Spectroscopic analysis of the candidate globular clusters NGC 1928 and 1939 in the Large Magellanic Cloud

C. M. Dutra,1*† E. Bica,1† J. J. Claría2*† and A. E. Piatti2†
1Departamento de Astronomía, Instituto de Física, UFRGS, C.P. 15051, 91501-970 Porto Alegre RS, Brazil
2Observatorio Astronómico de Córdoba, Laprida 854, 5000, Córdoba, Argentina

ABSTRACT
The integrated spectral properties in the range 3600–6700 Å of the candidate old clusters NGC 1928 and 1939 in the LMC bar are compared with those of old- and intermediate-age reference LMC clusters, the properties of which are better established. It has been possible to infer the age of the sample clusters by means of absorption features and the continuum distribution, in particular in the plane \( W_M \times W_B \) (where \( W_B \) is the average of H$_\alpha$, H$_\beta$ and H$_\delta$ equivalent widths, and \( W_M \) that of Ca II, K, G band and Mg i). The results indicate that NGC 1928 and 1939 are compatible with old clusters. The metallicity is derived with respect to galactic globular cluster templates: [Fe/H] = −1.2 and −2.0 for NGC 1928 and 1939, respectively. We also discuss the census of Population II clusters in the LMC, their spatial distribution and the possibility of a LMC core and a transient morphological classification for interacting late-type disc galaxies.

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1 INTRODUCTION
The Magellanic Clouds play a fundamental role in interpreting distant unresolved stellar populations because high signal-to-noise ratio integrated spectra can be collected for their star clusters, and it is becoming possible to obtain very deep colour–magnitude diagrams (CMDs) attaining even the main sequence (MS) of compact old clusters in crowded fields such as the Large Magellanic Cloud (LMC) bar (e.g. Olsen et al. 1998).

The construction of spectral libraries of star clusters of all ages is a fundamental reference in view of studying clusters in distant galaxies. Efforts in this direction have been made in different spectral ranges (e.g. Bica & Alloin 1986, 1987; Bonatto, Bica & Alloin 1995). Recently, globular clusters in M31 and NGC 5128 have been analysed by means of comparisons with templates in spectral libraries (Jablonka, Alloin & Bica 1992; Jablonka et al. 1995). The integrated spectral properties in the range 3600–6700 Å of the candidate old clusters NGC 1928 and 1939 in the LMC bar are compared with those of old- and intermediate-age reference LMC clusters, the properties of which are better established. It has been possible to infer the age of the sample clusters by means of absorption features and the continuum distribution, in particular in the plane \( W_M \times W_B \) (where \( W_B \) is the average of H$_\alpha$, H$_\beta$ and H$_\delta$ equivalent widths, and \( W_M \) that of Ca II, K, G band and Mg i). The results indicate that NGC 1928 and 1939 are compatible with old clusters. The metallicity is derived with respect to galactic globular cluster templates: [Fe/H] = −1.2 and −2.0 for NGC 1928 and 1939, respectively. We also discuss the census of Population II clusters in the LMC, their spatial distribution and the possibility of a LMC core and a transient morphological classification for interacting late-type disc galaxies.

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It would be important to establish the total population of old clusters in the LMC in order to determine its specific frequency, and to compare the LMC with other globular cluster systems in galaxies (Harris 1991). Another key point is how the old clusters are distributed in the LMC, whether they are concentrated towards the centre forming a Population II core region or not. Indeed, this might shed some light on the classification scheme of central regions of luminous barred magellanic irregulars and late-type spirals (van den Bergh 1995).

In this work, we present integrated spectra of the remaining two candidate old clusters NGC 1928 and 1939, which are interesting compact clusters in the LMC bar, to derive their ages. For comparison purposes, we also provide spectra of bonaﬁde old clusters (including most of the sample by Olsen et al. 1998) and some IACs in the LMC. In Section 2 we describe the observations and reductions. In Section 3 we present spectral measurements and discuss the results. Concluding remarks are given Section 4.

2 OBSERVATIONS

2.1 The spectral sample

The sample clusters are compact and some of them embedded in dense stellar ﬁelds. Their compact nature and high surface brightness make them good targets for integrated spectroscopy.

The observed star cluster sample is given in Table 1, where their designations in different catalogues are provided. We observed the candidate old clusters NGC 1928 and NGC 1939 and for comparison purposes: (i) the well-known genuine LMC globular cluster NGC 2210 by the presence of 12 RR Lyrae (Suntzeff et al. 1992) and properties observed in the deep CMD of Brocato et al. (1996); (ii) NGC 1754, 1898, 1916, 2005 and 2019, conﬁrmed as old globular clusters of the LMC (Olsen et al. 1998); (iii) the IACs NGC 1865, H7, NGC 2173, H3 and H6. The clusters NGC 1865 and H7 were candidate old clusters from integrated \(UBV\) photometry (Bica et al. 1996); however, CMDs showed them to be IACs of \(< 1\) Gyr (Geisler et al. 1997). According to simulations in the latter study they fell in the SWB VII-type zone probably because of a combination of stochastic effects produced by bright stars and by photometric errors for such faint clusters lying in crowded ﬁelds. NGC 2173, H3 and H6 are located in the SWB VI zone (Bica et al. 1996). NGC 2173 has published CMDs indicating an age in the range 1.5–2.0 Gyr (Mould, Da Costa & Wieland 1986; Corsi et al. 1994).

Fig. 1 shows the spatial distribution of the observed clusters compared with the LMC H I contours (Mathewson & Ford 1984). We note that NGC 2210 and 1754 are located in more external (and consequently less crowded) regions, whereas the other globular clusters and candidate old clusters are concentrated in more internal regions, especially in the LMC bar. Finally the IACs included in the present study are also indicated.

2.2 Observing procedures and reductions

The spectra were collected with the 2.15-m telescope at the Complejo Astronómico El Leoncito (CASLEO, San Juan, Argentina) in 1995 December. We employed a charge-couple device (CCD) camera attached to the REOSC spectrograph. The detector was a Tektronics chip of 1024 \(\times\) 1024 pixels of size 24 \(\times\) 24 \(\mu\)m\(^2\). We used a grating of 300 groove/mm\(^{-1}\) producing an average dispersion of \(\approx 143\) Å/mm\(^{-1}\) or 3.43 Å/pixel\(^{-1}\). The spectral coverage was 3600–6700 Å. At least two exposures of each object were taken in order to correct for cosmic rays. The exposure times are given in Table 1. The standard stars EG 21 and LTT 3864 (Baldwin & Stone 1984) were observed for ﬂux calibrations. He–Ar lamp exposures were taken following that of the object or standard star for wavelength calibrations. The slit width was 4 arcsec, providing a resolution [full width at half-maximum (FWHM)] of \(\approx 14\) Å from comparison lines. The slit was set in the E–W direction, and its length projected on to the chip (4.7 arcmin) provided a wide range of pixel rows for background subtractions.

The reductions were carried out at the Instituto de Física, UFRGS (Porto Alegre), using the IRAF package and following the standard procedures. The cluster spectra were extracted along the slit according to the cluster size and available ﬂux.

The following properties of observed clusters are listed in Table 1 by columns: (1) designations in different catalogues [H – Hodge (1960), SL – Shapley & Lindsay (1963), LW – Lynga & Westerlund (1963)]; (2) exposure times; (3) extraction window lengths; (4) and (5) heliocentric velocities; (6) and (7) galactic coordinates; (8) galactic reddening derived from the maps of Burstein & Heiles (1982); (9) aperture and (10) integrated \(V\) magnitude.

Table 1. The observed clusters.

<table>
<thead>
<tr>
<th>Designations</th>
<th>Exp(s)</th>
<th>Extrac.(arcsec)</th>
<th>V(km s(^{-1}))</th>
<th>V(km s(^{-1})) (\beta)</th>
<th>(\beta)</th>
<th>E(B – V) (\beta)</th>
<th>D(arcsec) (\beta)</th>
<th>(V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NGC 1754,SL91</td>
<td>2\times360</td>
<td>43</td>
<td>275 ± 33</td>
<td>236.</td>
<td>282.01</td>
<td>-35.13</td>
<td>0.09</td>
<td>100</td>
</tr>
<tr>
<td>NGC 1898,SL350</td>
<td>2\times600</td>
<td>52</td>
<td>300 ± 15</td>
<td>210.</td>
<td>280.49</td>
<td>-33.49</td>
<td>0.09</td>
<td>40</td>
</tr>
<tr>
<td>NGC 1916,SL361</td>
<td>2\times300</td>
<td>29</td>
<td>285 ± 39</td>
<td>278.</td>
<td>280.15</td>
<td>-33.38</td>
<td>0.09</td>
<td>44</td>
</tr>
<tr>
<td>NGC 1928,SL405</td>
<td>2\times600</td>
<td>51</td>
<td>346 ± 56</td>
<td>–</td>
<td>280.19</td>
<td>-33.17</td>
<td>0.09</td>
<td>34</td>
</tr>
<tr>
<td>NGC 1939,SL414</td>
<td>2\times600</td>
<td>27</td>
<td>139 ± 32</td>
<td>–</td>
<td>280.73</td>
<td>-33.03</td>
<td>0.09</td>
<td>38</td>
</tr>
<tr>
<td>NGC 2005,SL518</td>
<td>600\times300</td>
<td>37</td>
<td>300 ± 47</td>
<td>270.</td>
<td>280.35</td>
<td>-32.33</td>
<td>0.08</td>
<td>25</td>
</tr>
<tr>
<td>NGC 2019,SL554</td>
<td>2\times360</td>
<td>29</td>
<td>256 ± 44</td>
<td>269.</td>
<td>280.79</td>
<td>-32.11</td>
<td>0.08</td>
<td>72</td>
</tr>
<tr>
<td>NGC 2210,SL858,LW423</td>
<td>2\times420</td>
<td>43</td>
<td>456 ± 78</td>
<td>343.</td>
<td>279.33</td>
<td>-28.75</td>
<td>0.08</td>
<td>68</td>
</tr>
<tr>
<td>NGC 1865,SL307</td>
<td>2\times900</td>
<td>45</td>
<td>353 ± 61</td>
<td>–</td>
<td>279.55</td>
<td>-34.05</td>
<td>0.07</td>
<td>40</td>
</tr>
<tr>
<td>NGC 2173,SL807,LW348</td>
<td>3\times600</td>
<td>33</td>
<td>353 ± 34</td>
<td>241.</td>
<td>283.78</td>
<td>-29.25</td>
<td>0.10</td>
<td>150</td>
</tr>
<tr>
<td>H3,SL569</td>
<td>2\times900</td>
<td>43</td>
<td>456 ± 96</td>
<td>–</td>
<td>278.42</td>
<td>32.27</td>
<td>0.06</td>
<td>40</td>
</tr>
<tr>
<td>H6,SL668,LU274</td>
<td>2\times900</td>
<td>54</td>
<td>240 ± 68</td>
<td>–</td>
<td>282.32</td>
<td>-31.07</td>
<td>0.09</td>
<td>110</td>
</tr>
<tr>
<td>H7,SL735</td>
<td>2\times900</td>
<td>42</td>
<td>387 ± 87</td>
<td>–</td>
<td>277.75</td>
<td>-30.74</td>
<td>0.06</td>
<td>100</td>
</tr>
</tbody>
</table>

\(^a\)Measurements of radial velocity from Olzewski et al. (1991).

\(^b\)Foreground reddening according to Burstein & Heiles (1982).

\(^c\)Aperture and integrated \(V\) magnitude values from Bica et al. (1996).
Owing to the rather low resolution, the present spectra are not particularly suitable for accurate velocity measurements. At any rate, we could measure velocities using strong absorption features and transform them to heliocentric values. The results are compared in Table 1 with those from higher resolution spectra (Olszewski et al. 1991), when available. The agreement is good, and we used the present values to reduce the cluster spectra to the rest frame, which is necessary for the subsequent stellar-population analysis.

Fig. 2 shows the resulting rest-frame flux-calibrated and foreground reddening-corrected spectra of the LMC globular clusters.

Figure 1. Spatial distribution of the observed LMC clusters. H I contours 100, 200, 400 and 600 in units 10^{19} \text{atoms cm}^{-2} from Mathewson & Ford (1984). The solid line represents the LMC bar.

Figure 2. Spectra of LMC globular clusters and the candidates NGC 1928 and 1939, F_{\lambda} units normalized at 5870 Å. For clarity, a constant has been added, except for the bottom spectrum.
and the candidates NGC 1928 and 1939. The reddening correction was made by applying the galactic extinction law of Seaton (1979), and foreground $E(B - V)$ values from Table 1. We note that all these objects present similar spectra.

3 ANALYSIS

In the spectral analysis we employ measurements of equivalent widths ($W$) of strong absorption features and the continuum distribution. To improve the signal-to-noise ratio, the intermediate-age comparison clusters were averaged into a younger ($\approx 1\,\text{Gyr}$) and an older group ($\approx 2\,\text{Gyr}$): Int1 (H7 and NGC 1865), and Int2 (NGC 2173, H3 and H6). As a comparison we also include the templates of intermediate-age (I1 and I2) and old galactic globular clusters (G3, G4 and G5) from Bica (1988). The templates I1 and I2 correspond to ages $\approx 1$ and $2\,\text{Gyr}$, respectively, and were built from galactic open clusters and some LMC clusters. The globular-cluster metallicity sequence G3, G4 and G5 corresponds to [Fe/H] $= -1.0, -1.5, -2.0$, respectively.

In Fig. 3 we compare the foreground-reddening-corrected spectra of the candidate old clusters NGC 1928 and 1939 with those of the two LMC IAC groups and that of the globular cluster NGC 2210. Notice that the spectral distributions of the candidate old clusters resemble more those of NGC 2210.

Notice that a common feature between IACs and old metal-poor globular clusters is the enhanced Balmer lines and Balmer discontinuity (e.g. Bica et al. 1994). In the case of IACs, they arise from stars in the turn-off region, while in the globular clusters from blue horizontal branches. We search for possible differences between the properties of the two types of stellar population, in view of estimating the ages of the candidate old clusters.

3.1 Equivalent widths

We measured the equivalent widths ($W$s) of Ca ii K, CN, G-band, Mg i, Na i and four Balmer lines. We adopted the spectral windows (Table 2) and continuum tracings from Bica & Alloin (1986) and Bica et al. (1994). The continuum points are 3660, 4020, 4570, 5870 and 6630 $\AA$. Typical $W$ errors are $\approx 5$ per cent and depend mostly on uncertainties in the continuum location. The resulting $W$s are given in Table 2.

An average of the $W$s of Balmer lines versus $W$s of metallic lines can in principle segregate IACs from old clusters (Rabin 1982). We averaged the $W$s of lines H$\alpha$, H$\gamma$ and H$\beta$ ($W_B$) and of the metallic lines K, Mg i and G band ($W_M$).

Fig. 4 shows the behaviour of the objects in the $W_M \times W_B$ plane. We note that the three templates of galactic globular clusters, old globular clusters (except NGC 1916) and the candidate old clusters are located in the region in which $W_B \approx 15.5 \,\text{Å}$, while the IAC templates Int1, Int2, I1 and I2 are above this limit. This evidence indicates that the observed candidate old clusters NGC 1928 and 1939 present equivalent widths $W_B$ and $W_M$ compatible with those of a typical old globular cluster. It is important to note that NGC 1916 presents an enhanced $W_B$, shifted to the IAC loci (Fig. 4).

Olsen et al. (1998) detected a blue horizontal branch (HB) characterizing NGC 1916 as an old cluster; the enhanced Balmer lines with respect to the globular cluster sequence in Fig. 4 might arise from an exceptionally populated blue HB. Differential reddening and contamination precluded the detection of a clean low MS turn-off in Olsen et al.’s CMD. Indeed, NGC 1916 is embedded in a dense LMC bar field, which might contaminate the cluster spectrum causing the Balmer enhancement. Notice that the blue MS field star contamination is higher in the NGC 1916 CMD than for other bar clusters studied by Olsen et al. (1998). However, the high surface brightness of this cluster points against significant field contamination. Alternative possibilities are that this luminous old cluster has captured stars from the dense bar field, similar to the scenario proposed for some globular clusters in the bulge (Bica et al. 1997), or cannibalized one or more star clusters (de Oliveira, Dotti & Bica 1998), since the LMC bar is very populous in star clusters and contains several pairs (Bica, Clariá & Dottori 1992).

In Fig. 4 the three galactic globular cluster templates define a metallicity scale, which can be used to derive the metallicity of the clusters in the old cluster zone. For the candidate old clusters we...

Finally, we derive [Fe/H]N2210 = −1.5, which is somewhat higher than the CMD determination by Brocato et al. (1996) and Olszewski et al. (1991).

### 3.2 Continuum distribution

The continuum distribution can provide supplementary evidence for distinguishing IACs and old clusters. According to Fig. 3, IACs of ≈ 1 Gyr (INT1) are definitely bluer than the old clusters like NGC 2210; however, IACs of ≈ 2–3 Gyr (INT2) are as red as NGC 2210. We tested continuum ratios in detail and differences can be detected. The best discriminator involves the ratios 3660/4020 ≈ 4020/5870, where the first ratio is a measure of the Balmer jump. The observed and reddening-corrected values are shown in Table 3.

#### Table 3. Observed and reddening-corrected measurements of continuum ratios.

<table>
<thead>
<tr>
<th>Cluster</th>
<th>3660/5870 obs cor</th>
<th>4020/5870 obs cor</th>
<th>3660/4020 obs cor</th>
</tr>
</thead>
<tbody>
<tr>
<td>NGC 1754</td>
<td>0.55 0.65</td>
<td>0.89 0.97</td>
<td>0.62 0.63</td>
</tr>
<tr>
<td>NGC 1898</td>
<td>0.59 0.68</td>
<td>0.92 0.99</td>
<td>0.64 0.65</td>
</tr>
<tr>
<td>NGC 1916</td>
<td>0.52 0.61</td>
<td>1.03 1.17</td>
<td>0.50 0.52</td>
</tr>
<tr>
<td>NGC 1928</td>
<td>0.57 0.67</td>
<td>0.92 1.04</td>
<td>0.62 0.64</td>
</tr>
<tr>
<td>NGC 1916</td>
<td>0.73 0.85</td>
<td>1.08 1.18</td>
<td>0.68 0.70</td>
</tr>
<tr>
<td>NGC 2005</td>
<td>0.58 0.67</td>
<td>0.92 1.02</td>
<td>0.63 0.65</td>
</tr>
<tr>
<td>NGC 2173</td>
<td>0.58 0.67</td>
<td>0.92 1.02</td>
<td>0.63 0.65</td>
</tr>
<tr>
<td>NGC 2210</td>
<td>0.63 0.72</td>
<td>0.98 1.09</td>
<td>0.64 0.66</td>
</tr>
<tr>
<td>Int1</td>
<td>0.64 0.71</td>
<td>1.25 1.35</td>
<td>0.51 0.52</td>
</tr>
<tr>
<td>Int2</td>
<td>0.46 0.54</td>
<td>0.74 0.85</td>
<td>0.62 0.64</td>
</tr>
<tr>
<td>I1</td>
<td>0.54</td>
<td>0.96</td>
<td>0.56</td>
</tr>
<tr>
<td>I2</td>
<td>0.44</td>
<td>0.73</td>
<td>0.60</td>
</tr>
<tr>
<td>G3</td>
<td>0.55</td>
<td>0.82</td>
<td>0.67</td>
</tr>
<tr>
<td>G4</td>
<td>0.58</td>
<td>0.89</td>
<td>0.65</td>
</tr>
<tr>
<td>G5</td>
<td>0.62</td>
<td>0.98</td>
<td>0.63</td>
</tr>
</tbody>
</table>

Figure 4. The $W_M \times W_B$ plane. The solid lines connect old templates of different metallicities indicated in parentheses, and the dashed line connects the intermediate-age templates with ages in parentheses.
Figure 5. The 3660 Å/4020 Å × 4020 Å/5870 Å plane. The locus corresponding to the observed spectrum is shown by a point, and the connected line indicates the foreground reddening corrected value. Templates are also shown.

some present star-like or semistellar nuclei (van den Bergh 1995). The kinematical LMC centre is located in a lower density disc region, at ≈ 1º north of the bar (Westergaarden 1990; Dottori et al. 1996). Non-central bars are not uncommon among Magellanic Irregulars (de Vaucouleurs & Freeman 1972). Such displacements might be explained by interactions, in particular for the LMC, since at least one encounter occurred with the SMC (Fujimoto & Murai 1985). In this scenario, the LMC bar could have arisen from a central disc, because its stellar population is dominated by intermediate ages (Hardy et al. 1984; Bica et al. 1992). In addition to a Population II core region, one could ask whether the LMC ever possessed a semistellar nucleus like the late-type spirals NGC 300, NGC 7793 and M33 (van den Bergh 1995; Schmidt et al. 1990), or at least the seed of a semistellar nucleus. In the Sagittarius dwarf, the globular cluster M54 is apparently the galaxy nucleus (Sarajedini & Layden 1995). NGC 1916 is a candidate for a ‘manqué’ LMC nucleus, since it is a very bright cluster (Table 1) and occupies a nearly central position in the bar. Another candidate is the neighbouring bright globular cluster NGC 1855. Central velocity dispersions (Dubath, Meylan & Mayor 1997) indicate that these two clusters are massive ones.

The possible occurrence of a proto-semistellar nucleus in the LMC would have an impact on its morphological classification following the scheme discussed by van den Bergh (1995). This opens up the possibility that such classifications of late-type discs are transient evolutionary phases, in particular for interacting pairs.

4 CONCLUDING REMARKS

Absorption lines and the continuum distribution suggest that the candidate old clusters NGC 1928 and 1939 are as old as the old bonafide globular clusters in the LMC, such as NGC 2210. Their metallicities are [Fe/H]_{NGC1928} ≈ −1.2 and [Fe/H]_{NGC1939} ≈ −2.0.

We also studied spectroscopically NGC 1754, 1898, 2005, 2019 and 1916, which have been recently verified as globular clusters by means of HST colour–magnitude diagrams. These clusters present typical old globular-cluster integrated spectra, except NGC 1916, which has peculiarities.

The census of old globular clusters in the LMC indicates 15 objects, including NGC 1928 and 1939. For these compact clusters in crowded bar fields, HST photometry will be necessary for definitive diagnoses.

The old globular clusters in the LMC seem to be concentrated in the bar region. Such a population is reminiscent of an ancient bulge, which together with a central disc could have evolved into the LMC bar by SMC and/or Galaxy interactions.

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