Star cluster formation and evolution in Mrk 930: properties of a metal-poor starburst

A. Adamo, G. Östlin, E. Zackrisson, P. Papaderos, N. Bergvall, R. M. Rich and G. Micheva

1 Department of Astronomy, Stockholm University, Oscar Klein Center, AlbaNova, Stockholm SE-106 91, Sweden
2 Centro de Astrofísica da Universidade do Porto, Rua das Estrelas, 4150-762 Porto, Portugal
3 Department of Physics and Astronomy, Box 516, Uppsala University, 751 20 Uppsala, Sweden
4 Department of Physics and Astronomy, University of California at Los Angeles, Physics and Astronomy Building, 430 Portola Plaza, Box 951547, Los Angeles, CA 90095-1547, USA

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ABSTRACT
We present the analysis of the large population of star clusters in the blue compact galaxy (BCG) Mrk 930. The study has been conducted by means of a photometric analysis of multiband data obtained with the Hubble Space Telescope (HST). We have reconstructed the spectral energy distributions of the star clusters and estimated the age, mass and extinction for a representative sample. Similar to previous studies of star clusters in BCGs, we observe a very young cluster population with 70 per cent of the systems formed less than 10 Myr ago. In Mrk 930, the peak in the star cluster age distribution at 4 Myr is corroborated by the presence of Wolf–Rayet spectral features, and by the observed optical and infrared (IR) line ratios \([\text{O}\text{III}]/\text{H}\beta\) and \([\text{Ne}\text{III}]/[\text{Ne}\text{II}]\). The recovered extinction in these very young clusters shows large variations, with a decrease at older ages. It is likely that our analysis is limited to the optically brightest objects (i.e. systems only partially embedded in their natal cocoons; the deeply embedded clusters being undetected). We map the extinction across the galaxy using low-resolution spectra and the H\(\alpha\)-to-H\(\beta\) ratio, as obtained from ground-based narrow band imaging. These results are compared with the extinction distribution recovered from the clusters. We find that the mean optical extinction derived in the starburst regions is close to the averaged value observed in the clusters [more than 80 per cent of the systems have \(E(B-V) \leq 0.2\) mag], but locally, do not trace the more extinguished clusters. Previous HST studies of BCGs have revealed a population of young and extremely red super star clusters. We detect a considerable fraction of clusters affected by a red excess also in Mrk 930. The nature of the red excess, which turns up at near-IR wavelengths (\(I\) band and longwards), remains unknown. We compare the cluster formation history and the star formation history, the latter derived from the fit of spectral population synthesis models to the spectra. We find a general agreement between the two independently estimated quantities. Using the cluster properties, we perform a study of the host environmental properties. We find that the cluster formation efficiency (the fraction of star formation happening in clusters) is significantly higher, suggesting a key role of the environment for the formation of these massive objects.

Key words: galaxies: irregular – galaxies: starburst – galaxies: star clusters: general – galaxies: star formation.

The luminous ($M_\text{b} < -18.0$), massive ($\sim 10^9$–$10^{10} M_\odot$) blue compact galaxies (BCGs) show clear signatures of interactions and/or mergers (e.g. Otslin et al. 2001) and the numerous observed massive clusters are likely to be formed in these encounters (Otslin et al. 2003; Adamo et al. 2010a; Adamo et al. 2011a). The very bright ultraviolet and optical luminosities of these systems suggest rather low dust content and metallicity. Spectra dominated by emission lines clearly demonstrate that BCGs are undergoing a burst of SF event. The youth of the burst episode is also observed in the recovered age distribution of the star clusters, which shows a peak of cluster formation younger than 5 Myr. BCGs are considered to be analogues of high-redshift Lyman break galaxies (LBGs) and can probe galaxy formation and evolution at higher redshifts, when the Universe was younger and less enriched in metals.

The analysis of the young cluster populations in BCGs is quite challenging due to the rapid evolution a cluster experiences during the first 10 Myr (still partly in an embedded phase). Moreover, this analysis is based on the integrated luminosities of the clusters, which are mostly unresolved at the distance of the targets. Observations of resolved newly born star clusters in the Milky Way and in the Magellanic Clouds reveal that these are quite complex systems. A cluster forms from the collapse and fragmentation of giant molecular clouds (GMCs; Lada & Lada 2003). The compactness of the protocluster determines whether the conglomerate of stars will form a cluster or a loose association (Gieles & Portegies Zwart 2010; Portegies Zwart, McMillan & Gieles 2010). The massive and short-lived stars rapidly reach the main sequence and produce strong winds and ultraviolet (UV) radiation, which ionize the intracluster gas and create bubbles and shells. These H II regions surround the optically bright core of stars and significantly contribute to the integrated fluxes. However, a large fraction of the stars is still accreting material from their dusty discs (young stellar objects, hereinafter YSOs) or contracting (in the pre-main-sequence phase, hereinafter PMS phase). Simple stellar population models assume that PMS stars do not contribute to the integrated flux of the cluster. This assumption is valid at bluer spectral ranges but not in the infrared (IR). Meyer & Greissl (2005) estimated that PMS stars contribute between 5 and 17 per cent to the total flux in the H band during the first 3 Myr of cluster evolution. As a follow-up, Greissl et al. (2010) found direct evidence of PMS stars in the spectrum of an unresolved young star cluster in The Antennae system. Moreover, the edges of the clusters are places for triggered (Elmegreen 1998) and progressive SF (e.g. Walborn, Maiz–Apellániz & Barbá 2002; Carlson et al. 2007). Delayed or triggered SF processes in dense and dusty regions surrounding the cluster could explain a large fraction of massive YSOs contributing to the IR spectrum of a cluster a few Myr old.

A significant fraction of young star clusters in Haro 11 (Adamo et al. 2010a) and ESO 185–IG13 (Adamo et al. 2011a) show a clear signature of a flux excess in the near-IR (NIR). The models we use (Zackrisson et al. 2001, hereinafter Z01) include a self-consistent treatment of the photoionized gas, important during the first Myr of the cluster evolution (e.g. Krüger et al. 1995; Z01; Anders & Fritzmeier 2003; Zackrisson et al. 2008; Adamo et al. 2010b; Reines et al. 2010). Adamo et al. (2010b) show that nebular emission non-negligibly affects the spectral energy distributions (SEDs) of the clusters during the first 10–15 Myr of cluster evolution. In metal-poor environments, the contribution becomes smaller after 6 Myr on the blue side of the cluster spectrum, but lasts longer in the NIR wavebands, contributing between 10–40 per cent of the total NIR fluxes at ~10 Myr. Since the models used in Adamo et al. (2010a, 2011a) already include a contribution from photoionized gas, the cause of the excess in BCG star clusters resides in other mechanisms (e.g. YSOs, PMS stars, hot dust, etc.).

Mrk 930 is a BCG located at roughly 72 Mpc. The galaxy was imaged and catalogued in the mid-1960s and 1970s, during the first large-scale objective-prism survey for galaxies with blue and UV excess in their continuum radiation (Mazzarella & Balzano 1986), that is, the First Byurakan Spectral Sky Survey. Due to the low-metallicity content [$12 + \log$ (O/H) = 8.06, Izotov & Thuan 1998], Mrk 930 was included in the late 1990s in the group of galaxies studied for their similarity to high-redshift LBGs. Izotov & Thuan (1998) classified Mrk 930 as a Wolf–Rayet (WR) galaxy. Typically, WR signatures in the spectrum of a low-metallicity galaxy is a rare phenomenon because the duration of the WR phase is shorter when the metallicity decreases (see Guseva, Izotov & Thuan 2000 and references therein). The presence of WR features indicates that the galaxy is undergoing a young burst episode.

Mrk 930 was included in Malkan’s Hubble Space Telescope (HST) survey of local active galaxies (Malkan, Gorjian & Tan 1998) as a H II galaxy. The short F606W exposure of the galaxy revealed that two starburst knots observed in ground-based images were in reality formed by numerous bright star clusters (Östlin 2000). The presence of a very active starburst episode, the low-metallicity environment and numerous clusters makes Mrk 930 a galaxy of great interest to include in our statistical analysis of star cluster populations in extreme environments (Östlin et al. 2003; Adamo et al. 2010a; Adamo et al. 2011a).

A three-colour composition of Mrk 930, obtained with the high-resolution HST Planetary Camera (PC) (Fig. 1), shows a morphologically perturbed galaxy. Nebular emission surrounds the burst regions (the green regions are caused by strong nebular emission lines falling in the band pass of the wide V-band filter F606W), confirming the youth of the stellar population. Knot A is the brightest region in the galaxy. It is also the most rich in star clusters, resembling the cluster complexes observed in M82 (Smith et al. 2006) and Haro 11 (Adamo et al. 2010a). In the southern part, an extended tail is observed. The colour of the tail is redder than the main galactic body, suggesting an older stellar population. Such an evolved population has also been detected in the outskirts of the galaxy (Micheva et al., in preparation). The northern part of the galaxy is formed by two close cluster-rich regions B and C and a tidal tail. Optical Fabry–Perot interferometric imaging shows signatures of a recent merger event in the velocity field of the galaxy (Marquet et al., in preparation).

Here, we present a complete multwavelength analysis of the cluster population in Mrk 930. The data are described in Section 2. The cluster analysis and derived properties are discussed in Section 3. In this section, we propose possible scenarios to explain the origin of the red excess. In Section 4, we map the mean extinction distribution in the galaxy, using ground-based spectroscopy and imaging. We compare this mapping with the extinction derived locally from

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1 Value taken from the NASA/IPAC Extragalactic Data base (NED), corresponding to a distance modulus of 34.27 mag and a recession velocity of 5485 ± 10 km s$^{-1}$. These values are used in the present analysis.
the clusters. In Section 5, we discuss the properties of the galaxy as derived from the cluster formation history and star formation history (hereinafter CFH and SFH, respectively). Conclusions are summarized in the final section.

Throughout this paper, we will use the Vega magnitude system.

2 THE DATA

2.1 HST data: observations and photometric analysis

HST multiband high-resolution imaging of Mrk 930 was carried out in 2007 (associated with program # GO 10902, PI: G. Östlin). The galaxy was sampled with the same data set as for the ESO 185-IG13 target (Adamo et al. 2011a). The ACS solar blind channel (SBC) camera was used to image the galaxy in the far-UV (FUV) filter F140LP. The optical sampling of the galaxy was originally scheduled for the ACS/HRC and WFC but due to the failure of the instrument in 2007, we switched to the WFPC2 and in particular the PC aperture and obtained mages in the U (F336W), B (F439W), R (F606W) and I (F814W) bands. Finally, the IR (H band, F160W) imaging was performed by the NICMOS3 camera, which offers lower spatial resolution but a wider field of view. The frames were reduced, drizzled and aligned using the MULTIDRIZZLE task (Fruchter & Hook 2002; Koekemoer et al. 2002) in PyRAF/STSDAS. The WFPC2 F606W and F814W, the SBC/F140LP and the NIC 3 imaging was achieved using a dither pattern to improve the final resolution of the science frames. In the case of the F336W and F439W imaging, two exposures each were taken to perform cosmic-ray correction, but dithering was not applied due to the shorter available exposure time. The final UV and optical frames were rescaled to 0.025 arcsec pixel$^{-1}$. The best resolution we could achieve for the NIC3 final frame was of 0.067 arcsec pixel$^{-1}$. Aperture photometry on the sources was done using a radius of 0.1 arcsec. The sky annulus around the source was placed at 0.125 arcsec and had a width of 0.05 arcsec. Due to the crowding of the regions, we preferred to use the same aperture radius and sky annulus in all the frames and correct for the missing flux (caused by a fixed aperture), using estimated aperture correction values for each frame (see Table 1). A detailed description of the data reduction, cluster catalogue extraction, point source photometry and charge transfer efficiency correction is given in Adamo et al. (2010a, 2011a). A list of the filters, total exposure time, zero-points (ZPs) and other observational properties related to the reduction of the data are summarized in Table 1.

Figure 1. Three-colour image of the starburst galaxy Mrk 930: WFPC2 F814W filter in red, F606W filter in green and F336W filter in blue. Some intense blue spots are caused by an imperfect removal of cosmic rays from the WFPC2/F336W frame. Different star-forming regions can be observed in the galaxy. The youngest are surrounded by intense nebular emission (green diffuse light, due to the wide V-band filter F606W which transmits $[O\text{ III}]$ and H$\alpha$). Knot A is the brightest optical and UV region in the galaxy and is undergoing the most active starburst event. Regions B and C are less clustered and coeval to knot A. The colour of the extended tail in the south of the galaxy is redder than the starburst regions, probably formed by a more evolved stellar population. See the main text for more details.
Table 1. HST observations carried out within the framework of program # GO 10902 (PI: G. Östlin). For each filter, we list in the table the total exposure time; the corresponding ZPs (Vega magnitude system); the aperture corrections, $\alpha_i$; the number of objects detected with a S/N $\geq 5$; and the corresponding magnitude limit.

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Filter$^a$</th>
<th>Camera</th>
<th>Exposure time (s)</th>
<th>ZP (mag)</th>
<th>$\alpha_i$ (mag)</th>
<th>$N(\sigma \leq 0.2)$</th>
<th>mag limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACS</td>
<td>F140LP (FUV)</td>
<td>SBC</td>
<td>2532</td>
<td>20.92</td>
<td>$-0.54 \pm 0.05$</td>
<td>117</td>
<td>24.0</td>
</tr>
<tr>
<td>WFPC2</td>
<td>F336W (U)</td>
<td>PC</td>
<td>1200</td>
<td>19.43</td>
<td>$-0.42 \pm 0.05$</td>
<td>81</td>
<td>23.0</td>
</tr>
<tr>
<td>WFPC2</td>
<td>F439W (B)</td>
<td>PC</td>
<td>800</td>
<td>20.88</td>
<td>$-0.36 \pm 0.05$</td>
<td>79</td>
<td>24.1</td>
</tr>
<tr>
<td>WFPC2</td>
<td>F606W (R)</td>
<td>PC</td>
<td>4000</td>
<td>22.89</td>
<td>$-0.61 \pm 0.09$</td>
<td>207</td>
<td>27.1</td>
</tr>
<tr>
<td>WFPC2</td>
<td>F814W (I)</td>
<td>PC</td>
<td>4500</td>
<td>21.64</td>
<td>$-0.73 \pm 0.04$</td>
<td>207</td>
<td>26.0</td>
</tr>
<tr>
<td>NICMOS</td>
<td>F160W (H)</td>
<td>NIC3</td>
<td>4992</td>
<td>21.88</td>
<td>$-2.45 \pm 0.37$</td>
<td>78</td>
<td>25.9</td>
</tr>
</tbody>
</table>

$^a$Both the HST filter names and the abbreviated nomenclature indicated in parentheses are used hereinafter in the text.

As already found in Adamo et al. (2010a, 2011a), the number of clusters detected in the two deepest exposures, the $R$ and $I$ bands, is greater than in the other available filters (see Table 1). In total, we recovered 477 cluster candidates (with $\sigma \leq 1.0$ mag). Viewing the colour–magnitude diagram (CMD, Fig. 2) and evolutionary tracks, we expect the cluster population to show a wide range of masses and ages. After a photometric error cut at $\sigma \leq 0.2$ mag, 207 objects remain. Of these, 157 sources are detected in at least a third filter, so this is the number of objects we consider in the analysis of Mrk 930.$^3$

The completeness test was performed on the two $R$ and $I$ WFPC2 frames, the deepest filters used to extract the first cross-correlated source catalogue (Adamo et al. 2010a, 2011a). This type of analysis is useful in constraining the sensitivity of our method to recover objects. Similar to the Haro 11 and ESO 185-IG13 analyses, we defined a centre of the galaxy ($\alpha = 23^h31^m58.5^s; \delta = 28^\circ56'52"$) and a crowded region of 4.5 arcsec radius, where most of the starburst knots were contained. The surrounding region (an annulus of an inner radius of 4.5 arcsec and outer radius of 12.25 arcsec) is characterized by a low sky background, ideal for detecting faint objects. The number of recovered objects was compared to the crowding of the considered region. In Fig. 3, we show the total fraction of recovered detections. The two solid lines (green and black) show that in general we are able to detect most (90 per cent) of the objects with luminosity brighter of $\sim 26.8$ mag. At roughly 28 mag, we are still able to detect 50 per cent of the objects in both filters. However, this is an averaged result. Looking at the recovered fraction in the ‘inner’ (crowded) and ‘outer’ (starburst outskirts) areas, one can see that the detection of objects drops more rapidly in the crowded regions and changes quite abruptly. This behaviour is caused by the small area of the starburst region which does not allow to build a statistically populated sample of objects at different luminosity.

$^3$The complete photometric catalogue is available on request from the authors.

Figure 2. CMD of the cluster population. Top panel: the small green (grey) asterisks show the 477 cluster candidates detected in the galaxy. The black filled dots are the 207 clusters with photometric errors in $I$ and $R$, $\sigma_m \leq 0.2$. The extinction vector indicates the shift of a cluster in this plot, if corrected for $E(B-V) = 0$. The evolutionary tracks from Z01 are for $Z = 0.004$ and several values of the mass. In each model track, the squares, diamonds and triangles indicate 1, 10 and 14 Gyr, respectively. See the main text for details.

Figure 3. Completeness fraction as a function of the object magnitudes. The outputs of the $F606W$ frame are plotted in green (grey), while in black we show the fraction for the $F814W$ frame. See the main text for the definition of the ‘inside’ and ‘outside’ regions. The red dotted straight lines show the 90 and 50 per cent completeness limits.
bins. Since the quality and sensitivity of the used data for the three BCGs are similar (same exposure time and observational strategy), we can use the results of the completeness tests of Haro 11 and ESO 185-IG13 to consider approximately 26 mag as a threshold for 90 per cent completeness detection in the inner region for both filters.

2.2 Ground-based imaging and spectroscopy

2.2.1 NOT narrow-band imaging

Ground-based narrow-band imaging was carried out with the 2.56-m Nordic Optical Telescope (NOT) on La Palma with the ALFOSC instrument. The Hα observations were carried out in 2002 September. We obtained 1800 s of integration through NOT filter #70 approximately centred on Hα at the redshift of Mrk 930. For continuum subtraction, we obtained 2400 s of integration through filter #78. We also obtained exposures in both filters of the spectrophotometric standard stars BD+28°4211 and GD248. The data were reduced in a standard manner (bias, flat-fielding, zero-point calibration). To obtain the Hα flux in the continuum-subtracted image, we applied the following additional steps: (i) we corrected for the relative transmission of the filter at the redshifted wavelength of Hα; (ii) we corrected for the contribution of [N II] by taking the relative filter transmission at the redshifted wavelengths into account and by using spectrophotometrically determined line ratios which we assumed to have a spatially constant value over the face of the galaxy (this is reasonable due to the similar ionization potentials); and (iii) we multiplied with the equivalent rectangular width (the integral of the filter throughput function divided by the filter peak transmission) of the filter to obtain an image calibrated in units of erg s⁻¹ cm⁻².

The Hβ observations were carried out in 2007 August, using filter #113 (t_exp = 4900 s) to capture Hβ and filter #17 (Strömgren-b, t_exp = 2100 s) for the continuum, and the spectrophotometric standard Feige 110 for calibrations. The same reduction and calibration steps as for Hα were followed except that we did not need to correct for [N II].

In addition, we obtained exposures in filters #66 (600 s) and #18 (Strömgren-γ, 600 s) to capture the redshifted [O III]λ5007 line and its continuum. Seeing was close to 1 arcsec for all observations and conditions were photometric.

2.2.2 Spectroscopy

Low-resolution long-slit spectra of Mrk 930 along two position angles (PAs) were taken on 2009 November 14 with the 3.6-m Telescopio Nazionale Galileo (TNG) using the DOLORES focal reducer. We used the LR-B grism which yields a wavelength coverage between 3000 and 8430 Å and a resolution R ∼ 600 for our slit width of 1 arcsec. The data were acquired in 1 × 2 pixel binning, resulting in a spatial scale of 0.504 arcsec pixel⁻¹. Several spectrophotometric standard stars were observed at various airmasses (AMs) for the sake of flux calibration. The observations consisted of three consecutive 12-min exposures along each PA and were carried out in either case at a low AM (≤1.03). No corrections for differential atmospheric refraction were therefore applied.

Conditions were relatively good during the first pointing with the slit rotated to PA = 74.1° and encompassing regions B and C; comparison of multiple science and calibration exposures suggests transparency varied by ≤5 per cent. Despite the mediocre seeing (1.5–1.9 arcsec full width at half-maximum), we could clearly separate regions B and C. For the other slit positions, the seeing was worse, ≈2.5 arcsec, rendering a spatially resolved study of component A (PA = 108°) impossible. An intercomparison of individual galaxy and standard star spectra taken during that phase of the observing run has revealed transparency variations by a factor of 2, resulting in a significantly lower S/N for at least one of the three spectra taken. The data were reduced with MIDAS using a standard procedure.

3 EXTRACTING THE CLUSTER PROPERTIES FROM THEIR LUMINOSITY

3.1 The cluster luminosity functions

Young star clusters show a power-law luminosity function [CLF, dN(L) ∝ L^{-α} dL] and mass function [CMF, dN(M) = CM^{-γ} dM], with slopes of ~2.0. However, the CLF varies from galaxy to galaxy, showing a wide range of slopes, 1.8 ≤ α ≤ 2.4 (Larsen 2002; de Grijs et al. 2003; Hunter et al. 2003; Mora et al. 2009; Pellerin et al. 2010; Whitmore et al. 2010; among many others), or even a bend occurring roughly between ~8.0 and ~10.0 mag (Gieles et al. 2006a,b).

The CLF is composed of many cluster populations, formed in different periods of the SFH of the host. The absence or presence of variations in the slope of the CLF could probe (i) whether the CMF is a single power law with index ~2.0 (see Chandar et al. 2010; Whitmore et al. 2010) or has a Schechter function with a ‘soft’ truncation at a characteristic mass, related to the environmental properties of the host galaxy (see Gieles et al. 2006b; Bastian 2008; Larsen 2009); and (ii) whether cluster disruption is mass-dependent or mass-independent (see Lamers 2009 for a short summary).

In studies of star cluster properties in BCGs, it has been argued that the CLF in these systems is shallower than expected: α ∼ 1.8 in ESO 338-IG04 (Östlin et al. 2003); α ∼ 1.5 (but α ∼ 1.6 if only the brightest bins are included in the fit) in Haro 11 (Adamo et al. 2010a); and α ∼ 1.8 (but α ∼ 2.2 including only the brightest bins) in ESO 185-IG13 (Adamo et al. 2011a).

We present here the analysis of the CLF in Mrk 930. We use the numerous objects detected in the two deepest exposures, F606W and F814W, with photometric errors below 1.0 mag, to determine the slope of the CLF (similar results have been recovered if only the σ ≤ 0.2 sample is used). In the left-hand and middle panels of Fig. 4, we show the two recovered CLFs corrected for completeness. In the right-hand panel, we include the CLF for the H band. In this case, it is important to mention that we included all the positive detections obtained, making the derived distribution rather uncertain.

The fit to the R- and I-band CLFs, showed as a black solid line, includes all the luminosity bins up to the value where we recovered 90 per cent of objects in the completeness tests. The fit to the H-band CLF excludes the fainter bins where we note a decrement in the number of objects. The slopes in the three filters are, inside the uncertainties, similar and much flatter than expected. A second fit, confined to the brightest luminosity bins, produces higher values, slightly more consistent with the expected 2.0 value.

We have already discussed in Adamo et al. (2010a, 2011a) that blending can flatten the observed CLF. Moreover, the incompleteness could be much more severe than the values obtained in this analysis. Therefore, it is not possible to derive any conclusion with the current data. Simulations, which reproduce a blending effect and different CMF shapes, need to be used to explore the physical properties of the host environments by means of the CLF.
3.2 Analysis method: $\chi^2$ fitting

To extract the physical properties of the clusters, that is, age, mass and extinction, we compared spectral synthesis models to their reconstructed SEDs from multiband photometry. The models we used contain several assumptions and parameters:

(i) Clusters form in an instantaneous burst, that is, the stellar population is coeval;
(ii) The stars in the cluster have masses sampled by a Kroupa universal initial mass function (Kroupa 2001);
(iii) Both photoionized gas (important during the first $10^{7}$ Myr of the cluster evolution) and stars contribute to the total integrated fluxes;
(iv) Standard H II region values for the gas as input parameters to CLOUDY (version 90.05, Ferland et al. 1998): hydrogen gas density of $10^2$ cm$^{-3}$, filling factor of 0.01, covering factor of 1 (there is no leakage of ionizing photons; for example, all the Lyman continuum photons ionize the gas);
(v) The metallicity of the stars and the gas in the cluster is the same, that is, $Z = 0.004$ (corresponding to the values determined by Izotov & Thuan 1998).

A detailed description of the models can be found in Z01 and Adamo et al. (2010a, 2011a). The spectral synthesis models of Marigo et al. (2008, hereinafter M08) have been used to test the robustness of some of our results.

To constrain the model which most closely reproduced the observed cluster SED, we performed a $\chi^2$ fit. Applying the Calzetti attenuation law (Calzetti et al. 2000), we created a grid of models with the values of extinction, $E(B-V)$, ranging from 0.0 to 3.0 for each age step. The reddened model with the smallest weighted residuals was considered the best one and produced the age and extinction for the cluster. The mass was proportional to the normalization factor between the best model and the observation. A detailed description of the $\chi^2$ algorithm is given in Adamo et al. (2010a).

3.3 Reconstructing the SEDs of the clusters

A close look at the $\chi^2$-fit outputs reveals that also in Mrk 930 there is a fraction of clusters with an NIR excess (Adamo et al. 2010a, 2011a), that is, an observed luminosity at wavelengths larger than 0.8 $\mu$m which cannot be reproduced by our models. The fit procedure for clusters affected by a red excess and their analysis has widely been discussed in Adamo et al. (2010a, 2011a). Here, we summarize the main characteristics.

In sources affected by a red excess, the fit to the whole SED (from UV to IR) fails, for example, producing high residuals and wrong estimates of the cluster age (mass). To trace which of the clusters are affected by a red excess, two new fits are performed. In these two runs, we exclude once the IR band (H band) and in the other the I and H bands (the latter one if available). The requirement of at least three data points available, in order to perform the fit, is always retained. The outputs of the three fits are then compared and, for each cluster, we consider as a best fit the one which better reproduces the UV and optical shape of the observed cluster SED.

In general, we note that even if the I-band excess is less evident than the IR one and could be easily overlooked, it has an important impact on the estimated ages and masses (see Adamo et al. 2010a, 2011a).

In Mrk 930, we performed a $\chi^2$ analysis on a total of 157 objects. Of these objects, 61 per cent have normal SEDs and, inside the photometric uncertainties, the performed analysis produced fairly good fits. 12 per cent of clusters display an $I$-band flux excess (IR excess) and the remaining 22 per cent have a flux excess at $\lambda > 0.8$ $\mu$m (NIR excess). For these clusters, the age, mass and extinction have been estimated from the UV and optical SEDs. In a small number of cluster candidates (seven in total, ~5 per cent), the fit procedure failed and therefore are excluded from further analyses.

Finally, we carried out an individual analysis for a rather bright and isolated point-like system, whose nature remains unclear. This object is easily noted in Fig. 1 on the right-hand (west direction) side of region B, located at a projected distance of roughly 1 kpc. It looks reddish and different from the colour of the clusters in the starburst regions. Interestingly, it is not detected in the $FUV$ and $U$ bands and is only marginally detected in the $B$ band. Different scenarios can be advocated to explain the nature of this object: either a deeply embedded and very young cluster (similar cases have been found in ESO 185-IG13, Adamo et al. 2011a) or a background object (early-type galaxy at redshift $\sim$0.1 or Lyman break system at redshift $>3.0$).

Since it is isolated, we performed a new photometric analysis, using an aperture radius of 1.0 arcsec. The model fit to the SED of this cluster candidate produced an age of 35.0 Myr, a mass of $1.2 \times 10^6$ $M_\odot$ and $E(B-V) = 0.68$ ($A_V \sim 2.5$ and $A_B \sim 3.45$ mag). The properties constrained for this object are quite extreme. The mass is similar to the values found for W3 and W30 in the merger remnant.
NGC 7252, and the globular cluster (GC) G114 in NGC 1316 (Maraston et al. 2004; Bastian et al. 2006). These evolved clusters are located a few kiloparsecs away from their hosts, have ages between 400 Myr and 3 Gyr, and dynamical masses between $(1–8) \times 10^7 M_\odot$. The formation mechanism for such massive systems is unclear. Numerical simulations (Fellhauer & Kroupa 2005) suggest the possibility for these systems to form from the merger of super star clusters born inside the same cluster complex.

The cluster-like object in Mrk 930 is much younger than these supermassive evolved clusters, and even if it potentially could be a predecessor of such rare objects, we cannot exclude any scenario with the current data (i.e. background object). The extracted spectrum at the position of this cluster shows a few faint emission lines (e.g. H\(\alpha\) and H\(\beta\)) at the same rest-frame position of the galaxy. The continuum has a low S/N and disappears around 4200 Å, in agreement with the reconstructed SED from the photometric data. However, we note that locally the region surrounding the cluster has similar nebular emission lines, suggesting contamination from the galaxy. Due to the uncertain nature of this cluster-like object, we exclude it from the cluster analysis.

3.4 Cluster photometric properties

Colour–colour diagrams represent useful tools for analysing the massive Mrk 930 cluster population. In Fig. 5, we plot three different colours against \(R – I\), which is used as a reference. Generally, a negative \(R – I < 0\) colour indicates ages younger than 10 Myr and is produced by a strong nebular contribution to the \(R\) filter, which includes the bright H\(\alpha\) line. However, this assumption is not always valid due to the flux excess in the \(I\) band. The clusters, in the diagrams, have different symbols, depending on their observed SEDs: black dots indicate normal SEDs; red triangles indicate clusters with an excess at \(\lambda > 1.0 \mu m\) (hereinafter IR excess); and blue diamonds indicate SEDs which deviate at \(\lambda > 0.8 \mu m\) (hereinafter NIR excess). We note that clusters with a NIR excess have a \(R – I\) colour between 0.2 and 1.2 mag redder than the prediction made by the best-SED-fitting model. These residuals can be observed in Fig. 9 and will be discussed in Section 3.6. The \(R – I\) colour of the ‘blue’ cluster diamonds is such that, if overlooked, it causes age (and mass) overestimates, affecting the results of the optical-based cluster analysis.

Figure 5. Colour–colour diagrams of the cluster population in Mrk 930. Different filter combinations are compared to the \(R – I\) colour (\(F606W – F814W\)). Upper left-hand panel: \(UV – R\) (\(F140LP – F606W\)); upper right-hand panel: \(B – R\) (\(F435W – F606W\)); and lower panel: \(R – H\) (\(F606W – F160W\)). In each panel, the Z01 evolutionary tracks are plotted as a solid black line. Where predictions for the used filters were available, we included the M08 tracks (dashed lines) as well. The black triangles show the starting point of the tracks (1 Myr for Z01 and 4 Myr for M08), the red asterisks show the positions in the tracks at 10 Myr, and the black squares show the positions in the tracks at 14 Gyr. The black dots are clusters with fully fitted SEDs (from UV to IR). The red triangles are clusters with an excess at \(\lambda > 1.0 \mu m\). The blue diamonds show objects with an excess starting longward \(\lambda > 0.8 \mu m\). The black arrows indicate in which direction and in what quantity the colours of the clusters change if \(E(B – V) = 0.3\) is applied. Mean errors are included. The green square shows the position of the cluster-like system in the colour–colour diagram and the green arrow shows the position after an extinction correction of \(E(B – V) = 0.68\) is applied (see Section 3.3).
The $UV - R$ (upper left-hand panel) colour shows that the clusters detected in the $FUV$ are young, at least younger than 30–40 Myr. Many of the clusters with an NIR excess are located in an area where $R - I > 0$, for example, with ages older than 10 Myr. The $FUV$ band is sensitive to the reddening. Looking at the colour–colour diagram, one can see that clusters detected in the $FUV$ have extinctions, $E(B - V) \lesssim 0.3$ (e.g. the arrow in the plot). Therefore, we consider these very young $FUV$ bright clusters as systems which have already gone through the deeply embedded phase.

A combination of optical colours (upper right-hand panel) probes the impact of the contribution from photoionized gas. We compare our models (solid black line) to the Padova tracks (dashed black line; M08). The latter offer a better modelling of the asymptotic giant branch (the difference is evident in the IR colour, bottom panel). However, due to the age range of the cluster population we are studying, the impact is negligible compared to having a self-consistent treatment of the contributing nebular luminosity. More than 50 per cent of the clusters in the optical colour are located in areas of the diagram that can only be reproduced by models that include the photoionized gas.

Finally, the inclusion of the IR colour (bottom panel) clearly show that clusters with a flux excess at the redder wavelengths are mainly located in an area of the diagram where $R - I > 0$ and $H - R > 1.0$ mag. The IR colour of the clusters with a red excess suggests that the extinction in these objects should be much higher than the one predicted by the optical and UV colours. In other words, at the NIR wavelengths, it is possible that we are probing a different, more deeply embedded stellar population in the cluster indicating that these are very young systems. We will discuss the cluster properties and possible connections with the origin of the red excess in Section 3.6.

### 3.5 Age, mass and extinction of the cluster population

In this section, we present the derived age, mass and extinction distributions of the cluster population. For 57 per cent of the systems, we had at least four different data points (integrated fluxes) to perform the SED fit. The remaining fits were obtained from only three data points: 13 per cent with $R$, $I$ and $H$ fluxes (hereinafter $RIH$ fit); 20 per cent with $FUV$, $R$ and $I$ (hereinafter $FUV - RI$); and 10 per cent with a detection in $B$ or $U$ and $R$, and $I$.

The uncertainties associated with the recovered values depend on the used filter combinations; the photometric errors (including uncertainties produced by the quality of the data and the reduction process); the models [limited by our ability to reproduce the luminosity properties of the clusters, by assumptions on the initial mass function (IMF) and on the mass-to-light ratio ($M/L$)]; and the applied attenuation law.

In the cluster analysis, an important factor of uncertainty is produced by stochastic effects in the sampling of the stellar IMF. Several works (e.g. Cerviño & Luridiana 2004; Maíz Apellániz 2009; Silva-Villa & Larsen 2011, among many others) have pointed out that stochasticity becomes important in low-mass clusters ($<10^3 \text{M}_\odot$) and may drastically affect the photometric studies of clusters with masses lower than $10^4 \text{M}_\odot$. The spectral evolutionary models of star clusters are built assuming a continuously populated IMF. In reality, in low-mass clusters, the stars randomly sample the IMF, meaning that they may have formed a number of massive stars different from the predicted ones by the models. Massive stars dominate the colours of the clusters. Recently, Silva-Villa & Larsen (2011) have showed that the luminosity properties of the clusters of $<10^3 \text{M}_\odot$ change so drastically that the uncertainties in the age can be as big as 2.5 dex. A wrong age estimate has important consequences for the mass as well (e.g. if the age is overestimated, the mass will also be bigger than the actual value because of the increasing $M/L$ value as a function of the age). However, we show in Figs 6 and 7 that many clusters have masses higher than $10^4 \text{M}_\odot$, suggesting that the stochastic effects, although present, are not very important (the error in the age estimate is about 5–10 per cent Cerviño & Luridiana 2004). In Section 3.6, we again...
address stochasticity to explain the NIR excess observed in some clusters which luminosity could be dominated by red supergiant stars (RSGs).

In Adamo et al. (2011a), we discussed the uncertainties introduced by the set of data on the recovered estimates using Monte Carlo (MC) simulations. Since the data set, the models and the extinction law applied are the same as the ones used in the analysis performed on Mrk 930, we apply those recovered uncertainties to the present results.

The recovered age distribution shows, as expected, a very young cluster population (upper panel in Fig. 6). The most populated age bin is the 3–4 Myr one [log (age) = 6.5 Myr], similar to what already observed in Haro 11 (Adamo et al. 2010a) and ESO 185-IG13 (Adamo et al. 2011a). From MC tests (Adamo et al. 2011a), we know that the robustness of this peak is quite high (this age is recovered in 99 per cent of the cases).

A secondary peak is found at slightly older ages, between 10 and 20 Myr (signed with the vertical black dashed lines, log (age) = 7.1 and 7.3 Myr). These two age bins are the most uncertain in our analysis. Independently of the filter combination used, we observed in the MC tests that the recovered number of systems in the 10–20 Myr bins is doubled with respect to the initial number of objects; meanwhile, the age range between 20 and 150 Myr is emptied. The cause of this behaviour is the loop in the evolutionary tracks at ages between 10 and 40 Myr (see the upper right-hand and bottom panels in Fig. 5), and a degeneracy between age and extinction between 40 and 150 Myr, that is, the extinction vector lies roughly parallel to the evolutionary tracks (see also section 3.3 in Adamo et al. 2011a).

Estimates based on a three-data point SED are, in general, even more uncertain. The FUV – RI fit produces two spurious peaks at 12 Myr [log (age) = 7.1] and at 1 Gyr [log (age) = 9.1]. The age distribution of clusters with a FUV – RI fit (purple solid line histograms, upper panel in Fig. 6) has a considerable fraction of objects in the 12-Myr bin. Likely, two-thirds of these objects are in reality older. Similarly, the RHI fit produces spurious peaks at log (age) = 6.7 (dot-dashed line in Fig. 6) and log (age) = 7.3 Myr.

We see, however, that the number of objects in these two bins is small. We conclude that likely the secondary peak is not securely established and open for a scenario where the cluster production in the galaxy has started roughly 100 Myr ago and continued until the present time. Two much older peaks at 1 and 14 Gyr prove that the present starburst phase is not the first burst event in the galaxy.

The cluster mass distribution (middle panel in Fig. 6) covers a wide range of masses, from $10^4$ to $10^6 \, M_{\odot}$. We observe that more than 20 per cent of clusters are as massive or more massive than $10^5 \, M_{\odot}$ (the super star cluster range). MC tests showed that a significant fraction (roughly 30 per cent) of recovered masses are underestimated. The difference between input and recovered masses is, however, not higher than a factor of 2 (when FUV – RI and RHI fits are performed). Only in the case of a RHI fit, we noted (Adamo et al. 2011a) that in 20 per cent of cases the mass was overestimated by up to a factor of 2.

The mass–age plot (Fig. 7) shows the whole cluster population. In contrast to Haro 11 and ESO 185-IG13, we find no young clusters with masses $\sim 10^5 \, M_{\odot}$. Clusters with a NIR excess are all (except one) younger than 6 Myr. IR excess clusters have ages between 1 and 35 Myr. Even in Mrk 930 we observe a lack of low-mass ($<10^4 \, M_{\odot}$) and very young clusters (<4 Myr). As already discussed in Adamo et al. (2010a, 2011a), a fraction of these objects are likely not detected due to blending and crowding. We also expect that a considerable number of these clusters are still partially embedded in their birth cocoons of dust and gas. We estimated that a rather moderate extinction of $E(B – V) = 0.5$ mag ($A_V \approx 1.5$) is enough to make a cluster of mass below $10^5 \, M_{\odot}$ undetected at visual wavelengths.

The extinction distribution (bottom panel in Fig. 6) shows, as expected, that more than 80 per cent of the clusters have extinction $E(B – V) \leq 0.2$ mag. The remaining fraction are distributed in somewhat higher values, reaching 1.2 mag. Clusters with extinction higher than 0.4 mag could only be analysed with a RHI fit. The extinction–age plot (Fig. 8) clearly shows that those clusters with higher extinction are, in all cases (except two), systems younger than 10 Myr. Since these clusters are only observed at the redder wavebands, they are likely still partially embedded. Similar trends in the extinction distribution and extinction–age diagram have also been observed in the other BCGs, Haro 11 and ESO 185, and in
systems like The Antennae (Mengel et al. 2005) and M51 (Bastian et al. 2005).

3.6 The red excess in young star clusters

As already done in the previous studies of Haro 11 and ESO 185-IG13, we try to trace any potential relation between the UV- and optical-determined cluster properties and the intensity of the flux excess with respect to the best-fitting models. In Fig. 9, we plot the flux excess (residuals) against the corresponding age, mass and extinction. Represented by the dots are the clusters younger than 6 Myr and those represented by the squares are older systems. The color of the symbols is related to the type of excess constrained. If the observed excess is \( \lambda > 1.0 \mu m \), then the symbols are in red and if the excess is longward of \( \lambda > 0.8 \mu m \), then the symbols are in blue. As comparison, we include the distribution of the ‘normal’ clusters that are objects with regular SEDs (represented by the black and green crosses).

If we look at the age, mass and extinction of the clusters versus their residuals (\( \Delta m = m_{\text{mod}} - m_{\text{obs}} \)) in the \( H \) band (upper panels), we do not see any clear relation between the UV/optical properties and the strength of the IR excess. We have already noted from the IR–optical colour–colour diagram (bottom panel, Fig. 5) that the clusters affected by a red excess require much higher extinction values than the ones from the UV/optical colours (see the other two diagrams) to move towards the areas of the tracks corresponding to the estimated age. This property suggests that another mechanism contributes at the IR waveband and not in the optical.

The same analysis, but including the \( I \)-band residuals, shows a clear correlation between the age of the cluster and the \( I \)-band excess (bottom panels in Fig. 9). In all except one case, the \( I \) band is found in clusters younger than 6 Myr. The spread in mass and extinction is, however, similar to the trend observed in the upper panels.

The age of the clusters (even if determined by UV and optical luminosities) may give insights into the origin of the red excess. Possible origins for the NIR excess have been widely discussed in the literature, studied cases of IR excess in young embedded or partially embedded unresolved extragalactic clusters have explained the red excess as due to an important contribution by YSOs (Fernández-Ontiveros et al. 2009) or hot dust (Cabana, Vanzini & Adamo et al. 2010a, 2011a). Here, we will summarize the main aspects.

3.6.1 The \( I \)-band excess

Due to the narrow cluster age range for where the \( I \)-band excess is found, a viable explanation for this feature is the extended red emission (ERE, see Witt & Vijh 2004 for a review). The ERE is observed as a soft rising continuum between 0.6 and 0.9 \( \mu m \). It is observed around galactic and extragalactic \( H \alpha \) regions (among many others, Perrin, Darbon & Sivan 1995; Gordon et al. 2000) and caused by a photoluminescence reaction on dust grains heated by hard UV radiation. Such energetic photons are mainly produced in short-lived massive stars. This could explain why the \( I \)-band excess in our clusters is over after 6 Myr. A possible contribution from ERE to the \( I \)-band flux of unresolved clusters was also suggested by Reines, Johnson & Hunt (2008).

3.6.2 The IR excess

Several mechanisms can concur to make the flux at \( \lambda > 1.0 \mu m \) higher than predicted by models, which include stellar continuum and nebular contributions. The distance of the galaxy and the resolution achieved – the best with the current accessible facilities – limit our studies to the integrated properties of these massive star clusters. However, observations of much closer resolved clusters and numerical predictions of stellar populations in clusters can give us a hint of the mechanisms which are likely producing the observed red excess.

Among the youngest and massive resolved star clusters, 30 Dor (hereinafter 30 Dor) in the Large Magellanic Cloud represents the best reference to understand what a recently born star cluster looks like. 30 Dor is the central region of the extended Tarantula nebula. Multiwavelength studies of these regions have dissected the different components of the complex 30 Dor environment. Walborn & Blades (1997) identified five different stellar populations in the region: the bright-core early-O-type stars which are part of the compact star cluster R136; in the north and west regions, embedded massive YSOs; three more evolved stellar population groups in the southern region and 1.0 arcmin away in the western region. The R136 cluster has a mass of \( \sim 10^7 \text{M}_\odot \) and is 3 Myr old (Portegies Zwart et al. 2010 and references therein). This nuclear region (\( \leq 3 \text{ pc} \)) is dust and gas-free. Recent studies (Crowther et al. 2010) report that stars more massive than the usual assumed theoretical limit of \( 120 \text{M}_\odot \) reside in the core of R136, probing the extreme nature of the SF process in very massive star clusters. However, the aperture radius we are using in our analysis is much larger (radius of \( \approx 36 \text{ pc} \)) than the size of R136. Our apertures are comparable to the size of the image of 30 Dor showed in fig. 1 of Campbell et al. (2010). This suggests that while the optical range is dominated by the stellar and gas emission, the IR also transmits flux from the diffuse dust, heated by the hard UV radiation field, the embedded YSOs formed in triggered SF events at the edge of the nucleus, where most of the dense gas and dust filaments are located, and the low-mass stars still in the PMS phase (see Brandner et al. 2001; Walborn et al. 2002).

In the literature, studied cases of IR excess in young embedded or partially embedded unresolved extragalactic clusters have explained the red excess as due to an important contribution by YSOs (Fernández-Ontiveros et al. 2009) or hot dust (Cabana, Vanzini &

Figure 9. Strength of the flux excess in \( H \) and \( I \) bands as function of the cluster properties derived from fitting the blue side of the SEDs. The vertical dotted lines in the left side panels separate clusters younger than 6 Myr (filled dots) from older clusters (open squares). In red we show clusters affected by IR excess (\( H \) band), and in blue the ones with NIR excess (\( I \) and \( H \) bands). The black crosses show, for each bin, the median value of the residuals for normal clusters in the sample, represented by the underlining small green ones.
Sauvage 2005; Cresci, Vanzi & Sauvage 2005). Likely, the same mechanism is causing the red excess in young star clusters in BCGs.

After several Myr, this complex phase is over, so it cannot explain why we still observe objects with an IR excess at older ages. For these evolved clusters, a possible source of excess can be an important contribution from RSGs. These are rather massive (~25–70 M⊙) stars. They contribute mainly to the NIR for the cluster age between 8 and 60 Myr. Models usually predict the number of RSGs, assuming that the stars in a cluster fully populate the underlying IMF. However, this assumption is not valid, if the cluster is less massive than 10\(^6\) M⊙ (Laçon & Fouesneau 2010) and causes important variations for cluster masses below 10\(^2\) M⊙ (Cerviño & Luridiana 2004). Moreover, it has been observed that in metal-poor environments the number of observed RSGs tends to be higher than the predicted one from the ratio of blue versus RSGs (see Maeder & Meynet 2001; Eggenberger, Meynet & Maeder 2002). Therefore, both effects would be observed as a rise in the NIR-integrated flux of an unresolved cluster, which our current models cannot fully account for. It is not clear, however, why we do not see any mass dependence between the excess in the H band and the mass of the cluster, which could support the stochasticity scenario, or why our models cannot predict the correct number of RSGs only for some of the clusters. NIR spectroscopy is needed to provide direct evidence for these scenarios.

The environment of Mrk 930 is quite crowded and we cannot exclude that in some cases, the red excess could be caused by a newly formed cluster (visible only in the IR) in the same aperture or at the same line of sight as an older one.

Other ‘exotic’ explanations for the excess in clusters could be a bottom-heavy IMF, that is, a much steeper slope at low-mass ranges (higher number of low-mass stars), or a second stellar population formed after a long time-delay (~10 Myr). However, studies of IMF variations in massive star clusters (see Bastian, Covey & Meyer 2010; Greissl et al. 2010) do not find any sign of variation and second populations with delay of few tens of Myr have not been observed yet.

4 MAPPING THE EXTINCTION ACROSS THE GALAXY

We have estimated the extinction in the galaxy using three independent analyses: cluster SED fitting, the H\(\alpha\)-to-H\(\beta\) line ratio from long-slit low-resolution spectroscopy and the narrow-band H\(\alpha\)-to-H\(\beta\) imaging ratio.

Regions B and C are resolved in the two-dimensional spectrum (Pos-1); hence, we were able to extract a single spectrum for each of them. Knot A was blended in a single blob (Pos-2) so we extracted a single spectrum enclosing the total flux. The fluxes of the H\(\alpha\) and H\(\beta\) lines were measured in the three one-dimensional spectra.

To correct the two emission lines from the underlying stellar absorption, we performed a fit to the continuum using the Starlight fitting procedure (see Section 5.3). The H\(\alpha\) flux was also corrected for the contribution of the blended [N\(\alpha\)] line at 6548.0 Å. The flux of this emission line was estimated from the measured flux of the unblended [N\(\alpha\)] at 6584.0 Å and the expected line ratio [N\(\alpha\)]\(5840.0/[N\alpha]_{5568.0} = 0.33\) for case B recombination (Osterbrock & Ferland 2006). The final extinction was estimated using the galactic extinction law (Cardelli, Clayton & Mathis 1989). The line fluxes and the estimated extinction are all listed in Table 2.

We constructed an E(B – V) map from the H\(\alpha\)/H\(\beta\) images assuming a non-reddened H\(\alpha\)-to-H\(\beta\) ratio of 2.87 and the galactic extinction law. No correction for Balmer absorption was applied and hence E(B – V) is only indicative and may overestimate the extinction in regions where the H\(\beta\) emission is weak. In Fig. 10, we show the H\(\beta\) image (with logarithmic intensity scaling) and E(B – V) map in the left- and right-hand panels, respectively.

In Fig. 11, we have reconstructed the positions of the clusters in the galaxy and their recovered extinction. Clusters with E(B – V) ≤ 0.2 (blue triangles and purple diamonds) are in majority. Clusters with higher extinction are fewer and located around almost dust-free companions. The smaller number of highly extinguished clusters could be caused by a bias in the selection method. Since optical filters have been used to create a position catalogue (see Section 2.1), it is likely that those redder clusters have been missed. The positions of the two slits are indicated in Fig. 11. The slit is 1 arcsec in width; however, taking into account the seeing, it is likely that the regions close to the edges of the slit have also contributed to the transmitted spectrum. In general, we observe that the values recovered from the two hydrogen line ratios are very low and suggest that the spectra are dominated by an averaged value of the extinction observed in the clusters.

Similarly, we note that the resolution of the map in Fig. 10 is much lower than the one reached with the HST data, so the resulting E(B – V) values are averaged over a wider region than a typical cluster size. For this reason, we look at general trends and not at one-by-one analogies between a cluster and a pixel-map. Morphologically, we observe a correspondence among the brightest H\(\beta\) regions (left-hand panel, Fig. 10), the less-extinguished areas of the galaxy (right-hand panel), and the location of the very young and, in most cases, less-extinguished, star clusters (see also Fig. 12). These areas are also the ones which dominate the signal of the spectra, because of the very low E(B – V) values obtained from the optical line ratios. This feature suggests that the feedback from young star clusters has likely cleaned (destroyed) the dust in these regions (a large scale of the 30 Dor core). We observe a gradual increase in the extinction around the dust-free knots. The central (between the two bright clumps) and the most northern regions of the galaxy are the most extinguished. We only detect a dozen of clusters in these regions.
two regions: many of them have very low extinction, or not bigger than 0.4 mag, suggesting that highly extinguished clusters in this area have not been detected.

We conclude that the extinction maps of the galaxy agree fairly well on the average values, despite having been produced with different techniques. Locally, however, only the resolution reached by the study of the clusters allows us to explore extinction variations on much smaller and detailed scales. Of course, there is no a priori reason why the extinctions derived from nebular lines and continua should be the same even if we could match the \textit{HST} resolution since these spectral components may have different contributions from regions along the line of sight.

5 PROBING THE STARBURST PROPERTIES AND THE FORMATION HISTORY IN Mrk 930

5.1 The bursting nature of Mrk 930

To probe the bursting nature of Mrk 930, we constrain the \(b\)-parameter and the gas consumption time-scale, both considered starburst tracers.

The visual magnitude of Mrk 930 is \(M_V = 15.12\) mag (Micheva et al., in preparation), which corresponds to a total luminosity of \(L_V = 3.89 \times 10^9\ L_\odot\). A more detailed investigation of the underlying stellar population will be presented by Micheva et al. (in preparation) but to get an approximate estimate of the total stellar mass in Mrk 930 we take \(M/L = 0.87\) which is the median for the five luminous BCGs with well-constrained stellar masses in Östlin et al. (2001). We estimate in this way the total stellar mass in the galaxy, \(M_* \sim 3.4 \times 10^9\ M_\odot\). Hopkins, Schulte-Ladbeck & Drozdovsky (2002) estimated the SFR in Mrk 930 using the luminosity of the
galaxy at 60.0 μm (9.1 M⊙ yr⁻¹) and at 1.4 GHz (10.6 M⊙ yr⁻¹). Estimates of the SFR using the Hα luminosity give lower values, that is, SFR(Hα) = 5.34 ± 1.79 M⊙ yr⁻¹ (Rosa González et al. 2009). This value is in very good agreement with the estimate we obtained from the measured L(Hα) shown in Table 2. Applying the Kennicutt relation (Kennicutt 1998), we determine a slightly higher SFR(Hα) = 5.89 M⊙ yr⁻¹.

Hence we set an upper limit for the so-called b-parameter, that is, the ratio of the current SFR to the average SFR of the past in the galaxy (Scalo 1986). Galaxies with constant or declining SFRs have b ≤ 1, while systems which are undergoing a violent burst episode have b ≫ 1 (Kennicutt, Tamblyn & Congdon 1994). Using the estimates of M⋆ and SFR(Hα), we find b ≈ 16 for Mrk 930, confirming that the galaxy is truly a starburst. A similar conclusion can be reached from the gas consumption time-scale defined as the ratio between the available gas and the current SFR in the galaxy, that is, τgas = Mgas/SFR. Hopkins et al. (2002) estimated a mass of neutral hydrogen of MHI = 3.02 × 10⁹ M⊙. There are not available estimates of the molecular and ionized gas mass in the galaxy, so we assume that the total amount of gas is two times the determined MHI (Leroy et al. 2005). We find then that Mrk 930 will be able to sustain the current SFR for approximately another half Gyr (τgas = 1 Gyr).

5.2 Starburst propagation revealed by the star cluster ages

To trace the starburst properties and the formation history of Mrk 930, we compare the cluster properties with other probes: the [O iii]-to-Hβ ratio map of the galaxy and the fit to the stellar continuum spectra of the three starburst knots (see the next section).

Using the age of the clusters, we mapped the cluster formation and propagation in the galaxy (see Fig. 12). We clearly observe that the starburst regions are dominated by very young star clusters (blue dots) with an age <5 Myr. The [O iii]-to-Hβ ratio is known as a tracer of the mean ionization level and temperature of the photoionized gas (Baldwin, Phillips & Terlevich 1981). The stronger the UV radiation field is, the higher the [O iii]-to-Hβ ratio becomes. In Fig. 13, one can easily observe that the areas with higher ratio values are the ones where the younger star clusters are found. Izotov & Thuan (1998) estimated for Mrk 930 a [O iii]-to-Hβ ratio of ~4.5, in good agreement with an average estimate from our map and the classification of this target as a H II galaxy.

We observe that in the burst regions, very young star clusters are located around central older clusters, suggesting the progressive propagation of the cluster formation. In the extended tail, south of knot A, we mainly find older clusters in agreement with the colour shown in Fig. 1. The tidal tail and region C are separated by a group of older clusters all located in a small area. The cluster population in the tail is rather young and spans an age range of 1–25 Myr.

Assuming that we are complete in detecting clusters more massive than 1 × 10⁴ M⊙, we derive the CFH during the last 40 Myr of the SF in the galaxy. We consider that a full population of clusters forms with a CMF power law of index 2.0 and extrapolate the missing fraction of the cluster mass (see Adamo et al. 2010a for details). We then obtain a trend of the cluster formation rate (CFR) in the last 40 Myr (left-hand panel in Fig. 14), which shows a clear increase in the CFR during the last 20 Myr. The present CFR is ~1.3 M⊙ yr⁻¹.
that is, \( \sim 1.3 \, M_\odot \) of stars is formed per year in bound star clusters. The previous significant burst was between 30 and 40 Myr ago.

Comparing the present CFR to the SFR(H\alpha), we find that \( \sim 25 \pm 10 \) per cent of the SF is happening in bound clusters (\( \Gamma = \text{CFR}/\text{SFR} = 0.25 \), see Bastian 2008). The fraction is quite high, but comparable with the values we have found for Haro 11 and ESO 185-IG13. Goddard, Bastian & Kennicutt (2010) presented an empirical relation between the cluster formation efficiency, \( \Gamma \), and the surface density of the SFR, \( \Sigma_{\text{SFR}} \), in the host. This relation suggests that the SFR and the CFR are positively correlated or, in other words, that an enhancement in the SFR increases the number (mass) of the produced clusters.

We estimated the radius of the starburst area of the galaxy by integrating the luminosity flux in the B band within increasing aperture radius to include the outskirts of the galaxy. We observed that the radius, where 80 per cent of the light produced in the galaxy is collected, included the whole starburst area. We used this radius, \( r_{80\,\text{per cent}} \approx 1.7 \, \text{kpc} \), to estimate \( \Sigma_{\text{SFR}} \) in Mrk 930 and found \( \Sigma_{\text{SFR}} = 0.55 \, M_\odot \, \text{yr}^{-1} \).

In the right-hand panel of Fig. 14, we show the relation obtained by Goddard et al. (2010) and the position of Mrk 930. The agreement is good, showing evidence of a positive correlation between the mean properties of the host environment and the production of star clusters. The same correlation has been found in the others BCGs (Adamo et al. 2010a, 2011a), probing that the BCG environment, perturbed by the recent merger event, forms a higher fraction of stars in bound clusters. The results obtained by Weidner, Bonnell & Zinnecker (2010), by means of numerical simulations, support this scenario. They show that regular patterns, like spiral arms and shear, tend to fragment the collapsing GMCs and favour the formation of less-clustered systems (OB associations). On the other hand, in a merging system, the external pressure on the GMC yields a faster collapse and enhances the local SF efficiency inside the GMC.

Finally, we note that in our analyses (Haro 11, ESO 185-IG13, Mrk 930), it has not been possible to determine what fraction of the clusters we have studied are real bound clusters, following the definition by Gieles & Portegies Zwart (2010). The Goddard et al. relation has been obtained using similar analyses. We cannot exclude that an important contamination by systems which are gravitationally unbound could create this apparent relation. Unfortunately, with the current data, we are not available to test whether the relation would still hold or disappear, hence suggesting a universal cluster formation efficiency (Bastian 2008).

We will discuss this point and the starburst properties of the BCGs in a forthcoming paper (Adamo et al. 2011b).

While the current cluster formation is very high in Mrk 930, we find a small number of clusters at an age \( \sim 1 \) Gyr and \( \sim 10 \) Gyr. In the age range around 1 Gyr, we find the total cluster mass \( 5.4 \times 10^5 \, M_\odot \) (clusters more massive than \( 10^5 \, M_\odot \)). The expected mass in clusters below \( 10^5 \) is negligible, assuming that clusters in this age range has a Gaussian CMF \( [M_{\text{peak}} = 2 \times 10^3 \, M_\odot, \sigma = 0.6 \log (M) \, M_\odot] \). For old (age \( \sim 10 \) Gyr) GCs, we see a total mass of \( 4.5 \times 10^6 \, M_\odot \) when including clusters with masses down to \( 3 \times 10^3 \, M_\odot \). Assuming the same Gaussian CMF as in the previous example, the total estimated mass for the old GC population is \( 1.7 \times 10^6 \, M_\odot \). The stellar mass of the galaxy is \( M_\ast \sim 3 \times 10^9 \, M_\odot \) which would imply that the GCs in Mrk 930 make up \( \sim 1 \) per cent of the total host stellar mass. This value is smaller than what has been found for ESO 338 (Östlin et al. 2003) and ESO 185 (Adamo et al. 2011a).

5.3 STARLIGHT fit to the starburst knot spectra: the SFH

Star clusters are produced in the same global SF event which enriches the host of several stellar populations. Using the STARLIGHT population synthesis code\(^4\) (Cid Fernandes et al. 2005; Mateus et al. 2006; Asari et al. 2007; Cid Fernandes et al. 2007; see Cairós et al. 2009 for an application of STARLIGHT to BCGs) on our spectra for

\(^4\) STARLIGHT and SEAGAL: http://www.starlight.ufsc.br/
regions A through C, we try to shed further light on the SFH of Mrk 930 and check for a consistency in the age distribution of stellar clusters and discrete episodes of enhanced SFRs, as revealed from spectral syntheses.

Starlight synthesizes the observed SED of the stellar continuum as due to a linear combination of single stellar populations (SSPs) of different age and metallicity. The SSP library used is based on stellar models by Bruzual & Charlot (2003) for a Salpeter IMF, three stellar metallicities ($Z_{\odot}/19$, $Z_{\odot}/4.75$ and $Z_{\odot}/2.4$, assuming $Z_{\odot} = 0.019$) and 59 ages (between 0.25 Myr and 13 Gyr).

From the best-fitting SSP population vector, we derived a number of secondary quantities, of which we present here the luminosity-weighted and mass-weighted stellar age (see Fig. 15). Prior to spectral fitting, several emission lines and a spectral region around

![Figure 15](image)

**Figure 15.** In the top panels of Fig. 15, we show the Starlight fit for region B (the fits to the other two regions are in Fig. A1 of the appendix). The fit (orange solid line) is fairly good, as shown by the residuals in the lower panels. A hint to the WR bump observed by Izotov & Thuan (1998) is also visible in the residual emission spectrum above the best-fitting stellar SED. A comparably good fit has also been obtained for region C, while for region A, due to its relatively noisy spectrum, the SFH is more uncertain. The three plots at the bottom of the figure show the output SFH of the three regions (A in the left-hand panel, B middle panel and C in the right-hand panel), that is, the age distribution of the SSPs selected by Starlight as a function of their luminosity contribution (top insets) to the normalization wavelength and mass contribution (bottom insets). The thin grey vertical lines in the inset indicate the ages of the library SSPs. The shaded area in the lower diagram shows a smoothed version of the mass fraction represented by individual SSPs and is meant for the schematic illustration of the SFH.
7500 Å affected by sky line subtraction residuals were interactively flagged.

We remark that the input spectra are not corrected for the contribution of nebular continuum emission, thus introducing some uncertainty on the outcome of the fitting procedure. Ideally, in galaxies with very strong nebular emission, the preferable procedure would be to compute and subtract from the observed spectrum a synthetic nebular line and continuum spectrum, in order to recover and separately model the SED of the stellar background (see Papaderos et al. 1998 for an application to the metal-poor BCG SBS 0335—052E). However, in the case of Mrk 930, since the EW(Hβ) is relatively low (≈90 Å, Guseva et al. 2000), and due to the moderate S/N of our spectroscopic data, especially for region A, we prefer not to adopt that approach and only flag emission lines.

As spectral synthesis involves several free parameters and the SFH quoted from it is subject to uncertainties, we restrict ourselves to a qualitative comparison between the main SFH features, as derived from STARBURST99 models, with the reconstructed CFH based on our star cluster analysis.

In the top panels of Fig. 15, we show an example of the fit produced by STARBURST99 (the fits to the other two spectra are in Fig. A1 of the appendix). The fit to the observed spectrum of region B (orange solid line) is fairly good, as shown by the residuals in the panel below. A hint of the WR bump observed by Izotov & Thuan (1998) is also observed in the residual emission spectrum above the best-fitting stellar SED. A similar good fit has also been obtained for region C, while the output residuals of region A are quite noisy, suggesting a slightly poorer fit (see Fig. A1 of the appendix). The three plots at the bottom of Fig. 15 show the output SFH of the regions as a function of the fraction of luminosity (top insets) and stellar mass (bottom insets).

In regions B and C, between 76 and 80 per cent of the observed flux at the normalization wavelength (5200 Å) is due to a young stellar population formed in the past t\textsubscript{f} = 10\textsuperscript{8} yr. The mass fraction of these young stars, \(M_{\text{f}}\), is inferred to be 5.5 per cent in region B and up to ∼16 per cent in region C.

The dominant luminosity contribution of young stars is as well reflected upon the low-luminosity-weighted stellar ages of t\textsubscript{L} = 2.1 ± 1.3 and 0.6 ± 0.3 Gyr for regions B and C, respectively. This is by a factor of at least 5 lower than the respective mass-weighted stellar ages of t\textsubscript{M} = 11.5 ± 0.9 and 6.0 ± 1.9 Gyr, suggesting, consistently, that old stars dominate by mass and, more specifically, that 50 per cent of the total stellar mass was already at place 10 Gyr ago. With regard to the recent SFH of regions B and C, the bottom plots in Fig. 15 reveal at least two salient features: a very recent (∼5 Myr) and intense burst of SF which led to an estimated 4 and 13 per cent of the stellar mass in regions B and C, respectively, and a previous episode of strongly enhanced SF between 10 and ∼40 Myr ago. Spectral fits also suggest that region B has been relatively quiescent in the age interval ∼50 Myr to 1 Gyr, with merely a hint for a minor SF event ∼100 Myr ago. This is not the case, however, for region C which, according to our spectral models, has undergone significant SF activity between ∼200 and 350 Myr ago, with the stellar mass formed during that period being comparable to \(M_{\text{f}}\).

The lower S/N of our spectra for region A does not permit a conclusive investigation of possible WR features in it. Additionally, due to the poor seeing during the observations of that region, it has not been possible to disentangle and separately fit the spectrum of its north-western and south-eastern parts. Spectral synthesis to the integral spectrum of region A indicates that this region experienced a strong burst of SF between 25 and 30 Myr ago which produced ∼11 per cent of its stellar mass, followed by a weaker (∼1 per cent) SF episode about 5 Myr ago.

### 5.4 Comparing the SFH with CFH

Spectral fits consistently imply that a strong burst of SF was initiated ∼40 Myr ago almost coevally in regions B and C. This is in good agreement with the analysis of the star clusters which reveals a sizeable population in the age interval between 10 and 40 Myr in either component. Similarly, spectral synthesis models corroborate the evidence for a substantial population of very young (∼5 Myr) stars that was already drawn from the analysis.

Guseva et al. (2000) estimated from equivalent width measurements, EW(Hβ), a burst age of 4–5 Myr for Mrk 930. From the analysis of archival Spitzer Infrared Spectrograph data, O’Halloran, Satyapal & Dudik (2006) found for Mrk 930 a [Ne II]-to-[Ne II] ratio of 3.55. The ratio between these two IR lines is considered an indicator of the hardness of the UV radiation field (dominated by the short-lived massive stars) and can be converted into an estimate of the burst age. Using the estimates produced by Madden et al. (2006) of the [Ne III]/[Ne II] variation as a function of the burst age (fig. 13 in their paper), we find a consistent upper limit for the burst age of 4 Myr. One should be aware, however, that the line ratios depend on the ionization parameter, that is, the ratio of the mean photon flux to the mean atom density. Thus, both the radiation field and the pressure of the ambient interstellar medium should be considered. Dynamical modelling of the evolution of H\textsubscript{II} regions around young clusters shows that the ISM in the young cluster shows that there is a loose coupling between the age and mass of the cluster, and the ionization parameter which can then be constrained to a rather narrow range (Dopita et al. 2006). Using the results from Dopita et al., we find that the age determinations based on the [Ne II]-to-[Ne II] line ratios should be accurate to within a factor of 2. The age recovered by this line ratio corresponds, however, to a peak in the cluster production, as shown in the previous sections. The agreement among different tracers seems to suggest that the burst has reached a peak roughly 4 Myr ago or, in general, that it is actively producing stars at the present time.

There is a considerable amount of gas which can fuel the present burst. However, we are not able to predict whether this burst episode will evolve into a more quiescent phase or will continue converting the gas into stars with a constant rate for the next 1 Gyr.

The STARBURST outputs are consistent with the stellar component in Mrk 930 being predominantly old, with half of the stellar mass having being assembled ∼10 Gyr ago. Despite exhibiting a dramatic burst of SF at the present epoch, Mrk 930 seems to be an ancient system.

We have not found any very old (10–14 Gyr) cluster in the starburst regions. On the other hand, we do detect some GCs with such age range in the galaxy as showed in the mass–age diagram in Fig. 7. Their masses, however, are a few per mille of the estimated total stellar mass of the galaxy. These old clusters are in the outskirts of the starburst regions (Fig. 12) where an old stellar population has also been revealed (Micheva et al., in preparation). Two mechanisms may explain the presence of evolved GCs in the outskirts and not in the starburst regions. First, there are old clusters in these regions but they are not detected due to crowding and/or the bright and diffuse nebular emissions. Secondly, the merger event has probably perturbed the dynamical equilibrium of the involved systems. The old galactic stellar population has homogeneously settled on the new potential, while the old clusters have moved on more distant orbits, similarly to the old GCs observed at high galactic latitude in the Milky Way.
6 SUMMARY

We have described the starburst properties of the BCG Mrk 930 by undertaking a detailed multiwavelength study of its hundreds of resolved star clusters, using imaging from the WFC2 onboard the HST and support from ground-based narrow-band imaging.

Optical and IR line ratios ([O III]/Hβ, [Ne II]/[Ne I]) suggest that the burst age in Mrk 930 is \(\sim 4\) Myr. The age distribution of the star clusters supports this scenario, with a prominent peak in the cluster age distribution between 3 and 4 Myr. The derived CFH shows a rapid rise in the last 10–20 Myr, with a rate at the present time of \(1.3 \, \text{M}_\odot \, \text{yr}^{-1}\) of star formation in bound star clusters. In total, we find that roughly 25 percent of the SF is happening in clusters, supporting a scenario where the host environment favours the formation of more numerous and massive clusters.

The recent burst episodes traced by the analysis of the underlying stellar population are in fairly good agreement with the SFH reconstructed from the clusters. Young stellar populations dominate the total luminosity of the galaxy. However, the galaxy assembled more than 50 percent of its total stellar mass more than 10 Gyr ago. We detect a few very old GCs in the outskirts of the starburst region, additional support for the ancient origin of Mrk 930.

The recovered extinction in the young clusters shows considerable spread and decreases at older ages. Our analysis suggests that we are mainly seeing the optically bright objects, that is, systems that are still only partially embedded in their natal cocoons. The deeply embedded clusters are most likely too faint to be detected at visible wavelengths. We map the extinction across the galaxy using low-resolution spectra and ground-based imaging (Hα-to-Hβ ratio), and compare these results with the extinction distribution derived from the clusters. We find that the mean optical extinction derived in the starburst regions is very similar to the values typically observed in the clusters [more than 80 percent of systems have \(E(B - V) \leq 0.2\) mag], but do not trace clusters locally more extinguished.

Similarly to other BCGs, like ESO 185-IG13 and Haro 11, a considerable fraction of clusters in Mrk 930 show a flux excess at \(\lambda \geq 0.8\, \mu\text{m}\), evident from our I- and H-band photometry. The origin of the excess remains unknown, but we consider a range of possibilities. We note a correlation between the I-band excess and the age of the clusters (<6 Myr). The ERE remains the most plausible mechanism which may cause the I-band excess. The longer wavelength IR excess that shows up in the H band requires a different mechanism. At young ages it could be produced by hot dust and/or a high fraction of YSOs (hot dust in circumstellar discs). Both of these components have been observed in nearby resolved young star clusters. At greater ages, a contribution from RSGs or other more ‘exotic’ mechanisms is possible.

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REFERENCES

APPENDIX A: STARLIGHT FIT TO THE SPECTRA

Figure A1. STARLIGHT fit to the observed spectra (orange solid line), normalized at 5200 Å, of knot A (upper panel) and region C (lower panel) – see Fig. 15 and Section 5.3 of the main text for details. Superimposed is the best-fitting stellar SED (blue solid line). The corresponding residuals are displayed below each panel. The shadowed regions of the spectrum have been excluded from the fit.

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