

## THE GLOBULAR CLUSTER AM 4: YET ANOTHER YOUNG GLOBULAR ASSOCIATED WITH THE Sgr DWARF SPHEROIDAL GALAXY?

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### ABSTRACT

The complete census of globular clusters formerly belonging to the Sagittarius Dwarf Spheroidal (Sgr dSph) galaxy and now deposited into the Galactic halo is an important contribution to our comprehension of the evolution and disruption of this dwarf galaxy. We investigate in this study the possibility that the poorly known “old” globular AM 4 might be associated with the Sgr dSph galaxy, and at the same time provides more solid estimate of its basic parameters. New high-quality BVI photometry is presented, from which an improved color–magnitude diagram is constructed, and estimates of age and distance are then derived. The distance and Galactic position are finally investigated in detail. AM 4 is found to be a low-luminosity ( $M_V = -1.82$ ) cluster undergoing strong tidal stress by the Milky Way and on the verge to be dissolved. Besides, and at odds with previous suggestions, we provide evidences that AM 4 is indeed young, with an age around 9 Gyr (as Terzan 7), but somewhat more metal poor ( $[Fe/H] = -0.97$ ). AM 4 is located at  $33^{+3}_{-4}$  kpc from the Sun, in a direction and at distance not totally incompatible with the Sgr dSph stream. Although we significantly improved our knowledge of AM 4, further studies are encouraged to obtain radial velocity and metallicity to demonstrate more firmly (or deny) the association to Sgr.

*Key words:* globular clusters: general – globular clusters: individual (AM 4)

*Online-only material:* color figures

### 1. INTRODUCTION

The number of star clusters associated with the Sagittarius Dwarf Spheroidal (Sgr dSph) galaxy increased significantly in the last few years due to the very detailed photometric and spectroscopic studies (Mottini et al. 2008; Sbordone et al. 2007; Carraro et al. 2007; Cohen 2004), which allow us to derive precise ages, distances, velocities, and metallicities of these clusters, to be compared with Sgr main body and stellar populations (Monaco et al. 2005). The last cluster to enter the family was Whiting 1 (Carraro et al. 2007), but there are indications that the newly discovered Segue 1 (Belokurov et al. 2007) might be as well associated with Sgr.

By increasing the number of star clusters formerly belonging to Sgr, we aim at improving our understanding of the chemical evolution and star formation history of this dwarf.

In this paper, we make a new case for a possible cluster associated with the Sgr dSph: AM 4.

This loose and faint cluster was discovered by Madore & Arp (1982), who placed it at the impressive distance of 200 kpc, based on the assumption that the brightest stars in the cluster ( $B \sim 21$ ) are horizontal-branch (HB) stars.

Later on, Inman & Carney (1987) provided the first photometric investigation in the  $B$  and  $V$  passbands which showed that the brightest stars are indeed turnoff (TO) stars, and therefore the cluster had to be much closer to us. Unfortunately, the data they provide are very poor, since—as the author discuss—the observations were hampered by unlucky conditions, and a proper photometric calibration was not possible. Therefore, no firm conclusions on the cluster fundamental parameters—most importantly on age and distance—could be derived. It was only pointed out that AM 4 is probably an old and metal-poor globular. Strangely enough, AM 4 remained unstudied for the last

21 years. We made an attempt to search into various archives, especially the one hosted by ESO,<sup>2</sup> but—after proper reduction—did not find data of sufficient quality to improve on the Inman & Carney (1987) early study. This motivated the present study. This paper is mainly intended to draw more attention on this overlooked cluster and boost new observational campaigns to better characterize it.

The plan of this paper is as follows. In Section 2, we present and discuss the observational material and details of the reduction of the data. In Section 3, we describe the new color–magnitude diagram (CMD) we derived from the acquired data. Section 4 is dedicated to star counts and the determination of the cluster structural properties by using King models, whereas in Section 5 we derive the cluster luminosity function (LF) and integrated magnitude. AM 4 age, reddening, metallicity, and distance are discussed in Section 6. Section 7 addresses the possibility of the membership to Sgr and, finally, Section 8 summarizes our results and prospects further lines of investigation.

### 2. OBSERVATIONS AND DATA REDUCTION

The observations were performed at the Las Campanas Observatory, using the 1.0 m Swope telescope equipped with the Site 3 2048 × 3150 CCD camera. The field of view is about  $14'8 \times 22'8$  with a scale  $0.435 \text{ arcsec pixel}^{-1}$ . The observations were conducted on the nights of 2006 June 28. Preliminary processing of the CCD frames was done with standard routines in the IRAF package.

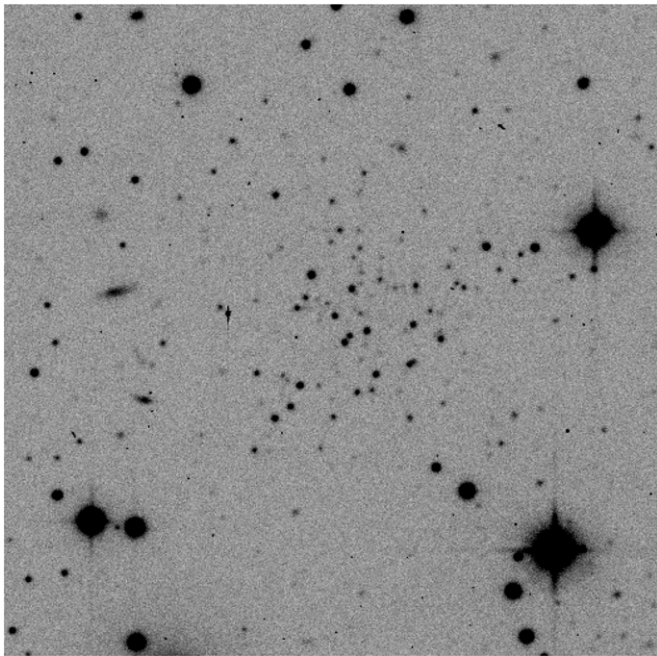
Both dome and sky flat-field frames were obtained in each filter, and the images have also been linearity corrected (Hamuy et al. 2006). The average seeing was  $1''.20$  along the entire night. We observed 96 standard stars from repeated observations of the three fields Mark A, PG 1657, PG 2213, and SA 110 (Landolt

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**Table 1**  
Log of Photometric Observations on 2006 June 28

Cluster	Filter	Exp. Time (s)	Airmass
AM 4	<i>B</i>	15, 300, 1500, 1800	1.00–1.18
	<i>V</i>	10, 30, 900, 1200	1.00–1.07
	<i>I</i>	10, 30, 180, 1000	1.01–1.20
SA110	<i>B</i>	60 × 2, 40 × 2	1.00–1.45
	<i>V</i>	30 × 2, 20 × 3	1.02–1.48
	<i>I</i>	30 × 2, 20 × 3	1.10–1.53
PG 1657	<i>B</i>	30 × 3, 300	1.11–1.40
	<i>V</i>	2 × 30, 25, 100	1.13–1.46
	<i>I</i>	2 × 10, 50, 150	1.19–1.55
Mark A	<i>B</i>	2 × 10, 300	1.00–1.15
	<i>V</i>	2 × 40, 50, 2 × 100	1.00–1.17
	<i>I</i>	2 × 10, 100, 2 × 150	1.02–1.20
PG 2213	<i>B</i>	2 × 40, 2 × 100,	1.17–1.59
	<i>V</i>	2 × 10, 25, 2 × 100	1.20–1.66
	<i>I</i>	2 × 10, 50, 2 × 150	1.27–1.80



**Figure 1.** Zoom of a  $V$  900 s exposure around AM 4 region. The North is up, and the East is to the left. The image is about  $6'$  on a side.

1992). A journal of the observations is reported in Table 1, where a zoom of a region around AM 4 is shown in Figure 1.

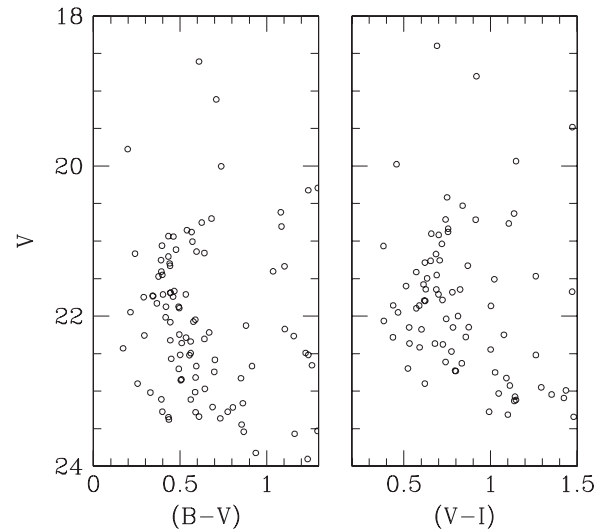
The following relations between the instrumental (lower case letters) and the standard colors and magnitudes were adopted, as derived using 80–100 standard stars:

$$V = 22.115(0.004) + v - 0.068(0.007) \times (B - V) + 0.16(0.02) \times X \quad (1)$$

$$B = 22.084(0.004) + b + 0.054(0.007) \times (B - V) + 0.30(0.02) \times X \quad (2)$$

$$I = 22.179(0.006) + i + 0.058(0.009) \times (V - I) + 0.06(0.02) \times X \quad (3)$$

where  $X$  is an airmass. Second-order color terms have been computed, but turned out to be negligible. The instrumental



**Figure 2.** CMDs in the area of AM 4. Only the stars having photometric errors both in color and magnitude smaller than 0.1 mag, and located within  $1/8$  from the cluster center, are considered. In the upper panel we show the  $V$  vs.  $(B - V)$  CDM, while in the lower panel the  $V$  vs.  $(V - I)$ .

photometry was extracted with the DAOPHOT/ALLSTAR V2.0 (Stetson 1987) package. Aperture photometry of standards was obtained with an aperture radius of  $6''.69$  (14 pixels). For stars from the cluster area, we obtained profile photometry and aperture, correct them before the transformation of instrumental photometry into the standard system, following the technique described in Patat & Carraro (2001, Appendix A1).

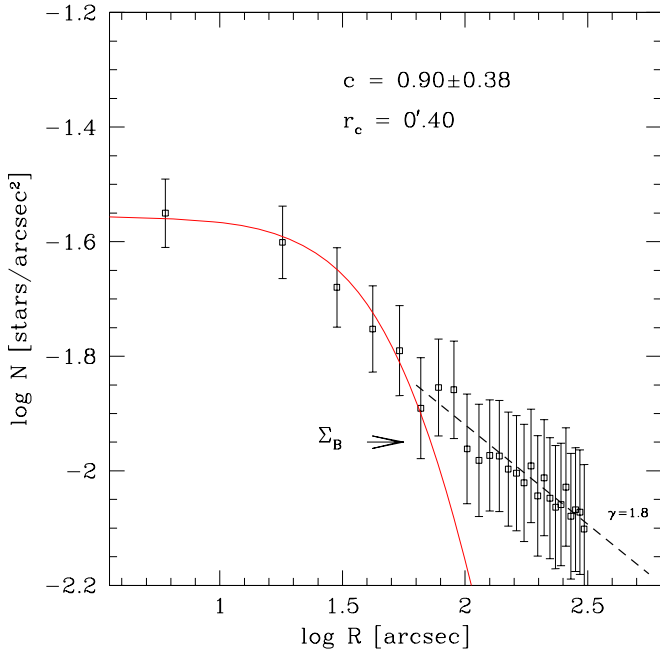
The coordinates of all objects were transformed to a common pixel grid defined by the reference image using DAOMATCH/DAOMASTER. We then corrected the photometry for the zero-point offset in each filter and created a master list of all objects. The instrumental magnitudes are calculated as weighted averages of magnitudes measured on individual frames. The final catalog contains 9477 stars and will be made available at the CDS database.

### 3. COLOR-MAGNITUDE DIAGRAM

We extracted all the stars (79 in number) within  $1/8$  from the cluster center and built up the CMD shown in Figure 2. Only the stars having photometric errors smaller than 0.1 both in color and magnitude have been considered. The left CMD is in the  $V$  versus  $(B - V)$  plane, whereas the right CMD is in the  $V$  versus  $(V - I)$  plane. The two CMDs look somewhat different. The left one is quite clear, with a TO point at  $V = 21.2$ ,  $(B - V) = 0.4$ , and, in general, looks much clearer than the Inman & Carney (1987) one. The subgiant branch is as well clear but, as already emphasized by Inman & Carney, the red giant branch (RGB) is almost absent, and no hints for an HB or red giant clump are visible. The main sequence (MS) however is well defined down to 23.5, below which our photometry lacks completeness (see Section 5). On the other hand, the right-panel CMD is much sparser, and we only recognize the TO, at  $V = 21.2$ ,  $(V - I) \sim 0.6$ . Due to the larger scatter in the star distribution in this color combination CMD, in the following we are going to use mainly the  $V$  versus  $(B - V)$  diagram for our analysis.

### 4. CLUSTER STRUCTURE

A glance at Figure 1 shows clearly that AM 4 is a faint and sparse cluster lacking any symmetry, such as Whiting 1



**Figure 3.** Surface density profile of AM 4. The solid line is the best-fit King model achieved with the parameters indicated in the upper right corner. Note the strong presence of extratidal stars out of  $\log(r) \sim 2$ .  $\Sigma_B$  indicates the mean level of the field.

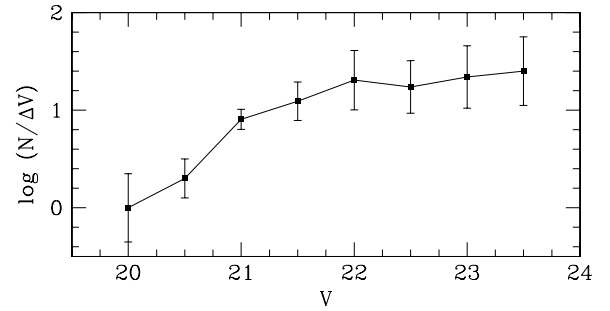
(A color version of this figure is available in the online journal.)

(Carraro et al. 2007) or Palomar 5 (Odenkirchen et al. 2001). We performed a star count analysis to provide an estimate of the cluster structural parameter. The center of the cluster has been chosen at R.A. = 13:56:21.7, decl = -27:10:03. We constructed around this position concentric rings 15'' wide to build up a radial density profile.

The result is shown in Figure 3, where the best-fit King profile is shown as solid curve, and drawn for the parameters indicated in the upper right corner. The symbol  $\Sigma_B$  indicates the mean level of the field, as counted in a region far away from the cluster, and amounting to 40 stars arcmin<sup>-2</sup>. As already found for Palomar 13 (Coté et al. 2002) and Whiting 1 (Carraro et al. 2007), we outline the presence of a conspicuous extratidal star population—in this case the tidal radius  $r_t$  is at about  $\log(r) = 2$ —whose slope in the profile is compatible with model expectations (Johnston et al. 1999). This result emphasizes how AM 4 is undergoing significant tidal stress by the Galactic potential, which is going to lead to the complete disruption of this cluster. Our best fit yields a concentration parameter  $c = 0.90$ , and a core radius of about half an arcmin.

## 5. LUMINOSITY FUNCTION AND INTEGRATED MAGNITUDE

With the aim of measuring the integrated apparent magnitude ( $V_t$ ) of AM 4 and its absolute magnitude, we have determined its LF. To do this, we estimated the completeness of our photometry by running experiments with artificial stars. We used the routine ADDSTAR within DAOPHOT to insert 1500 artificial stars at random positions over the whole field and within the magnitude range of the real stars. This number of artificial stars was chosen so that a reasonable number of them (about 30% of the real star population) would lie within the cluster radius ( $\sim 1/8$ ). This was done for both the long and the short exposures. We then reduced the images with the artificial stars in exactly the same



**Figure 4.** Completeness and field star corrected LF of AM 4.

**Table 2**  
Completeness Results for AM 4

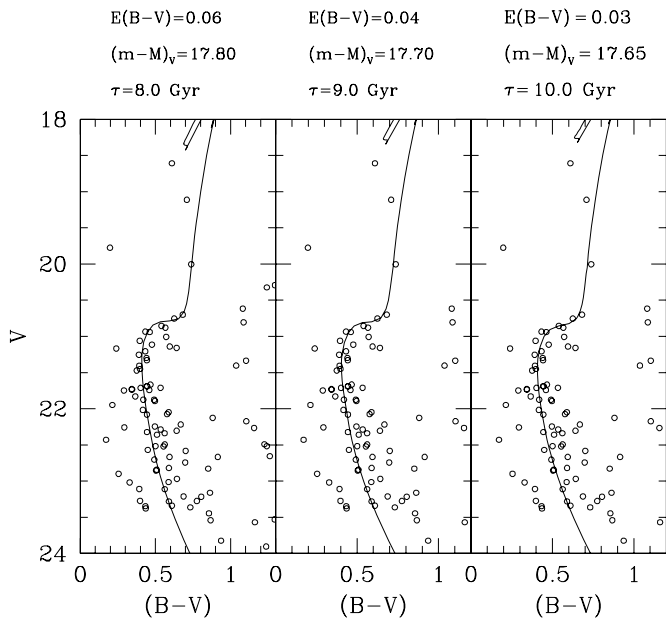
$V$	$R \leq 1/80$
20.5	100.0
21.0	99.2
21.5	96.9
22.0	83.6
22.5	75.0
23.0	68.5
23.5	59.6

manner as the real images. The ratio of the number of artificial stars recovered by ALLSTAR to the number inserted defines the completeness. This experiment was run 10 times using a different seed number with the random number generator that ADDSTAR uses in the calculation of the positions and magnitudes of the artificial stars. The mean values that were found for the completeness are listed in Table 2. To construct the faint part of the LF, we placed two curves on either side of the MS and parallel to the ridge line defined by the concentration of cluster stars. We then counted the number stars within this band that have  $20.0 \leq V \leq 23.5$ . In exactly the same way, we counted the stars in the field, far beyond the cluster radius, that lie in the same region of the CMD. This field contribution was normalized to the area and subtracted from each of the magnitude bins of the LF. The background and completeness corrected LF is shown in Figure 4, where the error bars are the ones indicated by Poisson statistics. The LF keeps raising down to  $V \approx 22$  mag, then flattens out toward faint magnitudes. In *normal* globular clusters, the LF continues to rise. Flat LFs that resemble AM 4's have been observed in globular clusters that appear to be undergoing tidal stripping by the gravitational field of the Milky Way (MW; e.g., Pal 5, Koch et al. 2004; Pal 13, Coté et al. 2002; Whiting 1, Carraro et al. 2007).

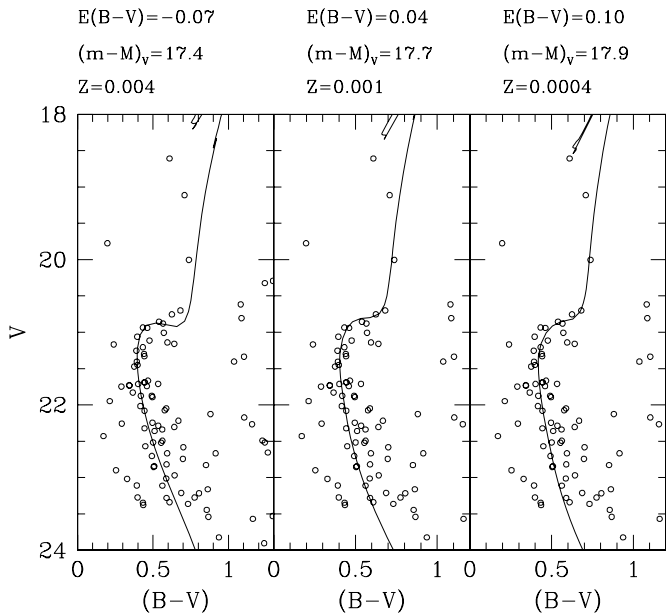
To obtain  $V_t$ , we use LF in Figure 5. The integration of this LF yields  $V_t = 15.88$ . This value and the distance modulus of  $(m - M)_V = 17.70$  yield  $M_V = -1.82$  for AM 4. We therefore confirm that AM 4 is the least luminous globular cluster in the MW halo (Harris 1996).

## 6. CLUSTER FUNDAMENTAL PARAMETERS

Lacking any estimate of AM 4 metal abundance, we rely on the comparison with theoretical isochrones from the Padova suite of models (Girardi et al. 2000) to derive the cluster fundamental parameters. This is quite a difficult exercise, since the CMD does not show any obvious HB or red clump stars, making it difficult to solve the age-metallicity degeneracy. For this reason, we adopt a conservative approach, which consists in exploring different ages at fixed metallicity and different



**Figure 5.** CMD of AM 4. Superimposed are different age isochrones adopting  $Z = 0.001$ . The fits in each panel have been obtained for the set of parameters indicated above each diagram.



**Figure 6.** CMD of AM 4. Superimposed are different metallicity isochrones adopting an age of 9 Gyr. The fits in each panel have been obtained for the set of parameters indicated above each diagram.

metallicity at fixed age. The exercise is shown in Figures 5 and 6, where we fit the star distribution in the  $V$  versus  $(B - V)$  CMD with fixed metallicity and varying age (Figure 5), and fixed age and varying metallicity (Figure 6). The only constraint we have is the reddening, which in the direction of AM 4 is  $E(B - V) = 0.05$  according to the Schlegel et al. (1998) maps. In Figure 5, we explore a possible age range assuming  $Z = 0.001$  as starting point, which turns into  $[\text{Fe}/\text{H}] = -1.27$ , and adjust isochrones for ages of 8 (left panel), 9 (middle panel), and 10 Gyr (right panel). Looking carefully at the fit it appears that for this metallicity an age around 8–9 Gyr provides a better match to the TO region for an acceptable value of the reddening.

Turning now to Figure 6, we try to fit the CMD assuming an age of 9 Gyr, and employing different metallicity isochrones, namely  $Z = 0.004$  (left panel),  $Z = 0.001$  (middle panel), and  $Z = 0.0004$  (right panel). This plot convincingly shows that the combination of 9 Gyr and  $Z = 0.001$  provides a good fit to the CMD, since the low-metallicity isochrone implies a too large reddening and poorly fits the TO, whereas the higher metallicity isochrone ( $Z = 0.004$ ) requires an unphysical negative reddening and at the same time produces a clear mismatch in the TO region.

Playing a bit more in detail with the best-fit isochrone, we suggest that AM 4 is  $9.0 \pm 0.5$  Gyr old and have a  $Z = 0.002$  ( $[\text{Fe}/\text{H}] = -0.97$ ) metal content. This final fit is shown in Figure 7 (left panel), whereas in the right panel we compare AM 4 with Terzan 7, which is known to be coeval (9–10 Gyr old), but metal richer ( $Z = 0.004$ ). The two clusters look almost indistinguishable in the TO region, with some indication that AM 4 is slightly older. The lack of an RGB in AM 4 clearly makes it difficult to compare the two clusters in term of metallicity. We emphasize that this result makes AM 4 much younger than believed before (Inman & Carney 1987) and open new horizons to understand its nature and origin.

For this age and metallicity, its reddening turns out to be  $E(B - V) = 0.04 \pm 0.01$ , and its apparent distance modulus  $(m - M)_V = 17.70 \pm 0.20$ . This implies a heliocentric distance of  $33^{+3}_{-4}$  kpc. If we assume 8.0 kpc as the Sun distance to the Galactic center (Harris 1996), we find that AM 4 has the following Galactic Cartesian coordinates:  $X = +21$ ,  $Y = -17$ , and  $Z = +18$  kpc and, hence, is 28 kpc far from the Galactic center.

## 7. MEMBERSHIP TO SAGITTARIUS?

With these results in hands, we address now the possibility that AM 4 is not a genuine Galaxy globular cluster, but was formerly associated with some dwarf galaxy which deposited it into the Galactic halo. The most appealing case is a possible relation with the Sgr dSph.

Lacking any estimate of AM 4 radial velocity, to investigate this association we make use of the Law et al. (2005) model of the Sgr stream for a spherical Galactic Dark Matter halo, and of the Majewski et al. (2003, 2004) Sgr M giants sample, and compare their position and distance with AM 4 in Figure 8.

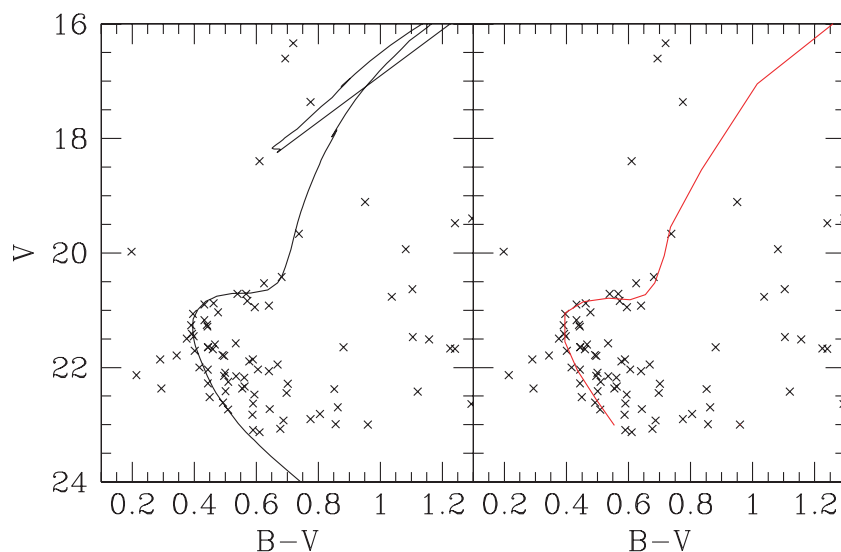
To perform this comparison, we first translate AM 4 coordinates and distance in the reference system of the Sgr orbital plane, following Majewski et al. (2003, 2004).<sup>3</sup> In the lower panel of Figure 8, we show the position of AM 4 in the  $\lambda_{\odot}$ ,  $\delta_{\odot}$  plane. Clearly, AM 4 position differs from the M giant sample, being much higher above the Galactic plane. Still, it is marginally compatible with the Law et al. model.

From the upper panel, we learn on the contrary that AM 4 position is basically consistent both with the model points and with the M giants. This seems to indicate a possible association with Sgr, which future studies have to confirm or deny.

## 8. CONCLUSIONS

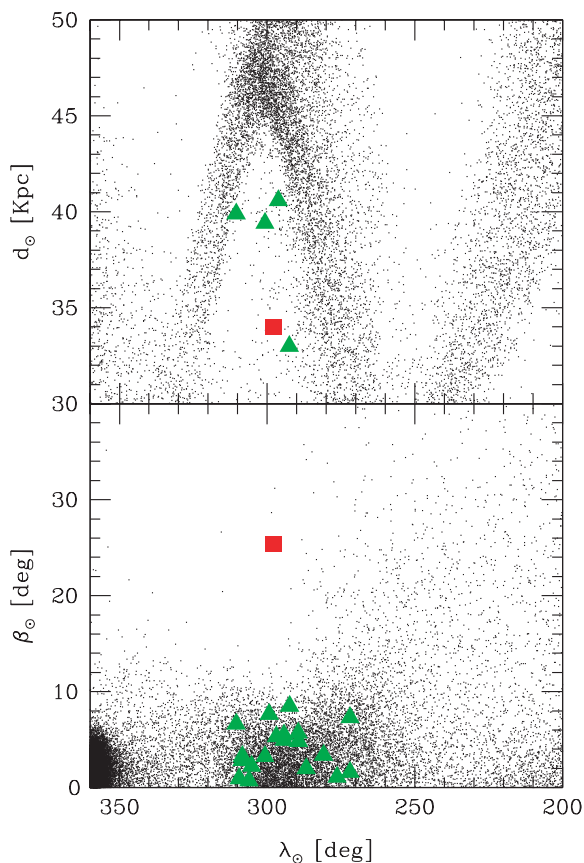
We have presented new CCD photometry in the field of the loose and faint globular cluster AM 4, and provided improved estimates of its fundamental parameters. The analysis of the radial density profile and LF demonstrates that AM 4 is undergoing a strong tidal interaction with the Galaxy potential,

<sup>3</sup> <http://www.astro.virginia.edu/srm4n/Sgr>



**Figure 7.** Best-fit isochrone for an age of 9 Gyr and a metallicity  $Z = 0.002$  is superimposed into AM 4 CMD (left panel). The right panel presents the same AM 4 CMD, with superimposed Terzan 7 ridge line from Buonanno et al. (1995).

(A color version of this figure is available in the online journal.)



**Figure 8.** Law et al. (2005) model of the Sgr tidal stream is indicated here by small dots. Big triangles represent Majewski et al. (2003, 2004) M giants belonging to the stream and finally the big square stands for AM 4.

(A color version of this figure is available in the online journal.)

resulting in a significant loss low-mass stars, mostly located outside the tidal radius. This explains the loose star distribution we see in Figure 1, which hardly resembles a normal globular cluster. However, this star distribution is the typical one of stripped globular clusters, such as Whiting 1, E 3, or several

Palomar clusters, which reinforces the idea of AM 4 being an almost dissolved star cluster, whose origin can indeed be extragalactic.

Interestingly, we find that the cluster is younger than previously thought, with an age close to or slightly larger than Terzan 7. The metallicity we propose is not lower than  $[\text{Fe}/\text{H}] = -1.0$ , but this value must be confirmed by future spectroscopic studies. The young age of AM 4 suggests that it came from the destruction of a satellite and the Sgr dSph is an obvious possibility. We have shown that the cluster distance and position in the halo are not totally incompatible with an association with the Sgr dSph which as well has to be more firmly investigated by measuring the radial velocity of AM 4. However, both the location, and the age and metallicity we infer lend some support to the possibility that AM 4 was formed inside Sgr, and then deposited into the Galactic halo.

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