The central density cusp of the Sagittarius dwarf spheroidal galaxy

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ABSTRACT

We present an analysis of the density profile in the central region of the Sagittarius dwarf spheroidal galaxy. A strong density enhancement of Sgr stars is observed. The position of the peak of the detected cusp is indistinguishable from the center of M54. The photometric properties of the cusp are fully compatible with those observed in the nuclei of dwarf elliptical galaxies, indicating that the Sgr dSph would appear as a nucleated galaxy independently of the presence of M54 at its center.

Key words: stars: Population II - galaxies: nuclei - galaxies: dwarf - Local Group

1 INTRODUCTION

Dwarf galaxies are considered the building blocks of the hierarchical merging process, a fundamental mechanism for the formation of large galaxies. Among dwarf galaxies, dwarf ellipticals are the most common type of galaxy in the nearby universe (Ferguson & Binggeli 1994, hereafter FB94). Therefore, the comprehension of their structural and evolutionary characteristics is a major task of modern cosmology.

A characteristic of many dE is an enhancement of the surface brightness in a small central region (nucleus). Such a feature defines the sub-class of nucleated dwarf ellipticals (dE,N).

The observed nuclei have surface brightness profiles similar to globular clusters, they also share with globulars the same general surface brightness - absolute magnitude relation and their luminosity function overlaps the luminosity range covered by globular clusters (FB94, Durrell 1996). Hence, the origin of dE nuclei is generally reconducted to two possible mechanisms, both related to massive star clusters, e.g. (a) the decay of the orbit of a pre-existing globular toward the tip of the galactic potential well, driven by dynamical friction, or (b) the in situ formation of a giant cluster from gas fallen to the center of the galaxy (see Durrell 1996).

Many authors (Bassino & Muzzio 1995; Sarajedini & Layden 1995; Da Costa & Armandroff 1995; Lavden & Sarajedini 2000, hereafter LS00) have suggested that the Sagittarius dwarf spheroidal galaxy (Sgr dSph, Ibata et al. 1994, 1994; 1997) is the relic of a dE,N and that the massive globular cluster M 54 is the nucleus of this galaxy. However, several authors also noted that Sgr stars of different age and/or metallicities are somewhat clustered around M 54 (Bellazzini et al. 1999a, 1999b). In this paper we fully resolve, for the first time, the structure of the overdensity of Sgr stars around M 54, showing that Sgr would appear nucleated independently of the presence of M 54.

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Davies & Phillips 1988; Bassino et al. 1995; van den Bergh 1986 (and references therein). dE nuclei may also be related with the Ultracompact Dwarf Galaxies (UCD), recently discovered in the Fornax cluster (Drinkwater et al. 2000; Phillips et al. 2001; Drinkwater et al. 2003). In summary, the phenomenon of dE nucleation is far from being fully understood and it is the subject of continuous investigation (see, e.g. Binggeli, Barazza & Jerjen 2000; Stiavelli et al. 2001; Miller et al. 1998; Graham & Guzman 2003). A local example would certainly provide a deeper insight on the phenomenon, but the only well-known case in the Local Group is M 32, a companion of the Andromeda galaxy whose stellar content may be studied in some detail only with HST (Grillmair et al. 1996).
2 THE NUCLEAR STRUCTURE

The Sgr stellar content is dominated by a metal-rich population ([M/H] ≃ −0.4/−0.6) with an age of ∼4−6 Gyr (see Monaco et al. 2002, and references therein). Therefore, the Color Magnitude Diagram (CMD) of Sgr shows the typical features of an old/intermediate-age metal-rich population with a clearly defined Red Clump (RC) of He-burning stars and a cool Red Giant Branch (RGB). On the other hand, M 54 is a quite old and metal poor globular cluster (Brown, Wallerstein, & Gonzalez 1999; Layden & Sarajedini 2000, hereafter LS00) with an extended blue Horizontal Branch (HB, see Rosenberg, Recio-Blanco, & García-Marín 2004) and a steep RGB. Hence, the evolved stars of the two systems can be easily discriminated in the CMD and allow us to study the respective spatial distributions (see Monaco et al. 2003, for examples and discussion).

In the following analysis we will use the photometric catalog of the Sgr dSph covering a region of about 1°×1° around the globular cluster M 54 already presented in Monaco et al. (2002, 2003). In order to better show the various sequences, only stars in the innermost 4′×4′ around M 54 are plotted in the CMD in Figure 1 (the CMD of the entire sample can be found in Figure 1 by Monaco et al. 2002). The boxes adopted to select the star samples are shown in Fig. 1 Similar boxes have also been defined in Bellazzini et al. (1999a, see their figure 12) in order to study the different stellar populations in Sgr. The reader can also refer to LS00 (see, in particular, figures 14 and 16) for a field subtracted view of the M 54 and Sgr CMDs.

In comparing the radial distributions of M54 and Sgr we will rely on Sgr RGB stars having V ≤ 17.0 (hereafter Sgr17), i.e. with similar completeness properties and with stars in similar evolutionary phase as the M54 RGB sample. The larger Sgr sample (from V ≃ 15.5 down to V ≃ 18.7) will be considered in order to trace the Sgr structure out to the edges of our field with the highest possible signal to noise (see Figure 3 below).

We also selected stars in the Blue Plume (BP) and upper Main Sequence (MS) regions. We expect the BP sample to be composed by young and, probably, metal rich Sgr stars. Some blue straggler star belonging to Sgr and/or M 54 may also be present in this box. We plotted in the MS region the M 54 (continuous line) and Sgr (crosses) mean ridge lines. Clearly, both M 54 and Sgr are expected to contribute to this sample.

In Figure 2 we show the spatial distribution of stars in the four samples selected in Fig. 1. The circle reported in each panel of Figure 2 represent the tidal radius of M 54 (r_{T, M54} = 7.5′, Trager, King, & Djorgovski 1993). All the samples show a strong concentration around M 54. This effect is somewhat obvious in the case of the M 54 and MS samples (lower panels), which are dominated or at least largely contaminated by M 54 stars. On the other hand, such a sharp concentration around M 54 is unexpected in the case of the Sgr and BP samples (upper panels) where the contamination from M 54 stars is virtually negligible.

In Figure 3 we show isodensity contours for M 54 (light grey continuous curves) and Sgr (heavy dotted-dashed curves). Each contour set is normalized to the respective maximum density and for each sample we show isodensity contours for M 54 (light grey continuous curves) and Sgr (heavy dotted-dashed curves). Each contour set is normalized to the respective maximum density and for each sample we show isodensity contours for M 54 (light grey continuous curves) and Sgr (heavy dotted-dashed curves). Each contour set is normalized to the respective maximum density and for each sample we show isodensity contours for M 54 (light grey continuous curves). Figure 1. Color-magnitude diagram of the Sgr dSph. The selection boxes define the samples of stars described in the text. In order to better show the various sequences, only stars in the innermost 4′×4′ around M 54 are plotted. The M 54 (continuous line) and Sgr (crosses) mean ridge lines are also plotted in the main sequence region. Figure 2. Spatial distribution of the stars in the samples shown in Figure 1. In each panel the tidal radius of M 54 (r_{T, M54} = 7.5′) is marked. The “holes” in the center of the right-hand panels are due to incompleteness effects.
The Sgr Nuclear Structure

Figure 3. M 54 (heavy dot-long dashed curve) and Sgr (light grey continuous curve) density contours.

curves ranging from 10% to the 90% of the peak value, in steps of 10%. The plotted area covers approximately $9' \times 9'$. The M 54 contours show a compact, strongly peaked, symmetric structure, typical of a globular cluster. The surprising feature of Figure 3 is that Sgr shows a very similar structure centered (at the best of our resolution, i.e. $6''$) exactly on M 54.

The scale length of the Sgr overdensity can be best appreciated by examining the radial density profile. Density profiles are obtained by dividing the surveyed area into quadrants and by computing the density of stars (star counts/area) for each quadrant in annuli of variable dimension. For each annulus, the densities in the quadrants are then averaged to give the final density and standard deviation on the density estimates.

We applied this procedure to stars in the M 54 and in the Sgr17 samples. As can be seen from Figure 1, the two boxes select the brightest region of the RGB, hence the radial profiles can be directly compared. In order to obtain a higher signal in the outer part of the profile, we also computed the radial profile for stars in the Sgr global sample. Then we shifted the Sgr radial profile in order to match the Sgr17 one in the region $15'' < r < 100''$ (upper panel in Figure 4). The adopted Sgr profile is thus computed using Sgr17 for $r \leq 25''$ (i.e. $log(r) \leq 1.4$) and the Sgr sample (normalized to the former) for $r > 25''$ (lower panel in Figure 4). As expected, the global Sgr sample is heavily incomplete in the innermost region. The effect of incompleteness is expected to be significantly lower in the Sgr17 sample, however, to be conservative, we consider the inner points ($r < 16''$) only as lower limits, hence they are plotted with different symbols in Figure 4.

In order to compute the radial surface brightness profile we followed two different approaches:

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1 The Sgr global sample certainly suffers some degree of contamination by M 54 stars. However, such a contamination is of the order 3-4% of the global sample. As can be realized looking at the upper panel of figure 4, the Sgr global sample and Sgr17 radial profiles are perfectly consistent each other, therefore the M 54 contamination should be negligible. Such contamination of M 54 stars do not affect any of the results presented in the paper.
(i) The brightness of each annulus (see above) has been computed as the sum of the luminosity of all the stars lying in it normalized to the annulus area. However, as expected, the brightness profile turns out to be quite noisy since it is affected by large fluctuations due to the small number statistics of few bright giants.

(ii) On the other hand, since the observed number of stars in any post-MS evolutionary stage is a function of the sampled luminosity and the duration of the considered evolutionary phase (see Renzini & Fusi Pecci 1988), the star density, N/area, can be easily converted into surface brightness by the relation: $\mu_V = -2.5 \times \log(N/\text{area}) + c$, where the value of $c$ depends on the considered evolutionary phase. Since both the M 54 and Sgr profiles sample approximately the same portion of RGB (see Figure 1), the normalizing the central surface brightness to the M 54 best fit King model (Trager, King, & Djorgovski 1995, upper continuous curve). Note that the surface brightness in the outer part of the Sgr profile ($r > 10'$, $\mu_V \approx 24.9$), is fully consistent with previous determinations by Ibata et al. (1997), Mateo et al. (1993, 1995), Majewski et al. (2002).

The radial surface-brightness profile from procedure (ii) turns out to be fully consistent but less noisy than the one obtained from procedure (i).

The derived radial surface brightness profiles for M 54 and Sgr are plotted in Figure 5 (empty triangles and circles, respectively) together with the M 54 best fit King model (Trager, King, & Djorgovski 1995, upper continuous curve). We also fitted the inner Sgr profile (hereafter Nuclear Structure, Sgr-NS) with a King model (lower continuous curve) having $r_{1/2}^{Sgr-NS} = 12.6'$ (which should be considered as an upper limit) and $r_{2/3}^{Sgr-NS} = 16.7$ as core and tidal radii, respectively. This King model can be used to derive a lower limit to the Sgr-NS integrated magnitude. It is also important to stress that a satisfactory fit to the Sgr-NS profile cannot be obtained using $r_{1/2}^{MS}$ as tidal radius. Thus, as a first result, we conclude that the Sgr-NS and M 54 do not share the same profile, the Sgr-NS being a more extended structure.

Indeed, the presence of the Sgr-NS and the Sgr field may have corrupted the $r_{1/2}^{MS}$ value derived by Trager, King, & Djorgovski (1995). However, the M 54 radial profile presented in Figure 5 confirms that $r_{1/2}^{MS} = 7.5'$ is a reasonable value. In any case, even if $r_{1/2}^{MS}$ was actually overestimated, our conclusions remain unchanged: the Sgr-NS and M 54 scale lengths and, hence, their radial profiles are different.

In Figure 6 we plotted the radial profiles obtained also for the BP (filled triangles) and MS (open circles) samples selected in Figure 4. Once again, we see two significantly peaked structures with respect to a constant value reached in the external part of the profiles. We recall here that the MS sample is composed by a mix of the M 54 and Sgr stellar populations while the BP sample is essentially composed by young and possibly metal rich Sgr stars (see Figure 4 and section 2 above and LS00, Bellazzini et al. 1999a,b). In the MS profile, the star density excess drops to zero at about $\sim 13'$, thereby it cannot be due only to M 54 stars. The BP profile, with its peaked shape, confirms the existence of a nuclear structure in Sgr. The BP profile seems to hold a density excess out to $\sim 15'$, even if with a low signal which prevents from drawing any firm conclusion. The BP in comparison with the MS profile seems to show a steeper decline. This somewhat unexpected trend may be, at least partly, due to the more severe incompleteness effect suffered by the fainter sample, i.e. the MS sample, in the most central regions.

In Figure 6 the surface brightness profile for the Sgr population obtained here is combined with the King model obtained by Majewski et al. (2003) for the external part of the Sgr galaxy. The position of the core radius of the main body of the system (r_{2/3}^{Sgr} = 224') is also shown in the Figure (large filled circle).

Figures 7 and 8 clearly show the presence of a central cusp in the Sgr dSph as first suggested by LS00 and more recently by Majewski et al. (2003). In particular LS00 (their Figure 19, panel c) found a density excess of Sgr RGB stars which drops significantly between 3' to $\sim 12'$ from the center of M 54 in agreement with the Sgr profile in Figure 4. They also find (Figure 20, panel a) that stars in the Blue Plume (their “1 Gyr” sample) show a star density excess which drops to zero between 12' and 19' from the M 54 center, consistently with our BP profile.
3 THE NATURE OF THE OVERTERTHE OF SGR STARS

In the previous section we demonstrated the presence of a strongly peaked structure in the densest region of Sgr. This structure (Sgr-NS) is made by stars belonging to the typical metal rich stellar population of Sgr (see Figure 5) and hence it is distinct from M 54. Its center, at best of our resolution, coincides with that of M 54 (as can be seen from Figure 4). While the Sgr-NS profile is more extended than the cluster one (see Figure 4).

The Sgr radial profile shown in Figure 4 is extremely similar to that of a nucleated dwarf galaxy (i.e. the combination of a large scale profile and a central cusp, see for instance [Stiavelli et al. 2003]). In order to test the compatibility of Sgr-NS with a dwarf elliptical nucleus, we now put some limit on its integrated magnitude ($M_0^{Sgr-NS}$). From the inspection of Figure 4 it is reasonable to assume $M_0^{Sgr-NS} > M_0^{M54} = -10.01$ (Harris 1996) as an upper limit.

Although the Sgr radial profile is certainly affected by severe incompleteness (in the innermost region, see Figure 4), it can be used to set a lower limit to the integrated magnitude of the Sgr central cusp, $M_0^{Sgr}$

By integrating the Sgr King model adopted in Figure 5 (lower curve) we obtained $L_{tot, bol} = 2.2 \times 10^7 L_\odot$ which corresponds to $M_V^{Sgr-NS} = -7.8$ by assuming $M_V = 4.83$ and the appropriate bolometric correction (see, e.g., Table 5 by Buzzoni 1983).

As in section 2, we performed a consistency check by using star counts. First we selected a region in which the incompleteness effects are expected to be negligible ($2' < r < 4'$ from the cusp center). By using the Sgr King model adopted in Figure 5 we estimate that the annulus contains $\sim 16\%$ of the global cusp luminosity. Then we use the number of HB stars observed in the considered annulus in order to calibrate the total luminosity. In the considered annulus we counted 56 HB stars. From this number we estimate a total HB population of $N_{HB}=56/0.16=350$ stars in the central cusp. As already mentioned, the number of stars observed in any given post-MS evolutionary stage is connected to the global luminosity and the duration of the phase by the equation: $N_J = B(t) \times t_J \times L$, where $N_J$ and $t_J$ are the number of stars and the duration of the J evolutionary stage and $B(t)$ is the specific evolutionary flux for the considered stellar population ($B(t) = 2 \times 10^{-11} yr^{-1} L^{-1}_\odot$ for an old stellar population). By assuming $t_{HB} = 10^6 yr$ and $N_{HB}=350$ we easily obtain the global luminosity: $L_{tot, bol} = 1.8 \times 10^7 L_\odot$ which corresponds to $M_V^{Sgr-NS} = -7.6$ under the same assumption about $M_V$ and the bolometric correction. Thus, the two estimates are in close agreement. However, we will consider a conservative global uncertainty of $\pm 0.5$ mag for our estimate.

We can now compare the photometric properties of the Sgr/Sgr-NS system derived above with those observed in dE. In Figure 5 the Surface Brightness of the envelope (at half light) is plotted vs the Nucleus Luminosity for a sample of dE in the Fornax cluster (filled circles, Drinkwater et al. 2003). The permitted range of parameter space for Sgr-NS is represented by the shaded area, where we assumed as surface brightness of the envelope the one at the core radius of the main body of Sgr, i.e. $\mu_V \approx 25.89$. As can be seen, in this plane the Sgr-NS behaves exactly as a nucleus.

As quoted in Sect. 1., the possibility that M 54 represent the nucleus of Sgr was already discussed in the literature. However, as noted by [Sarajedini & Layden 1995], galactic nuclei usually have colors similar to that of the surrounding galaxy field. Freeman 1993; Ferguson & Binggeli 1994; Lotz et al. 2004, even if a few nuclei bluer than the field do exist (Durrell 1997). At odds with M 54, Sgr-NS has the same color of the surrounding Sgr field.

Moreover the Sgr-NS shows a central surface brightness ($\mu_0 < 19$) more than 6 mag brighter than the central brightness of the main body of Sgr ($\mu_0 \approx 25$). This is a pretty typical value for a dE. Conversely, if M 54 is considered as the Sgr nucleus it would have a $\mu_0$ more than 10 mag brighter than the brightness of the Sgr envelope. Note that none of the 5 dE,N analyzed by Geha et al. (2002) and only one of the 14 analyzed by [Stiavelli et al. 2004] show such a large difference. It is therefore safe to conclude that the structural characteristics of Sgr-NS seem more typical of a dE nucleus than those of M 54.

The discovery of the Nuclear Structure presented here clearly demonstrates that the Sgr galaxy has its own nucleus. Now the most intriguing property of the Sgr nucleus is the spatial coincidence with M 54, which poses the main question: which is the relation between the Sgr-NS and the cluster M 54?

Figure 7. Sgr radial profile. The continuous curve is a King model having the structural parameters derived by Majewski et al. (2003) for the main body of Sgr. The filled circle indicates the main body core radius.
4 DISCUSSION

By selecting a sample of Sgr giants in the extensive CMD presented by Monaco et al. (2002), we have demonstrated the existence of a Nuclear Structure in the Sgr galaxy. The radial profile of the RGB overdensity (Sgr-NS) is well reproduced by a King model and it appears different from the profile of M54. We considered the characteristics of Sgr-NS (color, integrated magnitude, central surface brightness) with respect to the underlying Sgr field and we find that Sgr-NS behaves as a typical faint dwarf Elliptical Nucleus. While M 54 has been claimed to be the Sgr nucleus, the photometric properties of Sgr-NS are more typical of a dwarf elliptical nucleus than those of M 54. It is important to remark that the Sgr dSph would appear as a nucleated galaxy even if M54 would be removed from its center.

Nevertheless, the spatial coincidence of M 54 and Sgr-NS is impressive and needs to be explained. We can envisage three possible frameworks that may be consistent with the observations. First an in situ origin can be imagined for both M54 and Sgr-NS. In this scenario the first generation of (metal-poor) stars of Sgr formed a bright and compact nucleus at the bottom of the potential well of the galaxy (M54). The remaining enriched gas formed subsequent generations of stars following the same density profile, driven by a similar potential. Hence, the recycled (and chemically enriched) gas accumulated within and around M54 and subsequently formed the observed Sgr-NS. The difference in the density profiles of the two systems seems to militate against this hypothesis. Further interesting clues in this sense may be obtained comparing the velocity dispersion profiles of the two RGB samples within $r_{h54}$.

Second, the Sgr-NS can be made by star captured by M 54 from the Sgr field (a possibility already suggested by Smith, Rich, & Neil 1998). A reliable, quantitative exploration of this scenario would require properly designed dynamical simulations that are clearly beyond the scope of the present analysis.

Finally, M54 may be an ordinary globular that has been brought to the central nucleus of Sgr by the dynamical friction. This hypothesis would naturally explain the spatial coincidence of the cluster and Sgr-NS and the difference in the density profiles of the two structures that, in this case, would have different and independent natures. The viability of this scenario can be verified with simple analytical arguments.

The dynamical friction (DF) process is the deceleration experienced by a massive object due to the interactions with particles in the surrounding field. It is an N-body problem which does not admit an exact analytical solution. However, Binney & Tremaine (1987) studied the orbital evolution of a massive object immersed in an isothermal halo. By means of a few assumptions, they were able to derive a simple formula for the total time, $t_{DF}$, required for a body to spiral from an initial radius $R_i$ to the bottom of the halo potential well. In Figure 6 we plotted $t_{DF}$ as a function of $R_i$ for two objects of $10^4 M_⊙$ (the M 54 mass), and $10^4 M_⊙$ (roughly the mass of the other Sgr's globular clusters, see Pryor & Meylan 1993; Mandushev, Staneva, & Spasova 1994). We assumed as initial velocity (relative to the surrounding field) the Sgr central velocity dispersion as measured by Ibata et al. (1997), $σ=11.4$ km s$^{-1}$. We also assumed the Sgr tidal radius as maximum impact parameter of the massive body with a halo particle. We recall here that, assuming a distance modulus (m-M)$_0=17.10$ (Monaco et al. 2004), the core and tidal radii of the Sgr main body ($r_{c54}^S=224$, $r_{t54}^S=1801$) measured by Majewski et al. (2003) correspond, respectively, to 1.7 kpc and 13.8 kpc.

From the inspection of Figure 6 it is evident that a massive cluster like M54 would have been seriously affected by DF in an Hubble time (assumed to be 13 Gyr) for any initial distance shorter than $3 r_{c54}^S=5.1$ kpc from the galaxy center. Conversely the other Sgr globulars, due to their smaller masses, would have been affected by DF only for initial distances lower than $1 r_{c54}^S$, while their actual positions are outside $r_{c54}^S$ (for instance, Ter 7 lie at about 3 kpc from M 54).

Hence, the spatial coincidence of NS and M54 can be easily explained if Sgr-NS was formed in situ in the tip of the Sgr potential well and M 54 has been driven to the galaxy center by dynamical friction.
Figure 9. Dynamical friction time scale as function of the initial distance from the Sgr center for M 54 (right continuous curve) and the other Sgr’s clusters (left continuous curve). An initial velocity of 11.4 km s\(^{-1}\) is assumed.

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