Luminosity functions of globular clusters in five nearby spiral galaxies using HST/ACS images

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ABSTRACT
We here present the luminosity function (LF) of globular clusters (GCs) in five nearby spiral galaxies using the samples of GC candidates selected in Hubble Space Telescope mosaic images in $F_{435W}$, $F_{555W}$ and $F_{814W}$ filters. Our search, which surpasses the fractional area covered by all previous searches in these galaxies, has resulted in the detection of 158 GC candidates in M81, 1123 in M101, 226 in NGC 4258, 293 in M51 and 173 in NGC 628. The LFs constructed from this dataset, after correcting for relatively small contamination from reddened young clusters, are log-normal in nature, which was hitherto established only for the Milky Way (MW) and Andromeda among spiral galaxies. The magnitude at the turn-over (TO) corresponds to $M_V(0)=−7.41±0.14$ in four of the galaxies with Hubble types Sc or earlier, in excellent agreement with $M_V(0)=−7.40±0.10$ for the MW. The TO magnitude is equivalent to a mass of $≈3×10^5 M_\odot$ for an old, metal-poor population. $M_V(0)$ is fainter by $≈1.16$ magnitude for the fifth galaxy, M101, which is of Hubble type Scd. The TO dependence on Hubble type implies that the GCs in early-type spirals are classical GCs, which have a universal TO, whereas the GC population in late-type galaxies is dominated by old disk clusters, which are in general less massive. The radial density distribution of GCs in our sample galaxies follows the Sersic function with exponential power-law indices, and effective radii of 4.0–9.5 kpc. GCs in the sample galaxies have a mean specific frequency of $1.10±0.24$, after correcting for magnitude and radial incompleteness factors.

Key words: galaxies: star clusters – galaxies: formation – galaxies: evolution

1 INTRODUCTION
Globular clusters (GCs) are among the oldest objects in the universe. Their relatively high luminosities ($M_V=−5$ to $−10$) and compact sizes (half-light radius of a few parsecs) allow them to be readily detectable in nearby external galaxies (Harris 1996). Their low metallicities ($\log[Fe/H]≤−0.5$) and enhancements of $\alpha$ elements ($\log[O/Fe]≥0.20$) suggest that they are formed at very early epochs of galaxy formation (Binney & Merrifield 1998). The GC formation requires highly efficient star formation, usually associated with intense starburst activity (Bastian 2008). Star formation in the spheroids (early-type galaxies, spiral bulges and halos) represents one such activity in the early universe. Interactions and mergers between galaxies provided the next epochs of star formation efficient enough to form massive star clusters such as GCs (Whitmore & Schweizer 1995). These intermediate-age clusters are similar in size and mass as the young massive clusters, also known as Super Star Clusters (SSCs), seen in presently active starburst regions (O’Connell et al. 1995). In the present work, we refer to as SSCs all those relatively younger clusters associated to disks of galaxies and reserve the word GCs to describe old clusters associated to spheroids. Because of their early formation, the properties of GC systems in galaxies provide important constraints on models of galaxy formation and evolution (Ashman & Zepf 1998).

A variety of GC system properties that are potentially relevant to cosmological theories of galaxy formation have been identified. These include, colour distribution (Larsen et al. 2001; West et al. 2004), luminosity function (Reed et al. 1994; Whitmore et al. 1995), radial density distribution

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found catalog of Harris (1996) with 143 GCs, Jordán et al. (2007) found in elliptical galaxies (Ashman et al. 1994). Using the 1992; Reed et al. 1994), respectively. Within the errors of TO values in spite of GC systems being constituted of two independent sub-populations puts strong constraints on the formation scenarios of metal-rich and metal-poor sub-populations.

The most important characteristic of GC systems is the existence of bimodality in their colour distribution (Zepf & Ashman 1993; Gebhardt & Kissler-Patig 1999; Larsen et al. 2001). This bimodality is understood to be due to an underlying bimodal distribution of GC metallicities (Brodie & Strader 2006). Elliptical galaxies with well-determined metallicities confirm the existence of such a bimodal distribution in metallicities (e.g., Cohen et al. 1998; Usher et al. 2012). This has led to the division of GC systems into two sub-populations: red and blue, corresponding to metal-rich and metal-poor populations, respectively. These two sub-populations show differences in other properties, such as size and spatial distribution (Kundu & Whitmore 1999; Larsen & Brodie 2000a; Webb et al. 2012), suggesting possibly two independent formation channels of GC systems.

The GC luminosity function (GCLF) is another property that is well established in elliptical galaxies. GCLFs are described by log-normal distributions with $M_{0, V} = -7.40 \pm 0.25$ and $\sigma = 1.40 \pm 0.06$ (e.g., Reed et al. 1994; Whitmore et al. 1995). The GCLF is often suggested to be a universal function (e.g., Hanes 1977b; Richtler 2003) in elliptical galaxies, and have been used as a standard candle for the determination of distances to their host galaxies (e.g. Richtler 2003). Among spiral galaxies, the log-normal nature of LFs have been firmly established only in the Milky Way (e.g., Harris 1996; Bica et al. 2006) and Andromeda (e.g., Peacock et al. 2010), the only two spiral galaxies where GC system properties have been reasonably well-characterized, with values of $M_{0, V} = -7.33, \sigma = 1.23$ (Secker 1992; Reed et al. 1994) and $M_{0, V} = -7.6 \pm 0.15, \sigma = 0.82$ (Secker 1992; Reed et al. 1994), respectively. Within the errors of measurements, these values are in agreement with the TO found in elliptical galaxies (Ashman et al. 1994). Using the catalog of Harris (1996) with 143 GCs, Jordán et al. (2007) found $M_{0, V} = -7.40 \pm 0.10, \sigma = 1.15 \pm 0.10$ for MW. Fall & Zhang (2001) reproduced the log-normal form, as well as the TO value of the Galactic GCs by evolving dynamically clusters obeying power-law mass functions under the gravitational potential of the Milky Way. The uniformity in the TO values in spite of GC systems being constituted of two independently formed sub-populations puts strong constraints on the formation scenarios of metal-rich and metal-poor sub-populations.

The total number of GCs in galaxies ($N_{GC}$) is another property that strongly constrains the formation scenarios of galaxies. Hanes (1977a) found that $N_{GC}$ is proportional to the mass of its host galaxy and is independent of its morphology. Harris & van den Bergh (1981) defined the specific frequency, $S_N$, defined as the number of GCs per absolute magnitude in the $V$-band, normalized to $M_V = -15$ mag: $S_N = N_{GC} \times 10^{0.4(M_V + 15)}$. They found that $S_N$ of a galaxy is approximately proportional to the total luminosity of the spheroidal component in the galaxy. Recent studies have shown that elliptical galaxies have a higher $S_N$ as compared to that in spiral galaxies (e.g., Peng et al. 2008; Georgiev et al. 2010).

Classical models of formation of elliptical galaxies either by merging of disk galaxies or by the multi-phase dissipational collapse have serious short comings to explain all the above-discussed properties of GC systems. For example, the scenario of the formation of ellipticals by mergers of spiral galaxies predicts similar $S_N$ values in ellipticals as compared to spirals. These models require the metal-poor population forming earlier than the metal-rich clusters. On the other hand, under the hierarchical scenario of galaxy formation, metal-rich GC systems formed in-situ in the parent galaxy, which are defined as the highest peaks in density fluctuations, whereas the metal-poor GC systems formed in low-mass halos and got accreted into host galaxy (Côté et al. 1998). The predictions from these latter models depend critically on the assumed GC system properties in spiral and dwarf galaxies, which are yet to be well established beyond the Milky Way and Andromeda.

For firmly establishing GC system properties in spiral galaxies, the GC sample should cover a substantial area of the galaxy, reaching limiting magnitudes fainter than the expected TO magnitudes. In addition, it is desirable to have observations in one of the filters blueward of the Balmer jump (~3650 Å) at least in some fields in order to estimate the contamination of the GC sample by reddened SSCs. The first criterion requires analysis of multiple pointing Hubble Space Telescope (HST) images or ground based images taken with wide-field cameras, whereas the second one requires images deep enough to register $V \sim 23$ mag at distances less than 10 Mpc. The third criterion requires the availability of images in the $U$-band covering at least for some part of the target galaxies.

The existing works on spiral galaxies do not fulfill all the above three criteria. For example, Chandar et al. 2004 carried out a study of GCs in five spiral galaxies and Goudreau et al. (2003) of seven edge-on disk galaxies, both using HST/WFPC2 fields, but covered relatively small areas in each galaxy. Study by Young et al. (2012) of two edge-on spirals covered spatially their entire optical extents, but had a limiting magnitude slightly brighter than the expected TO. Other works on spiral galaxies include Santiago-Cortés et al. 2010 and Nantais et al. 2010b (M81; Sab), Hwang & Lee 2008 (M51; Sbc), Barnby et al. 2006; Simanton et al. 2015 (M101; Scd), Cantiello et al. 2017 (NGC 253; Sc) and González-Lópezlira et al. 2017 (NGC 4258 Sbc). None of these works fulfilled all the three criteria.

At present, multi-pointing HST data covering a good fraction of the galaxy angular size (see Figure 1) and ob-
Luminosity functions of globular clusters

Table 1. Sample of spiral galaxies

| Name | Hubble Type | RA (J2000) | DEC (J2000) | $A_V$ | $r_{25}$ | $a_{max}$ | $d$ | $m - M$ | Distance Method | $M_{V0}$ | $B - V_{0}$ | Scale | Source | Proposal ID | Number of fields |
|------|-------------|------------|-------------|-------|---------|----------|-----|-------|---------------|----------|------------|-------|--------|-----------|----------------|
| M81  | Sab         | 09:55:31.1 | 69:03:55    | 0.220 | 13.45   | 7.74     | 3.61| 27.79| Cepheids     | 1        | 21.10      | 0.91  | 0.87  | 120276  | 11570         |
| M101 | Scd         | 14:03:12.5 | 54:20:56    | 0.023 | 14.42   | 7.49     | 6.95| 29.21| Cepheids     | 2        | 21.37      | 0.44  | 1.68  | 9490.9492 | 12             |
| NGC4258 | Scb      | 12:18:57.5 | 47:18:14   | 0.045 | 9.31    | 8.60     | 7.576| 29.397| M31 field   | 3        | 21.03      | 0.67  | 1.84  | 1157       | 17             |
| M51  | Scb         | 13:29:56.2 | 47:13:50    | 0.095 | 5.61    | 3.40     | 8.43| 29.67| SNII         | 4        | 21.40      | 0.57  | 2.04  | 10452     | 6(4)           |
| NGC628 | Sc        | 01:36:41.7 | 15:47:01    | 0.192 | 5.23    | 5.1      | 9.77| 29.95| SNII         | 5        | 20.75      | 0.50  | 2.36  | 10402     | 3              |

Notes: (1) Galaxy Name, (2) Hubble morphological type from RC3 (Corwin et al. 1994), (3,4) Right ascension, Declination, in J2000, (5) Galactic extinction from Schlafly & Finkbeiner (2011), (6) $r_{25}$ from RC3 (Corwin et al. 1994), (7) $a_{max}$ is the angular size along the semi-major axis covered by observations, (8) Distance used in this work, (9) Distance modulus, (10) Distance estimation method, (11) Source of distances: 1.- Tully et al. (2013); 2.- Riess et al. (2016). 3.- Reid et al. (2019); 4.- Rodríguez et al. (2014); 5.- Hwang & Lee (2008); 6 Barmby et al. (2006); 7 Simanton et al. (2015); 8.- Adamo et al. (2017), (12) HST/ACS pixel scale in pc pixel$^{-1}$, (15) Reference to previous studies of stellar clusters: 1.- Santiago-Cortés et al. (2010); 2.- Nantais et al. (2010a); 3.- Gonzalez-Lopez et al. (2017); 4.- Whitmore et al. (2014); 5.- Hwang & Lee (2008); 6 Barmby et al. (2006); 7 Simanton et al. (2015); 8 Adamo et al. (2017), (16) HST1 proposal number, (17) Number of ACS fields of each galaxy used in this work.

These catalogues have been used by Whitmore et al. (2014) to study the luminosity function of star clusters in selected fields for a sample of 20 spiral and irregular galaxies. As a first step, we used these catalogues to select a sample of GCs. However, we noticed that the adjacent images had vastly different limiting magnitudes in some galaxies. A visual inspection of catalogued sources on the images suggested that the background values used in some images were inappropriate (see Appendix A). Since we are looking for a complete sample of GCs up to a given limiting magnitude, we decided to make our own catalogues on the downloaded images.

In Figure 1, we show the images of galaxies in F435W band, with footprints superposed. In Tables 2 and 3, we give logs of observations for four of our galaxies in the optical and F336W filters, respectively. Different columns tabulate pointing IDs, exposure times, zeropoints$^3$ ($\sigma$) in each filter. We also give the number of stars used for astrometry and RMS error in the coordinates. The fifth galaxy, M81, has been the subject of study previously by our group (Santiago-Cortés et al. 2010), and hence we directly use the GC catalog from that study.

2 SAMPLE OF SPIRAL GALAXIES AND DATA

With the aim of comparing the properties of GC populations in spiral galaxies with those in elliptical galaxies, we searched for nearby giant spiral galaxies with multiple pointing HST Advanced Camera for Surveys (ACS) images in at least three optical broadband filters. Galactic GCs typically have half-light radius $r_h \lesssim 10$ pc (Harris 1996). At the spatial resolution of $\sim 0.1$ arcsec (image scale=0.05 arcsec pixel$^{-1}$) offered by the ACS, majority of the GCs are more extended than the Point Spread Function (PSF) up to $\sim 10$ Mpc distances. Beyond this distance, GC selection would be heavily affected by incompleteness. Keeping this in mind, we looked for HST images of giant spiral galaxies at distances $< 10$ Mpc. We analysed such data for five galaxies. In Table 1, we list these galaxies along with their basic properties and source of images. All these galaxies have multiple pointing HST/ACS images in $F435W$ ($B$), $F555W$ ($V$), and $F814W$ ($I$) bands, covering a good fraction of their optical extent. In addition, all have at least one pointing in the $F336W$ ($U$) filter, which allows an estimation of the contamination of our GC catalogues by reddened SSCs.

The Hubble Legacy Archive$^1$ (HLA) provides images and photometric catalogues obtained with DAOPHOT$^2$ (Stetson 1987) and SExtractor$^3$ (Bertin & Arnouts 1996).

1 https://hla.stsci.edu/hlaview.html
2 http://www.star.bris.ac.uk/~mbt/daophot/
3 https://www.astromatic.net/software/sExtractor

3 SOURCE DETECTION AND CLUSTER SELECTION

We used images in $F814W$ band for detecting sources using SExtractor. The critical detection parameters used are: DETECT_MINAREA=5 pixel, DETECT_THRESH=1.4, BACKSIZE=32 pixel and BACKFILTERSIZE=3 pixel, where each pixel corresponds to 0.05 arcsec. Using these criteria, typically we obtained several tens of thousands sources in each frame. Elaborate filtering criteria need to be implemented to select GCs from this catalogue.

As discussed in the introduction, making a catalogue of GCs is more challenging in spiral galaxies as compared to elliptical galaxies. This is because, unlike elliptical galaxies, spiral galaxies show a lot of structures at the scale comparable to the size of GCs. These structures lead to a lot of spurious sources in the SExtractor catalogue. Filtering based on structural parameters (e.g. Mayya et al. 2008), colour (e.g. Fedotov et al. 2011), concentration index (e.g. 4 The zeropoints were obtained from ACS Zeropoints Calculator: https://acszeropoints.stsci.edu/.

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Figure 1. Sample of study. Galaxies are shown in $F_{435}W$ filter, with observation footprints superimposed. Cyan-coloured rectangles show the $F_{336}W$ filter footprints. The number in each footprint indicates the visit number within proposal. All galaxies are aligned such that north is up and east to the left. Black ellipses represent $R_{25}$ for NGC4258 and M51, and 0.5$R_{25}$ for M101 and NGC 628. See Figure 1 in Santiago-Cortés et al. (2010) for visualization of footprints in M81.

Whitmore et al. (2014), colour-colour diagrams (e.g. Muñoz et al. 2014; González-Lópezlira et al. 2017) or a combination of these, are the most commonly used methods. In this paper, we used the cluster selection method used in Mayya et al. (2008) and Santiago-Cortés et al. (2010), which consists of using SExtractor-derived structural parameters (FWHM, AREA, ELIPITCITY) to define a cluster sample, and photometric parameters (COLOUR) to separate young clusters from GCs. The method is described in detail in Sections 3.2 and 3.4, below.

3.1 Astrometric correction of HST images

Before running SExtractor it was necessary to astrometrize all HLA images. We performed this with the help of GAIA stars using Gaia Data Release 2 (Gaia DR2; Gaia Collaboration et al. 2016; Gaia Collaboration et al. 2018). We used the IRAF task ccmmap with a second order polynomial in coordinates to achieve this. Minimum of 10 stars were used in each pointing (5 stars in one pointing of NGC 4258), resulting in mean rms astrometric accuracies of $\sim$0.095 arcsec (M101), $\sim$0.014 arcsec (NGC 4258), $\sim$0.048 arcsec (M51),
Table 2. Log of HST/ACS optical observations of our sample galaxies.

| ID | $T_{exp}$ | $c_0$ | $F_{435W}$ | $F_{555W}$ | $F_{814W}$ | Astrometric RMS (arcsec) |
|----|------------|-------|------------|------------|------------|--------------------------|
|    | (s)        |       | (s)        | (s)        | (s)        |                          |
| M101 |            |       |            |            |            |                          |
| 01  | 900        | 25.792| 720        | 25.736     | 720        | 25.531                   | 93     | 0.0259 |
| 02  | 900        | 25.792| 720        | 25.736     | 720        | 25.531                   | 55     | 0.163  |
| 03  | 900        | 25.792| 720        | 25.736     | 720        | 25.531                   | 38     | 0.0385 |
| 04  | 900        | 25.792| 720        | 25.736     | 720        | 25.531                   | 41     | 0.0319 |
| 05  | 900        | 25.792| 720        | 25.736     | 720        | 25.531                   | 37     | 0.278  |
| a2  | 900        | 25.792| 720        | 25.736     | 720        | 25.531                   | 11     | 0.0766 |
| a1  | 900        | 25.792| 720        | 25.736     | 720        | 25.531                   | 41     | 0.0319 |
| a3  | 900        | 25.792| 720        | 25.736     | 720        | 25.531                   | 37     | 0.278  |
| b1  | 900        | 25.792| 720        | 25.736     | 720        | 25.531                   | 10     | 0.187  |
| c1  | 900        | 25.792| 720        | 25.736     | 720        | 25.531                   | 18     | 0.0925 |
| c2  | 900        | 25.792| 720        | 25.736     | 720        | 25.531                   | 21     | 0.0175 |
| 10  | 1080       | 25.792| 1080       | 25.736     | 1080       | 25.531                   | 13     | 0.0988 |
| 11  | 1080       | 25.792| 1080       | 25.736     | 1080       | 25.531                   | 29     | 0.0456 |
| 13  | 1080       | 25.792| 1080       | 25.736     | 1080       | 25.531                   | 11     | 0.0862 |

NGC 4258

| ID | $T_{exp}$ | $c_0$ | $F_{336W}$ | $RMS$ (arcsec) | Proposal ID |
|----|------------|-------|------------|----------------|-------------|
| 0d  | 1062       | 23.546| 33         | 0.0154         | 13364       |
| 74  | 1062       | 23.546| 15         | 0.0109         | 13364       |

M51

| ID | Proposal ID |
|----|-------------|
| 01  | 13340       |
| 0g  | 13364       |
| 0i  | 13364       |
| 76  | 13364       |
| 31  | 14149       |

NGC 628

| ID | Proposal ID |
|----|-------------|
| 19  | 13364       |
| 20  | 13364       |

and ~0.042 arcsec (NGC 628). We took into account these rms errors to identify and eliminate duplicate sources in the overlap zones between two adjacent frames. In Figure 2, we zoom in on an image section in M101 to illustrate a typical field before and after astrometric correction. The left image shows the HST coordinate system for this field, whereas the image on the right shows the corrected coordinate system. The circles show the coordinates of GAIA (Gaia DR2) stars in this field of view.

Table 3. Log of HST/WFC3 F336W-band observations of our sample galaxies.

| ID | $T_{exp}$ | $c_0$ | $N_{stars}$ | Proposal ID |
|----|------------|-------|-------------|-------------|
| M101 |            |       |            |             |
| 64  | 2361       | 23.546| -           | 13364       |
| 79  | 2382       | 23.546| -           | 13364       |
| 94  | 2382       | 23.546| -           | 13364       |
| 95  | 2382       | 23.546| -           | 13364       |

NGC 4258

| ID | Proposal ID |
|----|-------------|
| 0d  | 13340       |
| 74  | 13364       |

M51

| ID | Proposal ID |
|----|-------------|
| 01  | 13340       |
| 0g  | 13364       |
| 0i  | 13364       |
| 76  | 13364       |
| 31  | 14149       |

NGC 628

| ID | Proposal ID |
|----|-------------|
| 19  | 13364       |
| 20  | 13364       |

3.2 Selection criteria for defining a cluster sample

In this work, we aim to obtain a sample of GCs with properties similar to those in the Milky Way, which are marginally resolved on the HST/ACS images at the distances of sample galaxies. We considered all objects with $fwhm > 2.4$ pixel as GC candidates. This cut-off corresponds to 2.1 pc and 5.7 pc, in the nearest (M81) and farthest (NGC 628) galaxies of the sample. Thus, farther a galaxy is, lesser would be the number of compact objects we would detect. GCs do not show a mass-radius (or equivalently luminosity-radius) relationship (Gieles et al. 2010) and hence this bias is not expected to affect the LF of GCs. GCs are roundish objects, and hence their ellipticity parameter is expected to be close to zero. SExtractor-measured ellipticity even for roundish objects could be as high as 0.3, as it is measured at the isophote.
corresponding to the detection threshold on the background subtracted image. Another parameter that SExtractor calculates is \( \text{AREA} \), with \( h \) being the number of pixels enclosed by the isophote where \( \text{ELLIPTICITY} \) is measured. Both the \( \text{ELLIPTICITY} \) and \( \text{AREA} \) depend on the threshold used for the detection, and hence a cluster of same magnitude and \( \text{FWHM} \) can have different values of \( \text{ELLIPTICITY} \) and \( \text{AREA} \), depending on the underlying background.

We have carried out Monte Carlo simulations to understand the behaviour of these parameters for clusters of different \( \text{FWHM} \) and magnitudes, appropriate to the background and crowding encountered in each galaxy in the \( F814W \) band. In Section 4, we describe in detail these simulations. In Figure 3 (right), we show the simulated clusters in \( \text{AREA vs FWHM} \) diagram for each of our sample galaxies. Simulations were carried out for a range of magnitudes between 19 and 24 magnitudes, for fixed values of \( \text{FWHM} \). 100 mock clusters between 19-24 magnitudes are generated, which are shown by symbols of different sizes (successively smaller sizes for fainter sources; see the bottom-most right panel for a guide on the symbol size). Most of the clusters with \( \text{mag} > 23 \) lie below the parabola defining the minimum \( \text{AREA-FWHM} \) relation, and hence are rejected by our selection criteria.

Figure 3. \textit{Left:} Selected GCs (red dots) compared to all SExtractor sources (black dots) in \( \text{AREA vs FWHM} \) plane for our 5 sample galaxies. GCs have \( (B-I)_0 > 1.5 \) mag, \( 2.4 < \text{FWHM/pix} < 10 \) and are above the parabola (blue line). Clusters bluer than this limit are SSCs which are identified by blue dots. Black dots above the parabola are extended sources with \( \text{ELLIPTICITY} > 0.3 \), and hence do not satisfy all cluster selection criteria. \textit{Right:} \( \text{AREA vs FWHM} \) for simulated star clusters. The \( \text{FWHM} \) of mock clusters are fixed at 2.0 (black), 2.4 (cyan), 3.0 (blue), 4.0 (green), 5.0 (magenta), 6.0 (yellow), 7.0 (orange) and 8.0 (red) pixels. For each fixed \( \text{FWHM} \), 100 mock clusters between 19-24 magnitudes are generated, which are shown by symbols of different sizes (successively smaller sizes for fainter sources; see the bottom-most right panel for a guide on the symbol size). Most of the clusters with \( \text{mag} > 23 \) lie below the parabola defining the minimum \( \text{AREA-FWHM} \) relation, and hence are rejected by our selection criteria.

Figure 4. (Top) Distribution of \( \text{FWHM} \) for the candidate GCs in one of our galaxies (M101). (Bottom) Comparison of the two commonly used discriminators between clusters and stars, CI vs \( \text{FWHM} \). Data are consistent with a linear fit (solid line whose equation is given in the top left corner) above the dividing line between clusters and stars (horizontal dashed line at CI=1.15). Data correspond to M101, which has 45 GCs below the defining line (see text for details).
cut in magnitude or \textit{area} can also eliminate the contaminating objects, but the use of parabola is the most effective way to eliminate these contaminating sources, without missing many genuine clusters. GCs at the distance of sample galaxies are expected to have FWHM close to the observational lower limit of 2.4 pixels. In the top panel of Figure 4, we show the observed distribution of FWHM for our final GC sample for one of our sample galaxies (M101), which indeed peaks at the first bin. However, we include objects up to FWHM=10 pixels to account for possible errors in the measurement of FWHM at detection limits. Simulations suggest that even the brightest clusters (F814W = 19) do not occupy an \textit{area}>500 pixels as long as the FWHM<5 pixels, and hence we eliminated sources with \textit{area}>500 pixels.

The HLA catalogues include a parameter known as concentration index (CI), defined as the difference between magnitudes measured in 1 and 3 pixel radius apertures. Some studies have made use of this parameter to discriminate brightness measured in 1 and 3 pixel radius apertures. In the bottom panel of Figure 4, a direct discriminator between unresolved (stars) and resolved (extended) sources. In the top panel of Figure 4, galaxies are expected to have FWHM<4 pixels, which is the reason for the horizontal spread. The aperture corrections (open circles) obtained for 35 isolated clusters with good photometry (error < 0.005 mag in 9 pixel) is also shown in the Figure. Both the simulated and observed corrections smoothly increase with the FWHM. For the simulated data, we obtained mean values of measured FWHM and correction for each input FWHM and fitted these mean values by a straight line which is shown by the solid line. The fitted results (the slope \(m\), and the abscissa, \(b\)) for all the sample galaxies are given in Table 4.

### 3.3 Aperture photometry

#### 3.3.1 Magnitudes, colours and aperture correction

SExtractor was also used for obtaining photometry in the three bands for all the detected sources. The photometry was carried out in 10 apertures with radii between 1 and 15 pixel (0.05 arcsec to 0.75 arcsec), using the zeropoints (\(c0\)) tabulated in Table 2 for each frame. Unlike stars, aperture correction for clusters depend on the cluster size, which is parameterized by the FWHM in SExtractor. The aperture correction is defined as the difference between magnitude at 3 pixel (0.15 arcsec) radius and the magnitude at an infinite aperture (\(\Delta F_{\text{814W}} = m_{\text{814W}(3\text{pix})} - m_{\text{814W}(\text{tot})}\)). Even the most extended clusters (objects with Gaussian FWHM=9 pixel) contain more than 98% of their total flux within an aperture of 15 pixel radius, because of which we have used the magnitude in an aperture of 15 pixel radius as \(m_{\text{814W}(\text{tot})}\).

We used the results of our experiments with simulated clusters, described later in Section 4, to obtain the correction as a function of measured FWHM in each galaxy. The results are shown in Figure 5 for M101. A group of horizontally distributed points corresponds to the same input FWHM. The measured FWHM for fainter clusters tends to be systematically larger than the input FWHM, which is the reason for the horizontal spread. The aperture corrections (open circles) obtained for 35 isolated clusters with good photometry (error < 0.005 mag in 9 pixel) is also shown in the Figure. Both the simulated and observed corrections smoothly increase with the FWHM. For the simulated data, we obtained mean values of measured FWHM and correction for each input FWHM and fitted these mean values by a straight line which is shown by the solid line. The fitted results (the slope \(m\), and the abscissa, \(b\)) for all the sample galaxies are given in Table 4.

We applied these corrections to the F814W aperture magnitudes of 3 pixel radius of all cluster candidates to obtain their total magnitudes. Colours (\(F_{435W} - F_{814W}\), \(F_{435W} - F_{555W}\) and \(F_{555W} - F_{814W}\)), however are obtained by subtracting magnitudes in the corresponding filters at 3 pixel radius aperture. This procedure ensures that errors on colours are smaller than the aperture corrected magnitudes. The errors on colours were calculated by quadratically summing the magnitude errors in the two bands forming a colour.
Formal errors\(^5\) on photometric measurements are obtained using the formula: \(\text{MAGERR} = 1.086 \times (\text{FLUXERR}/\text{FLUX})\), where \(\text{FLUXERR} = \sqrt{\sum_i (\sigma_i^2 + g_i^2)}\), with \(\sigma_i\) representing the set of pixels defining the photometric aperture, \(g_i\) the standard deviation of noise (in ADU) estimated from the local background, \(p\), the background-subtracted image pixel value, and \(g_i\) the effective detector gain in e-/ADU at pixel \(i\). However, small-scale variations in the disk background gives rise to additional errors while carrying out photometry of non-stellar objects such as GCs, that are usually larger than the formal errors. We use the colour-colour diagram \((F_{435W} - F_{555W})_0\) vs \((F_{435W} - F_{814W})_0\) to estimate the real errors on our colours. In Figure 6, we illustrate the method adopted for this. In this plot, we show the colours for star clusters in NGC 4258, with the SSPs with \(Z=0.001\) and 0.019 metallicities from Bruzual & Charlot (2003). The reddening vector for \(A_V=4\) mag is also shown. The reddening vector and the evolutionary trajectory are parallel in this colour-colour diagram, implying the spread in the \((F_{435W} - F_{555W})_0\) colour for a fixed \((F_{435W} - F_{814W})_0\) colour (and vice versa) is entirely due to observational errors. We calculated the dispersions in colour for each axis for fixed bins of 0.2 mag width in the other axis. In the figure, we show these dispersions by crosses places at every 0.4 mag. There is a tendency for slightly higher error for the reddest colours. We take into account this dispersion in each colour as an additional source of error while comparing observational colours with model colours.

\(^5\) https://sextractor.readthedocs.io/en/latest/Photom.html

### Table 5. Source detection and selection statistics.

| Galaxy | All \(N_{\text{SSC+GC}}\) | \(N_{\text{GC}}\) | \(N_{\text{GC}}^{\text{SCC}}/N_{\text{GC}}\) | \(N_{\text{cont}}/N_{\text{GC}}\) |
|--------|-------------------------|-----------------|---------------------------------|-----------------------|
| M81    | 565438                  | 433 158         | 0.65                            | 0.20                  |
| M101   | 1215533                 | 30911123        | 0.14                            | 0.32                  |
| NGC4258| 1360607                 | 626 226         | 0.35                            | 0.35                  |
| M51    | 452747                  | 1196 293        | 0.52                            | 0.25                  |
| NGC628 | 224108                  | 608 173         | 0.43                            | 0.14                  |

Notes: (1) Galaxy. (2) All sources (stellar+non-stellar+spurious) detected by SExtractor in all the pointings over the target galaxy. (3) Those sources satisfying the criteria explained in Section 3.2 to be identified as a cluster. (4) Subset of red \((B-I > 1.5\) mag\) sources in column 3. (5) Fraction of total number CGs with photometry in an ultraviolet filter. (6) Fraction of contaminants (reddened SSCs) in our GC sample.

### 3.4 The sample of GCs

We define GCs as old (age>10 Gyr) metal-poor \((Z \lesssim 0.001)\) clusters, having properties similar to that for the sample of Galactic GCs. However, unlike the Galactic GCs, extragalactic GCs cannot be selected by their visual appearance even on the HST images. Our cluster sample contains GCs as well as relatively young clusters, such as SSCs. In Table 5, we list the source detection statistics in each galaxy. The second column contains all SExtractor-defined sources, with the column 3 containing the number of cluster sources. Cluster samples in spiral galaxies contain more SSCs than GCs, and hence quantitative criteria are required to discriminate between GCs and SSCs. Cluster colour is the most useful discriminator for achieving this. For example, metal-poor SSPs \((Z\lesssim 0.001)\) predict \(B-I > 1.5\) mag for populations older than \(\sim 3\) Gyr (Bruzual & Charlot 2003).

In Figure 7, we plot the distribution of \((F_{435W} - F_{814W})_0\) colours for all clusters (black histogram) and for clusters brighter than \(M_{814W} = -9\) mag (red histogram) in each galaxy. The latter is multiplied by a factor which is indicated in the figure annotation. For the bright cluster sample, four of the five galaxies studied here show a bimodality in the distribution, the exception being M101. The colour that separates the two distributions is nearly the same in all these galaxies, and corresponds to the \((F_{435W} - F_{814W})_0=1.5\) mag bin. The full cluster sample also shows a minimum in the distribution close to this colour in four of the galaxies. In M101, although the evidence for bimodality is not strong for the bright cluster sample, the total sample indicates bimodality with the saddle point again corresponding to the \((F_{435W} - F_{814W})_0=1.5\) mag. The blue and red distributions correspond to the SSCs, and GCs, respectively. Based on this, we use \((F_{435W} - F_{814W})_0=1.5\) mag to separate GCs and SSCs. Column 4 of Table 5 lists the number of clusters classified as GCs using this colour criterion. Coordinates and photometry for each of the selected GCs are given in Table 6. The Table in the body of the text contains data only for three brightest objects in each galaxy. The entire Table is available in electronic version.

The red tail of the reddened SSC colours most likely extends beyond the colour cut of \((F_{435W} - F_{814W})_0=1.5\) mag, and hence colour-selected GC sample in spiral galaxies is expected to have some contamination...
Figure 7. Colour histogram of all (SSC+GC) cluster candidates. The black line shows the colour distribution over the entire range of magnitudes, whereas the red histogram shows the distribution for bright ($M_I \leq -9$) clusters. The latter histogram values are multiplied by a factor indicated in each panel. The vertical line at $(F_{435W} - F_{814W})_0 = 1.5$ separates SSCs from GCs.

Figure 8. $M_{F814W}$ vs $(F_{435W} - F_{814W})_0$ CMD of all cluster candidates in our sample of galaxies. Candidates having $(F_{435W} - F_{814W})_0 > 1.5$ mag are GC candidates (red dots), and bluer objects are young disk cluster candidates (blue dots). The evolutionary locus of the SSPs from Bruzual & Charlot (2003) for two metallicities ($Z=0.001$, black solid line and $Z=0.008$, black dashed line), of mass=$1 \times 10^6 M_\odot$ and Kroupa IMF, are shown. Locations corresponding to selected ages (0.1, 0.5, 1, 3, 6 and 12 Gyr) are marked (cyan and magenta triangles in each SSP). The chosen colour cut separates clusters older than 3 Gyr from the younger ones for unreddened SSPs. The reddening vectors with $A_V = 1$ mag are shown for 3 cluster masses for an SSP of 12 Gyr age and $Z=0.001$, typical values expected for GCs. The majority of the GC candidates are in the zone occupied by clusters of mass $1 \times 10^5$ to $5 \times 10^6 M_\odot$ and $A_V$ between 0 and 1 mag. Encircled red dots correspond to compact GC candidates ($1.07 < C.I. < 1.15$; see section 3.2 for details) in our sample.
Table 6. Observational properties of the brightest three GCs in each sample galaxy.

| ID    | RA    | DEC   | I   | (B − I)₀ | (B − V)₀ | (U − B)₀ | FWHM | AREA  | CI   | M_F814W | r_p (kpc) | FLAG |
|-------|-------|-------|-----|----------|----------|----------|------|-------|------|---------|-----------|------|
| M81-GC1 | 148.94125 | 69.110425 | 16.13±0.03 | 2.06±0.10 | 1.10±0.10 | 1.63±0.10 | 3.62  | -     | -    | -0.16   | -0.20     | 0.16 |
| M81-GC2 | 148.94123 | 69.050997 | 16.75±0.03 | 2.24±0.10 | 1.27±0.10 | 2.05±0.10 | 3.45  | -     | -    | -0.10   | -0.14     | 0.06 |
| M81-GC3 | 149.11440 | 69.013880 | 16.65±0.03 | 1.78±0.10 | 1.09±0.10 | 1.43±0.10 | 5.82  | -     | -    | -0.13   | -0.17     | 0.02 |
| M101-GC1 | 210.82496 | 54.318723 | 18.76±0.02 | 2.51±0.00 | 1.20±0.17 | 1.31±0.41 | 3.07  | 449   | 1.30  | -11.57  | -0.03     | 0.03 |
| M101-GC2 | 210.88457 | 54.414166 | 18.57±0.02 | 2.74±0.00 | 1.14±0.17 | 3.38   | 394   | 1.50  | -10.63  | 9.82      | 0.00 |
| M101-GC3 | 210.88458 | 54.360237 | 18.10±0.02 | 2.48±0.00 | 1.46±0.17 | 2.92   | 301   | 1.39  | -10.10  | 6.31      | 0.00 |
| NGC4258-GC1 | 184.72970 | 47.264868 | 17.89±0.01 | 0.63±0.00 | 0.79±0.10 | -2.69  | 311   | 1.16  | -11.57  | 5.25      | 0.00 |
| NGC4258-GC2 | 184.86570 | 47.210389 | 17.92±0.00 | 3.37±0.01 | 1.13±0.10 | -2.79  | 165   | 1.18  | -11.50  | 16.78     | 0.00 |
| NGC4258-GC3 | 184.74590 | 47.301067 | 17.97±0.02 | 0.15±0.01 | 0.99±0.10 | 0.43±0.05 | 4.03  | 440   | 1.65  | -11.42  | 6.69      | 0.02 |

Notes: (1) Assigned name, which follows the convention of GAL-GCs, where GAL stands for galaxy name and n is 1 for the brightest object in the F814W filter, and increases sequentially as the magnitude increases, (2,3) Right ascension, Declination, coordinates in J2000, (4) Magnitude in F814W-band and magnitude error from SExtractor and aperture correction, added in quadrature, (5) (F435W − F814W)₀ magnitude, the error is the quadrature sum of the error in each band from SExtractor, (6) (F435W − F555W)₀ Colour, error is the quadrature sum as in column 5, In the case of M81 the colour is (F435W − F606W)₀, (7) (F555W − F606W)₀ colour, the error is the quadrature sum of the error in each band. In the case of M81 the colour is (u−g)₀. (8) FWHM in pixel units from SExtractor, (9) AREA in pixels from SExtractor, (10) Concentration index, defined as the difference between magnitudes measured in 1 and 3 pixel radius apertures, (11) Absolute magnitude in F814W-band, (12) Galactocentric distance of the GC in kiloparsecs, (13) FLAG classification: 00 clusters without U-band photometry; 01 determined as a young reddened cluster from U-band photometry; 02 - determined as bona fide GC from U-band photometry; and 03 - error in U-B is likely to be larger than the indicated formal error.

from the reddened SSCs. The SSC population has a long tail on the red side, which is either due to a spread in reddening, or/and due to a spread in ages of SSCs. In either case, the red tail of SSC distribution has very few clusters beyond (F435W − F814W)₀ > 1.5 mag. The estimation of contaminating objects in the GCs samples is discussed in Section 3.5.

In Figure 8, we plot all candidate clusters in a colour-magnitude diagram (CMD) formed using M_F814W vs (F435W − F814W)₀, where SSCs and GCs are shown by blue and red points, respectively. The evolutionary loci of clusters for Simple Stellar Population (SSP) models from Bruzual & Charlot (2003) at typical metallicities of SSCs (Z=0.008−1/3 solar) and GCs (Z=0.001) are shown. These models correspond to typical clusters of mass = 1 × 10⁶ M☉ obeying the Kroupa initial mass function (IMF) between masses 0.1 and 100 M☉. If the GCs are as old as 12 Gyr, the range of magnitudes covered by the GCs corresponds to mass range shown by the dashed vertical line, and the range of colours corresponds to reddening equivalent to AV=0 to $\sim$2 mag.

3.5 Contamination of the GC sample from reddened SSCs

Figure 8 suggests that the reddened SSC colours overlap with the GC colours. The colour histogram (Figure 7) also suggests that the distribution of the SSC colours (the bluer peak) most likely has a long tail on the redder side, that overlaps with the GC colours. Thus, contamination to some degree from reddened SSCs is unavoidable when selecting GC samples in spiral galaxies using colour-cuts. We use the sub-sample of clusters with U-band photometry to estimate the fraction of contaminants in each galaxy.

Use of colour-colour diagrams involving ultraviolet and optical filters is known to break the age-reddening degeneracy (e.g., Georgiev et al. 2006; Bastian et al. 2011; Fedotov et al. 2011). In particular, U − B colour separates clearly clusters younger (SSCs) and older (GCs) than $\sim$3 Gyr. Keeping this in mind, we searched the HST archives for images in the WFC3/F336W filter. All our sample galaxies have at least one pointing in this filter (see Table 3). For M101, the F336W images had good astrometry. For the fields in other galaxies, we carried out the astrometry following the same procedure as described in section 3.1.

WFC3/F336W image for M81 is available for only one pointing, as compared to the 29 pointings with the ACS, with only 7 GC candidates (4%) falling in the FoV of the F336W image. The contamination fraction obtained from such a small coverage of the FoV is not expected to be representative. On the other hand, Sloan Digital Sky Survey (SDSS) image of this galaxy obtained from multiple pointings covers the FoV of all the 29 HST/ACS pointings. The relative nearness of this galaxy allows the detection and photometric analysis of 65% of clusters that occupy the relatively uncrowded fields. We hence used the SDSS u − g colours for estimating the contamination fraction in M81. In column 5 of Table 5, we present the fraction of GC candidates with U-band images, i.e. SDSS-u for M81 and HST/WFC3 F336W for the rest. We performed photometry using the phot task in IRAF using the same photometric parameters as for the HST/ACS images.

In Figure 9, we plot all candidate clusters with F336W coverage in (F336W − F435W)₀ vs (F435W − F814W)₀ colour-colour diagram. For M81, we show the SDSS u − g colours (in the AB system) in the ordinate. The evolutionary loci of clusters in this diagram for theoretical SSPs

https://dr12.sdss.org/fields

MNRA 3 2 3 0 0 0 0 0 0 1 2 4 2 (2021)
Figure 9. The $U$-selected cluster candidates in $(u - g)_0$ vs $(F_{435W} - F_{814W})_0$ diagram for M81 and $(F_{336W} - F_{435W})_0$ vs $(F_{435W} - F_{814W})_0$ diagram for the rest of the sample galaxies. Candidates having $(F_{435W} - F_{814W})_0 > 1.5$ mag are GC candidates (red dots), and bluer objects are young disk SSC candidates (blue dots). The evolutionary loci of SSPs from Bruzual & Charlot (2003) for different metallicities using Kroupa IMF are shown by solid curves of different colours, following the colour notation shown in each panel. The bluest colour that a classical GC can have ($Z=0.0004$ and age 12 Gyr) is marked by a solid triangle. The reddening vector with $A_V = 1$ mag is shown. The reddened young SSCs that occupy the GC colours are contaminants, which are identified by red dots surrounded by circles of cyan colour.

Figure 10. The fraction of contaminants (reddened young SSCs) in our GC samples as a function of colour (left) and magnitude (right) for our five sample galaxies. The vertical dashed-line in the left figure corresponds to the reddest colours reached by SSPs for unreddened GCs. See text for details.
from Bruzual & Charlot (2003) of different metallicities are shown. The $U$–$B$ colours of reddened young (< 10 Myr) clusters are distinctly different from that of clusters older than $\sim$3 Gyr, which allows us to break the age-reddening degeneracy. Thus reddened young SSCs (contaminants) would lie below the SSP locus for age>3 Gyr. In other words, for a redder ($F_{435W} - F_{814W} > 1.5$) cluster to be considered a genuine GC, its $U$ – $B$ colour, after taking into account photometric errors, should correspond to a location above the SSP locus in the figure. As illustrated in Figure 6, the real errors in photometry are larger than the formal error bars, which limits the use of the colours for a precise determination of age. Nevertheless, the photometric quality is good enough to separate reddened SSCs from GCs. In the last column of Table 5, we give the fraction of contaminants in our GC samples. The values lie between 14–35% in the sample galaxies.

In Figure 10, we explore whether contaminant fraction in our GC samples depends on the colour and magnitude of the GCs. We carry out this analysis in bins of 0.5 mag in colours and magnitudes. In order to avoid fluctuations caused due to small number statistics in some of the bins, we plot only those values for which the number of contaminants in any bin was more than the Poisson error in that bin, taken as the square root of the total number of GC candidates in that bin. For the rest of the bins, we plot the global values. In general, all galaxies have higher contaminant fraction for ($F_{435W} - F_{814W}$) $>$ 2.2 mag, with as much as 50% of the GCs of ($F_{435W} - F_{814W}$) $>$ 2.5 mag being contaminants (reddened young SSCs) in M101 and M81. None of the galaxies show any significant dependence of the contaminating fraction with magnitude. We hence use the global values of the contaminant fraction to correct the LF obtained from our entire GC sample in Section 5 for all galaxies.

### 3.6 Comparison of our GC catalogues with those in the literature

In four of our five sample galaxies, there exists a previous catalogue of GCs. We reiterate that none of these catalogues are as complete as our catalogues in terms of spatial and magnitude coverages, as well as in the estimation of contamination fraction from reddened SSCs. We here compare our catalogues, obtained using uniform selection criteria, with the catalogues from other authors, using different selection criteria.

**M81**: Nantais et al. (2010b) reported a sample of 233 GC candidates in M81, that had made use of data from HST/ACS and SDSS. They used a FWHM $>$ 3 ACS pixel ($0.15$ arcsec) as the main discriminator. We find that 107 of our 154 GCs are present in the catalogue of Nantais et al. (2010b). Most of the remaining 49 GCs in our sample have 2.4 < FWHM $<$ 3 pixel, which is the main reason for their exclusion in Nantais et al. (2010b). Lower number of GCs in our sample as compared to that of Nantais et al. (2010b) is due to the more stringent filtering that we imposed in the selection of GCs.

**M101**: Similarly, using data from the HST/ACS, Simanton et al. (2015) reported a sample of 326 star clusters in M101. The selection was made using the concentration index and a colour cut. Their sample includes extended objects, and hence they used a magnitude cut of $M_V \leq -6.5$ to define GCs, resulting in a sample of 98 GC candidates. We find that 48 are present in their sample of GC candidates. Reasons for us missing 50 of their objects are that 25 of these have ELLIPTICITY $>$ 0.3, 19 do not meet the AREA criterion and the rest do not meet our FWHM criterion.

**NGC4258**: González-Lópezlira et al. (2017) reported a sample of 39 GCs in NGC 4258 using near infrared (NIR) data from CFHT (Canada France Hawaii Telescope) over a large FoV (1″ x 1″), but based on seeing-limited (~0.7 arcsec) dataset. The selection of the GCs was carried out using the colour-colour diagram $u' - i'K_s$ vs ($u' - i'$) (Muñoz et al. 2014). In comparison, our catalogue using HST/ACS images contains 226 GCs over a FoV of $\sim$ 12.3″ x 17.2″. From a spectroscopic follow-up of the objects, González-Lópezlira et al. (2019) concluded that the selection based on colour-colour diagram has between 10 to 30% contaminants (e.g., Muñoz et al. 2014; González-Lópezlira et al. 2019). Our FoV includes 29 objects of González-Lópezlira et al. (2017), of which 23 are in our catalogue. Out of the 6 missing objects in our sample, two are confirmed to be GCs using spectroscopic data by González-Lópezlira et al. (2019), another two are dwarf galaxies, with the remaining one being a foreground star. Reason for the two of their GCs to be absent in our sample is that they do not satisfy our selection criteria.

**M51**: Star clusters in M51 were catalogued by Hwang & Lee (2008) using HST/ACS images. They used the SExtractor parameters stellarity, FWHM and ellipticity for star cluster selection. They created two subsamples, one with 2.4<FWHM<$<$20 and the other with 2.4<FWHM<$<$40 pixel, resulting in a catalogue of 8400 stellar cluster candidates. If we applied their colour discriminator (($B - V$) $>$ 0.5 and ($V - I$) $>$ 0.8) in their catalogue we obtained a sub-catalogue of 224 red clusters, 214 of which have FWHM$<$10 ACS ACS pixels. Only 85 of these objects are in our catalogue of 223 GCs. We searched our master SExtractor output catalogue to find out the reasons for we missing 139 of their objects, and found that 85 of these have ELLIPTICITY $>$ 0.3, 15 do not meet the AREA criterion and the rest do not meet our FWHM criterion.

**NGC628**: The last galaxy of our sample, NGC 628, has also been a target for cluster searches using HST images by Ryu et al. (2017). However, they reported only young and intermediate-age clusters, and no GCs.

### 4 Completeness Corrections

We aim to study GC luminosity functions in our sample galaxies. In order to do that, we need to take into account possible sources of incompleteness in our catalogues. Two principal sources of incompleteness in our study are: i) incompleteness in magnitude and ii) incompleteness in radial coverage even with multiple HST pointings. In this section, we describe the method we have followed to correct for these observational limitations and obtain a final GC luminosity function.

#### 4.1 Monte Carlo cluster simulations

We generated mock clusters using the IRAF/DAOPHOT tasks addstars and mkobjects. A cluster is defined by an
intensity profile that follows a Gaussian function of a given FWHM and a total magnitude, with FWHM taking values of 2.0, 2.4, 3.0, 4.0, 5.0, 6.0, 7.0 and 8.0 pixels, and magnitudes varying between 19 and 24 magnitudes at interval of 0.5 mag. For a fixed FWHM, 1100 clusters were generated, 100 for each simulated magnitude.

Coordinates of these sources were randomly selected and were inserted onto an observed HST image. The faintest object that can be detected in an observation under uniform background conditions defines the detection limit of that observation. In real observations, the background is often non-uniform, and each non-point source has a different size. Further, crowding of objects in an image can lead to non-detection of objects that are brighter than the detection limit. Hence, for each galaxy, we chose HST images corresponding to two FoVs, representing zones of (i) low background and low crowding, and (ii) high background and high crowding. The former simulates the conditions typical of clusters in the external parts of galaxies, whereas the latter represents the characteristics of clusters in the bulge and spiral arms. For M81, which has as many as 29 pointings, simulations were carried out on an additional frame containing the bulge and nucleus (R09; see Figure 1 in Santiago-Cortés et al. 2010, for the footprint of M81). The results of these latter simulations were used exclusively in the analysis of radial density distribution of clusters in the inner part of this galaxy. The same object detection and selection criteria (§3.2) we had used for real objects were applied on the mock-object added frames. In Figure 11, we zoom-in on a randomly selected region of M101, before (left) and after (right) inserting mock sources. In the image the positions of the mock sources, which cover a range of magnitudes, are indicated by blue circles.

We have also used these simulations to establish criteria to select cluster candidates from all sources catalogued by the SExtractor, and apply FWHM-dependent aperture corrections, described in Section 3.3. We used the results of the simulations for low background and low crowding for this purpose.

4.2 Completeness corrections: magnitude

For a proper counting of a population, it is necessary to know completeness factor as a function of object magnitude. We used the results of our simulation to determine the completeness factors. This factor is expected to depend on the FWHM.

In the top panel of Figure 4, we plot the distribution of FWHM, which peaks at FWHM=3 pixel. Hence, we calculate the completeness factors for mock clusters of input FWHM=3 pixel. The completeness factor is defined as the ratio of the number of recovered objects ($N_{\text{rec}}$) to the inserted objects ($N_{\text{in}}$) at each inserted magnitude.

In Figure 12, we show completeness curves in the F814W-band for all of our sample galaxies, for low (circles) and high (triangles) background frames. In order to quantitatively obtain the magnitude at which the sample is 50% complete, $m_{50}$, we fitted the points with the Pritchet function (e.g., McLaughlin et al. 1994; Alamo-Martínez et al. 2013; González-Lópezlira et al. 2017) given by:

$$f(m) = \frac{1}{2} \left[ 1 - \frac{\alpha (m - m_{50})}{\sqrt{1 + \alpha^2 (m - m_{50})^2}} \right], \quad (1)$$

where $\alpha$ is a fitting constant that determines curve’s slope. These fitted curves are shown by dotted and dashed lines, for low and high background frames, respectively. The GCs are distributed homogeneously across galaxies, including regions with a high and low crowding. To make the correction for incompleteness of the luminosity function, we decided to use the values of the mean curve, which is shown by the solid curve. In Table 7, the values for the 50% completeness for three curves are given for the F814W-band.

### Table 7. Magnitude at 50% completeness in F814W-band, for three curves in Figure 12

| Galaxy     | Low | High | Average |
|------------|-----|------|---------|
| M81        | 22.93 $\pm$ 0.04 | 21.65 $\pm$ 0.04 | 22.32 $\pm$ 0.14 |
| M101       | 22.72 $\pm$ 0.06 | 22.11 $\pm$ 0.16 | 22.44 $\pm$ 0.17 |
| NGC 4258   | 22.60 $\pm$ 0.02 | 22.26 $\pm$ 0.00 | 22.46 $\pm$ 0.13 |
| M51        | 22.92 $\pm$ 0.01 | 22.45 $\pm$ 0.00 | 22.69 $\pm$ 0.06 |
| NGC 628    | 22.85 $\pm$ 0.01 | 22.72 $\pm$ 0.00 | 22.79 $\pm$ 0.01 |

Notes: $m_{50}$ is the magnitude at 50% completeness and $\alpha$ is a fitting constant defined in Equation 1.

4.3 Completeness corrections: radial distribution

While the images obtained from HST observations offer the best spatial resolution, they do not cover the whole extent of galaxies even with the multiple pointings. Thus, outer halo GCs are often missing in catalogues selected from HST images. The following analysis was carried out to correct for the absence of GCs beyond the galaxy's disk.

GCs are the most easily noticeable objects in the halos of galaxies. However, their surface density in the inner parts always outnumbers that in the halos (see e.g. Hargis & Rhode 2014; Kartha et al. 2014). In fact, the radial surface density distribution can be well described by the Sérsic function (Sersic 1968) in its classical form:

$$N(R) = N_e \exp \left[ -b_n \left( \frac{R}{R_e} \right)^{(1/n)} - 1 \right], \quad (2)$$

where, $R_e$ is the effective radius enclosing half the population, $n$ is the Sérsic index that controls the shape of the
Figure 12. Completeness correction curves in the F814W-band for our sample galaxies in low (dotted line passing through circles) and high (dashed line passing through triangles) background regions. The mean of these two curves is shown by the solid line. The identification codes of high and low background frames used in these simulations are shown in parenthesis.

profile and $b_n = 1.992n - 0.3271$. We show the radial distribution of surface number density in Figure 13. The radial axis is plotted in units of $R_25$. For two of our sample galaxies (M81: Perelmutter & Racine 1995, and NGC4258: González-Lópezlira et al. 2017), GC searches have been carried out using the ground-based data that complement the HST data in the outer parts, which have also been shown (green empty circles). The observed and completeness-corrected values are shown in solid circles of black and magenta colours, respectively, with the fits to these data shown by solid lines of corresponding colours. The numbers inside and outside the $R_e$ are corrected by the incompleteness factors corresponding to high and low surface brightness fields, respectively. For M81, the inner most number is corrected by the completeness factor obtained from simulation on the frame that included the bulge and the nucleus. The $R_e$ values before and after the incompleteness corrections are shown by dashed vertical lines of black and magenta colours, respectively. The effect of correction is to marginally shift the $R_e$ to lower values, which is noticeable only for NGC4258 and M51 in the figure. In Table 8, we show the values for Sérsic fit. $N_{GC,R_e}$ and $N_{GC,R_e}'$ are the numbers of GCs inside $R_e$ before and after correction for contaminants. To estimate the total number of GCs (see Section 5.6), we use the number of GCs within $R_e$, $(N_{GC,R_e}')$.

The number density obtained wide-field ground-based surveys underestimates the number of GCs inside $R_e$ by more than an order of magnitude in both the galaxies with such data. In NGC4258, the slope of our fit in the external part agrees with the observed number densities from wide-field survey, with the absolute values marginally below our predictions. On the other hand, number densities obtained from wide-field survey in M81 remain constant over a large radial range, which are likely due to some selection biases in the survey. On the other hand, the wide-field survey suggests an excess of GCs in the external parts of this galaxy as compared to our predicted values. This excess could be due to contamination from foreground stars and unbound intergalactic GCs in the M81 group (see e.g. Jang et al. 2012; Ma et al. 2017).

Two of the most well-studied spiral galaxies, the Milky Way and M31, have $n = 1.9$ and $R_e = 4.41$ kpc and $n = 1.6$ and $R_e = 4.59$ kpc (Battistini et al. 1993), respectively. In comparison, for elliptical galaxies the calculated values are larger, e.g., NGC 720 (E5): $n = 4.16 \pm 1.21$, $R_e = 13.7 \pm 2.2$ kpc; NGC 1023 (SO): $n = 3.15 \pm 2.85$, $R_e = 3.30 \pm 0.9$ kpc; NGC 2768 (E): $n = 3.09 \pm 0.68$, $R_e = 10.6 \pm 1.8$ kpc (Kartha et al. 2014). The $n$ and $R_e$ for our sample galaxies are in the range of expected values in spiral galaxies. The $n$ values are $< 1$ in four of our galaxies, suggesting flatter distribution in the inner parts of our galaxies, as compared to the Milky Way and M31.
start our analysis with the colour distribution. A foreground Galactic extinction using the now analyse the properties of the GC systems in these galaxies. Having obtained a sample of GCs in 5 spiral galaxies, we 5 GLOBULAR CLUSTER LUMINOSITY FUNCTIONS (GCLFS)

Having obtained a sample of GCs in 5 spiral galaxies, we now analyse the properties of the GC systems in these galaxies. All magnitudes and colours have been corrected for the foreground Galactic extinction using the $A_V$ values given in Table 1, and the Cardelli et al. (1989) reddening curve. We start our analysis with the colour distribution.

Table 8. Results of Sérsic profile fits to the radial distribution of GC surface density.

| Galaxy     | n  | $R_e$  | $N_{GC,R_e}$ | $N_{GC,R_e}$ |
|------------|----|--------|--------------|--------------|
| M81        | 0.57±0.07 | 4.29±0.16 | 93±11 | 74±9 |
| M101       | 0.33±0.05 | 7.68±0.28 | 635±24 | 432±16 |
| NGC4258    | 1.81±0.50 | 9.48±2.02 | 179±39 | 116±25 |
| M51        | 0.74±0.15 | 10.07±1.15 | 250±31 | 188±23 |
| NGC628     | 0.48±0.08 | 6.08±0.27 | 113±7  | 97±6  |

Notes: $R_e$ is the effective radius enclosing half the population, n is the Sérsic index from Equation 2. $N_{GC,R_e}$ is the total number of GCs inside $R_e$, whereas $N_{GC,R_e}$ is $N_{GC,R_e}$ after taking into account contamination from reddened young SSCs.

Table 9. The mean and mode of the colour distribution of sample galaxies and the MW.

| Galaxy     | $(B-I)_0$ | $(B-V)_0$ | $(V-I)_0$ | $A_V$(int) | $A_V$(int) |
|------------|-----------|-----------|-----------|------------|------------|
| M81        | 2.21      | 1.81      | 1.21      | 0.90       | 0.77       | 0.86       | 0.32       |
| M101       | 2.49      | 1.68      | 0.96      | 0.65       | 1.54       | 0.98       | 1.23       | 0.15       |
| NGC4258    | 2.02      | 1.64      | 0.92      | 0.81       | 1.11       | 0.87       | 0.60       | 0.10       |
| M51        | 2.04      | 1.71      | 0.93      | 0.87       | 1.10       | 1.03       | 0.68       | 0.19       |
| NGC628     | 2.11      | 1.58      | 0.72      | 0.63       | 1.39       | 1.00       | 0.73       | 0.01       |
| MW         | 2.34      | 1.70      | 1.01      | 0.72       | 1.33       | 1.01       | 1.04       | 0.17       |
| SSP        | 1.57      | 0.67      | 0.90      |            |            |            |            |

Notes: (1) Galaxy name. (2-7) Mean and statistical mode of the indicated colours. (8-9) Internal visual extinction obtained from mean and mode $(B-I)_0$.

5.1 Colour distribution

For comparing colours of our GCs with those in the MW, we transformed all our photometry into the Johnson-Cousins photometric system using the transformation equation $B_1$ and the corresponding coefficients in Table B1 in Appendix B, which were taken from Sirianni et al. (2005).

In Figure 14, we show the distributions of $(B-I)_0$, $(B-V)_0$ and $(V-I)_0$ colours of GC systems in our sample galaxies, where the sub-index 0 stands for Galactic reddening-corrected colours, using the $A_V$ values in Table 1. For comparison, we also plot the colour histograms of the GCs in the Milky Way using the data from Harris (1996). The black and blue histograms correspond to the observed and dereddened colours, respectively. In Table 9, we list the mean and mode of the distributions of the three colours $(B-I)_0$, $(B-V)_0$ and $(V-I)_0$ for our sample as well as for the MW sample from Harris (1996). We use only 97 Galactic GCs which had integrated colours available in Harris (1996). For comparison, we list the colour of a SSP of 13 Gyr with $Z=0.001$, the typical metallicity of old GCs, in the last row. The reddening-corrected colours of MW GCs agree within 0.1 mag with these SSP colours.

The mode is systematically bluer than the mean in all the three colours in our sample galaxies as well as in the MW. This difference is due to a noticeable skewness in the colour distributions, with the peak (mode) occurring on the bluest bin in $(B-I)_0$ and $(V-I)_0$, in all cases except in M81. The skewness is not due to a colour cut we have...
used to define GCs. In fact the choice of the cut-off colour between SSCs and GCs corresponds to the saddle point in the distribution of colours of all cluster candidates (see Figure 7), with the peak in the GC colours occurring in the first or second bin redward of the saddle point. We analyse the possible role of contaminants in our GC samples to the origin of skewness in colour distributions. For this, we use the fraction of contaminants as a function of colour (see left panel in Figure 10) to correct statistically the \((B-I)_0\) colour histogram, which is shown in Figure 14 in magenta. The contamination-corrected histograms maintain the blue skewness in the distribution. This suggests that the skewness in colour distribution is an intrinsic property of the GC systems.

The mean and mode colours of our GC systems should correspond to SSP colours of metal-poor old clusters, if reddening is negligible. We find that the mode is only marginally redder than the colours of the metal-poor SSPs at old ages, whereas the mean is much redder. The redward shift of the mode from the expected SSP colours and the long red tail of the colour distribution, even for the MW sample, illustrate that the GC colours are often reddened by dust. The typical reddening experienced by GCs in each of our sample galaxies can be determined by comparing the mode of the colour distribution with the colour of the metal-poor old SSPs. We made use of the \((B-I)_0\) colour to obtain the colour excess \(A_V(\text{int}) = \left[(B-I)_0 - (B-I)_{\text{SSP}}\right]/(E_B - E_I),\)

where \((B-I)_{\text{SSP}}\) is the \((F435W - F814W)_0\) colour of the SSP, \(E_B = 1.33\), and \(E_I = 0.60\) are the values of the the Cardelli et al. (1989) extinction curve at the effective wavelengths of \(B\) and \(I\)-bands. The resulting values of \(A_V(\text{int})\) using mean and mode are given respectively in columns 8 and 9 of Table 9. The \(A_V(\text{int})\) obtained from the mode for our galaxies range from 0.01 (NGC 628) to 0.32 mag (M81) which is comparable to the 0.17 mag for the MW. The \(A_V(\text{int})\) values obtained from the mean colours vary between 0.60 (NGC4 258) to 1.23 (M101), which is also comparable to the 1.04 mag for the MW.

The difference between the mean and median \(A_V\) values is ~0.5−1.0 in our sample galaxies, which is comparable to that for the Milky Way (0.87). Thus, GC systems in spiral galaxies experience relatively large mean extinctions. In fact, this is one of the reasons for the slow progress in establishing the properties of the GC systems in spiral galaxies. Some of the reddening could be due to dust internal to the clusters, whereas the majority is expected due to the dust along the line of sight in the disk of the host galaxy. The colour histogram in M101 shows a second peak at \((B-I)_0 \sim 3.5\) mag after correction for contaminants, suggesting the presence of a distinct red population. The analysis of LF below also suggests the presence of a population fainter than GCs. As we will see in Section 5.4, this population of faint red clusters corresponds to reddened intermediate-age (1−10 Gyr) SSCs. Under such a scenario, the basic assumption we have made in determining \(A_V\), namely the clusters are old (> 10 Gyr) is not applicable to all clusters in M101 and hence the \(A_V(\text{mean})\) would be an upper limit for this galaxy.

### 5.2 Luminosity function

We chose the Galactic extinction-corrected magnitudes in the F814W band to construct the GCLF. For this purpose, we constructed histograms in bins of 0.5 mag over the entire range of detected magnitudes for each galaxy. The resulting histograms are shown in Figure 15 with red solid lines. The magnitudes corresponding to 50% completeness, \(m_{50}\), at low and high surface brightness parts of for each galaxy are shown by dotted and dashed vertical lines, respectively. The observed numbers are corrected for incompleteness using the mean function shown in Figure 12. The corrected histograms are shown by gray bars. As expected, the correction factor is negligible at the bright end \((F814W \lesssim 21\) mag), and gradually increases at fainter magnitudes.

The GCLFs in the five galaxies show very similar form, increasing smoothly up to reaching a peak value, and then again decreasing smoothly. In other words, all our sample galaxies show a turnover, the TO. The TO values lie on the brighter side of \(m_{50}\) in all galaxies. The incompleteness-corrected histograms are fitted with a log-normal function given by:

\[
dN/dM = N_0 e^{-(M-M_0)/(2\sigma_M^2)},
\]

where \(N_0\) is a normalization factor, \(M\) is the absolute magnitude of the fitted bin, \(M_0\) is the absolute magnitude of TO and \(\sigma_M\) is the dispersion. It can be seen that the log-normal functions are good fits to the observed LFs.

We obtained the TO magnitude after correcting the LF in each galaxy for a possible contribution from the contaminants. Following the discussions in Section 3.5, we used the...
Table 10. Number of GCs and best-fit values for a log-normal distribution.

| Galaxy   | N_{GC}  | TO   | ∆TO  | σ_M  | ∆σ   | M_{14}^{st} | M_{14}^{rd} |
|----------|---------|------|------|------|------|-------------|-------------|
| (1)      | (2)     | (3)  | (4)  | (5)  | (6)  | (7)         | (8)         |
| M81      | 126     | 128±13 | 177±15 | 19.56±0.12 | -8.42±0.13 | -7.52±0.16 | -1.04±0.17 | -0.11 | -11.66 | -10.84 |
| M101     | 764     | 1325±60 | 1891±70 | 22.16±0.05 | -7.14±0.08 | -6.24±0.13 | 1.16 | 0.89±0.05 | -0.26 | -11.57 | -10.10 |
| NGC4258  | 147     | 166±31 | 290±51 | 21.19±0.11 | -8.26±0.11 | -7.36±0.15 | 0.04 | 0.97±0.15 | -0.18 | -11.57 | -11.40 |
| M51      | 220     | 261±24 | 536±44 | 21.44±0.07 | -8.34±0.07 | -7.44±0.12 | -0.04 | 0.64 ± 0.05 | -0.51 | -10.76 | -10.35 |
| NGC628   | 149     | 151±16 | 259±18 | 21.75±0.05 | -8.21±0.06 | -7.31±0.12 | 0.09 | 0.60±0.07 | -0.55 | -11.66 | -10.23 |

Notes: (1) Galaxy name. (2) Number of GCs after correcting for contamination from reddened SSCs. (3) Column 2 after correcting for incompleteness in magnitude. (4) Estimated total number of GCs determined using Equation 6. (5) Observed TO magnitude in MNRAS Table 10. The differences are well within 1σ of the TO magnitudes for our sample galaxies have the same TO as that in the MW. In all these four galaxies, Hence, the GCLFs in four of our sample galaxies have the same TO as that in the MW. In comparison, M31 value of M_{V} = −7.41 ± 0.14 mag. For obtaining the TO, we have used the distances tabulated in Table 1. The tabulated distances correspond to the most recent determination of distances using Cepheids for M81 and M101, and the MASER distance for NGC 4258. For M51 and NGC 628, SNII distances were used.

Using only the distances reported after the year 2000 in NED, we found 56 independent measurements for M81, 79 for M101, 77 for NGC 4258, 27 for M51 and 23 for NGC 628. The methods of distance measurements include those using Cepheids, MASER, tip of the red giant branch (TRGB), SNII-optical, and Tully-Fisher. We recalculated TO values for each of these measured distances, which are shown plotted against the corresponding distances in Figure 17. The value of TO for the best-determined distance (that in Table 1) is indicated by a thick circle, which is colour-coded according to the method that was used to estimate the distance, or an intrinsically different value of TO.

5.3 Distance errors and the universality of the TO

For obtaining the TO, we have used the distances tabulated in Table 1. The tabulated distances correspond to the most recent determination of distances using Cepheids for M81 and M101, and the MASER distance for NGC 4258. For M51 and NGC 628, SNII distances were used.

Using only the distances reported after the year 2000 in NED, we found 56 independent measurements for M81, 79 for M101, 77 for NGC 4258, 27 for M51 and 23 for NGC 628. The methods of distance measurements include those using Cepheids, MASER, tip of the red giant branch (TRGB), SNII-optical, and Tully-Fisher. We recalculated TO values for each of these measured distances, which are shown plotted against the corresponding distances in Figure 17. The value of TO for the best-determined distance (that in Table 1) is indicated by a thick circle, which is colour-coded according to the method that was used to estimate the distance, or an intrinsically different value of TO.

7 https://ned.ipac.caltech.edu/
8 https://ned.ipac.caltech.edu/bynam?objname=m81&hconst=67.8&omegamon=0.308&omegav=0.692&umap=4&crrors=1
9 https://ned.ipac.caltech.edu/bynam?objname=m101&hconst=67.8&omegamon=0.308&omegav=0.692&umap=4&crrors=1
10 https://ned.ipac.caltech.edu/bynam?objname=ngc4258&hconst=67.8&omegamon=0.308&omegav=0.692&umap=4&crrors=1
11 https://ned.ipac.caltech.edu/bynam?objname=m51&hconst=67.8&omegamon=0.308&omegav=0.692&umap=4&crrors=1
12 https://ned.ipac.caltech.edu/bynam?objname=ngc628&hconst=67.8&omegamon=0.308&omegav=0.692&umap=4&crrors=1
13 https://ned.ipac.caltech.edu/bynam?objname=ngc628&hconst=67.8&omegamon=0.308&omegav=0.692&umap=4&crrors=1
Figure 15. Best log-normal fits to the observed $F_{814W}$-band luminosity functions of GCs in our 5 sample galaxies. The data before (red histograms) and after (magenta-filled histograms) correction for possible contamination from reddened young SSCs are shown in the left and right panels, respectively. In each panel, fits were carried out to the completeness-corrected dataset (gray-filled histograms). Poisson error bars ($\sqrt{N}$) are indicated. The vertical dot and dashed lines indicate the magnitude at which the detection is 50% complete at low and high surface brightness parts of the galaxies, respectively. For reference, the turnover magnitude for the MW GCs is indicated in each plot by the blue vertical bar. The horizontal axes in the bottom and top contain observed and absolute magnitudes, respectively.

obtain the distance. The error on this best measurement is highlighted by the gray band. Most of the distance measurements for the 4 galaxies (M81, NGC4258, M51 and NGC628) agree with the value obtained by our best distance estimate, after taking into consideration the errors on each of them. In M101 where we found TO value fainter by 1.16 mag, some of the Cepheid distances are not consistent with the Cepheid distance (6.95 Mpc) we have used. If we use the farthest distance reported for this galaxy (8.99 Mpc, Macri et al. 2001), the TO value is still 8σ fainter than the universal value we have in other galaxies. Hence, we conclude that the TO value in M101 is intrinsically fainter compared to that in other galaxies of our sample, and investigate the possible physical reasons for this difference.

5.4 TO magnitude in M101 and late-type galaxies

Among the galaxies analysed in this study, M101 stood out from the rest for having a fainter derived TO value, as well as for having a large population of very red clusters ($(F_{435W} - F_{814W}) > 2.2$ mag), including a second peak at $(F_{435W} - F_{814W}) > 3.5$ mag in its colour distribution (Figure 14). We here discuss whether these differences are related to its late morphological type (Scd). In Figure 18, we plot the TO values with respect to that in the MW as a function of the morphological type of the host galaxies. In this plot, we include the MW, M31 and the Large Magellanic Cloud (LMC). We estimated the TO in the LMC using data from Mackey & Gilmore (2003) for clusters with age $\geq 1$ Gyr. TO values in all galaxies with morphological type Sc or earlier are in agreement with the value in the MW within the errors of measurements. The two galaxies later than Sc deviate from this trend. Thus, there is an indication that the different TO value found in M101 is indeed related to its late morphological type. In the following paragraphs, we discuss a possible scenario that naturally explains the fainter TO in late-type galaxies.

Classical GCs are among the oldest objects in galaxies, and their formation is related to the formation of halo and bulge (Brodie & Strader 2006). By definition, the prominence of these spherical components in galaxies decreases along the Hubble sequence. For this very reason, most of the searches of GCs were traditionally carried out in elliptical and early-type galaxies. Such studies have found relatively larger population of classical GCs in ellipticals as compared to that in spiral galaxies (e.g., Harris & Harris 2011; Harris et al. 2013). On the other hand, M101 has a weak bulge,
Luminosity functions of globular clusters

Figure 17. Dependence of the measured TO (circle) on the distance uncertainties. The measurement error on TO is shown by the width of the vertical gray band. Symbols in each plot are colour-coded depending on the method of distance determination.

classified as a pseudobulge by Kormendy et al. (2010), and a very poor stellar halo population (Jang et al. 2020), as expected for its late morphological type. These late-type systems are not expected to contain a large population of classical GCs. However, searches of GCs on HST images, including this study, find as many GCs in late-type galaxies as in early-type spirals. It is likely that not all the inferred GCs in late-type galaxies are classical GCs. We analyse this issue below.

Spiral and irregular galaxies are known to contain old SSCs that were formed in their disks and have survived the tidal shocks of their host galaxies. For example, González-Lópezlira et al. (2019) found that some of the objects classified as GCs in NGC 4258, one of the galaxies analysed in our study, belong to its disk and share the same kinematics as the disk HI gas. Formation and growth of galaxies through hierarchical merging, expects formation of such clusters during every epoch of merger involving gas-rich galaxies (Mamikonyan et al. 2017). The selection filters used for GC searches on HST and ground-based images do not distinguish these old stellar clusters from the classical GCs. Thus generally speaking the sample of objects observationally classified as GCs contains two kinds of objects, classical GCs related to the spherical component of galaxies, and old disk star clusters, formed in-situ or accreted onto, during galaxy mergers as part of the hierarchical growth of galaxies. It is the former one that is expected to have universal TO. The fraction of old star clusters is expected to increase towards later Hubble types as they are more gas-rich than the early types. Hence, the TO obtained in early-type spirals represents that of the classical GCs, whereas in late-type galaxies it represents the population of old SSCs in the disk. This is found to be true in the LMC, where 50% of the old cluster population that is used to obtain the TO has ages in the 1–10 Gyr range.

In Section 3.5, we have estimated the contamination fraction from reddened SSCs in our sample of GCs in each galaxy, using the photometry in the U-band. The technique we have used helps to distinguish reddened SSCs from GCs only for SSCs younger than \( \sim 3 \) Gyr. Thus, our GC samples, in principle, contain all clusters older than \( \sim 3 \) Gyr. The universality of the TO in all our galaxies earlier than Sc, suggests that these early-type spirals did not form significant amount of SSCs after the formation of halo and bulge, or even if they are formed, they did not survive the gravitational shocks.

The GC population in M101 has been the subject of study by Simanton et al. (2015). They found a total of 326 candidate GCs, with their luminosity function matching very well the LF for the Galactic GCs, but starts increasing
rapidly for $M_V \geq -6.5$ mag. They identified these relatively fainter faint clusters as belonging to a second population, which is statistically more extended than the brighter population, the so-called faint fuzzies (e.g., Larsen & Brodie 2000b; Brodie & Larsen 2002; Peng et al. 2006; Liu et al. 2016). They discuss these red extended clusters as old stellar clusters formed in the disk. Only 98 (i.e. 30%) of their clusters belonged to the brighter population, the classical GCs. Our selection criteria, which selects objects 2.4<FWHM<10 pixel, naturally rejects extended objects that Simanton et al. (2015) have found, but contains compact objects fainter than their magnitude cut of $M_V \geq -6.5$ mag. The fainter TO we have found suggests that our sample is dominated by a population of red faint compact clusters of ages between $\sim$1–10 Gyr. These properties correspond to relatively low-mass reddened SSCs in the disk of M101.

### 5.5 Physical parameters that control TO

The TO magnitude of a GC system is controlled by four physical parameters, namely, the mass function (MF) at birth, age, metallicity and internal extinction. In addition to these, a dynamical process changes the form of the mass function as the clusters evolve under the gravitational potential of their parent galaxies. At ages greater than a few billion years, dynamical evolution is mass-dependent, which leads to selective destruction of low-mass clusters. In general, a cluster of mass $M_{cl}$ loses all its mass over a time-scale, $t_{\text{dis}}$, given by,

$$t_{\text{dis}} = t_4 \left( \frac{M_{cl}}{10^5 M_\odot} \right)^{\gamma},$$

where $t_4$ is the destruction time for a cluster of $10^5 M_\odot$ under a specific gravitational potential, and the power-law index $\gamma$ is found to have a value of 0.6 (Boutloukos & Lamers 2003). The $t_4$ is expected to be shorter in strong gravitational field, such as massive early-type galaxies, and longer, in low-mass late-type galaxies. Fall & Zhang (2001) found that the net result of the dynamical evolution is to create a MF that is log-normal, like the one found in our study, almost independent of the initial form of the MF. The turnover of the resulting MF is shifted to higher masses, equivalently to brighter magnitudes, in early-type galaxies, as compared to the late-type galaxies. Thus, even if the four physical parameters are the same for all GC systems, dynamical evolution alone can introduce dispersion in the observed TOs in different galaxies. The TO is also shifted to higher masses (brighter magnitudes) at longer ages due to dynamical effects.

Using our TO absolute magnitude in the F814W filter, corrected for internal and Galactic extinction ($M_{\text{TO}}^{F814W_0}$), we can determine the TO mass of the cluster in our sample of galaxies using an SSP of age and metallicity typical of GCs.

$$\log M = -0.4 \times (M_{\text{TO}}^{F814W_0} - M_{\text{SSP}}^{F814W}),$$

where $M_{\text{SSP}}^{F814W}$ is the F814W magnitude of an SSP at 13 Gyr for a total mass of 1 $M_\odot$. The resulting mass values for two of the lowest metallicities ($Z=0.0004=1/50$ solar and $Z=0.001=1/20$ solar) are given in Table 11. The derived masses are 3% higher for $Z=0.0004$ as compared to that obtained using $Z=0.001$. In the four galaxies with almost universal TO, the mass corresponds to $\sim 3 \times 10^5$ $M_\odot$, whereas it is lower by a factor two in M101. The disk clusters of M101 are expected to be younger than the uniform age of 13 Gyr we have used. If they are as young as 8 Gyr, the masses will be further lower by $\sim$30%.

### 5.6 Total number of Globular Clusters and Specific frequency

GC searches in external galaxies using HST data are subjected to two kinds of incompleteness: (i) magnitude incompleteness arising due to the missing low-luminosity GCs beyond the detection limit, and (ii) area incompleteness due to non-coverage of outer-halo GCs because of the limited FoV of HST. The alternative strategy of searching GCs in wide-field ground-based surveys also suffers from these two effects, with the second effect arising due to confusion with stellar sources in the inner regions due to lack of spatial resolution. Characterization of the LF and the radial number density distributions with analytical functions, allows us to calculate the total number of GCs by integrating over the

| Galaxy | Z    | Age Gyr | $M_{cl}/M_\odot$ | $\sigma$ | $\log M$ |
|--------|------|---------|-----------------|---------|---------|
| M81    | 0.0004 | 13.0    | 5.58            | 0.05    |         |
| M101   | 0.0004 | 13.0    | 5.07            | 0.03    |         |
|        | 0.001  | 13.0    | 5.06            | 0.03    |         |
| NGC4258| 0.0004 | 13.0    | 5.52            | 0.04    |         |
|        | 0.001  | 13.0    | 5.51            | 0.04    |         |
| M51    | 0.0004 | 13.0    | 5.55            | 0.02    |         |
|        | 0.001  | 13.0    | 5.54            | 0.02    |         |
| NGC628 | 0.0004 | 13.0    | 5.53            | 0.04    |         |
|        | 0.001  | 13.0    | 5.52            | 0.04    |         |

Figure 18. TO$_V$–TO$_{MW}$ vs the Hubble Type of host galaxies. The plot includes our 5 sample galaxies, and other spiral (M31) and irregular (LMC) galaxies where such measurements are available. The error in the MW TO is indicated by the width of the gray band.
entire range of these functions. We carry out these integrations in two steps, as explained below.

First, we integrate over the fitted GCLF to obtain the number corrected for the missing low-luminosity GCs, which are given in column 3 of Table 10. We define the missing factor, \( f_{LF} = N_{GC}(LF)/N_{GC,\text{obs}} \). In order to correct for the GCs outside our FoV, we counted the number of GCs within \( R_e \). By definition, total number of detectable GCs is twice this number. The total number of GCs, corrected for contamination from reddened SSCs, and incompleteness both in luminosity and volume is:

\[
N_{GC,\text{TOT}} = f_{LF} \times 2 \times N_{GC,R_e}.
\]

Table 12. Specific frequency.

| Galaxy   | \( S_N \)   | \( S_{N,TOT} \) |
|----------|-------------|-----------------|
| M81      | 0.46±0.10   | 0.64±0.10       |
| M101†    | 2.16±0.46   | 5.35±0.82       |
| NGC 4258 | 0.57±0.26   | 1.12±0.30       |
| M51      | 0.61±0.17   | 1.48±0.22       |
| NGC 628  | 0.75±0.17   | 1.30±0.24       |

†Values estimated assuming the universality of TO applies to M101 are 0.47±0.27 and 0.94±0.33.

6 CONCLUSIONS

We used the HST images of five nearby spiral galaxies for which there are data taken with multiple pointings with ACS to enable a search of GCs in them. Images in F435W, F555W and F814W filters were used. We used SExtractor and a set of cluster-defining filters to define a sample of GCs in each of the analysed galaxies. Detection of simulated clusters was carried out to obtain the incompleteness as a function of magnitude. We used the U-band photometry for a subset of sample GCs using the SDSS u-band images for M81 and HST/WFC3 F336W images for the rest to evaluate the contamination of our GC samples by reddened SSCs. The contaminating fraction was found to be between 0.14–0.35. We used the dataset to construct luminosity function of GCs in spiral galaxies.

We find that the LF of GCs in all the five galaxies analysed is log-normal in nature, with the turn-over (TO) happening on the brighter side of the 50% incompleteness limit in all galaxies. This has enabled us to determine precise TO magnitudes for our sample of galaxies. We also determined typical internal extinction towards the population of GCs in our sample galaxies by comparing the mode of the observed colours with that from population synthesis models for a metal-poor (metallicity = 1/20 solar) population of SSCs. We hence made an alternative estimation of \( S_N \) assuming that the true GC population in this galaxy also has the universal TO. We hence counted the number of GCs brighter than \( M_V = -7.40 \) mag, and doubled that number to calculate \( N_{GC,\text{TOT}} \). The empty symbol for M101 in the figure corresponds to this revised \( S_N \). The mean value for our sample, including the revised value of M101 is ~1.10±0.24, which occupies a much smaller range as compared to the values for spiral galaxies from the compilation of Harris et al. (2013) (open circles). The large spread in the latter sample is expected as they are based on studies using very different detection and analysis techniques from Fischer et al. (1990), Harris (1996), Kissler-Patig et al. (1999), Harris & Harris (2000), Goudfrooij et al. (2003), Olsen et al. (2004), Rhode & Zepf (2004), Rhode et al. (2007), Di Nino et al. (2009), Mora et al. (2009), Nantais et al. (2010a), Peacock et al. (2010), Rhode et al. (2010), Adamo et al. (2011) and Young et al. (2012).
propose that this difference in \( M_{V_0}(TO) \) arises due to morphological differences, with spiral galaxies of the Hubble types Sc or earlier having a universal \( M_{V_0}(TO) \), whereas the Hubble types later than Sc have fainter \( M_{V_0}(TO) \). The universality of \( M_{V_0}(TO) \) in early-type spirals is due to the classical GCs dominating the GC population, whereas in late-type spirals GC population is often dominated by old disk clusters, which are in general less massive, and hence fainter than the classical GCs, but otherwise share the same observational properties as the classical GCs. The universal \( M_{V_0}(TO) \) is a function of GC colour. Taking into account the errors that the correction factor for contaminating reddened SSCs suggests us to carryout corrections for possible contamination of our GC samples from reddened young clusters.

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DATA AVAILABILITY

The data underlying this article are available in the article and in its online supplementary material.

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ISO (top row) and AREA (bottom row) of HLA catalogues, which are systematically fainter and from a HST system (SOURCE), to a TARGET system (T), by:

\[ TMAG = SMAG + F - 2 \times TCOL \]

where \( F \) and \( TCOL \) are colour terms in the Johnson-Cousins and Bessell systems, respectively. However, HLA MAG is from the Bessell system, and hence the observed differences in fields 02, a2, and 11 of M101 can be understood in terms of an underestimate of background in the HLA catalogues.

The distribution of the SExtractor parameters available at HLA coincided with that obtained from our own runs of SExtractor for all other frames where we made a comparison. However, in order to ensure uniform analysis of all sample galaxies, we downloaded the fits files and generated our own catalogues for each frame. The discussion presented here serves as a cautionary note while planning to use the HLA catalogues for quantitative scientific studies.

**APPENDIX B: TRANSFORMATION TO JOHNSON-COUSINS SYSTEM**

Majority of the photometric data for GCs in the MW and external galaxies are reported in the standard Johnson-Cousins $UBVRI$ system (Bessell 1990). Hence, in order to compare the results obtained from our study to that obtained in other galaxies, it is necessary to transform our $F435W$, $F555W$ and $F814W$ magnitudes and colours into the standard system. The corresponding transformation equations are discussed in detail by Sirianni et al. (2005). The transformation from a HST system (SOURCE), to a TARGET system (T), in our case, the Johnson-Cousins $UBVRI$ system, is given by:

\[ TMAG = SMAG + c_0 + c_1 \times TCOL + c_2 \times TCOL^2 \]  

where SMAG and TMAG are the magnitudes in the source and target systems, respectively, $TCOL$ is the colour in the Johnson-Cousins system.

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Figure A1. Frames covering M101 with incorrect values of AREA and MAG ISO values in the source catalogues of HLA. The frame numbers for set are indicated. Dashed histograms show the values from the HLA catalogues, whereas the solid histograms show values from our catalogue, using the same SExtractor input file as for the HLA catalogue.

Table B1. Transformation coefficients between HST and Johnson-Cousins systems.

| HST   | UBVRI TCOL | c1         | c2         | Range  |
|-------|-------------|------------|------------|--------|
| F435W | B           | B − I      | 0.022 ± 0.006 | −0.038 ± 0.011 | <1.0 |
| F435W | B           | B − I      | 0.008 ± 0.006 | −0.005 ± 0.001 | >1.0 |
| F555W | V           | B − V      | −0.083 ± 0.032 | 0.020 ± 0.115 | <0.2 |
| F555W | V           | B − V      | −0.087 ± 0.007 | 0.004 ± 0.002 | >0.2 |
| F814W | I           | B − I      | 0.013 ± 0.006 | −0.028 ± 0.112 | <0.3 |
| F814W | I           | B − I      | −0.010 ± 0.010 | −0.006 ± 0.002 | >0.3 |
| F606W | V           | B − V      | 0.170 ± 0.005 | 0.061 ± 0.002 | ... |

target system in the chosen bands, $c_0$ is the zeropoint, which is taken from Table 2 for the respective frames, $c_1$ and $c_2$ are the first and second order colour coefficients, whose values for the colour ranges of interest in this study are given in Table B1. Since TCOLs are in the TARGET system, their values are assumed to be the same as in the HST system to start with, which are updated iteratively, until the value of TCOLS converges.