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What stars can tell us about galaxies: star formation histories in the Local Group

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Abstract

The formation and evolution of Local Group galaxies can be studied in the greatest possible detail thanks to the possibility of obtaining photometry and spectroscopy of their individual stars. I present an overview of different methods that can be combined for their study, and discuss recent results on the star formation history of a sample of Local Group isolated dwarf galaxies, and the Large Magellanic Cloud.

1 Introduction

The nearest galaxies, which can be resolved into stars, offer the opportunity to study their formation and evolution in the greatest possible detail. For them, we can use the well established stellar evolution theory, together with spectroscopy and photometry of individual stars, to interpret their fossil record and to trace the evolution of each particular system from its formation to the present time. One could argue that this approach can be applied only to a very limited volume of the local Universe, and in its full power, only to the Local Group (LG). Among its approximately 40 galaxies, however, we have representatives -except mainly for a giant elliptical- of most galaxy types. The LG is dominated by two large spirals, the Milky Way (MW) and M31, which are centers of rich satellite systems. In addition, there are several isolated dwarf galaxies. For each of these galaxies we can obtain detailed information on the first episodes of star formation, and address questions of cosmological interest like *are the oldest stars in all these galaxies coeval?*, or *are there differences in the epoch or strength of the early star formation, depending on galaxy type and/or environment?* We can also test the hypothesis of hierarchical galaxy assembly via mergers, directly using observations of merger remnants in the MW, and the role of interactions on galaxy evolution through the study of different interacting systems in the LG (e.g. MW-LMC-SMC; M31-M32). Finally, their morphology, stellar population gradients and internal kinematics can constrain detailed models of dwarf galaxy formation and evolution.

We are combining three powerful sets of tools in order to obtain a detailed characterization of the evolutionary history of LG galaxies:

1.-Color magnitude diagrams (CMD) reaching the oldest main sequence turnoffs (oMSTO): they allow the most reliable derivation of the star formation history (SFH) because the information is obtained directly from the main sequence, which is the best understood phase of stellar evolution from the theoretical point of view, and also the one in which the location of stars in the CMD shows the highest sensitivity to age differences ([16]; see Sect. 2 below for more details).

2.- Variable stars: they are a key complement because they allow tracing stars in specific evolutionary phases. A key tracer of old populations are RR Lyrae stars, which have enabled the identification of old populations in all the MW satellites.

3.- Low- and high-resolution spectroscopy: stellar metallicities can be obtained using the CaII triplet [9] while for the study of elemental abundances, high resolution spectra are necessary.

For the MW satellites (except for the most distant ones, Leo I and Leo II), the three types of data are best obtained from the ground using wide field imagers on 4m-class telescopes and multi object spectrographs on 4-10m telescopes. For the rest of the LG, the ACS on board HST is required for imaging stars at the oMSTO level (e.g., [28, 20, 3]), and the same instrument is the ideal one for variable stars down to the horizontal branch (HB, [5]), even though it is possible to obtain the necessary data using imagers on 10m class telescopes under excellent seeing conditions [27]. Finally, low resolution spectra, though challenging, can be obtained for RGB stars over most of the LG using 10 m class telescopes [12].

In this paper, I will focus in results on the SFH of LG galaxies obtained through the analysis of CMDs reaching the oMSTOs. In Sect. 2, I will provide an overview of the techniques currently used, discuss the status of the knowledge we have reached with on the LG galaxies and summarize what still needs to be done. In Sect. 3, I will present the main conclusions of the LCID project[1]. Finally, in Sect. 4, I will present some findings on the spatial gradients of the SFH in both the LCID project galaxies and in the LMC.

2 Deriving SFHs from CMDs reaching the oMSTOs

Figure 1 displays a synthetic CMD, with stars of different ages drawn in different colors (see the caption for details). Notice the sequence of ages along the main sequence which, although somewhat blurred, is maintained after simulation of observational errors. In contrast, stars of different ages mix together in the red-clump and RGB areas, the situation being much worse in a more realistic case involving a range of metallicities. Figure 1 illustrates the much higher sensitivity to age differences of the main sequence as compared to the other features in the CMD, and how the number of stars of different luminosities in the main sequence can be used to measure the SFH over the whole galaxy history.

In practice, the SFH is obtained through comparison of the distribution of stars in the

[1]Local Cosmology from Isolated Dwarfs project: http://www.iac.es/project/LCID

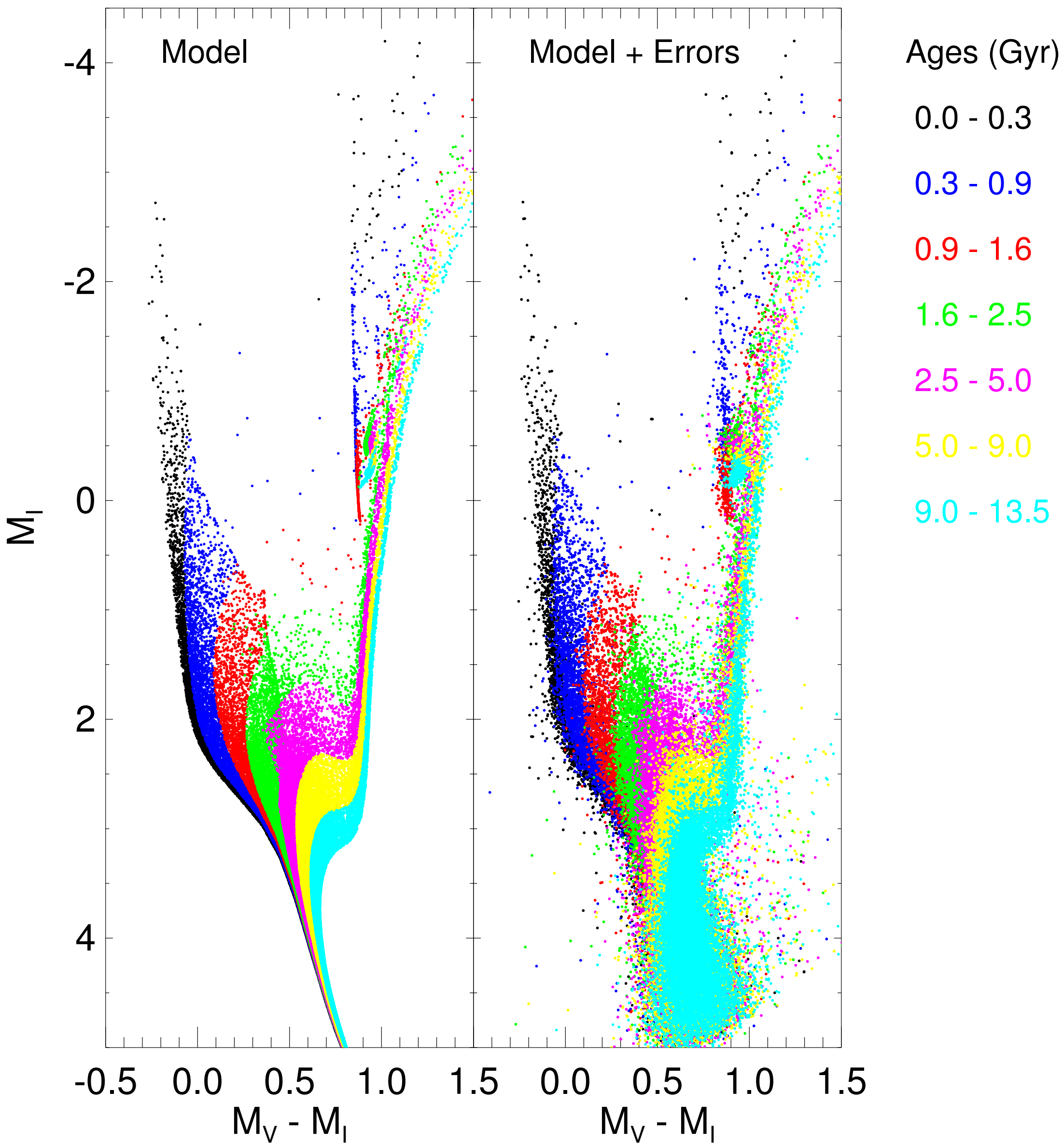

Figure 1: Synthetic CMD computed computed using IAC-star [1] assuming a constant star formation rate and a single metallicity Z=0.006 for all stars. The right panel shows the same synthetic CMD after simulation of observational errors typical of a MW satellite observed from the ground. Stars of different ages have been color-coded as indicated on the right.

observed CMD with that in a model CMD in which observational errors have been simulated. This model CMD has been divided in a number of simple stellar populations (defined as a population of synthetic stars in a small range of age and metallicity) and, by using a merit function, the combination of simple stellar populations that best reproduces the observed CMD is obtained. This provides the star formation rate and the chemical enrichment law, as a function of time. For details of this process using the IAC suite of programs IAC-star, IAC-pop and MInnIAC, see [20] and [29]. The quantitative SFH, as a function of time, obtained in this way, provides information on the evolution of the stellar populations in the galaxy and therefore, can give some insight on the processes driving that evolution. If a SFH is derived for different galactocentric distances within a given galaxy, valuable information is obtained on the galaxy's morphologic evolution through a Hubble time.

The necessary data to derive reliable SFHs exist for most MW 'classical' satellites[2] [11, 13, 30, 26, 33, 37], although in some cases, additional observations to cover the whole galaxy are still necessary (e.g. for the Magellanic Clouds, or Fornax). The process of deriving quantitative SFHs is, however, a very time consuming, complex process and has not still been completed satisfactorily for many of them. An additional important aspect to allow a reliable differential comparison of the results for different galaxies (see, for example, [28]) is that the analysis needs to be as homogeneous as possible (e.g. adopt similar assumptions on the ingredients used to compute the synthetic CMDs, such as the stellar evolution library or the IMF, attempt a similar age resolution, or use similar sampling schemes of the CMD). Such homogeneous analysis would allow us to reach more solid conclusions on the influence of environmental or intrinsic factors on galaxy evolution. Different groups in the field use slightly different methods and criteria, and an homogeneous reanalysis of some of the data would be desirable.

The existing work on the MW dSph satellite system has revealed a large variety of SFHs among the classical dSph. All of them contain an old population, as evidenced both by the CMD and the discovery of RR Lyrae variables. At least half of them are *predominantly* old (e.g. Ursa Minor, Draco, Sculptor, Leo II), although quite clearly not single-age systems. A number of systems contain an important fraction of intermediate-age population, and a morphology-density relation seems to exist, in the sense that the dSph more distant from the MW tend to be on average younger (e.g. Fornax, Carina, Leo I).

A similar study for the nearest satellite system, that of M31, is sorely lacking, and it is doable with an investment of some 150 orbits of HST with the ACS. It would allow us to determine if the first epochs of star formation in the M31 companions occurred at the same time as those in the MW companions, and whether the trend of older stellar populations for closer satellites, shown by the MW dwarf companions is reflected in the M31 population. More generally, it would answer the question of whether the earliest evolution of dwarf galaxies as revealed by the MW dSphs is representative, or whether, on the contrary, there is some sensitivity of the SFH of the satellite galaxies on the properties of the parent galaxy. Thirty orbits have been allocated on HST cycle 20 to start such project (PI. E. Skillman), by

[2] The more recently discovered 'ultra-faint dwarfs' host very few stars (see [32]), and suffer from an important amount of field contamination. This makes it very difficult to apply the synthetic CMD technique to derive their SFH.

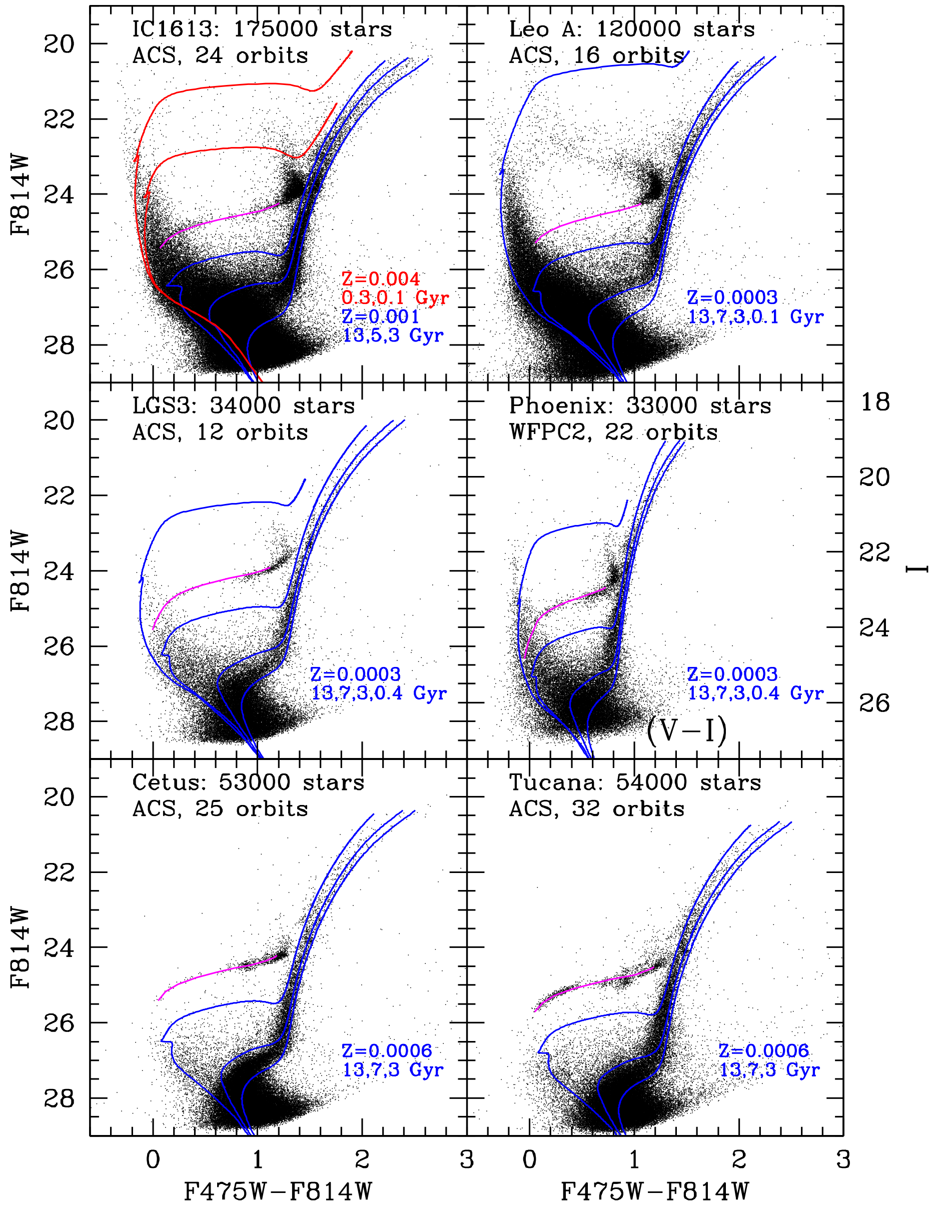

Figure 2: CMDs obtained for the six galaxies in our sample. Isochrones from [34] (overshooting set), with the ages and metallicities indicated in the labels, have been superimposed to serve as references to compare the different features among CMDs. The locus of the zero-age horizontal-branch (ZAHB) for Z=0.0006 or Z=0.0003 (depending on the metallicity of the main population) is also shown. Distance moduli of $(m - M)_0$ = 24.5, 24.5, 24.1, 23.2, 24.5 and 24.8 and reddenings of E(B-V)=0.04, 0.02, 0.05, 0.02, 0.03 and 0.03 for IC1613, Leo A, LGS3, Phoenix, Cetus and Tucana, respectively, have been adopted. Note the different band combination in the case of Phoenix.

observing two galaxies (And II and And XVI) of a representative sample of seven.

3 Global *versus* internal effects on the early SFH of dwarf galaxies

Isolated dwarf galaxies are important probes of the conditions of the early Universe, since their early SFH and subsequent evolution are predicted to have been influenced by global phenomena such as cosmic reionization. Within the LCID project, we have obtained CMDs reaching the oMSTOs for six isolated LG dwarf galaxies (two dIrr, IC1613 and Leo A; two dIrr/dSph, LGS3 and Phoenix; and the only two isolated dSph in the LG, Cetus and Tucana).

Figure 2 shows the CMDs of all galaxies in our sample. Note the variety of CMD morphologies, as evidenced by the comparison with selected isochrones. The most evident difference among morphological types is in the main sequence, which is more populated and extended to brighter magnitudes as the morphological type goes from dSph to dIrr/dSph to dIrr, reflecting an increasing fraction of young and intermediate-age populations. However, the similarities in the CMD of each pair of galaxies of the same morphological type are evident. The CMDs of Cetus and Tucana are particularly alike: both the metallicity and the age range of the main population are similar. The HB morphology of both galaxies, however, is clearly different, with a well populated blue HB in Tucana and just a few blue HB stars in Cetus. Also the characteristics of the variable star population are different [4, 5]. The SFHs obtained for both galaxies using the detailed information in the oMSTO area show some differences which may account for the different HB features (see below).

SFHs were homogeneously derived for all galaxies in the sample. A variety of input choices and SFH recovery methods were tested in order to search for possible systematics in the derived SFH (see e.g. [29] for details). The SFHs shown in this paper correspond specifically to the results obtained with the IAC suite of procedures (IAC-star, [1]; IAC-pop, [2]; and MinnIAC [20], which were upgraded from previous versions specifically for this project. However, all the main conclusions remain unchanged when other sets of reasonable assumptions and procedures are adopted (see [28, 29]).

Figure 3 (left, upper panel), displays the derived SFHs for the six galaxies in our sample. The two dSph, Cetus and Tucana share the common characteristic of having formed over 90% of their stars before 10 Gyr ago, and host no stars younger than 8-9 Gyr old [28, 29]. The SFH of the two dIrr/dSph galaxies [18, 20] are remarkably similar to those of the former: both formed most (over 80%) of their stellar mass before 9 Gyr ago. However, both show a residual amount of star formation during the rest of their evolution, including the present time, which is consistent with their currently low -but not null- gas content [44]. Finally, the SFH of the two dIrr galaxies show important amounts of star formation at intermediate and young ages: both formed over 60% of their stars *after* 9 Gyr ago [10, 38, 21]. Figure 3 (left, lower panel) represents the corresponding age-metallicity relations. It is interesting to note the similar behaviour (e.g., slope) of the relationship for each two galaxies of the same morphological type, and the shallower slope of the age-metallicity relation for the two dIrr/dSph galaxies as compared with that of the dSph, in spite of the very similar SFH.

3.1 Did reionization affect the SFHs of the LCID project dwarfs?

The most common expectation of dwarf galaxy evolution models regarding the effects of cosmic reionization on the early SFH of dwarf galaxies, is that a sharp drop in the star formation rate should be observed [8, 41, 35] near z≃6, the epoch when reionization was complete. Such a signature is not present in any of the galaxies in our sample. Taken at face value, their SFHs indicate that most of their star formation occurred *after* the end of reionization. This is particularly true for the two dIrr galaxies, and for Phoenix, which had a relatively high star formation rate when the Universe was fully reionized. In the case of the dSph and LGS3, their SFHs display a relatively sharp drop in the star formation rate at a relatively old epoch (though not as old as the ≃ 12.5 Gyr corresponding to z=6).

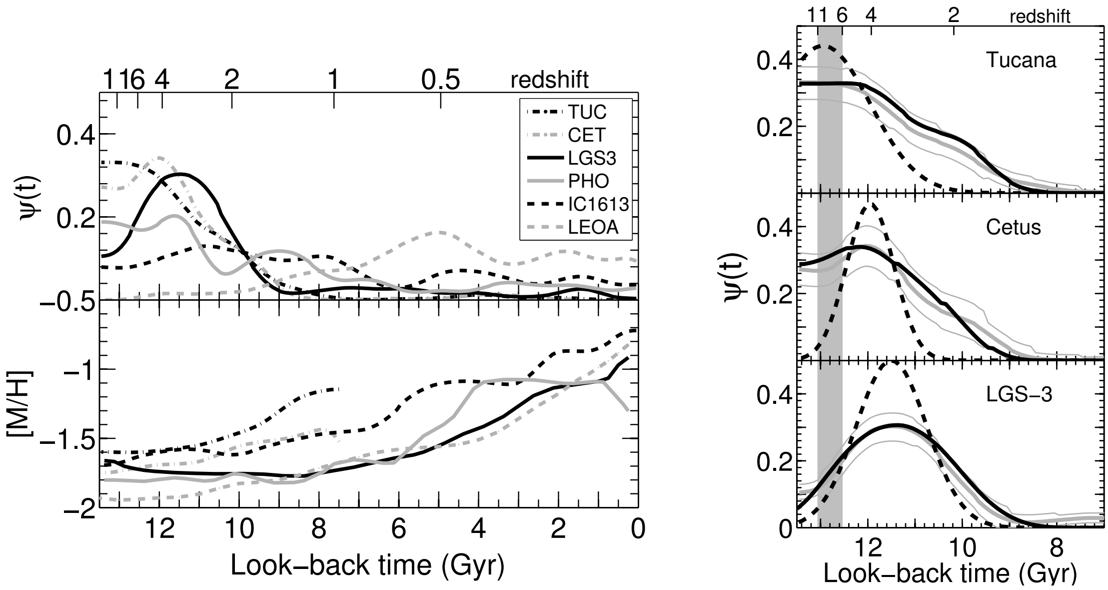

Figure 3: *Left panels:* Normalized star formation rate (upper panel) and age-metallicity relation (lower panel), as a function of look-back time, for the six LCID galaxies. Error bars have been omitted for clarity (see error bars in the right panel for three of the galaxies). *Right panel:* Some results of the tests performed with mock stellar populations. Input Ψ(t) (dashed line) for the mock stellar population that yielded a recovered Ψ(t) (solid line) closely matching the solution Ψ(t) for each galaxy (gray line). The shaded area indicates the duration of the reionization epoch.

However, it is reasonable to expect that the SFH features are broadened, and the recovered ages more uncertain at old epochs, due to the effects of the increased observational errors, and the intrinsic lower age resolution in the CMD. To quantify these effects and thus to assess how reliable the recovered ages are close to the reionization epoch, we have performed a number of tests with what we call *mock stellar populations*. In them, the CMD of a synthetic population with known SFH is computed, the observational errors simulated in it, and the SFH derived using the same procedures as for the CMDs of the real galaxies. The difference between the input and the derived SFH allows us to assess the reliability of the derived SFHs. Using mock stellar populations characterized by a single, narrow burst of star formation, we have verified that the ages of the star formation events are well recovered, while the SFH features are indeed broadened: the recovered SFH has a shape well represented by a Gaussian very approximately centered on the age of the burst, with increasing sigma for older age.

We have performed tests with mock stellar populations for Tucana, Cetus and LGS3, by testing (among others), a number of input SFHs with Gaussian shape of varying sigma, and approximately centered in the age of the derived peak star formation rate. In Fig. 3, the SFH of the mock stellar populations which yielded a recovered SFH best matching the observed one are shown for each galaxy. Note how closely the last matches the recovered SFH. Even if a similarly close recovered SFH can be obtained for mock populations with input SFH shapes different from Gaussian, we can reasonably consider that the assumed input SFHs are approximate representations of the true, underlying SFH of each galaxy. The fact that all these mock populations have formed most of their stars after the reionization epoch reinforces our conclusion that the SFH drop in the oldest galaxies in our sample cannot be directly and solely linked with reionization effects.

Using the quantitative information provided by the derived SFHs, we can infer both the total baryonic mass of each galaxy, the total number of type II SNe produced in the first main star formation event, and constrain their numbers per unit time. This allows us to make a direct estimate of the importance of feedback in the evolution of each galaxy. We have performed this calculation for Tucana, Cetus and LGS3, and compared the results with the predictions of the models by [24] on the conditions for blow-away, blow-out (i.e. partial mass-loss) and no mass loss of dwarf galaxies as a function of their baryonic mass and the mechanical luminosity of the SNe produced during a star formation event (see their Fig. 1). All three galaxies lie in the blow-out regime predicted by these models, close to the blow-away region. It seems therefore that, at least in the context of these models, SNe alone should not be able to remove the gas and halt star formation in them.

More recent models by [36] study, among others, the combined effect of feedback by type II SNe and the UV background radiation. They find that these two effects combined should have halted star formation at $z \simeq 6$ for galaxies with total mass below 8×10^8 $M_\odot$, but that above this value, self-shielding must become effective, allowing star formation to continue beyond $z \simeq 6$, with characteristics similar to what we infer for the two isolated dSph (see their Fig. 9). Though the total mass of these galaxies is extremely uncertain, it is interesting to note that the transition mass for the [36] models is quite close to the common mass inferred for dwarf galaxies by [40], and compatible with the masses inferred by [43]. This model, therefore, provides a simple possible framework to understand the early SFH of these galaxies, without the need to invoke environmental effects due to the interaction with a large galaxy (e.g., [25]). Note, however, that the [36] models do not necessarily explain the SFHs for all of the LG dSphs (in particular, those with significant intermediate age populations) and that a passage of Cetus and Tucana near the central regions of the LG cannot be precluded given their measured radial velocities [23, 12].

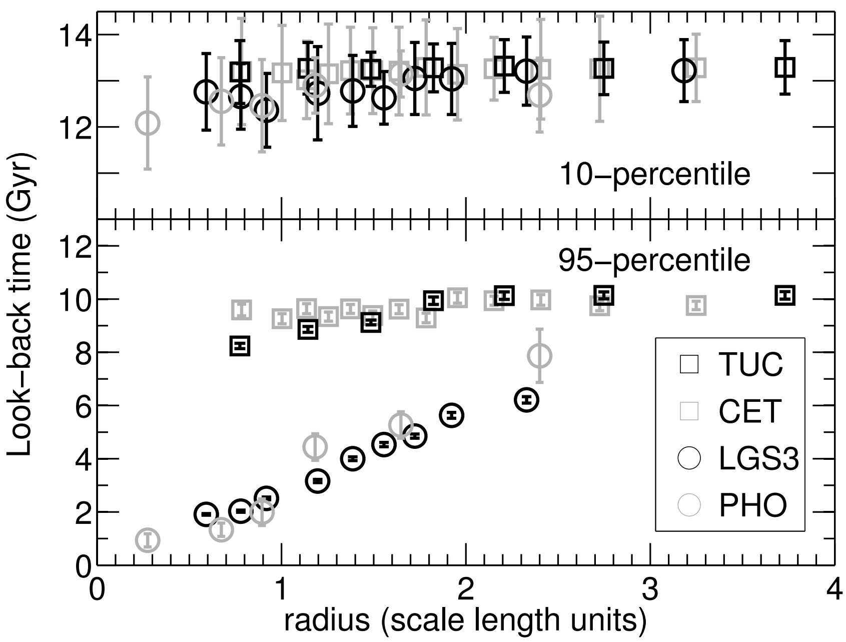

Figure 4: Age of the 10th (upper panel) and 95th (lower panel) percentile of the integral of $\Psi(t)$ for the entire life of the galaxies as a function of radius.

4 Morphologic evolution: SFHs as a function of radius

Stellar population gradients trace a galaxy's structural evolution, thus providing hints on additional mechanisms possibly shaping its evolution. In the case of dwarf galaxies, mechanisms such as self-shielding (e.g. [36]), the occurrence of a contracting envelope of star formation, or stellar migration related to SNe feedback [39] have been discussed and, in general, predict stellar populations which are older toward the outskirts of the dwarfs, in contrast with the inside-out formation scenario currently accepted for large spiral galaxies [6]. The Magellanic Clouds, and particularly the Large Magellanic Cloud, are on a middle ground. The models by [39], for example, would predict, beyond the central ~ 1 Kpc, a population younger on average at increasing galactocentric radius.

Evidence of stellar population gradients has been found for a long time in dwarf galaxies, using a variety of tracers (e.g. [19, 17, 42, 4]) and also in the Magellanic Clouds [15, 31]. Characterizing these population gradients through derivation of a full SFH provides important, unambigous insight on their nature, and we are in the process of performing such study on both the LCID galaxies and the Magellanic Clouds.

All LCID galaxies (except IC1613) have an apparent angular extent small enough for the ACS to sample radial distances out to around three times their scale length. This allowed us to derive their SFHs at different galactocentric distances. Specifically, we divided the field in elliptical regions containing equal numbers of stars, and used the stars in each region to obtain the corresponding SFH. In all cases, a trend is found in the sense that the stellar population

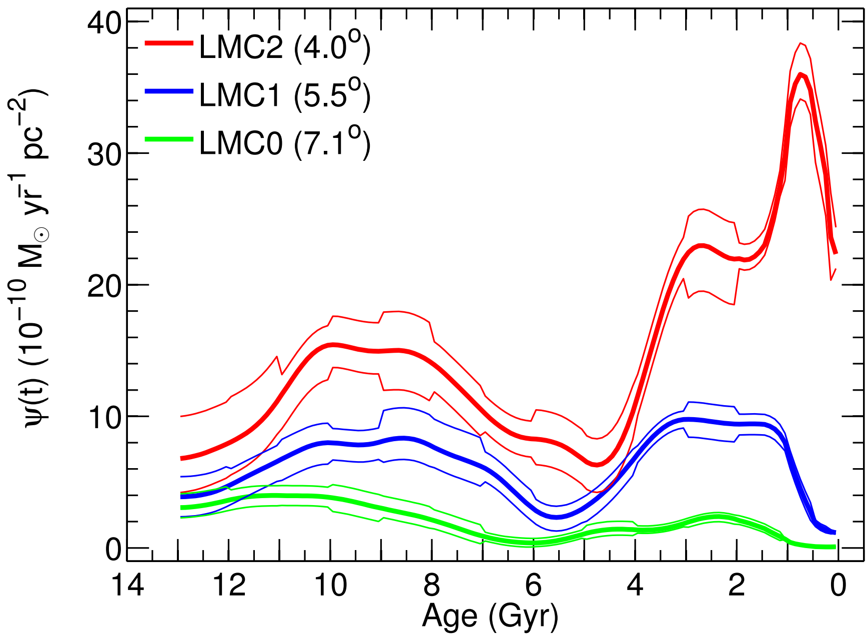

Figure 5: Comparison of $\psi(t)$ for the three LMC fields. The thin lines represent the uncertainties (see text for details).

is on average younger toward the central part of the galaxy, with the old population present over the whole studied field. One way to quantify this is through the age at which the 10th and the 95th percentile of $\int_0^T \psi(t)dt$ occur (where T is the age of the galaxy), as a function of radius. These values are represented in Fig. 4 for the two dSph and the two dIrr/dSph in our sample. The 10th percentile indicates the age of the first star formation event. In the upper panel of Fig. 4 we can see that it occurred at a very similar old age over the whole body of the studied galaxies. The 95th percentile provides an estimate of the age when star formation ended. The lower panel of Fig. 4 shows how the age of the 95th percentile changes as a function of radius, particularly in the case of the two dIrr/dSph galaxies, indicating that star formation ended much earlier in the outer parts.

In the case of the LMC, we have obtained CMDs reaching the oMSTO for three wide fields located at galactocentric distances of 4.5, 5.0 and 7.1 degrees (3.5, 4.8 and 6.2 Kpc). Figure 5 displays $\psi(t)$ for the three fields. It shows that the galaxy has experienced two main epochs of star formation, separated by a period of lower star forming activity. The *old* star forming epoch started $\simeq$ 13 Gyr ago, and peaked around 10-8 Gyr ago. The period of low star forming activity extends from $\simeq$ 7 to $\simeq$ 5-4 Gyr ago, after which the second star formation epoch occurs, and lasts till the present time in field LMC2, and till $\simeq$ 0.5 and $\simeq$1 Gyr ago in fields LMC1 and LMC0 respectively. This younger star forming period seems to split in at least two episodes, with the age of both peaks getting older at increasing galactocentric distances.

Interestingly, the ratio Y/O between the amount of star formation in the young and old star forming epochs (i.e. after and before the minimum $\psi(t)$) decreases with increasing galactocentric radius: Y/O=1.1, 0.8 and 0.4 for LMC2, LMC1 and LMC0. That is, the stellar population is older on average outwards. In the outermost field observed, LMC0, the star formation rate in the second half of the galaxy's life is lower than in the first half, both are similar in field LMC1, while in LMC2, it is substantially higher. In this innermost, field, in addition, the two episodes in which the young star forming epoch can be split have a different star formation rate, the younger half being more intense than the older half. These SFHs indicate an outside-in formation scenario (at least in the outer disk of the LMC, beyond R$\sim$ 3 Kpc), similar to the case of smaller galaxies, like the LCID dwarfs, which in principle would be in contrast with the models by, for example [39].

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