

Wide-field *HST*/ACS images of M81: the population of compact star clusters

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ABSTRACT

We study the population of compact star clusters (CSCs) in M81, using the *Hubble Space Telescope*/Advanced Camera for Surveys (ACS) images in the filters *F435W*, *F606W* and *F814W* covering, for the first time, the entire optical extent of the galaxy. Our sample contains 435 clusters of full width at half-maximum less than 10 ACS pixels (9 pc). The sample shows the presence of two cluster populations, a blue group of 263 objects brighter than $B = 22$ mag, and a red group of 172 objects, brighter than $B = 24$ mag. On the basis of analysis of colour–magnitude diagrams and making use of simple stellar population models, we find the blue clusters are younger than 300 Myr with some clusters as young as few Myr, and the red clusters are as old as globular clusters (GCs). The luminosity function of the blue group follows a power-law distribution with an index of 2.0, typical value for young CSCs in other galaxies. The power law shows unmistakable signs of truncation at $I = 18.0$ mag ($M_I = -9.8$ mag), which would correspond to a mass limit of $4 \times 10^4 M_\odot$ if the brightest clusters are younger than 10 Myr. The red clusters have photometric masses between 10^5 and $2 \times 10^7 M_\odot$ for the adopted age of 5 Gyr and their luminosity function resembles very much the GC luminosity function in the Milky Way. The brightest GC in M81 has $M_B^0 = -10.3$ mag, which is ~ 0.9 mag brighter than ω Cen, the most massive GC in the Milky Way.

Key words: catalogues – galaxies: individual: M81 – galaxies: spiral – galaxies: star clusters.

1 INTRODUCTION

With the advent of the *Hubble Space Telescope* (*HST*) a new class of stellar clusters have been identified: the compact star clusters (CSCs) with typical masses of $\sim 10^4$ to $10^6 M_\odot$ and sizes between 1 and 6 pc (Meurer 1995). CSCs have been found in several environments, including violent star-forming regions within interacting galaxies (Whitmore et al. 1999). The similarity between the compactness and mass of the CSCs and that of the globular clusters (GCs) is a reason to think of an evolutionary connection between them. Moreover, the compact stellar clusters are unique laboratories for studying diverse star formation processes related to the star formation history of the host galaxy. The detailed studies of GCs – with ages comparable to the age of the Universe – have revealed the early formation history of nearby galaxies and the Milky Way (MW; Harris 1996; Barmby 2003), whereas the studies of younger CSCs – ages < 1 Gyr – delineate the recent star formation history, that in some cases are related to interactions with neighbouring

galaxies (Holtzman et al. 1992; Whitmore et al. 1999; Mayya et al. 2008).

M81 (NGC 3031) is a large Sab spiral galaxy, very similar to M31 in appearance and roughly as massive as the MW. M81 at a distance of 3.63 Mpc ($m - M = 27.8 \pm 0.2$; Freedman et al. 1994) is the biggest member of the M81 group, which includes the prototype starburst galaxy M82. An interaction ~ 100 –500 Myr ago between different members of this group has been discussed by several authors (Brouillet, Combes & Baudry 1991; Yun 1999). Recent observations of M82 show that it has a large population of CSCs, with young clusters (age < 10 Myr) concentrated towards the centre, and relatively older clusters (~ 100 Myr) homogeneously distributed across the disc, the latter population having formed as a part of the disc-wide burst following the interaction (Mayya et al. 2006, 2008; Konstantopoulos et al. 2009). It is of interest to investigate whether the interaction also triggered CSC formation in M81.

The population of GCs in M81 has been studied in the past by several groups. Perelmuter & Racine (1995) used an extensive data base to find ~ 70 objects classified as cluster candidates in the inner 11-kpc radius of M81. After completeness corrections for the unobserved area, they estimated the total GC population would be 210 ± 30 . Perelmuter, Brodie & Huchra (1995) obtained spectra

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of 82 cluster candidates and confirmed 25 as bona fide GCs. The derived mean metallicity of the GCs was $[Fe/H] = -1.48 \pm 0.19$ confirming previous results from Brodie & Huchra (1991). Schroder et al. (2002) obtained spectra of 16 additional GC candidates selected from an extended list of Perelmuter & Racine (1995) catalogue and confirmed all of them to be GCs. Hence, in total there are 41 objects that are confirmed as GCs using spectroscopic data. The metallicity distribution of these GCs is similar to that in M31 and the MW, two galaxies that are morphologically very similar to M81. Hence, it of interest to determine whether M81 also contains a similar number of total GCs as in the MW.

Chandar, Ford & Tsvetanov (2001a) and Chandar, Tsvetanov & Ford (2001b) carried out a search for compact objects in M81 based on observations with the *HST*/Wide-Field Planetary Camera 2 (WFPC2) camera. They discovered 114 CSCs in an area of 40 arcmin². The analysis found, for the first time, two different cluster populations, 59 red clusters [$(B - I)_0 \geq 0.85$ mag] which are candidate for GCs and 55 young clusters with photometric ages <600 Myr. The authors related the latter population with the interaction between M81 and M82.

In the present work, we carried out a search for CSCs in 29 adjacent *HST*/Advanced Camera for Surveys (ACS) fields centred on the nucleus of M81. The present data set offers not only an improved spatial resolution, but also covers a field of view that is 8.5 times larger than that covered by Chandar et al. (2001b). Results obtained from a subset of 12 adjacent central fields were presented in Santiago-Cortés, Mayya & Rosa-González (2009).

This paper is organized as follows: Section 2 presents the observational material used in this work; Section 3 gives a summary of the cluster detection and selection method; Section 4 describes the analysis of colour–magnitude diagrams (CMDs) and luminosity functions (LFs) for the selected clusters; the discussion and conclusions of these studies are presented in Section 5.

2 OBSERVATIONS

The observations used in this work were carried out with the ACS Wide Field Channel on board the *HST*. They were part of the projects with proposal IDs 10250 (PI: John Huchra) and 10584 (PI: Andreas Zezas). Table 1 lists the details of the observations. The *HST* data base contains 29 adjacent fields covering a field of view of ~ 340 arcmin² (see Fig. 1), with a sampling of 0.05 arcsec pixel⁻¹ (0.88 pc pixel⁻¹). For each field, observations were carried out in the *F435W*, *F606W* and *F814W* filters, which for the sake of brevity we will refer to as *B*, *V* and *I* filters, respectively, throughout this paper. The standard pipeline process (CALACS) provided by the Hubble Heritage Team were used for bias, dark and flat-field corrections. The pipeline uses the IRAF/STSDAS MULTIDRIZZLE task to combine the images of a single field and produces weight maps related with the background and instrumental noise. Also this task corrects bad pixels, rejects cosmic rays and eliminates artefacts (Mutchler et al. 2007). However, images taken with different programs have slightly different astrometric coordinates. We used common stars in the adjacent images to tie all the images to a single coordinate system.

3 CLUSTER DETECTION AND SELECTION

We used the automatic detection code SExtractor to create an unbiased sample of cluster candidates. SExtractor automatically detects sources on fits images, makes photometry and generates a data catalogue (Bertin & Arnouts 1996). SExtractor first generates

Table 1. Filters and exposure times.

Field ID	Filter	Proposal ID	Exp. time (s)
F1	<i>F435W</i>	10584	1 × 900
F1	<i>F606W</i>	10584	1 × 880
F1	<i>F814W</i>	10584	1 × 895
F2	<i>F435W</i>	10584	3 × 1565
F2	<i>F606W</i>	10584	3 × 1580
F2	<i>F814W</i>	10584	3 × 1595
F3–F14	<i>F435W</i>	10584	2 × 1200
F3–F14	<i>F606W</i>	10584	2 × 1200
F3–F10	<i>F814W</i>	10250	3 × 1650
F11	<i>F814W</i>	10250	2 × 1100
F12–F14	<i>F814W</i>	10250	3 × 1650
F15–F16	<i>F435W</i>	10584	3 × 1565
F15–F16	<i>F606W</i>	10584	3 × 1580
F15–F16	<i>F814W</i>	10584	3 × 1595
F17	<i>F435W</i>	10584	2 × 665
F17	<i>F606W</i>	10584	1 × 350
F17	<i>F814W</i>	10584	1 × 350
R2–R13	<i>F435W</i>	10584	2 × 1200
R2–R13	<i>F606W</i>	10584	2 × 1200
R2–R13	<i>F814W</i>	10250	3 × 1650

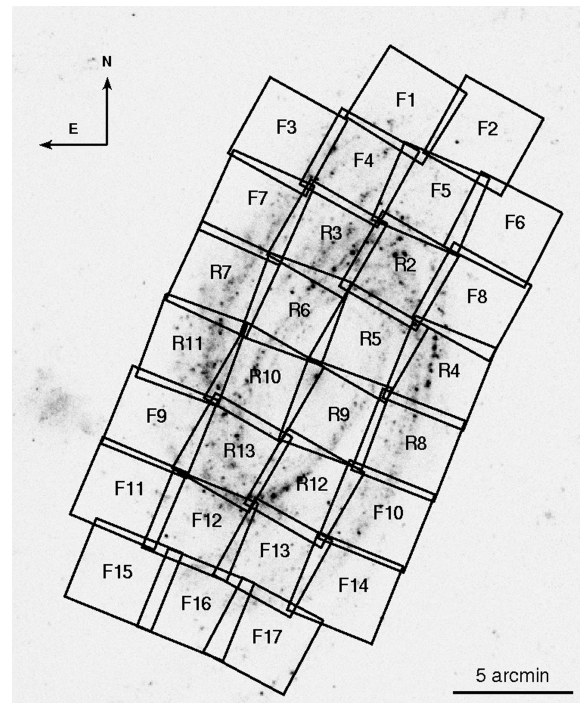


Figure 1. The footprints of 29 *HST*/ACS pointings superposed on a 23×28 arcmin² GALEX image of M81. Identification number of each field is indicated. These 29 pointings cover the entire optical/UV extent of the galaxy.

a background map by computing the mean and the standard deviation of every section of the image with a user-defined grid size for which we choose 64×64 pixels. The local background is clipped iteratively until the values in every remaining pixel is within $\pm 3\sigma$ of the median value. The mean of the clipped histogram is then taken as the local background. Every area of at least five adjacent pixels that exceeded the background by at least 3σ was called a source candidate.

The B band was used for the detection of candidates, and we carried out aperture photometry of all the detected sources in each of the B , V and I images. The process was repeated for each of the 29 fields, resulting in a preliminary list of 565 438 sources. This list contains both unresolved (stellar-like) and resolved (extended) objects. The distribution of sizes peaks at full width at half-maximum (FWHM) = 2.1 pixel, which corresponds to the typical point spread function (PSF) of the ACS images. We chose FWHM = 2.4 pixel as the dividing line to separate cluster candidates from point sources. Our aim is to create a catalogue of compact sized clusters and hence we restricted our catalogue to sources with FWHM < 10 pixel. Thus our preliminary list of CSC candidates includes all sources with $2.4 < \text{FWHM} < 10$ pixels.

Among the resolved objects selected using the above-mentioned criterion, we have two kinds of sources that contaminate the genuine CSCs. The first of these contaminating sources is formed by the unevenness of the local background due to the presence of dust and complex small-scale disc structures. The second type of contaminating sources is caused due to the blending of several point sources due to stellar crowding. These contaminating sources are rejected by using the AREA parameter (defined as the number of contiguous pixels above the 3σ detection limit) of SExtractor. By visual inspection of the images, we found that the fraction of contaminating sources is highest for sources having area less than 50 pixels. Hence, we rejected all sources if they have an AREA < 50 pixels. By numerical calculations, we found that even the most compact objects have AREA > 50 pixels if they are brighter than $B = 23$ mag, which effectively sets the completeness limit of our selection process.

While a great majority of blended stars are eliminated from the list by the imposed AREA criteria, some of them still sneak through. In order to eliminate such sources, we analysed the ellipticities of the sources. All genuine clusters are expected to be round with ellipticity $\epsilon < 0.1$. However, because SExtractor measures ellipticities at the limiting (3σ) isophote level, we found that some genuine clusters have $\epsilon > 0.1$. This happens when a cluster is surrounded by a diffuse background or is immersed within a stellar group. This kind of source is characterized by a prominent peak, with the aperture photometry saturating at a small radius. On the other hand, aperture magnitude of a source formed by an elongated chain of stars would continue to rise with increasing radius. This property allows us to separate clusters from the blended stars even when the measured ellipticities are > 0.1 . We found that if the difference between the aperture magnitudes of diameters 2 and 4 pixels is less than 1.5 mag, then they are true clusters. Hence, among the elongated sources, we retained only those sources if the difference in magnitudes between apertures of diameters 2 and 4 pixels is less than 1.5 mag. In summary, all sources with $2.4 < \text{FWHM} < 10$ pixels, AREA > 50 pixels and ellipticity < 0.1 are retained, whereas among the elongated sources, only those showing evidence of a compact core are retained.

Note that at the distance of M81, 2.4 pixels correspond to a physical scale of 2.1 pc. Given that the PSF of ACS images is 2.1 pixels, all clusters smaller than 1 pc of FWHM will have a measured FWHM of 2.4 pixels, and hence our method cannot recover clusters more compact than this, if present. A Gaussian FWHM of 1 pc corresponds to a core radius of 0.5 pc for a King profile with $c = r_t/r_c = 30$ (Chandar et al. 2001a), which is almost the limiting size for the compact clusters, and very few such clusters are known to exist (Ashman & Zepf 2001; Barmby et al. 2006; Scheepmaker et al. 2007). Hence, we are not missing many clusters because of this criterion. The measured FWHM > 5 pixel, the smearing due to the

PSF is only marginal. The upper cut-off of FWHM = 10 pixel used in this work, corresponds to a PSF-corrected physical size of 8.6 pc (core radius 4.3 pc).

We carried out a visual inspection of the images to make a list of objects that have diffraction spikes or are saturated in any one of the B -, V - or I -band images, with majority of them saturated only in the I band. A total of 83 such objects are found and there is no published information about the nature of these objects from spectroscopic surveys such as the one carried out by Sandage (1984), or several other follow-up studies. We hence analysed the colours of these objects in order to investigate whether some of these could be compact young star clusters. To avoid the use of the HST colours that may be erroneous due to saturation, we carried out photometry of these objects using the Sloan Digital Sky Survey (SDSS) images and constructed a $u-g$ versus $g-r$ diagram for the selected objects, which is shown in Fig. 2. The main-sequence colours are obtained using the Girardi et al. (2002) calculations for the grid of T_{eff} and $\log g$ that define each spectral type (Mas-Hesse & Kunth 1991). Notice that in this diagram the reddening vector is almost orthogonal to the track defined by the spectral types for stars earlier than A0. The colours of all except three objects are consistent with them being stars of spectral types later than F . These saturated objects are extremely bright to be stars of M81, and hence, are likely to be foreground Galactic stars. However, some of these objects could be GCs. Young clusters are expected to have colours of stars earlier than spectral-type B5, and there are only three candidates (shown by filled circles) that can be interpreted as dusty young clusters. None of these is brighter than the brightest selected cluster. Thus, our selection criteria have not eliminated possible bright clusters from our cluster sample.

The selection criteria described above resulted in a catalogue of 1123 compact stellar cluster candidates. Artificial sources due to stellar blending are still present in our catalogue, with their fraction increasing systematically at fainter magnitudes. These contaminating sources are relatively bluer in colour, limiting principally our capability of detection of blue clusters. Hence, we restrict most of our analysis to $B = 22$ mag for the blue clusters. For relatively

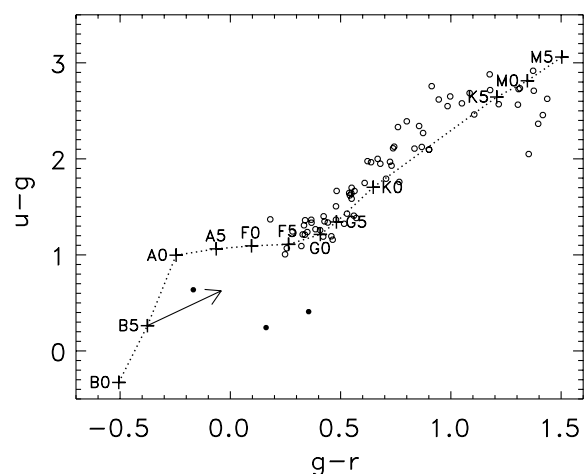


Figure 2. The SDSS $u-g$ versus $g-r$ diagram for all the objects that are saturated in at least one of the HST/ACS bands. The locus of the main-sequence stars as well the direction of the reddening vector for $A_V = 1$ mag (Cardelli, Clayton & Mathis 1989) are shown. Only three objects could be interpreted as reddened young clusters (colours bluer than B5 stars; shown by filled circles), with the rest following the track defined by the main-sequence stars of spectral types later than F .

redder clusters, contamination by stellar blending is not a serious limitation allowing us to retain them all the way to $B = 24$ mag. After applying this colour-based selection criterion, which will be discussed again in Section 4.2, we ended up with a list of 435 clusters. The catalogue of Chandar et al. (2001a) contains 114 clusters up to a limiting magnitude of $V = 22$. Thus, our wide-field search has more than tripled the number of clusters in M81.

The B magnitude used in this work is ISOMAG parameter calculated in SExtractor. This parameter measures the magnitude by integrating the background-subtracted counts in all the pixels that define the source. Colours were obtained by subtracting the magnitudes calculated within a fixed aperture of diameter = 20 pixels. Aperture corrections as suggested by Sirianni et al. (2005) were applied to the magnitudes in each filter. The method adopted by us to calculate colours ensures that the internal errors on the colours are minimum. We estimated the errors on the magnitudes and colours using the multiple observations of the same star as described below.

The 29 ACS fields used in this study offered around 10 per cent area overlap between the adjacent fields (see Fig. 1). The overlap region contained around 30 000 stars. We used the two independent photometric measurements for the common stars in each of the B , V and I bands to estimate typical photometric errors on the magnitudes. As expected, errors are found to be the least for bright stars (0.10 mag for $B < 20$ mag), increasing systematically for fainter stars (0.20 mag for $B = 24$ mag). Similar errors were estimated in all the three filters. Errors on any two bands are found to be uncorrelated, and hence errors on the colours were calculated by quadratically adding the errors on the magnitudes. All the magnitudes and colours quoted in this work are on the standard Vega system of magnitudes.

Our list contains 20 of the 41 spectroscopically confirmed GCs (Perelmuter et al. 1995; Schroder et al. 2002). Among the missing objects, eight are outside our field of view, and another eight have stellar appearance (most are saturated) on the ACS images. These objects could be very compact GCs. However, given that the galactic halo stars share the metallicities and radial velocities of the M81 GCs, these eight objects are most likely to be galactic stars, rather than very compact GCs. These objects are listed in Table 2 along with their observational properties. The remaining eight objects classified as GCs do not satisfy one or the other of our selection criteria. We also recover 53 of the 114 objects reported by Chandar et al. (2001b). The principal reasons for the absence of the rest of the Chandar et al. (2001b) clusters are either they are blended stars (ellipticity > 0.1) or that they are foreground or M81 field stars wrongly classified as clusters due to the relatively poorer spatial resolution of WFPC2 images as compared to our ACS images. Thus, our catalogue of CSCs supersedes Chandar et al. (2001a)

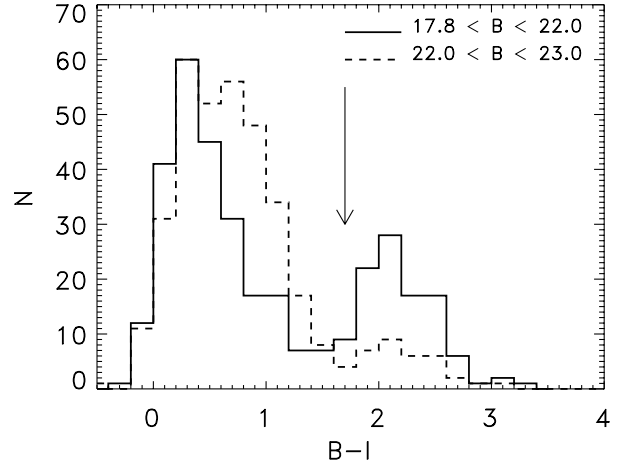


Figure 3. The $F435 - F814$ ($B - I$ for brevity) colour histogram for the CSC population is plotted separately for the bright ($B < 22$ mag) and relatively faint ($B = 22-23$ mag) clusters. Our CSC sample clearly divides into blue and red groups, with the dividing colour being $B - I = 1.7$, which is shown by the downward pointing arrow.

catalogue, both in its robustness of selection and in the spatial coverage.

4 ANALYSIS

4.1 Colour histogram

In Fig. 3, we present the $B - I$ colour histograms for the cluster candidates separately for bright ($B < 22$ mag; solid line) and faint ($22.0 < B < 23.0$ mag; dotted line) members of our catalogue. It can be easily noticed that the distribution is bimodal in nature, especially for the brighter sample. Bimodality is also seen in the distribution of the $B - V$ colours for our sample objects. This bimodality has been noticed previously by Chandar et al. (2001b), who used this property to separate GC candidates from the relatively younger clusters. In the next section, we use CMDs to firmly establish this interpretation. On the basis of bimodality, we separated the cluster sample into two groups: a blue group with $B - I < 1.7$ and a red group with $B - I > 1.7$. The colours of the red group members compare well with the colours of GCs in the MW and M31 (Harris 1996), and the colours of the blue clusters are similar to those of young- and intermediate-age clusters found in the Magellanic Clouds and M33 (Chandar, Bianchi & Ford 1999). In Table 3, we include the physical properties of the brightest compact clusters.

Table 2. *HST*/ACS point sources erroneously classified as GCs in previous studies.

ID	RA (2000)	Dec. (2000)	B (mag)	$B - I$	FWHM (pixel)	ID ^a	V_{rad}^a (km s ⁻¹)	[Fe/H] ^a
45861F1	09:55:03.823	69:15:38.10	19.09	1.33	2.27 ^b	Is40165	6	-1.57
9514F3	09:55:44.079	69:14:12.00	20.11	2.14	1.74 ^b	Is40181	46	0.64
113F10	09:55:06.265	68:56:24.78	18.60	1.00	2.47 ^b	Is50037	-18	-2.34
8041F11	09:56:40.582	68:59:52.44	19.68	1.95	2.61 ^b	Is50225	-7	-0.04
3740F6	09:54:19.980	69:09:11.57	19.97	1.45	2.02 ^b	Is51027	300	-2.47
901F17	09:55:56.866	68:52:13.42	19.63	1.60	1.85 ^b	Is60045	-28	-1.03
10870R8	09:54:58.754	69:00:58.21	20.97	1.72	2.19	Is50286	-9	-0.04
10600F9	09:56:31.774	69:02:38.47	21.38	2.20	2.15	Id50401	-283	-0.04

^aLast three columns data were taken from Perelmuter et al. (1995).

^bMildly saturated stars.

Table 3. Observational properties of compact stellar clusters of both blue and red groups.^a

ID ^b	RA (2000)	Dec. (2000)	B_{iso}^c (mag)	$B - I^d$	$B - V^d$	B_{aper}^c	FWHM (pixel)	ϵ
R05R06584	148.8418408	69.1105121	17.829	2.058	1.103	18.185	3.62	0.03
R13R13715	149.1149429	69.0194455	18.437	1.777	1.000	18.726	5.82	0.13
R04B15666	148.6774430	69.0606742	18.448	0.317	-0.067	18.652	4.41	0.28
R10R03509	148.9172358	69.0695361	18.595	1.811	1.020	18.797	7.44	0.04
R10R10692	149.0356195	69.0642516	18.758	2.164	1.204	19.118	3.65	0.15
R03B16992	148.8193827	69.1487218	18.762	0.146	0.118	19.071	3.62	0.19
R10R09559	148.9417949	69.0501834	18.771	2.240	1.267	18.996	3.45	0.12
R06R14272	148.8788369	69.1274761	19.050	2.054	1.160	19.317	3.39	0.12
R05R06792	148.7596607	69.0938767	19.068	1.996	1.137	19.328	5.34	0.09
R05R10583	148.8424549	69.0886357	19.140	2.122	1.228	19.257	3.74	0.02
R12B14433	148.9722627	68.9844062	19.258	0.282	0.137	19.305	3.02	0.36
R02B09480	148.7397628	69.1468477	19.309	0.001	-0.053	19.404	9.58	0.35
F14B08146	148.8935116	68.9303161	19.326	1.095	0.465	19.417	3.51	0.22
R04B12769	148.7003380	69.0560965	19.377	0.619	0.973	19.986	5.68	0.31
R13R19709	149.0469244	68.9835085	19.381	2.280	1.361	19.399	2.72	0.10

^aOnly the brightest 15 (in band B) are given here. A complete list is available in electronic version of the article (see Supporting Information).

^bThe first three digits of the ID indicate the ACS field number (Fig. 1), the fourth letter indicates whether the cluster belongs to the blue (B) or red (R) group, and the remaining part is the SExtractor identification number of the source.

^c B_{iso} is the ISOPHOT magnitude and B_{aper} is the aperture magnitude within a radius of 10 pixels (0.5 arcsec) as defined in SExtractor.

^d $B - I = F435W - F814W$ and $B - V = F435W - F606W$ are the Vega system colours in the *HST* filters $F435W$, $F606W$ and $F814W$. The colours are calculated using the aperture magnitudes within a radius of 10 pixels.

4.2 Colour–magnitude diagram

Compact stellar clusters are the closest observational analogues of the theoretically defined simple stellar population (SSP), where all the stars are assumed to form in a single burst. The age and mass of the CSCs can be obtained by comparing their observed colours and magnitudes with the corresponding quantities from a model SSP, in a CMD. In Fig. 4, we present the CMD, where all the clusters in our sample are plotted, with the blue clusters denoted by rhombus symbols, and the red clusters by circles. Typical photometric errors on colours and magnitudes for point sources are shown on the right-hand side of the plot. The errors on both the magnitudes and colours are expected to be slightly larger for extended objects, such as CSCs. Two SSPs of cluster masses 3×10^4 and $10^4 M_{\odot}$ are shown superposed on the blue group, between the age ranges of 3 Myr to 2 Gyr and 0.1–1 Gyr, respectively. For the red group, we show the locus of points for various cluster masses, all of age of 5 Gyr. The reddening vectors corresponding to $A_v = 1$ mag are shown at selected points on the SSP. Location of point sources in the CMD is shown by the dots, which occupy mainly the bottom left-hand part of the diagram. In order to avoid agglomeration of points in the plot, we show only one out of 25 stars. Extended sources formed by blending of these point sources are the principal contaminants of our cluster sample at magnitudes fainter than $B = 22$.

The plotted SSPs correspond to Girardi et al. (2002) solar metallicity ($z = 0.019$) models for the blue clusters and $Z = 0.008$ models for the red clusters. In their models, the colours and magnitudes were calculated directly for the *HST*/ACS filters and hence there was no necessity of converting the magnitudes into standard Cousins–Johnson filter system. The models assume a Kroupa initial mass function (IMF; Kroupa 2001).¹

The brightest blue and red clusters of our sample have $B = 18.45$ and 17.83 mag, respectively. In the field of view of M81,

there are 83 compact objects brighter than these limits. However, from the analysis of their SDSS colours (see Section 3), we found that only three of the 83 objects have $u - g$ colours consistent with those of blue clusters, with none of these three brighter than the brightest blue cluster, even after taking into account possible reddening. However the possibility exists, that some of the stellar-like objects are compact GCs in M81.

The difference in colour between the blue and red group clusters is more than a magnitude for the brightest clusters, with the separation gradually decreasing at fainter magnitudes. Before discussing the SSP ages of these populations, we first discuss the mean amount of reddening expected towards the clusters. The foreground Galactic reddening towards M81 is $E(B - V) = 0.08$ mag (Schlegel, Finkbeiner & Davis 1998). Kong et al. (2000) used photometry in 13 bands to map the reddening in spatial scales of 1.7 arcsec. The reddening values they measured in the bulge region were comparable to that expected for the foreground Galactic reddening, indicating the absence of dust there. They estimated a mean reddening of $E(B - V) = 0.2$ mag [$A_v = 0.6$ mag using $A_v/E(B - V) = 3.1$] for the disc, including in the spiral arms. However, at the spatial scales of CSCs (few parsecs), reddening could be different, and there are no such measurements for M81. Moreover, one may expect higher reddening values when the clusters are young, with the reddening decreasing once the clusters move out of, or destroy, their parental clouds (Bastian et al. 2005; Mengel et al. 2005). Clusters in the blue group are associated with the spiral arms (see Section 4.3), and hence we cannot rule out them being very young clusters. For example, most of the clusters with $B = 19$ – 20 mag, could be reddened young (age < 3 Myr) clusters of mass $3 \times 10^4 M_{\odot}$ for a reddening value of $E(B - V) = 0.5$ mag. A visual examination of these clusters indicates that there are dusty features around some of them.

Taking into account the small expected reddening, the plotted SSPs for the masses 3×10^4 and $10^4 M_{\odot}$ represent well the observed distribution of blue group clusters with $B < 22$ mag in the CMD. The brightest clusters are expected to be the youngest in a normal star-forming galaxy such as M81 (Bastian 2008). In such a scenario, the masses for the brightest two clusters would be between 1 – $2 \times 10^4 M_{\odot}$. The remaining clusters that lie within the

¹ The public distribution of SSPs uses a slightly modified IMF. We multiplied the masses by a factor of 2.5, as suggested by the authors, to bring it to the standard Kroupa IMF.

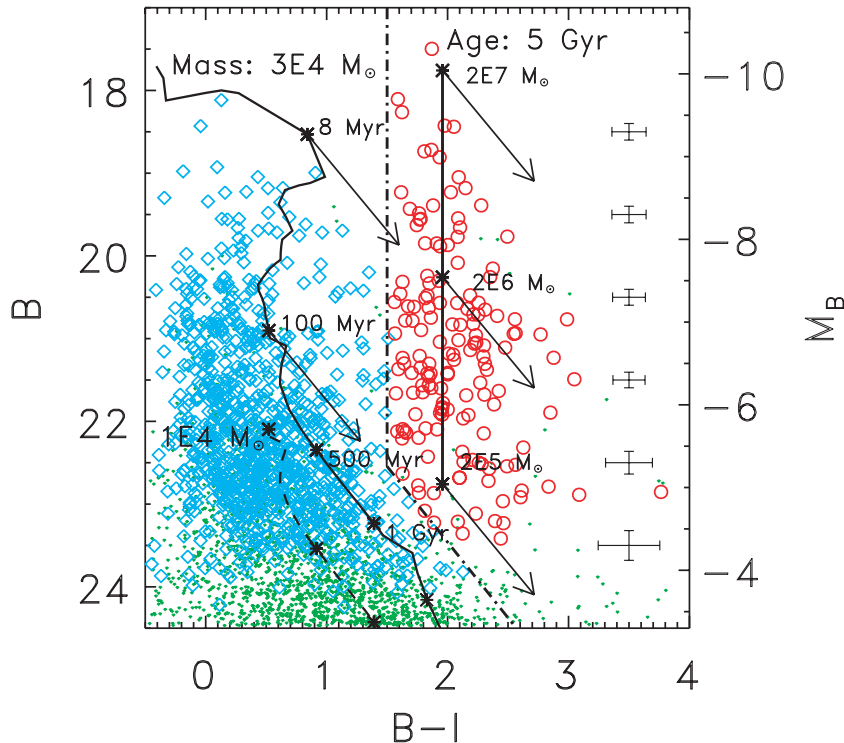


Figure 4. $F435W - F814$ versus $F435W$ ($B - I$ versus B for brevity) CMD for the M81 CSC population: rhombus for the blue group clusters and circles for red group clusters. The point-dashed line is the adopted line that separates the two groups. Typical photometric errors on magnitudes and colours are shown at selected magnitudes on the right-hand side. The small points in the bottom part of the figure represent point sources which are mainly field stars in M81. Only one out of 25 stars are plotted, for the sake of clarity. Blue clusters fainter than $B \sim 22$ mag are severely contaminated by sources formed by blending of these stars. An evolutionary track for a solar metallicity ($Z = 0.019$) SSP (Girardi et al. 2002) of mass $= 3 \times 10^4 M_{\odot}$ and age ranging from 3 Myr to 2 Gyr is shown by the thick line. Another SSP for a mass of $10^4 M_{\odot}$ is shown between ages 0.1 and 1 Gyr by the dashed line. Note that majority of blue clusters lie between these two SSPs. A $Z = 0.008$ SSP of constant age of 5 Gyr, but with masses in the range of $2 \times 10^5 - 2 \times 10^7 M_{\odot}$ is also shown. It fits the colours and magnitudes for the red group which are GC candidates. Reddening vectors corresponding to a robust upper limit of $A_V = 1$ mag are shown at selected positions on the tracks. All the observational points are corrected for the foreground Galactic reddening using $E(B - V) = 0.08$ mag.

1σ observational error from the SSP could be objects with masses marginally above $10^4 M_{\odot}$, with their ages ranging between 3 and ~ 100 Myr. The ages could reach up to 300 Myr if their masses are less than $10^4 M_{\odot}$. At fainter magnitudes ($B > 22$ mag) there are several clusters bluer than the SSP which share the same colour range as that for individual stars. Many of these sources may not be clusters and instead blended stars and hence we exclude them from detailed analysis.

While the observed distribution of blue group clusters closely follows the plotted evolutionary track for mass $= 3 \times 10^4 M_{\odot}$, the spread in $B - I$ colour is clearly more than that can be accounted by the observational errors. After around 10 Myr, model colour lies between 0.6 and 0.8 up to around 300 Myr, whereas most of the clusters brighter than $B = 22$ mag have $B - I$ colour between 0 and 1 mag, with the distribution peaking at $B - I = 0.25$ mag (see Fig. 3). The scatter on the redder side can be understood in terms of interstellar reddening. On the other hand, the blueward shift of the distribution with respect to the colour expected for the 10–300 Myr SSP could be due to the stochastic sampling of the stellar IMF that affects the colours of low-mass clusters (Cerviño & Luridiana 2004; Maiz-Apellaniz 2009). Hence, the presence of many clusters bluer than $B - I < 0.5$ mag suggests that majority of the clusters has mass of $< 10^4 M_{\odot}$.

The clusters in the red group are consistent with an SSP of age between 2 and 12 Gyr, with the mean colour of the group corresponding to an age of 5 Gyr. The distribution of the B magnitudes

is entirely caused by the distribution of masses of these clusters. Observed range of B magnitudes corresponds to a mass range of $10^5 - 2 \times 10^7 M_{\odot}$. Notice that a change in the age by a factor of 2 implies a change in the mass by also a factor of 2 in this range of ages. The derived range of masses is similar to the values expected for GCs (Harris 1996). It may be noted that 20 of our objects have been spectroscopically confirmed as GCs. Thus it is very likely that most of the red group objects are GCs.

The above analysis has established the blue and red groups as two distinct families, the former belonging to the class of super stellar clusters seen in starburst environments, and the latter being GCs. There is a possibility, though very unlikely, that both belong to a single family, and extinction separates them artificially into blue and red groups. For this to happen, all red group clusters should be experiencing an extinction $A_V \sim 1.5$ mag. This would imply that the red clusters are preferentially associated to high extinction zones such as the spiral arms. The discussion in the next section, where we analyse the spatial distribution of the clusters in these two groups, clearly discards such a possibility.

4.3 Spatial distribution

The spatial distribution of the blue clusters brighter than $B = 22$ mag is presented in Fig. 5, where the grey-scale image is the near ultraviolet (UV) image obtained from the *Galaxy Evolution*

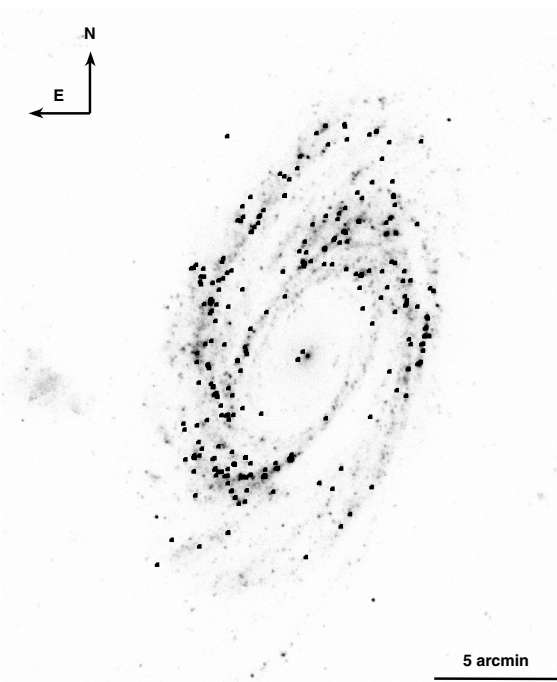


Figure 5. Spatial distribution of clusters in the blue group, superposed on the *GALEX* near UV image. It is clear that the blue clusters trace the spiral arms of M81.

Explorer (*GALEX*) archive.² The UV image traces star-forming regions younger than 1 Gyr and delineate the position of the spiral arms in M81 (Martin et al. 2005). The young clusters are located mainly on top of the spiral arms, suggesting that they are spatially and kinematically related to the population producing the UV emission.

On the other hand, the red clusters are homogeneously distributed over the face of M81 (see Fig. 6). Most of the clusters are seen at small radii, superposed on the bulge, with their number decreasing rapidly in the outer parts. It may be recalled that the bulge region hardly suffers any interstellar extinction (Kong et al. 2000), and hence the association of the red clusters with low-extinction zones again re-iterates the idea that reddening is not the reason for their red colours, instead they are GCs.

4.4 Luminosity functions

4.4.1 Blue group clusters

A histogram of the *B*-band LF of the clusters of the blue group is shown in Fig. 7. In the magnitude range $B = 19$ – 22 mag, the histogram follows a power law of index $\alpha = 2.0$ (dotted line). An unbiased fitting method which makes use of variable bin sizes (Maíz Apellániz & Úbeda 2005) gives a value for the power-law index $\alpha = 1.952 \pm 0.104$. The histogram shows a peak at around 23 mag, deviating systematically from the power law at fainter magnitudes. This decrease could be due to an intrinsic drop of the number of low luminosity (and mass) clusters. However, incompleteness of the sample at $B > 23$ mag contributes significantly to the turnover. The incompleteness originates due to one of the selection criteria we have imposed which requires selected clusters to have a minimum

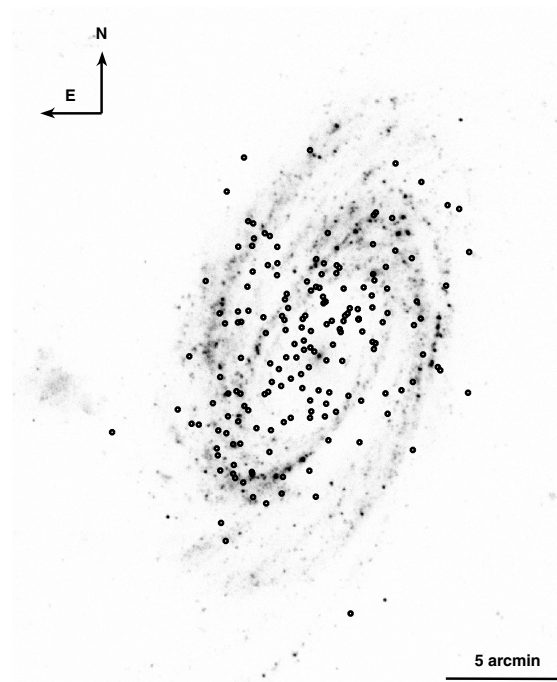


Figure 6. Spatial distribution of clusters in the red group, superposed on the *GALEX* near UV image. The red clusters are uniformly distributed over the face of M81.

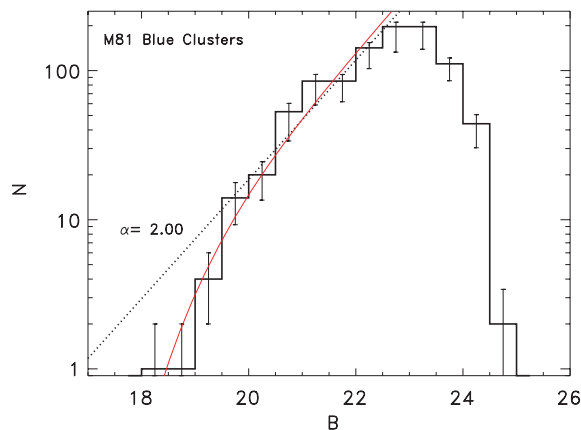


Figure 7. The LF of the blue group clusters (histogram). A power-law function of $\alpha = 2.0$ (dotted line) and the best-fitting Schechter function (solid line) are also plotted. Statistical errors calculated as \sqrt{N} are shown.

AREA of 50 pixels. Compact clusters (FWHM < 5 pixels) fainter than $B > 23$ mag do not satisfy this criteria, and hence are missing from our cluster sample.

A power-law index of $\alpha = 2.0$ obtained in this study is the canonical value found in young stellar clusters in many starburst galaxies (Elson & Fall 1985; de Grijs et al. 2003). On the brighter end of the *B*-band LF, the observed number of clusters is systematically smaller than that expected for a power law of index 2 – the sample contains six blue clusters brighter than $B = 19.5$ mag, whereas 18 such clusters are expected for a power law of index $\alpha = 2.0$. Significantly, there are no blue clusters brighter than $B = 18.45$ mag (i.e. mass $3.0 \times 10^4 M_{\odot}$; see Fig. 4). Gieles (2009) has found that a Schechter function fits better the observational data than a power-law function in the whole range of cluster luminosities. We show in Fig. 7 that a Schechter function fits our data also very well. The

² <http://galex.stsci.edu/GR4/>

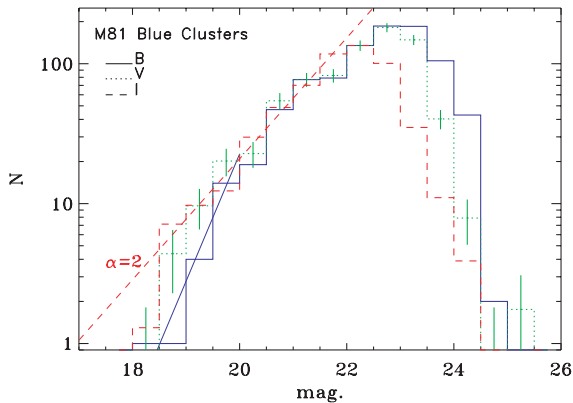


Figure 8. Comparison of the LFs of the blue group clusters (histogram) in B , V and I bands. A power-law function of $\alpha = 2.0$ (dotted line) is shown, which fits very well the I -band data over the range 18–22 mag. On the other hand, B -band data show steepening at magnitudes brighter than $B = 20$ mag.

characteristic luminosity of the best-fitting function is $B = 19$ mag, which is more than 2 mag fainter than that expected for the characteristic mass obtained by Gieles (2009). This issue is discussed more in detail later in this section.

Gieles (2009) studied the steepening of the power law as a function of wavelength, and found that the function steepens more at longer wavelengths as expected for Schechter functions. This tendency for steepening of the LF at high luminosities (or equivalently mass) has been noted in several recent studies (Haas et al. 2008; Larsen 2009). Given the relatively small number of clusters in our M81 sample, we could reliably obtain slopes in only two magnitude ranges – the dividing magnitude being 20. The resulting piecewise linear fit to the B -band data is shown in Fig. 8, where we can clearly see that the brighter end slope is steeper. In the other two bands, a power law with $\alpha = 2$ fits well the entire range. Thus, we do not see the trend reported by Gieles (2009) for M51 in our data set for M81. The extinction seems to be the reason for the steepening at the bright end. We examined the *HST* image around the 10 brightest I -band clusters, and found traces of dust lanes running close to these clusters, which agrees with the above interpretation. Hence, the conclusions derived from only the B -band LF could be misleading unless it is confronted with the I -band LF. Whereas the B -band LF can be fitted with a Schechter function, the I -band LF shows signature of a truncated power law. We carried out the statistical tests suggested by Maschberger & Kroupa (2009) and firmly established the existence of a truncation in the LF as can be seen in Fig. 9. The modified maximum likelihood method gives us an index of $\alpha = 2.219 \pm 0.130$ and an upper limit of 18.0 mag. The graphical inspection of the data through the stabilized percentile–percentile plot (Fig. 9) and the different goodness of fit test applied to the data confirm the nature of the observed LF.³ The observed truncation in LF corresponds to a mass of $2.4 \times 10^4 M_{\odot}$ for clusters of 7 Myr age, and $3.8 \times 10^4 M_{\odot}$ for 10 Myr age. If the clusters are younger than 7 Myr, the truncation mass would be even less. This mass is an order of magnitude lower as compared to the universal characteristic mass suggested by Larsen (2009). Only if all the brightest clusters are as old as 100 Myr, the truncation mass in M81 would

³ We carried out the 10 different tests suggested by Maschberger & Kroupa (2009), and all of them are consistent with the observed distribution being a truncated PL.

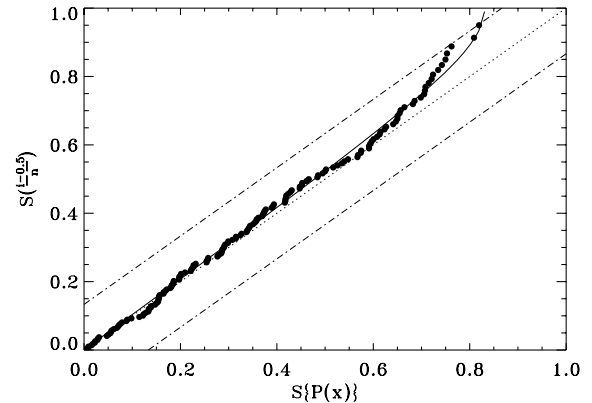


Figure 9. The resulting stabilized percentile-percentile plot for the I -band LF. Two different null hypothesis have been plotted, an infinite power law (dotted line) and a truncated power law with index of $\alpha = 2.2$ and an upper limit of 18.0 mag. (solid line). Clearly the observed data (solid symbols) supports the truncated power law hypothesis. The acceptance region of the Kolmogorov–Smirnov statistic (significance level 5 per cent) is given by the two parallels to the diagonal.

correspond to the values obtained by Larsen (2009). In general, the brightest clusters in normal star-forming galaxies such as M81 are also the youngest (Bastian 2008). Hence, it is very unlikely that bright clusters in M81 are as old as 100 Myr. Thus, the inescapable conclusion from the above analysis is that the cluster data of M81 are not consistent with the idea that the characteristic mass of the LF is universal at $\sim 2 \times 10^5 M_{\odot}$.

The lower truncation mass in M81 can also be inferred by the relation between the absolute magnitude of the brightest cluster, $M_V(\text{brightest})$ versus the star formation rate (SFR) of the host galaxy, as is illustrated by Bastian (2008). For the currently observed SFR of $0.75 M_{\odot} \text{ yr}^{-1}$ (Karachentsev & Kaisin 2007) in M81, the expected $M_V(\text{brightest}) = -11$ mag, whereas the observed brightest cluster has $M_V = -9$ mag, which lies about 2σ below the relation found in Bastian (2008). Such a low truncation mass is also observed in M31 (Vansevicus et al. 2009), which is another normal star-forming galaxy like M81.

The interaction between M81 and its neighbour M82 had triggered a disc-wide starburst in M82 around 300 Myr ago that formed a rich population of compact clusters in the disc of M82 (Mayya et al. 2006, 2008). It is very likely that the population of intermediate-age clusters in M81 is also formed following the same interaction event, and hence are coeval with the cluster population of M82. So, it is interesting to compare the LFs of the cluster populations of these two galaxies. Though the two galaxies are at the same distance, the vast difference in extinction between the two galaxies (< 0.6 mag in M81 as compared to 1–6 mag in M82) inhibits a direct comparison of the observed LFs. In M82, a power-law index of $\alpha = 1.5$ was obtained for the mass function, which is expected to be the index of the LF. Thus, observed indices of the intermediate-age populations are distinctly different in M81 and M82. Another important difference in the cluster populations in these two galaxies is the mass range of clusters – there are no clusters massive than $\sim 3 \times 10^4 M_{\odot}$ in M81, whereas all the reported 393 intermediate-age clusters of M82 have masses $> 2 \times 10^4 M_{\odot}$. The low value for the truncation mass observed in M81 is the reason for the absence of massive clusters.

A possible reason for the absence of high-mass clusters in M81 is that it is a normal galaxy, whereas objects analysed by Bastian (2008) are either starburst galaxies or small galaxies with localized star-forming sites. As discussed by Ashman & Zepf (2001), the

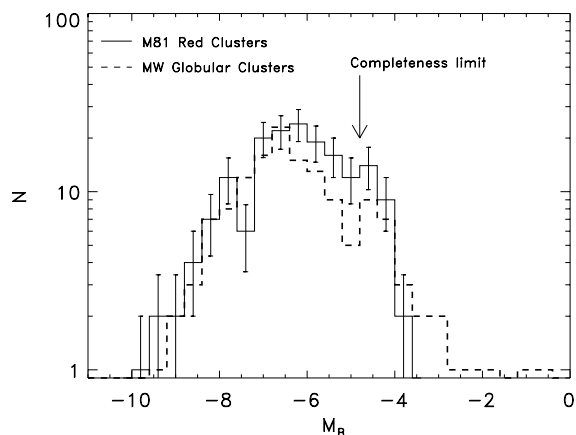


Figure 10. The LF of GCs detected in M81 (histogram) and the MW (dashed line). Statistical errors calculated as \sqrt{N} are shown and the completeness limit of our detection is also marked with a downward pointing arrow.

formation of high-mass compact clusters requires very high density gas, which is possible only if the available gas mass is concentrated locally in regions of few tens of parsecs. Such a condition can be easily satisfied in starburst galaxies/regions such as studied by Bastian (2008), but not in normal giant galaxies such as M81, where the star-forming sites (clusters) are distributed throughout its large disc, as is illustrated in our Fig. 5. The specific SFR – defined as the SFR per unit of mass – could play an important role in the formation of the most massive clusters observed in a galaxy. Therefore, it will be interesting to extend the study of the cluster population to more quiescent galaxies in order to establish whether the M_V (brightest) depends on the global SFR or on the specific SFR.

4.4.2 Red group clusters

The LF for the red group clusters is plotted in Fig. 10 along with that for the MW GCs from Harris (1996). It can be seen that the two distributions agree very well for $M_B < -4.5$ mag ($B \sim 23$ mag), which is the completeness limit of our observations. The turnover in the distribution of MW GCs at $M_B \sim -6.7$ ($M_V \sim -7.5$; Harris 1996) is also present in the distribution of the red group clusters of M81. Notice that we have detected 172 GCs, which compares well with the 146 GCs in the MW. It is heartening to find that the numbers and the LF between M81 and the MW coincide, in spite of the complexity involved in the selection process.

Our data set allows us to compare the basic observational parameters of the brightest GC in M81 (R05R06584; Table 3) to the corresponding ones in other nearby galaxies, in particular those in the MW (ω Cen) and M31 (G1). Its colours are marginally bluer as compared to the typical MW GCs, and suggest an age of <5 Gyr. Its absolute $F435W$ -band magnitude corrected for Galactic extinction is $M_B^0 = -10.3$ mag, which is ~ 0.9 mag brighter than ω Cen, and ~ 0.3 mag brighter than G1 (Meylan et al. 2001). We derive a photometric mass of $2.5 \times 10^7 M_\odot$, using the Girardi et al. (2002) $Z = 0.008$ metallicity models. These derived properties indicate that the brightest GC in M81 is the most massive among the nearby galaxies. Follow-up spectroscopic studies of this object will be invaluable in refining its mass and metallicity.

5 DISCUSSION AND CONCLUSIONS

Thanks to the superb spatial resolution of the ACS camera on board the *HST*, we were able to obtain the largest sample of CSCs in M81

until now. We found a total population of 435 CSCs brighter than $B = 22$ mag, which increases by a factor of 3 the number of M81 CSCs catalogued previously by Chandar et al. (2001a). The sample is divided into two well-defined populations: (a) a blue group with ages <300 Myr, masses $\sim 10^4 M_\odot$ and distributed along the spiral arms of M81, and (b) a red group with ages 2–12 Gyr, masses between 10^5 and $2 \times 10^7 M_\odot$ that are distributed uniformly across the face of M81.

Multiband photometric and spectroscopic work on the M82 cluster population seems to strongly favour an age of the M81/M82 interaction at 200–300 Myr. These ages are in agreement with the results from numerical simulations (Yun, Ho & Lo 1994; Yun 1999). Hence, it is very likely that the same interaction also triggered the formation of blue clusters in M81 as speculated by Chandar et al. (2001a). However, it is important to remember that a firm conclusion on this will have to wait for the spectroscopic confirmation of the ages. Moreover, there is a large number of clusters below our confusion limit of $B = 22$ mag, which could have been formed before the interaction event (age >300 Myr; Fig. 4) if they are more massive than $\sim 10^4 M_\odot$. If the age of this population is confirmed to be older than ~ 300 Myr, then these faint clusters could be part of the normal star formation occurring in the disc of M81. In such a case, the observed population of $B < 22$ mag clusters discussed throughout this paper could as well be due to the normal star formation occurring in the disc of M81 independent of the interaction.

The I -band LF of young clusters follows a power-law distribution with an index $\alpha = 2.21 \pm 0.13$. However, the commonly used B -band LF is better fitted with a double power law or a Schechter function with a characteristic magnitude of $M_B = -9$. After careful examination of the I -band brightest objects, which are probably the youngest, we conclude that the difference between the LFs in the I and B bands arises due to systematically higher extinction towards bright regions, thus affecting the high end of the LF of the B band. The I -band LF truncates at the bright end at $I = 18.0$ mag ($M_I = -9.8$), which corresponds to a mass of $<4 \times 10^4 M_\odot$, if the brightest clusters are younger than 10 Myr. Thus, there is a clear absence of massive clusters in M81 as compared to those observed in M82 (Mayya et al. 2008) and other starburst galaxies (Bastian 2008). Models advocating universal characteristic masses of $2 \times 10^5 M_\odot$ are inconsistent with the inferred low truncation mass in M81.

M81 is comparable to the MW in its mass and morphology. GCs provide a means to investigate the early formation history of galaxies. We find that the total number of GCs as well as their luminosity distribution in M81 is very similar to that for the MW. Thus, both these galaxies had very similar formation histories. The close encounter of M82 with M81 possibly created a new generation of compact clusters in the disc but did not affect the distribution of old clusters that were in place at the time of the encounter.

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SUPPORTING INFORMATION

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

Table 3. Observational properties of compact stellar clusters of both blue and red groups.

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