Further developments in star cluster spectral libraries

Andrea V. Ahumada(1,2,3), J.J. Clariá(2,3), E. Bica(4), A.E. Piatti(2,5), J.F.C. Santos, Jr.(6),
M.L. Talavera(7), T. Palma(2,3), D.B. Pavani(8), M.C. Parisi(2,3), M.C. Torres(3) & C.M. Dutra(9)

(1)European Southern Observatory (Chile). (2)CONICET (Arg.). (3)Observatorio Astronómico-Univ. Nacional de Córdoba (Arg.).
(4)Univ. Federal do Rio Grande do Sul (Bzl). (5)IAFE (Arg.). (6)Univ. Federal de Minas Gerais (Bzl). (7)Univ. Nacional Autónoma de Honduras. (8)Univ. Federal de Pelotas (Bzl). (9)Univ. Federal do Pampa (Bzl)

Abstract: We present flux-calibrated integrated spectra in the optical spectral range of Galactic open clusters (GOCs) and Magellanic Clouds' (MCs) stellar clusters (SCs) obtained at CASLEO (Argentina). The SC parameters were derived from the template matching procedure by comparing the line strengths and continuum distribution of the cluster spectra with those of template spectra with known parameters and from the equivalent width (EW) method. MCs cluster reddening values were also estimated by interpolation between the available extinction maps. The derived ages for the GOCs range from 3 Myr to 4 Gyr, while those of the MCs' SCs vary from 3 Myr to 7 Gyr. E(B-V) colour excess values in the MCs appear all to be lower than 0.17, while those of the GOCs range from 0.00 to 2.40. The present data led us to upgrade the spectral libraries of reference spectra or templates of solar-metallicity and MCs metallicities.

Introduction

It is well known that SCs are building blocks of galaxies: young associations, open and globular clusters. SCs in general, are powerful tracers of the formation and evolution of their parent galaxies. This work is an ongoing systematic spectroscopic survey of GOCs and MCs' SCs, and the main goal of this long term study is to collect and analyze a large sample of these SC integrated spectra with the aim to derive their fundamental parameters and making them available as template spectra complementing previous spectral libraries.

Galactic Open Clusters

GOCs have always played a prominent role in the delineation of the chemical as well as of the dynamical evolution of the Galactic disk. This is due to the fact that their fundamental parameters may be determined more easily and more accurately than those for isolated stars. However ~ 50% of the 1787 OCs known to exist in the Milky Way (Dias et al. 2002) are unstudied objects. Basic OC parameters have been mostly derived from CMDs and/or from photometric studies of individual giants. However, integrated spectra of small angular size OCs has proved a very useful tool in increasing the number of OCs studied and a valuable means to provide independent information about reddenings, ages and, in some cases, metallicities. Several years ago, Bica & Alloin (1986a) carried out a pioneer work about integrated spectroscopy applied to composite stellar populations.

Concentrated SCs are the most suitable objects to carry out integrated spectroscopic observations with a middle size telescope. The studied sample was selected using the WEBDA database (Paunzen & Mermilliod, 2009), where most of selected OCs are compact clusters (D < 5'). At this state of affairs, we have observed by means of integrated spectroscopy and study in the last 10 years 71 GOCs. Table 1 shows the cluster sample.

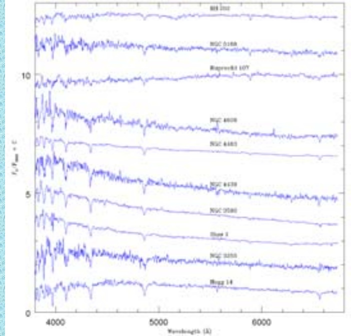

Figure 1. Observed integrated spectra of 10 GOCs.

Observations

All the observations were carried out with the 2.15 m "*Jorge Sahade*" telescope at the "Complejo Astronómico El Leoncito" (CASLEO, Argentina) in several runs. We employed a CCD camera with a chip of 1024x1024 pixels attached to a REOSC spectrograph (simple mode). The slit was oriented in the east-west direction and the observations were performed scanning the slit across the objects in the north-south direction. A grating of 300 grooves/mm was used. The spectral coverage was the visible range: ~ (3600–6800) Å, with an average dispersion in the observed region of ~140 Å/mm (3.46Å/pix). The slit width was 4.2", resulting in a resolution of ~14 Å. In Figure 1 we present, as an example, part of the studied sample of GOC integrated spectra. All the spectra are in relative flux units, normalized to $F_\lambda = 1$ at $\lambda = 5800$ A. The spectral lines and different slopes of the continuum energy distributions in both figures are primarily the result of age effects.

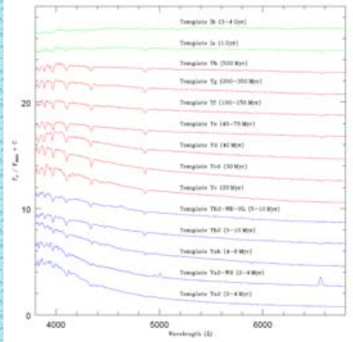

Figure 2. GOC template spectra for the young (Y) and intermediate (I) age groups

Reddening and age determination

Age and foreground reddening values of the selected clusters were simultaneously derived by means of a template matching method. This was done by achieving the best possible match between the continuum and lines of the analyzed cluster's integrated spectrum with those from a template of integrated spectra with known properties. To apply the template matching method, a direct reddening-independent age estimate was first obtained from EWs of the Balmer absorption lines in each spectrum. This was done by interpolating the EW values in the age calibration of Bica & Alloin (1986b). Based on this age estimate, we select among the available templates libraries, a subset of templates to compare with the observed spectrum. This selection allows us to constrain our search of the most appropriate template as those selected are within a certain age range. The final age determination is made in a second step by varying reddening and template values until the best match of continuum, Balmer and metal lines to that of the best fitting template is obtained. To perform reddening corrections, we used the standard reddening law of Seaton (1979) and the relation Av = 3E(B–V).

Results obtained for the whole GOC sample are shown in Table 1. The columns show: the first cluster designation, the derived foreground reddening E(B–V) value and the age finally adopted for the cluster, taking into account the Balmer and the template ages. Note that the uncertainty in the adopted E(B–V) values represents the minimum reddening variation needed to distinguish the cluster spectrum from that of the matching template. The E(B–V) derived for the whole sample range from 0.0 in ESO445-SC74 to 2.4 in Tr 27, while the ages vary from 3 Myr in NGC 6604 and BH 151 to 4 Gyr in Rup 2.

Table 1. GOC's parameters

Cluster	E(B–V)	Adopted age (Myr)
Berkeley 75	0.05±0.03	3000 1000
BH 132	0.60±0.05	150 50
BH 217	0.80±0.05	35 15
BH 87	0.10±0.03	150 50
Bochum 12	0.30±0.03	45 15
ESO429-SC13	0.00±0.03	100 20
Haffner 7	0.10±0.03	100 20
Hogg 11	0.24±0.05	8 6
Hogg 12	0.04±0.03	85 15
Hogg 15	1.05±0.05	4.5 2
Hogg 3	0.15±0.03	75 25
Lynga 11	0.12±0.03	450 50
Melotte 105	0.31±0.02	200 100
NGC 2368	0.12±0.03	50 10
NGC 2635	0.05±0.03	1500 500
NGC 5606	0.31±0.03	4.5 2
Pismis 17	0.19±0.04	4.5 2
Pismis 21	1.50±0.06	80 30
Ruprecht 144	0.32±0.03	150 50
vdB-RN 80	0.38±0.03	4.5 2
Basel 18	0.30±0.03	50±10
Berkeley 80	0.80±0.05	800±200
BH 151	1.70±0.08	3±1
Bochum 2	0.81±0.03	5±2
Berkeley 77	0.30±0.05	3500±1000
ESO324-SC15	0.00±0.02	1000±500
Dolidze 34	0.70±0.03	600±100
ESO429-SC2	0.30±0.03	7.5±2.5
ESO445-SC74	0.00±0.03	2500±1000
Hogg 10	0.50±0.03	30±10
Hogg 22	0.65±0.05	4.5±2.0
Hogg 9	0.05±0.01	300±100
Lynga 1	0.38±0.03	100±30
Markarjan 38	0.37±0.03	10±10
NGC 2311	0.15±0.02	300±50
NGC 2409	0.25±0.03	50±10
NGC 5281	0.25±0.03	30±5
NGC 6204	0.40±0.03	50±10
NGC 6604	1.20±0.05	3±1
Pismis 20	1.23±0.06	3±1
Pismis 24	1.90±0.06	5±2
Pismis 7	0.40±0.03	3000±1000
Ruprecht 2	0.10±0.03	4000±1000
Trumpler 21	0.20±0.03	30±10
Bochum 14	1.55±0.10	3±1
Ruprecht 158	0.05±0.03	700±300
BH 55	0.20±0.03	600±200
Ruprecht 159	0.25±0.05	2000±1000
BH 92	0.07±0.03	350±150
BH 90	0.08±0.03	600±300
Trumpler 15	0.50±0.10	5±3
Ruprecht 164	0.10±0.04	800±200
BH 121	0.45±0.03	3±1
Collinder 258	0.09±0.03	100±50
ESO065-SC07	0.35±0.03	2500±1000
Pismis 23	1.00±0.03	300±150
BH 205	0.31±0.02	10±5
NGC 6268	0.43±0.03	60±15
Trumpler 27	2.40±0.80	3±2
NGC 2587	0.00±0.03	1000±500
BH 58	0.03±0.05	400±200
NGC 3255	0.10 ±0.03	400 ±200
Sher 1	0.45 ±0.04	30±10
NGC 3590	0.25 ±0.03	40±20
NGC 4439	0.20 ±0.02	40±20
Hogg 14	0.29 ±0.03	300±50
NGC 4463	0.60 ±0.05	30±20
NGC 4609	0.05 ±0.02	100±20
Rup 107	0.30 ±0.04	3000±500
NGC 5168	0.25 ±0.03	100±50
BH 202	0.10 ±0.03	2000 ±500

GOCs template library

Efforts to create reference spectra of SCs in different spectral ranges and to define grids of their properties to be used as templates for different ages and metallicities in the study of composite stellar populations, were made by different authors, such as Bica & Alloin (1986a), Bica (1988), Bonatto et al. (1995), Santos et al. (1995) and more recently by Schiavon et al. (2005).

SCs may be considered as stellar population units of a given age and metallicity, so there spectral properties have been used for stellar population synthesis and interpretation of galaxy spectra. We collected part of the OCs spectra presented here and averaged them into templates, together with previously available spectra of well studied OCs, with a view of obtaining the highest possible S/N and higher time resolution to study their integrated light evolution (Piatti et al. 2002 and Ahumada et al. 2007). Figure 2 shows the spectral evolution up to intermediate ages (Ia and Ib) of stellar populations around the solar metallicity. For the youngest populations, we constructed different templates (Ya and Yb), taking into account the foreground, the mean (Ya2 and Yb2) and the internal reddening. Also, at these young ages, luminous stars play an important role in the resulting slope of the continuum energy distribution and they were taken into account (Y*-WR-SG).

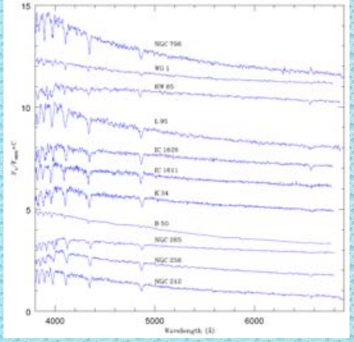

Figure 3. Observed integrated spectra of 11 SMC's clusters.

MCs' SCs

The study of extragalactic stellar systems provides relevant information on the star formation and chemical histories of the host galaxies. Despite the multiple observational as well as theoretical projects undertaken in the last years, our current knowledge of these processes is, in general, incomplete. Even for the galaxies in the Local Group. In this state of affairs, the SCs of the MCs, on account of their proximity, richness, and variety, may furnish us with the ideal ground to conduct a detailed examination of the processes mentioned before. One of the goals of the present study is to collect and analyze a large sample of MCs' SCs spectra with the aim of studying the integrated light properties of such metal deficient clusters, deriving their fundamental parameters; and making them available as template spectra complementing previous sub-solar metallicity libraries.

Cluster sample

The main denomination of the 42 observed SMC's SCs are shown in Table 2. Most of them are relatively populous and compact clusters to allow a good star sampling in the integrated spectra. Some of the SCs are very well known clusters and they were observed to have a template spectrum in the SMC at that age. Table 3 shows the denomination of the 54 LMC's SCs selected for this study. Most of the LMC clusters were classified as type II (30-70 Myr), according to the work of Searle, Wilkinson and Bagnuolo (1980). Figures 3 and 4 show a group of integrated spectra of SCs belonging to the LMC and SMC respectively.

Besides the template matching method mentioned before, we determined ages using diagnostic diagrams involving the sum of EWs of selected spectral lines together with the calibrations with age and metallicity by Santos. & Piatti (2004). By means of the Burstein & Heiles (1982) maps we determined another E(B-V) value, which turned out to be very similar to the one derived from the template matching method. E(B-V) colour excess values in the MCs appear all to be lower than 0.17. Tables 2 and 3 show the ages determined for SMC and LMC SCs respectively. Here we point out that few years ago, Piatti et al. (2007) constructed CMDs for three SCs of our sample (NGC643=L111, L114 and NGC796=L115) finding excellent agreement for NGC643 and NGC796, but for L114 the CMD age was much younger (140 Myr). This age difference probably arises because the integrated spectrum is influenced by bright late-type stars superimposed on the central part of the cluster.

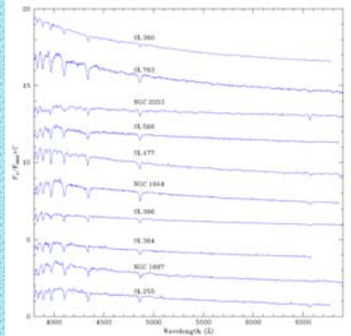

Figure 4. Observed integrated spectra of 10 LMC's clusters.

Future work

Among some previously-defined consecutive spectral groups, we are working on defined new GOC template spectra with the aim to refine the spectral library of Piatti et al. (2002) and to improve its temporal resolution. The present MCs data constitute part of the elements to enhance the spectral libraries at the metallicity levels of the SMC and LMC SCs. In a near future, we are planning to extend the existing libraries to the NIR and we will create new libraries for other metallicities, which will be very useful to study the stellar populations in more distant galaxies.

Table 2. Ages of SMC's clusters

Cluster	Adopted Age (Myr)	Cluster	Adopted Age (Myr)	Cluster	Adopted Age (Myr)
L 5	3000	NGC419	1200	B 50	< 10
K5	1200	L 114	5600	K 34	200
K3	7000	NGC643	1000	IC 1611	200
K6	1600	NGC416	5600	IC 1626	200
K7	3500	HW73	50	IC 1641	400
HW8	50	IC1624	50	L 95	60
NGC269	600	L 56	6	HW 85	10
L 39	15	NGC306	30	WG 1	10
K28, L 43	1500	L 48	40	NGC 796	100
NGC294	300	NGC290	30	NGC242	50
L 51	15	NGC265	100	L 28	1000
K42, L 63	45	NGC256	100	NGC121	12000
L 66	15	NGC241	20	NGC422	300

Table 3. Ages of LMC's clusters

Cluster	Adopted Age (Myr)	Cluster	Adopted Age (Myr)	Cluster	Adopted Age (Myr)
SL 551	40	NGC 1828	60	NGC 2136	60
SL 14	10	NGC 2097	800	NGC 2172	60
NGC 1695	70	SL 152	130	SL 234	50
NGC 1944	60	NGC2130	40	SL 56	70
SL58	65	H9	800	SL 116	50
SL79	100	NGC 1732	60	NGC1775	60
SL76	50	NGC2118	50	NGC 2000	50
HS 109	70	SL168	60	NGC 1986	50

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