HST-ACS photometry of the isolated dwarf galaxy VV124=UGC 4879

Detection of the blue horizontal branch and identification of two young star clusters

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Received 17 May 2011 / Accepted 9 July 2011

ABSTRACT

We present deep V and I photometry of the isolated dwarf galaxy VV124=UGC 4879, obtained from archival images taken with the Hubble Space Telescope – Advanced Camera for Surveys. In the color-magnitude diagrams of stars at distances greater than 40′ from the center of the galaxy, we clearly identify a well-populated, old horizontal branch (HB) for the first time. We show that the distribution of these stars is more extended than that of red clump stars. This implies that very old and metal-poor populations dominate in the outskirts of VV124. We also identify a massive (\(M \approx 1.2 \pm 0.2 \times 10^4\) M\(_\odot\)) young (age \(\approx 250 \pm 50\) Myr) star cluster (C1), as well as another of younger age (C2, \(\lesssim 30 + 10\) Myr) with a mass similar to classical open clusters (\(M \lesssim 3.3 \pm 0.5 \times 10^3\) M\(_\odot\)). Both clusters lie at projected distances less than 100 pc from the center of the galaxy.

Key words. galaxies: dwarf – Local Group – galaxies: structure – galaxies: stellar content – galaxies: individual: UGC 4879 – galaxies: ISM

1. Introduction

The dwarf galaxy VV124=UGC 4879 has been recently recognized to lie at the outer fringes of the Local Group (LG), near the turn-around radius (Kopylov et al. 2008; Tikhonov et al. 2010). It is extremely isolated, being at a distance equal to one turn-around radius (Kopylov et al. 2008; Tikhonov et al. 2010).

In VV124=UGC 4879, obtained from archival images taken with the Hubble Space Telescope – Advanced Camera for Surveys, the presence of a well-populated, old horizontal branch (HB) can be clearly identified for the first time (see also their Fig. 1). In Paper I, Bellazzini et al. (2011) present Hubble Space Telescope photometry of the isolated dwarf galaxy VV124=UGC 4879, obtained from archival images taken with the Hubble Space Telescope – Advanced Camera for Surveys. In the color-magnitude diagrams of stars at distances greater than 40′ from the center of the galaxy, we clearly identify a well-populated, old horizontal branch (HB) for the first time. We show that the distribution of these stars is more extended than that of red clump stars. This implies that very old and metal-poor populations dominate in the outskirts of VV124. We also identify a massive (\(M \approx 1.2 \pm 0.2 \times 10^4\) M\(_\odot\)) young (age \(\approx 250 \pm 50\) Myr) star cluster (C1), as well as another of younger age (C2, \(\lesssim 30 + 10\) Myr) with a mass similar to classical open clusters (\(M \approx 3.3 \pm 0.5 \times 10^3\) M\(_\odot\)). Both clusters lie at projected distances less than 100 pc from the center of the galaxy.

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* Based on observations made with the NASA/ESA Hubble Space Telescope, obtained at the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS 5-26555. These observations are associated with program GO-11584 [PI.: K. Chiboucas].
** Photometry catalogue is only available at the CDS via anonymous FTP to cdsarc.u-strasbg.fr (130.79.128.5) or via http://cdsarc.u-strasbg.fr/viz-bin/qcat?J/A+A/533/A37

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Since the young population is concentrated in the innermost part of the galaxy, it can be traced in much deeper detail with the ACS data. This, in turn, prompts a more stringent comparison with the H I distribution.

We identified a candidate cluster located near the center of the galaxy and within the sheet of young stars (Cluster 1, C1 hereafter). The integrated spectrum of the source, shown in Paper I, shows strong H_{2} in absorption, suggesting a young age. With the high spatial resolution ACS image, we can hope to ascertain the real nature of C1 and look for other conspicuous clusters, if any.

There is no reason to repeat the excellent analysis of J11, so we focus strictly on the scientific cases listed above. In the following, we adopt the parameters ofVV124 derived in Paper I (see their Table 1), if not stated otherwise. In particular, we adopt D = 1.3 Mpc (in good agreement with J11) and E(B−V) = 0.015 (from Schlegel et al. 1998). At this distance 1" corresponds to 6.3 pc, 1' to 378 pc. We also adopt the deprojected coordinate system X,Y of Paper I, centered on the center ofVV124 and rotated to let the X axis coincide with the major axis of the galaxy.

Finally, we use the elliptical radial distance from the center of the galaxy r_{e}. To give an example, stars fulfilling the condition r_{e} ≤ 1' are enclosed within an ellipse whose major axis coincides with the major axis ofVV124 and has a = 1' and ε = 0.44 (see Fig. 1, below). The normal (projected) radial distance from the center of the galaxy will be denoted by K_{e}. All theoretical models used for comparison with observed CMDs are from the (canonical, solar-scaled) BASTI set (Pietrinferni et al. 2004; Percival et al. 2009), in the native ACS- Wide Field Channel (WFC) VEGAMAG system.

The plan of the paper is as follows. In Sect. 2 we describe the observational material and the data reduction process, and in Sect. 3 we present the clear detection of the extended HB in the external regions of the ACS field and discuss the radial distribution of the various stellar populations ofVV124. Section 4 is devoted to a brief discussion of the correlation between the spatial distribution of the H I and of the young stars, and in Sect. 5 we study the candidate luminous star clusters identified here and in Paper I. Finally we briefly summarize and discuss our main results in Sect. 6.

2. Observations and data reduction

The observational material consists of two pairs of F606W and F814W ACS-WFC images obtained within the program GO-11584, which we retrieved from the HST archive. The total exposure time of the stacked drizzled images is 1140 s for the F606W and 1150 s for the F814W image. The WFC is a mosaic of two 4096 × 2048 px² CCDs, with a pixel scale of 0.05 arcsec px^{-1}. The center ofVV124 is placed at the center of one of the mosaic chips (chip 1).

Positions and photometry of individual stars were obtained with the ACS module of the point spread function (PSF) – fitting package DOLPHOT v.1.1 (Dolphin 2000), as described, for example, in Galleti et al. (2006). The package identifies the sources on a reference image (in this case the drizzled F814W image, as in Mackey et al. 2006) and performs the photometry on individual frames, also considering all the information about image cosmetics and cosmic-ray hits that is attached to the observational material. We adopted a threshold of 3σ above the background for the source detection. DOLPHOT automatically provides magnitudes both in the WFC VEGAMAG system and in the Johnson-Kron-Cousins system (Dolphin 2000). As done in Galleti et al. (2006) and Perina et al. (2009, 2010), we selected the sources according to the quality parameters provided by DOLPHOT, to clean the sample from spurious or badly measured entries. In particular, we retained only stars having quality flag = 1 in the final catalog (i.e. best-measured stars), chi < 2.0, |sharp| < 0.5, crowding parameter crowd < 0.3, and photometric error <0.3 mag in both filters (see Dolphin 2000, for details on the meaning of the various parameters). In the following sections we always adopt this selected catalog that contains 44894 sources, in total.

We transformed the star positions from this system into J2000 RA and Dec by fitting a fourth degree polynomial to 5038 stars in common between the ACS catalog and the LBT catalog of Paper I, using the CataPack suite of codes. The rms of the residual was 0.07" in both RA and Dec. The positions of the stars in the ACS field with respect to the LBT sample are shown in the upper panel of Fig. 1. In the lower panel of the same figure we zoom on the part of the ACS field containing the center of the galaxy. It is particularly interesting to note that a

1 http://193.204.1.62/index.html
2 http://www.stsci.edu/hst/acs/
3 http://americano.dolphinsim.com/dolphot/
4 We relax this selection criterion to crowd < 1.0 in Sect. 5, to study in more detail the star clusters, where stars are significantly more crowded than average.
5 This catalog is available in electronic form at the CDS.
6 Developed by Paolo Montegriffo at INAF – Osservatorio Astronomico di Bologna.
large number of stars are detected beyond the $R_p \leq 40''$ limit of the sample used by J11 for their determination of the SFH. It is beyond that radius, and especially beyond $r_c = 1.5'$ where we expect to detect the extended HB of VV124, an obvious tracer of very old (age $\geq 10$ Gyr) and metal-poor populations.

2.1. Artificial stars experiments

To study the completeness of the sample and the photometric uncertainties, we performed a set of artificial star experiments, following the same procedure adopted by Perina et al. (2009, see that paper for a detailed description and references). We produced $\approx$200,000 artificial stars having $21.0 \leq F606W \leq 28.0$, with colors in the range covered by the bulk of observed stars, i.e. $-0.4 \leq F606W - F814W \leq 1.3$.

The results of the experiments are presented in Fig. 2. The upper panels show that the photometric accuracy is better than 0.1 mag for $F606W \leq 25.0$; a quantitative summary of the results displayed in these panels is presented in Table 1. The lower panels show the completeness factor ($C_T$) as a function of magnitude for two radial ranges and for two color ranges. At magnitudes fainter than $F606W = 25.0$, the completeness is slightly worse for blue stars than for red stars. However, even blue stars in the inner radial bin have $C_T \geq 50\%$ for $F606W \leq 26.5$. In the outer radial bin, the same level of completeness is reached at $F606W \approx 27.2$.

3. The extended HB of VV124

In the upper lefthand panel of Fig. 3 we show the ACS CMD of VV124 in the same radial range as studied by J11 ($R_p \leq 40''$). The two CMDs are very similar, as expected, since they are obtained from the same dataset and with the same photometry package.

The most obvious features are the broad RGB, with the RGB tip located at $F814W \approx 21.5$, and the red clump (RC) of intermediate/large mass core He burning stars around $F814W \approx 25.3$. A handful of asymptotic giant branch stars is present on the extension of the RGB above the tip. The obvious blue plume of young main sequence stars (YMS) runs over all the considered magnitude range around $F606W - F814W \approx 0.0$. The sparse plume protruding from the RGB at $F814W \approx 23.5$ toward the blue has been identified by J11 as composed of blue loop (BL) stars of metallicity [Fe/H] $\sim -0.7$; these are the evolved counterpart of the YMS.

J11 noted that the synthetic CMD best reproducing the observations included HB stars reaching colors as blue as $V - I = F606W - F814W \approx 0.4$ that were not identified in the observed CMD. We note, on the other hand, that it seems possible to discern a blue extension of the HB in our CMD around $F814W \approx 25.8$ and $0.0 \leq F606W - F814W \leq 0.6$. This impression is confirmed by the CMD of stars beyond the region studied by J11 displaying an obvious extended HB (upper righthand panel of Fig. 3), with a higher-density portion between $F606W - F814W \approx 0.6$ and $F606W - F814W \approx 0.3$, and a less populated part reaching $F606W - F814W \approx -0.4$.

The extended HB becomes more evident when more external regions are considered, as shown in the lower panels of Fig. 3. This should be partially due to the decreasing crowding, which allows to get more accurate photometry, thus decreasing the width of the other CMD sequences that may partially overlap with the HB. However, the most important effect is the decreasing impact of the young MS plume, which contributes to hiding the blue HB near the center of VV124. We show below that, in addition to these observational factors, there is also a genuine population gradient making the HB stars more abundant in the outer regions of the galaxy. The lower righthand panel of the figure shows the CMD in the same radial region where we tentatively detected the extended HB from the LBT data, thus providing a direct confirmation of that finding.

In the upper righthand panel of Fig. 4, we superposed a synthetic HB population, produced from the BASTI theoretical models (Pietrinferni et al. 2004) with the dedicated web tool7 to the observed CMD of the outermost region of VV124 sampled

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|}
\hline
$F814W$ & $\sigma(F814W_\text{art} - F814W_\text{obs})$ & $\sigma(\text{col}_\text{art} - \text{col}_\text{obs})$ \\
\hline
20.0 & 0.009 & 0.006 \\
21.0 & 0.010 & 0.009 \\
22.0 & 0.013 & 0.014 \\
23.0 & 0.021 & 0.024 \\
24.0 & 0.040(0.045) & 0.044(0.045) \\
25.0 & 0.077(0.085) & 0.084(0.087) \\
26.0 & 0.153(0.164) & 0.175(0.180) \\
27.0 & 0.236(0.242) & 0.281(0.286) \\
\hline
\end{tabular}
\caption{Photometric errors from artificial stars experiments.}
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Notes. \(^{(a)}\) $\text{col}_\text{art} = F606W_\text{art} - F814W_\text{art}; \text{col}_\text{obs} = F606W_\text{obs} - F814W_\text{obs}$. \(^{(b)}\) The reported errors are standard deviations computed for recovered artificial stars having $F814W_\text{art}$ within $\pm 0.5$ mag from the value reported in Col. 1. \(^{(c)}\) Numbers within parentheses refer to the sample with $\text{CRO} \leq 1.0$, which is adopted in the analysis of the clusters. All the other values refer to the standard $\text{CRO} \leq 0.3$ sample. The alternative value is reported only when it differs by more than 0.001 mag from the standard value.

by the ACS data. The synthetic population (1000 stars) have $Z = 0.001$ (appropriate for the old population of the galaxy, according to Kopylov et al. 2008, Paper I and J11), a mean mass of $0.494 M_\odot$, and a dispersion $\sigma = 0.2 M_\odot$, and it has been shifted to the distance and reddening of VV124. This is not intended to reproduce the observed HB but only to provide a sanity check for interpreting of the sequence and to have a hint of the classification of stars within the HB (color-coded according to the classification provided by the model). In particular, it is evident that the galaxy very likely hosts a significant population of RR Lyrae variables, since there are many HB stars in the color range typical of these variables. Clearly their definitive classification as genuine RR Lyrae would need time series photometry, which is not available to us. The detection of such a rich population of candidate RR Lyrae and blue HB stars is fully compatible with the SFH derived by J11, who conclude that $\geq 90\%$ of the stars were formed between 14 and 10 Gyr ago.

For $F606W - F814W \lesssim 0.0$, the bluest portion of the observed HB seems to depart from the behavior predicted by the models, showing only a modest decline in the mean magnitude with color, while the synthetic population plunges towards much fainter luminosity. This may be from a combination of effects, including imperfect temperature-color transformations in this extreme color regime and photometric errors/completeness/blending effects due to the proximity of the limiting magnitude level, which becomes brighter for bluer colors. In Fig. 5 we simulate the observational effects on a subsample of the synthetic HB stars. The experiment demonstrates that the apparent mismatch can be fully accounted for by the effects of photometric errors and blending. As a result, most of
The upper lefthand panel of Fig. 4 shows the boxes we adopted for selecting stars on the YMS, in the RC and in the extended HB, to compare their spatial distributions. For the HB we adopted a box covering a relatively narrow color range, approximately matching the one of RR Lyrae variables. This choice was forced by the need to avoid contamination from RC stars on the red side and, above all, from faint YMS stars on the blue side. This would have been particularly problematic since (a) YMS are obviously much more centrally concentrated than older stars, and (b) the YMS blue plume becomes wider and reaches redder colors at faint magnitudes (V ≤ 23) clearly overlapping with the blue HB in the central region. We verified that the actual radial distribution of HB stars bluer than the adopted selection box is fully compatible with a population having the same radial distribution as the HB sample plus a strong contamination of YMS in the innermost −0.5′. The selected HB sample can therefore be considered as a fair tracer of the old HB population as a whole, including BHB. The selected RC and HB samples should have similar completeness properties, since they have similar magnitudes and colors. To verify this hypothesis we compared the behavior of the completeness as a function of $r_e$ for the two samples, using our set of artificial stars. It turned out that the two completeness curves are indistinguishable, hence, any observed difference in the radial distribution of RC and HB stars cannot be accounted for by completeness effects.

The cumulative radial distributions of the three selected populations are compared in the lower panel of Fig. 4. In addition to the striking (and already noted) difference between the YMS and the older RC and HB populations, it is clearly revealed that the HB stars have a more extended distribution than do RC stars. A Kolmogorov-Smirnov test gives that the probability that the two samples are extracted from the same parent population is $P < 10^{-10}$, thus firmly establishing the significance of the difference. It must be concluded that VV124 displays the classical population gradient observed in all dwarf galaxies, with the older and/or more-metal-poor populations becoming increasingly more abundant at larger radii and younger and/or more-metal-rich being more concentrated toward the center (Harbeck et al. 2001; Bellazzini et al. 2002a, 2005; Tolstoy et al. 2009).

3.1. The color distribution of RGB stars

In Paper I, the comparison of the observed RGB with empirical templates from Galactic globular clusters revealed the possible presence of a small metallicity gradient in the same sense. The analogous comparison, performed with the much more accurate ACS photometry is presented in Fig. 6, to check the findings of Paper I and to verify that the distribution and mean color of RGB stars is compatible with the gradient found with the HB stars. It must be stressed that the following analysis is not intended to provide accurate metallicity estimates, since it is well known that photometric determinations of the metallicity can be affected by serious degeneracies when the underlying age distribution is not well constrained (see Cole et al. 2005; Lianou et al. 2011, and references therein). On the other hand we look for differences in the inner and outer samples of RGB stars that may or may not be in agreement with the observed HB gradient. In the analysis we adopt the global metallicity parameter [M/H] introduced by Salaris et al. (1993) to allow meaningful experiment several times and verified that the HB morphology in output does not depend on the specific random realization. For an example of detailed modeling of an HB population in a similar context see Monelli et al. (2010, and references therein).
4. The spatial distributions of H I and young stars

In Fig. 7 we compare the location of those stars identified as YMS with the H I distribution. This comparison clearly shows that, when considered on large scales, there is a very good spatial correspondence between the distribution of the YMS stars and that of the H I, and both show the same asymmetry. Such an overall correspondence is not entirely unexpected, because, after all, stars form from gas. On smaller scales (i.e., less than 100 pc), the spatial correspondence between YMS stars and the H I is not as good, with the peak of the H I somewhat displaced from the YMS stars. This situation is typical for small galaxies, because a good correlation between star formation and H I on large scales and the breakdown of it on smaller scales is observed in many small galaxies (Begum et al. 2006; Roychowdhury et al. 2009).

The close overall correspondence between the YMS and the H I also suggests that the observed kinematics of the H I is also connected to the formation of those stars we now observe on the YMS. As discussed in Paper I, if the H I tail is interpreted as an outflow, the energy output of roughly a dozen OB stars would be enough to drive it. However, an interesting alternative is that the tail corresponds to infall of gas and that VV124 is re-accreting part of the gas that was expelled by the formation of the stars we now see as an old population. That such re-accretion may occur is suggested by some recent simulations (e.g., Sawala et al. 2011), and would also be very consistent with the fact that VV124 has been dormant for a long period of time since the early phase of star formation and has only very recently started to form young stars again. The metallicity of the young stars in VV124 ([Fe/H] ~ −0.7, as estimated by J11 from the observed morphology of the BL) also suggest that, if they formed from the H I gas cloud, this cloud must contain enriched material and hence it consists of re-accreted material.

5. Luminous star clusters in VV124

The zoomed view of the galaxy center shown in Fig. 8 shows that the candidate star cluster identified in Paper I (Cluster 1, C1 hereafter) is indeed largely resolved into stars in the ACS images, hence it is likely a genuine star cluster (see below). On the other hand, the two bright sources to the west of C1 are a background galaxy and a foreground star, respectively. There are several small groups of young stars in this regions that may be possibly classified as open clusters or associations. However, the only other group of size/luminosity comparable to C1 is the one indicated as Cluster 2 (C2) in the figure. C2 appears to coincide with the position of the H ii region identified by Kopylov et al. (2008, by means of a long slit optical spectrum). With the available data and that of the H I, and both show the same asymmetry. Such an overall correspondence is not entirely unexpected, because, after all, stars form from gas. On smaller scales (i.e., less than 100 pc), the spatial correspondence between YMS stars and the H I is not as good, with the peak of the H I somewhat displaced from the YMS stars. This situation is typical for small galaxies, because a good correlation between star formation and H I on large scales and the breakdown of it on smaller scales is observed in many small galaxies (Begum et al. 2006; Roychowdhury et al. 2009).

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**Fig. 8.** The two candidate clusters (C1 and C2) are indicated on this image of the center of VV124 (from the drizzled F606W image). The circle around C1 has a radius of 2.5′′, the one around C2 a radius of 2.0′′. The ellipse has the same ellipticity and orientation of the VV124 isophotes and semi-major axis $a = 25''$. The center of the galaxy is indicated by a cross.

<table>
<thead>
<tr>
<th>Cluster Name</th>
<th>Cluster E</th>
<th>CF N</th>
<th>CF W</th>
<th>Min. Excess $c$</th>
<th>Max. Excess $d$</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1$^a$</td>
<td>0.84 ± 0.16</td>
<td>0.11 ± 0.04</td>
<td>0.13 ± 0.04</td>
<td>0.28 ± 0.06</td>
<td>3.3σ</td>
</tr>
<tr>
<td>C2$^b$</td>
<td>0.70 ± 0.16</td>
<td>0.22 ± 0.06</td>
<td>0.13 ± 0.04</td>
<td>0.29 ± 0.08</td>
<td>2.3σ</td>
</tr>
</tbody>
</table>

**Table 2.** NB/NR ratios for the candidate star clusters and their control fields.

**Notes.**

(a) NB is the number of stars having $F606W - F814W \leq 0.2$ and $24.0 < F814W < 26.0$, while NR is the number of stars having $F606W - F814W \geq 0.4$ in the same magnitude range.

(b) The definitions of NB and NR are the same as for C1, except for the magnitude range that is $22.0 < F814W < 26.0$, in this case.

(c) Difference between the $\frac{NB}{NR}$ in the cluster and in the CF showing the lowest value of this parameter, in units of $\sigma$.

(d) Difference between the $\frac{NB}{NR}$ in the cluster and in the CF showing the highest value of this parameter, in units of $\sigma$.

it is not possible to establish whether the H II region is associated to the cluster or it is just a chance superposition.

In Sects. 5.1 and 5.2, below, we will study in deeper detail these two small stellar systems. The insight into the physical properties of the clusters is greatly hampered by stellar crowding which is maximized with respect to the surrounding field. Indeed, to reach $F814W \sim 26.5$ in the very small areas enclosing the clusters, we had to relax the selection on the crowding parameter, accepting stars up to $\text{crowd} < 1.0$. In addition, the contamination by field stars provides additional problems to the interpretation of the CMDs. For these reasons, the best we can hope to obtain from the analysis of the clusters CMD are age estimates with uncertainties of order 20%–50%, also due to the uncertainty in the associated metallicity and the systematics associated with uncertainties in the theoretical models (Gallart et al. 2005). However such large age uncertainties translates into uncertainties of 10%–20% in the mass estimates obtained by converting total luminosity into mass (see Perina et al. 2009, 2010, and references therein).

In the following analysis we will try to estimate ages by fitting the cluster CMD with BASTI isochrones, following Perina et al. (2009). As a reference value for the cluster metallicity we assume $Z = 0.004$, i.e. the mean value estimated by J11 for the young population of VV124. Since the two clusters are clearly associated with this young component, this is by far the best guess on the metallicity of the clusters. While we will present only solutions with $Z = 0.004$, we have attempted to fit the observed CMDs also with isochrones with metallicity ranging from $Z = 0.001$ to $Z = 0.02$ and we found that the $Z = 0.004$ models always provide the best overall fit. Estimates obtained with the Girardi et al. (2000) isochrones, for comparison, gives age values larger by $\sim 30\%$ that those obtained with BASTI isochrones.
and the MS fainter than $F814W \sim 24.0$ are the only features of the C1 CMD that can be unequivocally attributed to the cluster, as they are significantly over-abundant in the C1 field than in the CFs. On the other hand, one can be tempted to interpret the five stars of the C1 CMD lying in the region $F606W − F814W < 0.2$ and $F814W < 24.0$ as very young MS stars associated to the cluster. However this interpretation has no statistical basis, since in the same region there are 3, 1, and 3 stars in CF$_E$, CF$_W$, and CF$_V$, respectively. Hence this handful of bright and blue stars in the C1 CMD is fully compatible with the expectations for the field population. Moreover, we did not find an isochrone that simultaneously matches these very blue stars and the BL population, that is unequivocally associated with C1.

In the upper left panel of Fig. 9 we show also the comparison of the observed CMD of C1 with the isochrone corresponding to our preferred solution. In the age range covered by the young population of VV124, the luminosity of the BL is a very sensitive age indicator (Dohm-Palmer et al. 1997): the BL of C1 is well matched by the adopted isochrone, of age $\approx 250$ Myr, and simultaneous matches these very blue stars and the BL population, that is unequivocally associated with C1.

Table 3. Observed and derived parameters of cluster C1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha_0$</td>
<td>09:16:03.14</td>
<td>J2000</td>
</tr>
<tr>
<td>$\beta_0$</td>
<td>+52:50:27.0</td>
<td>J2000'</td>
</tr>
<tr>
<td>age</td>
<td>$250 \pm 50$ Myr</td>
<td>$\sigma$</td>
</tr>
<tr>
<td>$[M/H]$</td>
<td>$-0.7$</td>
<td>$\sigma$</td>
</tr>
<tr>
<td>$R_E$</td>
<td>$4.3''$</td>
<td>$\sigma$</td>
</tr>
<tr>
<td>$r_h$</td>
<td>$1.5''$</td>
<td>$\sigma$</td>
</tr>
<tr>
<td>$V_{bol}$</td>
<td>$18.4 \pm 0.1$</td>
<td>$\sigma$</td>
</tr>
<tr>
<td>$I_{bol}$</td>
<td>$18.1 \pm 0.1$</td>
<td>$\sigma$</td>
</tr>
<tr>
<td>$M_V$</td>
<td>$-7.2 \pm 0.16$</td>
<td>$\sigma$</td>
</tr>
<tr>
<td>$L_V$</td>
<td>$6.5 \pm 1.0 \times 10^3 ~ L_{\odot}$</td>
<td>total $V$ luminosity</td>
</tr>
<tr>
<td>$M_{stars}$</td>
<td>$1.2 \pm 0.2 \times 10^4 ~ M_{\odot}$</td>
<td>stellar mass$^a$</td>
</tr>
</tbody>
</table>

Notes. $^a$ In the astrometric system embedded in the $F606W$ drizzled fits image. $^{b(c)}$ From the isochrone fit of Fig. 9 (See Sect. 5). $^{(b)}$ Projected distance from the center of VV124. $^{(c)}$ From aperture photometry on concentric annuli, assuming a limiting radius $r_l = 3.0''$. $^{(d)}$ From aperture photometry with radius $r = 3.0''$. $^{(e)}$ Assuming $(M/L)_V = 0.188$ from the BASTI database, for a model having Age = 250 Myr, Z = 0.004 and a Kroupa IMF. $^{(f)}$ Integrated magnitudes have been transformed from $F814W$ to $V$. $^{(g)}$ Using the transformations by Sirianni et al. (2005).

5.1. Cluster 1

In Fig. 9 we compare the CMD in a small area (inner radius = 0.6", outer radius = 2.5") centered on C1 with those from identical areas centered on positions symmetric with respect to the center of VV124 and which are used as control fields (CF, see the upper right panel of the figure). It is quite clear that, even if the C1 region has a larger area devoid of measured stars because of the higher crowding associated to the cluster center, the C1 CMD show an excess of MS stars fainter than $F814W \approx 24.5$ and, in particular, an obvious excess of BL stars, with respect to all the considered CFs. This is clearly observed even if the analysis is limited to stars with $crow < 0.3$. In particular in the C1 CMD there are 18 stars lying in the superposed BL selection box, while 3, 5, and 4 are found in the CF$_E$, CF$_V$, and CF$_W$ CMDs, respectively. The associated excess of BL stars in C1 with respect to the three CFs is at the $3.3\sigma$, $2.7\sigma$, and $3.0\sigma$ level. If we limit to the sample of stars with $crow < 0.3$, we find 11 stars in the BL box of the C1 CMD, while only 3 stars are found in the CMD of each CF.

In Table 2 the ratio of stars bluer than $F606W − F814W = 0.2$ ($N_B$) to the stars redder than $F606W − F814W = 0.4$ ($N_R$) in the range $24.0 < F814W < 26.0$ is shown to be significantly larger (at a $> 3\sigma$ level) in C1 than in any considered CF. Given the regular, compact and roundish appearance of C1 and the obvious excess of young stars found in the C1 area, we conclude that C1 is a genuine star cluster. It is worth noting that the BL and the MS fainter than $F814W \sim 24.0$ are the only features of the C1 CMD that can be unequivocally attributed to the cluster, as they are significantly over-abundant in the C1 field than in the CFs. On the other hand, one can be tempted to interpret the five stars of the C1 CMD lying in the region $F606W − F814W < 0.2$ and $F814W < 24.0$ as very young MS stars associated to the cluster. However this interpretation has no statistical basis, since in the same region there are 3, 1, and 3 stars in CF$_E$, CF$_V$, and CF$_W$, respectively. Hence this handful of bright and blue stars in the C1 CMD is fully compatible with the expectations for the field population. Moreover, we did not find an isochrone that simultaneously matches these very blue stars and the BL population, that is unequivocally associated with C1.

In the upper left panel of Fig. 9 we show also the comparison of the observed CMD of C1 with the isochrone corresponding to our preferred solution. In the age range covered by the young population of VV124, the luminosity of the BL is a very sensitive age indicator (Dohm-Palmer et al. 1997): the BL of C1 is well matched by the adopted isochrone, of age $\approx 250$ Myr, and simultaneous matches these very blue stars and the BL population, that is unequivocally associated with C1.

We obtained estimates of the integrated $V$ and $I$ magnitudes from aperture photometry within a circular radius $r = 3.0''$, corresponding to 15.7 pc$^9$. These, as well as other relevant cluster parameters, are listed in Table 3. While the cluster may be slightly more extended than the adopted radius, this choice should be a reasonable compromise between including most of the cluster light and avoiding strong contamination from the dense field population. The sky level for aperture photometry on concentric annuli, assuming a limiting radius $r_l = 3.0''$.

$^9$ Integrated magnitudes have been transformed from $F606W$, $F814W$ to $V$, $I$ using the transformations by Sirianni et al. (2005).
is within the range of \( r_h \) values measured by Barmby et al. (2009) in M31 clusters of similar ages and masses (see below).

The total V luminosity is \( L_V = 6.5 \pm 1.0 \times 10^4 L_\odot \). Assuming \( M/L_V = 0.188 \), from a simple stellar population (SSP Renzini & Fusi Pecci 1988) model having \( Z = 0.004 \), age = 250 Myr, we obtain \( M_* = 1.2 \pm 0.2 \times 10^3 M_\odot \). This implies that \( C1 \) is signficantly brighter than Galactic open clusters of similar ages and it is more massive than Galactic open clusters of any age (Bellazzini et al. 2008b; Perina et al. 2009), except for very few (and much younger) young massive clusters discussed in Figer (2008) and Messineo et al. (2009). On the other hand, it appears very similar in age, mass, and size to the young massive clusters found in relatively large numbers in many star-forming galaxies of any mass (see Larsen & Richtler 1999; Perina et al. 2010; Barmby et al. 2009; Vanzi & Sauvage 2006; Larsen et al. 2011, for references and discussion). In the cluster classification scheme adopted by Larsen & Richtler (2000) and Billett et al. (2002) \( C1 \) clearly belongs to the class of regular star clusters \( (M_V < -8.5, \text{see Annibali et al. 2009}) \).

5.2. Cluster 2

\( C2 \) appears more irregular in shape than \( C1 \), because it is clearly dominated by a few bright stars. This suggests a younger age than for \( C1 \). We performed the same kind of analysis as for \( C1 \). The \( \frac{M_*}{L_V} \) ratio indicates an overdensity of young stars in \( C2 \) with respect to all the CFs, albeit at a lower level of significance than in the case of \( C1 \) (Table 2). We conclude that \( C2 \) is also a likely genuine cluster.

It is very hard to age-date this cluster. If the H\( \alpha \) region is indeed physically associated with \( C2 \), the age is constrained to be \( \leq 10 \) Myr, and the three stars brighter than \( F814W = 21.0 \) are not cluster BL stars. This is clearly possible since, even if two of them are redder than \( F606W - F814W = 0.0 \) and do not have direct counterpart in the CMD of the CFs, this may merely be due to fluctuations inherent in such small numbers of stars.

On the other hand, if these stars are interpreted as genuine cluster BL stars, the age should be greater than the above value and the coincidence with the H\( \alpha \) region must be considered a chance superposition. Unfortunately, the accuracy of the positioning of the H\( \alpha \) region is not sufficient to check the degree of spatial coincidence with \( C2 \) on scales smaller than \( 1'' - 2'' \) (see Fig. 2 in Kopylov et al. 2008). Considering the three brightest stars as cluster members, the best fit is obtained with an isochrone of age \( 30 \pm 10 \) Myr. Given the above discussion, we take this value as an upper limit to the age of \( C2 \).

The total V luminosity is \( L_V = 5.4 \pm 0.8 \times 10^4 L_\odot \), the half-light radius is \( r_h = 0.6'' \), corresponding to \( -4 \) pc (all the estimates as been obtained in the same way as for \( C1 \), see above). Assuming \( M/L_V = 0.061 \), from an SSP model having \( Z = 0.004 \), age = 30 Myr from the BASTI set, we obtain \( M_* \leq 3.3 \pm 0.7 \times 10^3 M_\odot \). This is on the high-mass side of the Galactic open cluster distribution, but not out of the range covered by those stellar systems. Also \( C2 \) should be included among regular star clusters (Larsen & Richtler 2000; Billett et al. 2002).

6. Summary and conclusions

We have presented a new reduction and analysis of archival HST-ACS images of the isolated dwarf galaxy VV124. A detailed study of the SFH in the innermost regions of the galaxy, from the same data, has been already presented by another group (J11). Here we focused our attention on a few specific issues that have been raised in Paper I and were not addressed in the J11 paper.

- We provide a clear detection of an extended horizontal branch population. It was shown that HB stars have a spatial distribution that is less concentrated than the RC population. This strongly supports the idea that very old and metal-poor stars become more and more dominant farther from the center of VV124.

- The near coincidence of the asymmetric sheet of young stars near the center of VV124 and the density peak of the (also asymmetric) associated H\( \alpha \) cloud strongly support the idea

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\textbf{Table 4. Observed and derived parameters of cluster C2.}

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \sigma_0 )</td>
<td>09:16:05.69</td>
<td>J2000</td>
</tr>
<tr>
<td>( \delta_0 )</td>
<td>+52:50:20.4</td>
<td>J2000'</td>
</tr>
<tr>
<td>age</td>
<td>( \leq 30 \pm 10 ) Myr</td>
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</tr>
<tr>
<td>([M/H]_0)</td>
<td>( -0.7 )</td>
<td>a</td>
</tr>
<tr>
<td>( R_p )</td>
<td>11.9''</td>
<td>b</td>
</tr>
<tr>
<td>( r_h )</td>
<td>( -0.6'' )</td>
<td>c</td>
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<tr>
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<td>18.6 \pm 0.1</td>
<td>d</td>
</tr>
<tr>
<td>( L_V )</td>
<td>( 18.6 \pm 0.1 )</td>
<td>d</td>
</tr>
<tr>
<td>( M_V )</td>
<td>( -7.0 \pm 0.16 )</td>
<td></td>
</tr>
<tr>
<td>( L_V )</td>
<td>( 5.4 \pm 0.8 \times 10^4 L_\odot )</td>
<td>total V luminosity</td>
</tr>
<tr>
<td>( M_{d_{tot}} )</td>
<td>( \leq 3.3 \pm 0.5 \times 10^3 M_\odot )</td>
<td>stellar mass</td>
</tr>
</tbody>
</table>

\textbf{Notes.} (a) From the isochrone fit of \( F90W \) (see Sect. 5). (b) Projected distance from the center of VV124. (c) From aperture photometry on concentric annuli, assuming a limiting radius \( r = 2.0'' \). (d) Assuming \( (M/L)_V = 0.061 \) from the BASTI database, for a model having age \( 30 \) Myr, \( Z = 0.004 \) and a Kroupa IMF.

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\[ \text{Table 10. The same as Fig. 9 for Cluster 2. In this case the CF}_a \text{ field is not symmetric with respect to the other CFs, to avoid including a significant portion of C1, whose position is also indicated in the map.} \]
that the complex kinematics and velocity gradients observed in the gas in Paper I are most likely associated with the dynamics of the star formation episode. It is interesting to note that some of the isolated dwarfs in the simulations by Sawala et al. (2011) lose all their H i at very early times and are able to re-accrete some of the expelled gas at later times. This scenario would be fully consistent with the observed properties of the H i in VV124 and would provide a natural explanation for the long period of quiescence between the early phase of star formation and the very recent sprout of activity that created the sparse population of young MS stars that are currently observed (see J11).

- We confirm that the candidate cluster identified in Paper I (C1) is a genuine young massive star cluster (see Perina et al. 2010, and references therein). It has an age of ∼250 Myr and a total mass of M ≃ 1.2 × 10^4 M⊙. The cases of such low-mass, early-type dwarf galaxies with massive clusters are quite rare in the Local Group (M98). We identified another likely cluster (C2), significantly younger (age ≤ 30 Myr) and less massive (M ≤ 3.3 × 10^3 M⊙) than C1.

Acknowledgements. We warmly thank Andy Dolphin for his precious assistance in the data analysis. We are also grateful to M. Tosi, A. Sollima, and M. Cignoni for critical reading of a draft version of the manuscript. M.B. and S.P. acknowledge the partial financial support for this research by INAF through the PRIN-INAF 2009 grant CRA 1.06.12.10 (PI: R. Gratton). Partial financial support was also provided by A SI through contracts COFIS ASI-INAF and INAF 2009 grant CRA 1.06.12.10 (PI: R. Gratton). We confirm that the candidate cluster identified in Paper I (C1) is a genuine young massive star cluster (see Perina et al. 2010, and references therein). It has an age of ∼250 Myr and a total mass of M ≃ 1.2 × 10^4 M⊙. The cases of such low-mass, early-type dwarf galaxies with massive clusters are quite rare in the Local Group (M98). We identified another likely cluster (C2), significantly younger (age ≤ 30 Myr) and less massive (M ≤ 3.3 × 10^3 M⊙) than C1.

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