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Segue 3: the youngest globular cluster in the outer halo⋆

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ABSTRACT

Deep Galileo (Telescopio Nazionale Galileo) *B*, *V* and *I* images of Segue 3, reaching $V \sim 25$, reveal that it is the youngest globular cluster known so far in the Galaxy. A young age of 3.2 Gyr is found, differently from a previous estimate of 12 Gyr. It also appears to be moderately metal rich with [Fe/H] ~ -0.8, rather than [Fe/H] ~ -1.7, as previously suggested by Fadely et al. A main difference in the age derivation relative to Fadely et al. comes from the consideration of subgiant branch stars in the isochrone fitting. A deduced distance of $d_{\odot} = 29.1$ kpc is compatible with the outer halo location of other low luminosity globular clusters.

Key words: Hertzsprung–Russell and colour–magnitude diagrams – globular clusters: individual: Segue 3 – Galaxy: halo.

1 INTRODUCTION

Segue 3 was discovered within the Sloan Digital Sky Survey (SDSS; Belokurov et al. 2010). The object was identified as a Milky Way star cluster, at a distance of ~16 kpc in Pegasus, possibly related to the Hercules–Aquila cloud. The cluster is located at J2000 $\alpha = 21^{\rm h}21^{\rm m}31^{\rm s}$, $\delta = +19°07'02''$, with Galactic coordinates $l = 69\overset{\circ}{.}4, b = -21\overset{\circ}{.}27$. It is a faint small object in the halo, with half-light radius of only 3 pc.

Fadely et al. (2011, hereafter F11) showed that seven Milky Way satellite star clusters are made evident from their absolute magnitudes in the ranges $-4 < M_{\rm V} < 0$ versus effective radius in the range $1 < r_{\rm eff} < 5$ pc. These clusters are AM-4, Koposov 1,2, Whiting 1, Pal 1, Segue 3 and Pal 13. Their distances range from 16 kpc (Pal 1) to 40 kpc (Koposov 1,2). In Table 1 are given the parameters for these clusters according to Harris (1996, updated in www.physics.mcmaster.ca/Globular.html), and additional references as given in the table. This cluster sample is characterized by having very low luminosities, showing probable association with stellar streams in the Galaxy. The ultra faint dwarf galaxies show similarly very low luminosity, but much larger effective radii, indicating the presence of dark matter (F11). Therefore, the low luminosity end of globular clusters, as Segue 3 and other members of its group, should be rather a product of dynamical evaporation (Koposov et al. 2007).

In this paper, we present deep photometry of Segue 3, that helped to better constrain its age, metallicity, reddening and distance. These results can help understanding if these faint globular clusters were formed early in the Galaxy, or if accreted from a dwarf galaxy, or else if formed in a gas stream during the passage of dwarf galaxy.

2 OBSERVATIONS

Johnson–Cousins *V* and *I* images were obtained at the Telescopio Nazionale Galileo (TNG), equipped with the spectrograph/focal reducer DOLORES, with a 2000×2000 pixels of 8.5×8.5 arcmin^2 CCD giving 0.25 arcsec pixel^{-1}, during the night of 2011 June 26–27. Additional *B*, *V* and *I* photometry was obtained, with the same equipment, in the night of 2012 June 17–18. The sky conditions were photometric. The log of observations is given in Table 2. The frames have been flat-fielded using sky flats and trimmed. The flat-fields present a sky concentration (effect of reflection) at the centre of the field of 4.5 per cent in *V*, 5 per cent in *I*. Instead of removing the sky concentration from the flat-field, we preferred to correct the relative photometry a posteriori. *B*, *V* and *I* have slightly different sky concentration, increasing from *B* to *I*. The residual correction from twilight flat-fields and sky background, leads to residuals within ~1.5 per cent (see also Ortolani et al. 2009).

The photometry of the single stars was performed using DAOPHOT II (Stetson 1994) installed in MIDAS. The absolute calibration was obtained from five independent Landolt fields (Landolt 1992) distributed along the night. The resulting calibration equations are: $V = 28.99 - 0.06\,(V - I) + v$ and $I = 28.60 - 0.09\,(V - I) + i$, for exposure times of 20 s in *V* and 15 s in *I*. *V* and *I* are the calibrated magnitudes and v, i are the instrumental ones, measured with the aperture magnitude commands of MIDAS. Fig. 1 shows the *V*, *I* and *B*, *V* colour–magnitude diagrams (CMDs). The tables of *V* and *I*

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Table 1. Characteristics of low luminosity star clusters. Basic information from Harris (1996, 2010 edition).

Cluster	$E(B-V)$	[Fe/H]	$R_{\odot}$ (kpc)	R_{GC} (kpc)	Age (Gyr)	Reference
Palomar 1	0.15	−0.65	11.1	17.2	7/5	1–2
Whiting 1	0.03	−0.65	31.1	34.5	6.5	3
AM-4	0.05	−0.97	32.2	27.8	9	4
Koposov 1	0.01	–	48.3	49.3	–	
Koposov 2	0.08	–	34.7	41.9	14	5
Palomar 13	0.05	−1.88	26.0	26.9	–	
Segue 3	0.1	−1.7	16.9	10.0	12	6
			Present results			
Segue 3	0.09	−0.8	29.1	24.0	3.2	7

References: (1) Rosenberg et al. (1998); (2) Sarajedini et al. (2007); (3) Carraro, Zinn & Moni Bidin (2007); (4) Carraro (2009); (5) Côté et al. (2002); (6) Fadely et al. (2011); (7) present work.

Table 2. Log of observations.

Filter	Exposure (s)	Seeing (arcsec)	Airmass	Filter	Exposure (s)	Seeing (arcsec)	Airmass
	2011				2012		
V	30	1.0	1.04	V	180	1.0	1.03
V	30	1.0	1.04	V	30	1.0	1.03
V	30	1.0	1.04	B	30	1.2	1.04
V	2400	1.0	1.04	B	1200	1.3	1.03
I	30	1.1	1.04	I	180	1.2	1.02
I	20	0.9	1.04	I	30	1.0	1.02
I	900	1.0	1.04	I	30	0.8	1.04

photometry will be available in electronic form only. The zero-point errors of the calibration equations are around ±0.015 mag.

The errors in our photometry both in the short and long exposures, in V and I, from the statistical list of Poissonian errors given by DAOPHOT, are shown in Fig. 2. The width of the main sequence between $V = 20.2$ and 22.5 gives 0.03 mag, very close to the V and I combination errors (0.02×1.4). This demonstrates that our photometric errors are very close to the theoretical statistical photon errors. A comparison of the 2011 and 2012 reductions are remarkably consistent, indicating that there are no zero-point offsets.

3 COLOUR–MAGNITUDE DIAGRAMS

Fig. 1 shows the V versus $V - I$ and V versus $B - V$ CMDs of Segue 3, for an extraction of radius r of 140 pixels or 35 arcsec. This extraction was chosen based on the cluster densest parts according to fig. 5 by F11, showing that in this area, the cluster star density is almost a factor of 100 above the background field stars. The CMD is obtained by combining short and long exposures, at the limit of $V = 20.2$. We adopt a reddening $E(V - I) = 0.12$ or $E(B - V) = 0.09$ from Schlafly & Finkbeiner (2011). We used an apparent distance modulus $(m{-}M) = 17.6$, corresponding to a dereddened distance modulus of $(m - M)_{\circ} = 17.6{-}0.28 = 17.32$. This is converted to a distance of 29.1 kpc. This extinction is not negligible for the distance and age determinations, and expected from the cluster galactic latitude of $b = -21.^{\circ}3$. A new Padova isochrone (Bressan et al. 2012) is overplotted on the observations, for $Z = 0.003$, age = 3.2 Gyr (solid line), together with Girardi et al.'s (2010) previous set of Padova isochrones for $Z = 0.004$, age = 2.8 Gyr. These ages and metallicities resulted from a diagnostic diagram presented in Fig. 3, as follows: log (age) versus metallicity [Fe/H] for the dereddened

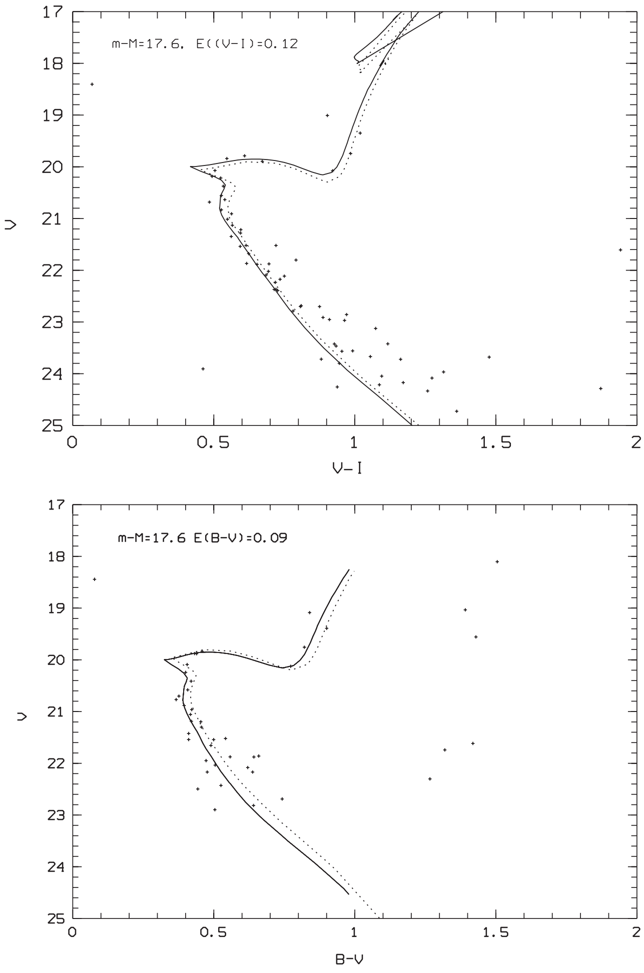

Figure 1. Segue 3: V versus $V - I$ and V versus $B - V$ CMD (crosses) for an extraction of radius r = 140 pixels or 35 arcsec. Padova new isochrone (Bressan et al. 2012) of $Z = 0.003$, age = 3.2 Gyr (solid line) and $Z = 0.004$, age = 2.8 Gyr isochrone (Girardi et al. 2010) (dotted line), are overplotted on the observed diagram.

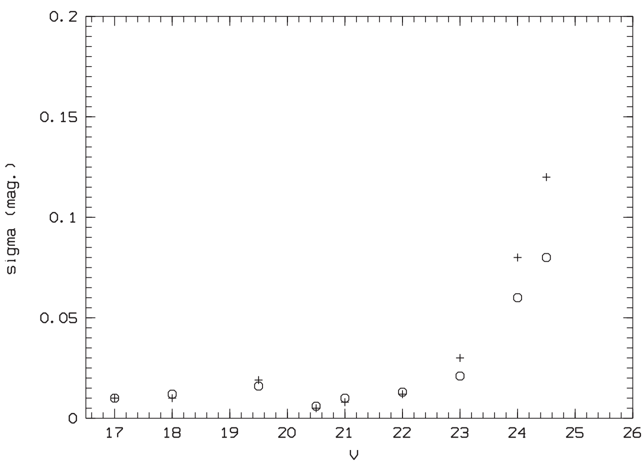

Figure 2. Photometric errors in V (crosses) and I (circles).

turnoff (TO) colour $(V - I)_{\rm TO} = 0.4$ given as a solid line, and the $(V - I)$ colour difference between the TO and the base of the red giant branch (RGBbase) $\Delta(V - I)^{\rm TO}_{\rm RGBbase} = 0.4$ (value measured in Fig. 1). The crossing point of the two lines gives a best combination

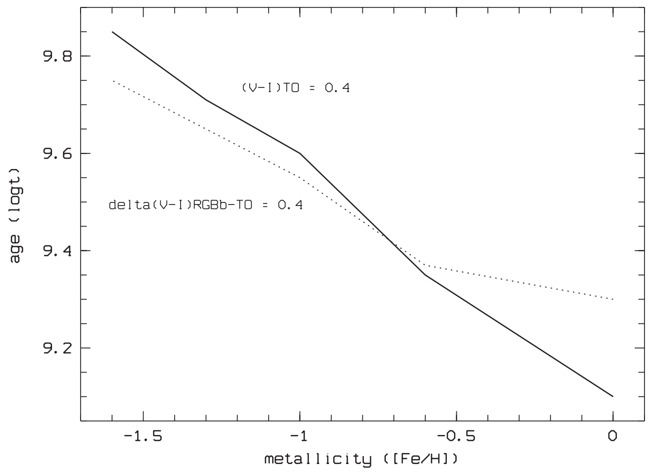

Figure 3. Diagnostic diagram: log (age) versus metallicity [Fe/H] for the dereddened TO colour $(V-I)_{\rm TO} = 0.4$ (solid line), and the $(V-I)$ colour difference between the TO and the base of the red giant branch (RGB base) $\Delta(V-I)^{\rm TO}_{\rm RGBbase} = 0.4$ (dotted line). The crossing point of the two lines gives the best combination of age and metallicity.

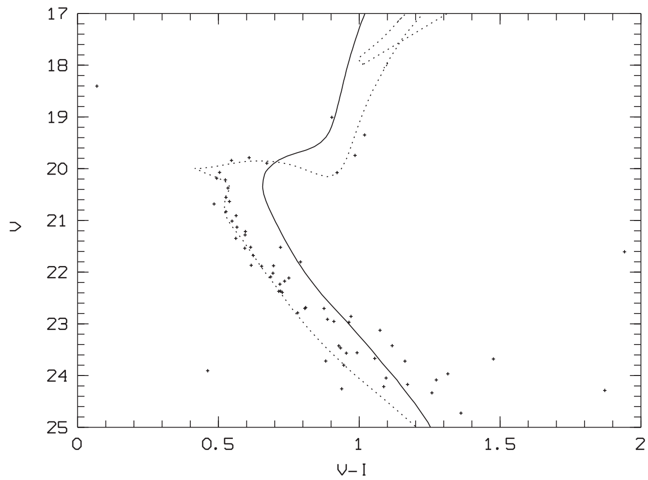

Figure 4. V versus $(V-I)$ CMD (crosses) overplotted with the Bressan et al. (2012) isochrones for the present solution ($Z = 0.003$, $t = 3.2$ Gyr, $E(V-I) = 0.12, m-M = 17.6$) (dotted line) and Fadely et al.'s (2011) solution ($Z = 0.0004$, $t = 12$ Gyr, $(m-M)_\circ = 16.14$) (solid line).

of age and metallicity. The result in apparent distance modulus is $m-M = 17.6$ for the best fit in Fig. 1 (solid line). The final choice was derived from the two best isochrone fits within a grid of 0.05 dex in age, and 0.001 in metallicity. Note that the new Padova isochrones are about 0.15 mag brighter than the previous ones (Marigo et al. 2008; Girardi et al. 2010), and 15 per cent older, at a fixed distance modulus. Fig. 1 shows a best fit using both sets of isochrones. The errors on metallicity and age can be estimated from the photometric error propagation into the isochrones. An uncertainty of ± 0.05 mag at the TO, translates into 10 per cent on the age and 0.25 dex in [Fe/H]. A comparison between Padova and Yale (Demarque et al. 2004) isochrones with $Z = 0.003$ indicates very little difference if any. We estimate a final error of 0.5 Gyr on the age, with a maximum age around 4 to 4.5 Gyr.

The present derived values of age and metallicity are different from those by F11. From the comparison of stars in the same central extraction of 35 arcsec between our photometry (see Fig. 1) and F11's published photometry, we obtained an average difference, around the TO luminosity level, of $(V-I)-(g-r) = 0.3$ mag. A difference at the TO of 0.29 is deduced from the g versus $g-r$ and V versus $V-I$ isochrones with metallicity $Z = 0.003$ and age $t = 3.2$ Gyr. However, if we take into account that F11's published photometry has been dereddened by $E(B-V) = 0.1$ mag (Fadely, private communication), we have a difference of 0.09 mag in the zero-point of the two photometries. Fadely et al.'s results are relatively redder than the equivalent $V-I$ (or our $V-I$ is bluer). This explains why F11 found an older age. We emphasize that the sample used in the CMDs is not exactly the same: while we have 24 stars brighter than $V < 21.5$ in the 35 arcsec central extraction, only eight stars are present in the published photometry of Fadely et al.'s that were spectroscopically measured (F11's tables 2 and 3), where TO stars are missing. According to their radial velocity selection, all their stars are cluster members. The other stars in their CMDs are farther out in the field.

In Fig. 4 are plotted both the present solution ($Z = 0.003$, $t = 3.2$ Gyr, $E(V-I) = 0.12, m-M = 17.6$ or $(m-M)_\circ = 17.32$) and F11's solution ($Z = 0.0004$, $t = 12$ Gyr, $(m-M)_\circ = 16.14$). Additionally, the two crucial stars at the base of the subgiant branch (SGB) that they have in their CMDs, considered as contaminants, are not the same we have, since they are farther from the centre of the cluster. We interpret that there are at least four or five stars at the base of the SGB, very likely belonging to the cluster, indicating the young age. The interpretation of the TO shape in terms of age is not dependent on the absolute photometry, but it is consistent with our relatively bluer absolute colour, as compared to F11's. We could not find an explanation for the photometric difference of 0.09 mag in $V-I$ between our photometry and F11's $g-r$ converted one. It is higher than our estimated zero-point error of the colour photometry at the TO, combining all the sources of errors (up to 0.05 mag, see above). Tentative explanations are a combination of transformation uncertainties (0.05 mag on the isochrone colours, Marigo, 2012, private communication) and zero-point errors and/or a different treatment of the reddening.

3.1 Cluster parameters

Adopting the true distance modulus of $(m-M)_\circ = 17.32$, the resulting distance to the Sun is $d_\odot = 29.1$ kpc. Galactic coordinates are $X = -13.0, Y = -6.1, Z = -19.2$ and Galactocentric distance $R_{\rm GC} = 24.0$ kpc. This farther distance is compatible with a younger age, as compared with the older age and closer distance found by F11. The farther distance is also more compatible with the properties of the outer halo low luminosity clusters (Table 1).

It is interesting to note that the main sequence from the TO down to $V \sim 22.5$ in Fig. 1 is narrow and well defined. Below this magnitude the main sequence appears depleted along the isochrones, while a parallel brighter main sequence is present, that could be due to binaries. This corresponds to a mass of 0.8 $M_\odot$, whereas at the TO it is around 1.3 $M_\odot$. These CMD features are very similar to the main sequence of Palomar 1 in fig. 8 of Sarajedini et al. (2007). This may be providing a more detailed evidence for evaporation processes depleting the single and lower mass stars below a certain threshold.

In Fig. 5 is shown the Segue 3 luminosity function (LF) built along the main sequence, from the TO to the photometric limit. We cleaned the sample from the few redder field stars (Fig. 1), and it was corrected for completeness. We tested the photometric incompleteness by means of retrieval of artificial stars. The flat character of the Segue 3 LF essentially does not change with these

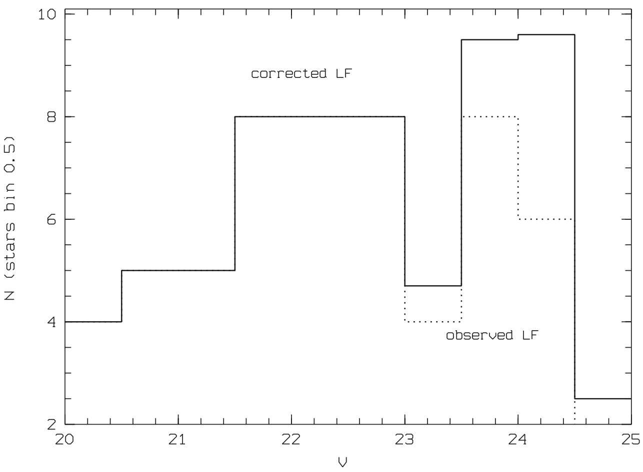

Figure 5. Observed and 100 per cent completeness corrected luminosity function of Segue 3, in *V* and within 35 arcsec, from the TO to the photometric limit.

corrections. The LF is flat below the TO, likewise those observed in the similarly young and relatively metal-rich halo globular clusters Whiting 1 and Palomar 4 (Carraro et al. 2007; Frank et al. 2012). All these three unusual globular clusters possibly suffered significant tidal shocks with the Milky Way. Tidal stripping, as evidenced by shallow LFs, has also been observed in other underluminous globular clusters such as Palomar 5 and Palomar 13 (Koch et al. 2004; Côté et al. 2002).

4 CONCLUSIONS

Deep *V* and *I* photometry of Segue 3's central region indicates a young age of 3.2 Gyr, and a moderately high metallicity of [Fe/H] ~ -0.80. Within age uncertainties, Segue 3 appears to be the youngest globular cluster so far known in the halo, or in the whole Galaxy altogether. Whiting 1 is related to the Sagittarius Stream (Carraro et al. 2007), and the evidence that Segue 3 also could be related to a stream, suggests that it was formed from enriched gas in a dwarf galaxy, and subsequently encountered the Milky Way. Its relatively high metallicity is typical of most low luminosity outer halo clusters. It might be that this metallicity is a characteristic of this category of objects. Among the clusters in Table 1, the unique metal-poor cluster is Pal 13, which is 2 mag brighter than the others (F11, Fig. 8). There is an unidentified 0.09 colour difference between the CMDs of F11' and ours. A main difference in the age derivation however is due to the consideration of SGB stars in our isochrone fitting. It would be interesting to observe Segue 3 in the infrared in an 8 m telescope, and to obtain spectroscopy of SGB stars, to derive their radial velocities and metallicities.

The revised distance to the Sun of 29.1 kpc places Segue 3 in a more compatible location, relative to the other very low luminosity Milky Way satellites. It also puts Segue 3 as more plausibly associated with the Hercules–Aquila debris.

According to Fadely et al. (2011), Segue 3 and similar clusters are possibly stripped objects from more massive globular clusters, likely related to streams. Their central brightness is higher than that of Milky Way dwarfs, suggesting that they are probably not related to them.

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SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article:

Tables of *V* and *I* photometry (http://mnras.oxfordjournals.org/lookup/suppl/doi:10.1093/mnras/stt865/-/DC1).

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