Star clusters: basic galactic building blocks
Proceedings IAU Symposium No. 266, 2009
R. de Grijs & J. R. D. Lépine, eds.

doi:10.1017/S1743921309991827

Washington photometry of five star clusters in the Large Magellanic Cloud

Andrés E. Piatti,[1] **Doug Geisler,**[2] **Ata Sarajedini**[3] **and Carme Gallart**[4]

[1]Instituto de Astronomía y Física del Espacio, CC 67, Suc. 28, 1428, Ciudad de Buenos Aires, Argentina
email: `andres@iafe.uba.ar`

[2]Grupo de Astronomía, Departamento de Astronomía, Universidad de Concepción, Casilla 160-C, Concepción, Chile
email: `dgeisler@astro-udec.cl`

[3]Department of Astronomy, University of Florida, PO Box 112055, Gainesville, FL 32611, USA
email: `ata@astro.ufl.edu`

[4]Instituto de Astrofísica de Canarias, Calle Vía Láctea, E-38200, La Laguna, Tenerife, Spain
email: `carme@iac.es`

Abstract. We present CCD photometry in the Washington-system C and T_1 passbands down to $T_1 \sim 22.5$ mag in the fields of NGC 1697, SL 133, NGC 1997, SL 663, and OHSC 28, five mostly unstudied star clusters in the LMC. Cluster radii were estimated from star counts in appropriately sized boxes distributed throughout the entire observed fields. We perform a detailed analysis of field-star contamination and derive cluster colour–magnitude diagrams (CMDs). Based on the best fits of isochrones computed by the Padova group to the ($C - T_1$,T_1) CMDs, the $\delta(T_1)$ index and the 'standard giant-branch' procedure, we derive metallicities and ages for the five clusters. With the exception of NGC 1697 (age = 0.7 Gyr, [Fe/H] = 0.0 dex), the remaining four clusters are of intermediate age (from 2.2 to 3.0 Gyr) and relatively metal poor ([Fe/H] = −0.7 dex). We combine our sample with clusters with ages and metallicities on a similar scale and examine relationships between position in the LMC, age and metallicity. We confirm previous results that clusters younger than ∼ 1 Gyr were formed during an outside-in process; this occurred after a burst of cluster formation that took place mainly in the outer disk and peaked ∼ 2 Gyr ago. Finally, the cluster and field age–metallicity relations (AMRs) show evidence for a metallicity offset but do overlap, particularly on the upper-envelope side of the cluster AMR.

Keywords. galaxies: individual (Large Magellanic Cloud), galaxies: star clusters, techniques: photometric

1. Estimates of the fundamental parameters of the LMC clusters

Figure 1a shows the observed colour–magnitude diagram (CMD) of NGC 1697. To construct the cluster radial profiles, we computed the number of stars per unit area at a given radius, r, as is shown in Figure 1b. We then estimated background levels, the radii of the FWHM ($r_{\rm FWHM}$), and the cluster radii ($r_{\rm cl}$). Cluster dimensions are relatively small: four of the clusters have FWHMs between 50 and 110 pixels, while that of OHSC 28 is only 25 pixels, and they fade into the stellar field populations at a distance of twice or three times $r_{\rm FWHM}$.

Figure 2a shows the $r_{\rm cl}$-extracted CMD for SL 663 (upper right). We also show a close-up schematic finding chart of the cluster. We statistically cleaned the cluster CMDs of stars that can potentially belong to the foreground field or have relatively large $\sigma(C-T_1)$. The resulting SL 663 field CMD is shown in the bottom left panel of Figure 2a. We then

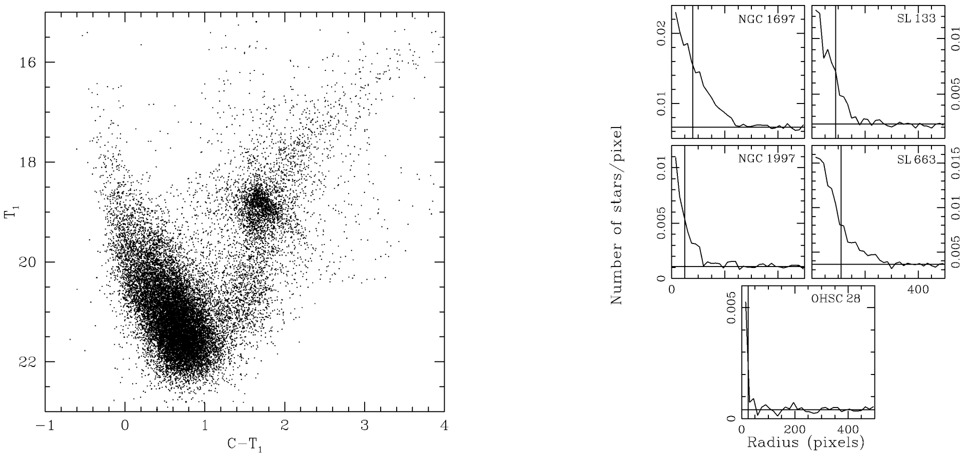

Figure 1. *(a)* $(C-T_1,\ T_1)$ colour–magnitude diagram of all measured stars in the field of NGC 1697. *(b)* Stellar density profiles of the selected clusters. The horizontal lines correspond to the background levels far from the clusters, while the vertical lines indicate $r_{\rm FWHM}$.

subtracted from each cluster CMD, for different bins with sizes $[C-T_1, T_1] = (0.5,\ 0.2)$ mag, the corresponding number of stars counted in the field CMDs. In the bottom right panel of Figure 2a, we show the CMD of the remaining cluster stars. In the subsequent analysis, we use these CMDs to estimate the fundamental parameters of each cluster.

Cluster reddening values were estimated by interpolating the extinction maps of Burstein & Heiles (1982). As for the cluster distance moduli, we adopt for all the clusters a value for the LMC distance modulus of $(m-M)_0 = 18.50 \pm 0.10$ mag. We then selected a set of isochrones and superimposed them onto the cluster CMDs, once they were properly shifted. Finally, we chose the isochrone which best reproduces the cluster's main features. Figure 2b shows the results of the isochrone fits. We also derived the ages of the four clusters older than 1 Gyr from the $\delta(T_1)$ index—calculated by determining the difference in T_1 magnitude between the red-giant clump and main-sequence turnoff in the cluster CMD—and equation (4) of Geisler *et al.* (1997). We then averaged the ages obtained from the isochrone fits and those derived from the $\delta(T_1)$ index since they are in very good agreement.

We followed the 'standard giant-branch' (SGB) procedure of inserting absolute M_{T_1} magnitudes and intrinsic $C-T_1$ colours for the clusters into figure 2 of Geisler & Sarajedini (1999) to obtain (by interpolation) the clusters' metal abundances ([Fe/H]). These derived metallicities were corrected for age effects using the prescription given in Geisler *et al.* (2003). The corrected metallicities for the cluster sample show excellent agreement with the Z values of the isochrones which best resemble the cluster features. Olszewski *et al.* (1991) and Grocholski *et al.* (2006) found $[\mathrm{Fe/H}] = 0.43 \pm 0.20$ dex and 0.54 ± 0.05 dex for NGC 1997 and SL 663, respectively, from the spectra of three and eight stars taken at the infrared Ca II triplet. Bearing in mind our metallicity error and that of Grocholski *et al.* (see also their figure 12), we find good agreement between both estimates of SL 663's metal abundance.

2. Analysis of cluster chemical evolution in the LMC

To investigate the chemical evolution of the LMC, we added the clusters studied here to a list of 54 selected LMC clusters. We plot in Figure 3a the cluster ages and metallicities as a function of their deprojected angular distance for four metallicity intervals, [Fe/H]

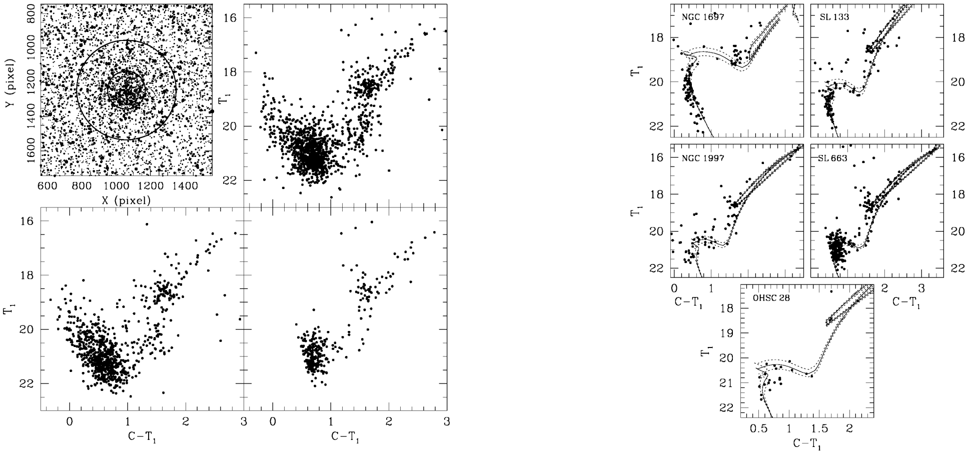

Figure 2. *(a)* Schematic finding chart of SL 663 *(upper left)*, with three extracted CMDs (see text for details). *(b)* $(C-T_1,\, T_1)$ CMDs for the selected star clusters. Isochrones from Girardi *et al.* (2002) are overplotted. The solid and dashed lines correspond to the derived cluster ages and to the ages taking into account their associated errors.

< -1.20 (pentagons), $-1.20 \leqslant$ [Fe/H] $\leqslant -0.80$ (□), $-0.80 <$ [Fe/H] < -0.4 (○) and [Fe/H] $\geqslant -0.4$ dex (△), respectively. We included, in the upper panel, an enlargement for young clusters with deprojected distances $< 6°$. The bottom panel of Figure 3a reveals that the most metal-rich clusters are preferentially located in the inner disk, where they were probably formed, since most are younger than 1 Gyr (see top panel). In contrast, clusters with [Fe/H] < -0.5 dex exist across the entire disk out to 10°. Thus, the distance from the galaxy centre alone does not appear to be the main variable describing the cluster spatial–metallicity relationship. Our result agrees with Grocholski *et al.* (2006). However, in contrast to our Figure 3, they found that clusters with [Fe/H] > -1.0 dex show a tight distribution ([Fe/H] $= -0.48 \pm 0.09$ dex), with no tail towards solar metallicities. According to the metallicity distribution of our larger cluster sample, we find a noticeable peak at [Fe/H] ~ -0.7 dex and a notable concentration of more metal-rich clusters.

The top panel of Figure 3a shows that the most metal-poor clusters are also the oldest ones in the LMC, as expected. There also exists a quiescent period of cluster formation between 11 and 3 Gyr ago, before a large number of intermediate-age clusters (IACs) were mainly formed in the outer disk, starting ~ 3 Gyr ago. The enlargement in the top panel shows that subsequent cluster formation has been concentrated to the inner disk. Indeed, here a possible gradient exists, in which the younger clusters are formed closer to the galaxy centre. We find in this last result a hint for an outside-in cluster-formation scenario. Note that this putative outside-in formation took place in the inner disk after the burst formation process was triggered mainly in the outer disk beginning ~ 3 Gyr ago.

Figure 3b shows the resulting age–metallicity relation (AMR), where open circles represent individual clusters, while filled triangles and circles represent average metallicities, for a sample of stars in the bar (Cole *et al.* 2005) and the disk field (Carrera *et al.* 2008), respectively. From the metal-poor end of the AMR, we find that several old clusters have [Fe/H] $\leqslant -2.2$ dex, while the mean metallicity of the poorest field stars reaches [Fe/H] $= -1.4$ dex. Even so, there are also old clusters within the metallicity range of the oldest field-star populations. Towards the region of the IACs, we find a similar behaviour of

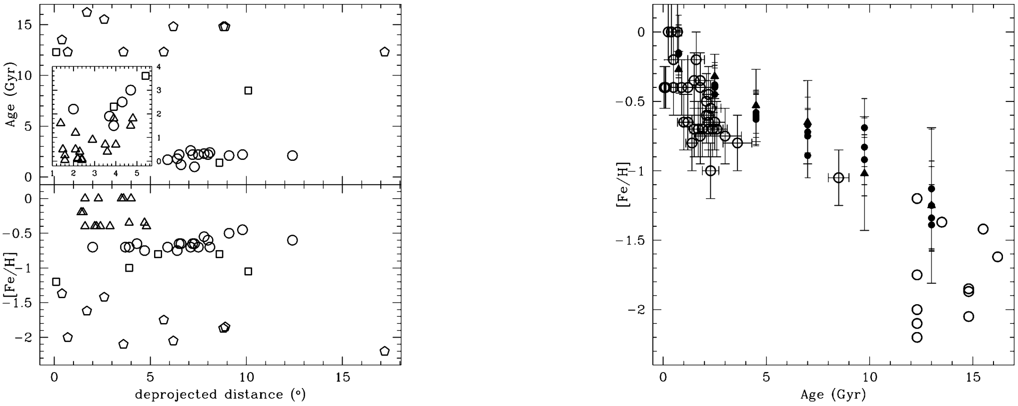

Figure 3. *(a)* Relationships between LMC cluster ages and metallicities and the deprojected distance for [Fe/H] < −1.20 (pentagons), −1.20 < [Fe/H] < −0.80 (□), 0.8 < [Fe/H] < −0.4 (◯) and [Fe/H] > −0.4 dex (△). *(b)* Age–metallicity relation for LMC clusters (open circles) and that derived by Carrera *et al.* (2008) for the LMC bar (filled triangles) and disk (filled circles) systems.

cluster and field-star abundances in the sense that the field-star metallicities tend to delimit the upper envelope of the cluster metallicities. The offset between the clusters and the field population may reflect a metallicity-scale difference. For ages younger than 1 Gyr, it seems that clusters and field stars share, on average, similar metallicity ranges. Note that in the cluster age gap, the only cluster present is at the metal-poor end of the field-star distribution. This result agrees, in turn, with theoretical models that suggest the bar and IACs formed as a result of a close encounter with the Smal Magellanic Cloud 4 Gyr ago (Bekki & Chiba 2005). In this scenario, that encounter peaked ∼ 2 Gyr ago and triggered the formation of a large number of clusters in both Magellanic Clouds (MCs). Recently, Bekki (2008) proposed that the MC system has a common halo, produced either by dynamical coupling that started ∼ 4 Gyr ago or by a remnant of a small group of galaxies destroyed through tidal stripping by the Galaxy. Unfortunately, we cannot favour either of these suggested scenarios based on the available cluster data. However, since the AMR for the open clusters in the Galaxy does not show enhanced cluster formation like that which occurred in the MCs 2 Gyr ago, perhaps both MCs have been interacting more like members of a binary system than isolated entities of a group of galaxies which includes the Milky Way.

References

Bekki, K. 2008, *ApJ* (Letters), 684, L87

Bekki, K. & Chiba, M. 2005, *MNRAS*, 356, 680

Burstein, D. & Heiles, C. 1982, *AJ*, 87, 1165

Carrera, R., Gallart, C., Hardy, E., Aparicio, A., & Zinn, R. 2008, *AJ*, 135, 836

Cole, A. A., Tolstoy, E., Gallagher III, J. S., & Smecker–Hane, T. 2005, *AJ*, 129, 1465

Geisler, D., Bica, E., Dottori, H., Clariá, J. J., Piatti, A. E., & Santos Jr., J. F. C. 1997, *AJ*, 114, 1920

Geisler, D. & Sarajedini, A. 1999, *AJ*, 117, 308

Girardi, L., Bertelli, G., Bressan, A., Chiosi, C., Groenewegen, M. A. T., Marigo, P., Salasnich, B., & Weiss, A. 2002, *A&A*, 391, 195

Grocholski, A. J., Cole, A. A., Sarajedini, A., Geisler, D., & Smith, V. V. 2006, *AJ*, 132, 1630

Olszewski, E., Schommer, R., Suntzeff, N., & Harris, H. C. 1991, *AJ*, 101, 515