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Integrated spectroscopic study of 7 star clusters in the Small Magellanic Cloud

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We present flux-calibrated integrated spectra for 7 star clusters belonging to the Small Magellanic Cloud in the optical range (≈3600–7000 Å), obtained at CASLEO (Argentina). Three out of the 7 clusters were not previously studied so their ages and reddening values are determined for the first time in the current study. Using the equivalent widths of selected spectroscopic lines and comparing the cluster spectra with template spectra of known properties, we derive foreground interstellar reddening and age. The clusters are in the (5–300) Myr age range and their $E(B-V)$ colour excesses were in all cases smaller than 0.12. The present data also contribute to enlarge the cluster spectral library at the metallicity level of the Small Magellanic Cloud. The buildup of such database, which also includes Galactic and Large Magellanic Cloud clusters, is a long-term project that we have been developing and which has proved to be useful in the analysis of stellar populations of extragalactic systems.

1 Introduction

The study of extragalactic star clusters (SCs) provides relevant information on the star formation and chemical histories of the host galaxies. Despite several studies recently developed, our knowledge of such processes is in general incomplete, even for the galaxies in the Local Group. In this context, SCs in the Magellanic Clouds (MCs) play a crucial role because they can help us to have a better insight into the star formation history of the galaxies as a whole. This is due to their nearness, richness and star systems variety. One of the powerful techniques to study SCs in more distant galaxies is integrated spectroscopy (e.g., SCs in NGC 3256, Trancho et al. 2007; SCs in the Large Magellanic Cloud (LMC), Palma et al. 2008a; in the MCs, Ahumada et al. 2009; and globular clusters in M 31, Schiavon et al. 2007). Efforts to create reference spectra of SCs and grids of their properties to be used as templates for different ages and metallicities in the study of composite stellar populations were made, among others, by Bica & Alloin (1986a, 1986b), Bica (1988), Santos et al. (1995), Piatti et al. (2002), Schiavon et al. (2005), and Ahumada et al. (2007).

The analysis of the continuum and absorption lines of the integrated spectra of SCs provides us with accurate estimates of their ages and metallicities. As we mentioned before, Bica & Alloin (1986a) created a library of star cluster spectra in which age and metallicity trends were searched by plotting equivalent widths (EWs) of various spectral features as a function of age and metallicity. They show that the EW of each Balmer line is a bivalued function of age and that the EWs of prominent metallic features are metallicity indicators for old clusters. Bica & Alloin (1987) also studied the near-infrared spectral properties of SCs and galactic nuclei. The determination of these properties for distant compact SCs in which individual stars are not observable, needs a calibration based on SCs of well-known ages and metallicities. These age and metallicity calibrations are established by means of EWs measurements. Based on these data, it is possible to characterize SCs of unknown properties as well as to use reference integrated spectra (templates) to investigate more complex stellar systems. Integrated spectra of SCs in the MCs (e.g., Bica et al. 1990; Santos et al. 1995; Ahumada et al. 2002; Piatti et al. 2005; Santos et al. 2006; Palma et al. 2008a) and in the Milky Way (e.g., Santos & Bica 1993; Ahumada et al. 2000, 2001, 2007; Palma et al. 2008b) have been observed, catalogued (Santos et al. 2002) and analyzed (Santos & Piatti 2004). Alongside with these works, we think it is crucial to create a template library containing a representative range of SCs metallicities and ages.

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The SCs presented here are part of a systematic spectroscopic survey of SCs in both MCs. Here we present flux-calibrated integrated spectra for 7 SCs belonging to the SMC with the aim of determining their fundamental parameters as well as adding new entries in the growing library of cluster integrated spectra at the SMC metallicity level. Preliminary results for 6 out of the 7 clusters here analysed are presented in Talavera et al. (2007).

2 Cluster sample and spectroscopic observations

We have selected 7 relatively populous, compact and high brightness SMC's SCs. They lie in the surroundings and in the main body of the SMC. The observed SC sample is given in Table 1, where cluster designations in different catalogues are provided. We also include the equatorial coordinates and angular sizes taken from Bica et al. (2008), and the integrated $(U-B)$ and $(B-V)$ colours reported by Rafelski & Zaritsky (2005), when available.

Figure 1 shows XDSS red images ($5' \times 5'$extractions) of the whole SC sample. All the clusters are relatively concentrated objects. For this reason, they have been selected to perform integrated spectroscopic observations. Fundamental parameters for many SCs of the MCs were derived for the last 10 years from integrated spectroscopic observations undertaken at CASLEO (Complejo Astronómico El Leoncito, San Juan, Argentina). The observations were carried out with the Jorge Sahade 2.15-m Ritchey-Chrètien telescope during several nights in different years. We employed a CCD camera attached to the REOSC spectrograph during the different runs. The detector was a Tektronics chip of 1024×1024 pixels of size 24 μm each. One pixel corresponds to $0.94''$on the sky. The slit was set in the East-West direction and the observations were performed by scanning the slit across the objects in the North-South direction in order to get a proper sampling of the SCs populations. By means of a grating of 300 grooves/mm, we obtained spectra with an average dispersion of $\sim$140 Å/mm (3.46 Å/pix). The CCD operated with a gain of 1.98 e^-/ADU and a readout noise of 7.4 e^-/ADU. The spectral coverage was $\approx$3600–7000 Å. The slit length, corresponding to $4.7'$ on the sky, allowed us to sample regions of background sky. The slit width was 400 μm ($\sim 4.2''$ in the sky), providing a resolution of 17 Å as measured from the full width at half-maximum (FWHM) in the comparison lamp lines. Standard stars from Stone & Baldwin (1983) were observed for flux calibrations. Bias, darks, dome and twilight sky flat-fields were taken for reduction purposes.

For each of the sample objects, a series of spectra were taken each of them having an exposure time of 20–30 min so that the total exposure time of each object varied between 60 and 90 min, depending on their brightness. Reductions were carried out with the IRAF software package, following standard procedures (Massey et al. 1992) at the Observatorio Astronómico de la Universidad Nacional de Córdoba (Argentina). The spectra were extracted along the slit according to the cluster size and available flux. We subtracted the master bias and used master flat-field frames to correct the frames for high and low spatial frequency variations. Background sky subtractions were then performed using pixel rows from the same frame after removing cosmic rays from the background sky regions. Precautions were taken so no significant background sky residuals were present on the resulting spectra. Wavelength calibrations were carried out with a Cu-He-Ar lamp with exposures following that of the object or standard star. The rms errors involved in these calibrations are typically 0.50 Å (0.14 pixel). Atmospheric extinction corrections according to the site coefficients given

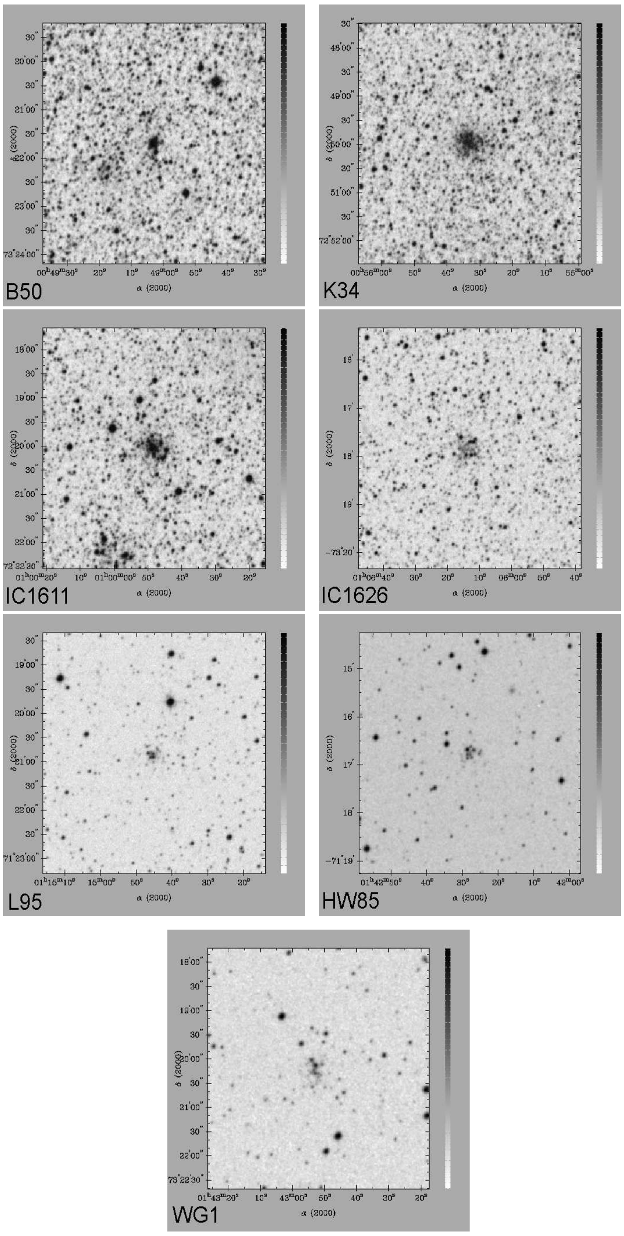

Fig. 1 $5' \times 5'$ field, red plate of CADC XDSS images of cluster sample.

Table 1 The sample clusters. Cluster identifications are from Kron (1956, K), Lindsay (1958, L), Pietrzynski et al. (1998, SMC-OGLE), Rafelski & Zaritsky (2005, RZ), Lauberts (1982, ESO), Bruck (1976, B), Westerlund & Glaspey (1971, WG), Hodge & Wright (1974, HW). Coordinates and angular sizes (major × minor diameter) were taken from Bica et al. (2008). The integrated ($U - B$) and ($B - V$) colours were taken from Rafelski & Zaritsky (2005).

Cluster	α_{2000} (h:m:s)	δ_{2000} (°:′:″)	Size (′×′)	$U - B$	$B - V$
B 50	00:49:02	–73:21:44	0.55×0.55		
K 34, L 53, SMC-OGLE 104, RZ 96	00:55:33	–72:49:58	1.20×1.20	0.09	0.36
IC 1611, K 40, SMC-OGLE 118, L 61, ESO29-SC27, RZ 115	00:59:48	–72:20:02	1.50×1.50	–0.12	0.30
IC 1626, K 53, L 77, ESO29-SC30, RZ 156	01:06:13	–73:17:49	1.00×1.00	0.15	0.19
L 95	01:14:45	–71:20:49	1.00×1.00		
HW 85	01:42:28	–71:16:45	1.00×1.00		
WG 1	01:42:52	–73:20:11	1.10×0.95		

by Minniti et al. (1989) and flux calibrations were then applied. Note that while some field star contamination may be expected in the observed spectra, only bright field stars could affect the spectra significantly. As for those clusters showing bright stars in their fields, a special discussion is later presented.

3 Reddening and age determinations

Integrated spectra of SCs of small angular diameter allow us to determine their basic properties, such as reddening, age and metallicity (Bica & Alloin 1986a). A direct reddening-independent age estimate was first obtained from EWs of the Balmer absorption lines in each spectrum by interpolating these values in the age calibration of Bica & Alloin (1986b). Then we derived age and foreground reddening $E(B - V)$ values of the selected SCs simultaneously by means of the template matching method. This was done by achieving the best possible match between the continuum and the lines of the analysed cluster integrated spectrum and these same features of a template integrated spectrum with known properties. Before applying the template matching method, we consider the direct reddening-independent age estimate. Based on this first estimate, we selected among the templates of Piatti et al. (2002, hereafter PBCSA) and Santos et al. (1995, hereafter SBCPGD) databases, a subset of templates to compare with the observed spectrum. This selection allowed us to constrain our search of the most appropriate template since the previously selected templates fall within a limited age range. The reddening corrections were performed using the interstellar absorption law derived by Seaton (1979) and adopting the most frequently used factor 3.2 for the ratio of total-to-selective extinction (Straizys 1992). We note that the uncertainty in the adopted reddening represents the lowest reddening variation necessary to distinguish the cluster spectrum from that of the corresponding template. The ages obtained by applying these methods are given in Table 2.

We also determined the aforementioned parameters in two other ways. We derived age values from Santos & Piatti (2004, hereafter SP) calibrations. With this in view, we used the sum of EWs of selected spectral features, along with their relationships with age (e.g., Santos et al. 2006). We also estimated cluster reddening values by interpolation between the extinction maps of Burstein & Heiles (1982, hereafter BH). The BH maps provided us with foreground $E(B - V)$ colour excesses as measured from the H I (21-cm) emission data. Schlegel et al. (1998, hereafter SFD) obtained full-sky maps from 100-μm dust emission. They found that at high-latitute regions, the dust map correlates well with maps of H I emission, but deviations are coherent in the sky and are especially conspicuous in regions of saturation of H I emission towards denser clouds and of formation of H_2 in molecular clouds. Since the $E(B-V)_{\rm SFD}$ values for our clusters are much higher than the $E(B - V)_{\rm BH}$ values for these clusters, the SFD values are assumed to be saturated and we used the BH values. The foreground reddening as well as the age derived from the EWs of Balmer H lines, K Ca II, G-band (CH) and Mg I (5167 + 5173 + 5184 Å), using SP's calibrations, are also shown in Table 2.

4 Analysis of individual clusters

In this section we discuss the results obtained for individual clusters. Ages estimated by other authors in previous works of some of the clusters studied here are included in Table 2.

B 50 The isophotal contours obtained by de Oliveira et al. (2000) indicate an interaction of B 50 with BS 41 and L 39. Although the integrated light of the cluster is influenced by the bright star SMC 12412, a massive object according to Massey (2002), the observed integrated spectrum of B 50 compares reasonably well with the YA_SG.LMC template of (3–5) Myr from SBCPGD's library (see Fig. 2). We note that the Balmer lines are deeper in the template, but the continuum is well matched if no reddening correction is applied. This template age is similar to the one obtained from the EWs method (Table 2). Chiosi et al. (2006) derived age and reddening values of SMC clusters by means of isochrone fitting on CMDs based on VI photometry. For B 50 they obtained $E(V - I) = 0.08$ and an age of 10 Myr.

Table 2 Cluster parameters: reddening and age.

Cluster	$E(B-V)$ (BH)	$E(B-V)$ (Template)	Age (Literature) (Myr)	Age (Balmer) (Myr)	Age (S_h, S_h) (Myr)	Age (Template) (Myr)	Age (Adopted) (Myr)
B 50	0.03	0.00 ± 0.02	10[a], <30[b]	<10	5	3–5	5 ± 2
K 34	0.03	0.04 ± 0.02	400[a,d,e]	50	290	200–350	300 ± 100
IC 1611	0.06	0.08 ± 0.02	126[a], 100[b,c], 158[d], 112[e]	50–100	119	100–150	130 ± 30
IC 1626	0.03	0.11 ± 0.02	100[e]	300	57	200-350	250 ± 50
L 95	0.03	0.00 ± 0.02		50–100	57	45–75	50 ± 20
HW 85	0.03	0.01 ± 0.02		10–50	82	10–20	20 ± 10
WG 1	0.03	0.12 ± 0.02		<10	14	5–10	10 ± 5

[a] Chiosi et al. (2006); [b] de Oliveira et al. (2000); [c] Piatti et al. (2007); [d] Pietrzynski & Udalski (1999); [e] Rafelski & Zaritsky (2005).

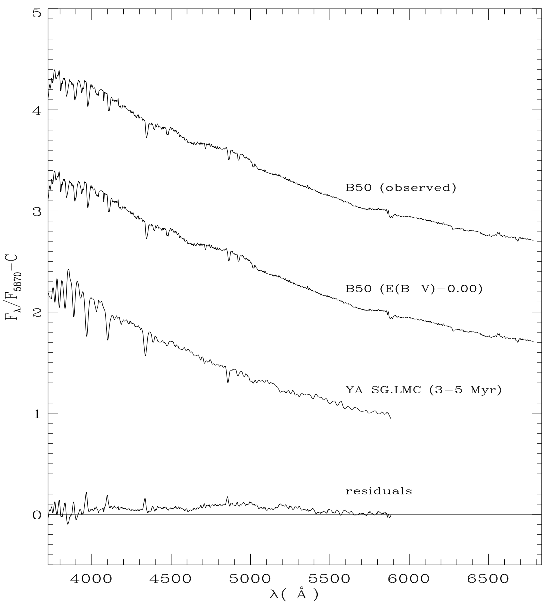

Fig. 2 Observed integrated spectrum of B 50 (top), the spectrum corrected for the adopted reddening and the template spectrum which best matches it (middle), and the residuals between both (bottom). The spectra are in relative flux units, normalized to F_λ = 1 at $\lambda \sim$ 5870 Å and shifted vertically for comparison purposes.

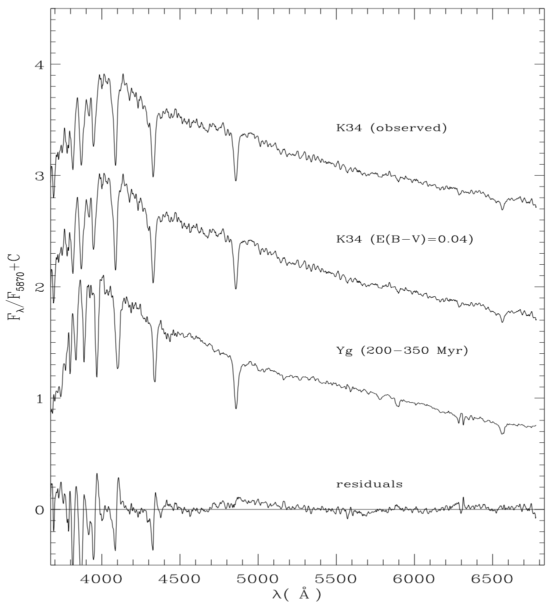

Fig. 3 Same as Fig. 2 for K 34.

This reddening was converted to $E(B-V) = 0.06$ by using the relation $E(V-I) = 1.242\ E(B-V)$ given by Dean et al. (1978). de Oliveira et al. (2000) also established that B 50 is younger than 30 Myr and has a colour excess $E(B-V) = 0.10$. The cluster parameters shown in Table 2 should not be taken as definitive since the bright star SMC 12412 could be contaminating the cluster spectrum.

K 34 The observed integrated spectrum of K 34 resembles the Yg template of (200–350) Myr of PBCSA's library, once it has been corrected for a colour excess of $E(B-V) = 0.04$ (Fig. 3). According to Pietrzynski & Udalski (1999) and Chiosi et al. (2006), K 34 is a moderately young cluster with an age of about 400 Myr and a colour excess $E(B-V) = 0.06$, in reasonable agreement with our results. Rafelski & Zaritsky (2005) determined parameters of almost 200 SMC clusters based on the comparison of integrated colours measured from the MCs Photometric Survey with models of simple stellar populations. The extinction corrected age derived by them is 400^{+44}_{-12} Myr for this object. Taking into account the integrated colours derived by Rafelski & Zaritsky (2005) and using Bica et al. (1996) colour-SWB classification and its relation with age, we classified this cluster as a SWB IV type and ranked it within the (200–400) Myr range.

IC 1611 According to de Oliveira et al. (2000), this object forms a system of 4 clusters, together with H 86, IC 1612 and K 42.

We achieved the best fitting for this cluster spectrum after comparing it with the Yf template of (100–150) Myr from PBCSA, correcting the observed spectrum for a colour excess of $E(B-V) = 0.08$ (Fig. 4). As shown in Table 2, there is good agreement between our results and those ex-

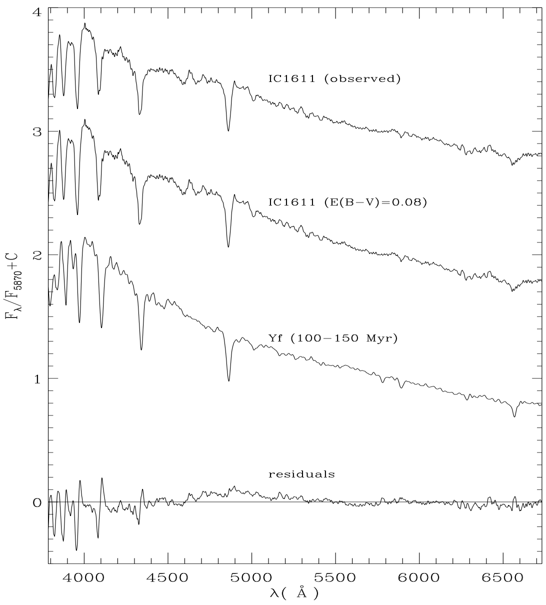

Fig. 4 Same as Fig. 2 for IC 1611.

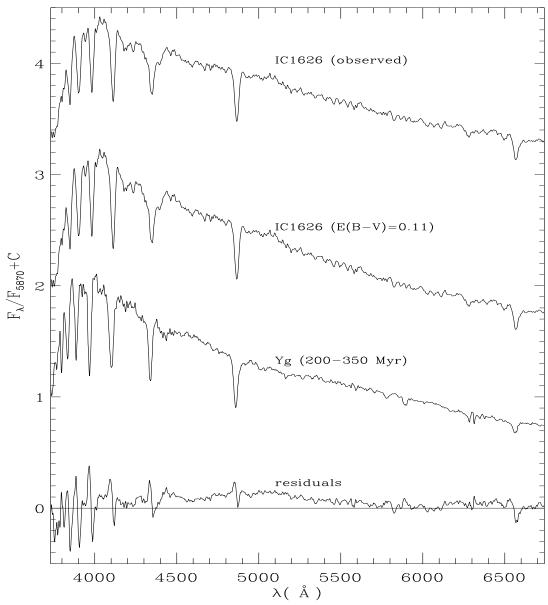

Fig. 5 Same as Fig. 2 for IC 1626.

isting in the literature. The extinction corrected age derived by Rafelski & Zaritsky (2005) is 112^{+160}_{-8} Myr for this object. Applying Bica et al. (1996) scheme, we classified this cluster as SWB III type, corresponding to the (70–200) Myr age range.

IC 1626 The Yg template of (200–350) Myr from PBCSA's library, provides the best match with the observed spectrum corrected for $E(B-V)=0.11$ (Fig. 5). Rafelski & Zaritsky (2005) estimated that IC 1626 has an extinction corrected age of 100^{+56}_{-4} Myr. Following Bica et al. (1996), IC 1626 belongs to the SWB III type, so it is within the (70–200) Myr age range.

L 95 The best match of the observed spectrum was obtained with the Ye template of (45–75) Myr, without any reddening correction needed (Fig. 6). Even though the template continuum is slightly redder than that of the cluster, the line depths are similar. There are no previous studies on this object.

HW 85 The fitting to the YC_SG.LMC template of (10–20) Myr from SBCPGD's library is excellent, after correcting the observed spectrum of HW 85 for a small foreground reddening value, $E(B-V)=0.01$ (Fig. 7). This template represents the LMC young stellar group with important flux contributions from intermediate temperature supergiant stars. There are no previous studies on this object.

WG 1 The Yb template of (5–10) Myr is the best match to the integrated spectrum of WG 1, correcting it for a colour excess of $E(B-V)=0.12$ (Fig. 8). There are no previous studies on this object either.

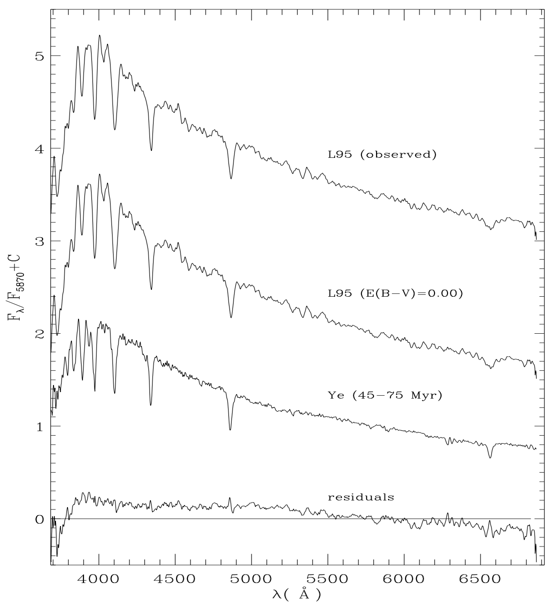

Fig. 6 Same as Fig. 2 for L 95.

5 Concluding remarks

We obtained integrated spectra of 7 SMC star clusters at Complejo Astronómico El Leoncito (CASLEO, Argentina). Five clusters belong to the SMC main body and their ages range between 5 and 300 Myr. The remaining objects are HW 85, aged 20 Myr, located just outside the SMC to the east and WG 1, aged 10 Myr, located in the SMC Wing (Westerlund & Glaspey 1971). The latter clusters are certainly related to star forming processes which, as a result of their interaction, generated the Bridge connecting the Magellanic Clouds (Bica et al. 2008, and references therein).

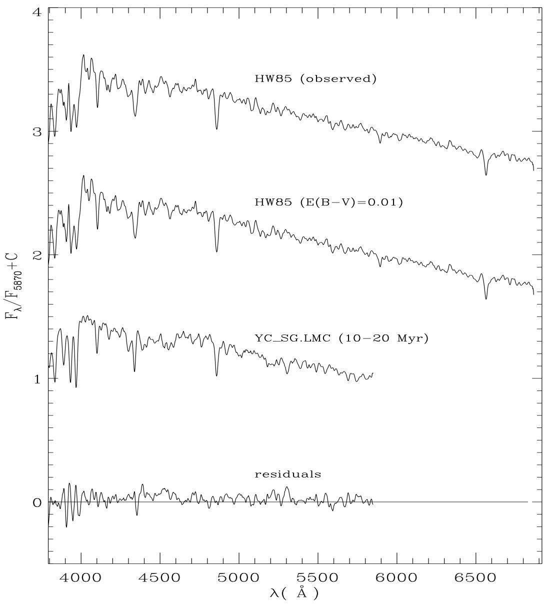

Fig. 7 Same as Fig. 2 for HW 85.

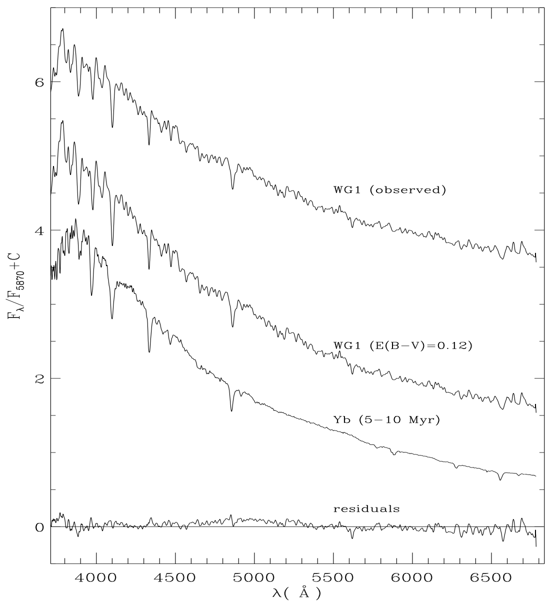

Fig. 8 Same as Fig. 2 for WG 1.

We would like to add that we are still working on this long-term project obtaining integrated spectra of MCs' SCs aiming at improving the time and spectral resolution. In a near future we intend to extend the library to the near-infrared spectral domain and hopefully to different metallicities. This library is already very useful to study stellar populations in more distant galaxies.

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