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The Sagittarius Dwarf Galaxy Survey (SDGS): Constraints on the Star Formation History of the Sgr dSph

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Abstract. The main characteristics of a wide photometric survey of the Sgr dwarf spheroidal galaxy are briefly presented. V and I photometry has been obtained for ~90 000 stars toward Sgr and for ~9 000 stars in a region devoid of Sgr stars (for decontamination purposes).

The full potential of this large database is far from being completely explored. Here we present only preliminary results from the analysis of statistically decontaminated Color Magnitude Diagrams, trying to set a scheme of the Star Formation History of the Sgr Galaxy. A scenario is proposed in which star formation in Sgr began very early and lasted for several Gyr, with progressive chemical enrichment of the Inter-Stellar Medium (ISM). Nearly 8 Gyr ago the star formation rate abruptly decreased, perhaps in coincidence with the event that led to the gas depletion of the galaxy. A very small rate of star formation continued until relatively recent times (~ 1 Gyr ago).

1. Introduction

The Sagittarius Dwarf Spheroidal galaxy (Sgr dSph) is the nearest Milky Way satellite. The detailed study of this stellar system can potentially provide important insights on topics ranging from the evolution of dwarf galaxies to the formation of the Milky Way halo (see Ibata et al. 1997 and Bellazzini, Ferraro & Buonanno 1998, for details and references).

Despite its relative nearness, the Sgr dSph represents a noticeable challenge from an observational point of view because of its very low surface brightness (one needs to sample wide fields to adequately populate the brightest part of the Color-Magnitude Diagram (CMD)) and because of the strong contamination by foreground stars from the Milky Way bulge and disk (statistical decontamination of the CMD is necessary).

In an attempt to overcome both problems we planned a large photometric survey of the galaxy. Three large ($9' \times 35'$) fields placed in different regions of the Sgr dSph have been observed in the V and I passbands. Calibrated photometry has been obtained for nearly 90 000 stars in these fields. An additional ~ 8 000

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stars have been observed in a control field devoid of Sgr stars, for statistical decontamination purposes. Observations have been carried out at the ESO-NTT and data have been reduced with the ROMAFOT package.

In Table 1 the main characteristics of the observed fields are reported[1]. The best photometric quality has been achieved for the SGR34 and SGRWEST fields. The limiting magnitude for these fields is around $V \sim 23$ while in the case of the SGR12 and GAL fields it is some 1 mag brighter. The GAL field samples the foreground population at the same galactic latitude as SGR12 but outside the body of the Sgr dSph. Deeper (V, I) photometry of the GAL region has been obtained by Mateo et al. (1995: MUSKKK) and has been adopted as the final control field sample for decontamination of the faintest part of our CMDs.

Table 1. Names and positions of SDGS Fields.

Name	l^o	b^o	Field Size	$N_\star$
SGR34	6.5	-16	$35' \times 9'$	22603
SGR12	6	-14	$35' \times 9'$	25793
SGRWEST	5	-12	$35' \times 9'$	41462
GAL	354	-14	$21' \times 9'$	8336

A deep analysis of the obtained CMDs has been performed before attempting statistical decontamination and a first paper dealing with distance, reddening, degree of foreground contamination in the various fields and many other topics has been submitted (Bellazzini, Ferraro & Buonanno 1998, hereafter PAP-I). For the present purposes it is useful to recall two of the results of PAP-I, i.e. (1) the reddening differences between the various SDGS fields are tiny and (2) there is evidence for the presence of a population as metal poor as $[Fe/H] = -2.0$ associated with the Sgr dSph.

Here we just present preliminary results from the analysis of the statistically decontaminated CMDs of the SGR34 and SGR12 fields, providing some constraint on the age and metallicity distribution of Sgr stars and proposing a general scheme for the Star Formation History (SFH) in this galaxy.

2. Metallicity

Comparing the RGB stars distribution (from decontaminated CMDs) with ridge lines from template globular clusters, it is concluded that the stars belonging to the main population of the Sgr dSph span a wide metallicity range (more than 1 dex), from $[Fe/H] \sim -2.0$ to $[Fe/H] = -0.7$, the bulk of the stars having $-1.3 < [Fe/H] < -0.7$. Probably a few stars more metal rich than $[Fe/H] = -0.7$ are present in the SGR12 field, confirming previous claims of a small metallicity gradient toward the Sgr center of density (Sarajedini & Layden 1995; Marconi et al. 1998).

[1] The original CMDs are not presented in the written version of the contribution, because of the limited space available.

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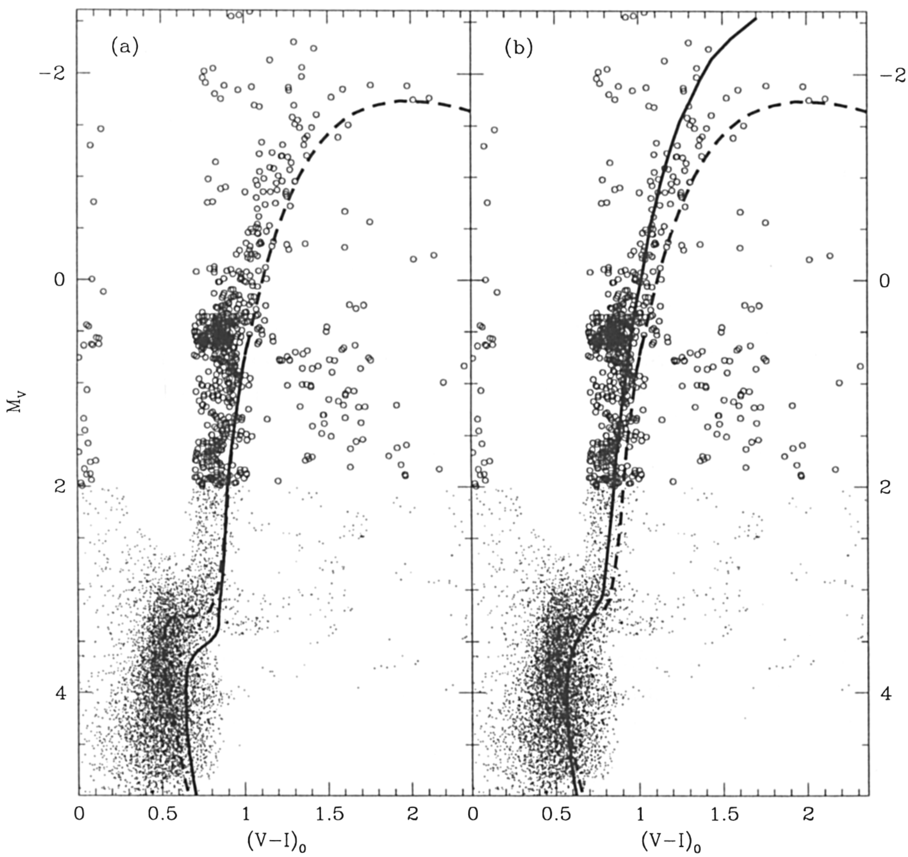

Figure 1. The decontaminated CMD of the SGR34 field is reported in both panels. Two different kind of symbols have been adopted to represent stars brighter than $M_V = 2$ (open circles) and stars fainter than $M_V = 2$ (tiny points), in order to let the superposed ridge lines remain visible despite the large number of stars present in the TO region. In panel (a) the ridge lines of 47 Tuc (continuous line; classical old globular with [Fe/H] = −0.7) and of Pal 1 (dashed line; the same metallicity as 47 Tuc but $\sim$ 4 Gyr younger) are also reported). From this panel it can be concluded that the more metal rich stars in the SGR34 region are significantly younger than 47 Tuc and have an age similar to Pal 1, whose ridge line provides an excellent fit of the TO region. The continuous ridge line reported in panel (b) is that of M3 (old and with [Fe/H] = −1.3), also consistent with the observed CMD of the TO region. It can be noted that the two reported ridge lines [M3 and Pal 1 (dashed line)] provide a global fit to the observed CMD, simultaneously reproducing the TO region and the broad RGB.

3. A Possible SFH for the Sgr dSph

The decontaminated CMD of the SGR34 field is shown in Fig. 1. The obvious "globular cluster-like" features are typically associated with an intermediate-old main population (MUSKKK; Marconi et al. 1998). Hereafter we will refer to this component as Sgr Pop A. The sparse Blue Plume of stars around $M_V \sim 3$ and $(V - I)_0 \sim 0.3$ is usually interpreted as an extended Main Sequence associated with more recent star formation episodes[2] (hereafter, Sgr Pop B).

Till now, the standard way to deal with the age of Sgr Pop A was to assign an average metallicity to the population and then derive an age via isochrone fitting of the Turn-Off (TO) region. The present day data are consistent with a single TO point (or, at least, with few slightly different and unresolved TO points superposed in the same CMD region). Stellar evolution teaches us that populations of different metallicity can share a common TO point only if they differ also in age, in the sense that more metal rich populations have to be younger (i.e., the usual sense of any well-behaved age-metallicity relation). We propose this kind of solution for the SFH of Sgr Pop A as the most likely from many points of view (see Bellazzini, Ferraro & Buonanno 1999). This is the first attempt to provide a global fit to both the TO region and the broad RGB of the Sgr CMD.

In panel (a) of Fig. 1 the ridge lines of 47 Tuc (from Kaluzny et al 1998; continuous line) and of Pal 1 (from Rosenberg et al 1998a; dashed line) are superposed on the observed CMD. The two clusters have the same metallicity ([Fe/H] = -0.7; Rosenberg et al 1998b) but Pal 1 is younger than 47 Tuc by $\sim$ 4 Gyr. While the ridge line of 47 Tuc clearly does not fit the TO region of Sgr an excellent fit is provided by Pal 1. At present, this is the best fit to the whole Sgr CMD based on empirical $(V, V - I)$ ridge lines. It is concluded that the more metal rich stars in SGR34 are significantly younger than 47 Tuc and have nearly the same age as Pal 1. However the ridge line of Pal 1 can't provide, obviously, a satisfying fit to the broad RGB of the Sgr galaxy, a more metal poor component is also needed.

The continuous line reported in panel (b) is the ridge line of the globular cluster M3 (a classical old globular with [Fe/H] = -1.3; Ferraro et al. 1997), while the dashed line is (again) the Pal 1 ridge line. The M3 ridge line is not inconsistent with the observed CMD in the TO region and provides a good fit for a number of Sgr RGB stars. Coupling the two ridge lines a (qualitative) simultaneous fit of all the observed characteristics of the CMD of Pop A is provided[3]. The comparisons shown in Fig. 1 strongly suggest that a spread in age is coupled with the observed metallicity spread.

The same scheme can be checked through comparison with theoretical isochrones, as shown in Fig. 2. The dashed lines superposed on the CMD of the SGR34 field are isochrones of ([Fe/H] = -1.3; age = 12 Gyr) and

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[2]This interpretation is mainly based on the detection of Carbon stars in Sgr, taken as a clear signature of the presence of young stars. However, a significant fraction of the stars in the Blue Plume can well be genuine Blue Straggler stars (see PAP-I).

[3]The ridge line of Ter 8 (old and with [Fe/H] = -2.0; not shown here) is also consistent with the observed TO and fits the bluest RGB stars in the SGR34 CMD

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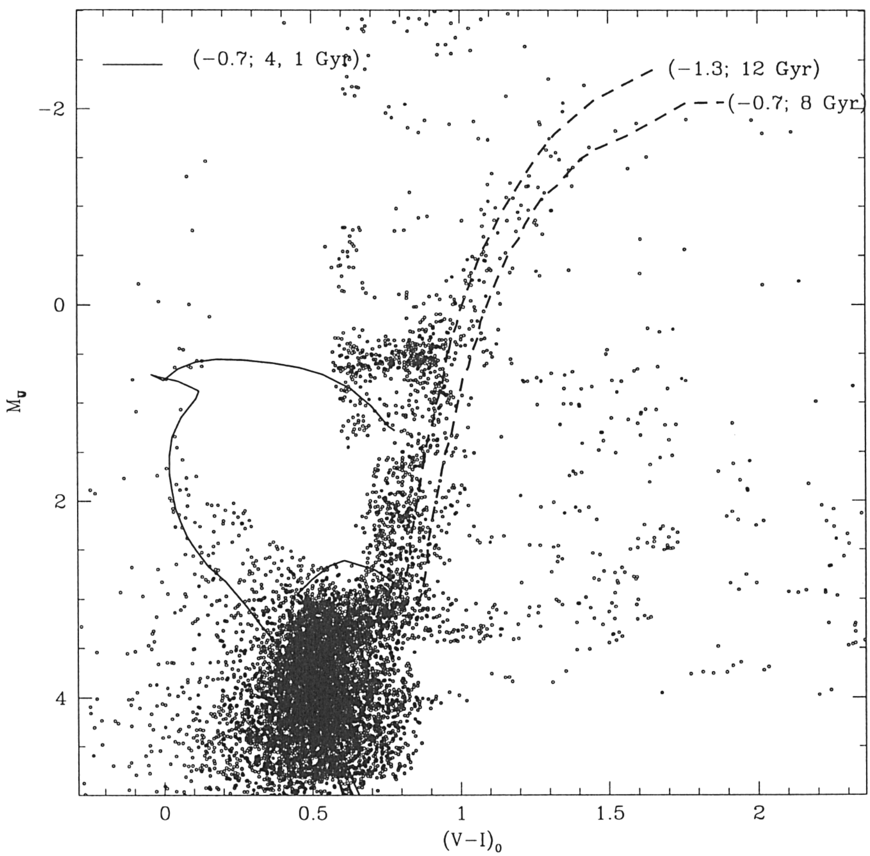

Figure 2. Decontaminated CMD of the SGR34 field. Dashed lines are "old" isochrones, fitting the main population (Pop A). Age (in Gyr) and [Fe/H] values are indicated in parenthesis. Continuous lines are (from left to right) a 1 Gyr isochrone and a 4 Gyr isochrone at [Fe/H] = −0.7, bracketing the Blue Plume stars distribution. All the reported isochrones are from Bertelli et al (1994).

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([Fe/H] = −0.7; age = 8 Gyr) respectively (see caption). Coupling the two, a consistent solution can be found fitting both the TO region and the broad RGB. Adding an ([Fe/H] = −2.0; age = 16 Gyr) isochrone would complete the scheme, providing a satisfying interpretation for all the properties of Pop A: a long-lasting *old* (age > 8 Gyr) star formation event accompanied by progressive chemical enrichment. This SFH scheme is also supported by the Age-Metallicity Relation derived by Montegriffo et al. (1998) for the globular cluster system of the Sgr dSph galaxy.

A clear-cut confirmation of the proposed scheme is not possible at the moment, given the accuracy of the SDGS data at the TO level. However, HST photometry (Mighell et al. 1997) will certainly allow a much more accurate analysis of the TO region, checking the present hypothesis and providing more details of the scenario.

The Blue Plume stars are nicely bracketed between 1 Gyr and 4 Gyr isochrones, both at [Fe/H] = −0.7. The adoption of higher metallicity isochrones would have only the effect of shifting the age range of Pop B to younger ages. It is concluded that major star formation in the Sgr dSph suddenly stopped several Gyr ago (Pop A), while more marginal episodes lasted until recent times (Pop B provides less than 10% of the whole Sgr dSph stellar content; PAP-I).

The proposed scheme can be applied to all the observed regions of the galaxy, since the stellar content is found to be remarkably homogeneous over the whole sampled scale ($\sim$ 3.5 kpc along the major axis).

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Discussion

Mighell: I would like to note that there will be no single main-sequence turnoff point for a dwarf spheroidal galaxy like Sagittarius which has a long star formation history and a large metallicity spread. In general, one must be very careful when applying standard globular cluster analysis techniques to dwarf galaxies with complex star formation histories.

Bellazzini: There could be a single turnoff, as I showed you before, if you assume the "right" coupling between age and metallicity. However, I'm not saying that the turnoff is singular (I've not sufficient resolution). I'm saying that the data are not consistent with a single-age population, given the observed metallicity spread and the observed morphology of the turnoff region. So I'm forced to propose a SFH scheme to provide a consistent fit of the whole CMD. For that purpose, empirical comparisons with template globulars are sufficient and are much more robust and reliable than simulations from evolutionary tracks. Grebel and Tolstoy here have shown us that many uncertainties affect isochrones.

Geisler: The "decontaminated" CMD shows a huge spread at the blue end of the HB. This of course is the region where field star contamination is severe, which is continuous. However, in your subtracted CMD, some regions show significant clumping of stars. Is this real?

Bellazzini: No. They are spurious results from the decontamination process. I can identify most of the spurious features by means that are too lengthy to explain here. You'll find it in the final paper.

Gallart: Do you believe the bright blue stars may be from Sagittarius, implying, therefore, stars of very young age?

Bellazzini: The association of "blue plume" stars with the Sgr galaxy can be reasonably assessed only for stars fainter than $V \sim 19.5$. Stars brighter than this, on the apparent extension of the blue plume, are few, and could well be associated with the field.

van den Bergh: Is there any population component that might be identified with the last passage of SDG through the Galactic plane?

Bellazzini: It is difficult to give a clear-cut answer to this question. However, I showed you that the lower limit for the age of the stars in the blue plume is ~ 1 Gyr, shifting to younger ages if a higher metallicity is adopted. If you compare the former figure with present estimates of the orbital period of the Sgr dSph (~ 0.76 Gyr) you find that they are quite consistent. So it is possible to associate the younger blue plume stars with the last disk passage. The whole blue plume distribution is not inconsistent with a series of bursts triggered by disk passages, from ~ 4 Gyr ago until ~ 1 Gyr ago or even later.

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Terndrup: Your analysis of the age-metallicity relation as you present it was qualitative. Have you performed a quantitative computation of the age-metallicity relation, taking into account, for example, the metallicity spread on the giant branch and the expected relative contribution to the turnoff?

Bellazzini: Not yet, as I said these are preliminary results. However, the reliability of the approach you suggest is somehow lessened in this case by the decontamination process.