NEAR-INFRARED PHOTOMETRY OF FOUR STELLAR CLUSTERS IN THE SMALL MAGELLANIC CLOUD*

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ABSTRACT

We present high-quality \( J, H, \) and \( K_s \) photometry of four Small Magellanic Cloud stellar clusters with intermediate ages in the 1–7 Gyr range (namely NGC 339, 361, 416, and 419). We obtained deep color–magnitude diagrams to study the evolved sequences and provide a detailed census of the red giant branch (RGB), asymptotic giant branch (AGB), and carbon star populations in each cluster and their contribution to the total cluster light. We find that in the \( \sim 5–7 \) Gyr old clusters AGB stars account for \( \sim 6\% \) of the total light in the \( K_s \) band, carbon stars are lacking, and RGB stars account for \( \sim 45\% \) of the total bolometric luminosity. These empirical findings are in good agreement with the theoretical predictions. Finally, we derived photometric metallicities computed by using the properties of the RGB and find an iron content of \([Fe/H] = -1.18, -1.08, -0.99, \) and \(-0.96\) dex for NGC 339, 361, 416, and 419, respectively.

Key words: Magellanic Clouds – globular clusters: general – techniques: photometric

1. INTRODUCTION

The history and the evolution of the Large and Small Magellanic Clouds (LMC and SMC, respectively) are intimately related to the gravitational interactions between the two clouds and the Milky Way. In particular, the main episodes of star-formation enhancement in the SMC are triggered by the near, perigalactic passages of the LMC and of the Milky Way (Harris & Zaritsky 2004; Zaritsky & Harris 2004). The epoch and rate of the main star-formation episodes in the Magellanic Clouds (MCs) are still a matter of debate and several scenarios have been proposed. For the SMC, while Harris & Zaritsky (2004) suggest three episodes occurred 400 Myr, 3 Gyr, and 9 Gyr ago, Dolphin et al. (2001) favor a more continuous star formation in the halo with a dominant episode 5–8 Gyr ago. Rafelski & Zaritsky (2005) argue that the cluster age distribution shows a few peaks, but no significant gaps as in the LMC (see also Chiosi et al. 2006).

MCs host a globular cluster (GC) system which includes objects with different ages and metallicities, thus representing a formidable probe of the various stellar populations in the MCs as well as ideal templates for the study of stellar evolution and population synthesis. In this respect, the near-infrared (NIR) spectral range is particularly suitable to sample the evolved stellar sequences, whose giant stars are characterized by low surface gravities and effective temperatures.

In our previous papers (Ferraro et al. 2004; Mucciarelli et al. 2006; hereafter Paper I and Paper II, respectively), the NIR color–magnitude diagrams (CMDs) of 19 young-intermediate age LMC clusters (from \( \sim 80 \) Myr to \( \sim 3 \) Gyr) have been analyzed, providing a quantitative estimate of the asymptotic giant branch (AGB) and red giant branch (RGB) contributions to the total light, as a function of the cluster age. The AGB contribution to the total luminosity starts to be significant at \( \sim 200 \) Myr, with a maximum (\( \sim 80\% \)) at \( \sim 500–600 \) Gyr. At this same epoch, the RGB phase transition occurs and for ages older than 1 Gyr the RGB itself becomes fully developed, while the contribution of AGB is progressively reduced.

The present paper reports the results for four SMC clusters belonging to the intermediate-age population of the SMC. The principal aims of this work are the study of the main features of their NIR CMDs and the contribution to the total cluster luminosity of the AGB and RGB stars. This sample of SMC clusters allows us to check the contribution of the AGB and RGB stars for clusters in an age range (\( \sim 5–7 \) Gyr) not covered by the LMC cluster system (because it corresponds to the so-called Age-Gap), thus providing complementary information.

The paper is organized as follows: Section 2 describes the observations and photometric analysis. Section 3 presents the NIR CMDs and their main features, the inferred metallicities, and the integrated magnitudes. Section 5 describes the procedure adopted to estimate the completeness correction and the field decontamination. Section 6 describes the detailed census of the AGB and carbon stars in each cluster, and their contribution to the total luminosity, while Section 7 analyzes the RGB stellar population.

2. OBSERVATIONS AND DATA REDUCTION

A set of \( J, H, \) and \( K_s \) images of four stellar clusters (namely NGC 339, 361, 416, and 419) in the SMC has been selected at the European Southern Observatory (ESO), La Silla, on 2006 January 1–3 (Program ID: 076.D-0381(B)), by using the New Technology Telescope (NTT) 3.5 m telescope and the NIR imager/spectrometer SOFI (Son OF Isaac), equipped with a \( 1k \times 1k \) HAWAII array detector. All the observations have been performed by using \( 0.292 \) pixel\(^{-1} \) scale, providing a \( \sim 5'' \times 5'' \) field of view each frame.

Total integration times of \( 4 \) minutes in \( J, 8 \) minutes in \( H, \) and \( 16 \) minutes in \( K_s \) (split into sets of shorter exposures) have been secured, allowing to reach a magnitude threshold of \( J \sim 19, H \) and \( K_s \sim 18.5 \). All the secured images have been roughly centered on the cluster center. Moreover, for each target cluster, a control field (a few arcminutes away from each cluster center) has been observed adopting the same

* Based on observations collected at La Silla ESO Observatory under proposal 076.D-0381(B).
instrumental configuration; these field images have been used to construct median–average sky frames. High signal-to-noise (S/N) flat fields in each band have been acquired by using a halogen lamp alternatively switched on and off. The final cluster and field frames have been sky-subtracted and flat-field corrected. The observations have been obtained in good seeing conditions (0.′8–0.7′′ on average).4 The point-spread function (PSF) fitting procedure has been performed by using the ALLSTAR routine of the DAOPHOT (Stetson 1987) reduction package. The detection of the stellar sources has been performed in the J image, then this list of stellar objects has been used as reference for the reduction of the images in the other two filters. The output catalog, obtained by cross-correlating the single-filter catalogs, includes all stars measured in at least two bands. The instrumental magnitudes have been transformed into the Two Micron All Sky Survey (2MASS) photometric system, by using the large number of stars (a few hundreds) in common between SOFI and the 2MASS. No significant color term in each band has been found. Finally, the brightest stars that turned out to be saturated in the SOFI images have been recovered from the 2MASS catalog (the typical saturation limit in our images is $K_s \sim 11$). A final catalog listing ~1500–2500 stars has been obtained in each program cluster. Each cluster center of gravity $C_{\text{gray}}$ (see Table 1) has been computed by averaging the $\alpha$- and $\delta$-coordinates of stars lying within a fixed radius (typically $\sim 90''$) from a guess center (estimated by eye).

3. THE CMDs

Figure 1 reports the ($K_s, (J - K_s)$) CMDs of the four clusters of our sample. For each cluster the age $s$-parameter5 (Elson & Fall 1985) is also reported; Figure 2 shows the CMDs of the corresponding control fields. For each cluster, Table 1 summarizes the coordinates of the center of gravity and other cluster properties, in particular:

1. Reddening: for three stellar clusters (namely NGC 416, 339, and 361) we adopted the $E(B - V)$ computed by Mighell et al. (1998), from optical Wide-Field Planetary Camera 2/Hubble Space Telescope (WFPC2/HST) CMDs. For NGC 419 the typical reddening value of the SMC (Hunter et al. 2003) has been adopted. However, it is worth noticing that the small amount of reddening in the direction of these clusters has a negligible impact on the near IR photometry.

2. Age: as already discussed in Papers I and II, the lack of a homogeneous age scale for the Magellanic clusters based on the measurement of the main sequence turn off represents a severe limitation. In accordance with Papers I and II, we adopted the Elson & Fall (1985) $s$-parameters as an age indicator and the most recent age calibration derived by Girardi et al. (1995): $\log(\text{Age}) = 6.227 + 0.0733 \cdot s$. By using WFPC2/HST photometry, Mighell et al. (1998) derived turn off ages for NGC 339, 361, and 416 in the 5–7 (± 1.1–1.3) Gyr range (see Table 1). Recently, new determinations of the ages of NGC 339, 416 and 419 have been presented by Glatt et al. (2008), based on high-resolution Advanced Camera for Surveys/HST photometry, deriving an age of 6 Gyr for the first two clusters. In the case of NGC 419, the authors list only an age range (between 1.2 and 1.6 Gyr) because of the complex Turn-Off morphology. This age is also in agreement with the previous estimate (see Rich et al. 2000). All the direct age estimates are consistent with those inferred from the $s$-parameter.

The main features of these CMDs are summarized as follows: (1) an extended and fully populated RGB; (2) a bulk of stars at $K_s \sim 17.5$, corresponding to the He clump; (3) the brightest objects with $K_s < 13$ are likely AGB stars; (4) the cluster and field population have similar features.

The presence of a well-defined and populated RGB in each cluster is in agreement with the relatively old age of the clusters which have already experienced the RGB phase transition (as...
discussed in Papers I and II). We note that the CMDs of NGC 416 and of its surrounding field show a blue stellar population (located at \((J - K_s) \sim -0.1\) and with stars brighter than \(K_s \sim 16.5\)). This younger population has been also detected in the optical photometry presented by Mighell et al. (1998).

4. METALLICITY

As well known, the properties (morphology and position) of the RGB are sensitive function of the overall metallicity of the population. Hence, the presence of a well-populated RGB in the CMDs shown in Figure 1 allows us to derive a photometric population. Hence, the presence of a well-populated RGB in the RGB are sensitive function of the overall metallicity of the parameters (in the IR plane) in terms of the cluster metallicity (1998).

Recently, Valenti et al. (2004) have presented a calibration of a set of morphological RGB parameters (in the IR plane) in terms of the cluster metallicity for a sample of old Galactic globular clusters, by adopting both the Carretta & Gratton (1997) iron metallicity scale and the global metallicity \([M/H]\), as computed by taking into account the enhancement of the \(\alpha\)-elements. Since the sparse available chemical information for the SMC stellar population indicates a solar scaled value of the \([\alpha/Fe]\) abundance ratio (see Hill 1997), we use the \([Fe/H]\) scale as reference. We used the entire set of RGB parameters defined by Valenti et al. (2004) in the IR planes \((K_s, J - K_s)\) and \((H, J - H)\), namely the \((J - K_s)\) color at different absolute magnitudes \(M_K = (-3, -4, -5, -5.5), (J - H)\) color at \(M_H = (-3, -4, -5, -5.5), \) the \(K_s\) absolute magnitude at fixed \((J - K_s) = 3\), the H absolute magnitude at \((J - H) = 3\) and the slope of the RGB. All the photometric parameters have been measured along the RGB cluster mean ridge lines. These fiducial ridge lines have been computed following the procedure described in Ferraro et al. (1999) and Valenti et al. (2004). First, we selected (by eye) stars belonging to the RGB in order to exclude He clump, AGB, and field stars, then the second-order polynomial has been fitted to the observed distribution. The ridge line has been transformed into the absolute plane by adopting a distance modulus of \((m - M)_0 = 18.99\) (Cioni et al. 2000), the reddening listed in Table 1, and the extinction law by Rieke & Lebofsky (1985). Once the photometric parameters were measured, the various estimates of the cluster metallicity were computed from the equations listed in Appendix A of Valenti et al. (2004). All these estimates turn out to be consistent one to each other (with average dispersion of \(\sim 0.1\)), so we assumed for each cluster metallicity the mean value (and reported in Table 2), thus finding \([Fe/H] = -1.18, -1.08, -0.99,\) and \(-0.96\) dex for NGC 339, 361, 416, and 419, respectively.

Mighell et al. (1998) give a photometric estimate of the cluster metallicity by using the RGB slope in the optical plane

| Cluster  | \(\alpha(J2000)\) | \(\delta(J2000)\) | \(s\) | \(Age_c\) (Gyr) | \(Age_{TO}\) (Gyr) | \([Fe/H]\) | \(E(B-V)\) |
|----------|-----------------|-----------------|-----|---------------|---------------|--------|---------|
| NGC 419  | 01:08:17.35     | -72:53:04.30    | 38  | 1.0           | 1.2 - 1.6     | -0.60   | 0.08    |
| NGC 416  | 01:07:58.82     | -72:21:18.96    | 46  | 4.0           | 5.6 ± 6.0     | -0.89, -1.44 | 0.08, 0.07 |
| NGC 361  | 01:02:10.09     | -71:36:18.73    | 48  | 5.6           | 6.8 ± 6.3     | -1.45   | 0.07    |
| NGC 339  | 00:57:46.19     | -74:28:17.58    | 49  | 6.6           | 5.0 ± 6.4     | -0.70, -1.12, -1.50 | 0.03    |

Notes. Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds. The \(s\)-parameter is from Elson & Fall (1985). \(Age_c\) and \(Age_{TO}\) indicate the ages inferred by the calibration of \(s\)-parameter by Girardi et al. (1995) and by direct TO measurements, respectively. The ages are from (a) Mighell et al. (1998) and (e) Glatt et al. (2008). The metallicities are from (a) Mighell et al. (1998), (b) de Freitas Pacheco, Barbuy & Idiart (1998), and (c) Da Costa & Hatzidimitriou (1998). The reddening are from (a) Mighell et al. (1998) and (d) Hunter et al. (2003).

4.1. Integrated Magnitudes

In order to compute the integrated magnitudes of the target clusters, we performed aperture photometry, with different aperture radii centered on the center of gravity. A crucial step in this procedure is the correct decontamination from the field population. To do this we performed an equivalent aperture photometry on each control field. The resulting field luminosity has been subtracted from the cluster luminosity. The instrumental integrated magnitude was then calibrated into the 2MASS system following the procedure described in Section 2.

For each cluster, Table 2 lists the integrated \(K_s\) magnitude, \((J - K_s)\) and \((H, J - H)\) colors and the \(K_s\) bolometric luminosities, as computed by adopting an aperture radius representative of the entire cluster extension (typically 90–100′).

| Cluster  | \(K_s\) | \((H - K_s)\) | \((J - K_s)\) | \(L^2_{bol}\) | \(L^2_{tot}\) | \([Fe/H]\) |
|----------|--------|--------------|--------------|-------------|-------------|--------|
| NGC 419  | 7.49   | 0.31         | 1.00         | 92.05       | 23.22       | -0.96  |
| NGC 416  | 8.68   | 0.13         | 0.68         | 30.76       | 14.01       | -0.99  |
| NGC 361  | 8.94   | 0.11         | 0.78         | 24.21       | 9.73        | -1.08  |
| NGC 339  | 9.38   | 0.10         | 0.72         | 16.14       | 6.84        | -1.18  |

Note. The derived photometric metallicities are calibrated in the Carretta & Gratton (1997) metallicity scale.

(see Table 1). We find their metallicities to be \(-0.3\) dex more metal-poor than ours; this discrepancy can be mainly ascribed to the different adopted metallicity scales. Indeed, the relations of Valenti et al. (2004) are calibrated on the Carretta & Gratton (1997) scale, while the slope\([Fe/H]\) relation of Mighell et al. (1998) is on the Zinn & West (1984) scale.

6 In all the clusters the bulk of the luminosity lies within a \(\sim 50–60′\) radius.
et al. 2000), bolometric corrections (by using the \((J - K_s)_{0}\) color) empirically calibrated by Montegriffo et al. (1998), and solar values of \(M_{Bol}^\odot = 4.75\) and \(M_{K}^\odot = 3.41\). In the following all the derived luminosities are expressed in units of \(10^4 L_\odot\). The main sources of error in this case are the uncertainty in the integrated magnitudes and in the bolometric corrections (an additional variation of \(\sim 10\%\)) which translate into a \(\sim 5\%\) and \(\sim 10\%\) uncertainty in luminosity.

5. STAR COUNTS AND POPULATION RATIOS

In order to estimate the RGB and AGB contributions to the total cluster light, we use star counts and population ratios, as obtained by adopting suitable selection boxes for each evolutionary sequence (He clump, RGB, and AGB), as discussed in Sections 6 and 7 (see also Papers I and II). Two main effects must be taken into account in the definition of these quantities, the incompleteness of the photometric catalog and the contamination by field stars.

5.1. Completeness and Field Decontamination

The degree of completeness can be quantified by adopting the widely-used artificial star technique, discussed in Mateo (1988). For each cluster we have derived the RGB fiducial line and then a population of artificial stars, having magnitudes, colors, and luminosity functions resembling the observed distributions has been generated and added to the original images (by using the DAOPHOT task ADDSTAR). The frame area sampling the cluster has been divided into three concentric regions with radii \(r < 20\'\), \(20\' \leq r < 60\'\) and \(60\' \leq r < 90\'\), in order to take into account different crowding conditions and the completeness has been estimated independently in each of them. The maximum spatial extension of each cluster has been estimated from the cluster radial density profile. A total of \(\sim 200,000\) artificial stars have been simulated in each cluster in about 1000 simulation runs. Indeed, in order to not alter the crowding conditions, \(\sim 100–200\) stars have been simulated in each run, corresponding to \(\sim 10\%\) of the total stellar population. The fraction of recovered objects in each magnitude interval has been estimated as \(\Lambda = \frac{N_{rec}}{N_{sim}}\): the completeness curve was obtained in each radial subregion and shown in Figure 3. The correction for incompleteness in each radial region was performed by dividing each observed distribution by the corresponding \(\Lambda\) factor. The total number of stars has been obtained by summing the number of stars in each subregion.

It is worth noticing that this procedure allows to take into account only the loss of faint stars due to the crowding but not the possible excess of bright stars due to blending effects of two or more faint stars into a brighter one. However, this latter effect is marginal in the NIR.

Another important effect which needs to be investigated is the degree of contamination of the selected samples by the foreground/background stars. In this paper we have applied a statistical decontamination, by using a control field adjacent to the cluster. The total number of stars observed in each evolutionary sequence (AGB, RGB, and He clump) has been counted according to the selection boxes both in the cluster and field CMDs, and corrected for incompleteness (see above). The star counts in the field population have been scaled to take into account the different surveyed area, and their contributions have been subtracted from the cluster population.

In summary, for each radial region, each selection box corresponding to each evolutionary stage has been divided in bins of magnitude (typically 0.2 mag wide). Then, the “corrected” number of stars in each bin has been computed as follows:

\[
n_{corr} = n_{obs} + (n_{obs}(1/\Lambda - 1)) - n_f
\]

where \(n_{obs}\) is the number of stars observed in that bin, the second term is the number of stars lost for incompleteness, \(n_f\) is the expected number of field stars. The total luminosity of each evolutionary stage can be computed according to the following relation:

\[
L_{corr} = \left( \sum_{i=1}^{n} L_{i}^{obs} \right) + (n_{comp} \times L_{eq}) - (n_{f} \times L_{eq})
\]

where the term \(\sum_{i=1}^{n} L_{i}^{obs}\) is the total luminosity of stars observed in a given bin, \(n_{comp}\) is the number of stars lost for incompleteness, \(n_f\) is the expected number of field stars, and \(L_{eq}\) is the equivalent luminosity of that bin, that is the luminosity of a star with magnitude equal to the mean value of the bin.

Finally, star counts and total luminosity of each evolutionary stage have been obtained by summing the contribution of all the bins.

6. THE AGB AND C-STARS POPULATION

The AGB stars are the main contributors to the integrated SSP light between \(\sim 10^8\) and \(\sim 10^9\) yr (Renzini & Buzzoni 1986; Maraston 1998). AGB stars are initially oxygen-rich, but if massive enough (with an initial mass \(M > 10^8 M_\odot\)) a star undergoes the so-called Third Dredge-Up event during the

\[\sigma_p = \sqrt{\frac{\sigma_1^2 + \sigma_2^2}{R}}\]

with \(R = N/D\), \(N\) being the numerator and \(D\) the denominator of the ratio, and by assuming that star counts follow a Poisson statistics.
thermal-pulse (TP-AGB) phase, and freshly processed carbon is carried to the surface, producing a C-rich AGB star.

Frogel et al. (1990) analyzed 39 Magellanic clusters in order to identify AGB stars and concluded that up to 40% of the bolometric luminosity comes from stars with $M_{\text{bol}} < -3.6$, likely belonging to the TP-AGB phase. In Paper II, we studied the AGB population in the young-intermediate LMC clusters (with ages less than $\sim3$ Gyr), finding that the maximum contribution of the AGB to the cluster light occurs at an age of $\sim500$–700 Myr, with a dominant contribution from the C-stars population.

We classify as AGB stars only those stars that satisfy the three following criteria: (1) stars brighter than $(K_{\text{s}})_{0} = 12.62$ (corresponding to the RGB tip level for the SMC, see Cioni et al. 2000), in order to minimize the impact of possible RGB stars contamination; (2) in order to separate the cluster stars and the most bright background/foreground stars, only stars located within the overplotted box used in Figure 4 are considered; (3) stars located within 50% of the distance from the cluster center. None of the LMC clusters previously studied (Paper II) shows a comparable number of C stars. The paucity of C stars in the observed LMC clusters with the same age could be ascribed to a metallicity effect (see Figure 5 in Maraston 2005). We note that outside the cluster radius only three O-rich AGB stars have been detected and no C stars.

A possible source of error in the computation of the AGB counts and luminosities is the location of the RGB Tip; however, a variation of 0.2 mag implies the inclusion of a few fainter AGB stars only (with a variation in the total AGB luminosity less than 10%).

Table 3 lists the final star counts and luminosities of the AGB and C stars in each cluster. Figure 5 (top panel) shows the $K_{s}$-band luminosity of the AGB stars normalized to the total luminosity as a function of age (black points); for comparison the values obtained for the LMC clusters in Paper II are also plotted (gray points). It is worth noticing the higher ($\sim50\%$) luminosity ratio of NGC 419 compared to the value ($\sim10\%$) of the other three, significantly older clusters. Figure 5 (bottom panel) shows the same distribution but binned in age as discussed in Paper II for what concerns the LMC clusters, while only three out of four SMC clusters, in our sample namely NGC 339, 361, and 416, with similar ages have been binned.

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Theoretical predictions computed by Maraston (1998, 2005) for $[M/H] = -0.33$ (solid line) and $-1.35$ dex (dashed line) are also plotted for comparison. The theoretical AGB and RGB population ratios have been computed by using SSP models by Maraston (1998; 2005),
obtained with an evolutionary code that estimates the energetics of any post-main-sequence stage by following the prescriptions of the fuel consumption theorem defined by Renzini & Buzzoni (1986; see also Ferraro et al. (2004) for more details).

Similarly, Figure 6 shows the $K_s$-band luminosity of the C stars only, normalized to the total luminosity, as a function of age. Note that in NGC 419 ~80% of the AGB light is provided by the C-stars population.

We thus confirm previous results discussed by Frogel et al. (1990) that C stars are only detectable in relatively young (less than 2 Gyr) clusters of IV–VI SWB Type and theoretical predictions which require a minimum envelope mass for the occurrence of the Third Dredge-Up. Stars with less than 1.2 $M_\odot$ initial mass have a residual (if any) envelope mass which is too small to experience the Third Dredge-Up.

7. THE RGB POPULATION

In order to calculate the RGB population ratios we adopted the same procedure used in Papers I and II. Three observables have been identified to study the degree of development of the RGB as a function of age and metallicity: (1) the number of RGB stars normalized to the number of He clump stars ($N_{\text{RGB}}/N_{\text{He-Cl}}$), (2) the bolometric luminosity of the RGB normalized to the He-clump one ($L_{\text{bol,RGB}}/L_{\text{bol,He-Cl}}$), and (3) the bolometric luminosity of the RGB normalized to the total cluster luminosity ($L_{\text{bol,RGB}}/L_{\text{TOT}}$).

In order to identify the mean loci of the upper RGB and He clump stars, we use the cumulative, dereddened $K_0 - (J - K)_0$ CMD as a diagnostic diagram. As in Papers I and II (see their Figure 5 and Figure 9, respectively) we define two boxes for these evolutionary stages. The size of each box has been defined to sample the bulk of the population, assumed to be ~5 times the photometric uncertainty at a given level of magnitude. The upper limit of the RGB box is the magnitude of the RGB Tip, the same used to define the bottom limit of the AGB box (Section 6).

The final population ratios (by counts and luminosities) have been computed following the procedure described in Section 5.1, by also applying the incompleteness correction and the statistical field decontamination. The results (star counts for the He clump and bright RGB, and the corresponding bolometric luminosities) are reported in Table 4. In NGC 419 star counts and luminosities have been computed excluding the innermost region (with a radius of 20$''$), where completeness at the He clump magnitude level drops down to 60% (as shown in Figure 3).

Figures 7 and 8 plot the resulting observables for the four SMC clusters (black points) presented in this study and for the LMC clusters (gray points) discussed in Papers I and II. Theoretical predictions for the [M/H] = −0.33 and −1.35 dex (solid and dashed lines, respectively) metallicities are also plotted for comparison.

The cluster NGC 419 displays population ratios (both in counts and luminosities) slightly higher with respect to the theoretical predictions (similarly to the LMC cluster NGC 1783 in Paper II) but still consistent with the occurrence of the RGB phase transition. NGC 339, 361, and 416 show $N_{\text{RGB}}/N_{\text{He-Cl}}$ ratios somewhat in between the two model predictions. Their location is consistent with our photometric estimates of the cluster metallicity (see Table 2), slightly higher than those obtained by Mighell et al. (1998).

8. CONCLUSIONS

By using high-quality NIR photometry of four SMC stellar clusters with intermediate ages we derived new photometric metallicities. All the observed clusters show similar metallicities ([Fe/H] ~ −1) with only a weak dependence with the age. Actually, the age–metallicity relation for the SMC is not well known and the different metallicity indicators, namely stellar clusters, planetary nebulae and field stars, still exhibit strong
Figure 7. Behavior of the number counts of RGB stars normalized to the He clump stars as a function of the age. Same symbols as in Figure 5. The solid and dashed lines represent the theoretical predictions computed by using canonical models and global metallicity of [M/H] = −0.33 (solid line) and −1.35 (dashed line).

Figure 8. Top: bolometric luminosity of the RGB normalized to the He clump as a function of the age for the observed MC clusters. Same symbols as in Figure 5. Bottom: bolometric luminosity of the RGB normalized to the total luminosity for the same clusters.

discrepancies. The most recent survey of SMC field giants based on the Ca ii triplet by Carrera et al. (2008) indicates a value of [Fe/H] ~ −1 dex in the age range between ~3 and ~10 Gyr, and [Fe/H] ~ −0.7 dex at ~1 Gyr.

Furthermore, we investigated the contribution of the AGB and RGB evolutionary stages to the total cluster luminosity. The cluster NGC 419, with an age of ~1 Gyr, exhibits population ratios for AGB and RGB that follow the behavior already observed in the LMC clusters for objects of similar age. The other three clusters, with older ages in the ~5–7 Gyr range, show a negligible (~6%) luminosity contribution by the AGB, lacking bright C stars, and an increasing contribution by the RGB population with respect to clusters of younger ages like NGC 419 and those in the LMC. We find a general agreement between the empirical population ratios and those predicted by theoretical models at [M/H] = −1.35 dex.

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