A Wide-angle VIMOS Survey of the Sagittarius Dwarf Spheroidal Galaxy

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Using VIMOS in imaging and spectroscopy modes and FLAMES spectroscopy data, we have mapped the Sagittarius dwarf spheroidal galaxy (Sgr dSph) photometrically and spectroscopically over eight fields along the galaxy minor and major axes. We have found, for the first time, striking evidence of multiple populations in the peripheral zones of this near companion of the Milky Way. These data, together with previous analyses of the Sgr dSph core and streams, supply a detailed picture of this galaxy, and will give us the opportunity to reconstruct the history of this object and its influence on the evolution of the Milky Way.

Sagittarius dSph

For many decades two competing scenarios for the formation of the Milky Way (MW) have been presented. In the "monolithic collapse" scenario (Eggen, Lynden-Bell & Sandage, 1962, hereafter ELS) our Galaxy formed quickly through the collapse of an isolated protogalactic cloud. Early star formation populated the Halo and the globular clusters (hereafter GCs), while dynamical friction led the bulk of the gas to form a thin disc. In the competing "hierarchical merging" scenario (Searle & Zinn, 1978, hereafter SZ), the Galaxy would have formed by the coalescence of a large number of substructures over a timescale of many gigayears.

At the moment there is no universally accepted scenario for the formation of the Milky Way, although some progress was made towards a description which, not surprisingly, appears as a compromise between the ELS and SZ models. The Galactic Halo was formed by hierarchical merging of substructures, while the thin and thick Disc components formed as the result of the monolithic infall of a diffuse gaseous component that was ejected from the substructures prior to the merging event.

In 1994 Ibata et al., during a spectroscopic study of the Milky Way Bulge, discovered a new dwarf spheroidal galaxy at only 25 kpc from the Sun, the Sagittarius dSph, hereafter Sgr dSph. This object is orbiting inside the MW Halo with a period of about 1 Gyr, and probably was captured about 10 Gyr ago (Ibata et al., 1997). It was quickly theorised that the Sgr dSph should be in the process of being tidally destroyed by its interaction with the MW, its stellar content being dispersed in the Halo along a massive stellar stream. The stream was indeed observed, and constitutes the most prominent Halo substructure detected by wide field surveys such as the Two Micron All Sky Survey and the Sloan Digital Sky Survey. The Sgr dSph and its stream now constitute the most dramatic evidence (albeit not the only piece) that hierarchical merging processes have contributed heavily to the build up of the MW, and continue to do so today.

The residual, bound Sgr dSph main body is still a remarkable object. Four globular clusters (M54, Terzan 7, Terzan 8 and Arp 2) are currently associated with it and M54 is the second most massive GC known in the MW, lying at the centre of Sgr dSph main body (Bellazzini et al., 2008). At least one more GC (Pal 12) almost certainly originated in the Sgr dSph system and was consequently stripped (Sbordone et al. [2007] and references therein). Spectroscopic studies of stars in the very centre of the Sgr dSph showed that the galaxy underwent an impressive degree of chemical evolution. The central population has a mean metallicity, *[Fe/H]* of −0.5, unusually high for a dSph, a sizeable metal-rich population at *[Fe/H]* ≈ 0, and a metal-poor tail likely reaching down to almost *[Fe/H]* = −3. The associated GCs also span about two orders of magnitude in metallicity, between *[Fe/H]* = −2.6 in Terzan 7 and *[Fe/H]* = -0.6 in Terzan 8 (Sbordone et al., 2007; Mottini et al., 2008).

Except for the analyses in the associated GCs, he large size (roughly 15 × 7 degrees on the sky) and low surface density of the Sgr dSph have so far prevented any large-scale photometric and spectroscopic study outside a tiny central region. Thus the kinematics, star formation history and chemical composition remain unexplored over most of the galaxy. In the present article, and in forthcoming papers, we describe the first attempt to map the Sgr dSph stellar populations and chemical composition over most of its surface.

A wide-angle VIMOS survey

The main body of Sgr dSph is located near the Milky Way disc, and on the opposite side of our Galaxy, so discriminating between MW and Sgr dSph stars is a real challenge. Fortunately, by combining photometric and spectroscopic data it is possible to select an almost uncontaminated sample of Sgr dSph stars. Given the impressive angular size of the Sgr dSph, we decided to concentrate our efforts on its centre and on seven peripheral fields located along the minor and major axis of the galaxy (see Figure 1 for the positions of these fields).

Photometrically, the red giant branch (RGB) stars of the Sgr dSph are clearly visible as a nearly vertical sequence on a colour–magnitude diagram (CMD) of the area, and are separated from the bulk of the MW Disc and the Bulge+Halo population. But this is not enough, because a large number of Bulge and Halo stars could be present in that region of the CMD. A further selection can only be performed dynamically: Sgr dSph stars are co-moving along their orbital trajectories due to gravitational interaction with the Milky Way, and this common motion is identifiable through radial velocity measurements, distinguishable from the motions of MW stars. This

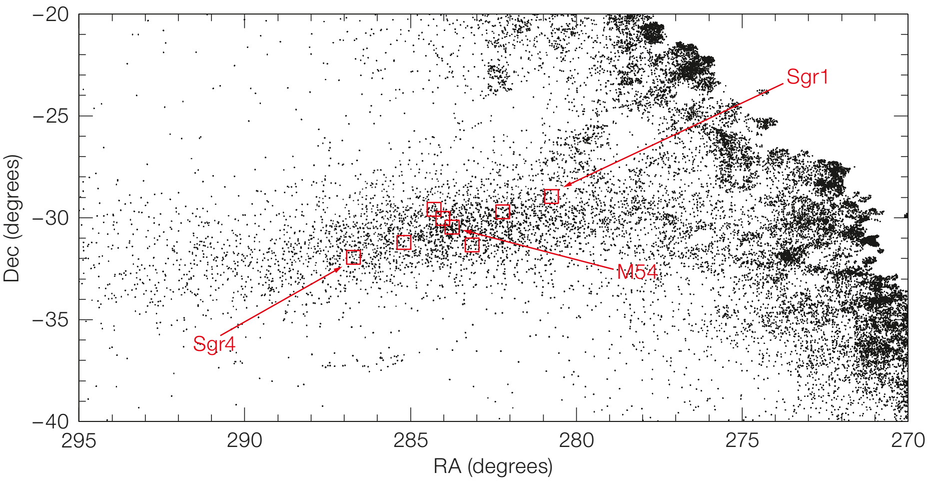

Figure 1. Map of the catalogued stars and clusters in the Sgr dSph galaxy obtained from 2MASS and UCAC catalogues selected in *K* and *J*–*K* (see Majewski et al. [2003] for the selection criteria). The boxes show the position of the fields observed with VIMOS and FLAMES.

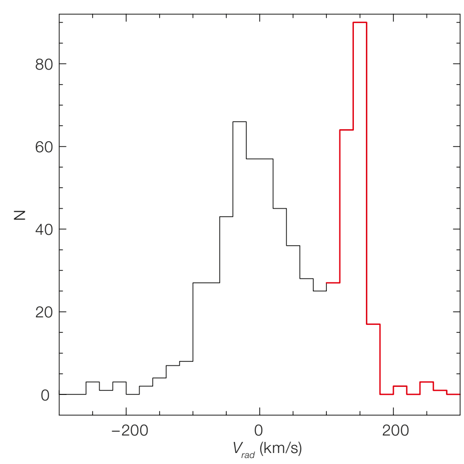

Figure 2. The radial velocity distribution of the FLAMES sample of stars observed in the direction of the Sag dSph. In red the candidate Sgr dSph members; the other stars belong to the Milky Way.

uncontaminated sample of stars could be successively observed with a high resolution spectrograph to characterise in detail the dynamics and chemical content of the Sgr dSph.

The programme for sampling the stellar populations across the Sgr dSph was performed in three steps. We secured the first images of the eight selected fields with VIMOS on the ESO Very Large Telescope (VLT); second, we selected targets from the RGB of Sgr dSph and other luminous stars to observe with the VIMOS Multi Object Spectroscopy (MOS) with the high resolution red grism (645–860 nm, $R = 2500$) mode, with an exposure time of 600 s for each pointing. With these data a first dynamical selection has been performed: while the bulk of contaminant MW stars have radial velocities (V_{rad}) not exceeding 90–100 km/s, the Sgr dSph stars have a narrow V_{rad} distribution centred around 140 km/s (see Figure 2). Finally, we performed a follow-up spectroscopic analysis with FLAMES of candidate Sgr dSph members in the seven peripheral fields. We decided not to include the central M54 field in the FLAMES follow-up, since a large number of observations were already available for that field.

Imaging observations with VIMOS were obtained over five different nights. Each pointing consisted of two exposures: a 10 s exposure in the *I*-band, and a 15 s exposure in the *V*-band. Atmospheric seeing, evaluated using the full width at half maximum (FWHM) of the observed point spread function for a sample of bright, isolated stars, was in the range 0.7 to 1.3 arcseconds, perfectly suited for our purposes. The analysis of this photometric data reveals a fairly homogeneous scenario (Giuffrida et al., 2010): all the Sgr dSph fields appear to be characterised by the presence of a dominant population whose progeny is the ubiquitous RGB, visible also in the border fields (Sgr1 and Sgr4). In Figure 3 we show the CMD obtained from three of our fields: Sgr4, M54 and Sgr1. It is interesting also to observe the different MW contribution to these fields: from the less contaminated (Sgr4), to the most contaminated one (Sgr1). The central field is characterised by the presence of the M54 GC superimposed on the general Sgr dSph population: along with the RGB of the Sgr dSph population, the RGB of the M54 population is clearly visible; finally the highly populated horizontal branch is visible only in this central field. The combination of imaging and multi-object spectroscopy with VIMOS and multi-object spectroscopy with FLAMES Medusa mode guarantees a sample of more than 200 confirmed Sgr dSph stars localised in the seven peripheral fields (Giuffrida et al., 2010).

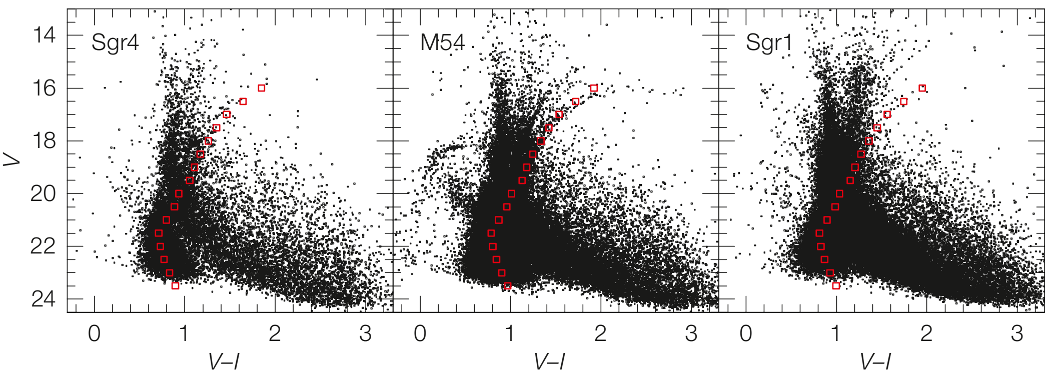

Figure 3. VIMOS colour–magnitude diagrams (CMD) for three of the observed fields are shown with, superimposed, the fiducial line of the dominant Sgr dSph population. Left: CMD for the Sgr4 field; centre: CMD of the central (M54) field; right: CMD of the Sgr1 field.

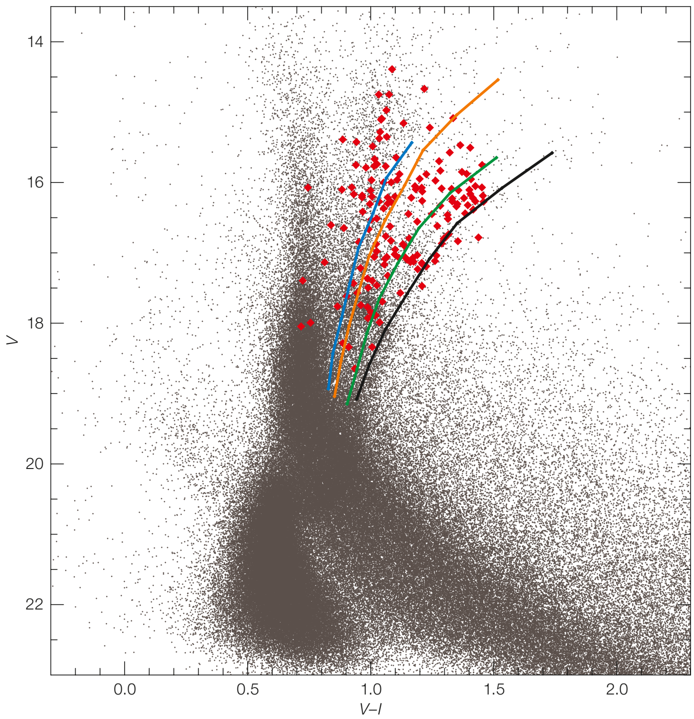

Figure 4. Colour–magnitude diagram for all the stars detected in the seven Sgr dSph peripheral fields with, overplotted, the stars observed with FLAMES and showing radial velocities compatible with a membership of the Sgr dSph. Fiducial lines of three galactic globular clusters are superimposed. From left to right: M92, M5 and 47Tuc characterised by *[Fe/H]* = −2.52, −1.24 and −0.67 respectively. The bold black line follows the position of the RGB of Sgr dSph main population.

In Figure 4 we superimpose the confirmed (radial velocity) Sgr dSph members observed with FLAMES over the global CMD (obtained joining all the data of the seven peripheral fields). An inspection of this figure reveals a complex scenario: while many stars are located on the main RGB of Sgr dSph, a large number of them are located on different sequences. To better characterise these populations, we superimposed fiducial lines of three well-known Galactic GCs, namely M92, M5 and 47 Tuc. These GCs are representative of a metal-poor population (M92, *[Fe/H]* = −2.52), intermediate metallicity population (M5, *[Fe/H]* = −1.24) and a metal-rich population (47 Tuc, *[Fe/H]* = −0.67). This large metallicity span is in agreement with the data collected on the Sgr dSph core, with two remarkable exceptions, namely the presence of a well-populated intermediate population (*[Fe/H]* ≈ −1) and large numbers of bright stars lying at the blue edge of the RGB ($17 < V < 14$ mag and $0.9 < V–I < 1.1$ mag) that cannot be reproduced with a "M92-like" population. The hypothesis that these "blue-edge" stars are high velocity halo interlopers cannot be rejected, but they can also correspond to a very metal-poor Sgr dSph population: the results from the high resolution abundance analysis will allow us to clarify this question.

We are completing the analysis of the FLAMES spectra, and dynamical and chemical measurements are currently underway; there are still many open questions regarding this galaxy, such as a possible rotation of the main body around one of the axes, or the presence of an ultra metal-poor population (*[Fe/H]* < −2.5). Unveiling the history of this fascinating companion to the Milky Way will be extremely useful for our understanding of both the local and the distant Universe.

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The interacting galaxy NGC 4027 (Arp 22) is shown in this colour composite image formed from exposures in three broadband filters (*B*, *V* and *R*) and two narrowband filters (Hα and [O III] 5007A) taken with EFOSC on the NTT. This barred spiral galaxy is a member of the NGC 4038 Group and shows evidence of interaction from its distorted northern spiral arm.