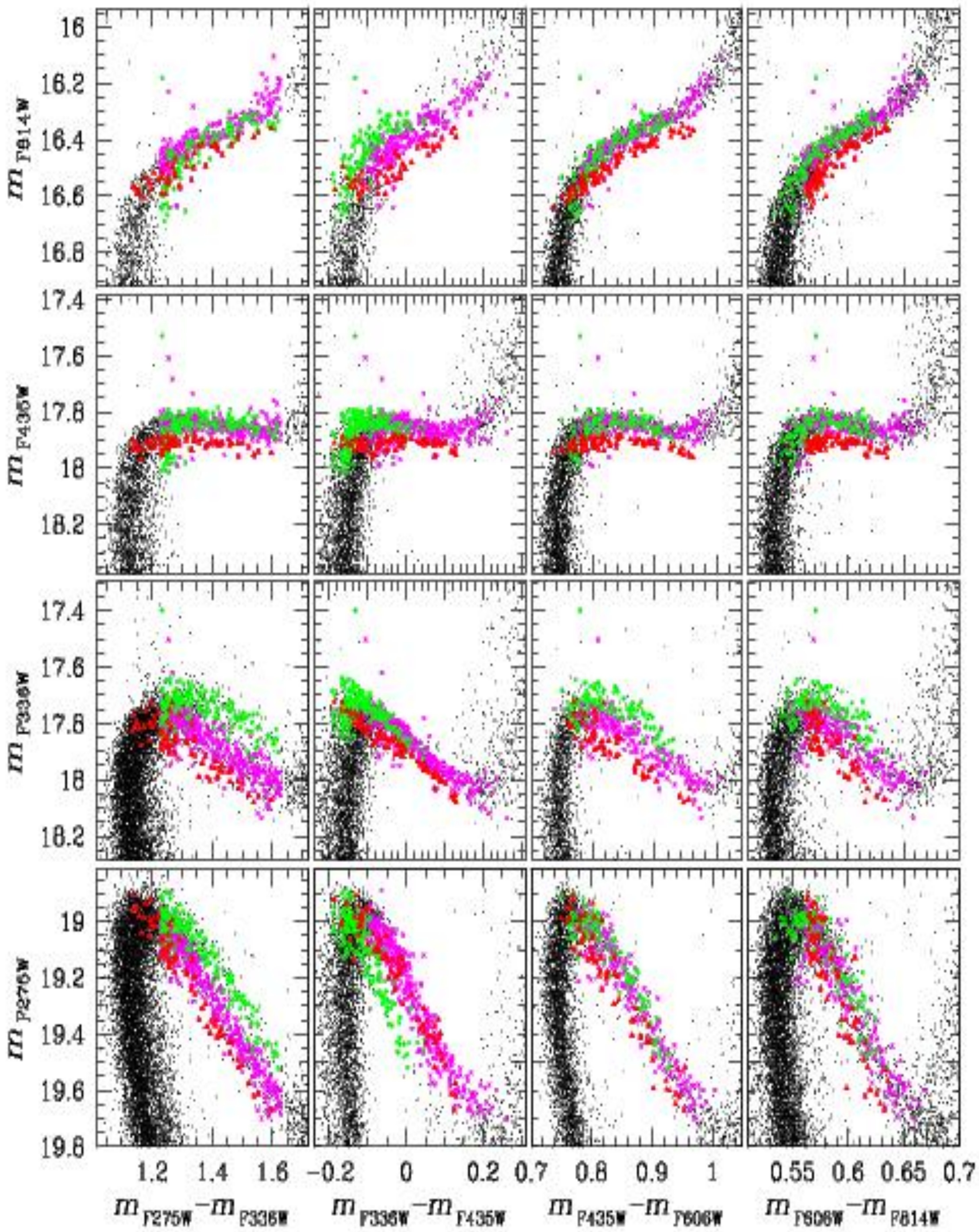




By analogy to what done for MS stars, we plot the UV two-colour diagram, where we see again a bimodal distribution.

Note that nearly all the faint-SGB stars belong to the SGBb.

The SUB-GIANT BRANCH



SGBa stars share similarities with MSa:

- In the CMDs that use the F275W-F336W colour they are redder than the other SGB stars. but when the F336W-F435W is used instead they move on the blue

- SGBa stars are brighter in the F336W band.

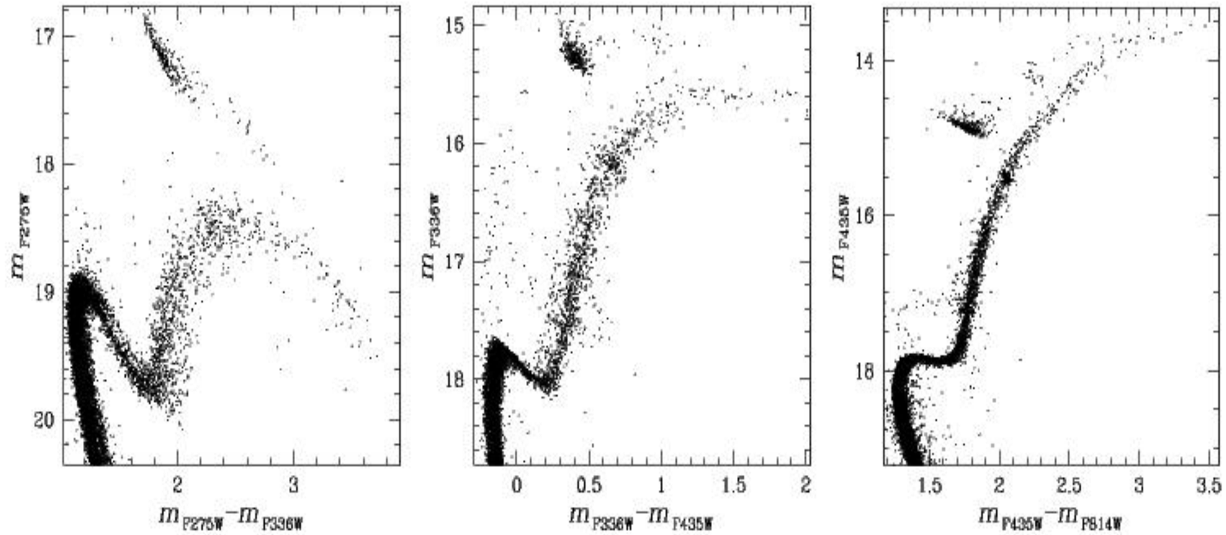
- In all the CMDs, faint SGB stars follow the same trend ad the bulk of SGBb stars, with the faint SGB running parallel to the SGBb

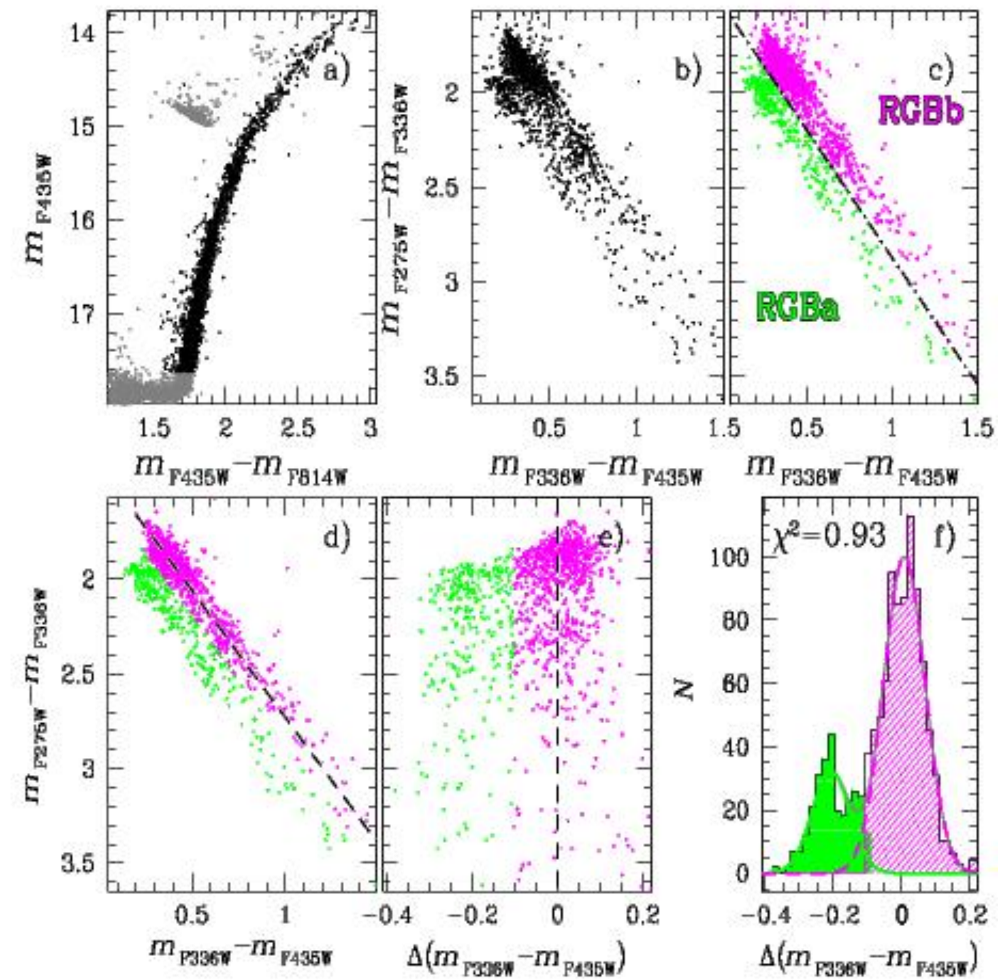
The RED-GIANT BRANCH

Both the F275W vs. F275W-F336W and the F336W vs. F336W-F814W CMDs suggest that the RGB is intrinsically broad.

The observed colour spread of 0.1-0.2 mag is much larger than the observational error, which for these bright stars is less than 0.01 mag.
However in the F435W vs. F435W-F814W the RGB is quite narrow.

The UV two-colour diagram shows a bimodal RGB, with about 20% of stars belonging to the RGBa.

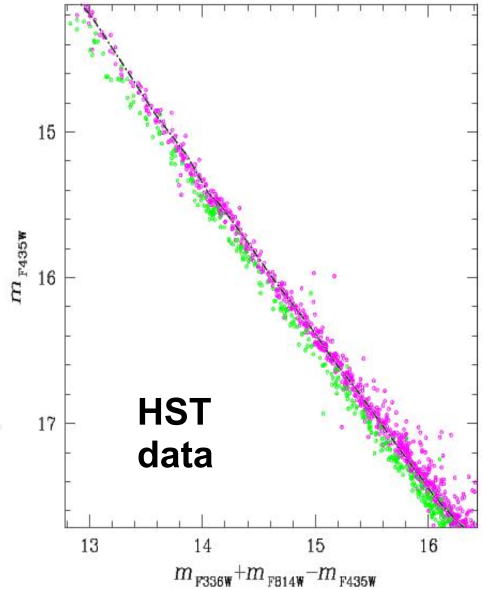


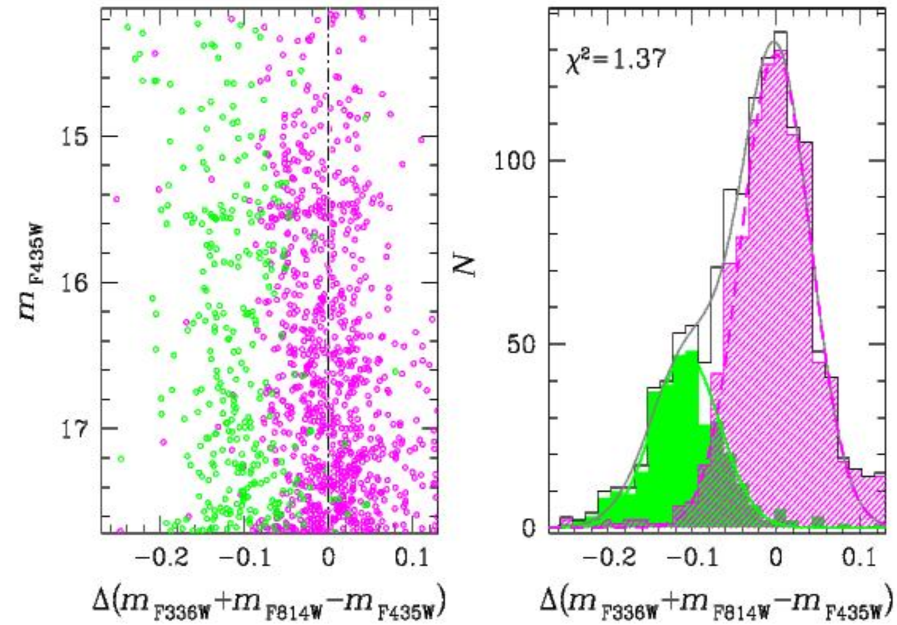


The RED-GIANT BRANCH

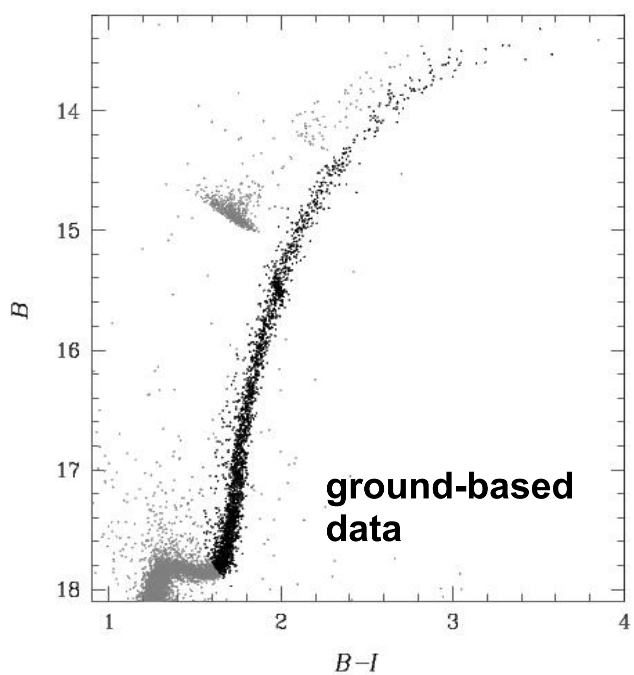
Ground-based photometry available for a wide field allows us to investigate the radial behaviour of the populations.

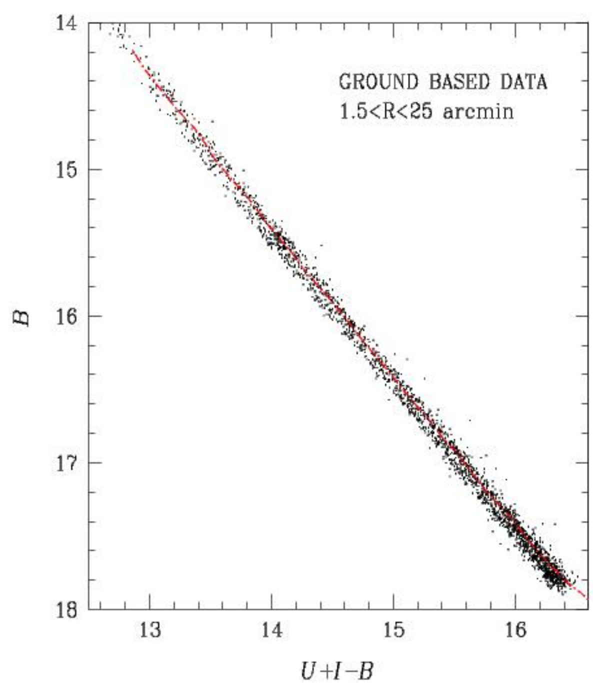
The lack of the F275W filter deprives us of our sharpest tool and we must look for the best discriminant among the ground-based passbands.





As a result, we found that the RGB stars separate into two groups when we plot F435W against the combination of F336W+F814W-F435W.



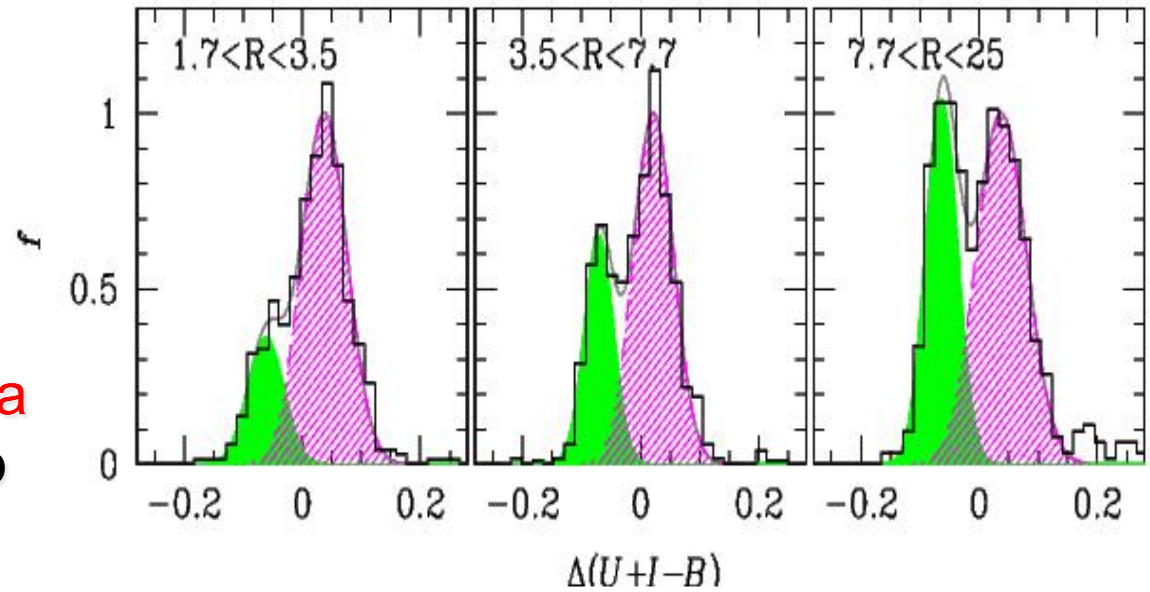


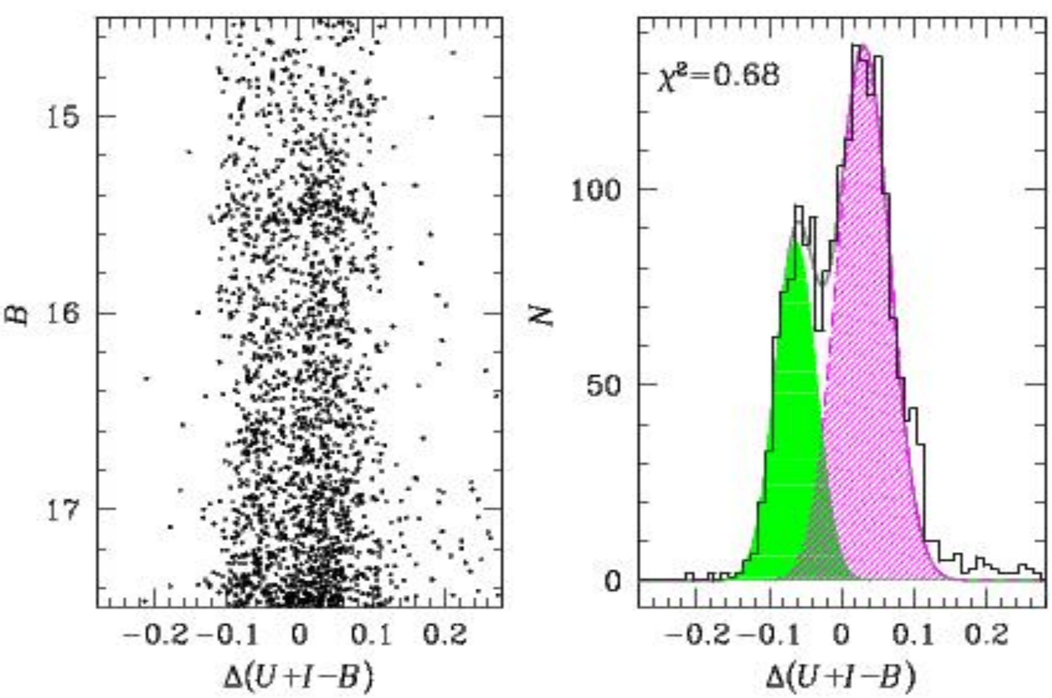
Since F336W, F435W, and F814W filters are similar to the Johnson U, B, I this is analogous to plot B vs. U+I-B.

The RED-GIANT BRANCH

The RGB is clearly bimodal over all the field of view.

It is clear that RGBb is more centrally concentrated than RGBa (in close analogy with the group of CN-strong stars identified by Norris & Freeman 1979).



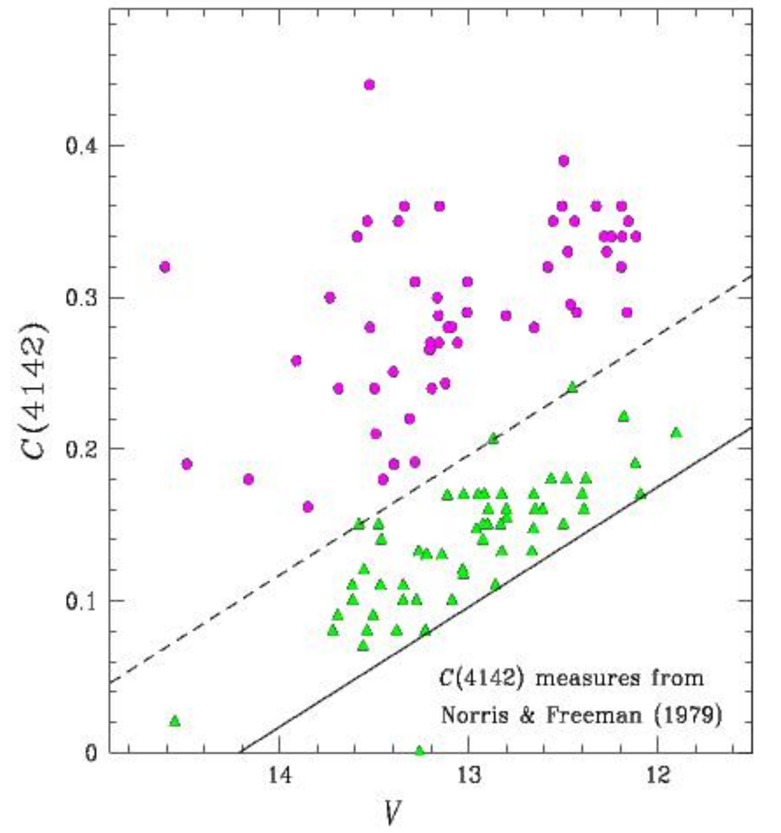


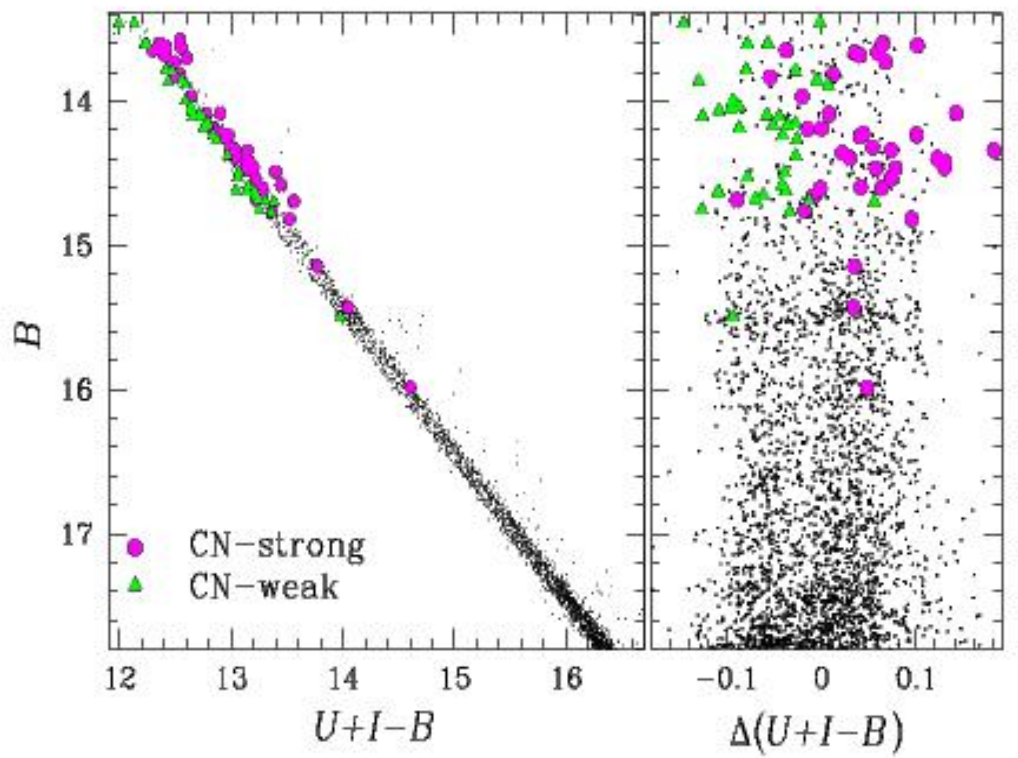
The fraction of RGBa stars ranges from 0.22+/-0.04 in the1.7-3.5 arcmin bin to 0.32+/-0.04 at radial distance from 3.5 to 7.7 arcmin up to 4.2+/-0.04 in the 7.7-25 arcmin bin.

The chemical composition of the double RGB

Norris & Freeman (1979) and Briley (1997) measured CN-band strengths in a large sample of RGB stars.

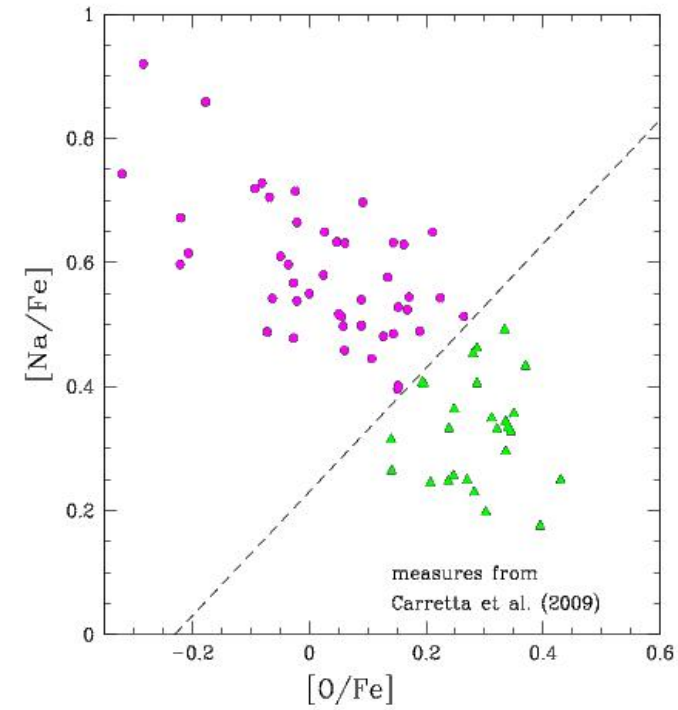
They found a clear bimodal distribution with CN-strong stars more centrally concentrated.





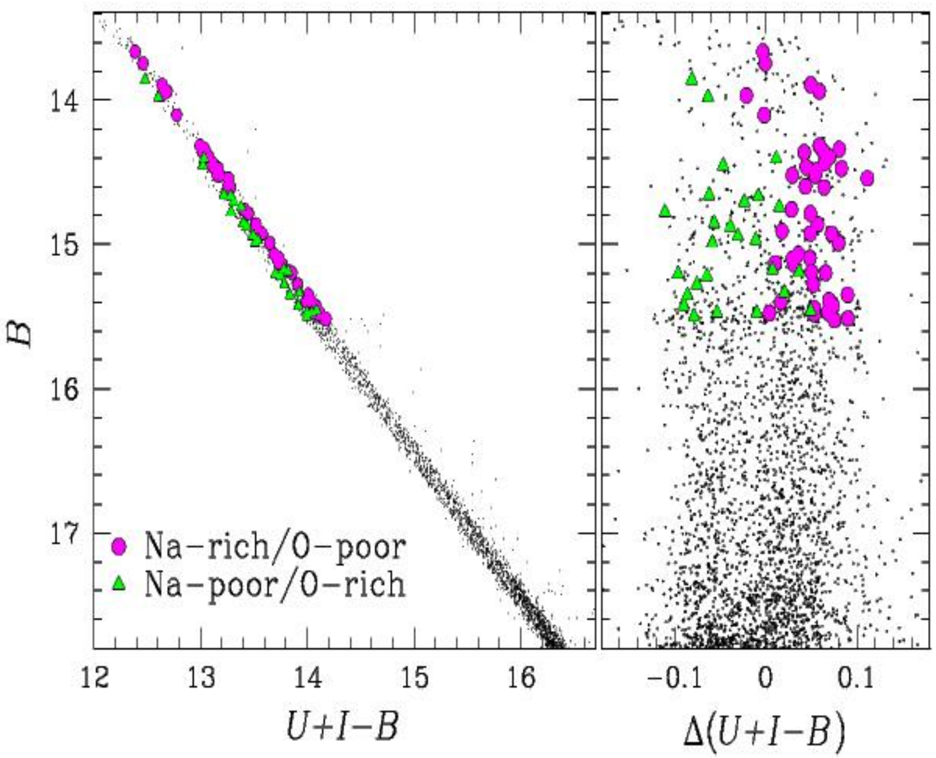
Most of CN-strong stars belong to the RGBb and nearly all the CN-poor stars lie on the RGBa.

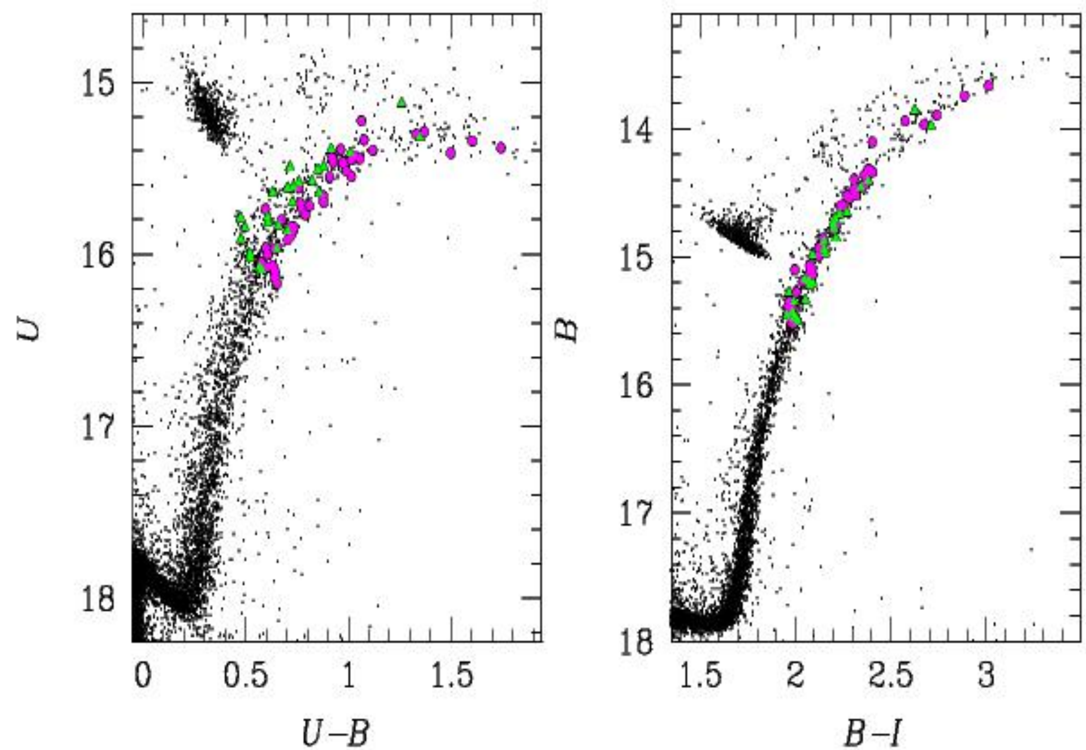
We associate the two groups of CN-strong and CN-weak stars with the two RGBs.



Also the groups of Na-poor and Na-rich stars populate the RGBa and the RGBb respectively.

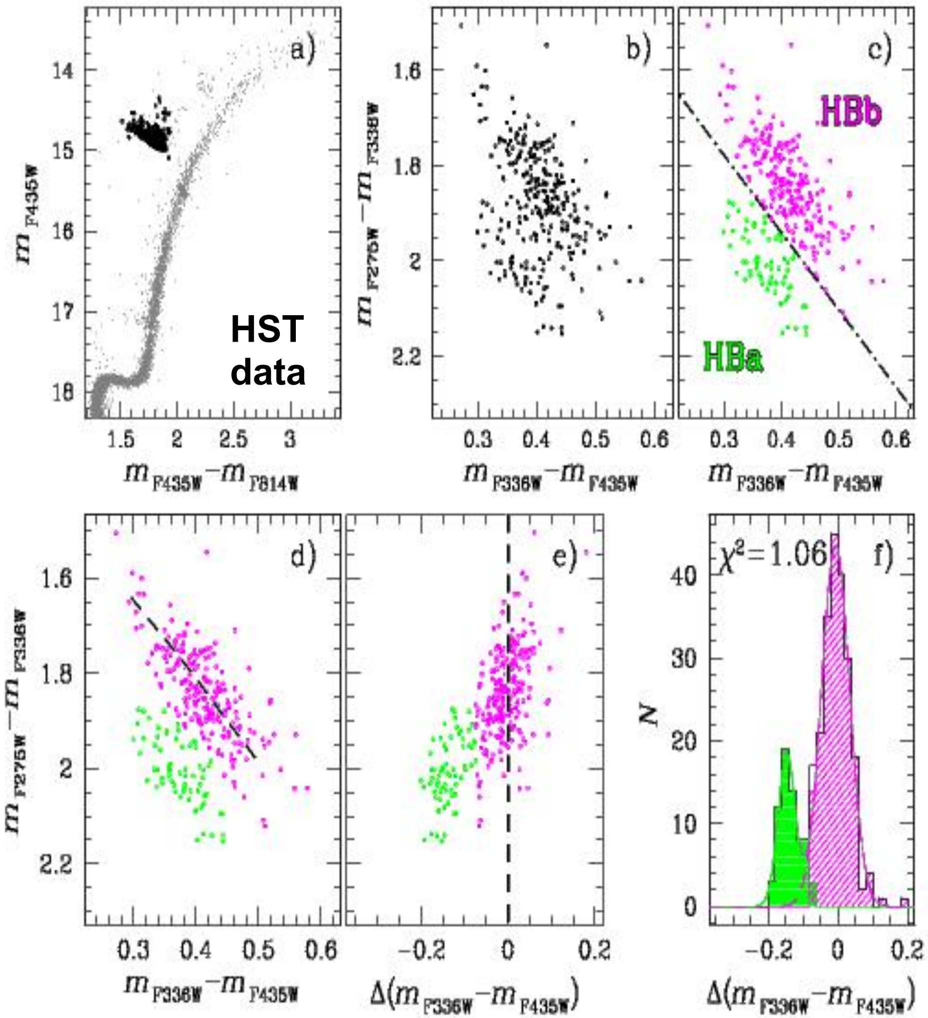
Interestingly, in the U vs. (U-B) CMD Na-rich stars populate a sequence on the red side of the RGB while Na-poor are located on the blue.
The two groups of Na-rich and Na-poor stars are well mixed in the B vs. (B-I) in close analogy with what found by Marino et al. (2008) for M4, (see also Yong et al. 2008).

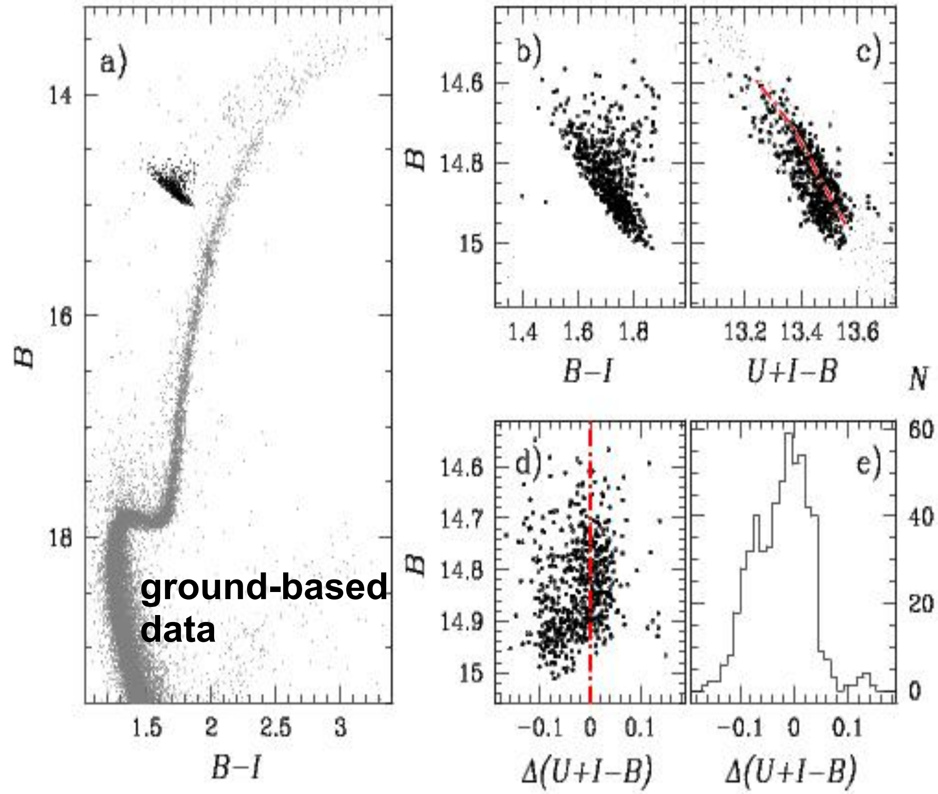




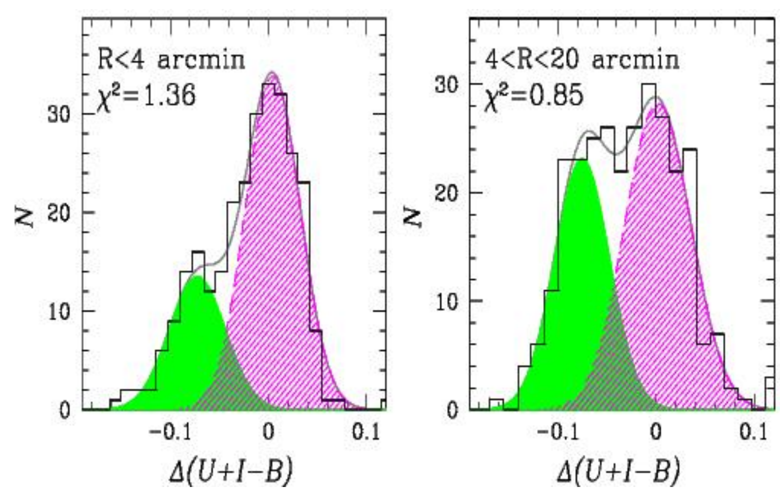
The double red Horizontal-Branch

Both the F275W-F336W vs. F336W-F435W two-colour diagram (from HST data) and the B vs. U+I-B (ground-based photometry) show that **the red HB of 47 Tuc is bimodal.**



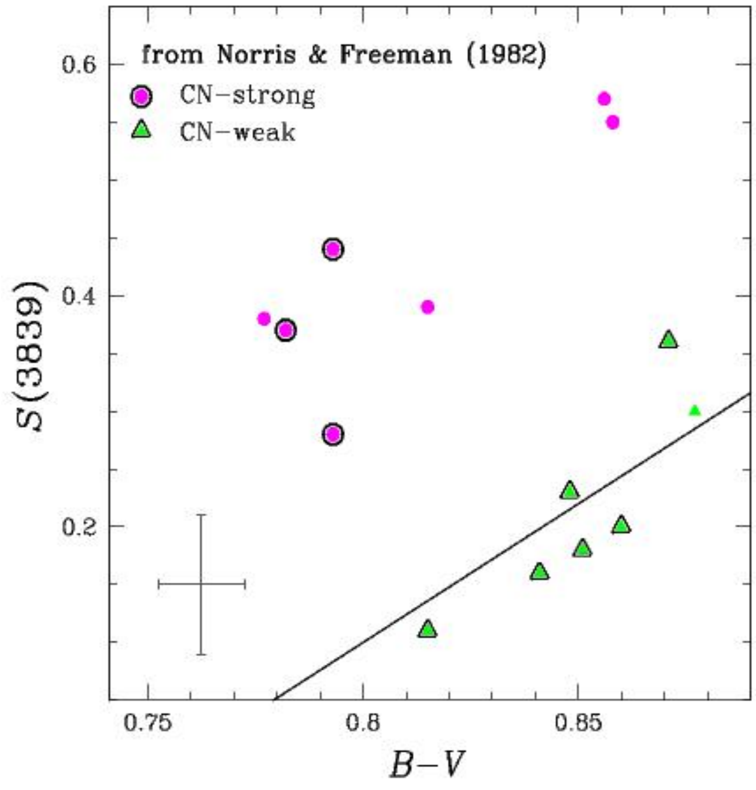


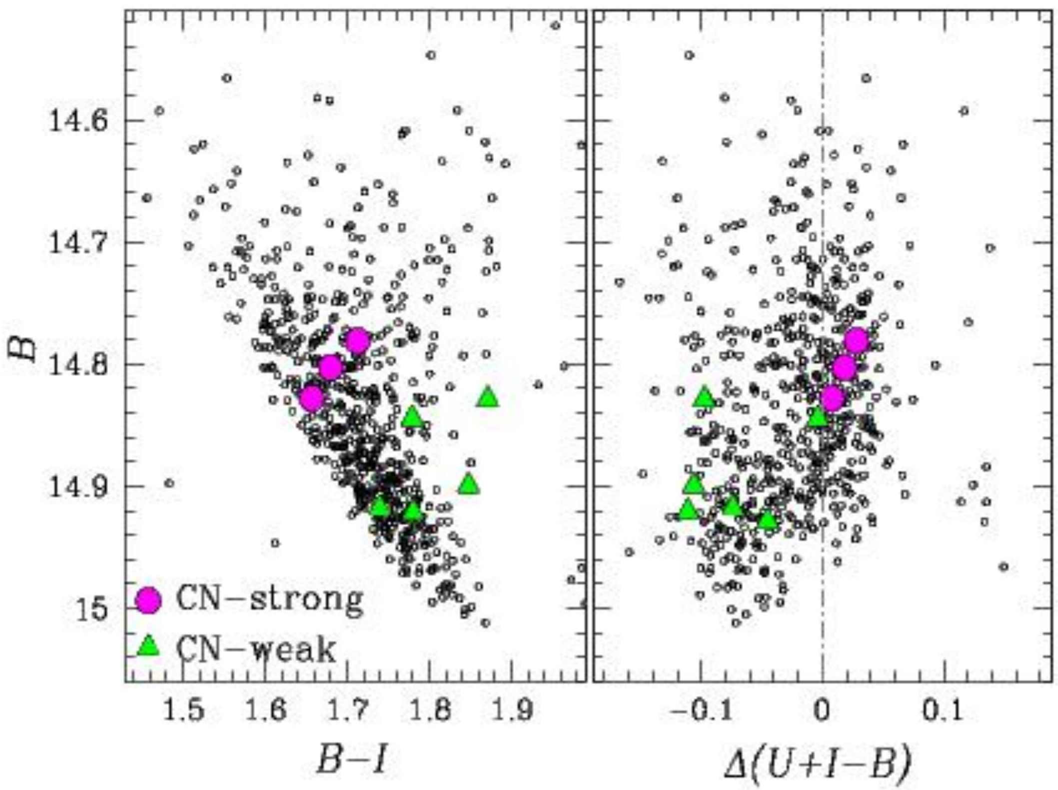
Similarly to the MSb and the RGBb also **the HBb is more centrally concentrated than the HBa.**



The chemical composition of the double red HB

Norris & Freeman (1982) found a bimodal CN-strengths distribution along the red HB, with CN-weak stars fainter than the bulk of red HB stars in the V band.

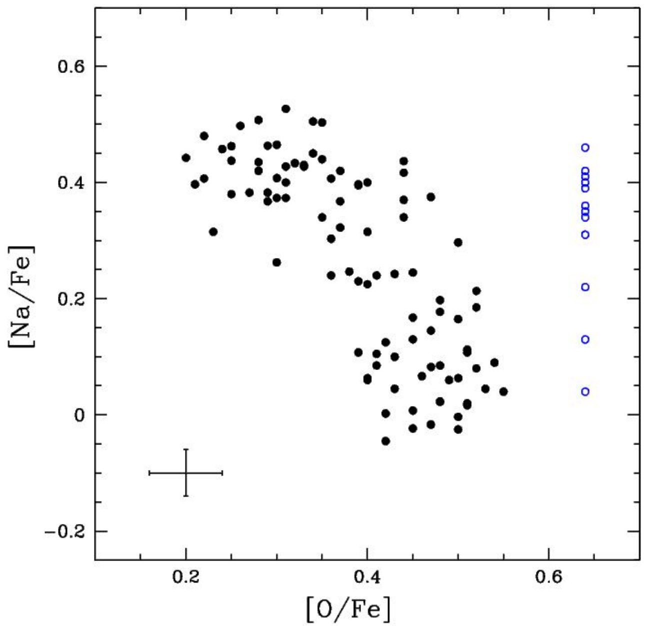




CN-strong stars belong to the HBb and nearly all the CN-poor stars lie on the HBa.

As in the case of the RGB we could associate the two groups of CN-strong and CN-weak stars with the two red HB components.

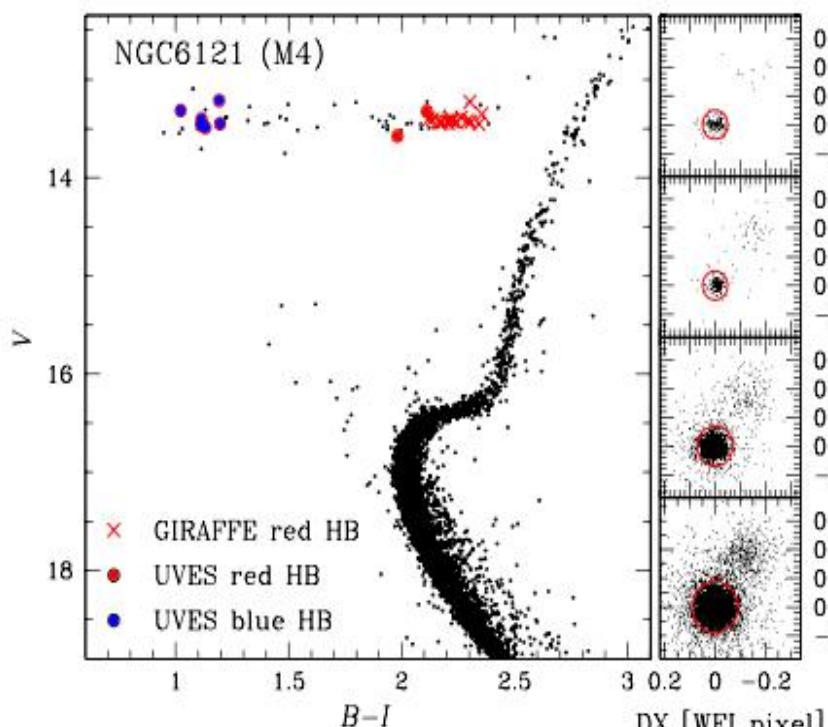
A solution for the second-parameter problem of the HB morphology?

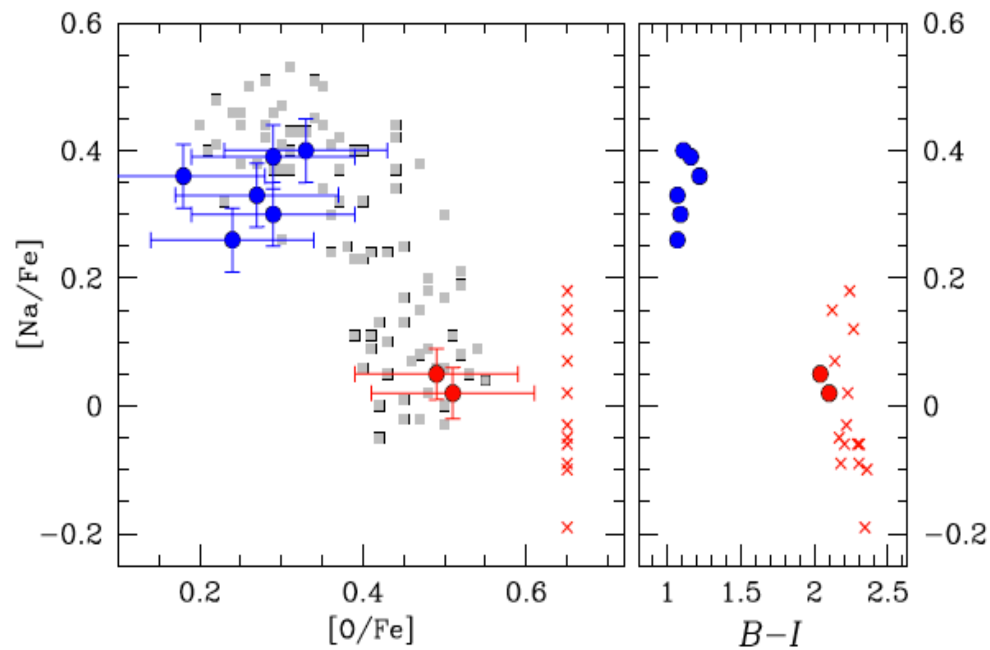


Ivans et al. 1999, AJ, 118, 1273
Marino et al., 2008, A&A 490, 625

The classical second-parameter problem, i.e. the fact that globular clusters with the same metallicity have HB with quite different morphology, still lacks a comprehensive explanation.

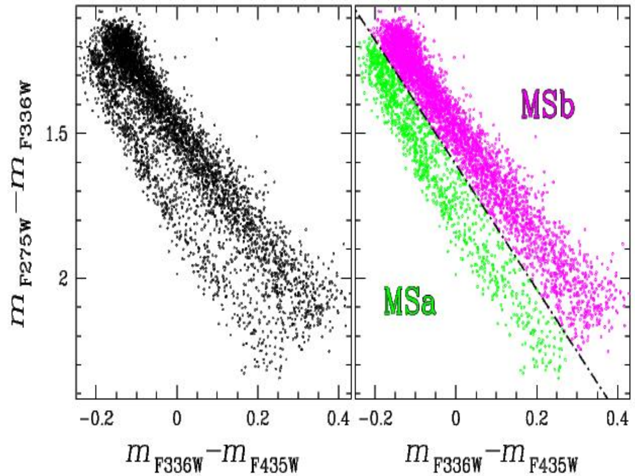
In M4, as well as in 47 Tuc, the two HB segments correspond to the two stellar populations with different N,O,Na,He content. It is very tempting to speculate that, in some clusters, multiple stellar populations are strictly connected with the HB morphology.

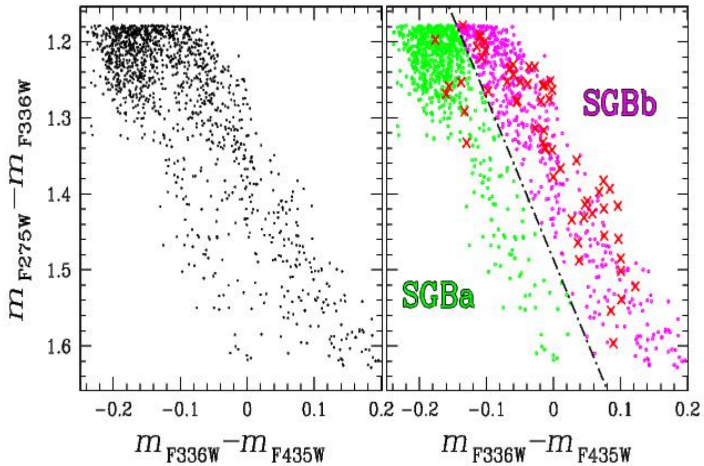


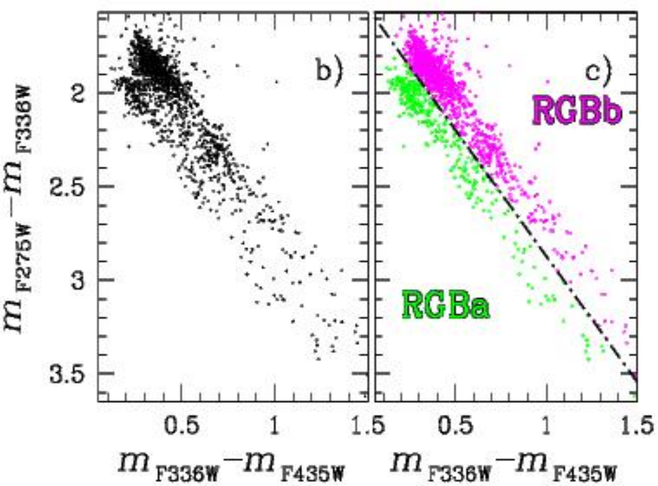


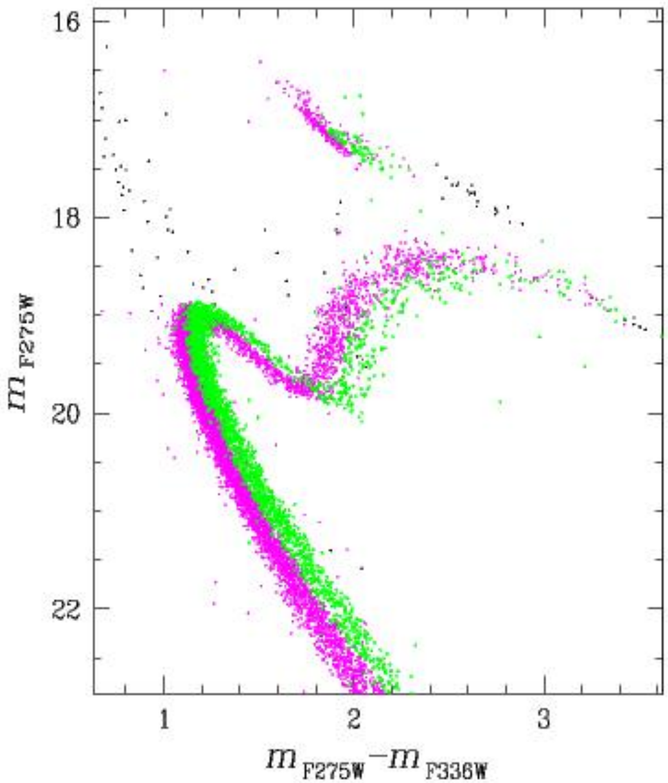
Marino et al., 2011, ApJL, 730, L16

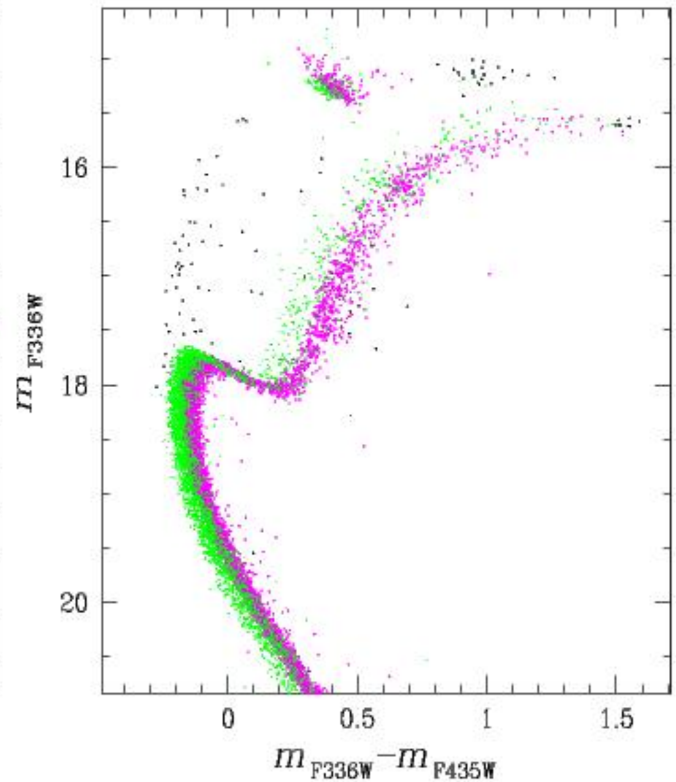
Connecting multiple sequences along the MS, SGB, RGB, and HB

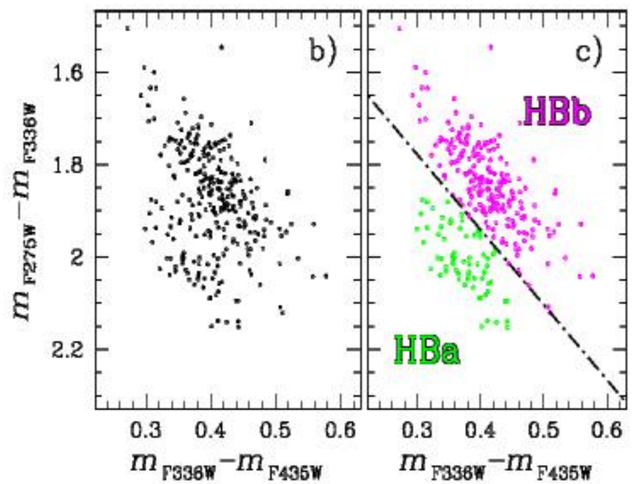








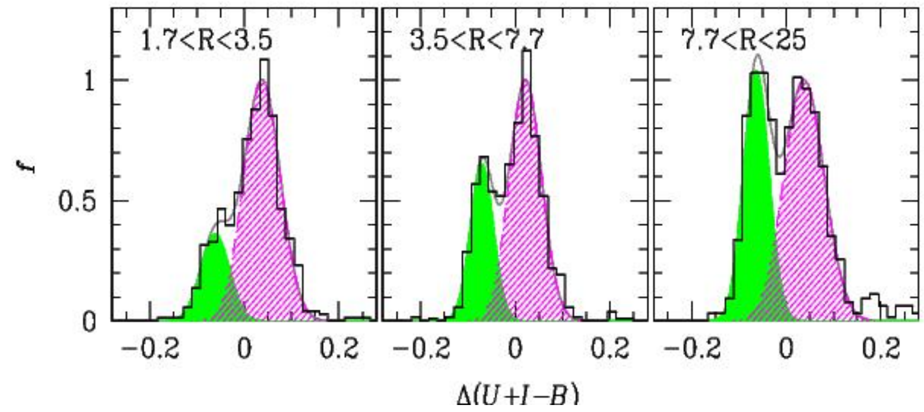


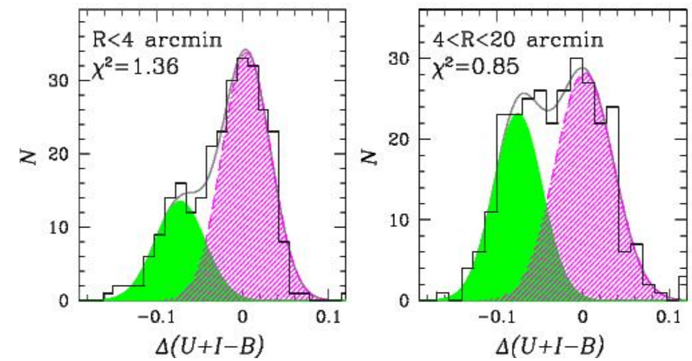


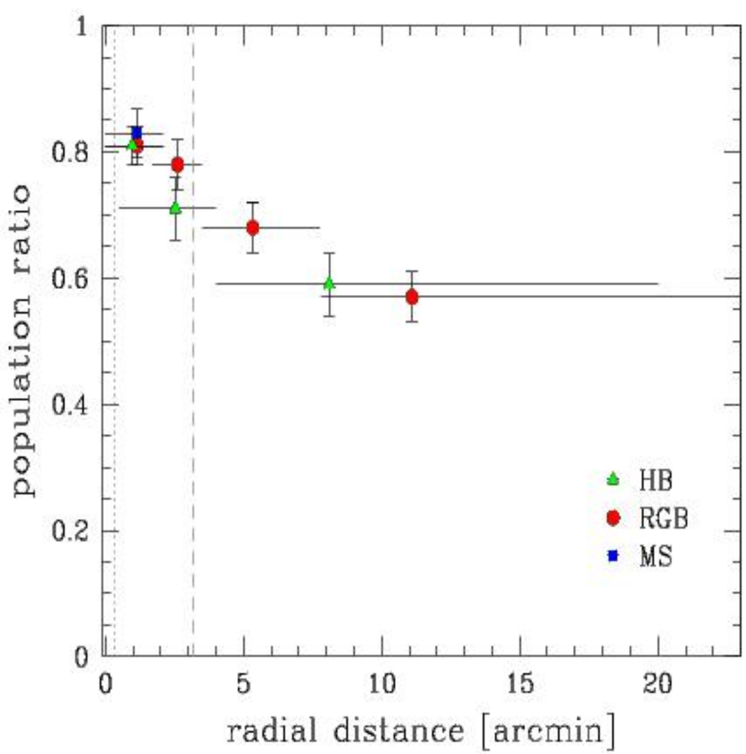
Pop.	color	sequence	Chemical composition	Fraction R<2arcmin	Fraction R>15arcmin
Pop I	green	MSa+SGBa+RGBa+HBa	CN-weak, O-rich, Na-poor,Y~0.25	~20%	~40%
Pop II	magenta	MSb+SGBb+RGBb+HBb	CN-strong, O-poor, Na-rich,Y~0.27	~80%	~60%

The radial distribution of multiple stellar populations

Our photometric analysis confirms that the second stellar population (MSb+SGBb+RGBb+HBb) is more centrally concentrated than the population a. In agreement with spectroscopic results Norris & Freeman (1979) and Briley (1997).



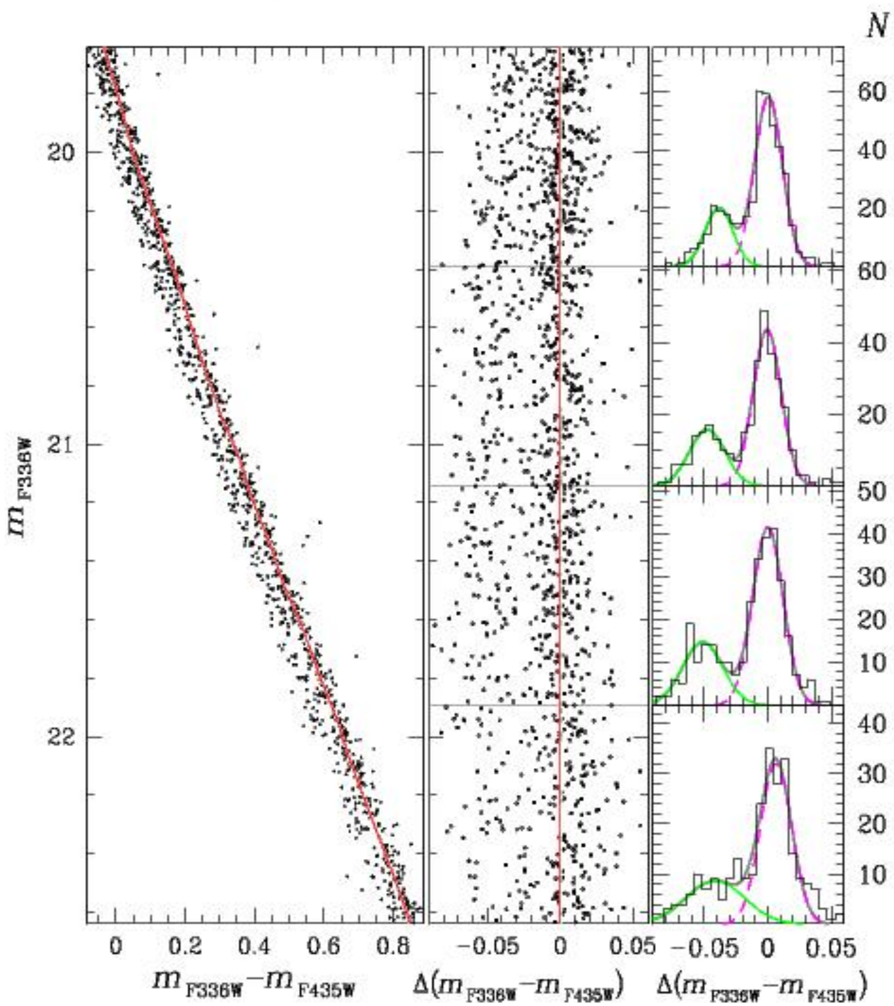


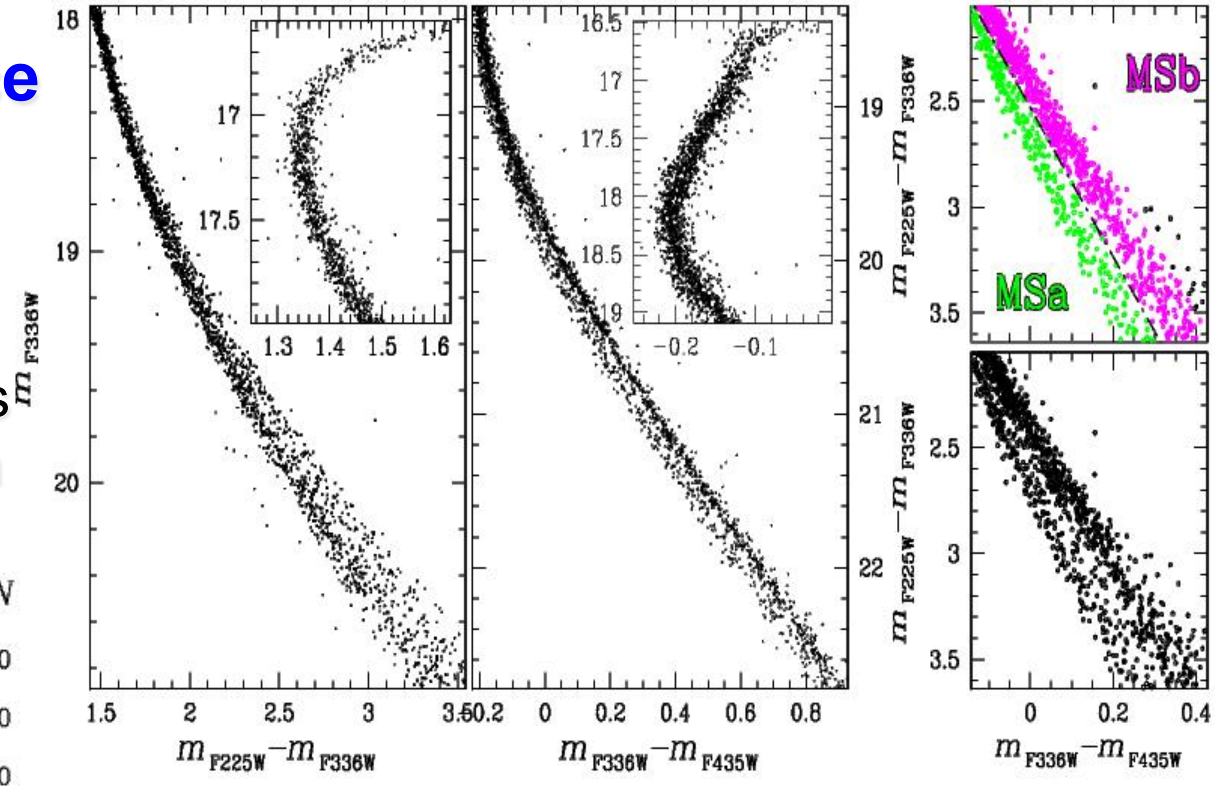


An integration of the a/b population ratio, adopting the appropriate King model, reveals that globally:
the first generation accounts for the 30% of the present-day stellar content of the cluster, while the second generation accounts for the 70% majority share of the cluster.

The double main sequence of NGC 6397

The combination of some UV and visual filters is a powerful tool to separate multiple populations in the CMD and two-colour diagram of globular clusters.





By following the approach used for 47 Tuc we found that the MS of NGC6397 splits into two components made up of the 30% and 70%.

The split is consistent with the presence of two populations: a primordial one that has a composition similar to field stars and a second generation with enhanced Na and N, depleted C and O and a slightly enhanced helium abundance (ΔY~0.01).