



Publication Year	2018
Acceptance in OA	2020-10-15T13:16:51Z
Title	The STREGA survey - II. Globular cluster Palomar 12
Authors	MUSELLA, ILARIA, DI CRISCIENZO, Marcella, MARCONI, Marcella, RAIMONDO, Gabriella, RIPEPI, Vincenzo, Cignoni, M., Bono, G., BROCATO, Enzo, DALL'ORA, Massimo, Ferraro, I., GRADO, ANIELLO, Iannicola, G., Limatola, L., MOLINARO, Roberto, Moretti, Maria Ida, Stetson, P. B., Capaccioli, M., Cioni, M. -R. L., GETMAN, FEDOR, SCHIPANI, Pietro
Publisher's version (DOI)	10.1093/mnras/stx2543
Handle	http://hdl.handle.net/20.500.12386/27841
Journal	MONTHLY NOTICES OF THE ROYAL ASTRONOMICAL SOCIETY
Volume	473



The STREGA survey – II. Globular cluster Palomar 12[★]

I. Musella,^{1†} M. Di Criscienzo,^{2†} M. Marconi,¹ G. Raimondo,³ V. Ripepi,¹
M. Cignoni,⁴ G. Bono,⁵ E. Brocato,² M. Dall’Ora,¹ I. Ferraro,² A. Grado,¹
G. Iannicola,² L. Limatola,¹ R. Molinaro,¹ M. I. Moretti,¹ P. B. Stetson,⁶
M. Capaccioli,⁷ M.-R. L. Cioni,^{8,9} F. Getman¹ and P. Schipani¹

¹INAF–Osservatorio Astronomico di Capodimonte, Salita Moiarriello, 16, I-80131, Napoli, Italy

²INAF–Osservatorio Astronomico di Roma, Via Frascati 33, I-00044 Monte Porzio Catone, Italy

³INAF–Osservatorio Astronomico Collurania, via M. Maggini, I-64100 Teramo, Italy

⁴Dipartimento di Fisica ‘Enrico Fermi’, Università di Pisa, largo Pontecorvo 3, I-56127 Pisa, Italy

⁵Dipartimento di Fisica, Università degli Studi di Roma–Tor Vergata, via della Ricerca Scientifica 1, I-00133 Roma, Italy

⁶NRC Herzberg Astronomy and Astrophysics, 5071 West Saanich Road, Victoria, BC V9E 2E7, Canada

⁷Dipartimento di Fisica, Università ‘Federico II’, Via Cinthia, I-80126 Napoli, Italy

⁸Leibniz–Institut für Astrophysik Potsdam, An der Sternwarte 16, D-14482 Potsdam, Germany

⁹University of Hertfordshire, Physics Astronomy and Mathematics, College Lane, Hatfield AL10 9AB, UK

Accepted 2017 September 26. Received 2017 September 25; in original form 2017 July 6

ABSTRACT

In the framework of the STREGA (STRucture and Evolution of the GALaxy) survey, two fields around the globular cluster Pal 12 were observed with the aim of detecting the possible presence of streams and/or an extended halo. The adopted stellar tracers are the main sequence, turn-off and red giant branch stars. We discuss the luminosity function and the star counts in the observed region covering about 2 tidal radii, confirming that Pal 12 appears to be embedded in the Sagittarius Stream. Adopting an original approach to separate cluster and field stars, we do not find any evidence of significant extra-tidal Pal 12 stellar populations. The presence of the Sagittarius stream seems to have mimicked a larger tidal radius in previous studies. Indeed, adopting a King model, a redetermination of this value gives $r_T = 0.22 \pm 0.1$ deg.

Key words: Hertzsprung–Russell and colour–magnitude diagrams – globular clusters: individual: Palomar 12 – Galaxy: halo – Galaxy: structure.

1 INTRODUCTION

This paper is the second of a series devoted to the results of the STRucture and Evolution of the GALaxy (STREGA) survey (Marconi et al. 2014). This is a guaranteed-time project that uses the ESO Very Large Telescope Survey Telescope (VST) to observe extensive regions around a number of globular clusters (GCs) and satellite galaxies of the Milky Way, in order to map the existence of extended haloes and/or tidal streams with the final aim of constraining the formation and evolution of the Galactic halo. A detailed description of this survey is reported in Marconi et al. (2014). In this paper, we describe the results we obtain by exploring a region of more than 1 square degree around the GC Pal 12. This target is located at $(l, b) = (30.51, -47.68)$ deg, it has an absolute visual magnitude $M_V = -4.47$ mag, a half-light radius of 1.72 arcmin (=

0.03 deg), a tidal radius r_T and a core radius r_C , obtained on the basis of a King model with a central concentration $c = \log(r_T/r_C)$ (Harris 1996; McLaughlin & van der Marel 2005), of 17.42 arcmin (= 0.29 deg) and 0.02 arcmin (= 0.0003 deg, with $c = 2.98$), respectively. It is worth noting that van den Bergh (2011) pointed out that the small stellar sample contained in the cluster and the presence of substructures might cause errors in the measured central concentration and in the determination of the structural radii. This GC is probably younger and more metal rich than the majority of the Galactic GCs (GGCs, Gratton & Ortolani 1988; Stetson et al. 1989; Rosenberg et al. 1998). On this basis, many authors have suggested the possibility that this GC was accreted from a surrounding galaxy such as, for example, the Magellanic Clouds (e.g. Lin & Richer 1992; Zinn 1993, and references therein). Conversely, Irwin (1999) pointed out that distance and radial velocity of Pal 12 are consistent with the hypothesis that it has been captured by our Galaxy in a tidal interaction with the Sagittarius dwarf Spheroidal (Sgr dSph) galaxy. The latter hypothesis was supported by Dinescu et al. (2000) through the determination of the proper motions and the 3D orbit of Pal 12. The presence of an additional stellar population

[★] In memory of our beloved colleague and friend Geppina Coppola.

† E-mail: ilaria.musella@oacn.inaf.it (IM); marcella.marconi@oacn.inaf.it (MM)

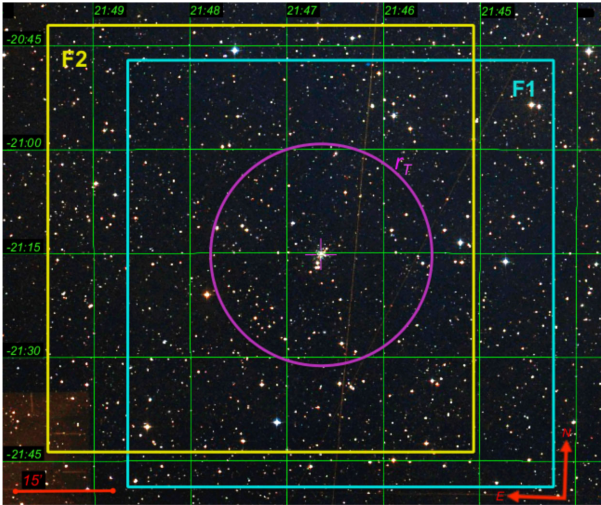


Figure 1. A DSS Image of the region around Pal 12 covered by the two selected VST fields labelled as F1 and F2. The magenta circle shows the area included in the tidal radius of 0.29 deg.

in the direction of this GC was detected by Martínez-Delgado et al. (2002) analysing a large field around Pal 12 and by Bellazzini et al. (2003) using data from the 2-Micron All-Sky Survey. This population appears to be at the same distance (within the uncertainties), but more metal poor than Pal 12, even if with a significant spread in metallicity and/or age, as expected for a dSph galaxy. This stellar population was confirmed to be a part of the Sgr stream through a comparison of its colour–magnitude diagram (CMD) with that of the Sgr dSph main body and/or with previous CMDs of portions of the Sgr southern stream (see e.g. Majewski et al. 1999; Newberg et al. 2002, and references therein).

In this paper, exploiting the potentiality of the large field of view of VST, we study the stellar populations around this cluster to better investigate its properties and the extent of its halo, taking into account the already known presence of the Sgr stream.

In Section 2, the observations and the data reduction procedures are described. An analysis of the Pal 12 CMD is presented in Section 3 and the luminosity function and the star counts around this cluster are discussed in Sections 4 and 5, respectively. The summary closes the paper.

2 OBSERVATIONS AND DATA REDUCTION

In the first paper of the STREGA survey (Marconi et al. 2014), we presented preliminary results obtained for one field centred on the GC Pal 12 (F1). In this field, a large part of the cluster fell in the central gap of the VST camera OMEGACAM, and for this reason we subsequently observed another field (F2) with Pal 12 centred in one of the CCDs.

The final observed region is shown in Fig. 1. The observations of the F1 and F2 fields were performed on 2013-07-1/2 and 2014-07-21/22, with exposure times of 170 s, 160 s and 405 s for the g , r and i bands, respectively.

The data reduction was carried out with the VST-Tube imaging pipeline (Grado et al. 2012). The detailed procedure is described in Marconi et al. (2014).

To derive stellar photometry, we used the DAOPHOT/ALLSTAR (Stetson 1987) programs that allowed us to perform point spread function (PSF) fitting method to obtain accurate photometry even for the stars

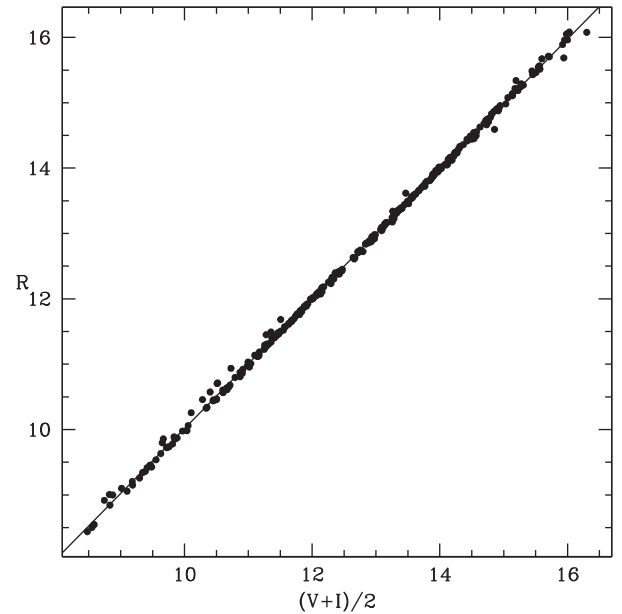


Figure 2. R versus $(V + I)/2$ for the Landolt standards used to calibrate the Johnson–Kron–Cousins photometric system (Landolt 1992).

in the crowded centre of Pal 12. First, we combined the photometry of the two fields in each band, assuming for the stars in the overlapping region with two different magnitude estimates, an average of the two values weighted with the photometric uncertainties. To minimize the non-stellar or spurious objects, the final gri catalogue includes only the stars with $\chi < 1.5$.¹

This catalogue was calibrated on the basis of independent and accurate BVI photometry (Stetson, private communication), already used in Marconi et al. (2014). This photometry was transformed into the $ugriz$ photometric system, using the equation in table 3 in Jordi, Grebel & Ammon (2006), and the well-defined relation between R and $(V + I)/2$ for the Landolt standards used to calibrate the Johnson–Kron–Cousins photometric system (Landolt 1992):

$$R = 0.003(\pm 0.001) \times (V + I)/2 + 0.08(\pm 0.02)$$

with a rms = 0.04. This relation is shown in Fig. 2. This means that we have calibrated photometry in three SDSS bands (gri) and in four Johnson–Kron–Cousins ($BVRI$) bands.

In our photometric data, we have areas with two exposures (the central region overlap between F1 and F2 except for the gaps between the Omegacam CCDs) and areas with a single observation as the quoted gaps and the region external to the fields overlap. In Fig. 3, we report the number of stars in magnitude bins for the three bands, g (black line), r (green line) and i (red line) for the external (left-hand panel) and central (right-hand panel) regions, respectively. From this plot we infer that to obtain the same completeness limit for all the covered area, we need to take $g_{\text{lim}} = 23$ mag, $r_{\text{lim}} = i_{\text{lim}} = 22$ mag corresponding to the limit magnitudes for single exposure areas. The photometric uncertainties in the g , r and i bands, within these magnitude limits, are less than 0.05 mag.

¹ The DAOPHOT/ALLSTAR χ parameter of each star is a robust estimate of the ratio of the observed pixel-to-pixel scatter of the fitting residuals to the expected scatter. The χ in the final catalogue is an average of the χ values in the single frame and single band file.

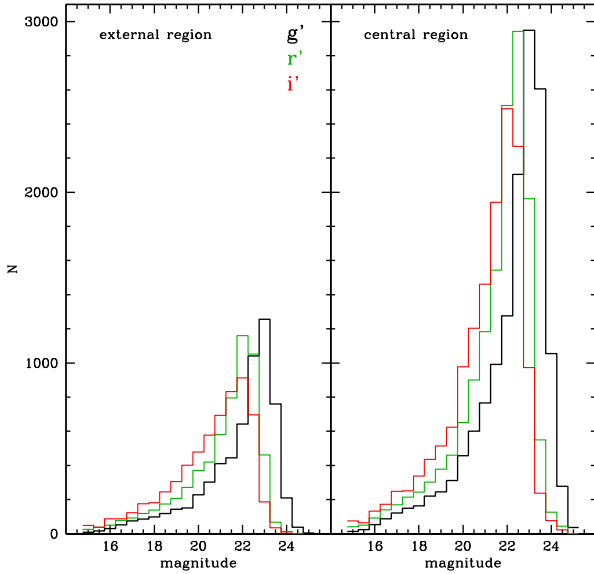


Figure 3. Histogram of number of stars in magnitude bins for the three bands, g (black line), r (green line) and i (red line) for the external (left-hand panel) and central (right-hand panel) regions.

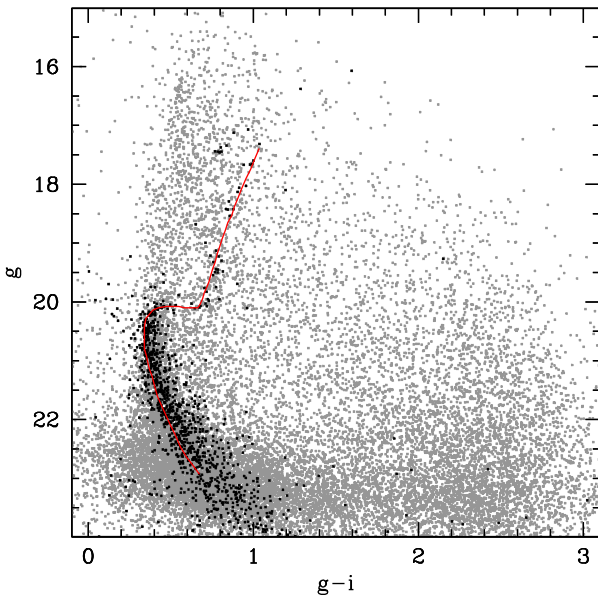


Figure 4. The g , $g-i$ CMD for all the stars in the observed area (grey dots). The stars in the region centred on Pal 12 and with radius less than the half-mass radius are in black and the derived empirical ridge line is in red.

3 PAL 12 CMD

In Fig. 4 we show the g , $g-i$ CMD for the entire area (grey dots). Black symbols represent stars included in the region centred on Pal 12 within the known half-mass radius ($r_h = 0.03$ deg, Harris 1996). The red line represents the Pal 12 ridge line obtained taking into account the stars with $r < 0.05$ deg from cluster centre.

In their paper (see their fig. 1), Martínez-Delgado et al. (2002) have used a CMD with a particular combination of bands ($\langle V \rangle = (B+R)/2$ versus $B-R$) that shows the presence of a well-defined structure, distinct from the Pal 12 main sequence (MS), bluer than Pal 12 and overlapping the cluster MS for $B-R \sim 0.8$ mag and V magnitude fainter than 21 mag.

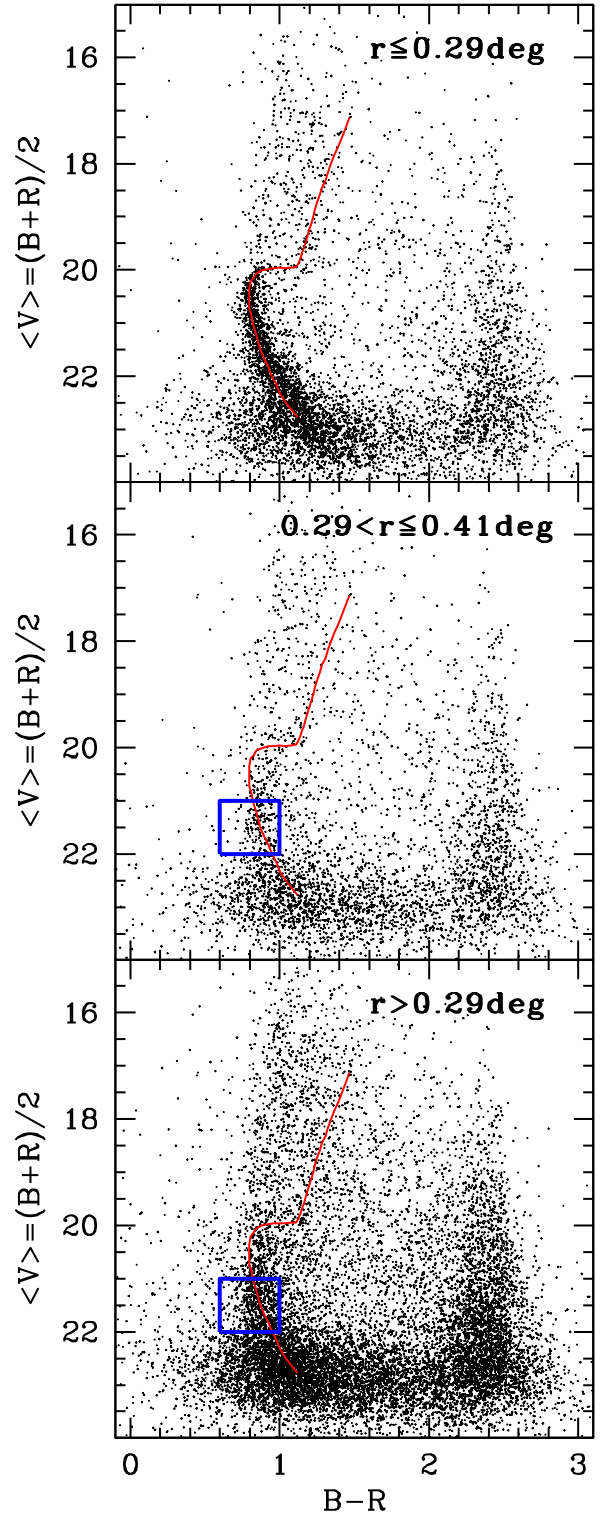


Figure 5. $\langle V \rangle$, $B-R$ CMDs for the stars with radius less than and greater than the tidal radius r_T are plotted in the upper and lower panels, respectively. The red line is the derived empirical ridge line for Pal 12. The blue box shows the overdensity pointed out by Martínez-Delgado et al. (2002)

In Fig. 5, we show the CMD for stars with $r \leq r_T$ (upper panel) and $r > r_T$ (lower panel). In the middle panel, we plot the CMD for the annular region with $r > r_T$ and area equal to that included within one tidal radius ($0.29 < r \leq 0.41$ deg). The red line represents the Pal 12

ridge line as in Fig. 4. To better distinguish the stellar overdensity identified by Martínez-Delgado et al. (2002) for $\langle V \rangle$ fainter than about 21 mag and $B - R$ colour between 0.6 and 1.0 mag, we use a blue box to mark this CMD region. The presence of this overdensity in our data will be more evident using the luminosity functions (LFs) in the next section.

Using a control field located in the north at $l = 28.7$ and $b = 42.2$ deg, Martínez-Delgado et al. (2002) showed that this structure cannot be ascribed to the Galactic halo. They pointed out that this population shows a significant width in colour, signature of a possible range in metallicity and/or age and/or depth, typical of a stream of a dwarf galaxy. Moreover, they conclude that on the basis of its position and extension on the sky, this structure could be part of the Sgr tidal stream (see e.g. Newberg et al. 2002).

To analyse our data and get information about the stellar content in Pal 12 and in the above mentioned overdensity (see next section), we used the stellar population synthesis code Stellar POPulation Tool (SPoT, Brocato et al. 1999, 2000; Raimondo et al. 2005; Raimondo 2009) to compute both synthetic CMDs and LFs. Here, we used the version of the code optimized to reproduce the properties of poorly populated stellar systems, like those studied in this work. For this purpose, the code relies on Monte Carlo techniques to generate stars according to an initial mass function (IMF), in a way that takes into account statistical effects due to the number of stars in the different evolutionary phases in low-luminosity stellar systems. In the present version, the IMF is assumed to be a Kroupa-like function from 0.1 to $100 M_{\odot}$, the evolutionary tracks are from the Basti data base (Pietrinferni et al. 2004, and references therein), and the stellar atmospheres come from Castelli & Kurucz (2003).

Earlier studies of Pal 12 CMD (see Section 1) suggested that the cluster is somewhat younger than the vast majority of Galactic GCs with a metallicity of $[\text{Fe}/\text{H}] \sim -1.0$ dex (e.g. Gratton & Ortolani 1988; Stetson et al. 1989; Rosenberg et al. 1998). Spectroscopic studies of a few cluster stars concluded that Pal 12 is quite metal-rich, with values ranging from $[\text{Fe}/\text{H}] = -0.6$ dex (Armandroff & Da Costa 1991, from low-resolution spectroscopy) to $[\text{Fe}/\text{H}] = -1.0$ dex (Brown, Wallerstein & Zucker 1997) and $[\text{Fe}/\text{H}] \sim -0.8$ dex (Cohen 2004) from high-resolution spectroscopy. Interestingly, these studies found that Pal 12 stars do not show α -elements enhancement, but rather very peculiar abundance ratios (Cohen 2004), which seem to further support the scenario of a cluster tidally stripped from the Sgr galaxy (Cohen 2004; Sbordone et al. 2007). Bearing in mind this complex picture, in Fig. 6 we plot the CMD of the stars within the half-light radius of Pal 12 ($r \leq r_h$) – in such a way as to avoid large field star contamination – together with three synthetic simple stellar populations with ages $t = 8, 9$ and 10 Gyr, metallicity $[\text{Fe}/\text{H}] = -0.96$ dex (left-hand panels) and $[\text{Fe}/\text{H}] = -0.66$ dex (right-hand panels), both with a solar-scaled composition ($[\alpha/\text{Fe}] = 0.0$). The fitting values for the distance modulus and interstellar reddening (as labelled in Fig. 6) depend on the adopted age and metallicity. Using the values labelled in Fig. 6, the inferred mean distance and reddening are $(m - M)_0 = 16.3 \pm 0.1$ mag, which is consistent – within the uncertainties – with estimates published in the literature (e.g. Rosenberg et al. 1998, and references therein) and $E(B - V) = 0.03 \pm 0.01$ mag in agreement with $E(B - V)$ by Schlegel, Finkbeiner & Davis (1998) (recalibrated by Schlafly & Finkbeiner (2011), see also fig. 8 in Marconi et al. 2014). On this basis, we confirm an age of 8 – 10 Gyr, and a rather high metallicity ($[\text{Fe}/\text{H}] - 0.96$ to -0.66 dex) for a GC in the Galaxy’s outer halo. Note that a small contamination by stars belonging to the Sgr stream is not excluded.

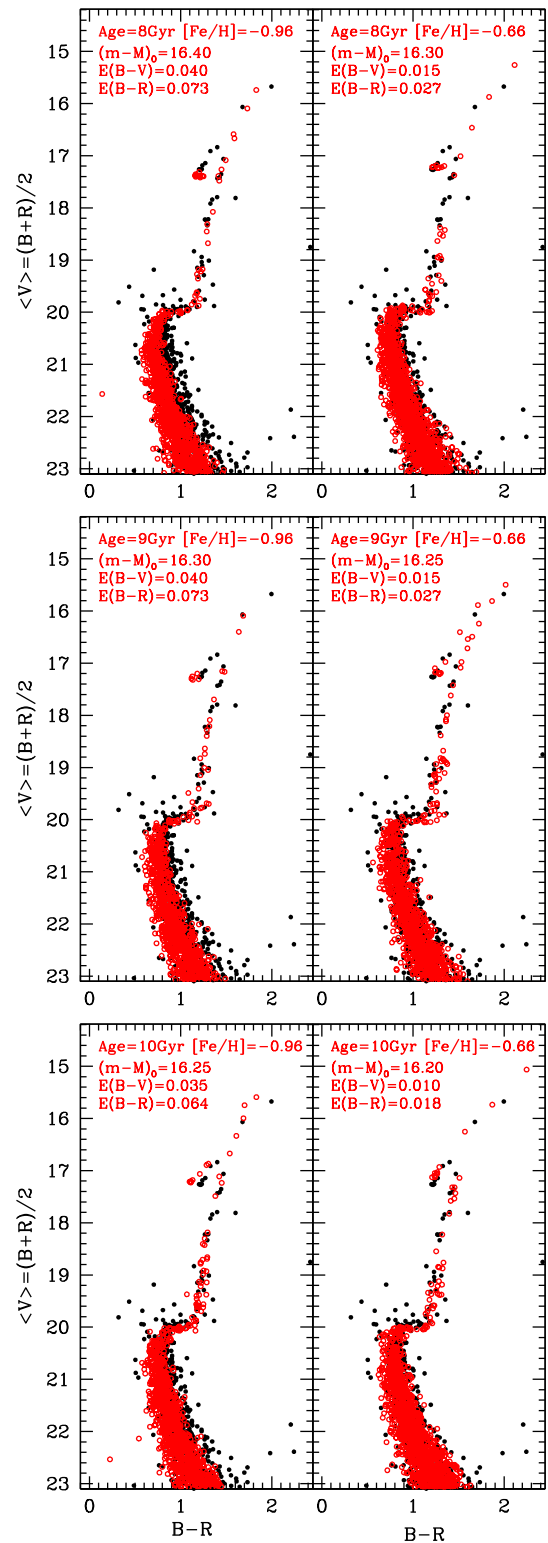


Figure 6. Three simple stellar populations (red open circles) aged 8 (top), 9 (middle) and 10 Gyr (low) with $[\text{Fe}/\text{H}] = -0.96$ dex (left) and $[\text{Fe}/\text{H}] = -0.66$ dex (right) are superimposed on the CMD of stars within the half-light radius of Pal 12 (black filled circles). Each simulation accounts for a total V magnitude of ~ -3.7 mag, corresponding to the magnitude at the half-light radius as derived from Harris’s catalogue. Some photometric uncertainty is also included. The fitting values for distance modulus and interstellar reddening are labelled in figure. The extinction law adopted is that by Cardelli, Clayton & Mathis (1989).

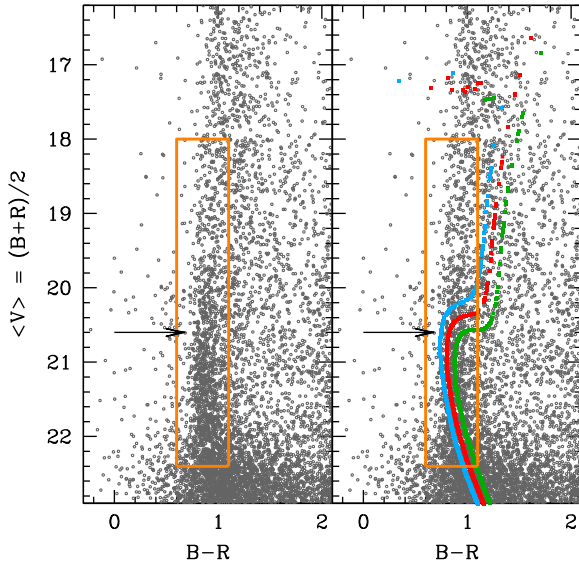


Figure 7. Left-hand panel: CMD of stars in the extra-tidal region of F1 field (grey circles). The selection box is shown in orange. Right-hand panel: synthetic stellar populations (squares) with $t = 13$ Gyr and $[\text{Fe}/\text{H}] = -1.27$ dex (sky blue), $[\text{Fe}/\text{H}] = -0.96$ dex (red) and $[\text{Fe}/\text{H}] = -0.66$ dex (green), representative of the old components in the Sgr dSph galaxy, are overlaid. A distance modulus of 16.30 mag and $E(B - V) = 0.03$ mag are adopted. In each panel the arrow indicates the feature at $\langle V \rangle = 20.6$ mag, see the text.

4 LUMINOSITY FUNCTIONS

In their paper, Martínez-Delgado et al. (2002) compared the LF of the apparent stellar overdensity to that of the control field, and to a theoretical LF obtained in the same colour and magnitude range and with the same distance and reddening as Pal 12. From this comparison, the authors argued the presence of a stellar population with an age of 12.6 Gyr and $Z = 0.001$, although the number of detected stars is too small to reach a firm conclusion. Our analysis is based on a wider field of view that contains a larger number of stars. Therefore, we proceeded to investigate the stellar overabundance shown in Fig. 5 by analysing the LF of stars in the extra-tidal region, where the contribution of the Pal 12 stars is negligible. For this purpose we take into consideration only the F1 field and select stars with $r > r_T$ in the $\langle V \rangle$ magnitude range 18–22.4 mag and $(B - R)$ colour between 0.6 and 1.1 mag (as in Martínez-Delgado et al. 2002). $V = 22.4$ mag is the completeness limit in the visual band on the basis of the g , r and i limit magnitudes obtained in Section 2. These choices allow us not only to avoid objects with large photometric uncertainties and serious field contamination, but also to take into consideration the possible presence of multiple stellar populations and/or a distance spread. The left-hand panel of Fig. 7 illustrates the CMD of all extra-tidal stars in F1 (grey circles) and the colour-magnitude box (orange rectangle) considered in our analysis.

In each panel of Fig. 8 we show the LF of stars in the selection box (black solid line), compared to that of all stars in the extra-tidal field (black dotted line). The former LF likely includes stars belonging to the Sgr stream with a contamination of Galactic field and possibly of extra-tidal Pal 12 stars. As stated above, it has been proved with many different tracers that the disruption of the Sgr dSph galaxy produces huge tidal tails extending for many tens of kiloparsecs from the parent galaxy, with tidally stripped stars wrapping a full 360° around the celestial sphere (see e.g. Newberg et al. 2002;

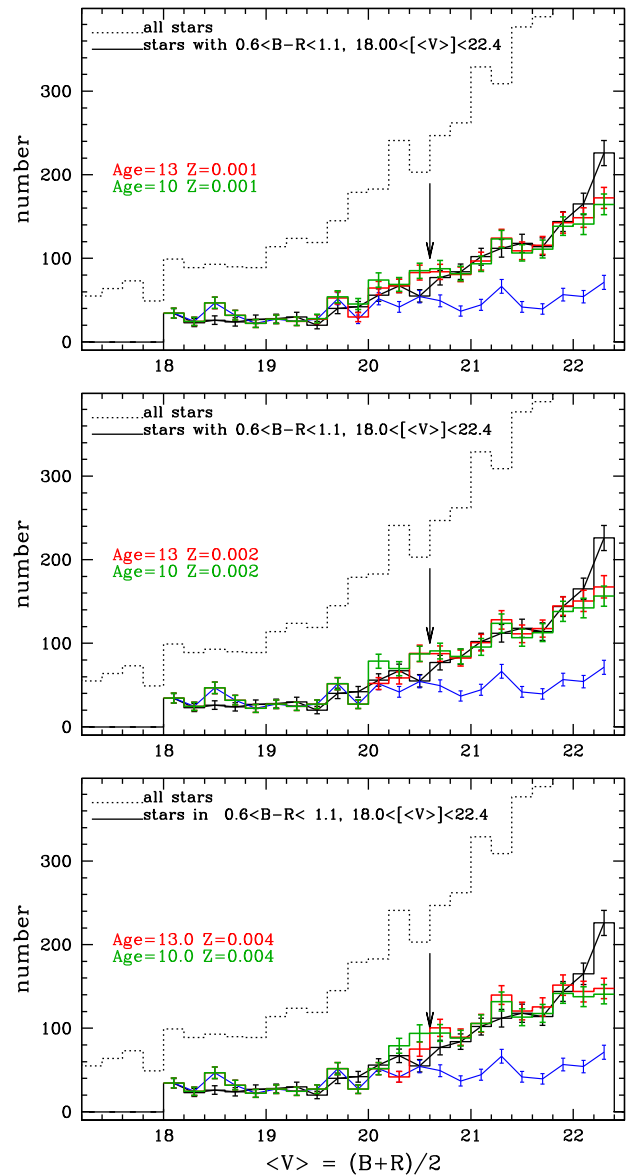


Figure 8. Luminosity functions of all extra-tidal-field stars in F1 (black dotted line) and of stars in the selection box (black solid line) are plotted together with the LF of stars in the control field (blue line, see the text for details). From upper to lower panel: the observed LFs are compared with the synthetic ones obtained for stellar populations with the indicated age and metallicity, for which a distance modulus of 16.3 mag and $E(B - V) = 0.03$ mag have been adopted. The arrow is drawn at magnitude $\langle V \rangle = 20.6$ mag (see the text and Fig. 7).

Majewski et al. 2003; Martínez-Delgado et al. 2004; Belokurov et al. 2014). Recent simulations also predict the existence of several arms extending to hundreds of kiloparsecs (see e.g. Dierickx & Loeb 2017). Since we did not observe a reference field far away from the stream, to investigate the star overdensity we considered the contribution of Galactic field stars using the LF in the control field observed by Martínez-Delgado et al. (2002, see their fig. 2) and rescaled to the area covered by our extra-tidal region (blue solid line in Fig. 8). From Fig. 8 one may note that in the magnitude range from $\langle V \rangle \sim 18$ to ~ 19.9 mag the control-field and the extra-tidal star LFs are comparable. Hence, in this magnitude range,

we do expect stars likely belonging to the Galaxy only, while for magnitudes fainter than 20.6 mag (this value is marked with an arrow in Fig. 7) the observed LF displays an overabundance which increases with the magnitude, and likely includes stars of the Sgr stream.

To tentatively analyse the stellar content of such a stellar over-density, we consider the limiting case of a negligible amount of extra-tidal Pal 12 stars (i.e. none). According to Bellazzini et al. (2006), the bulk of the stellar population in the Sgr galaxy is mainly composed of stars older than ~ 8 Gyr with metallicity $Z \lesssim 0.004$, with the age limit decreasing if the metallicity increases to $Z = 0.008$. Amongst the population older than 1–2 Gyr, Monaco et al. (2003) established from the analysis of a sample of horizontal branch stars that a fraction, around ~ 10 per cent, have an age $\gtrsim 10$ Gyr and metallicity $[\text{Fe}/\text{H}] \lesssim -1.3$ dex. Additional populations composed of very metal-rich stars with an age of 1 Gyr or younger have been detected, e.g. by Bonifacio et al. (2004). Moreover, high-resolution spectroscopic studies showed that some abundance anomalies are present also in stars of the Sgr dwarf spheroidal galaxy (e.g. Carretta et al. 2010; McWilliam, Wallerstein & Mottini 2013). Anyway, taking into account the photometric and other uncertainties, the assumption of solar-scaled models to predict theoretical LFs for the stream stars does not introduce biases into our analysis. Assuming that the overdensity is located at nearly the same average distance adopted for Pal 12 [$(m - M)_0 = 16.3$ mag with an uncertainty of ~ 0.1 mag], with an interstellar reddening of $E(B - V) = 0.03$ mag, we perform a comparison with several synthetic populations with different ages and metallicities. From this analysis, the feature at 20.6 mag (showed in the right-hand panel of Fig. 7) appears to be consistent with old ($t \gtrsim 10$ Gyr) populations with the best-fitting synthetic population model corresponding to $t \sim 13$ Gyr and mean metallicity $Z \lesssim 0.004$ with the more metal-poor stars at bluer colours and the more metal-rich stars at redder colours. This result is shown in the right-hand panel of Fig. 7 in which we plot the synthetic populations with $t = 13$ Gyr and metallicities $Z = 0.001, 0.002, 0.004$ (corresponding to $[\text{Fe}/\text{H}] = -1.27, -0.96$ and -0.66 dex).

In the three panels of Fig. 8, we also show the theoretical LFs resulting from the sum of the control-field stars and of the synthetic stars with $t = 10$ and 13 Gyr and $Z = 0.001, 0.002, 0.004$, always assuming a Pal 12 distance of 16.3 mag. In detail, for each assumed age and metallicity, the synthetic LF is derived by averaging the number of stars in each magnitude bin over 100 CMD simulations, with uncertainty due to statistical effects. A variation of the Pal 12 distance modulus from 16.2 to 16.4 mag does not cause visible changes. The number of stars in each simulation is chosen to be equal to the observed number of stars in the selection box after subtracting control-field stars. This means about 690 stars, likely belonging to the stream and distributed at the distance of Pal 12. As already stated, we assumed a negligible number of Pal 12 stars in the extra-tidal field, so that the previous number represents an upper limit for stream stars. Each of the adopted models can produce an equally good fit taking into account the uncertainties due to photometric measurements, interstellar reddening and distance. On this basis, we cannot obtain firm constraints on the age and chemical composition of the overdensity, likely populated by a mixture of old and metal-poor/intermediate-metallicity populations. This hypothesis is in agreement with Bellazzini et al. (2006), who analysing the horizontal branch (HB) stars in the core of the Sgr galaxy and in a wide field located tens of kpc away from the centre of the galaxy itself, concluded that old and metal-poor populations appear to be preferentially stripped from the Sgr galaxy during the past peri-Galactic passages with respect to the

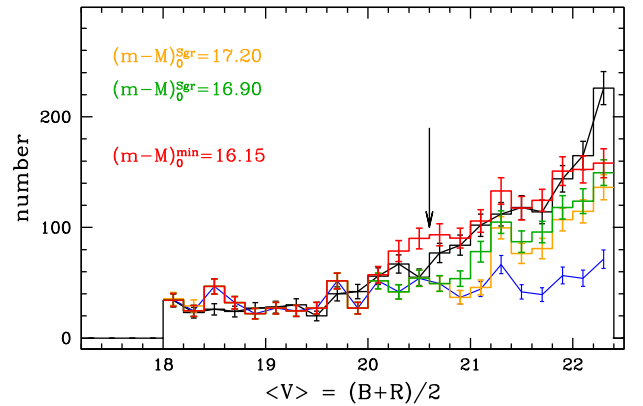


Figure 9. The LF of the extra-tidal stars in the selection box (black) is compared to the LF of a synthetic population with age 13 Gyr and $[\text{Fe}/\text{H}] = -0.96$ dex located at a minimum distance of $(m - M)_0 = 16.15$ mag (red) and at the distance of Sgr galaxy, for which we consider a minimum (maximum) value of $(m - M)_0 = 16.9$ mag (17.2 mag), green and orange line, respectively.

intermediate-age intermediate-metallicity population that presently dominates its bound core.

To investigate the impact of a possible distance spread of stream stars, we considered different assumptions about their distance modulus, from a value as near as $(m - M)_0 = 16.15$ mag ($d \sim 17$ kpc), suggested by Martínez-Delgado et al. (2002), up to the Sgr distance. Note that the lower limit is within the uncertainty of the distance for Pal 12 published in the literature (e.g. Gratton & Ortolani 1988): $(m - M)_0 = 16.1 \div 16.5$ mag. On the other hand, the available estimates of the Sgr distance range from a short value of $(m - M)_0 = 16.90 \pm 0.15$ mag (Alard 1996) to a long distance of $(m - M)_0 = 17.25^{+0.10}_{-0.20}$ mag (Bellazzini, Ferraro & Buonanno 1999). More recent estimates have been provided with different methods, and, in general, appear to favour long distances. For instance, from the analysis of the red giant tip, Monaco et al. (2004) obtained $(m - M)_0 = 17.10 \pm 0.15$ mag ($d = 26.3 \pm 1.8$ kpc) while from a sample of Sgr RR Lyrae stars of the MACHO data base, Kunder & Chaboyer (2009) found $d = 24.8$ kpc [$(m - M)_0 \sim 16.97$ mag]. More recently from the analysis of a large RR Lyrae stars sample from the OGLE-IV observations, Hamanowicz et al. (2016) obtained for the cluster M54 in the core of the galaxy $d = 26.7 \pm 0.03_{\text{stat}} \pm 1.3_{\text{sys}}$ kpc [$(m - M)_0 \sim 17.13$ mag]. In order to take into account these differences, we recomputed the theoretical LF assuming distances spanning from the shortest to the longest values mentioned above. In Fig. 9, we compare the LF of the F1 extra-tidal stars in the selection box (black solid line) to the synthetic LF obtained from a population with age 13 Gyr, and $[\text{Fe}/\text{H}] = -0.96$ dex located at 17 kpc (red line), 24 kpc (green line, the shortest distance value of the dwarf galaxy) and 27.5 kpc (orange line, the longest distance). The figure suggests that, even if a better agreement is found for a Pal 12 distance modulus of $(m - M)_0 = 16.3$ mag (Fig. 8), we cannot exclude the presence of a fraction of stars with longer or slightly shorter distances.

5 STAR COUNTS AROUND PAL 12

On the basis of the CMD for the stars included in the tidal radius (see top panel of Fig. 5) and following the procedure already adopted in Marconi et al. (2014), we consider as possible cluster members the stars lying in a range of ± 0.1 mag around the ridge line of Pal 12,

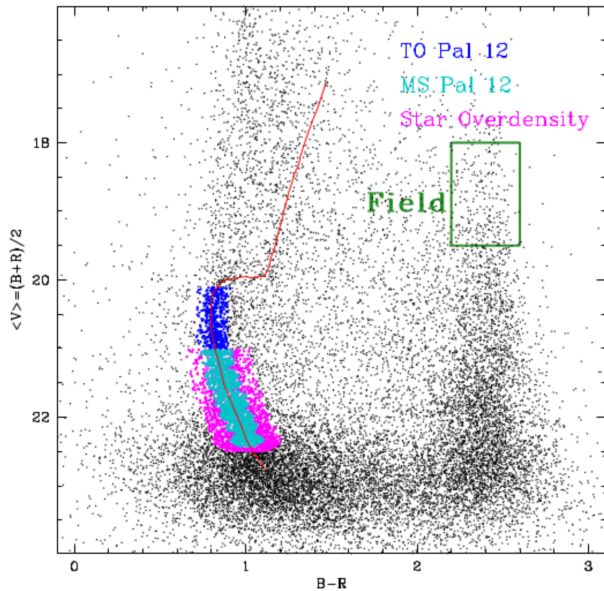


Figure 10. The $\langle V \rangle$, $B - R$ CMD with the stars with a distance of ± 0.1 mag from the ridge line (the red line) highlighted: blue and cyan for the Pal 12 TO and MS stars, respectively. The magenta stars have a colour distance ranging between 0.1 and 0.2 mag from the ridge line. The magenta and cyan regions include the star overdensity identified in Fig. 5.

marked in blue and cyan in Fig. 10. Blue dots represent the stars apparently belonging to the Pal 12 turn-off (TO); this CMD region is identified as ‘TO Pal 12’. The cyan CMD region includes stars possibly belonging to the Pal 12 MS, and therefore identified as ‘MS Pal 12’. Magenta stars are those with a colour distance from the ridge line ranging between 0.1 and 0.2 mag. Cyan and magenta regions include Pal 12 MS stars, but also stars belonging to the star overdensity already discussed. Finally, the region included in the green rectangle, labelled as ‘Field’, is not expected to host cluster members and can be used for comparison in our analysis. We adopt different ‘Field’ rectangle selections always obtaining the same result within the Poisson errors (see below).

In Fig. 11, we plot the radial counts of the normalized star densities for the different star selections in Fig. 10²: (i) in the upper-left panel, we show the blue and cyan stars labelled as ‘TO + MS Pal 12’; (ii) in the upper-right panel are the results obtained using the blue stars labelled as ‘TO Pal 12’; (iii) in the bottom-left panel, we show the results for the cyan and magenta stars labelled as ‘Star Overdensity’; and (iv) in the bottom-right panel are the star counts within the ‘Field’ green rectangle. To obtain these counts, we adopted 25 equally spaced annuli (1.2 arcmin), from the centre up to 0.5 deg, corresponding to about two tidal radii. For each selection, the star density in the i -th annulus is normalized to the total star density computed in the circle with the radius of 0.5 deg. The error bars result from the propagation of the Poisson errors and the vertical dashed line indicates the nominal Pal 12 tidal radius of 0.29 deg (Harris 1996). For all the selections, we obtain the typical profile of the globular cluster (see e.g. King 1966; Wilson 1975), except, as expected, for the ‘Field’ stars. The red line represents the King profile for the nominal values of Pal 12 core radius and tidal radius. For the region around the Pal 12 TO, the star count distribution follows the computed King profile. In the other two regions

² To plot these counts and the King profile in a logarithmic scale we add to the radial counts the average of the ‘Field’ counts.

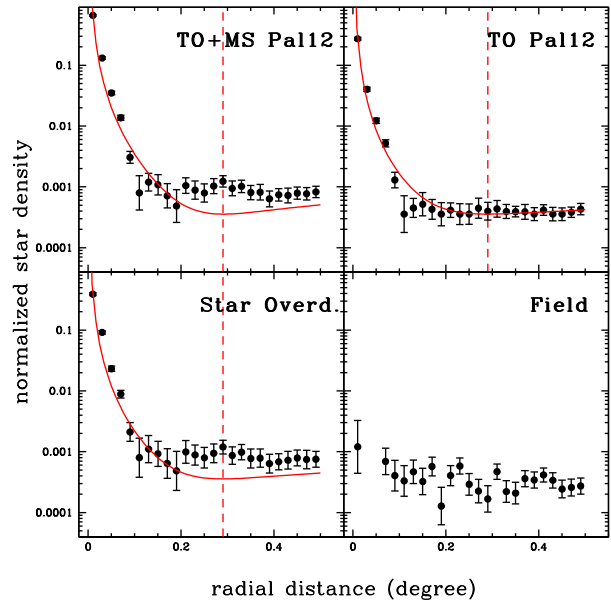


Figure 11. Radial counts of the normalized star densities for different star selections in Fig. 10 (see the text for details). The red solid line represents the King profile of Pal 12 for the core radius and tidal radius by Harris (1996) and the red vertical dashed line marks the r_T value.

(including the stellar overdensity), the normalized stellar density shows a shift towards higher values for radii larger than 0.2 deg. This shift is anomalous and is probably due to the presence of the overdensity. This might affect the determination of the King profile parameters, but it could also be due to the procedure adopted to select Pal 12 stars. To check this behaviour, we use an innovative and more complex approach to perform a more accurate separation of field and cluster stars. In particular, we adopt a procedure similar to that suggested by Di Cecco et al. (2015) and Calamida et al. (2017) that we call a ‘3D procedure’ to distinguish it from the previous one.

The key steps are the following: we estimated the ridge lines in the r , $g - r$ and r , $r - i$ CMDs tracing the cluster red-giant branch (RGB), the main sequence and the main sequence turn-off (MSTO). The candidate horizontal branch stars were not included since they are a small fraction of the cluster stellar population. The ridge lines were estimated neglecting the stars located in the innermost cluster regions ($r \leq 1'$) and applying severe cuts in radial distance and photometric accuracy. Fig. 12 shows the resulting 3D ridge line (red line) and the initial separation between candidate field (pink dots) and cluster (blue dots) stars.

Subsequently, we performed a linear interpolation amongst the r , $g - r$ and r , $r - i$ ridge lines and adopted two different statistical parameters to separate field and cluster stars. They are given below.

- (a) We assigned a figure of merit to the difference in the slopes of the three apparent magnitudes of each individual star and the three magnitudes of the cluster ridge line.
- (b) We estimated the cumulative standard deviation amongst the magnitudes of each individual star and the magnitudes of the cluster ridge line.

Then we generated a new 3D plot (see Fig. 13) in which candidate field (pink dots) and cluster (blue dots) stars were plotted as a function of the r -band magnitude, the difference in the slope and the cumulative standard deviation. We estimated two new ridge lines

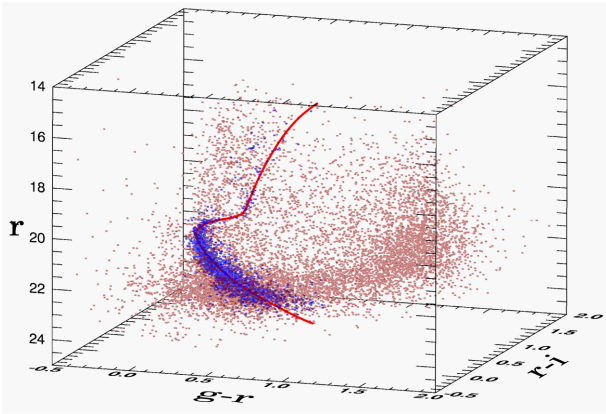


Figure 12. r , $g - r$, $r - i$ CMD of Pal 12. The blue dots are candidate cluster stars, while the pink dots are candidate field stars. The red solid line shows the 3D ridge line. See the text for more details concerning the selection criteria based on the ‘3D procedure’.

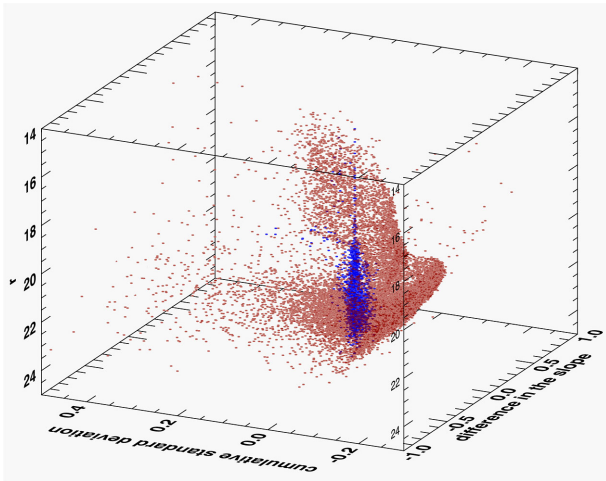


Figure 13. 3D plot showing the r -band magnitude as a function of the cumulative standard deviation and of the difference in the slope. The colour coding is the same as in Fig. 12, blue dots are candidate cluster stars, while pink dots are candidate field stars.

and the distance of individual objects from them was eventually adopted to provide the final separation between candidate field and cluster stars. Note that this approach was conservative, i.e. it was preferable to lose some possible candidate cluster members rather than including any possible candidate field stars.

Fig. 14 shows the g , $g - i$ (lower panels) and g , $g - r$ (upper panels) CMDs obtained with the 3D approach in which candidate field and cluster stars were plotted as pink and blue dots, respectively. The outcome for both filter combinations is the same not only concerning the candidate cluster stars, but also the magnitude and colour distribution of field stars.

Fig. 14 points out the advantages in using this multidimensional approach when compared with the classical approach based on bi-dimensional ridge lines: (i) data plotted in the left-hand panels show that the candidate cluster stars were properly selected not only along the RGB and the MSTO, but also in the fainter portion of the MS ($g \leq 22$ mag), i.e. in a region of the CMD in which field and cluster stars overlap in classical optical CMDs; (ii) the field star magnitude and colour distribution in the right-hand panel is quite homogeneous

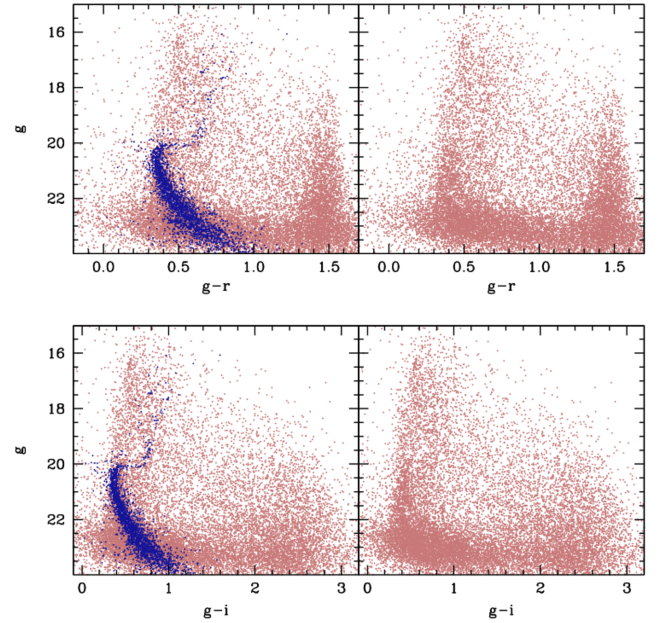


Figure 14. The g , $g - i$ and g , $g - r$ CMDs are shown in the lower and upper panels, respectively. Pink and blue dots represent the field and cluster stars, respectively, as obtained by the ‘3D procedure’ (see the text and Figs 12 and 13 for details).

and does not show the typical gaps left around bi-dimensional ridge lines.

In Fig. 15, we report the $\langle V \rangle$, $B - R$ CMD resulting from the ‘3D procedure’. In both panels, we show in grey the stars recognized as field, and in the upper panel, we plot in red the selected Pal 12 members. From inspection of the lower panel, excluding the selected Pal 12 members, the structure with magnitude fainter than 20 mag and colour ranging between 0.7 and 1.1 mag (blue rectangle) already noted in Fig. 5 is clearly present. The green rectangle, labelled ‘Field’ in the upper panel of Fig. 15, selected as in Fig. 4, represents a CMD region where we do not expect stars belonging to Pal 12 or the Sgr stream. It will be used for comparison in the following analysis.

The spatial distributions of the cluster (red dots) and field stars (black dots) in the blue rectangle are shown in the upper and lower panels of Fig. 16, respectively (the red cross in the lower panel marks the Pal 12 centre). In the lower panel we do not note any particular spatial overdensity and the comparison with the cluster stars in the upper panel suggests that at most few Pal 12 members have been missed by the adopted ‘3D procedure’. For this reason, in this structure we expect to have MW halo stars and, taking also into account the results of Martínez-Delgado et al. (2002), the overdensity due to the Sgr stream. Moreover, from this analysis it is clear that the ‘3D procedure’ appears to work very well to select Pal 12 members. On the other hand, with this approach it is very difficult to distinguish Pal 12 from Sgr stream stars due to the very similar CMD characteristics. For this reason, we expect that a fraction of the stream stars are assigned to Pal 12 and a fraction to the field.

In Fig. 17, we plot the radial counts of the normalized star densities for the different star selections in Fig. 15: (i) in the left-upper panel, we show the red stars, labelled ‘Pal 12’; (ii) in the right-upper and in the left-bottom panels, are the results obtained using only the stars with $V < 21$ and $V \geq 21$ mag, respectively; and (iii) in the right-bottom panel are the star counts for the ‘Field’ stars. To obtain these counts, we adopted the procedure described above. A

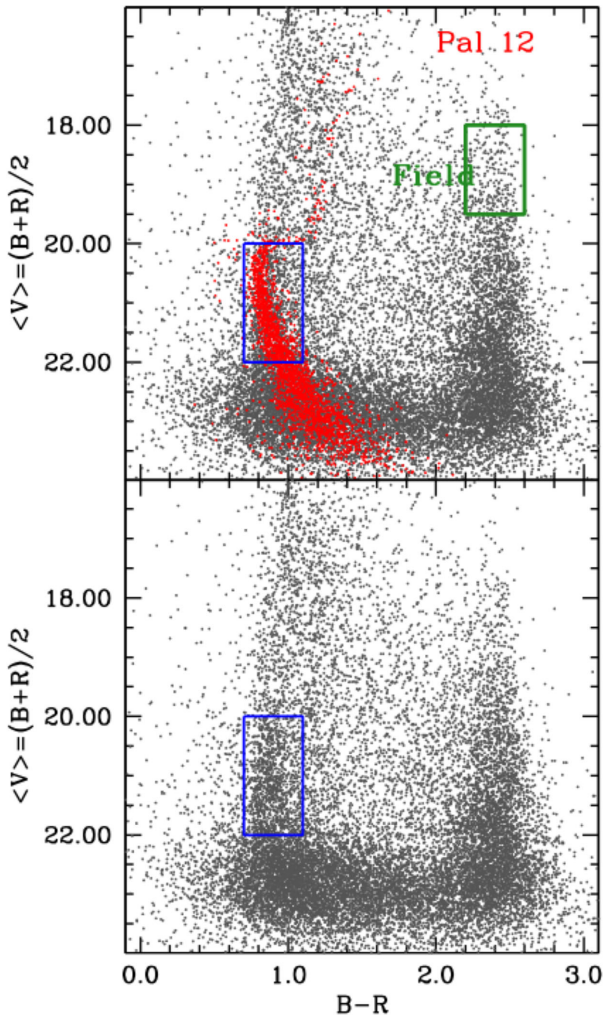


Figure 15. $\langle V \rangle$, $B - R$ CMD. In both panels, grey dots represent the field stars obtained by the ‘3D procedure’. In the upper panel the red dots are the selected cluster member stars and the green rectangle, labelled as ‘Field’, is a CMD region where we do not expect stars belonging to Pal 12 or the Sgr stream. The blue rectangle in the lower panel marks the overdensity CMD region. See the text for details.

comparison between Figs 11 and 17 shows that the selection of the cluster stars by the 3D procedure produces smaller Poisson errors (also in this case, we added to the radial counts the average of the ‘Field’ counts). For all the star selections in Fig. 17 we obtain a profile typical of a GC (see e.g. King 1966; Wilson 1975). ‘Field’ stars, as expected, are the same as in Fig. 11. Also in this case, the red line represents the King profile for the nominal value of Pal 12’s core radius and tidal radius. For the two selections in the left-hand panels (including the stellar overdensity), the normalized star density shows the expected excess of stars around the nominal tidal radius (vertical red dashed line) due to the stars belonging to the Sgr stream that our procedure cannot distinguish from Pal 12 members. For Pal 12 stars with $V < 21$ mag, we have an almost negligible overdensity around 0.29 deg, and the nominal tidal radius seems to be too high. Fitting a King profile to these data we obtain the blue solid line with $c = 1.68$, $r_c = 0.28$ arcmin and $r_T = 13.2$ arcmin = 0.22 deg (vertical blue dashed line). On the basis of these results, the presence of the Sgr stream seems to have mimicked a larger tidal radius (see Salinas et al. 2012). However we note that for $V < 21$

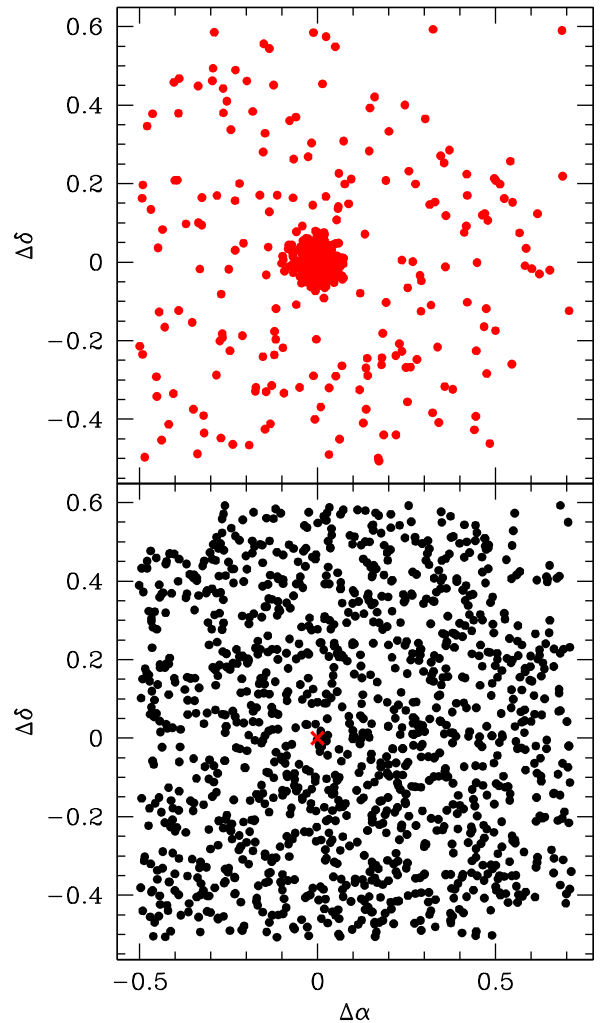


Figure 16. The spatial distribution of the cluster (red dots in the upper panel) and field stars (black dots in the lower panel) included in the blue rectangle of Fig. 15. The red cross in the lower panel marks the Pal 12 centre.

the number of stars is too small to get firm constraints on the King profile parameters.

6 CONCLUSIONS

In this paper, we have studied the LF and the star counts in a region around the globular cluster Pal 12, covering about two tidal radii. We have compared our analysis with previous studies that identified a CMD star overabundance, a possible signature of the Sgr stream from which Pal 12 was probably originated. Our study confirms the presence of a stellar overdensity at $\langle V \rangle$ fainter than ~ 20.5 mag and $B - R$ colour ranging between 0.6 and 1.0 mag. The analysis of the overdensity’s LF and CMD suggests a dominant stellar population older than 10 Gyr and with a mean metallicity $[\text{Fe}/\text{H}] \sim -1$ dex, consistent with the old stellar components in the Sgr dwarf galaxy. Most of these stars appear to be located at the distance of Pal 12 (~ 18.2 kpc), with a possible fraction of stars at shorter/longer distances (down to ~ 17 kpc/up to the Sgr distance).

The presence of the Sgr stream affects our evaluation of star counts as a function of the radial distance from the centre of Pal 12. This is more evident when adopting the ‘classical’ (bi-dimensional) approach of selecting the stars in a magnitude range around the

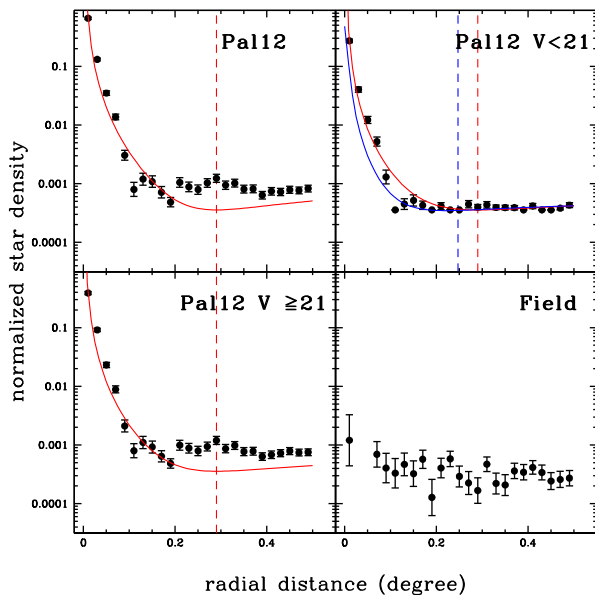


Figure 17. Radial counts of the normalized star densities for different star selections in Fig. 15 (see the text for details). The red solid line represents the King profile of Pal 12 for core radius and tidal radius by Harris (1996) and the red vertical dashed line marks this tidal radius. The blue solid line represents the King profile obtained in this paper from fitting the radial counts for Pal 12 stars with $V < 21$ mag, and the blue vertical dashed line marks the derived tidal radius.

ridge line in a specific CMD, to identify Pal 12 candidate members. On the other hand, the use of an innovative procedure based on a 3D ridge line (magnitude-colour-colour) allowed us to perform a better separation between Pal 12 and field stars and to significantly reduce the contamination from the Sgr stream.

We do not find evidence of significant extra-tidal Pal 12 stellar population. On the contrary, the presence of the Sgr stream might have simulated a larger tidal radius in previous studies.

ACKNOWLEDGEMENTS

This study is based on data collected with the ESO INAF – VLT Survey Telescope and OmegaCAM at the European Southern Observatory, Chile (ESO Programme 091.D-0623, 093.D-0170). This work has made use of BaSTI web tools. Partial financial support for this work was provided by PRIN-INAF 2011 Tracing the formation and evolution of the Galactic halo with VST (PI: M. Marconi), PRIN-INAF 2011 Galaxy Evolution with the VLT Surveys Telescope (VST) (PI: A. Grado) and PRIN-INAF 2014 project EX-CALIBURS (PI: G. Clementini).

REFERENCES

Alard C., 1996, *ApJ*, 458, L17
 Armandroff T. E., Da Costa G. S., 1991, *AJ*, 101, 1329
 Bellazzini M., Ferraro F. R., Buonanno R., 1999, *MNRAS*, 307, 619
 Bellazzini M., Ibata R., Ferraro F. R., Testa V., 2003, *A&A*, 405, 577
 Bellazzini M., Correnti M., Ferraro F. R., Monaco L., Montegriffo P., 2006, *A&A*, 446, L1
 Bellazzini M., Newberg H. J., Correnti M., Ferraro F. R., Monaco L., 2006, *A&A*, 457, L21
 Belokurov V. et al., 2014, *MNRAS*, 437, 116

Bonifacio P., Sbordone L., Marconi G., Pasquini L., Hill V., 2004, *A&A*, 414, 503
 Brocato E., Castellani V., Raimondo G., Romaniello M., 1999, *A&AS*, 136, 65
 Brocato E., Castellani V., Poli F. M., Raimondo G., 2000, *A&AS*, 146, 91
 Brown J. A., Wallerstein G., Zucker D., 1997, *AJ*, 114, 180
 Calamida A. et al., 2017, *AJ*, 153, 175
 Cardelli J. A., Clayton G. C., Mathis J. S., 1989, *ApJ*, 345, 245
 Carretta E. et al., 2010, *ApJ*, 714, L7
 Castelli F., Kurucz R. L., 2003, in N. Piskunov N., Weiss W. W., Gray D. F., eds, *Proc. IAU Symp. 210, Modelling of Stellar Atmospheres, Poster Contributions*. Kluwer, Dordrecht, p. A20
 Cohen J. G., 2004, *AJ*, 127, 1545
 Di Cecco A. et al., 2015, *AJ*, 150, 51
 Dierickx M. I. P., Loeb A., 2017, *ApJ*, 836, 92
 Dinescu D. I., Majewski S. R., Girard T. M., Cudworth K. M., 2000, *AJ*, 120, 1892
 Grado A., Capaccioli M., Limatola L., Getman F., 2012, *Mem. Soc. Astron. Ital. Supplementi*, 19, 362
 Gratton R. G., Ortolani S., 1988, *A&AS*, 73, 137
 Hamanowicz A. et al., 2016, *Acta Astron.*, 66, 197
 Harris W. E., 1996, *AJ*, 112, 1487
 Irwin M., 1999, in Whitelock P., Cannon R., eds, *Proc. IAU Symp. 192, The Stellar Content of Local Group Galaxies*. Kluwer, Dordrecht, p. 409
 Jordi K., Grebel E. K., Ammon K., 2006, *A&A*, 460, 339
 King I. R., 1966, *AJ*, 71, 64
 Kunder A., Chaboyer B., 2009, *AJ*, 137, 4478
 Landolt A. U., 1992, *AJ*, 104, 340
 Lin D. N. C., Richer H. B., 1992, *ApJ*, 388, L57
 Majewski S. R., Siegel M. H., Kunkel W. E., Reid I. N., Johnston K. V., Thompson I. B., Landolt A. U., Palma C., 1999, *AJ*, 118, 1709
 Majewski S. R., Skrutskie M. F., Weinberg M. D., Ostheimer J. C., 2003, *ApJ*, 599, 1082
 Marconi M. et al., 2014, *MNRAS*, 444, 3809
 Martínez-Delgado D., Zinn R., Carrera R., Gallart C., 2002, *ApJ*, 573, L19
 Martínez-Delgado D., Gómez-Flechoso M. Á., Aparicio A., Carrera R., 2004, *ApJ*, 601, 242
 McLaughlin D. E., van der Marel R. P., 2005, *ApJS*, 161, 304
 McWilliam A., Wallerstein G., Mottini M., 2013, *ApJ*, 778, 149
 Monaco L., Bellazzini M., Ferraro F. R., Pancino E., 2003, *ApJ*, 597, L25
 Monaco L., Bellazzini M., Ferraro F. R., Pancino E., 2004, *MNRAS*, 353, 874
 Newberg H. J. et al., 2002, *ApJ*, 569, 245
 Pietrinferni A., Cassisi S., Salaris M., Castelli F., 2004, *ApJ*, 612, 168
 Raimondo G., 2009, *ApJ*, 700, 1247
 Raimondo G., Brocato E., Cantiello M., Capaccioli M., 2005, *AJ*, 130, 2625
 Rosenberg A., Saviane I., Piotto G., Held E. V., 1998, *A&A*, 339, 61
 Salinas R., Jiřková L., Carraro G., Catelan M., Amigo P., 2012, *MNRAS*, 421, 960
 Sbordone L., Bonifacio P., Buonanno R., Marconi G., Monaco L., Zaggia S., 2007, *A&A*, 465, 815
 Schlafly E. F., Finkbeiner D. P., 2011, *ApJ*, 737, 103
 Schlegel D. J., Finkbeiner D. P., Davis M., 1998, *ApJ*, 500, 525S
 Stetson P., 1987, *PASP*, 99, 191S
 Stetson P. B., Hesser J. E., Smith G. H., Vandenberg D. A., Bolte M., 1989, *AJ*, 97, 1360
 van den Bergh S., 2011, *PASP*, 123, 1044
 Wilson C. P., 1975, *AJ*, 80, 175
 Zinn R., 1993, in Smith G. H., Brodie J. P., eds, *ASP Conf. Ser. Vol. 48, The Globular Clusters-Galaxy Connection*. Astron. Soc. Pac., San Francisco, p. 38

This paper has been typeset from a \LaTeX file prepared by the author.