First detection of the RGB-bump in the Sagittarius dSph$^{1,2}$

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**ABSTRACT**

We present V, I photometry of the Sagittarius Dwarf Spheroidal galaxy (Sgr) for a region of $\sim 1^\circ \times 1^\circ$, centered on the globular cluster M 54. This catalog is the largest database of stars ($\sim500,000$) ever obtained for this galaxy. The wide area covered allows us to measure for the first time the position of the RGB-bump, a feature that has been identified in most Galactic globular clusters and

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$^1$Based on observations made with the European Southern Observatory telescopes, using the Wide Field Imager, as part of the observing program 65.L-0463. Also based on data obtained from the ESO/ST-ECF Science Archive Facility.

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only recently in a few galaxies of the Local Group. The presence of a single-peaked bump in the RGB differential Luminosity Function confirms that there is a dominant population in Sgr (Pop A).

The photometric properties of the Pop A RGB and the position of the RGB bump have been used to constrain the range of possible ages and metallicities of this population. The most likely solution lies in the range $-0.6 < [M/H] \leq -0.4$ and $4 \text{ Gyr} \leq age \leq 8 \text{ Gyr}$.

Subject headings: galaxies: individual (Sagittarius dwarf spheroidal) — stars: evolution

1. Introduction

The Sagittarius dwarf spheroidal (Sgr dSph) galaxy (Ibata et al. 1994, 1997) is an in vivo example of an accretion/disruption event of a Galactic satellite (Newberg et al. 2002): a process that may have been one of the main mechanisms for the assembly of the Galactic halo (Searle & Zinn 1978; Côté 2000). Hence, the study of the stellar content, star formation history and chemical evolution (see Layden & Sarajedini 2000; Bellazzini et al. 1999; Smecker-Hane & McWilliam 2002, for references) of this disrupting system is a fundamental step in order to reconstruct the evolutionary history of the Milky Way.

As part of a long-term project devoted to understand the origin and the evolution of the building blocks of the Galactic Halo, we present here the first result of a new wide-field V,I photometry of the Sgr in a region ($\sim 1^\circ \times 1^\circ$) around the globular cluster M 54. Almost 500,000 stars have been measured in the area, allowing us to unambiguously identify, for the first time, the RGB-bump in the Sgr. This feature was identified in a relevant number of Galactic globular clusters (Fusi Pecci et al. 1990; Ferraro et al. 1999; Zoccali et al. 1999) and only in a few galaxies in the Local Group: Sculptor (Majewski et al. 1999), Sextans (Bellazzini et al. 2001) and Ursa Minor (Bellazzini et al. 2002).

The RGB-bump magnitude is mainly driven by the metal content and, to a lesser extent, by the age of the population. In this Letter we use this feature to constrain the metallicity and age of the main stellar population in the Sgr galaxy (Pop A). Such constraints are particularly useful in the case of the Sgr dSph, where the strong foreground contamination makes a clear-cut interpretation of the Color Magnitude Diagram (CMD) more difficult (see Bellazzini et al. 1999; Layden & Sarajedini 2000, hereafter B99 and LS00, respectively) and where some inconsistency between the photometric and spectroscopic metallicity estimates has emerged (Cole 2001; Bonifacio et al. 2000; Cseresnjes 2001; Smecker-Hane & McWilliam ...
2. Observations and results

The data presented here consist of a sample of images obtained at the 2.2m ESO/MPI telescope at la Silla, Chile, using the Wide Field Imager (WFI), a mosaic of eight 2048×4096 pixels CCD arrays. The scale is 0.238″/px, giving a total field of view of ∼ 34′ × 33′. A set of V and I images in the vicinity of the Globular Cluster M 54 were secured during an observing run on 7-8 July 2000, with typical exposure times ranging from 10 to 400 sec. To complement this data-set, we retrieved a set of public WFI images from the ESO/ST-ECF Science Archive Facility. The public data were originally obtained in the framework of the ESO pre-FLAMES survey, covering a wide region of ∼ 1° × 1° around M 54.

The entire data-set was homogeneously treated: in short, the raw images were corrected for bias and flat-field using standard IRAF\(^3\) procedures, within the noao.mscred package. The relative photometry was performed with the Point Spread Function (PSF) fitting package DoPhot (Schechter et al. 1993). The stars were searched independently on each image using a spatially variable PSF. We used the large overlapping regions between adjacent WFI pointings to transform the instrumental magnitudes into a homogeneous system, eventually correcting for the zero-point differences between chips and obtaining a final catalog of homogeneous magnitudes and coordinates. Finally, the photometric calibration was performed using more than 1000 stars in common with the Sarajedini & Layden (1995) catalog (hereafter SL95).

The \((V, V − I)\) CMD for ∼493,000 stars measured in the global field of view is shown in Figure 1. At least three main populations can be distinguished:

\(i\) the RGB of the Sgr’s metal-rich population at the red side of the diagram, extending to a very red color, \((V − I) \sim 2.7\), with the corresponding, well populated red HB clump at \(V \sim 18.22\). The RGB bump of the Sgr can easily be seen as a clump of stars along the RGB at \(V \sim 18.5\) and \((V − I) \sim 1.2\).

\(ii\) a second, much steeper RGB, barely visible at \((V, V − I) \sim (16.5, 1.3)\), belonging to the much metal-poorer population of M 54. Its blue HB is clearly seen at \((V, V − I) = (18.2, 0.2)\).

\(^3\)IRAF is distributed by the National Optical Astronomy Observatories, which is operated by the association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.
(iii) the field population, a nearly vertical sequence around $V - I = 0.8$ and, at slightly redder colors ($V-I \sim 1.1$), the evolved Milky Way bulge/disk stars.

The photometric properties of the Sub Giant Branch and Main Sequence Turn Off (TO) region (at $V \sim 21.5$) will be discussed in a forthcoming paper.

3. The RGB-bump

The so-called *RGB-bump* is an evolutionary feature predicted by the theoretical models of stellar evolution (Thomas 1967; Iben 1968). The physical origin of the RGB-bump is well known: in the stellar interior during the first ascent of the giant branch, the H-burning shell is moving constantly outwards until it reaches the discontinuity in the H radial profile, left by the innermost penetration of the convective envelope inside the star. At the discontinuity, the luminosity of the star drops for a while, until the shell adapts to the new environment, and then it rises again in a regime of constant H content. Observationally, the RGB-bump appears as a peak in the differential luminosity function (LF), due to the non-monotonic evolution of the star in luminosity. It appears also as a jump and a change in slope of the integrated LF, due to the change in the evolutionary rate, caused by the sudden change of molecular weight of the material in which the H-burning shell is moving. According to Fusi Pecci et al. (1990), the change in the slope of the integrated luminosity function is the safest way to identify the location of the bump, since it makes use of stars contained in several magnitude bins (see also Ferraro et al. 1999, F99 hereafter).

Since its first detection in 47 Tuc (King, Da Costa, & Demarque 1984), the RGB-bump has been identified in many globular clusters (see Fusi Pecci et al. 1990; Ferraro et al. 1999; Zoccali et al. 1999), and only recently in a few Local Group dwarf galaxies (Majewski et al. 1999; Bellazzini et al. 2001, 2002). In complex stellar populations, such as galaxies, the RGB-bump appears sometimes as a double-peaked feature in the differential LF (see the case of Sculptor and Sextans). Since the RGB-bump magnitude depends on the metal content and age of the population (F99), the double-peak has been interpreted as a signature of the existence of two main stellar populations in the galaxy stellar mix (Majewski et al. 1999; Bellazzini et al. 2001).

In Figure 2, we show the differential (lower panel) and cumulative (upper panel) luminosity functions for the RGB of Sgr, selected from Figure 1. As can be seen, more than 5000 stars have been counted along the brighter ($V < 19$) portion of the Sgr RGB. The RGB-bump is clearly identified in both panels of figure 2: it is located at $V^{\text{bump}} = 18.55 \pm 0.05$. *This is the first detection of such a feature in the Sgr dSph.* In the simplest scenario the
presence of a single-peaked bump in the differential LF suggest the existence of a dominant stellar population, relatively homogeneous in metallicity and age, in the inner regions of the Sgr galaxy\(^4\) (Marconi et al. 1998; Bellazzini et al. 1999; Cacciari, Bellazzini & Colucci 2001; Dolphin 2002).

4. Boxing the metallicity and age of the Sgr main population

Several authors (Marconi et al. 1998; Bellazzini et al. 1999; Layden & Sarajedini 2000) have found evidence that the dominant population (Pop A, in the nomenclature introduced by Bellazzini et al. 1999) in the central part of Sgr is similar to the globular cluster Terzan 7 (a member of the Sgr galaxy), i.e., significantly younger than the typical Galactic globular but still several Gyr old (Buonanno et al. 1995).

A first hint on the metal content of Pop A can be obtained by comparing the position and the shape of the Sgr RGB with the ridge lines of a set of template globular clusters. Such a comparison, in the \((I, V - I)\) and in the \((K, V - K)\) planes, is shown in Figure 3. The \((K, V - K)\) CMD has been obtained by combining the catalog presented here with the Two Micron All Sky Survey (2MASS)\(^5\) J,H,K\(_S\) dataset. We used the color transformations computed by Carpenter (2001) to convert the 2MASS magnitudes into the standard system (Elias et al. 1982). The comparison with the mean ridge lines of three reference globulars of different metallicity (NGC4590, 47Tuc, and NGC6528 from Ortolani et al. 1995; Saviane, Rosenberg, Piotto, & Aparicio 2000; Walker 1994, respectively) is shown in Figure 3. In both planes the ridge line of 47 Tuc ([M/H] \(\approx -0.6\)) reproduces well the RGB of Pop A.

Now, we can use the RGB-bump to obtain an additional, independent estimate of the mean metallicity of Pop A. In particular, we use the reddening-free and distance-independent parameter \(\Delta V_{HB}^{bump}\) (see F99), namely the difference between the V magnitude of the RGB-bump and the Zero Age Horizontal Branch (ZAHB) level. To evaluate \(V_{ZAHB}\) we followed the procedure described in details in F99: we found \(V_{ZAHB}=18.33 \pm 0.07\) and finally \(\Delta V_{HB}^{bump} = 18.55 - 18.33 = 0.22 \pm 0.10\). Using the F99 database, we obtain a relation for the global metallicity as a function of \(\Delta V_{HB}^{bump}\):

\[
[M/H] = -0.522(\Delta V_{HB}^{bump})^2 + 1.115\Delta V_{HB}^{bump} - 0.862
\]

\(^4\)It is important to recall that the present analysis refers to the center of the Sgr dSph, since a significant population gradient is present in this galaxy. The outer region hosts a more metal poor dominant population (see B99, LS00, Alard 2001, and references therein).

\(^5\)See: http://www.ipac.caltech.edu/2mass
From this equation we obtain \([M/H] = -0.64 \pm 0.12\) for Pop A in the Sgr dSph.

The similarities between the Sgr Pop A and 47 Tuc allow us to perform a more detailed differential comparison between these two populations. In doing this, we found that the RGB-bump of Pop A is significantly brighter than that of 47 Tuc by \(\Delta V_{bump}^{47\text{Tuc} - \text{Sgr}} = 0.12 \pm 0.07\) mag. The result is confirmed by the comparison of the \(\Delta V_{bump}^{47\text{Tuc} - \text{Sgr}}\) above with the \(\Delta V_{bump}^{47\text{Tuc}} = 0.33 \pm 0.1\) listed by F99 for 47 Tuc, giving \(\Delta V_{bump}^{47\text{Tuc} - \text{Sgr}} = 0.11 \pm 0.15\) mag. If the metallicity of the two populations is the same, then such a difference in the RGB-bump position corresponds to an age difference of \(\approx 5\) Gyr (since \(\Delta M_{bump}^{V} / \Delta t(\text{Gyr}) = 0.024\), Cassisi & Salaris (1997)), Pop A being younger than 47 Tuc. This finding is in excellent agreement with the results obtained by B99 and LS00 from the study of the Main Sequence Turn Off (TO) of the Sgr galaxy.

On the other hand, since at a fixed metallicity a younger age implies bluer RGB colors, we have to conclude that the mean metallicity of Pop A should be higher than that of 47 Tuc (see, e.g. Cole 2001). This is in good agreement with the most recent spectroscopic measures: eight of the fourteen Sgr stars observed by Smecker-Hane & McWilliam (2002) have \(-0.6 \leq [Fe/H] \leq -0.3\) and \(< [\alpha/Fe] >\approx 0.0\) (hence \([Fe/H] = [M/H]\)). Since it is reasonable to assume that these stars are representative of Pop A, we can deduce that the mean metallicity for this population is \([M/H] \leq -0.4\).

As can be seen from Figure 4, by adopting this metallicity the observed \(\Delta V_{bump}^{47\text{Tuc} - \text{Sgr}}\) suggests an age difference of \(\sim 7\) Gyr. In a scale in which the age of 47 Tuc is 12 Gyr (Carretta et al. 2000), the absolute age of Pop A turns out to be \(\sim 5\) Gyr, in good agreement with the results by LS00.

5. Discussion

The growing wealth of independent observational material about the Sgr dSph is beginning to provide a self-consistent view of the properties of this galaxy. For instance, the presence of a metal poor population \((-2.0 \lesssim [Fe/H] \lesssim -1.4)\), first suggested by B99, has been confirmed by further photometric studies (LS00, Cole 2001), by the analysis of the pulsational properties of the RR Lyrae variables (Cseresnjes 2001) and also by the spectroscopic survey by Smecker-Hane & McWilliam (2002). Moreover, the existence of a significant metallicity (and/or age) spatial gradient, with the stars in the outer regions being more metal deficient than those near the center of the galaxy, has been put into evidence by different
authors (B99, LS00 Alard 2001).

Conversely, some reason of concern was provided by the estimate of the mean metallicity of the stellar population that dominates the inner region of the galaxy. While photometric estimates were typically in the range $-1.0 \lesssim [Fe/H] \lesssim -0.5$, the first high-resolution spectra of two member stars by Bonifacio et al. (2000) suggested a much higher metal content ($[Fe/H] \simeq -0.2$). The larger sample provided by the spectroscopic analysis of Smecker-Hane & McWilliam (2002) suggests that, while stars having $[Fe/H] \simeq -0.2$ are indeed present in Sgr, they do not represent the dominant population. The majority of stars in the Smecker-Hane & McWilliam (2002) sample has $[\alpha/Fe] \simeq 0.0$ (and thus $[Fe/H]=[M/H]$) and $-0.6 \leq [Fe/H] \leq -0.3$. Furthermore, previous photometric estimates based on the comparison of the RGB with template globular clusters, neglected the effects of age and the difference in the $\alpha$-elements enhancement, as correctly pointed out by Cole (2001).

In this Letter we have revisited the problem of the metallicity and age of the Sgr main population, taking into account all of the above considerations and adding to the usual photometric metallicity indices (i.e., the position and the shape of the RGB) an additional constraint provided by the position of the RGB-bump. The main results can be summarized as follows:

1. The mere detection of a single-peaked bump in the differential LF of the RGB confirms the existence of a dominant population (Pop A) in the Sgr dSph stellar mix.

2. The Pop A RGB is well fitted by the RGB ridge-line of the globular cluster 47 Tuc, that has $[M/H] \simeq -0.6$. However, a significant difference in the RGB-bump luminosity between Sgr and 47 Tuc has been measured. This fact suggests that Pop A is several Gyr younger than 47 Tuc, in good agreement with previous results based on the comparison of the Main Sequence Turn Off’s (B99, LS00). Hence, $[M/H] \simeq -0.6$ has to be considered as a lower limit to the mean metallicity of Pop A.

3. A full self-consistency among the spectroscopic and photometric constraints (including the RGB-bump) is achieved if a mean metallicity of $-0.6 < [M/H] \leq -0.4$ and a mean age of $7 \geq age \geq 4$ Gyr are assumed for Pop A, in good agreement with the results by LS00. Ages younger than $\sim 4$ Gyr are excluded by the observed morphology of the TO (see Figure 11 by B99 and Figure 16 by LS00). The detailed discussion of this region of the CMD will be the subject of a forthcoming paper in preparation.

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REFERENCES

Alard, C. 2001, A&A, 377, 389
Bellazzini, M., Ferraro, F. R.; Buonanno, R. 1999, MNRAS, 307, 619 (B99)
Bellazzini, M., Ferraro, F. R., Pancino, E. 2001, MNRAS, 327, L15
Bellazzini, M., Ferraro, F. R., Origlia, L., Cacciari, C., Pancino, E., Monaco, L., Oliva, E. 2002, AJ, submitted
Bonifacio, P., Hill, V., Molaro, P., Pasquini, L., Di Marcantonio, P., & Santin, P. 2000, A&A, 359, 663
Buonanno, R., Corsi, C. E., Pulone, L., Pecci, F. F., Richer, H. B., & Fahlman, G. C. 1995, AJ, 109, 663
Cacciari, C., Bellazzini, M. & Colucci, S., 2001, in Extragalactic Star Clusters, IAU Symp. 207, E.K. Grebel, D. Geisler and D. Minniti Eds., S. Francisco: ASP, in press (astro-ph/0106013)
Carpenter, J. M. 2001, AJ, 121, 2851
Carretta, E., Gratton, R. G., Clementini, G., & Fusi Pecci, F. 2000, ApJ, 533, 215
Cassisi, S. & Salaris, M. 1997, MNRAS, 285, 593
Cole, A. A. 2001, ApJ, 559, L17
Côté, P., Marzke, R.O., West, M.J., & Minniti, D., 2000, ApJ, 533, 869
Cseresnjes, P. 2001, A&A, 375, 909
Dean, J.F., Warren, P.R., & Cousins, A.W., 1978, MNRAS, 183, 569
Dolphin, A. E. 2002, MNRAS, 332, 91
Elias, J. H., Frogel, J. A., Matthews, K., & Neugebauer, G. 1982, AJ, 87, 1029
Ferraro, F. R., Messineo, M., Fusi Pecci, F., de Palo, M. A., Straniero, O., Chieffi, A., Limongi, M. 1999, AJ, 118, 1738

Ferraro, F.R., Montegriffo, P., Origlia, L., & Fusi Pecci, F., 2000, AJ, 119, 1282

Fusi Pecci, F., Ferraro, F. R., Crocker, D. A., Rood, R. T., Buonanno, R. 1990, A&A, 238, 95

Ibata, R. A., Gilmore, G., & Irwin, M. J. 1994, Nature, 370, 194

Ibata, R. A., Wyse, R. F. G., Gilmore, G., Irwin, M. J., & Suntzeff, N. B. 1997, AJ, 113, 634

Iben, I. Jr. 1968, Nature, 220, 143

King, C. R., Da Costa, G. S., & Demarque, P. 1984, BAAS, 16, 529

Layden, A.C. & Sarajedini, A. 2000, AJ, 119, 1760 (LS00)

Majewski, S. R., Siegel, M. H., Patterson, R. J., & Rood, R. T. 1999, ApJ, 520, L33

Marconi, G., Buonanno, R., Castellani, M., Iannicola, G., Molaro, P., Pasquini, L., & Pulone, L., 1998, A&A, 330, 453

Newberg, H. J. et al. 2002, ApJ, 569, 245

Ortolani, S., Renzini, A., Gilmozzi, R., Marconi, G., Barbuy, B., Bica, E., & Rich, R. M. 1995, Nature, 377, 701

Rosenberg, A., Piotto, G., Saviane, I., Aparicio, A. 2000, A&AS, 144, 5

Sarajedini, A. & Layden, A. C. 1995, AJ, 109, 1086

Savage, B. D. & Mathis, J. S. 1979, ARA&A, 17, 73

Saviane, I., Rosenberg, A., Piotto, G., & Aparicio, A. 2000, A&A, 355, 966

Searle, L. & Zinn, R. 1978, ApJ, 225, 357

Shechter, P., Mateo, M., & Saha, A. 1993, PASP, 105, 1342

Smecker-Hane, T. A., & McWilliam, A., 2002, ApJ, submitted (astro-ph/0205411)

Thomas, H.-C. 1967, Z. Astrophys, 67, 420

Walker, A. R. 1994, AJ, 108, 555
Zoccali, M., Cassisi, S., Piotto, G., Bono, G., & Salaris, M. 1999, ApJ, 518, L49

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Fig. 1.— Color-magnitude diagram of 493,000 stars in the Sgr dSph, covering a region of about $1^\circ \times 1^\circ$ around the globular cluster M 54. Three main populations, i.e., the field stars, M 54 and the Sgr, are clearly visible.
Fig. 2.— Differential (lower panel) and cumulative (upper panel) luminosity functions for the stars selected in the region of the RGB of the Sgr. The arrows indicate the location of the RGB-bump at $V=18.55\pm0.05$. 

$log(\Sigma \Phi_{\text{RGB}})$

$\Phi_{\text{RGB}}$

$V$
Fig. 3.— Color-magnitude diagrams in the absolute $M_I$ vs $(V-I)_0$ (left panel) and $M_K$ vs $(V-K)_0$ (right panel) planes. We adopted the distance and reddening estimates by LS00, and the reddening laws by Dean, Warren & Cousins (1978) for the V and I passbands, and by Savage & Mathis (1979) for the infrared colors. The ridge-lines of three template globular clusters of different metallicities are overplotted (see text for references). The assumed reddening and distance moduli for these clusters are from F99.
Fig. 4.— The observed difference in magnitude between the RGB-bump in the Sgr Pop A with respect to 47 Tuc is plotted as a large filled dot. The solid lines are theoretical isochrones computed using equation 3 by F99, for various age differences. A global metallicity of $[M/H] = -0.6$ and an age of 12 Gyr was assumed for 47 Tuc.