Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY LETTERS

Mon. Not. R. Astron. Soc. **418,** L69–L73 (2011) doi:10.1111/j.1745-3933.2011.01145.x

Towards a comprehensive picture of the star cluster age–metallicity relationship in the Small Magellanic Cloud

Andrés E. Piatti★

Instituto de Astronomía y Física del Espacio, CC 67, Suc. 28, 1428 Ciudad de Buenos Aires, Argentina

Accepted 2011 August 25. Received 2011 August 16; in original form 2011 August 5

ABSTRACT

We present the results on the age and metallicity estimates of 11 Small Magellanic Cloud (SMC) clusters obtained from CCD Washington CT_1T_2 photometry. The 11 clusters reproduce the ∼2 Gyr bursting formation paradigm when entering them into the age–metallicity relationship (AMR). Once these clusters were added to the largest known SMC cluster sample with ages and metallicities put into an homogeneous scale, we found that a comprehensive picture of the cluster AMR can be obtained, which includes the following components: two enhanced formation processes at $t \sim 2$ and 5–6 Gyr, which have taken place throughout the entire body of the galaxy; the absent of a metallicity gradient and a relative spread in metallicity for clusters older than ∼7 Gyr. Furthermore, such picture should not significantly change due to incompleteness in the number of studied clusters. Indeed, based on the statistics of catalogued and studied clusters, we found that a total of seven relatively old/old clusters have not yet studied, and even a smaller number is obtained if the cluster spatial distribution is considered.

Key words: techniques: photometric – galaxies: individual: LMC – Magellanic Clouds – galaxies: star clusters: general.

1 INTRODUCTION

The study of the age–metallicity relationship (AMR) of Small Magellanic Cloud (SMC) clusters has been the subject of an exciting debate which has led to interesting different results. Briefly, Da Costa (1991) noted from results of nine clusters that the most metal-poor ones have similar metallicities and apparently very different ages, indicating that this galaxy has experienced an unusual chemical enrichment history. Then, Mighell, Sarajedini & French (1998) using results of seven additional clusters found that a theoretical model punctuated by bursts of star formation is in better agreement with their observational data than a closed-box continuous star formation model. The bursting cluster formation at ∼2 Gyr was successively confirmed from both observational (Piatti et al. 2001, 2005) and theoretical (Bekki et al. 2004) results, the former being obtained from 15 studied clusters in addition to the previously known cluster sample. However, Rich et al. (2000) found that seven clusters studied by them are congregated in two different age bins: one at 2 ± 0.5 Gyr and another at 8 ± 2 Gyr, the latter being recently also predicted theoretically (Tsujimoto & Bekki 2010).

On the other hand, Kayser et al. (2007) presented for the first time an AMR that is fully based on spectroscopic metallicity estimates for 12 clusters. This relation shows that at a given age there may be a metallicity spread of up to 0.4 dex, which exceeds the uncertainties in [Fe/H] by a factor of 3, thus leading the authors to conclude that the SMC has experienced a complex star formation history (SFH). However, Piatti et al. (2008) using ages and metallicities of 39 clusters found a more simple interpretation for the SMC SFH, in the sense that the further a cluster is from the centre of the galaxy, the older and more metal poor it is, with some dispersion, although clusters associated with the Magellanic Bridge clearly do not obey the general trend. On the other hand, Parisi et al. (2009) did not arrive to results similar to those of Carrera et al. (2008, see their fig. 13), although both used Ca II triplet spectroscopy of 14 clusters and 350 red field giants, respectively. While Parisi et al. did not account for any indication of a radial metallicity gradient, Carrera et al. (2008, see their fig. 13) obtained AMRs similar to those obtained by Piatti et al. (2008). Finally, Piatti (2011, hereafter P11) has recently presented an updated version of the cluster AMR using ages and metallicities for 50 clusters, and the resulting dispersion in these quantities appears to blur the apparent clear understanding of the AMR arrived one decade ago. Obviously, further and more detailed work would appear to be needed to clarify and quantify these last suggested trends.

The question arises unavoidably: what final picture of the SMC AMR will lead the increase in the studied cluster sample to? Precisely, in this Letter we present results which allow us to reach a comprehensive picture of the observed cluster SMC AMR. As far as we are aware, subsequent results should not substantially change

★E-mail: andres@iafe.uba.ar

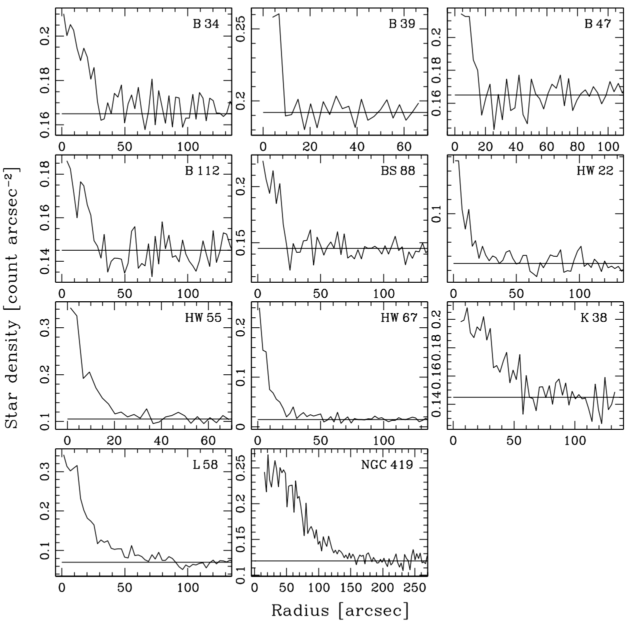

Figure 1. Density profiles for the studied clusters.

the present conclusions, unless significative corrections must be introduced in the cluster ages and metallicities and/or an important percentage of faint old clusters is discovered. The Letter is organized as follows. Section 2 describes the analysis of 11 poorly studied intermediate-age clusters [IACs; $1 \lesssim t\,(\mathrm{Gyr}) \lesssim 8$] whose ages and metallicities show clear signs of the ∼2 Gyr bursting formation episode. Section 3 deals with the aforementioned question, whereas Section 4 summarizes our results.

2 FUNDAMENTAL PARAMETERS OF POORLY STUDIED IACs

P11 performed a search within the National Optical Astronomy Observatory (NOAO) Science Data Management archives[1] looking for Washington photometric data towards the SMC. As a result, he found images corresponding to 11 different fields spread throughout the SMC obtained at the Cerro Tololo Inter-American Observatory 4-m Blanco Telescope with the Mosaic II camera attached ($36 \times 36\,\mathrm{arcmin}^2$ field on to an $8\,\mathrm{K} \times 8\,\mathrm{K}$ CCD detector array). They encompass 124 catalogued star clusters (Bica et al. 2008). When examining their colour–magnitude diagrams (CMDs) and colour–colour diagrams, we found nine relatively old clusters (see his cited letter), 11 IACs (present studied sample), 14 clusters with some sign of evolution, 37 very young clusters and 53 asterisms (a detailed study will be presented in a forthcoming paper). Since we are interested in clusters older than ∼1 Gyr, we focus herein on the 11 identified IACs, namely B 34, 39, 47, 112, BS 88, HW 22, 55, 67, K 38, L 58 and NGC 419. Particularly, B 34 (Piatti et al. 2007) and NGC 419 (Piatti et al. 2008) served us as control clusters for age and metallicity estimates.

Following the route outlined by P11 for the reduction and the analysis of the data, and for the estimation of the cluster ages and metallicities, Fig. 1 depicts the cluster radial profiles which served us to adopt representative cluster radii (see column 2 of Table 1). Then, we carried out a statistical field star cleaning in the cluster CMDs to highlight the cluster features we are interested in, namely the red clump (RC) and the main-sequence turnoff (MSTO). These features are used to estimate the cluster ages from the δT_1 index defined by Geisler et al. (1997) (see columns 4–6 of Table 1). Note that this age measurement technique does not require absolute photometry. The resultant CMDs do contain not only cluster stars but also the unavoidable residuals. Fig. 2 shows the observed cluster CMDs (left-hand panel), the respective equal area star field CMDs (middle panel) and the resultant cleaned cluster CMDs (right-hand panel). Note that, for example, we hardly reach the MSTO of HW 22, mainly due to crowding effect. In addition, B 39 resulted to be the nearest cluster of the sample (Crowl et al. 2001).

Finally, the cluster metallicities have been estimated by comparing the cluster red giant branches (RGBs) with the standard fiducial globular cluster RGBs from Geisler & Sarajedini (1999). The scattering of the data in the $[M_{T_1}, (C - T_1)_0]$ plane, with the different iso-abundance lines superimposed, was used to assign the random errors to the metallicities. To enter in this diagram, we corrected the observed T_1 magnitudes and $C - T_1$ colours by using a distance modulus of $(m - M)_0 = 18.90 \pm 0.10$ recently reported by Glatt, Grebel & Koch (2010) and reddening values taken from the Burstein & Heiles (1982) extinction map (column 3 of Table 1). This derived metallicity was then corrected for age effects via the prescription given in Geisler et al. (2003). The resulting metallicities are listed in the last column of Table 1, where we took into account errors associated with the age correction.

Fortunately, the ages and metallicities derived for B 34 and NGC 419 are in excellent agreement with the values previously published by Piatti et al. (2007) and Piatti et al. (2008), respectively. We also checked the derived ages by fitting theoretical isochrones of Girardi et al. (2002) to the cluster CMDs (see right-hand panels of Fig. 2). We used isochrones for $Z = 0.001$, 0.004 and 0.008 since there is none available for $Z = 0.002$, and confirmed the derived cluster ages of Table 1, the average metallicity differences (absolute values) being within 0.1 dex. We recall that Chiosi et al. (2006) and Glatt et al. (2010) have studied some of the present studied clusters assuming that they are clusters younger than 1 Gyr. As they mentioned, this could be due to their limited photometric depth and/or biased field star contamination cleaning.

3 COMPREHENSIVE PICTURE OF THE CLUSTER AMR

The 11 studied clusters astonishingly tightly reproduce the bursting SFH of Pagel & Tautvaišienė (1998), represented in the bottom left-hand panel of Fig. 3 by blue boxes and a solid line, respectively. In the figure, black boxes correspond to the largest known cluster sample compiled by P11 with ages and metallicities put into the same present scale. Therefore, up to now, the cluster SMC AMR can be described by two phases: an earlier epoch (age $\gtrsim$ 2.5 Gyr) wherein any remarkable trend does not apparently prevail, and the bursting epoch (age $\lesssim$ 2.5 Gyr) engraved by a large development in [Fe/H]. Since the former epoch is more susceptible to changes in our understanding, any effort to improve our knowledge of ages and metallicities of clusters older than 2.5 Gyr is welcome.

We assume for the SMC cluster spatial distribution the elliptical framework used by Piatti et al. (2007, see their fig. 7) depicted in the top left-hand panel of Fig. 3. Then, bearing in mind the cluster sample catalogued by Bica et al. (2008) and the cluster sample studied until now (distinguishing those younger and older than 2.5 Gyr), we calculated the number of clusters older than 2.5 Gyr that presumably have not been yet studied. The studied cluster sample consists

[1] http://www.noao.edu/sdm/archives.php

Table 1. Fundamental parameters of SMC clusters.

Name	r (arcsec)	$\langle E(B-V)\rangle$ (mag)	T_1(MSTO) (mag)	T_1(RC) (mag)	δT_1 (mag)	Age (Gyr)	[Fe/H]
B 34	30 ± 10	0.03	20.20 ± 0.10	19.00 ± 0.05	1.20 ± 0.15	1.50 ± 0.10	-0.70 ± 0.25
B 39	10 ± 5	0.01	19.20 ± 0.10	18.00 ± 0.10	1.20 ± 0.20	1.50 ± 0.15	–
B 47	15 ± 5	0.01	20.00 ± 0.20	18.90 ± 0.10	1.10 ± 0.30	1.40 ± 0.20	-0.30 ± 0.25
B 112	30 ± 10	0.05	20.10 ± 0.10	18.80 ± 0.05	1.30 ± 0.15	1.60 ± 0.15	-0.70 ± 0.25
BS 88	20 ± 5	0.04	20.40 ± 0.10	18.80 ± 0.05	1.60 ± 0.15	2.00 ± 0.20	-0.70 ± 0.25
HW 22	20 ± 10	0.06	21.50 ± 0.15	18.90 ± 0.05	2.70 ± 0.20	6.00 ± 1.30	-1.30 ± 0.25
HW 55	20 ± 5	0.02	20.90 ± 0.20	19.00 ± 0.10	1.90 ± 0.30	2.50 ± 0.70	-1.00 ± 0.25
HW 67	20 ± 5	0.02	20.70 ± 0.10	18.70 ± 0.10	2.00 ± 0.20	2.80 ± 0.60	-1.20 ± 0.25
K 38	60 ± 10	0.02	20.90 ± 0.20	18.80 ± 0.15	2.10 ± 0.35	3.10 ± 1.10	-1.10 ± 0.25
L 58	70 ± 10	0.02	20.40 ± 0.15	18.80 ± 0.05	1.60 ± 0.20	2.00 ± 0.30	-0.90 ± 0.25
NGC 419	150 ± 20	0.03	20.00 ± 0.15	18.90 ± 0.10	1.10 ± 0.25	1.40 ± 0.20	-0.50 ± 0.25

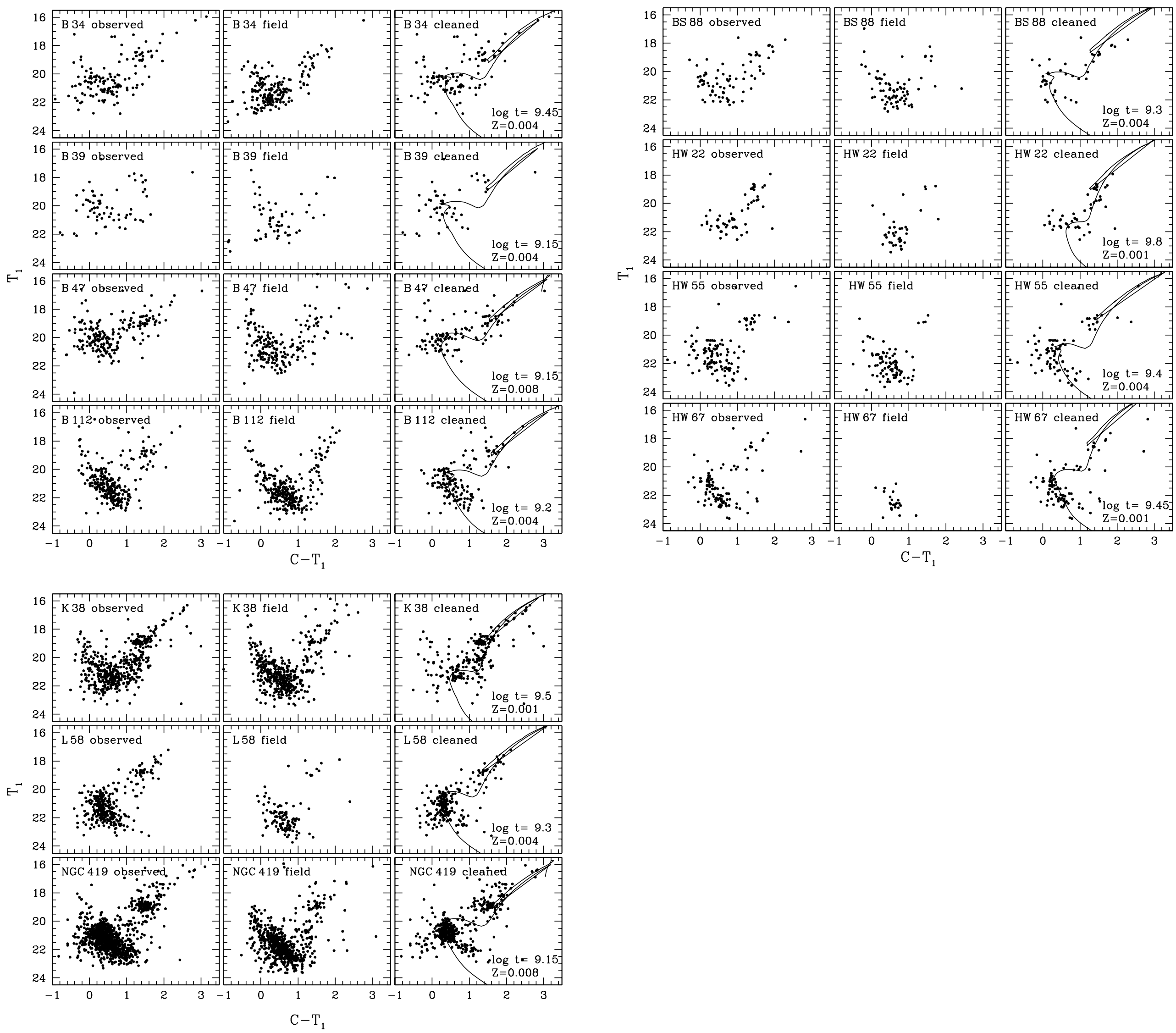

Figure 2. Extracted Washington T_1 versus $C - T_1$ CMDs for stars distributed within the cluster radius (left), the cluster surrounding field for an equal cluster area (middle) and the cluster cleaned from field contamination (right). The available isochrone of Girardi et al. (2002) which best resembles the cluster feature is overplotted.

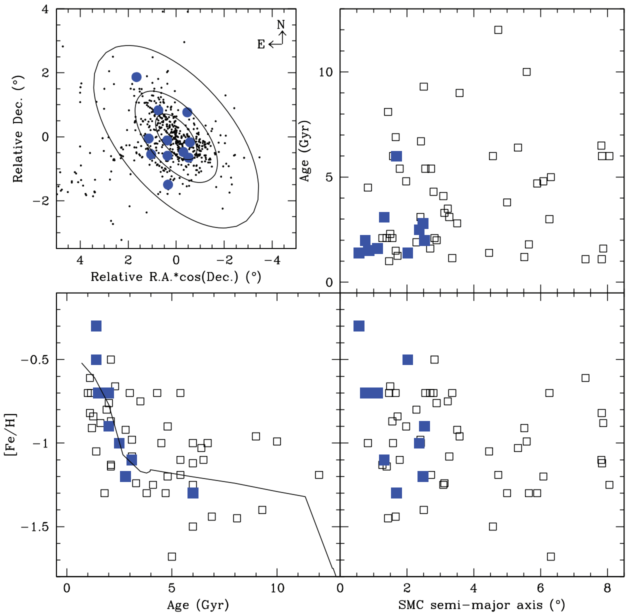

Figure 3. Top-left: spatial distribution of the SMC clusters (dot) and of the 11 studied clusters (blue circle). Ellipses with semimajor axes of 1°, 2° and 4° are overplotted. Bottom-left: AMR for the 50 IACs/old clusters compiled by P11 (open square) and for the 11 studied clusters (blue square); the bursting model of Pagel & Tautvaišienė (1998) is overplotted with a solid line. Right: relationships between the cluster ages (top) and metallicities (bottom) with the semimajor axis (a).

Table 2. Statistics of SMC clusters.

a (^{o})	Number of catalogued clusters	Number of unstudied clusters	Number of studied clusters[a]	Estimated number of clusters unstudied[a]
1	234	20	1	0
1–2	206	44	5	1
2–4	120	41	15	5
>4	43	4	12	1

[a]Clusters with ages larger than 2.5 Gyr.

of those clusters analysed by Chiosi et al. (2006, 311 clusters), Glatt et al. (2010, 324 clusters) and the 124 clusters mentioned in Section 2. We use four elliptical regions which adequately delineate the spatial cluster distribution, the semimajor axis (a) being the free parameter. Table 2 summarizes our results. As can be seen, we should expect to identify a total of seven relatively old/old clusters not studied yet within those catalogued by Bica et al. (2008). At first glance, such a number of unstudied clusters does not appear to strongly change the observed AMR, even less if we consider their distribution in the different elliptical rings.

The resultant statistics of Table 2 could be affected by three types of uncertainties: (i) clusters assumed to be young by Chiosi et al. (2006) and Glatt et al. (2010), but they would turn out to be IACs if a deeper cleaned photometry were available; (ii) large errors in the used ages and metallicities and (iii) undiscovered old clusters. With respect to the first source of uncertainty, we note that the clusters studied by Chiosi et al. and Glatt et al. are located in the central part of the galaxy ($a \lesssim 2°$), where it is hardly possible to find old clusters (see Table 2 and right-hand panels of Fig. 3). Likewise, Fig. 3 reveals that the observed spread in age and metallicity exceeds by three to five times and two to four times, respectively, the quoted uncertainties, so that, even though spectroscopic ages/metallicities would tune up these quantities, the general trend would not seem to change too much. Finally, the most recently updated catalogue of SMC clusters (Bica et al. 2008) includes very small and faint candidates. As Bica et al. stated, such a number of objects is large enough to allow for a statistically significant analysis. In addition, several of them have turned out to be asterisms (see Section 2). Obviously, we have not taken into account those old clusters that have been disrupted. However, based on the recent review by Santiago (2009) we could conclude that the presently observed AMR should not be so different with respect to the intrinsic one, because clusters tend to live much longer in the Magellanic Clouds than in the Galaxy as a result of slower disruption processes. For example, by using the masses obtained by Mackey & Gilmore (2003) for six SMC clusters with ages between 1.5 and 12 Gyr, we derive relaxation times notably larger than their respective ages (Santiago 2009).

Thus, a comprehensive picture of the cluster AMR can then be summarized as follows. (i) The cluster system has experienced two enhanced formation processes that peaked at $t \sim 2$ and 5–6 Gyr, the former being more prominent and constrained in time. (ii) Both enhanced formation processes have taken place throughout the entire body of the galaxy, a feature which is also seen along the whole lifetime of the SMC. Note, however, that the larger number of clusters formed inside $\sim$4°. (iii) There is no metallicity gradient, because both bursts have formed clusters anywhere within a wide [Fe/H] range. The spread in metallicity observed between $\sim$2.5 and 5 Gyr may be due to the not-well-mixed enriched gas produced during the earlier burst. (iv) Clusters older than $\sim$7 Gyr have been formed from a primordial not-well-mixed gas cloud. Note that the present cluster AMR is in an overall agreement with results coming from the study of the field AMR (Dolphin et al. 2001; McCumber, Garnett & Dufour 2005; Cignoni et al. 2009; Noel et al. 2009; Sabbi et al. 2009).

4 SUMMARY

In this study we present, for the first time, CCD Washington CT_1T_2 photometry of stars in the field of nine SMC IACs, namely B 39, 47, 112, BS 88, HW 22, 55, 67, K 38 and L 58, and two additional studied clusters (B 34 and NGC 419), which served us as control clusters for age and metallicity estimates. The analysis of the photometric data leads to the following main conclusions.

(i) CMD cluster features – mainly cluster RCs and MSTOs – turn out to be identifiable when performing annular extractions around their respective centres, once they were cleaned from field star contamination.

(ii) We estimated ages for the cluster sample using the δT_1 index, and metallicities from the SGB technique. The resultant ages and metallicities for the control clusters are in excellent agreement with those previously published, thus confirming our present age/metallicity scale. We also confirmed the ages and metallicities derived for the remaining clusters by fitting theoretical isochrones of Girardi et al. (2002) to the cluster CMDs. The 11 studied clusters reproduce the bursting SFH of Pagel & Tautvaišienė (1998), tightly.

(iii) Based on the statistics of catalogued and studied clusters, we should expect to identify a total of seven relatively old/old clusters not studied yet within those catalogued by Bica et al. (2008). At first glance, such a number of unstudied clusters does not appear to strongly change the observed AMR, even less if we consider their spatial distribution in the different elliptical rings.

(iv) We found that a comprehensive picture of the cluster AMR is composed by two enhanced formation processes at $t \sim 2$ and 5–6 Gyr, which have taken place throughout the entire body of the galaxy, by the absent of a metallicity gradient and by a relative spread in metallicity for clusters older than ∼7 Gyr, since they have been formed from a primordial not-well-mixed gas cloud.

ACKNOWLEDGMENTS

We greatly appreciate the comments and suggestions raised by the reviewer which helped me to improve the manuscript. This research draws upon data as distributed by the NOAO Science Archive. NOAO is operated by the Association of Universities for Research in Astronomy (AURA), Inc. under a cooperative agreement with the National Science Foundation. This work was partially supported by the Argentinian institutions CONICET and Agencia Nacional de Promoción Científica y Tecnológica (ANPCyT).

REFERENCES

Bekki K. et al., 2004, ApJ, 610, L93
Bica E. et al., 2008, MNRAS, 389, 678
Burstein D., Heiles C., 1982, AJ, 87, 1165
Carrera R. et al., 2008, AJ, 136, 1039
Chiosi E. et al., 2006, A&A, 452, 179
Cignoni M. et al., 2009, AJ, 137, 3668
Crowl H. H. et al., 2001, AJ, 122, 220
Da Costa G. S., 1991, in Haynes R., Milne D., eds, Proc. IAU Symp. 148, The Magellanic Clouds. Dordrecht, Kluwer, p. 183
Dolphin A. E. et al., 2001, ApJ, 562, 303
Geisler D., Sarajedini A., 1999, AJ, 117, 308
Geisler D. et al., 1997, AJ, 114, 1920
Geisler D. et al., 2003, MNRAS, 341, 771
Girardi L. et al., 2002, A&A, 391, 195
Glatt K., Grebel E. K., Koch A., 2010, A&A, 517, 50
Kayser A. et al., 2007, in Vazdekis A., Peletier R. F., eds, Proc. IAU Symp. 241, Stellar Populations as Building Blocks of Galaxies. Cambridge Univ. Press, Cambridge, p. 351
McCumber M. P., Garnett D. R., Dufour R. J., 2005, AJ, 130, 1083
Mackey A. D., Gilmore G. F., 2003, MNRAS, 338, 120
Mighell K. J., Sarajedini A., French R. S., 1998, AJ, 116, 2395
Noël N. E. D. et al., 2009, ApJ, 705, 1260
Pagel B. E. J., Tautvaišienė G., 1998, MNRAS, 299, 535
Parisi M. C. et al., 2009, AJ, 138, 517
Piatti A. E., 2011, MNRAS, 416, L89
Piatti A. E. et al., 2001, MNRAS, 325, 792
Piatti A. E. et al., 2005, MNRAS, 358, 1215
Piatti A. E. et al., 2007, MNRAS, 377, 300
Piatti A. E. et al., 2008, MNRAS, 389, 429
Rich R. M. et al., 2000, AJ, 119, 197
Sabbi E. et al., 2009, ApJ, 703, 721
Santigo B., 2008, in van Loon J. Th., Oliveira J. M., eds, Proc. IAU Symp. 256, The Magellanic System: Stars, Gas, and Galaxies. Cambridge Univ. Press, Cambridge, p. 69
Tsujimoto T., Bekki K., 2010, ApJ, 700, L69

This paper has been typeset from a TEX/LATEX file prepared by the author.