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# Old open clusters in the Sagittarius dwarf spheroidal galaxy tidal stream – kith or kin?

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## ABSTRACT

A widely supported formation scenario for the Galactic disc is that it formed inside-out from material accumulated via accretion events. The Sagittarius dwarf spheroidal galaxy (Sgr dSph) is the best example of such an accretion, and its ongoing disruption has resulted in that its stars are being deposited in the Milky Way halo and outer disc. It is therefore appealing to search for possible signatures of the Sgr dSph contribution to the build-up of the Galactic disc. Interestingly, models of the Sgr dSph stream clearly indicate that the trailing tail passes through the outer Galactic disc, at the same Galactocentric distance as some anticentre old open star clusters. We investigate in this Letter the possibility that the two outermost old open clusters, Berkeley 29 and Saurer 1, could have formed inside the Sgr dSph and then left behind in the outer Galactic disc as a result of tidal interaction with the Milky Way. The actual location of these two star clusters, inside the Sgr dSph trailing tail, is compatible with this scenario, and their chemical and kinematical properties, together with our present understanding of the age–metallicity relationship in the Sgr dSph, lend further support to this possible association. Hence, we find it likely that the old open star clusters, Berkeley 29 and Saurer 1, have extragalactic origins.

**Key words:** Galaxy: disc – Galaxy: evolution – open clusters and associations: general – open clusters and associations: individual: Berkeley 29 and Saurer 1 – galaxies: dwarf – galaxies: individual: Sgr dSph.



## 1 INTRODUCTION

The Sagittarius dwarf spheroidal galaxy (hereafter simply referred to as the Sgr dSph) is a nucleated dwarf galaxy on the verge of dissolving into the Milky Way. Since its discovery in the 1990s (Ibata, Irwin & Gilmore 1994), an impressive amount of observational data has been collected to measure its properties, and significant theoretical efforts have been made to characterize its formation and evolution history. As a result, we now know that at the photometric centre of Sgr dSph lies in M54 (NGC 6715), a massive globular cluster showing multiple stellar populations (Siegel et al. 2007), which ended up in the centre of the Sgr dSph as a result of dynamical friction. Besides, the Sgr dSph left behind an impressive star stream in the Galactic halo composed of a leading and a trailing tail (Newberg et al. 2002). This stream has been traced in detail by Majewski et al. (2004) with M giants from Two-Micron All-Sky Survey (2MASS) using low-resolution spectroscopy. Additional information derives from spectroscopic studies which allowed to characterize the metallicity of the Sgr dSph centre and trailing stellar stream (Monaco et al. 2007). Important differences have been found, with the stream being more metal-poor than the centre. A family of star clusters has been found to be associated with the Sgr dSph. Apart from M54, the other star clusters which are associated with the Sgr dSph are Terzan 7, Terzan 8 and Arp 2 close to the core of the Sgr dSph (Ibata et al. 1994), and Palomar 12 (Dinescu et al. 2000), Palomar 2 (Majewski et al. 2004) and Whiting 1 (Carraro 2005; Carraro et al. 2007b) in the stream. All of them are globular clusters spanning ages from 7 to 12 Gyr. Recently, Siegel et al. (2007) pointed out the presence of a much younger population associated with Sgr dSph, detected in the centre of the dwarf galaxy, close to M54. This implies that Sgr dSph has had protracted star formation episodes during its lifetime.

The youngest globular clusters are, on the other hand, found in the stream, far from the central region (except for Terzan 8), and therefore one can expect to find traces of young stellar populations also outside the Sgr dSph centre.

In this Letter, we investigate the possibility that the two outermost old open star clusters in the Galactic disc, Berkeley 29 and Saurer 1, could have formed inside Sgr dSph, and then left behind in its trailing tail due to tidal interactions with the Milky Way. These two star clusters appear to be twins, since they have very similar ages and metallicities. At the same time, they bear significant differences

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**Table 1.** Relevant parameters of the clusters under investigation. Coordinates are for J2000.0 equinox. Coordinates in the Sgr orbital plane are defined following Majewski et al. (2004). RA and Dec. are also provided to allow direct comparison with Martínez-Delgado et al. (2004) models.

| Cluster | $l$ (°) | $b$ (°) | RA (°) | Dec. (°) | $V_R$ (km s$^{-1}$) | $V_{GSR}$ (km s$^{-1}$) | Age (Gyr) | $d_\odot$ (kpc) | $d_{GC}$ (kpc) | $Z$ (kpc) | $\lambda_\odot$ (°) | $\beta_\odot$ (°) | [Fe/H] | [Mg/Fe] | [Ca/Fe] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Berkeley 29 | 197.98 | +8.05 | 103.3 | +1.9 | 24.6 | −51.1 | 4.5 | 13.2 | 21.6 | 1.8 | 177.2 | 11.8 | −0.44 | −0.02 | +0.10 |
| Saurer 1 | 214.68 | +7.38 | 182.6 | +16.9 | 104.6 | −32.7 | 5.0 | 13.2 | 19.2 | 1.7 | 181.8 | 27.8 | −0.38 | +0.03 | +0.18 |

with the bulk of old open clusters in the Galactic disc (Carraro et al. 2007b). First, as mentioned, they are currently the two most distant old open clusters that have been observed in the Galaxy; secondly, they are located significantly above the Galactic plane (see Table 1). Furthermore, a detailed elemental abundance analysis of red giant stars in the two clusters by Carraro, Zinn & Moni Bidin (2007a) revealed that they are more metal-poor than open star cluster of similar age in the solar vicinity.

While this might simply reflect the evidence for a Galactic radial abundance gradient (Magrini et al. 2009), we cannot exclude the possibility that they formed outside the Galactic disc. In fact, an association with the tidal debris of the Sgr dSph would strengthen the general idea that the Galactic disc formed inside-out from material deposited by accretion events. The outer metallicity plateau found for old open clusters in the Galactic disc (Magrini et al. 2009) would then be naturally explained, and would lend support to the models of Galactic chemical evolution proposed by Portinari & Chiosi (1999) and Hou, Prantzos & Boissier (2000).

## 2 KINEMATICAL SIGNATURES

To probe the possible association of Berkeley 29 and Saurer 1 with the Sgr dSph, we will first consider how the position and velocity of these two star clusters compare with the Sgr dSph kinematics.

Law, Johnston & Majewski (2005) modelled the on-sky distribution and kinematics of 2MASS M giant stars from the Majewski et al. (2004) sample to predict and map the spatial and kinematical properties of Sgr dSph trailing and leading tidal tails as a function of the shape (spherical, prolate or oblate) of the Galaxy dark matter (DM) halo. The $N$-body realization for the favoured spherical DM halo is depicted in the three panels of Fig. 1 for a suitable $\lambda_\odot$ range. $\lambda_\odot$, together with $\beta_\odot$, is longitude and latitude in a reference frame centred on Sgr dSph (the Sgr dSph orbital plane), defined by Majewski et al. (2004)[1] so that the results for Berkeley 29 and Saurer 1 could be directly compared with theirs for M giant stars and with the theoretical models of Law et al. (2005). For comparison, we also mark the M giant stars observed by Majewski et al. (2004) (green triangles) in the same region of the Milky Way. In the Sgr dSph coordinate system, the main body of Sgr dSph is located at $\lambda_\odot = 0°$, and $\lambda_\odot$ increases in the direction of the trailing stream.

The three panels show, from the bottom to the top, the model predictions for $\beta_\odot$, the heliocentric distance $d_\odot$ and Galactocentric rest-frame velocity $V_{GSR}$ of the debris particles, respectively. The same quantities are plotted for the M giant stars as well. $V_{GSR}$ has been calculated by adopting the same procedure and the choice of solar motion used by Majewski et al. (2004). Such plots have been routinely used both to select possible debris candidates for spectroscopic follow-up (Monaco et al. 2007) and for investigating and establishing the membership of star clusters to Sgr dSph (NGC 5634: Bellazzini, Ferraro & Ibata 2002; Whiting 1: Carraro et al. 2007a,b; AM 4: Carraro 2009). The two red squares indicate Berkeley 29 and Saurer 1. Unfortunately, it is not possibly to compare the locations of these two clusters with M giant stars, since no M giant stars have been observed in this region of the sky. Nevertheless, the coordinates of Berkeley 29 and Saurer 1 (lower panel in Fig. 1) show that on the sky they lie in the direction of the trailing stream, although somewhat higher on to the orbital plane than the typical height of the closest M giant stars. In the middle panel, we show that the heliocentric distance of the two clusters is compatible with the mean heliocentric distance of closest-to-the-Sun members of the same trailing stream. Although several M giant stars lie at comparable distances, no one unfortunately has been measured close to these Galactic directions. Finally, in the upper panel we plot the Galactocentric rest-frame velocity $V_{GSR}$ of Berkeley 29 and Saurer 1, and show that they are moving on similar orbits as the Sgr dSph trailing tail model particles.

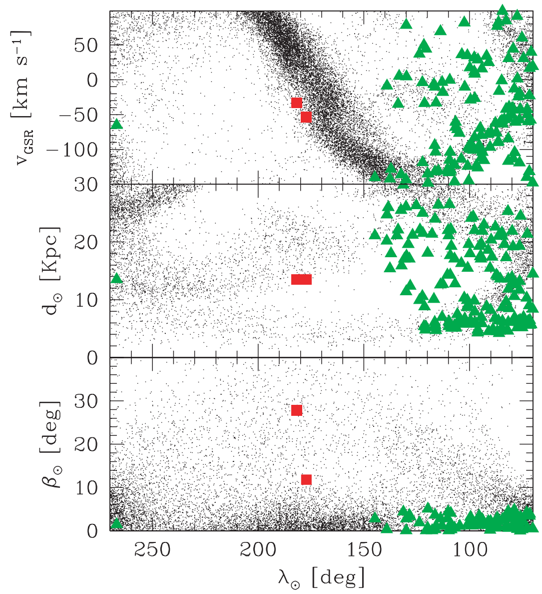


**Figure 1.** Location of Berkeley 29 and Saurer 1 (red squares). Bottom panel shows the position of the two clusters in the Sgr dSph orbital plane; middle panel, their position as a function of heliocentric distance; upper panel, their position as a function of Galactocentric rest-frame velocity. Dotted symbols are Sgr dSph points from Law et al. (2005) model, which assumes a spherical halo. Green triangles are the 2MASS giants from Majewski et al. (2004).

We also investigate whether the estimates for the distance, location and radial velocity of Berkeley 29 and Saurer 1 are consistent with the Martínez-Delgado et al. (2004) and Helmi (2004) model predictions, which are provided in Galactic coordinates and heliocentric radial velocity. A quick inspection of their plots indicates the same level of agreement we find with the Law et al. (2005) model.

These pieces of evidence suggest that it is likely that both Berkeley 29 and Saurer 1 originated inside the Sgr dSph. In the next section, we will look at the chemical properties of these two

[1] See also http://www.astro.virginia.edu/smr4n/Sgr.

 

clusters, and compare them with our present understanding of the chemical evolution and star formation history of the Sgr dSph.

## 3 CHEMICAL SIGNATURES

A detailed elemental abundance analysis of the Berkeley 29 and Saurer 1 open star clusters has been carried out by Carraro et al. (2004) and has been discussed in the general framework of the outer Galactic disc chemical properties by Carraro et al. (2007) and Magrini et al. (2009). As reported in Table 1, Berkeley 29 and Saurer 1 have similar ages and metallicities. At the age of these two clusters (4–5 Gyr), the Galactic disc age–metallicity relation shows quite a large spread in metallicity (Carraro, Ng & Portinari 1998; Friel et al. 2002): from [Fe/H] ≈ −0.5 up to the solar metallicity of M67 (NGC 2682). Such a spread is larger than observational uncertainties and is typically interpreted as being caused by ancient merger events in the Galactic disc. On the contrary, the age–metallicity relation of the Sgr dSph appears to be better constrained (Forbes, Strader & Brodies 2004; Siegel et al. 2007). The last determination by Siegel et al. (2007) – which is based on Layden & Sarajedini 2000 – is shown in Fig. 2, and it is consistent with a closed-box model and multiple bursts of star formation over its entire lifetime (see Layden & Sarajedini 2000 for additional details). Berkeley 29 and Saurer 1 possess the right combination of age and metallicity to fit perfectly into the age–metallicity relation of the Sgr dSph (see Fig. 2). The two clusters are probably part of an intermediate Sgr population (as defined by Siegel et al. 2007). This population has an average age between 4.5 and 6 Gyr, and a metallicity of [Fe/H] ≈ −0.5.

Additional evidence of a possible kinship between the two open star clusters and the Sgr dSph can be inferred from their detailed elemental compositions. Fig. 3 shows the [Ca/Fe] and [Mg/Fe] abundance ratios as a function of [Fe/H] for 12 red giant stars in the Sgr dSph trailing tail analysed by Monaco et al. (2007) and another 27 stars from the Sgr dSph main body analysed by Sbordone et al. (2007). On top of the data for the Sgr dSph main body and trailing tail in Fig. 3, we plot the two open clusters from Carraro et al. (2004). The error bars in the figure represent total error including the formal error in the mean abundance (i.e. line-to-line scatter divided by the square root of the number of lines used), and uncertainties in the abundances due to the uncertainties in the stellar parameters ($T_{\rm eff}$, log $g$ and [Fe/H]) (all errors were added in quadrature). Also in the figure, we show a sample of ∼700 F and G dwarf stars in the solar neighbourhood by Bensby, Feltzing & Lundström (2003), Bensby et al. (2005) and Bensby et al. (in preparation).

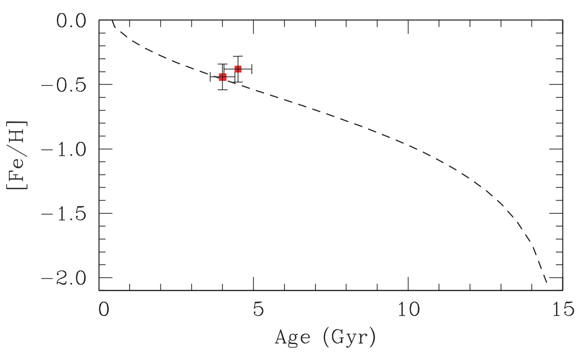


**Figure 2.** The age–metallicity relationship for Sgr dSph from Layden & Sarajedini (2000) is plotted as thick dashed line. The position of Berkeley 29 and Saurer 1 is indicated with red squares. Crosses refer to uncertainties in age and metallicity.

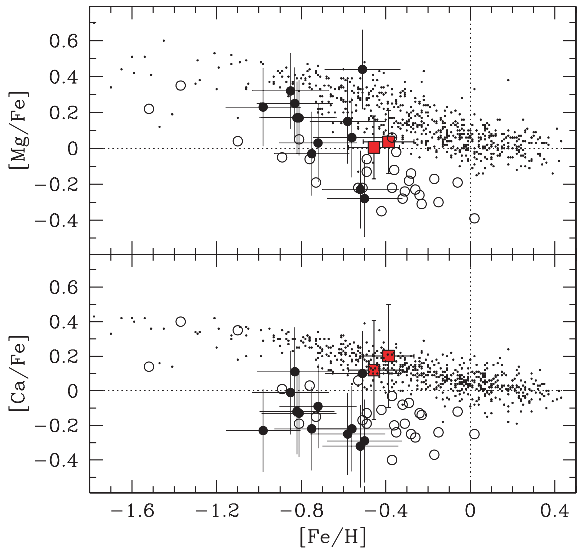


**Figure 3.** [Mg/Fe] and [Ca/Fe] abundance ratios versus [Fe/H]. Filled circles mark the Sgr dSph trailing tail stars by Monaco et al. (2007), open circles the Sgr dSph main-body stars from Sbordone et al. (2007) and the red squares the Berkeley 29 and Saurer 1 open star clusters by Carraro et al. (2004). Error bars represent the total errors due to line-to-line scatter and uncertainties in the adopted stellar parameters. Small dots mark the thin and thick disc stars from (Bensby et al. 2003, 2005) and Bensby et al. (in preparation).

From Fig. 3, it is evident that both the stars of the Sgr dSph main body and trailing tail follow the same abundance trend, and that they with increasing [Fe/H] show a greater underabundance of $\alpha$-elements. The only difference is that the stream stars appear to be on average slightly more metal-poor than the main-body stars. We note that the $\alpha$-element abundances of Berkeley 29 and Saurer 1 are in good agreement with the Sgr dSph trailing tail as far as [Mg/Fe] is concerned. A slight discrepancy seems to exist for Ca. However, taking the uncertainties into account and the fact that there might be slight systematic offsets between the data sets due to different ways of normalizing the abundances, we also find that Ca is in reasonable agreement. Comparing to the local disc stellar sample by Bensby et al., we see that the two open clusters clearly have lower Mg abundances but similar Ca abundances. A truly differential abundance analysis between all these stellar populations would be preferable, eliminating uncertainties arising from different analysis methods that different studies use.

## 4 DISCUSSION AND CONCLUSIONS

The formation and origin of the oldest open star clusters in the outer Galactic disc have recently been discussed (e.g. Frinchaboy et al. 2004; Carraro et al. 2007). In fact, in the widely accepted scenario of inside-out formation of the Galactic disc (Magrini et al. 2009), one would expect that the open star clusters of the outer Galactic disc showed signatures of extragalactic origin. Therefore, Frinchaboy et al. (2004) proposed that several globular clusters and old open clusters may be associated with the Monoceros Ring (MRi), a gigantic star stream encompassing the entire Milky Way. The MRi is believed to be tidal debris left behind by the in-plane accretion of a dwarf galaxy that occurred 4–8 Gyr ago (Newberg et al. 2002).

Carraro et al. (2007) investigated this possibility in detail with the available information on the kinematical and chemical

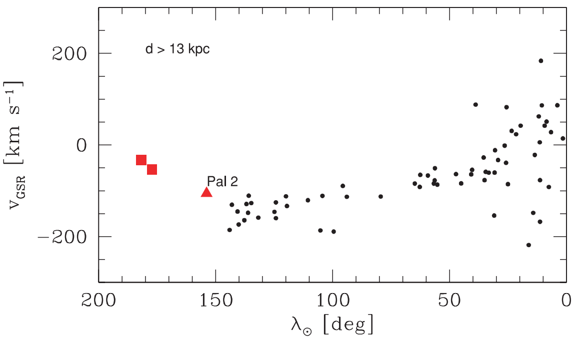


**Figure 4.** The trailing tail of Sgr dSph as defined by M giant stars (Majewski et al. 2004). The big red squares mark the Berkeley 29 and Saurer 1, while the red triangle indicates the position of the globular cluster Palomar 2.

properties of the MRi, together with model predictions by Peñarrubia et al. (2005). However, the poor knowledge of the MRi properties prevented any firm conclusions and led to a conservative suggestion that Berkeley 29 and Saurer 1 were members of the Galactic disc.

In this Letter, we have compared the properties of Berkeley 29 and Saurer 1 with the Sgr dSph, whose chemical and kinematical properties are much better known (than the MRi). In particular, the trailing tail of Sgr dSph passes close to the Galactic disc periphery at the same distance as the two clusters. We have shown that both kinematical and chemical properties of Berkeley 29 and Saurer 1 are compatible with the membership to the Sgr dSph.

A possible weak point in the investigation could be that since no M giant stars from the Majewski et al. (2004) survey lie in the same region of the sky as the two open clusters, the connection to the Sgr dSph had to be investigated by considering model predictions from Law et al. (2005) only. However, Majewski et al. (2004) investigated the possibility that several globular clusters might be associated with Sgr dSph. As for Palomar 12, it lies very close to the trailing tail, as defined by M giant stars, and additional chemical and kinematical evidence from Cohen (2004) supports its association with the Sgr dSph. Palomar 2, on the other end, falls in a region of the sky where no M giant stars are present, as is the case for the two open clusters, Berkeley 29 and Saurer 1, in this study. However, Palomar 2 lies in a zone where the trailing tail, as defined by M giant stars, likely continues, and where such an extrapolation looks very reasonable, since Law et al. (2005) models perfectly match the position of Palomar 2. It is, therefore, reassuring to find that Berkeley 29 and Saurer 1 happen to be situated in the same trailing tail extrapolation (see Fig. 4), lending further support to their association with the Sgr dSph.

Our suggestion that Berkeley 29 and Saurer 1 have formed inside Sgr dSph and then have been deposited in the outer Galactic disc about 5 Gyr ago provides support to a scenario in which the Galactic disc has grown through repeated accretion events. Additionally, this provides an explanation, several times advocated, for the radial abundance gradient in the Galactic disc and its time evolution (Carraro et al. 1998; Friel et al. 2002; Magrini et al. 2009). In this context, chemical evolution models employing an inside-out formation mechanism for the disc (Portinari & Chiosi) are clearly favoured.

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