Studying galaxy formation and evolution from Local Group galaxies.

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Summary. In this contribution I present the main research activities of the IAC “Stellar Populations in Galaxies” research Group, with emphasis on the subtopics directly related with the study of the evolution of nearby galaxies. In particular, I discuss preliminary results of ongoing research on the Magellanic Clouds using deep ground-based observations, and on a sample of isolated Local Group dwarf galaxies, using data from the ACS on board the HST. Future plans with the GTC are discussed.

1 Introduction

The process of galaxy formation and evolution is driven by two sets of parallel mechanisms: stellar formation, evolution and death, which drive the evolution of the stellar populations and of the gas and metal content of the galaxy, and the mass assembly process, which determines its morphological type and dynamical evolution, and which in turn may induce star formation. In the nearest objects, and in particular in those that can be resolved into stars like Local Group galaxies, these mechanisms can be studied in great detail. We are conducting a comprehensive study of Local Group galaxies using a number of complementary tools to shed light on these two main mechanisms that determine galaxy formation and evolution, namely:

1. The star formation history (SFH), and its influence on galaxy evolution, through: i) The study of deep colour–magnitude diagrams (CMDs) of each galaxy; ii) the spectroscopic abundances of resolved stars; iii) the analysis of the properties of their variable stars; iv) the study of the Milky Way Cluster system.

2. The mass assembly and the dynamical evolution of each system, through: i) The stellar population gradients and kinematics of stars of different ages; ii) the dynamics of the Local Group and the influence of interactions on galaxy evolution.
This project is designed to make the best use of the GTC and its first-light instruments, especially OSIRIS. In this contribution, I will present examples of ongoing research in several of the aspects quoted above.

2 The star formation history from deep colour–magnitude diagrams.

The CMD, and in particular those reaching the oldest main-sequence turnoffs, is the best tool for retrieving in detail the SFH of a stellar system. In this case, information on the distribution of ages and metallicities of the stars present in the galaxy can be obtained directly from stars on the main sequence, which is the best understood phase of stellar evolution from the theoretical point of view. It is also the one in which stars are more separated in colour and magnitude as a function of age. The range of ages and metallicities present can be determined through comparison with theoretical isochrones. To quantitatively determine the SFH, it is necessary to compare the observed density distribution of stars with that predicted by stellar evolution models (see [11]).

Our group has been traditionally dedicated to the derivation of SFHs from deep CMDs, through comparison of observed and synthetic CMDs (e.g. [9], [2], [5], [3]; see also http://iac-star.iac.es/iac-star/). We are currently involved in two major programmes in this regard. The first aims at providing spatially resolved SFHs for both Magellanic Clouds, using ground-based observations. These, however, have produced CMDs of quality comparable (but covering a much larger area) to CMDs obtained in the central regions of both objects using the WFPC2 on HST (e.g. [14], [17]). The second is devoted to obtaining detailed SFHs for a sample of isolated Local Group dwarf galaxies, using ACS CMDs reaching the oldest main-sequence turnoffs.

2.1 The LMC

In the case of the LMC (and as part of the PhD thesis of I. Meschin), we have observed 12 half degree fields, six to the north and three each to the east and west of the galaxy centre, using the MOSAIC camera at the 4 m CTIO and the WFI at the 2.2 m in La Silla. These fields sample galactocentric distances (from 3° to 10°, or 2.6 to 8.8 kpc) not explored before to this photometric depth, i.e. with CMDs reaching the oldest main-sequence turnoffs. Through comparison with synthetic CMDs, these data will allow us to obtain detailed SFHs for all these fields and characterize the population gradients present in the galaxy. Figure 1 shows the CMDs for four fields observed to the north of the galaxy, obtained from the MOSAIC data. Isochrones from [16] in a suitable range of age and metallicity have been superimposed. It can be noticed that the age of the youngest population varies from field to field, in the sense that star formation has proceeded down to more recent epochs toward the galaxy centre: while in the fields situated at 3° and 5°, star formation has basically
Fig. 1. CMDs for the four LMC fields observed with the MOSAIC Camera at the 4 m CTIO, located at ≃ 3°, 5°, 6° and 8° from the LMC centre (clockwise from top left, respectively). Isochrones from [16] (scaled solar, overshooting set), with the ages and metallicities indicated in the labels, have been superimposed. The locus of the zero-age horizontal-branch is that of the lowest metallicity considered. A distance modulus of \((m - M)_0 = 18.5\) and reddenings of \(E(B - V) = 0.1, 0.05, 0.04\) and 0.03 have been assumed to transform the data to absolute magnitudes and colours. Determinations of the SFH of each field are under way through comparison with synthetic CMDs.
continued to the present time, the field at 6° seems not to have stars younger than \( \approx 200 \) Myr. Finally, the field at 8° formed the bulk of its stars before 2.5 Gyr, with some residual star formation up to 1.5 Gyr ago. The presence of an important intermediate-age population in this field, together with the fact that the surface brightness profile of the LMC remains exponential to this large galactocentric radius and shows no sign of disk truncation, led [10] to conclude that the LMC disc extends (and dominates over a possible stellar halo) out to a radius of at least 7 kpc.

### 2.2 The SMC

For the SMC (and as part of the PhD thesis of N. Noël), we have similar CMDs for 13 smaller fields observed with the 100" telescope at LCO ([15]). These fields are distributed in different parts of the SMC such as the “Wing” area and to the west and south, and in a range of galactocentric distances (from \( \approx 1° \) to 4°, or 1 to 4.1 kpc). Several studies (e.g. [19], [6]) have found that the SMC intermediate-age and old population has a spheroidal distribution, and that the asymmetric appearance of the SMC is primarily caused by the distribution of young stars. With our deeper data, we can shed new light on the age distribution of these structures. In particular, we confirmed that the underlying spheroidal population is composed of both intermediate-age and old stars, and found that its age composition does not show strong galactocentric gradients. The three fields situated in the “Wing” region show very active current star formation, but only the one closer to the centre seems to present a substantial enhancement in recent star formation with respect to a constant SFR(\( t \)). The fields corresponding to the western side of the SMC present a much less populated young main sequence as compared with those on the east side, even at similar galactocentric radius, with signs of a greatly diminished SFR(\( t \)) from 2 Gyr ago to the present time. As in our LMC study, none of the studied fields, out to a galactocentric radius of 4° (or 4.2 kpc), is dominated by an old stellar population.

### 2.3 Isolated Local Group dwarf galaxies

We are participating in two HST-ACS programs (P. ID: 10505, P.I. Gallart; P. ID: 10590, P.I. Cole) with a total of 113 awarded orbits, in addition to an HST-WFPC2 program (P. ID: 8706, P.I. A. Aparicio), to obtain CMDs reaching the oldest main-sequence turnoffs in 6 isolated Local Group galaxies (two dIrr galaxies: Leo A and IC1613, the two isolated dSph galaxies discovered so far in the Local Group: Cetus and Tucana, and two transition type dIrr/dSph galaxies: LGS3 and Phoenix).

Figure 2 shows the CMDs of four of the galaxies in the sample. Note the variety of SFHs, as hinted at by the comparison with selected isochrones from [16]. This is the first time that data of this high quality has been obtained for dwarf galaxies beyond the Milky Way satellite system. These data will
allow us to obtain detailed and accurate SFHs for all these systems, through comparison with synthetic CMDs, and using additional constraints from the characteristics of their variable star population (see Section 4 below, and the contribution by E. Bernard et al. in these Proceedings).

The details of the early SFHs of tiny dwarf galaxies can shed light, in particular, on the role in galaxy formation of the reionization which occurred at high redshift. Isolated dwarfs are ideal probes since their evolution is not complicated by environmental effects owing to the vicinity of the Milky Way or M31.

2.4 The study of stellar population gradients

In all these programmes, in addition to the derivation of accurate and detailed SFHs, we pay special attention to the study of the stellar population gradients. Their presence in dwarf galaxies, with the youngest population concentrated towards their centre, is well known (e.g. [1], [4], [13]). In the Milky Way satellites, for which we have CMDs reaching the oldest main-sequence turnoffs, the nature of these gradients can be investigated in detail; here the difficulty is due to the large areas that need to be surveyed. For example, in the case of the Magellanic Clouds, their total extension and the presence or not of an old halo is still a matter of debate. In the case of the more distant dIr galaxies, the actual nature of the outer older structure, and its extension, is still uncertain due to the faintness of the stars that need to be measured. Recent studies show the existence of both young and old populations in the central parts of dIr galaxies, while young stars gradually disappear towards the outer regions. But they don’t offer enough proof of the actual nature of these extended structures, and in particular, whether they represent a true halo population (i.e., old and tracing the initial conditions of galaxy formation).

Recent results for the LMC ([10]) and Phoenix ([12]), using CMDs that reach the oldest main-sequence turnoffs indicate that these extended regions are not exclusively old, and that a smooth age gradient exists from the centre of the galaxy to its outer parts. This suggests an outside–in formation scenario, contrary to what seems to happen to the discs of spiral galaxies.

With the CMDs of isolated dwarfs shown in the previous Section, it will be possible to investigate in detail the age distribution of the stellar populations in each galaxy as a function of radius, thus shedding new light on the possible formation mechanisms. An additional key diagnostic is the kinematics of stars (e.g., [15]) of different ages, which will provide information of the dynamical evolution of the galaxy, possibly indicating the presence or otherwise of differentiated disc–halo structures, or the presence of distinct kinematic entities, possibly originating in the accretion of smaller systems (according to the predictions of hierarchical galaxy formation models). This is a field still to be explored for dwarf galaxies outside of the Milky Way satellite system, and Flames at the VLT and OSIRIS at the GTC will be key instruments for this purpose.
Fig. 2. CMDs obtained with the ACS on board HST for four isolated Local Group dwarf galaxies. In order to give a first indication of the range of ages and metallicities present in each galaxy, isochrones from [16] (scaled solar, overshooting set), with the ages and metallicities indicated in the labels, have been superimposed. The locus of the zero-age horizontal-branch has also been represented. Distance moduli of \( (m - M)_0 = 24.4, 24.0, 24.45 \) and 24.7 and reddenings of \( E(B-V) = 0.04, 0.05, 0.03 \) and 0.03 for IC1613, LGS3, Cetus and Tucana, respectively, have been adopted to transform the isochrones to the observational plane. Determinations of the SFH of each system are under way through comparison with synthetic CMDs.
3 Metallicities using the Ca II triplet.

We have obtained (PhD, R. Carrera) a new calibration of the CaII triplet strength in red giant branch (RGB) stars as a function of metallicity, which is valid for a higher range of ages ($13 \leq \text{Age(Gyr)} \leq 0.25$) and metallicities ($-2.2 \leq [\text{Fe/H}] \leq +0.5$) than previously published calibrations (see [7] for the most recent one). This calibration has been used to obtain metallicities for a large number of stars in different fields of the LMC and the SMC (see the contribution by R. Carrera et al. in these Proceedings for details).

With the GTC and OSIRIS we plan to extend this type of work to the remaining galaxies in the Local Group, situated at a distance of $\approx 1$ Mpc. Candidate RGB stars are in the magnitude range $I \approx 21–21.5$. They will densely populate the OSIRIS field of view ($\approx 30$ stars per sq. arcminute) to allow us efficient use of multiobject spectroscopy. The high brightness of the sky in the CaII triplet region implies that the possibility of micro-slit nod-and-shuffle will be important for this project.

4 Variable stars

Variable stars can complement the information offered by CMDs to interpret the stellar populations of a galaxy. In particular, RR Lyrae reveal the presence of a very old ($\approx 10$ Gyr) stellar population, while short-period classical Cepheids and anomalous Cepheids are tracers of populations up to a few hundred Myr old and a few Gyr old respectively ([8]). Using variable stars as stellar population indicators is especially important when it is not possible to obtain CMDs reaching the oldest main-sequence turnoffs.

The ACS data mentioned in Section 2 is also excellent for obtaining a census of the variable star population in each galaxy of the sample. Such a study is already under way (see the contribution by E. Bernard et al. in these Proceedings). The good sensitivity and relatively large field of OSIRIS at the GTC will allow us to carry on a systematic characterization of the variable star populations in Local Group galaxies (both isolated dwarfs and M31 dSph companions, and some strategic fields in the large M31 and M33 spirals). Such surveys will complement in a key way our ACS imaging project: with ACS, only a handful of galaxies will be studied, and in some cases only part of their total extent will be covered. To find RR Lyrae stars, the most challenging and interesting part of this project, we need to reach $g' \approx 25.5$ in relatively short exposure times. OSIRIS will allow us to do that in 10–15 minutes. In addition, its field of view is very well suited to cover most Local Group dwarf galaxies in one to a few fields.

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