# OUTSIDE-IN DISK EVOLUTION IN THE LARGE MAGELLANIC CLOUD

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## ABSTRACT

From the analysis of the color-magnitude diagrams and color functions of four wide LMC fields located from $\simeq$2 to 6 kpc from the kinematic center of the LMC we present evidence that, while the oldest population is coeval in all fields, the age of the youngest component of the dominant stellar population gradually increases with galactocentric distance, from currently active star formation in a field at 2.3°, to 100 Myr, 0.8 Gyr, and 1.5 Gyr in fields at 4.0°, 5.5°, and 7.1°, respectively. This outside-in quenching of the star formation in the LMC disk is correlated with the decreasing H I column density (which is $\lesssim 2 \times 10^{20}$ cm$^{-2}$ in the two outermost fields with little or no current star formation). Other work in the literature hints at similar behavior in the stellar populations of irregular galaxies and in M33. This is observational evidence against the inside-out disk formation scenario in low-mass spirals and irregular galaxies. Alternatively, it could be that the age distribution with radius results from interplay between the evolution with time of the star-forming area of the LMC and the subsequent outward migration of the stars.


*Subject headings:* galaxies: evolution — galaxies: formation — galaxies: individual (LMC) — Magellanic Clouds

*Online material:* color figure

## 1. INTRODUCTION

Modern hydrodynamical simulations suggest that, within the LCDM cosmology, galaxies form from the inside out; i.e., their inner parts formed first, and they subsequently grew up to their present-day size (e.g., Brook et al. 2006; Roškar et al. 2008). This can be interpreted either in terms of the age of the oldest population, which would be younger toward the external parts, or in terms of the mixture of populations, which would be younger on average there. However, the formation of a realistic disk galaxy within such simulations remains elusive (e.g., Governato et al. 2007; Abadi et al. 2003) and it is essential to augment such studies with detailed observations.

Observationally, two main avenues have been used to investigate disk formation and evolution. The first relies on the direct comparison of the actual physical sizes (or related parameters) of high-$z$ disk galaxies with those of nearby galaxies (e.g., Trujillo & Aguerri 2004; Pérez 2004; Reshetnikov et al. 2003). The second focuses on nearby galaxies, and typically uses indicators of the ratio of recent to total star formation rate (SFR) as a function of radius (e.g., Muñoz-Mateos et al. 2007; Taylor et al. 2005). Taylor et al. (2005) found, in agreement with previous studies, that late-type spirals and irregular galaxies become on average redder outward. Since no plausible galaxy formation theory predicts positive metallicity gradients, they offer stellar age effects or dust as possible causes of this effect. The use of integrated properties makes it difficult to derive mass fractions as a function of age (and thus to distinguish between these two possibilities), or to determine the age of the oldest population as a function of radius. A direct census of stellar ages in a resolved galaxy would provide the necessary information to trace the characteristics of the stellar population as a function of radius, and thus to provide direct insight on formation and evolution mechanisms.

Nearby galaxies offer this possibility. Indeed, if the oldest main-sequence (MS) turnoffs are reached, the age of the oldest population as a function of radius can be measured and a quantitative age profile can be determined at each radius. In dIrr galaxies, a young population is routinely found in their central parts, but it disappears in the outskirts (e.g., Bernard et al. 2007; Vansevičius et al. 2004). In the cases where a color-magnitude diagram (CMD) reaching the oldest MS turnoffs is available, it has been found that an intermediate age population extends to large distances from the center, and that it very gradually disappears toward the outer part (S. L. Hidalgo et al. 2008, in preparation; Gallart et al. 2004; Noël & Gallart 2007), suggesting a "shrinking scenario" of star formation in dwarf galaxies (Hidalgo et al. 2003). A similar result is found in the case of M33 (see Barker et al. 2007).

In this paper we analyze four 36′ × 36′ fields in the LMC at different galactocentric distances, using CMDs reaching the oldest MS turnoffs, in order to shed light on its stellar population gradients and thus on its formation and evolution.

## 2. OBSERVATIONS AND DATA REDUCTION

We obtained $V$ and $I$ images of four LMC fields with the Mosaic II camera on the CTIO Blanco 4 m telescope in 1999 December and 2001 January. Fields were chosen to span a range of galactocentric distances, from $\simeq$2.3° to 7.1° (2.0–6.2 kpc) northward from the kinematic center of the LMC. Note that the position angle of the LMC bar is 120°, and its center is slightly offset to the southeast of the kinematic center. We will name the fields according to their right ascension and declination (J2000.0) as LMC 0512−6648, LMC 0514−6503, LMC 0513−6333, and LMC 0513−6159, in order of increasing galactocentric distance.

The Mosaic frames were reduced in a standard way, using

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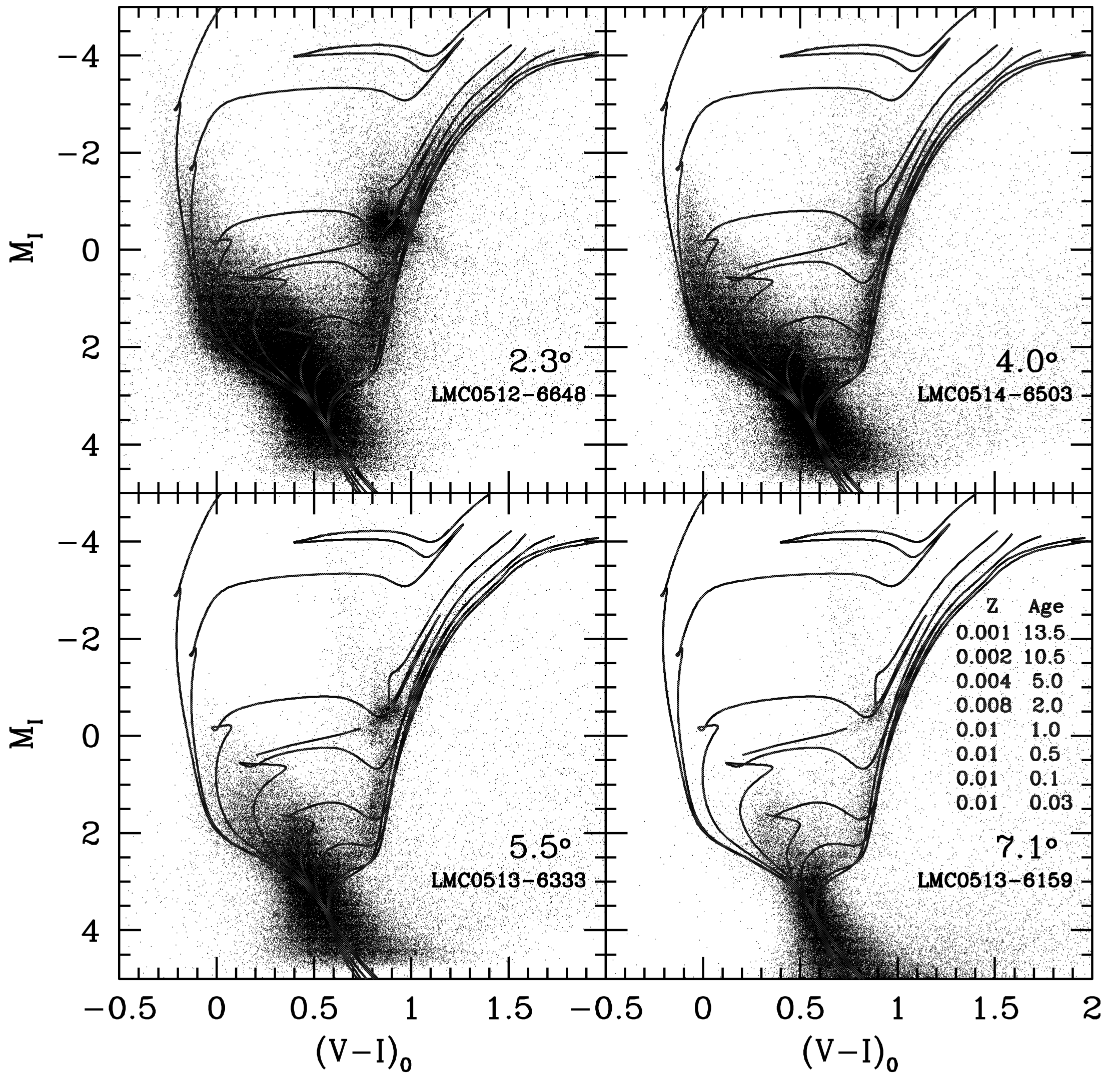


FIG. 1.—[$(V-I)_0$, $M_I$] CMDs for the four fields. Isochrones with ages and metallicities as labeled, and a zero-age horizontal branch of $Z = 0.001$ by Pietrinferni et al. (2004) have been superimposed. A distance modulus of $(m-M)_0 = 18.5$ and $E(B-V) = 0.10$, 0.05, 0.037 and 0.026 mag, respectively, have been assumed. For the two outermost fields, the reddening values given by Schlegel et al. (1998) have been used. For the two innermost fields their value is not accurate and we have estimated a mean value of the reddening by requiring a good fit of the CMD by the same isochrones. The tightness of the sequences, and in particular of the RC, in the different CMDs indicates that differential reddening in these fields is small, except for the innermost field, where the whole CMD gets noticeably blurred, and a tail of reddened stars is clearly visible in the RC area.

the MSCRED package within IRAF.[6] Profile-fitting photometry was obtained with the DAOPHOT/ALLFRAME suite of codes (Stetson 1994) and calibrated to the standard system using observations of several Landolt (1992) fields obtained in the same runs. Finally, a large number of artificial star tests were performed in each frame following the procedure described in Gallart et al. (1999); these are used both to derive completeness factors and to model photometric errors in the synthetic CMDs. I. Meschin et al. (2008, in preparation) will provide a detailed description of the observations and data reduction.

## 3. STELLAR POPULATION GRADIENTS IN THE LMC

Figure 1 shows the [$(V-I)_0$, $M_I$] CMDs of the four LMC fields, with isochrones superimposed. The number of stars observed, with good quality photometry, down to $M_I \lesssim 4$ in each field, in order of increasing galactocentric distance are 300000, 214000, 86000, and 39000, respectively. All the CMDs reach the oldest MS turnoff ($M_I \simeq 3.0$) with good photometric accuracy, and completeness fractions over 75% (except for the innermost field, in which crowding is very severe). The two innermost fields show a CMD with a prominent, bright MS and a well-populated red clump (RC) typical of a population which has had ongoing star formation from ≃13 Gyr ago to the present time. The two outermost fields clearly show a fainter MS termination, indicative of a truncated or sharply decreasing star formation in the last few hundred Myr or few Gyr, respectively (see below). No extended horizontal branch is observed in any of the fields but all fields host a number of stars redder than the RGB tip (and redder than the color interval shown in the figure), which are candidate AGB stars.

### 3.1. *The Comparison with Isochrones*

In Figure 1 the observed CMD for each field is compared with isochrones from the overshooting set of the BaSTI library (Pie-

[6] IRAF is distributed by the NOAO, which is operated by the AURA, Inc., under cooperative agreement with the NSF.

trinferni et al. 2004).[7] The metallicities of the isochrones have been chosen to approximately reproduce the common chemical enrichment law for the same fields derived by Carrera et al. (2008), using Ca II triplet spectroscopy. Note how well this combination of ages and $Z$ reproduce the position and shape of the RGB.

The area around the old MS turnoff is well populated in all four CMDs, indicating that star formation started at about the same time in all four fields, or that old stars have been able to migrate out to the galactocentric radii observed here. The 13.5 and 10.5 Gyr isochrones of $Z = 0.001$ and $Z = 0.002$, respectively, almost overlap due to the substantial metallicity increase measured in this period. The main stellar population differences among the fields are instead related to the recent star formation history. The MS of the innermost field, LMC 0512−6648, is well populated up to the 30 Myr isochrone or younger. Field LMC 0514−6503 shows a MS populated up to the same isochrone, but there is an apparent change in the density of stars at the position of the ≃100 Myr old isochrone that might indicate a lower SFR from 100 Myr ago to the present time. In the next field, LMC 0513−6333, an apparent change in the stellar density on the MS occurs at age ≃0.8 Gyr while in the outermost field, LMC 0513−6159, it occurs at age ≃1.2 Gyr. The comparison with isochrones, therefore, indicates a gradual increase in the age of the youngest component of the bulk of the stellar population with galactocentric radius. No obvious gaps indicating a discontinuous star formation history are present in the MS of any of the fields.

### 3.2. *CFs*

The use of the color function (CF) for a semiquantitative assessment of the stellar population present in a CMD has been discussed in detail by Gallart et al. (2005) and Noël et al. (2007). The CF accounts naturally for the fact that the stellar density is different in the various fields. The top panel of Figure 2 represents the observed CFs of the four LMC fields. Red lines represent the CF of a synthetic CMD computed using IAC-STAR (Aparicio & Gallart 2004), assuming a constant SFR from 13 Gyr ago to the present time and the $Z(t)$ derived by Carrera et al. (2008). Observational errors have been simulated based on the artificial star tests performed on the outermost and innermost fields. As in the case of the outermost field, the errors corresponding to the intermediate fields do not substantially change the overall shape of the CF. The bottom panel displays the CF for the same synthetic CMD without any errors simulated (*black thick line*), together with the CF corresponding to stellar populations within limited age ranges, as labeled (see the figure caption for more details).

As discussed in Noël et al. (2007), the CF of a synthetic CMD computed assuming a constant SFR can be divided into three main features: a blue elevation composed by young stars, a main central peak which contains stars of all ages, and a red peak which corresponds to the RGB and RC. Since metallicity affects the RGB and RC position more strongly than the other CMD features, the coincidence in color between the observed and the synthetic red peaks indicates that the assumed chemical enrichment law is consistent with the data.[8] Once this metallicity agreement is verified, the shape of the CF mainly provides

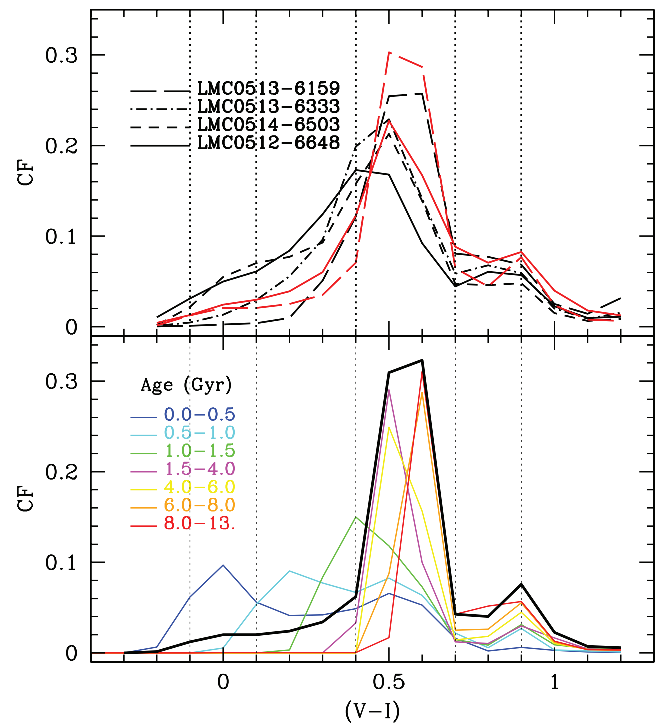


Fig. 2.—*Bottom panel*: The black line shows the CF of a synthetic CMD computed assuming the $Z(t)$ derived by Carrera et al. (2008) using the Ca II triplet, a constant SFR from 13 Gyr ago to the present time, a Kroupa (2001) IMF, and 50% of binaries ($q \geq 0.7$). The BaSTI stellar evolution models (Pietrinferni et al. 2004) have been assumed and the CF has been normalized to unity. The colored lines show the CF of the same synthetic CMD within limited age ranges, as labeled. Here the normalization factor of each CF is half that of the CF for the whole range of ages. *Top panel*: The black lines of different line types show the observed CFs for each LMC field. The red lines show the CF of the global synthetic CMD used in the bottom panel, but with observational errors simulated using completeness information from the outermost (*long-dashed lines*) and the innermost (*solid line*) fields, which are the lower and upper limits for the observational errors, respectively. In all cases, the CF integrates the information in the CMD between $M_I = -4$ and $M_I = 3.5$. Vertical dotted lines have been drawn in order to guide the eye in the comparison between the synthetic and the observed CFs.

information on age and relative importance of the stellar populations younger than ≃1.5 Gyr.

Note that redder than $(V-I) \simeq 0.3$ the position and width of the LMC 0513−6159 CF are very similar to those of the synthetic CMD; bluer than this color the observed CF does not show the blue elevation composed of young stars. This indicates a significant decrease in star formation around ≃1.5 Gyr ago, in agreement with the information provided by the isochrones. For the remaining fields, the main peak blue side is shifted to the blue with respect to that of the synthetic CF, possibly indicating enhanced star formation, as compared to a constant SFR, in the age range ≃4–1 Gyr. The blue elevation of field LMC 0513−6333 is lower than the synthetic one for $(V-I) \lesssim 0$, confirming reduced star formation in this field starting ≳0.5 Gyr ago. Finally, the CFs of fields LMC 0514−6503 and LMC 0512−6648 show a blue elevation substantially enhanced compared to a constant SFR, indicating increased star formation from ≃1–1.5 Gyr ago to the present time.

The CFs, therefore, confirm the information provided by the isochrones: (1) a possible truncation of the bulk of the star formation in the outermost fields LMC 0513−6159 and LMC 0513−6333 at ages ≃1.5 and 0.8 Gyr respectively; and (2) the suggestion of enhanced star formation (as compared to a con-

[7] The new 2008 version of the BaSTI stellar evolution models (see http://www.oa-teramo.inaf.it/BASTI) is used through the Letter. This set shows a much better agreement with other stellar evolution models than the older one.

[8] The fact that the observed CFs reach higher values in the color range $(V-I) = 0.7$–09 than the synthetic CF may be attributed to the foreground contamination, which is relatively important in this color range.

stant SFR) in the innermost fields LMC 0514−6503 and LMC 0512−6648 in the same time range, likely having started even earlier, ∼4 Gyr ago. Enhanced star formation starting around 4 Gyr ago possibly extended also to field LMC 0513−6333; however, in this case it would have been followed by the truncation discussed above.

## 4. DISCUSSION

We have presented CMDs and CFs of four wide LMC fields spanning galactocentric distances, from ≃2 to 6 kpc northward from the center of the LMC. The oldest population is of similar age in all fields and the CFs of the three innermost fields indicate a likely enhancement of the SFR ≃4 Gyr ago, in agreement with former studies (e.g., Carrera et al. 2008; Holtzman et al. 1999; Olsen 1999; Bertelli et al. 1992). Finally—and most importantly for the purpose of this Letter—there is a gradual increase with radius in the age of the youngest component of the dominant stellar population (from currently active star formation to 100 Myr, 0.8 Gyr, and 1.5 Gyr from the innermost to the outermost field, respectively). This age gradient in the youngest population is correlated with the H I column density as measured by Staveley-Smith et al. (2003): the two innermost fields are located ≃0.7 kpc at either side of $R_{\mathrm{H}\alpha}$, LMC 0512−6648 on the local maximum of the azimuthally averaged H I column density with $\simeq 1.63 \times 10^{21}$ cm$^{-2}$ (close to the H I threshold for star formation; Skillman 1987) and LMC 0514−6503 where the azimuthally averaged H I column density is only $\simeq 5 \times 10^{20}$ cm$^{-2}$. Finally, the two outermost fields are close to the H I radius considered by Staveley-Smith et al. at the H I density of $10^{20}$ cm$^{-2}$. The outermost field, LMC 0513−6159, is approximately halfway to the tidal radius (van der Marel et al. 2002). If the youngest stars in each field were formed in situ, we are observing an outside-in quenching of the star formation at recent times (≃1.5 Gyr) in the LMC, possibly implying a decrease in size of the H I disk able to form stars. Alternatively, the youngest stars may be migrating outward from their formation site with higher H I density (e.g., Roškar et al. 2008). In fact, it is expected that both star formation sites and stars migrate across the LMC disk due to tidal interactions with the Milky Way and the SMC (e.g., Bekki & Chiba 2005).

Taylor et al. (2005) offered two possible explanations for the fact that the late-type galaxies in their sample become redder outward: a change in the mean age of stellar population, or a change in the dust characteristics. The present work shows that the youngest, bluest stars are progressively missing outward in the LMC disk. Therefore, a reddening of the intrinsic integrated color is expected: for example, from the synthetic population used in this Letter, we measure $(V-I)$ colors of 0.85, 0.97, or 1.03 if star formation continues to the present time, or is truncated 0.8 or 1.5 Gyr ago, respectively. Other irregular galaxies (and M33) are not close enough for such a detailed picture to be obtained, but the evidence from shallower CMDs is that the situation is similar, so that current star formation is concentrated in their central parts, and the youngest population becomes gradually older outward. This is observational evidence against the inside-out disk formation scenario in the case of small spirals and irregular galaxies.

Alternatively, it could be that the age distribution of the stars varies with radius because of the interplay between the evolution of the star-forming region (as a consequence of gas accretion and consumption) and the outward migration of the stars, as in the simulations by Roškar et al. (2008; which however apply only to isolated, nonbarred galaxies). In this case, a position in between the two innermost fields—which approximately coincides with the outermost extension of the H I disk with density above the threshold for star formation—could be the maximum radius reached by a growing star-forming zone and may coincide with the break radius observed in other more distant galaxies. In fact, a break in the surface brightness profile at $R \simeq 240'$ is hinted at in Figure 1 of Gallart et al. (2004)[9] and also in van der Marel (2001).

C. G. acknowledges interesting discussions with A. Aparicio, M. Balcells, K. Bekki, E. Bernard, S. Cassisi, V. Debattista, B. Elmegreen, J. C. Muñoz-Mateos, N. Nöel, I. Pérez, J. Read, I. Trujillo, R. Zinn, and A. Zurita. The data presented in this Letter were obtained as part of a joint project between the University of Chile and Yale University funded by the Fundación Andes. C. G. acknowledges partial support from the IAC and the Spanish MEC (AYA2004-06343). This work has made use of the IAC-STAR Synthetic CMD computation code. IAC-STAR is supported and maintained by the computer division of the IAC.

*Facilities*: Blanco

[9] In that figure, the radius was calculated from the center of the LMC bar; $R = 300'$ in that figure corresponds approximately to $R = 240'$ from the LMC kinematic center.

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