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Age and metallicity of star clusters in the Magellanic Clouds*

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Abstract. Spectral indices as defined by the Lick group (Hβ, Mg$_2$, Fe5270, Fe5335 and NaD) were measured for a sample of 14 clusters in the Magellanic Clouds. Iron and hydrogen indices, together with the integrated colours (B-V) and (V-K) for these clusters, were used to estimate their ages and metallicities, using calibrations based on single stellar population models. The resulting ages and metallicities are in agreement with ages estimated from colour-magnitude diagrams, and metallicities derived from spectroscopic analises or narrow band photometry.

Key words: Magellanic Clouds – galaxies: star clusters – galaxies: abundances

1. Introduction

The study of stellar populations in galaxies beyond the Local Group has to rely on the analysis of their integrated light. Population synthesis models are therefore necessary to interpret the observed integrated properties, and to make predictions on the spread in age and metallicity of stars in unresolved stellar systems. Certainly, one of the main problems related to population synthesis is the coupling between age and metallicity, which are difficult to distinguish in integrated light (see Worthey 1994 and references therein). The Magellanic Clouds (MC) clusters of a wide range of ages and metallicities constitute a unique sample to test models on this old and yet not satisfactorily solved problem.

The calibration of narrow and wide band spectrophotometric indices for single stellar populations (SSP) is the first step to approach such a problem. Models for the calibrations of spectral indices in SSPs have recently been developed by several authors, using different methods (Barbuy 1994; Worthey 1994; Bressan et al. 1994; Borges et al. 1995), some of these restricted to old systems. An important question to be answered concerns the ability of models to disentangle age and metallicity effects.

Detailed abundance derivations in the Clouds are limited nowadays to young objects like HII regions (Dufour 1984; Garnett et al. 1995), planetary nebulae (e.g. de Freitas Pacheco et al. 1993) and supergiant stars (e.g. Hill et al. 1995, 1997).

The large number of star clusters in the Clouds, which amount to about 550 in the SMC (Bica & Schmitt 1995) and $>$ 2000 in the LMC (Olszewski et al. 1996), showing ages between a few million years up to 14 Gyr, make them interesting probes to check population synthesis models as well as the chemical evolution of these nearby galaxies.

Spectral indices measurements combined to such methods were practically never applied to clusters in the Magellanic Clouds (MC). Nevertheless, we should mention the work by Bica et al. (1990), who performed a study on young MC clusters ($\tau < 0.5$ Gyr), aiming to carry out population synthesis of starburst galaxies.

In the present work we apply SSP models that we have developed in the past few years to MC clusters. The accuracy of our age and metallicity determination based on integrated indices is checked against well-determined ages obtained with Colour-Magnitude Diagrams (CMDs) and metallicities derived from spectroscopy of individual stars.

We have observed a sample of 14 objects amongst those most well studied clusters in the Clouds. These objects will also make a basis for future studies.

In Sect. 2 the observations are reported and spectral indices measured are given. In Sect. 3 the method for age and metallicity derivation is described. In Sect. 4 the application of the method to individual clusters is discussed. Conclusions are given in Sect. 5.

2. Observations

2.1. Data reduction

A sample of 6 clusters in the SMC and 8 ones in the LMC were respectively observed at the *Laboratório Nacional de Astrofísica* (LNA), Brazil and the *European Southern Observatory* (ESO), Chile.

The SMC data were obtained with a Boller & Chivens Cassegrain spectrograph attached to the 1.6m telescope of the

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* Based on observations collected at the European Southern Observatory, La Silla, Chile and the Laboratório Nacional de Astrofísica, Pico dos Dias, Brazil

LNA. The detector was a SITE CCD camera of 1024x1024 pixels with pixel size of 24 μm used with a grating of 900 l/mm. This allows a reciprocal dispersion of 1.3 Å/pixel and an average spectral resolution of 5 Å(FWHM). Spectra were centered at Mgb λ5170, including the indices Hβ λ4861, Fe λ5270, Fe λ5335 and Mg$_2$. A slit of 3' x 1", with a fixed E-W orientation was used for all objects, centered in their brightest regions.

The LMC data were obtained at the 1.52m ESO telescope also with a Boller & Chivens Cassegrain spectrograph and the CCD ESO # 39 with 2048x2048 pixels, and a pixel size of 15 μm. A grating of 400 l/mm allowed a reciprocal dispersion of 2.8 Å/pixel. Spectra were also centered at Mg b, including the previous indices and the NaD λ5895. As before, the slit (4.1'x 2") was centered in the brightest regions, but the orientation (N-S or W-E) was adopted in order to optimize the observations.

Most of the objects were observed at least twice, with a typical integration exposure of about 30 minutes. Incandescent and HeAr lamps were observed for flat-field correction and wavelength calibration. Spectrophotometric standard stars (Taylor 1984 and Stone & Baldwin 1983) were measured on each night for flux calibration. Additionally, 8 bright stars were observed for a correct scaling to the Lick system (Idiart & Freitas Pacheco 1995).

Reductions were carried out using the IRAF package in the standard way: bias subtraction, flatfield correction, spectra extraction, wavelength and flux calibrations as well as atmospheric extinction correction. Spectra of four sample clusters are shown in Fig. 1. The log of observations is given in Table 1.

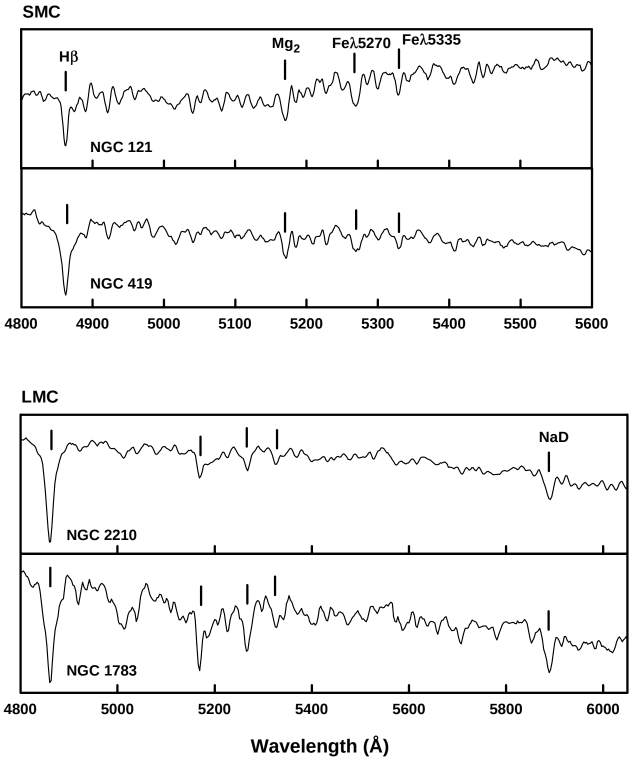

Fig. 1. Integrated spectra of globular clusters in the SMC and LMC. Each spectrum is the sum over at least 2 integrations. Observed features are indicated.

2.2. Spectral Indices

The indices Hβ, Mg$_2$, Fe5270, Fe5335 and NaD were measured using the continuum and central bandpasses defined by Faber et al. (1985). Observational errors were estimated from the rms deviation for different measurements for each object and weighted by their integration time. Deviations from the Lick system were corrected using observations of common stars. In the case of SMC clusters, no common stars were observed, and we have used the corrections derived by Idiart & de Freitas Pacheco (1995), since their data were obtained with the same equipment. Table 2 gives the resulting indices for the MC clusters with their respective error estimates.

3. Age and metallicity derivation

Borges et al. (1995) and Idiart et al. (1997) computed a series of SSP models from which integrated spectrophotometric indices and colours were derived as a function of age, metallicity and relative abundances. For the sake of completeness, we just recall here the basic assumptions on which those models are founded.

The mass spectrum was assumed to be a power law with an exponent equal to 2.35 (Salpeter's law). The evolutionary tracks used in the calculations are those of VandenBerg et al. (1983) for masses lower than 0.6 $M_\odot$ and those by Bressan et al. (1993) and Fagotto et al. (1994a,b,c) for higher values. In order to obtain a required grid density in the plane "mass vs. metallicity", we have constructed by interpolation-extrapolation, and by using 2D spline techniques, a library of about 1000 tracks. The accuracy of these tracks was checked by comparing evolutionary trajectories generated by our procedure to original ones. Differences were always within 10-15 % although errors in some extrapolated tracks may be slightly higher. Bolometric and colour transformations to an observational CMD were taken from VandenBerg (1992). The relations between indices and stellar parameters are empirical, and can be found in the original papers by Idiart & de Freitas Pacheco (1995) and Borges at al. (1995).

Our models provide a series of equations of the form

$$X_i = F_i(\tau, [Fe/H])$$

where X_i is a given index as a function of age (τ) and metallicity ($[Fe/H]$). In the present work the indices $<$ Fe $>$, Hβ, $(B-V)_o$ and $(V - K_{CIT})$ were used to derive ages and metallicities. Explicit fitting formulae derived from our models are given in Borges et al. (1995) for the first three indices. The (B-V) colours were adopted from van den Bergh (1981) and Gordon & Kron (1983).

The colour $(V - K_{CIT})$ was synthesized using the same procedure described above, adopting the temperature scale, $\log g$ and $(V - K_{\rm CIT})_0$ from the work by Frogel et al. (1983), since the $(V - K_{\rm CIT})$ data for the MC clusters by Persson et al. (1983) were obtained in the same photometric system. The derived expression is:

$$(\mathrm{V} - \mathrm{K_{CIT}}) = 2.676 + 0.180 \ln\tau + 0.547[\mathrm{Fe/H}]$$

Table 1. Log of observations. In the last column is given the SWB type (Searle et al. 1980), in some cases revised by Bica et al. (1986).

Cluster	α (2000)	δ (2000)	Tel.	sp. range (Å)	Date	N_{exp}	T_{exp} (min)	V	SWB type
SMC									
Kron 3	00 24 46	-72 47 38	LNA	4700-5600	02.08.1996	2	30+30	12.05	(V)/VI,VII
NGC 121	00 26 43	-71 31 57	LNA	4700-5600	02.08.1996	3	30+30+30	11.24	VII
NGC 339	00 57 45	-74 28 12	LNA	4700-5600	02.08.1996	2	30+30	12.84	VII
NGC 411	01 07 53	-71 46 01	LNA	4700-5600	03.08.1996	3	25+25+20	12.21	V/VI
			LNA	4700-5600	04.08.1996	2	40+40		
NGC 416	01 08 08	-72 21 01	LNA	4700-5600	03.08.1996	3	30+30+30	11.42	VI
NGC 419	01 08 24	-72 53 01	LNA	4700-5600	03.08.1996	3	30+30+30	10.61	V
LMC									
NGC 1466	03 44 34	-71 40 24	ESO	4000-9751	19.02.1997	2	30+30	11.59	VII
NGC 1783	04 59 09	-65 59 18	ESO	4000-9751	19.02.1997	3	30+30+30	10.93	V
NGC 1795	04 59 48	-69 48 04	ESO	4000-9751	21.02.1997	2	30+30	12.42	V
NGC 1978	05 28 46	-66 14 14	ESO	4000-9751	18.02.1997	2	20+30	10.70	VI
			ESO	4000-9751	20.02.1997	3	30+30+30		
NGC 2121	05 48 13	-71 28 52	ESO	4000-9751	22.02.1997	2	30+30	12.37	VI
NGC 2173	05 57 59	-72 58 45	ESO	4000-9751	20.02.1997	2	30+30	11.88	V/VI,VI
NGC 2210	06 11 32	-69 07 20	ESO	4000-9751	18.02.1997	2	30+30	10.94	VII
			ESO	4000-9751	20.02.1997	3	30+30+30		
Hodge 11	06 14 24	-69 50 52	ESO	4000-9751	19.02.1997	3	30+30+30	11.93	VII

Table 2. Measured spectral indices

Cluster	Hβ	Fe52	Fe53	Mg$_2$	NaD
SMC					
Kron 3	3.34±0.68	0.88±0.93	1.35±0.29	0.043±0.006	–
NGC 121	1.78±0.30	1.55±0.30	0.95±0.20	0.078±0.006	–
NGC 339	3.85±0.30	0.05±0.20	2.64±0.20	0.072±0.006	–
NGC 411	4.04±0.06	2.07±0.13	1.52±0.08	0.065±0.001	–
NGC 416	2.62±0.15	1.34±0.04	0.70±0.08	0.042±0.005	–
NGC 419	4.06±0.06	1.84±0.09	1.40±0.33	0.052±0.008	–
LMC					
NGC 1466	2.48±0.20	1.38±0.22	0.98±0.36	0.048±0.005	1.16±0.09
NGC 1783	2.90±0.28	1.77±0.28	1.21±0.22	0.099±0.005	1.18±0.16
NGC 1795	3.41±0.32	0.88±0.27	1.71±0.61	0.099±0.015	1.49±0.27
NGC 1978	3.01±0.20	1.81±0.23	1.44±0.34	0.109±0.006	1.34±0.10
NGC 2121	3.12±0.26	2.65±0.29	3.51±0.49	0.184±0.029	3.27±0.39
NGC 2173	2.70±0.17	1.86±0.44	1.17±0.47	0.117±0.006	1.92±0.13
NGC 2210	2.60±0.18	1.09±0.18	0.82±0.18	0.036±0.004	0.81±0.08
Hodge 11	3.07±0.52	1.05±0.40	0.37±0.20	0.017±0.010	1.01±0.36

A numerical code searches the pair (τ, $[Fe/H]$) which gives for each object the best fit between the set of observational parameters and model predictions. The code allows one to assign relative weights to different indices, according to the data quality. Errors were estimated by linearizing the set of equations defining the considered indices with respect to metallicity and fractional age (see also de Freitas Pacheco 1997). Then, for each object the error matrix was calculated. For the colours (B-V) and (V-K) we have adopted errors of 0.05 and 0.15 mag respectively.

In Table 3 we compare ages derived from our method with those obtained from CMDs. Inspection of Table 3 indicates that ages can be estimated with an uncertainty of about 40% for young and intermediate age clusters. For older objects, the relative error increases up to 50%. These results are comparable to the study on M31 clusters by de Freitas Pacheco (1997), where the same procedure was applied. In Table 4 we compare the metallicities we have derived with those in the literature. Typical errors in the metallicity estimates are of the order of 0.28 dex, which are slightly higher than spectroscopic estimates of individual stars. Ages and metallicities of individual clusters will be discussed in the next section.

It is interesting to compare the synthesized indices with the observed ones, to give an idea of the fitting quality. This is done in Table 5: the first entry of each object corresponds to the present data whereas the second entry corresponds to theoretical values. First of all, we notice that no systematic effects are

Table 3. Ages: values obtained with the present models compared with the literature

Cluster	present	literature	ref.
LMC			
NGC 1466	12±6	≥ 12	1
NGC 1783	3.0±1.3	1.1	1
NGC 1795	1.9±1.0	0.8-1.1, 0.9	1,2
NGC 1978	3.0±1.0	2,2	1,3
NGC 2121	1.5±0.6	0.4-0.7, 1.4	1,2
NGC 2173	4.0±1.6	1.8, 1.4, 1.15	1,2,4
NGC 2210	12±5	≥ 12, 14, 15	1,2,5
Hodge 11	14±8	12,14,15	1,2,6
SMC			
Kron 3	3.5±1.5	5,5-8	2,7
NGC 121	12±5	9,12	2,8
NGC 339	2.0±0.7	3	2
NGC 411	1.3±0.5	1.2	2
NGC 416	4.0±1.5	2.5	2
NGC 419	1.2±0.5	1.3	2

References to Table 3: 1 Sagar, R., Panday, A.K. 1989, A&AS, 79, 407; 2 Seggewiss, W., Richtler, T. 1989, in *Recent developments of MC Research*, eds. K.S. de Boer, F. Spite & G. Stasinska, Obs. de Paris, p. 45 3 Bomans, D.J., Vallenari, A., de Boer, K.S. 1995, A&A, 298, 427; 4 Girardi, L., Chiosi, C., Bertelli, G., Bressan, A. 1995, A&A, 298, 87; 5 Brocato, E., Castellani, V., Ferraro, F.R., Piersimoni, A.M., Testa, V. 1996, MNRAS, 282, 614; 6 Mighell, K.J., Rich, R.M., Shara, M., Fall, S.M. 1996, AJ, 111, 2314; 7 Rich, R.M., Da Costa, G.S., Mould, J.R. 1984, ApJ, 286, 517; 8 Stryker, L.L., Da Costa, G.S., Mould, J.R. 1985, ApJ, 298, 544

Table 4. Metallicities: values obtained with the present models compared with literature

Cluster	present	literature	ref.
LMC			
NGC 1466	-1.70±0.40	-2.0,-2.17,-1.85	1,2,3
NGC 1783	-0.75±0.23	-0.45	1
NGC 1795	-0.44±0.30	-0.23	2
NGC 1978	-0.60±0.21	-0.42,-0.4	2,4
NGC 2121	-0.10±0.21	-0.95,-0.61	1,2
NGC 2173	-0.50±0.28	-0.75,-0.24	1,2
NGC 2210	-1.85±0.40	-2.0,-1.97	1,2
Hodge 11	-2.40±0.50	-2.1,-2.06,-2.0	1,2,5
SMC			
Kron 3	-1.00±0.28	-0.6,-1.2	1,6
NGC 121	-1.20±0.32	-1.1,-1.4	1,7
NGC 339	-0.70±0.22	-1.5	8
NGC 411	-0.70±0.22	-0.9	1
NGC 416	-0.80±0.23	> -1.0	1
NGC 419	-0.60±0.21	> -1.0	1

References to Table 4: 1 Seggewiss, W., Richtler, T. 1989, in *Recent developments of MC Research*, eds. K.S. de Boer, F. Spite & G. Stasinska, Obs. de Paris; 2 Olszewski, E.W., Schommer, R.A., Suntzeff, N.B., Harris, H.C.: 1991, AJ, 101, 515; 3 Suntzeff, N.B., Schommer, R.A., Olszewski, E.W., Walker, A.R. 1992, AJ, 104, 1743; 4 Bomans, D.J., Vallenari, A., de Boer, K.S. 1995, A&A, 298, 427; 5 Mighell, K.J., Rich, R.M., Shara, M., Fall, S.M. 1996, AJ, 111, 2314; 6 Rich, R.M., Da Costa, G.S., Mould, J.R. 1984, ApJ, 286, 517; 7 Stryker, L.L., Da Costa, G.S., Mould, J.R. 1985, ApJ, 298, 544; 8 Bica, E., Dottori, H., Pastoriza, M. 1986, A&A, 156, 261

present in the indices (B-V), (V-K) and $< Fe >$. The dispersion of the differences $(X_{theor} - X_{obser})$ are consistent with the observational errors. However, in the case of the index $H\beta$, we found that our best fit models are, on the average, 0.12 Å smaller than the observed values. In the case of old clusters, the horizontal branch stars give an important contribution to the total Hβ strength (de Freitas Pacheco & Barbuy 1995). For young clusters, it is possible that advanced evolutionary stages contributing to this index are not properly taken into account. Recent HST UV-imaging with WFPC2 by Cole et al. (1997) revealed a number of "anomalous" UV-bright stars in the intermediate age LMC cluster NGC 1783. Such evolved stars are not included in our code and might contribute to strengthen the Hβ index.

For comparison, we have also synthesized the indices <Fe>, Hβ and (B-V)$_o$ using Worthey's models (Worthey 1994) for ages and metallicities derived in this work. The agreement is quite good and residuals are comparable to our own results. However the $H\beta$ index, as in our model calculations, show a systematic difference of about 0.11 Å, comparable but in the opposite sense relative to the values found from our models.

In Fig. 2 the derived metallicities [Fe/H] are plotted against age for our sample clusters. The temporal metal enrichment of both galaxies is clearly seen, but they are probably a consequence of different evolutionary histories. The age gap seen in the LMC, with no clusters in the age range between 6-10 Gyrs, is not confirmed in HST studies of the field stellar population (e.g. Gallagher et al. 1996). This means that, for the LMC, the clusters can be used as probes of the chemical enrichment, but the field star distribution has to be used to derive star formation rates. The age-metallicity relation for both galaxies will be discussed in a forthcoming paper.

4. Comments on individual clusters

Ages and metallicities for the sample clusters available in the literature are summarized in Tables 3 and 4.

The metallicities and ages available until 1989 were compiled by Sagar & Pandey (1989) and Seggewiss & Richtler (1989), and those values are reported here. For more recent data the references are given in the notes to Tables 3 and 4.

NGC 1795, NGC 1978, NGC 411, NGC 416, NGC 419

For these young and intermediate age clusters, ages and metallicities derived here are in agreement with other determinations.

NGC 2210, Hodge 11

These are two old clusters in the LMC. In spite of the large error in our age estimates, they agree with CMD determinations.

Table 5. Comparison of observed indices with synthesized ones.

Cluster	Hβ	$<$ Fe $>$	(B-V)$_o$	(V-K$_{CIT}$)$_o$
SMC				
Kron 3	3.33	1.12	0.62	2.12
	3.04	1.10	0.61	2.35
NGC 121	1.78	1.25	0.70	2.25
	2.08	1.22	0.72	2.46
NGC 339	3.84	1.34	0.62	2.21
	3.37	1.33	0.62	2.41
NGC 411	4.04	1.80	0.55	–
	3.92	1.21	0.57	2.34
NGC 416	2.62	1.02	0.69	2.26
	2.72	1.38	0.67	2.48
NGC 419	4.06	1.62	0.59	2.84
	3.90	1.33	0.58	2.38
LMC				
NGC 1466	2.48	1.18	0.59	2.12
	2.43	0.81	0.63	2.19
NGC 1783	2.90	1.49	0.53	2.33
	2.97	1.37	0.65	2.46
NGC 1795	3.41	1.30	0.71	–
	3.14	1.70	0.67	–
NGC 1978	3.01	1.62	0.67	2.58
	2.82	1.59	0.68	2.54
NGC 2121	3.12	3.08	0.74	3.12
	3.05	2.24	0.74	2.70
NGC 2173	2.70	1.52	0.77	2.99
	2.50	1.82	0.74	2.65
NGC 2210	2.60	0.96	0.61	1.90
	2.54	0.73	0.60	2.11
Hodge 11	3.07	0.71	0.52	–
	2.84	0.60	0.52	1.84

Metallicities indices for Hodge 11 are quite small, confirming that this cluster is indeed a metal poor object similar to galactic halo clusters.

NGC 1466

Our results are in good agreement with the most recent [Fe/H] values by Suntzeff et al. (1992), and the old age indicated in Sagar & Panday (1989).

NGC 1783

Mould & Aaronson (1982) estimated an age of 4 Gyr for this cluster, based on the presence of asymptotic giant branch (AGB) stars, among which 2 carbon stars. On the other hand, based on isochrone fitting of turn-off Gunn-Thuan photometry, Mould et al. (1989) obtained an age of 0.9±0.4 Gyr. The age of 3 Gyr derived in the present work is consistent with the above age range, but closer to the earlier estimation of 4 Gyr. Our derived metallicity of [Fe/H] = -0.75 is consistent, within errors, with the unique metallicity determination of -0.45 by Cohen (1982).

NGC 2121

For this cluster, the age we find is compatible with the literature values, but our <Fe> index indicates a metallicity higher than previous values (Table 4). Our data for this object are rather noisy so that we cannot presently claim that NGC 2121 is a metal rich object. Therefore, it would be interesting to carry out detailed analyses of individual stars, and in particular to check if calcium is deficient relative to iron, since the Olszewski et al. (1991) metallicity determination is based on the near-infrared CaII triplet.

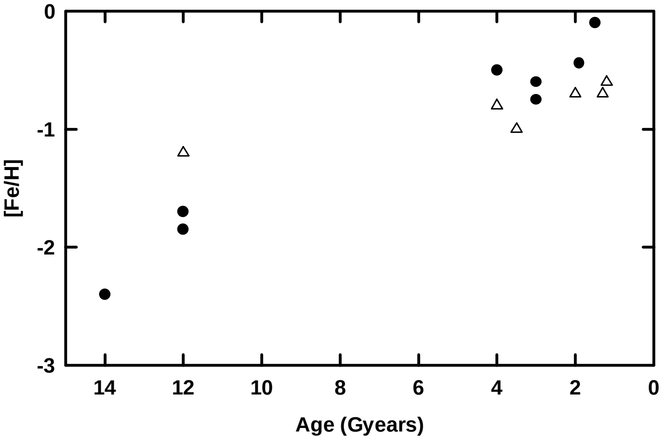

Fig. 2. Age-metallicity data for the LMC (black dots) and the SMC (open triangles)

NGC 2173

For this cluster, the metallicity is consistent with literature values, whereas our derived age (4 Gyr) is older than CMD estimates (1.2 - 1.8 Gyr), but compatible within errors.

NGC 121

For this unique old and metal-poor SMC cluster, the ages and metallicities derived here are among the best determined, in terms of accuracy obtained in our method, and in very good agreement with the literature.

NGC 339

Curiously not much attention has been given to this bright cluster. Our age determination of 2 Gyr is in agreement with the unique age determination by Olszewski et al. (1988) of 3 Gyr. However the classification of NGC 339 as SWB class VII is not compatible with this intermediate age.

The only metallicity determination of [Z/Z$_\odot$] = -1.5 by Bica et al. (1986) was based on DDO indices and their metallicity calibration was based on Galactic globular clusters. We note that [α-elements/Fe] $\approx$ 0.4 for the Galactic globulars, whereas [O/Fe] $\approx$ -0.2 for the LMC young stars (Hill et al. 1997), and this could be a possible explanation for the discrepancy with our value of [Fe/H] = -0.7 (if the cluster is indeed young).

Kron 3

The metallicity we derive is in good agreement with the literature (Rich et al. 1984 and references therein). The age determinations in the literature range between $4 < \tau < 8$ Gyr. Rich et al. give 5 Gyr for a SMC distance modulus of (m-M) = 19.3 or 8 Gyr for (m-M) = 18.8. Massey et al. (1995) from the study of 512 young stars in SMC have estimated, via spectroscopic parallax, a distance modulus of 19.1±0.3 which would favour our age estimate.

We can conclude that for a few clusters some discrepancy with literature values reveal in which cases new CMDs and detailed spectrocopic analyses are necessary: in particular, the metallicity of NGC 2121 and the age of Kron 3 are to be further checked.

5. Summary

We have obtained integrated spectra for 14 clusters in the Magellanic Clouds, on which the spectral indices Hβ, Mg$_2$, Fe5270, Fe5335 and NaD, as defined by Faber et al. (1985), were measured. As far as we know, no other similar measurements are reported in the literature for MC objects.

Selecting indices whose behaviour depends essentially on age and metallicity (Hβ and $< Fe >$), together with (B-V) and (V-K) colours, we were able to determine ages and metallicities for these clusters, using calibrations based on single stellar population models (Borges et al. 1995).

The comparison of our results for ages and metallicities with literature values, based on CMDs and spectroscopy of individual giants are quite satisfactory, and encourages to further exploit this method.

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