

A NEW GIANT BRANCH CLUMP STRUCTURE IN THE LARGE MAGELLANIC CLOUD

ANDRÉS E. PIATTI^{1,2} AND DOUG GEISLER

Departamento de Física, Universidad de Concepción, Casilla 160-C, Concepción, Chile; piatti@gemini.cfm.udec.cl, doug@stars.cfm.udec.cl

EDUARDO BICA

Departamento de Astronomia, Instituto de Física, UFRGS, CP 15051, 91501-970 Porto Alegre, RS, Brazil; bica@if.ufrgs.br

JUAN J. CLARÍA¹

Observatorio Astronómico de Córdoba, Laprida 854, 5000, Córdoba, Argentina; claria@oac.uncor.edu

JOÃO F. C. SANTOS, JR.¹

Departamento de Física, ICEx, Universidade Federal de Minas Gerais, CP 702, 30123-970 Belo Horizonte, MG, Brazil; jsantos@fisica.ufmg.br

ATA SARAJEDINI

Astronomy Department, Van Vleck Observatory, Wesleyan University, Middletown, CT 06459; ata@urania.astro.wesleyan.edu

AND

HORACIO DOTTORI

Departamento de Astronomia, Instituto de Física, Universidade Federal do Rio Grande do Sul, CP 15051, 91501-970 Porto Alegre, RS, Brazil; dottori@if.ufrgs.br

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ABSTRACT

We present Washington C and T_1 CCD photometry of 21 fields located in the northern part of the Large Magellanic Cloud (LMC), and spread over a region of more than 2.5 deg^2 approximately 6° from the bar. The surveyed areas were chosen on the basis of their proximity to SL 388 and SL 509, whose fields showed the presence of a secondary giant clump, observationally detected by Bica et al. We also observed NGC 2209, located $\sim 14^\circ$ away from SL 509. From the collected data, we found that most of the observed field CMDs do not show a separate secondary clump, but rather reveal a continuous vertical structure (VS), which is clearly seen for the first time. The VS also appears in the field of NGC 2209. Its position and size are nearly the same throughout the surveyed regions: it lies below the red giant clump (RGC) and extends from the bottom of the RGC to $\sim 0.45 \text{ mag}$ fainter, spanning the bluest color range of the RGC. In two fields in addition to the NGC 2209 field the RGC is slightly tilted, following approximately the reddening vector, while the VS maintains its verticality. We found that the number of stars in the VS box defined by $\Delta(C - T_1) = 1.45\text{--}1.55 \text{ mag}$ and $\Delta T_1 = 18.75\text{--}19.15 \text{ mag}$ has a strong spatial variation, reaching the highest VS star density just northeast of SL 509. Moreover, the more numerous the VS stars in a field, the larger the number of LMC giants in the same zone. We also found that, in addition to SL 509, two relatively massive star clusters, SL 515 and NGC 2209, separated by more than 10° from each other, develop giant clumps with a considerable number of VS stars. This result demonstrates that VS stars belong to the LMC and are most likely the result of some kind of evolutionary process in the LMC, particularly in those LMC regions with a noticeable large giant population. Our results are successfully predicted by the models of Girardi in the sense that a large proportion of 1–2 Gyr old stars mixed with older stars and with metallicities higher than $[\text{Fe}/\text{H}] \simeq -0.7$ should result in a fainter and bluer secondary clump near the mass at which degenerate core He burning takes place. However, our results apparently suggest that in order to trigger the formation of VS stars, there should be other conditions in addition to the appropriate age, metallicity, and the necessary red giant star density. Indeed, stars satisfying the requisites mentioned above are commonly found throughout the LMC, but the VS phenomenon is only clearly seen in some isolated regions. Finally, the fact that clump stars have an intrinsic luminosity dispersion further constrains the use of the clump magnitude as a reliable distance indicator.

Key words: galaxies: individual (Large Magellanic Cloud, Small Magellanic Cloud) — galaxies: photometry — galaxies: stellar content

1. INTRODUCTION

The Large Magellanic Cloud (LMC) has long been a favorite stellar laboratory, providing us not only with valuable information about its own complex star formation history but also with important clues for understanding the formation and evolution of distant galaxies. Moreover,

interest in studying different astrophysical aspects of this galaxy has been rapidly increasing recently, mainly due to the advent of more powerful telescope/instrument combinations and computing facilities.

Recently, Geisler et al. (1997, hereafter Paper I) carried out a search for the oldest star clusters in the LMC by observing with the Washington C and T_1 filters candidate old clusters spread throughout the LMC disk. Although they did not find any genuine old cluster comparable to the Galactic globular clusters, their study has considerably increased the sample of intermediate-age clusters ($t \sim 1\text{--}3 \text{ Gyr}$) with ages determined with a high degree of confidence.

¹ Visiting Astronomer, Cerro Tololo Inter-American Observatory, which is operated by AURA, Inc., under cooperative agreement with the National Science Foundation.

² Gemini Fellow, NOAO/CTIO, Universidad de Concepción, Chile.

In addition, their results reinforce the conclusion that an important epoch of cluster formation, which began ~ 3 Gyr ago, must have been preceded by a quiescent period of many billion years, unless dissipation processes have been more effective than previously thought (e.g., Olszewski 1993). In addition, they determined the properties not only of the clusters but also of their surrounding fields. From the relatively wide field covered by their images ($\sim 15'$ on a side) they found that clusters and fields have on average similar ages and metallicities, except in three cases in which clusters are ≈ 0.3 dex more metal-poor than the surrounding field, suggesting that the chemical evolution was not globally homogeneous (Bica et al. 1998, hereafter Paper II).

A further intriguing result of Paper II was the discovery of what appeared to be a well-populated secondary clump in the color-magnitude diagrams (CMDs) of two fields located in the northern part of the LMC near the clusters SL 388 and SL 509. This unusual feature, made up of stars distributed uniformly across the fields, lies below the prominent red giant clump (RGC), slightly toward its bluest color, and extends 0.45 mag fainter. The feature also appears in the very populous SL 769 field located $\sim 6^\circ$ away, thus representing around 10% of the whole sample of fields observed in Paper I. Since this feature appeared as a roughly distinct secondary clump, Bica et al. coined the term “dual clump” to describe this phenomenon. The authors tentatively suggested that these stars are evidence of a depth effect, with a secondary component located behind the LMC disk at a distance comparable to the Small Magellanic Cloud (SMC), perhaps due to debris from previous interactions of the LMC with the Galaxy and/or the SMC. However, they also mentioned arguments against this scenario and noted other possible explanations.

Westerlund et al. (1998) have also found a similar feature in the CMDs of three fields located in the northeast of the LMC. On the basis of their BV photometry, they suggested that the red giant clump is bimodal and contains stars from an old population ($t \geq 10$ Gyr) and from another, younger population ($t \geq 0.3$ –4 Gyr), in the sense that the fainter the clump the older the stars. In addition to their observational findings, Girardi et al. (1998) and Girardi (1999) have theoretically predicted that stars slightly heavier than the maximum mass for developing degenerate He cores should define a secondary clumpy structure, about 0.3–0.4 mag in the I band below the bluest extremity of the red clump. According to Girardi (1999), this evolutionary effect should be seen in CMDs of composite stellar populations containing ~ 1 Gyr old stars and with mean metallicities higher than $Z = 0.004$. However, the current state of both observational and theoretical results makes it impossible to determine whether this intriguing feature is caused by the presence of an old stellar population or by an evolutionary effect, or even by a layer of stars located behind the LMC. Furthermore, not only its origin but also its morphology remains uncertain, and this must be known before the magnitude of the red giant clump can be used as a robust distance indicator (e.g., Paczyński & Stanek 1998).

In this paper we report on the first observations carried out with the aim of mapping the extent and determining the nature of the “dual clump” phenomenon. Indeed, the apparent dual clumps from the limited sample of Paper II are now found to merge and form a continuous feature. The selection and observation of the fields and the reduction of the data are presented in § 2. In § 3 we present the results

and discuss them in light of recent theoretical and observational interpretations. Finally, in § 4 we summarize our main conclusions.

2. OBSERVATIONS AND REDUCTIONS

The fields for mapping out the extent of the secondary clump phenomenon were selected on the basis of their proximity to SL 388 and SL 509 and the presence of star clusters that had not been observed with Washington photometry. The first criterion aims at observing not only LMC regions located in the line of sight between SL 388 and SL 509, but also those placed around them within 1° from the midpoint of both clusters. The nearest cluster from this center from Paper II is SL 262, which is located 1.5° from SL 388, and no dual clump structure is visible in its CMD. In order to maximize the assigned telescope time, we centered the fields so that they included clusters without, or with only very unreliable, age and metallicity determinations for our continuing study of the chemical evolution of the LMC. The clusters having integrated UBV photometry were taken from Bica et al. (1996), and the fainter ones were taken from the recent revised catalog of star clusters, associations, and emission nebulae (Bica et al. 1999). We also observed the field of NGC 2209 for the purpose of checking the possible evolutionary origin of the dual clump. This cluster is located $\sim 14^\circ$ toward the southeast from SL 509, and is placed by Corsi et al. (1994) photometric data in the minimum of the relationship between red giant clump and main sequence (MS) termination magnitudes. Table 1 lists the selected fields and the clusters contained within these fields. Note that fields 5, 16, 17, 23, and 26 were not observed.

The observations were carried out at the CTIO 0.9 m telescope during six photometric nights in 1998 November. The Cassegrain Focus IMager (CFIM) and the CCD Tek 2K No. 3 were employed in combination with the Washington C and Kron-Cousins R filters. Geisler (1996) has shown that the R_{KC} filter is a very efficient and accurate substitute for the Washington T_1 filter. The pixel size of the detector was 0.4 per pixel, resulting in a field ~ 13.5 wide. We used the Arcon 3.3 data acquisition system in quad mode (four amplifiers), with a mean gain and readout noise of $1.5 e^-ADU^{-1}$ and $4.2 e^-$, respectively. During each night, exposures of 2400 s in C and 900 s in R_{KC} were taken for the selected fields as well as for standard fields (Geisler 1996), with air masses approximately ranging from 1.1 up to 1.6. In addition, a series of 10 bias and five dome and sky flat-field exposures per filter were obtained nightly. The weather conditions kept very stable, with a typical seeing of 1.0 – 1.2 , although some images have slightly larger FWHMs due to temperature changes of up to 2° C. In general, the secondary mirror was focused twice per night. We covered a total area of ≈ 1 deg², spread over ~ 2.6 deg².

The collected data for a total of 21 selected fields and the NGC 2209 field were fully processed at the telescope using the QUADPROC package in IRAF.³ The distribution of the observed fields is shown in Figure 1. After applying the overscan-bias subtraction for the four amplifiers indepen-

³ IRAF is distributed by the National Optical Astronomy Observatories, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

TABLE 1
SELECTED FIELDS

Name	R.A. (2000)	Decl. (2000)	Cluster Name
Field 1	05 34 59.7	-63 43 08.4	OHSC 22
Field 2	05 33 05.7	-63 42 27.4	LW 238
Field 3	05 31 11.7	-63 40 45.5	OHSC 20
Field 4	05 28 16.5	-63 41 27.6	OHSC 17
Field 6	05 25 29.7	-63 39 48.6	
Field 7	05 23 35.7	-63 30 47.2	
Field 8	05 21 41.7	-63 30 47.2	
Field 9	05 18 12.4	-63 27 31.3	SL 354
Field 10	05 16 18.4	-63 25 09.5	
Field 11	05 16 18.4	-63 12 24.5	SL 345, SL 346
Field 12	05 20 06.4	-63 04 19.6	OHSC 10
Field 13	05 25 06.8	-63 06 44.6	SL 448, LW 209, KMHK 854
Field 14	05 31 25.7	-63 53 30.5	SL 540
Field 15	05 30 46.9	-64 06 15.5	SL 525
Field 18	05 30 37.4	-63 28 42.6	SL 515, SL 529
Field 19	05 30 47.5	-63 15 57.6	NGC 1997, LW 230
Field 20	05 30 03.2	-63 03 12.6	OHSC 18
Field 21	05 25 06.8	-63 18 54.7	
Field 22	05 24 27.4	-63 52 33.6	NGC 1942
Field 24	05 20 48.8	-64 03 56.9	SL 401
Field 25	05 18 54.8	-64 05 03.8	SL 372
NGC 2209	06 08 36.0	-73 54 00.0	

NOTE.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

dently, we carried out flat-field corrections using a combined sky-flat frame, which was previously checked for nonuniform illumination pattern with the averaged dome-flat frame. Then, we did aperture photometry for the standard fields (~30 stars per night) using the PHOT task within DAOPHOT II (Stetson 1991). The relationships between instrumental and standard magnitudes were

obtained by fitting the equations

$$c = a_1 + C + a_2 X_C + a_3(C - T_1), \quad (1)$$

$$r = b_1 + T_1 + b_2 X_R + b_3(C - T_1), \quad (2)$$

where a_i and b_i ($i = 1, 2,$ and 3) are the coefficients derived through the FITPARAM routine in IRAF, and X rep-

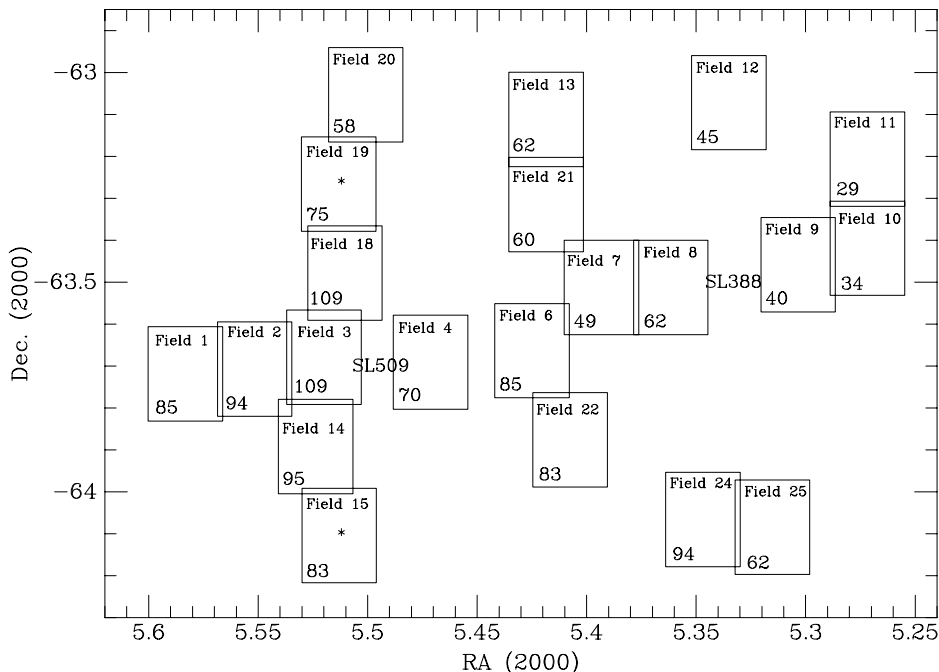


FIG. 1.—Schematic mosaic of the 21 fields observed in the north of the LMC. The number of VS stars in each field is also indicated. Note the strong concentration just northeast of the cluster SL 509. Fields marked with an asterisk have a tilted RGC (see § 3.1 for details).

resents the effective air mass. Capital and lowercase letters represent standard and instrumental magnitudes, respectively. The resulting coefficients and their standard deviations are listed in Table 2; the typical rms errors of equations (1) and (2) are 0.017 and 0.015 mag, respectively.

Point spread function (PSF) photometry for the LMC fields and the NGC 2209 field was performed using the stand-alone version of the DAOPHOT II package (Stetson 1994), which provided us with X - and Y -coordinates and instrumental c and r magnitudes for all the stars identified in each field. The PSFs were generated from two samples of 30–35 and ~ 100 stars selected interactively. For each frame, a quadratically varying PSF was derived by fitting the stars in the larger sample, once their neighbors were eliminated using a preliminary PSF obtained from the smaller star sample, which contained the brightest, least contaminated stars. We then used the ALLSTAR program to apply the resulting PSF to the identified stellar objects and create a subtracted image, which was used to find and measure magnitudes of additional fainter stars. The PSF magnitudes were determined using as zero points the aperture magnitudes yielded by PHOT. This procedure was iterated three times on each frame. Next, we computed aperture corrections from the comparison of PSF and aperture magnitudes using the subtracted neighbor PSF star sample, resulting in typical values of around -0.016 ± 0.010 mag. Note that PSF stars are distributed throughout the whole CCD frame, so that variations of the aperture correction should be negligible. Finally, the standard magnitudes and colors for all the measured stars were computed by inverting equations (1) and (2), once positions and instrumental c and r magnitudes of stars in the same field were matched using Stetson's DAOMATCH and DAOMASTER programs. Thus, we achieved accurate photometry for $\sim 242,000$ stars, with mean magnitude and color errors for stars brighter than $V = 19$ of $\sigma(T_1) = 0.014$ and $\sigma(C - T_1) = 0.022$ mag, respectively.

Later on, with the aim of gathering both astrometric and photometric information in a self-consistent way, we built a master file that contains the positions for all the stars referred to a unique coordinate system. For some fields we only applied the appropriate offsets in the X - and Y -values, while in other fields we matched from tens up to hundreds of stars in common using DAOMASTER and our own routines. We also averaged their T_1 magnitudes and $C - T_1$ colors and recomputed their photometric errors based on the difference. The typical mean difference (absolute value) for approximately 500 stars brighter than $V = 19$ in common turned out to be $\Delta T_1 = 0.026 \pm 0.021$ and $\Delta(C - T_1) = 0.030 \pm 0.023$. In total, 7760 stars have two measurements of their magnitude and color. This photometry can be obtained from the first author upon request.

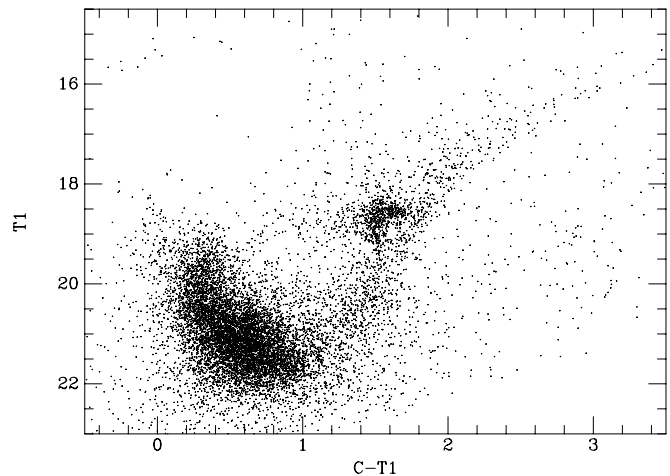


FIG. 2.—Typical Washington T_1 vs. $C - T_1$ CMD for a selected field in the northern part of the LMC. Each field contains on average 12,000 stars.

3. ANALYSIS AND DISCUSSION

3.1. Description of CMDs

The CMDs of the 21 observed LMC fields certainly show a mixture of different stellar populations. They appear to be dominated by a 3–4 Gyr old population as deduced from the δT_1 index, which measures the difference in magnitude between the mean magnitude of the clump/HB and the MS turnoff (see Paper I). Figure 2 illustrates a typical field CMD of the surveyed region. Likewise, the MS is well populated and extends along ~ 3 mag. Assuming that the MS comes from the superposition of MSs with different turnoffs, we estimated an age range of 3 up to 7.5 Gyr using the δT_1 index, with an average of 4.5 ± 1.0 Gyr for all the fields. This significant age range is also supported by the presence of a subgiant branch (SGB) with a broad vertical extension due to the transition of MS stars with different ages to the SGB. The red giant branch (RGB) is also clearly visible, covering a wide range in color from $C - T_1 \sim 1.8$ up to 3.6. However, the most striking feature of these CMDs is the giant clump region. In addition to the normal RGC, most of the field CMDs also show a vertical structure (VS) composed of stars that lie below the RGC and extend from the bottom of the RGC to ~ 0.45 mag fainter. The VS spans the bluest color range of the RGC and also appears in the CMD of NGC 2209. This intriguing feature does not clearly appear in the CMDs of our previous LMC clusters survey, which only show a dual clumpy structure in around 10% of the cluster sample (see Paper II). To our knowledge, such a feature has not been observed previously.

In order to delimit and characterize this intriguing feature, we first estimated its position and size and exam-

TABLE 2
TRANSFORMATION COEFFICIENTS

Date (UT)	a_1	a_2	a_3	b_1	b_2	b_3
1998 Nov 18	2.414 ± 0.021	0.295 ± 0.013	-0.047 ± 0.005	2.164 ± 0.020	0.077 ± 0.013	-0.014 ± 0.005
1998 Nov 19	2.428 ± 0.031	0.284 ± 0.019	-0.048 ± 0.007	2.134 ± 0.019	0.102 ± 0.013	-0.014 ± 0.005
1998 Nov 20	2.488 ± 0.030	0.242 ± 0.022	-0.058 ± 0.006	2.123 ± 0.025	0.091 ± 0.019	-0.007 ± 0.004
1998 Nov 21	2.391 ± 0.034	0.348 ± 0.023	-0.084 ± 0.007	2.115 ± 0.031	0.106 ± 0.022	0.004 ± 0.005
1998 Nov 22	2.352 ± 0.033	0.358 ± 0.024	-0.063 ± 0.007	2.047 ± 0.025	0.178 ± 0.018	-0.016 ± 0.004
1998 Nov 23	2.517 ± 0.023	0.222 ± 0.015	-0.047 ± 0.004	2.178 ± 0.019	0.070 ± 0.012	-0.011 ± 0.004

ined its shape going through the individual field CMDs. An enlargement of the area of interest in these CMDs is shown in Figure 3. As can be seen, the RGCs are nearly located at the same magnitude and color, centered at ≈ 18.5 and 1.60 mag, respectively. The constancy of the location in the CMD also appears to be the case for the VS, even in those fields where the VS arises as a small and sparse groups of stars. In two fields (marked with an asterisk in Fig. 1) the RGC is slightly tilted, following approximately the reddening vector, but the mean positions of both the RGC and the VS remain unchanged. Moreover, the VS maintains not only its mean position but also its verticality. Therefore, given that the locus of the VS in the CMD does not seem to show any correlation with position in the LMC and that reddening variations over our survey field should be minimal, in order to highlight the VS phenomenon we built a composite CMD using all the measured stars. The resulting diagram is shown in Figure 4, in which we also include our published Washington photometry for SL 338 and SL 509 (see § 3.2). We define VS stars as those stars that fall in the rectangle $T_1 = 18.75\text{--}19.15$ and $C - T_1 = 1.45\text{--}1.55$. This definition results in a compromise between maximizing the number of VS stars and minimizing contamination from, among other sources, MS, SGB, RGB, and red horizontal branch stars. The continuous nature of this feature is clearly evident. We are unsure of the reason why this feature appeared as a “dual clump” in two of our Paper II fields. In none of our present fields is there any significant bifurcation. The composite CMD of Figure 4 thus should present the best representation of this feature.

3.2. The VS Phenomenon

It was mentioned above that VS stars appear to be present in most of the fields of Figure 1, although in some of

them they could hardly be recognized. Therefore, it would be appropriate to map out the extent of the VS phenomenon in order to have a more quantitative estimate of its dimensions. For that purpose, we counted the number of stars lying within the VS rectangle, assuming for all the fields the same Galactic field star distribution. This assumption is particularly true if the CMDs of cluster fields located in different parts of the LMC disk (see Fig. 4 of Paper II) are compared with that of the outermost field (OHSC 37), for which we found no evidence of LMC field stars (see Santos et al. 1999, hereafter Paper III). Furthermore, in an area of the same size as the selected LMC fields, the OHSC 37 field has only two stars within the VS box, so we did not perform any correction for foreground-star contamination. The number of stars we counted for the northern LMC fields are shown in Figure 1. The VS stars show a *strong spatial variation*, reaching their highest density just north-east of SL 509.

We also repeated the same counting procedure for the fields of SL 126, SL 262, SL 388, SL 509, and SL 842 by revisiting our Washington data published in Paper II. SL 126, SL 262, and SL 842 are the nearest clusters to SL 388 and SL 509. Both present and published data sets were obtained by following the same stellar object selection criteria, so that they can be compared directly. There are 37 and 106 VS stars in SL 388 and SL 509, respectively, which numbers successfully match the trend followed by the selected LMC fields (see Fig. 1). On the other hand, the fields of SL 126, SL 262 and SL 842 turn out to have 4, 9, and 9 VS stars, respectively, placing an upper limit to the size of the VS region. All these results suggest that the region in which the VS phenomenon is concentrated extends over at least $\sim 2\text{ deg}^2$ and that the feature is not clearly seen either in the field of SL 262, which is $\sim 1^\circ 5$ to the northwest of SL 388, or in SL 842, located $\sim 4^\circ 5$ to the northeast of SL 509.

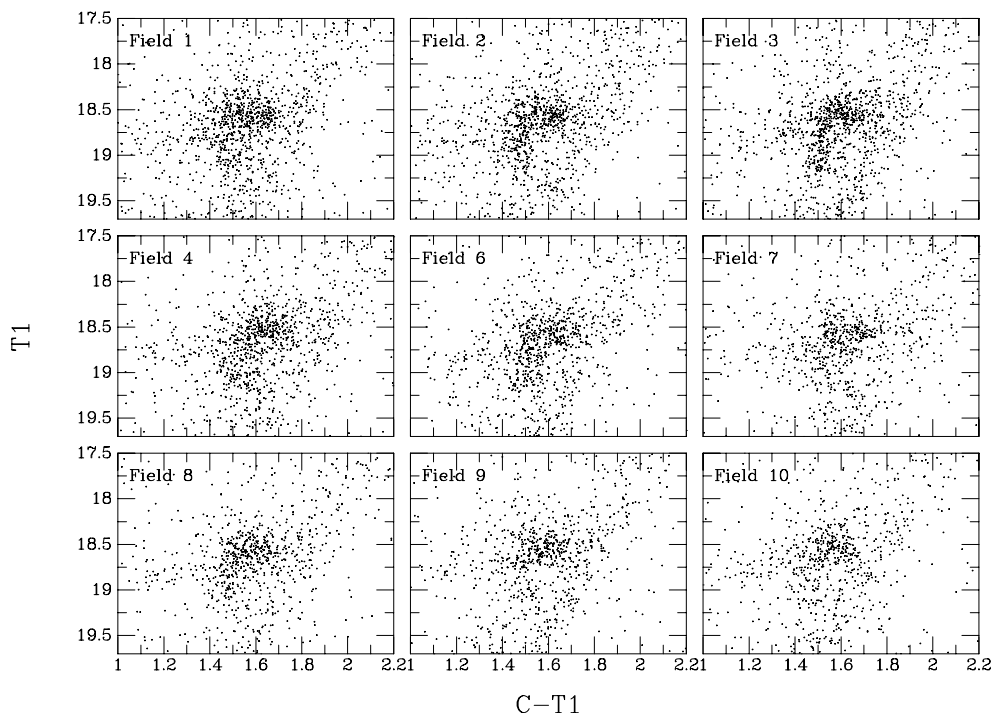
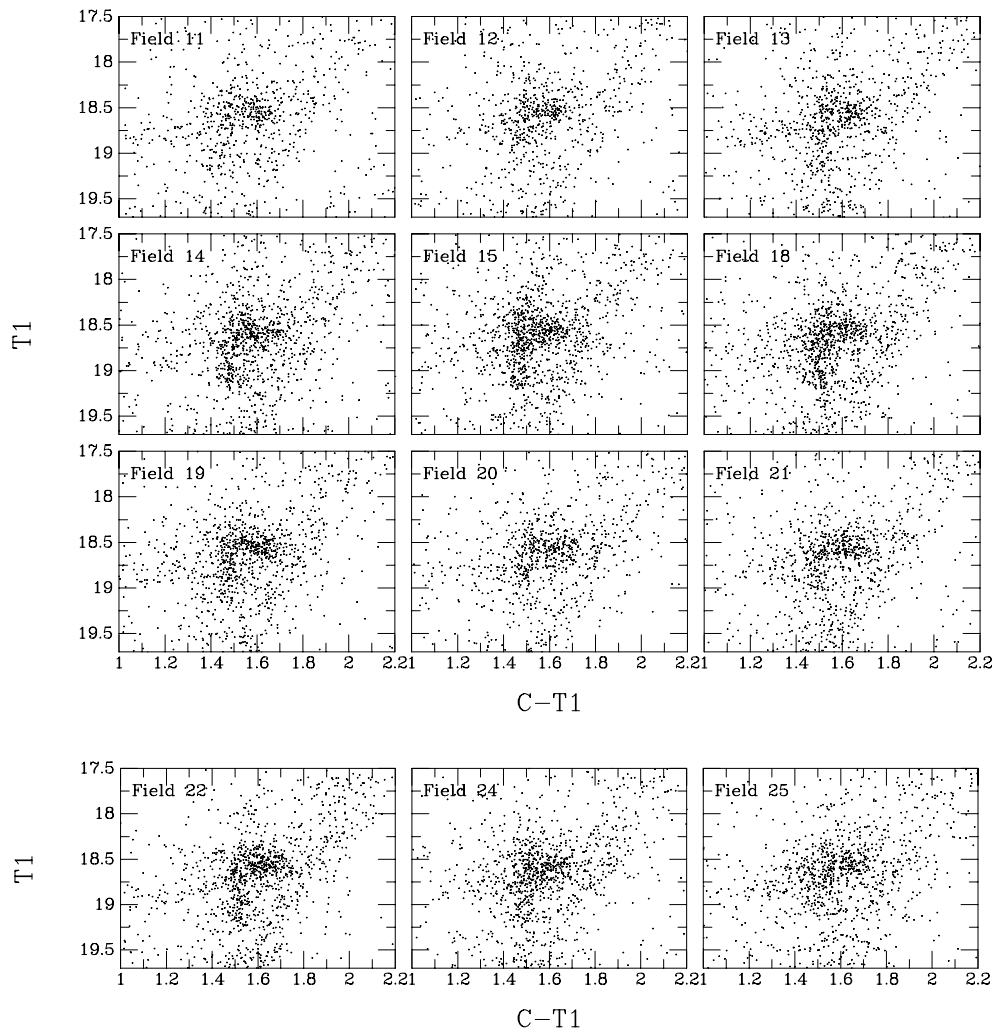


FIG. 3.—Enlargement of the RGC region in the Washington T_1 vs. $C - T_1$ CMD for each selected LMC field. Field identification is also shown (see Table 1).

FIG. 3.—*Continued*

With the aim of looking into whether VS stars are also found in LMC *clusters*, we took advantage of the fact that there is roughly one star cluster in each selected field, the

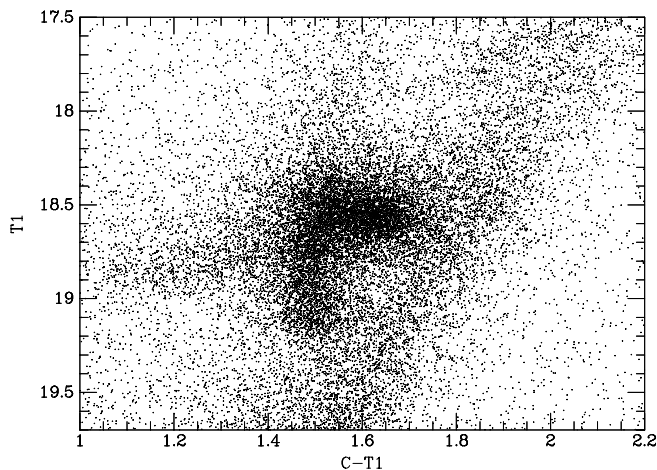


FIG. 4.—Composite Washington T_1 vs. $C - T_1$ CMD using all the measured stars in the selected LMC fields. The SL 388 and SL 509 cluster fields are also included (see § 3.2 for details). Note that VRC and HB stars are also present (see § 3.4 for details).

total cluster sample being 21. First we determined the cluster centers and selected their radii by eye, judging the variation of the stellar density in the cluster surroundings. Cluster radii vary between 20 and 110 pixels, with an average of 45 pixels ($20''$). We then performed VS star counts within both cluster radii and four circular LMC field areas on the same image chosen for comparison purposes. The four circular field areas were distributed throughout the entire image; none of them were closer to the corresponding cluster than 3 cluster radii, thus avoiding cluster star contamination. They were also located far away from the image edges, avoiding vignetting and flat-field residuals effects. Finally, the radii of the four comparison areas in each image were fixed at one-half of the cluster radii. Eighty percent of the selected LMC comparison fields contained no VS stars, while one and two VS stars were found in two and one LMC comparison fields, respectively. These results are in very good agreement with the total number of VS stars found in each frame once they are scaled to the cluster area. Similarly, star clusters apparently also have no VS stars, except in the case of SL 515, which has 12 VS stars, five of them lying inside half the cluster radius ($r \sim 45''$). SL 515 is located in one of the selected LMC fields with the highest VS star densities, as can be seen in Figure 1. However, 9' to the southeast from SL 515 there is another star cluster (SL 529) that only has two VS stars. Therefore,

the excess of VS stars in SL 515 would not seem to be related to the peak in the field VS star distribution, but to some property of the cluster itself, presumably its mass (see § 3.3). By looking at the images and comparing the cluster radii, we found that SL 515 is the largest and perhaps the most massive cluster in the sample. We also made the same comparison for the SL 388 and SL 509 fields and found one and five cluster VS stars, respectively, and no field VS stars. Both clusters have relatively large radii ($r \sim 30''$).

An additional test used to explore the nature of the VS phenomenon consists of comparing the number of VS stars with the total number of stars in the CMDs of different regions, to investigate whether there is any trend of the ratio between them with their spatial distributions [number of VS stars/total number of CMD stars = $F(\text{position})$]. For this test, we decided not to use the whole CMD of each selected LMC field because of different incompleteness factors at fainter magnitudes. Thus, we did not consider MS stars but rather a box defined by $T_1 = 17.5\text{--}19.7$ and $C - T_1 = 1.0\text{--}2.2$, which are precisely the limits of the CMD in Figure 4. This box (the RG box) includes all the red giant phases, so that if there were any correlation between VS and LMC giant stars [strictly, $\text{VS} = f(\text{RG} - \text{VS})$], it should arise without any bias from the presence of MS or other kinds of stars. Figure 5 shows the resulting relationship, in which we also include the fields of SL 126, SL 262, and SL 842. There is a strong correlation between the number of VS stars in the field and the number of LMC giants in the same zone. The lowest VS star counts occur in the outermost LMC fields, such as that of OHSC 37, where the number of red giants is also at a minimum.

3.3. The NGC 2209 Case

The giant clump luminosity is one of the best indicators of the development of the RGB, and consequently an important tool for studying the nature of the VS phenomenon. Indeed, the RGC luminosity varies along a sequence that depends on the age (mass) of the giant stars. Furthermore, Corsi et al. (1994) data and Girardi (1999) models show that the clump magnitude (V_{clump}) has a maximum (faintest value) as a function of the termination MS magni-

tude (V_{TAMS}) that corresponds to an age of $\approx 1.0\text{--}1.5$ Gyr. Precisely, our interest in observing NGC 2209 comes from the fact that this cluster falls onto the faintest magnitude in the V_{clump} versus V_{TAMS} relationship shown in Corsi et al. (1994), thus providing us with a valuable opportunity to test whether the VS is caused by evolutionary effects. NGC 2209 is located $\sim 14^\circ$ away from the selected LMC fields, and therefore any local effects in our VS area should be negligible.

Using our Washington photometry, we performed an analysis similar to that carried out for the selected LMC fields, i.e., we first looked at the NGC 2209 field CMD. Its main features resemble those of the northern LMC fields, as shown in Figure 6. The RGC is tilted and shifted with respect to Figure 1 by $\Delta(C - T_1) \approx 0.20$ and $\Delta T_1 \approx 0.30$ mag. According to the relations $E(C - T_1) = 1.966E(B - V)$ and $A_{T_1} = 2.62E(B - V)$ (Geisler 1996), these offsets are consistent with a mean reddening ≈ 0.10 mag higher. Figure 6 also reveals the presence of a VS at the same position relative to the RGC, reinforcing the conclusion that VS stars belong to the LMC. Its shape and magnitude extent are essentially the same as described in § 3.1, while its color range is somewhat wider. The fact that the tilted RGC follows approximately the reddening vector (see Fig. 6) could suggest the existence of differential reddening, although evolutionary effects could also yield an inclined clump. According to Catelan & Freitas Pacheco (1996), horizontal branch (HB) stars could result in a tilted clump if the helium content were very high ($Y = 0.30$). They also argued that a differential reddening as small as $\delta E(B - V) = 0.06$ mag cannot cause a CMD dispersion as large as the one originating from the evolution away from the zero-age HB itself. Note that tilted clumps also appear in two fields marked with an asterisk in Figure 1, but their positions and sizes (magnitude and color dispersions) are nearly the same as the remaining fields (see § 3.1). On the other hand, Hodge (1960) noticed an apparently dark patch in NGC 2209 $\sim 15''$ in diameter, about $10''$ from the cluster center, suggesting either an internal or a foreground origin for the globule. In addition, using BV CCD photometry and CMD analysis, Dottori, Melnick, & Bica (1987) concluded that the globule should be internal to the cluster, so

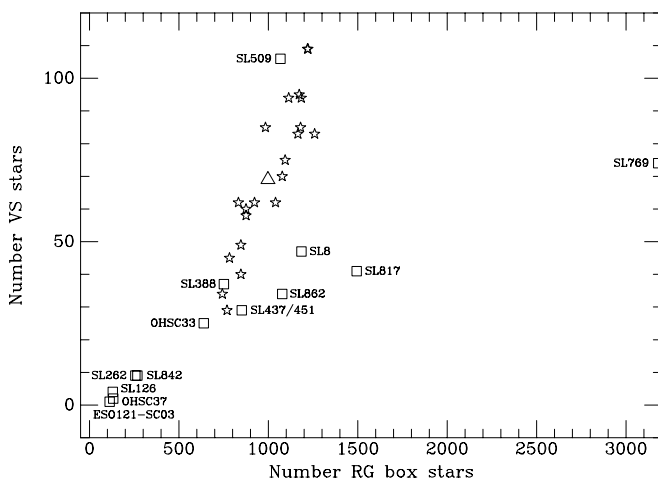


FIG. 5.—Relationship between the number of field VS stars and the number of RG box stars. Symbols represent selected LMC fields (stars), NGC 2209 field (triangles), and previously published LMC cluster fields (squares) (see §§ 3.2 and 3.4 for details).

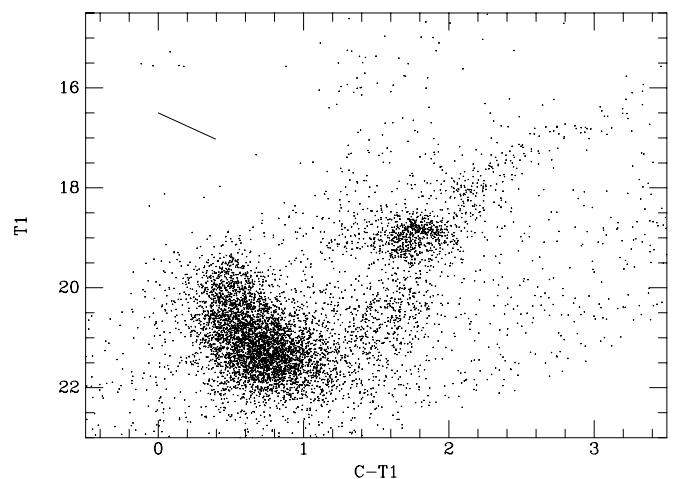


FIG. 6.—Washington T_1 vs. $C - T_1$ CMD for the NGC 2209 field, which is located $\sim 14^\circ$ away from the selected fields in the northern part of the LMC. A line following the direction of the reddening vector [$\Delta E(B - V) = 0.20$] is also shown.

that differential reddening is not unexpected. Indeed, we estimated a VS width approximately twice that of the northern selected fields. The extracted CMD of NGC 2209 also shows a remarkable color dispersion not only for giant clump stars, but also for SGB stars, which appear to be distributed at both edges of their whole color range (see Fig. 6).

Next, we counted the VS stars distributed in the NGC 2209 field using a box with the same dimensions as for the northern LMC fields and reddened by $\Delta E(B-V) = 0.10$. We also applied the same shift to the RG box, thus centering the RGC. The number of VS stars in the NGC 2209 field and in the cluster itself ($r \sim 45''$) was 69 and 10, respectively, whereas no VS stars were found in four circular field areas (equal cluster area criterion), as expected. This result is in very good agreement with that found for SL 515, in the sense that relatively massive clusters can develop giant clumps with a considerable number of VS stars. Finally, if we compare the number of field VS stars with that corresponding to the RG box, we can conclude that LMC regions with a noticeable large giant population can also be reservoirs of VS stars. The fact that NGC 2209, located many degrees from our main VS area, also shows this feature argues against a depth-effect interpretation (e.g., background galaxies or debris) and for an evolutionary origin.

3.4. Comparison with Theory

It is known that stars defining the RGC in CMDs of intermediate age and old open clusters are in the stage of central helium burning (Cannon 1970; Faulkner & Cannon 1973). However, according to Girardi (1999) models, computed using a grid of masses with a resolution of $\sim 0.1 M_{\odot}$ in the vicinity of the onset of helium-burning mass, the position of GC stars in the CMD depends on the masses of the stars. Particularly, stars with $M \leq M_{\text{Hef}} \sim 2\text{--}2.5 M_{\odot}$ form electron-degenerate cores with masses nearly constant ($M_c \simeq 0.45 M_{\odot}$) after the central hydrogen exhaustion, thus allowing stars to reach similar luminosities. These stars correspond to our RGC stars. On the other hand, for stars with $M > M_{\text{Hef}}$ helium ignition takes place under nondegenerate conditions, and both M_c and luminosity increase with M_{Hef} , the minimum luminosity being about 0.4 mag fainter than those of stars with slightly lower masses. Girardi's models predict that such stars should define a secondary clumpy feature located below the RGC and at its bluest extremity, reminiscent of our VS feature. The spread in the intrinsic luminosity of stars burning helium in their cores evidenced by this feature provides a further constraint on using the magnitude of the GC stars as a self-consistent distance indicator.

Now we can check Girardi's (1999) predictions in light of the present observational findings, so that new constraints to the theory can improve our knowledge of stellar evolution and the star formation history in the LMC. In contrast to the tentative explanation of debris from a dwarf galaxy located behind the LMC suggested in Paper II, Girardi claimed that the secondary clump in the CMDs of SL 388 and SL 509 fields might have been caused by a population younger (of higher mass) than RGC stars. However, in the present work we did not find such a separated fainter clump, but rather a VS having approximately the same number of stars per magnitude interval and peaking at its brightest limit. The peak of the VS luminosity function has

TABLE 3
LUMINOSITY FUNCTION FOR
VS STARS

T_1 (mag)	Number of Stars
18.775.....	1094
18.825.....	957
18.875.....	949
18.925.....	771
18.975.....	815
19.025.....	791
19.075.....	771
19.125.....	798

approximately 25% more stars than the remaining fainter part of the VS, independent of the bin sizes (see Table 3 and Fig. 7). Therefore, the VS can be described as the faint tail of a long continuous vertical distribution formed by stars developing nondegenerate helium cores; the upper part of this long VS is represented by the so-called "vertical red clump" (VRC), recently extensively discussed in the literature (e.g., Zaritsky & Lin 1997; Beaulieu & Sackett 1998; Gallart 1998; Ibata, Lewis, & Beaulieu 1998). The presence of VRC stars in the Hess diagram (density-coded CMD) of a $2^{\circ} \times 1.5^{\circ}$ region located $\sim 2^{\circ}$ northwest of the center of the LMC was interpreted by Zaritsky & Lin (1997) as red clump stars that are closer to us than those in the LMC. However, according to Girardi et al. (1998) and Beaulieu & Sackett (1998), among others, evolutionary effects appear to describe its nature more satisfactorily. Thus, VRC stars should be the more massive clump stars, while stars with $M \sim 2 M_{\odot}$ should define the lower magnitude limit (Girardi's secondary clump); stars with even smaller masses are grouped in the RGC. Figure 4 shows the presence of not only VS stars but also VRC and HB stars. Note that even though both the Zaritsky & Lin (1997) and our present surveyed areas are roughly similar in size, VRC stars are clearly much less numerous than VS stars in our Figure 4, which surprisingly contrasts with their Hess diagrams, where no VS stars are seen despite the presence of the VRC. Certainly, if an LMC field contains both high-mass (VRC)

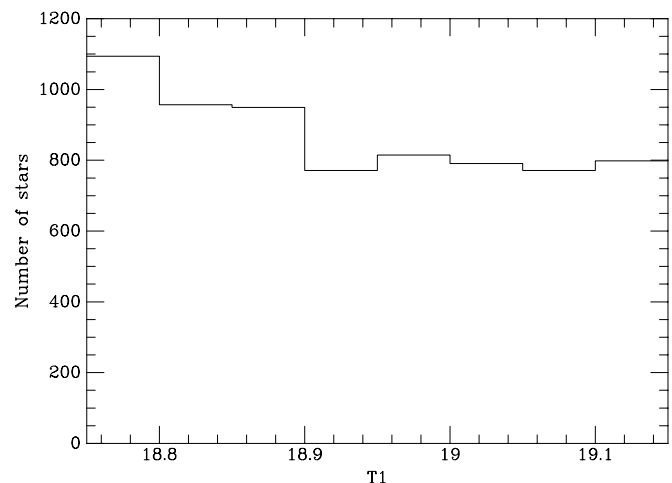


FIG. 7.—Luminosity function for VS stars

and low-mass (RGC) stars, we should also expect to find intermediate-mass stars (VS stars), which were not detected in the Zaritsky & Lin survey data. We are uncertain as to what causes this paradox.

On the other hand, bearing in mind the differences mentioned above, it would be interesting to investigate how fundamental properties of VS stars compare with those predicted by Girardi for secondary clump stars. Note that Girardi predicted that secondary clumps should be observed in fields with an important number of 1 Gyr old stars ($M \sim 2 M_{\odot}$) mixed with older stars, and with metallicities higher than about $Z = 0.004$ ($[\text{Fe}/\text{H}] \simeq -0.7$). In addition, he pointed out that neither main nor secondary clumps should be mixed due to differential reddening, distance dispersions, or photometric errors. We first derived the ages of NGC 2209 and SL 515 and compared them with those of Girardi's models. The cluster ages were estimated using the δT_1 index as defined in Paper I, yielding values of 1.5 and 1.6 Gyr for NGC 2209 and SL 515, respectively. These values are in good agreement with the ages associated with stars having M_{HeF} just in the limit for nondegenerate helium cores. We also estimated the ages for the remaining star clusters contained in the selected LMC fields, all of which appear to be on average younger than 1.5 Gyr old. The ages derived for SL 388 and SL 509 in Paper II are 2.2 and 1.2 Gyr, so that slightly older stars than those predicted by Girardi's models could also fall into the CMD VS region. However, most of the clusters and surrounding fields of Paper II (except ESO 121-SC03) have ages in the range 1.0–2.2 Gyr, but only in two of them were secondary clumps clearly distinguished. Moreover, the metallicity of SL 509 is $[\text{Fe}/\text{H}] = -0.85$, while the metallicities of the surrounding cluster fields are all in the range -0.35 to -0.7 .

In order to find some explanation for such a paradoxical result, which would appear to be opposite to the predictions of Girardi's secondary clump models, we counted VS and RG box stars for all the surrounding fields of clusters analyzed in Paper II, and put these values into the VS versus RG box plane. We applied reddening corrections with respect to the SL 388 and SL 509 fields [$E(B-V) = 0.03$] and adopted the same foreground star contamination for all the fields, given the similar galactic star distribution in their CMDs compared to the field CMD of OHSC 37 (see Fig. 4 of Paper II). Figure 5 shows the resulting relationship (*squares*), in which we also included the 9 Gyr old field centered on ESO 121-SC03, the outermost OHSC 37 field, and the inner disk SL 769 field. In particular, the younger SL 769 field turnoffs are younger than 1 Gyr, thus providing an important number of RG stars. As can be seen, fields with only a few RG box stars do not have many VS stars either, independent of their ages and metallicities, while VS stars become more important as the number of RG box stars increases. However, the surrounding fields do not seem to show the same correlation in Figure 5 as the selected LMC fields (Fig. 5, *stars*). In the case of SL 769, the number of VS stars is near the average of those in the selected LMC fields, but RG box stars are nearly 3 times more numerous. Furthermore, the fields around SL 388 and SL 817 share similar ages, metallicities, and number of VS stars, while the number of RG box stars in the SL 817 field is twice that in the SL 388 field, which suggests that a large number of RG stars alone is not a sufficient requirement for the appearance of the VS pheno-

menon. The number of VS stars in the fields of SL 509 and SL 862 are also quite different, although their ages, metallicities, and number of RG box stars are very similar. Furthermore, SL 509 itself has five VS stars (see § 3.2), whereas no VS stars appear to be associated with SL 862. All these results apparently suggest that there should be other conditions besides age, metallicity and necessary RG star density that would trigger the formation of VS stars, such as the environment of the VS star-forming regions, different star formation rate, mass function, etc. Nevertheless, nonuniform spatial distribution of VS stars in the LMC reveals that nonhomogeneously distributed star formation events occurred in this galaxy about 1–2 Gyr ago.

4. CONCLUSIONS

From the analysis of Washington photometry for 21 selected fields located in the northern part of the LMC and 14 cluster fields distributed throughout the LMC disk, we conclusively identify the existence of a vertical structure of stars that lies below the RGC at its bluest color and up to 0.45 mag fainter. Our previous data (Paper II) uncovered two northern fields that contained what appeared to be a “dual clump,” with a secondary clump lying fainter and bluer than the RGC. Stars lying in the same CMD region were described as very old stars ($t \sim 10$ Gyr) by Westerlund et al. (1998) from BV photometry of three fields located in the northeast of the LMC. However, our much larger present database indicates that there exists a continuous distribution of stars, which we term VS (“vertical structure”) stars, not only in the CMDs of field stars but also in certain intermediate-age star clusters. These results demonstrate that VS stars belong to the LMC and that they are not composed of old objects in the LMC or of a background population of RGC stars. We also determine that VS stars are only found in those fields that satisfy some particular conditions, such as containing a significant number of 1–2 Gyr old stars and having metallicities higher than $[\text{Fe}/\text{H}] \approx -0.9$ dex, in good agreement with Girardi's (1999) models, which predicted that a minimum in the luminosity of core He burning giants is reached just before degeneracy occurs. These conditions constrain the VS phenomenon to appear only in some isolated parts of the LMC, particularly those with a noticeable large giant population. However, a large number of RG stars of the appropriate age and metallicity is not a sufficient requisite for forming VS stars. Thus, for example, we found an area spread over 2.6 deg^2 centered just to the northeast of SL 509 with 3 times fewer RG stars than the inner disk cluster SL 769, but with approximately the same number of VS stars. Clusters with the appropriate age and metallicity to contain a significant number of VS stars are also required to be relatively massive; NGC 2209, for example, constitutes a good example of Girardi's predictions. Finally, although Girardi's models successfully predict the existence of red giants fainter and bluer than RGC stars on the basis of an evolutionary effect, there is still a need for more detailed studies to explain, for example the VS vs. RG relationship, the ratio between the number of VS and VRC stars, whether tilted RGCs are related to VS features, the VS luminosity function, etc. The fact that Zaritsky & Lin (1997) found red clump stars with high and low masses, but none at the intermediate degenerate mass limit required to form VS stars, also remains unexplained. Indeed, 1–2 Gyr old stars with $[\text{Fe}/\text{H}] \sim -0.3$ dex are very common in the LMC,

although VS stars are only clearly seen in certain parts of the galaxy, which constitutes an unresolved mystery.

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