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

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

M. Bellazzini1, S. Perina1, S. Galleti1, and T. Oosterloo2

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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 (\(M = 1.2 \pm 0.2 \times 10^5 M_\odot\)) young (age \(\geq 250 \pm 50\) Myr) star cluster (C1), as well as another of younger age (C2, \(\leq 30 \pm 10\) Myr) with a mass similar to classical open clusters (\(M \leq 3.3 \pm 0.5 \times 10^3 M_\odot\)). 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 \(\sim 1.3\) Mpc from the nearest giant galaxy (the Milky Way) and at \(\sim 0.7\) Mpc from the nearest dwarf (Leo A).

In Bellazzini et al. (2011, Paper I hereafter) we presented new deep wide-field photometry of VV124, which allowed us to confirm and refine the distance estimate by Kopylov et al. (2008), to study in some detail the stellar content of the galaxy and, in particular, its structure out to large radii, revealing the presence of low surface brightness structures in the outskirts. We also presented the first detection of H\(_I\) in VV124, obtained with the Westerbork Synthesis Radio Telescope (WSRT). \(10^5\ M_\odot\) of H\(_I\) were found, with a maximum column density of \(\geq 50 \times 10^{18}\) cm\(^{-2}\). It is worth noting that the distribution of H\(_I\) is less extended than the stellar body of the galaxy.

Jacobs et al. (2011, J11 hereafter) present Hubble Space Telescope (HST) – Advanced Camera for Surveys (ACS) observations of VV124, resolving the stars very well down to \(F814W \geq 27\), also in the most central region of the galaxy. In particular, they studied the stellar content in the innermost 40′′ (see their Fig. 1), deriving the star formation history (SFH) in that region by means of the synthetic color-magnitude diagram (CMD) technique (see, for example Rizzi et al. 2002; Cignoni & Tosi 2010, and references therein). J11 conclude that most of the SF (\(\sim 93\) percent of the total, in mass) occurred at the earliest epochs between 14 and 10 Gyr ago. After this, the SF ceased until 1 Gyr ago, when \(\leq 6\) percent was formed between 1 and 0.5 Gyr ago and nearly 1 percent in the last 0.5 Gyr. The derived SFH is similar to that observed in other nearby dwarf irregular/transition-type galaxies (see, for example Weisz et al. 2011). The prevalence of old stars seems to increase at greater distances from the center (see also Paper I). From the morphology of the blue-loop region, J11 infer that the metallicity of the youngest stars is [\(M/H\)] = –0.7.

In the present contribution, we use the same observational material of J11 to address three issues raised in Paper I and not considered by J11. These are, in particular:

- The tentative detection of an extended horizontal branch (HB), including stars in the color range of RR Lyrae variables and blue HB stars, in the CMD of the less-crowded outer regions of the galaxy (see Fig. 9 of Paper I). While J11 report that a population of HB stars reaching \(V - I \sim 0.4\) is likely present in their CMD, its clean identification and quantification is hampered by the overlap with the young main sequence (MS) in the central region they consider. It would be interesting to search for the HB in the outer portion (\(R_p > 40″\)) of the ACS field, where young stars should be quite rare and the old component should be dominant.
- A possible correlation was noted between the asymmetric distributions of the young stars and of the neutral hydrogen.
Fig. 1. Upper panel: stars detected in the ACS images (dark dots) are superposed to the stars from the LBT sample of Paper I (gray dots) in a projected coordinate system centered on the center of VV124 and rotated to have the X axis coincide with the major axis of the galaxy (see Paper I). Only stars brighter than \( I = 26.5 \) from the ACS sample have been plotted, for clarity. Lower panel: zoomed view of the central part of the ACS sample in the same coordinate system. Two concentric ellipses of semi-major axis \( a = 1.0' \) and \( a = 1.5' \) with the same orientation and ellipticity of the galaxy isophotes (see Paper I) are overplotted (in white and in black, respectively). The white circle has a radius \( R_0 = 40'' \), enclosing the region studied by J11. Blue stars lying on the young main sequence (YMS; \( \beta \leq 0 \)) are enclosed within an ellipse whose major axis coincides with the major axis of the \( H_1 \) 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 px \(^2\) CCDs, with a pixel scale of 0.05 arcsec px\(^{-1}\). The center of VV124 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\(^1\) (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), \( \chi_2 < 2.0 \), \( |\text{sharp}| < 0.5 \), crowding parameter \( \text{crowd} < 0.3 \), 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.\(^5\)

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\(^6\). 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 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 \( F606W \approx 27.2 \).

Table 1. Photometric errors from artificial stars experiments.

<table>
<thead>
<tr>
<th>F814W</th>
<th>( \sigma(F814W_c - F814W) )</th>
<th>( \sigma(\text{col}_c - \text{col})^a )</th>
</tr>
</thead>
<tbody>
<tr>
<td>20.0^b</td>
<td>0.009</td>
<td>0.006</td>
</tr>
<tr>
<td>21.0</td>
<td>0.010</td>
<td>0.009</td>
</tr>
<tr>
<td>22.0</td>
<td>0.013</td>
<td>0.014</td>
</tr>
<tr>
<td>23.0</td>
<td>0.021</td>
<td>0.024</td>
</tr>
<tr>
<td>24.0</td>
<td>0.040(0.045)^c</td>
<td>0.044(0.045)</td>
</tr>
<tr>
<td>25.0</td>
<td>0.077(0.085)</td>
<td>0.084(0.087)</td>
</tr>
<tr>
<td>26.0</td>
<td>0.153(0.164)</td>
<td>0.175(0.180)</td>
</tr>
<tr>
<td>27.0</td>
<td>0.236(0.242)</td>
<td>0.281(0.286)</td>
</tr>
</tbody>
</table>

Notes. \(^a\) \( \text{col}_c = F606W_c - F814W_c \); \( \text{col} = F606W - F814W \). The reported errors are standard deviations computed for recovered artificial stars having \( F814W_c \) within \( \pm 0.5 \) mag from the value reported in Col. 1. \(^c\) Numbers within parentheses refer to the sample with \( CRO \leq 1.0 \), which is adopted in the analysis of the clusters. All the other values refer to the standard \( CRO \leq 0.3 \) sample. The alternative value is reported only when it differs by more than 0.001 mag from the standard value.

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 \( F814W \sim 21.5 \), and the red clump (RC) of intermediate/low mass core He burning stars around \( F814W \sim 25.3 \). 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 \( F606W - F814W \sim -2.0 \). The sparse plume protruding from the RGB at \( F814W \sim 23.5 \) toward the blue has been identified by J11 as composed of blue loop (BL) stars of metallicity \([\text{Fe/H}] \sim -0.7\), 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 \( V - I \sim F606W - F814W \approx 0.4 \) 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 \( F814W \sim 25.8 \) 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 decreased 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 tool\(^7\), to the observed CMD of the outermost region of VV124 sampled

\(^7\) http://193.204.1.62/index.html
Fig. 3. Upper panels: CMD of VV124 from the ACS data within (left panel) and outside (right panel) a circle of radius $R_p = 40''$. The average photometric errors are reported as error bars in the left panel. Lower panels: CMDs in other regions of the ACS field delimited by the ellipses plotted in Fig. 1. The right panel regards a radial region similar to that considered in Paper I to tentatively detect the extended HB population (see their Fig. 9). In all the panels stars are plotted as black points in regions of the CMD with a few stars and as gray squares otherwise, with the scale of gray proportional to the local density of stars in the CMD (lighter tones of gray correspond to higher density).

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 $F606W - F814W < 0.0$, 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 ≤ 25′), 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] $\sim$ $-0.7$, 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 region identified by Kopylov et al. (2008, by means of a long slit optical spectrum). With the available data...
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 2. $N_{<}$ $N_{>}$ ratios for the candidate star clusters and their control fields.

<table>
<thead>
<tr>
<th>Cluster Name</th>
<th>Cluster</th>
<th>CF$_{&lt;}$</th>
<th>CF$_{&gt;}$</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>
<td>4.4σ</td>
<td></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>
<td>3.4σ</td>
<td></td>
</tr>
</tbody>
</table>

Notes. ($^a$) $N_{<}$ is the number of stars having $F606W - F814W \leq 0.2$ and $24.0 < F814W < 26.0$, while $N_{>}$ is the number of stars having $F606W - F814W \geq 0.4$ in the same magnitude range. ($^b$) The definitions of $N_{<}$ and $N_{>}$ 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 $N_{<}$ in the cluster and in the CF showing the lowest value of this parameter, in units of $σ$. ($^d$) Difference between the $N_{>}$ in the cluster and in the CF showing the highest value of this parameter, in units of $σ$.

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 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 ~30% that those obtained with BASTI isochrones.
In Table 2 the ratio of stars bluer than $F606W < F814W$ to the stars redder than $F606W - F814W = 0.4$ ($N_0$) 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$_4$, CF$_5$, and CF$_6$, 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 $\sim 250$ Myr. Such a young age agrees with the integrated spectra of C1 we presented in Paper I. Following Perina et al. (2009), we associate an uncertainty of $\pm 50$ Myr to our age estimate. All the age estimates we obtained by adopting isochrones of different metallicity (in the range $Z = 0.001-0.02$) lie within this errorbar.

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 was estimated in a nearby region to also subtract the contribution from field stars of VV124. From aperture photometry on concentric annuli, and assuming $r = 3.0''$ as the limiting radius of the cluster, we also obtained a rough estimate of the half-light radius, $r_h \approx 1.5''$ has been consistently obtained from both the $F606W$ and the $F814W$ images, corresponding to $\approx 9.5$ pc. This

\begin{table}[h]
\centering
\caption{Observed and derived parameters of cluster C1.}
\begin{tabular}{lcc}
\hline
Parameter & Value & Notes \\
\hline
$\alpha_0$ & 09:16:03.14 & J2000.0 \\
$\delta_0$ & +52:50:27.0 & J2000.0 \\
age & $250 \pm 50$ Myr & \\
$[M/H]$ & $-0.7$ & \\
$R_0$ & $4.3''$ & \\
$r_h$ & $\approx 1.5''$ & \\
$V_{tot}$ & $18.4 \pm 0.1$ & \\
$I_{tot}$ & $18.1 \pm 0.1$ & \\
$M_V$ & $-7.2 \pm 0.16$ & \\
$L_V$ & $6.5 \pm 1.0 \times 10^7 L_\odot$ & total V luminosity \\
$M_{stars}$ & $1.2 \pm 0.2 \times 10^4 M_\odot$ & stellar mass$^a$ \\
\hline
\end{tabular}
\end{table}

Notes. \(^a\) In the astrometric system embedded in the $F606W$ drizzled fits image. \(^b\) From the isochrone fit of Fig. 9 (See Sect. 5). \(^c\) Projected distance from the center of VV124. \(^d\) From aperture photometry on concentric annuli, assuming a limiting radius $r_h = 3.0''$. \(^e\) From aperture photometry with radius $r = 3.0''$. \(^f\) Assuming $(M/L)_V = 0.188$ from the BASTI database, for a model having Age = 250 Myr, $Z = 0.004$ and a Kroupa IMF.

$^9$ Integrated magnitudes have been transformed from $F606W$, $F814W$ to $V$, $I$ using the transformations by Sirianni et al. (2005).
All the BASTI SPSS models adopt a Kroupa (2001) initial mass function (IMF).

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>$\alpha_0$</td>
<td>09:16:03.69</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>
<td>$^a$</td>
</tr>
<tr>
<td>$[M/H]$</td>
<td>$-0.7$</td>
<td>$^a$</td>
</tr>
<tr>
<td>$R_p$</td>
<td>11.9$^{\prime\prime}$</td>
<td>$^b$</td>
</tr>
<tr>
<td>$r_h$</td>
<td>$-0.6^\prime\prime$</td>
<td>$^c$</td>
</tr>
<tr>
<td>$V_{out}$</td>
<td>18.6 $\pm$ 0.1</td>
<td>$^d$</td>
</tr>
<tr>
<td>$I_{58}$</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>$M_{stars}$</td>
<td>$\leq 3.3 \pm 0.5 \times 10^5 M_\odot$</td>
<td>stellar mass</td>
</tr>
</tbody>
</table>

Notes. ($^a$) In the astrometric system embedded into the F560W drizzled fits image. ($^b$) From the isochrone fit of Fig. 9 (See Sect. 5). ($^c$) Projected distance from the center of VV124. ($^d$) From aperture photometry on concentric annuli, assuming a limiting radius $r = 2.0^\prime\prime$. ($^e$) Assuming ($M/L)_V = 0.061$ from the BASTI database, for a model having Age = 30 Myr, Z = 0.004 and a Kroupa IMF.

Fig. 10. The same as Fig. 9 for Cluster 2. In this case the CF$_p$ 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.

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 $L_V = 6.5 \pm 1.0 \times 10^5 L_\odot$. Assuming $M_V = 0.188$, from a simple stellar population (SSP Renzini & Fusi Pecci 1988) model having Z = 0.004, age = 250 Myr, we obtain $M \simeq 1.2 \pm 0.2 \times 10^4 M_\odot$. This implies that C1 is significantly 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 ($M_V < -8.5$, 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 $M/L$ 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 $1^\prime\prime$−$2^\prime\prime$ (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 $r_h = 0.6^\prime\prime$, corresponding to $4 \pm 4$ pc (all the estimates as been obtained in the same way as for C1, see above). Assuming $L_V = 0.061$, from an SSP model having Z = 0.004, age = 30 Myr from the BASTI set, we obtain $M \simeq 3.3 \pm 0.7 \times 10^4 M_\odot$. 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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10 All the BASTI SPSS models adopt a Kroupa (2001) initial mass function (IMF).
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\textsc{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\textsc{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 \(\approx 1.2 \times 10^4 M_\odot\). 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 \(\leq 30\) Myr) and less massive (\(M \leq 3.3 \times 10^3 M_\odot\)) than C1.

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