The star formation history of resolved galaxies: 
Composite H-R diagram.

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Abstract. I discuss the information provided by color-magnitude diagrams of different absolute magnitude limits in the study of the star formation histories of nearby galaxies. I review the recent progress made in the field, with emphasis on the results for Local Group dwarf galaxies.

1. Introduction

We can study the evolution of the nearest galaxies in exquisite detail from the information contained in the H-R diagram -or Color-Magnitude Diagram, CMD- of their resolved stars. From it, it is possible to retrieve the star formation and chemical enrichment histories (SFH and Z(t)), with a level of detail that mainly depends on the magnitude limit of the available CMD. For CMDs reaching the oldest main-sequence (MS) turnoffs, it is possible to break the age-metallicity degeneracy that affects most methods of retrieving SFHs. Even if we can pursue this kind of study only in a very limited volume of the Universe, it is a worthwhile task, key to understand galaxy formation and evolution in general, because:

• In our neighborhood, we have representatives of almost any kind of galaxies in the Universe: in the Local Group there are three spirals, and a large number of dwarf -both dIr and dSph- galaxies; the nearest gE, NGC5128 is at \( \simeq 4.0 \) Mpc, and similarly, the nearest BCD and LSB galaxies are in the M81 group, also at \( \simeq 4.0 \) Mpc. In addition, by studying the details of the SFHs in the nearest galaxies, we may be able to identify the evolved counterparts of distant objects that are experiencing characteristic star forming episodes.

• This kind of study provides detailed information on the first events of star formation in the nearest galaxies. Therefore, we can address questions like “have the oldest stars in galaxies all the same age?” or, “are there differences, in the epoch or strength of the early star formation, depending on environment”.

• We can test the hypothesis of galaxies being assembled by merging through the almost direct observation of the merging history of the Milky Way.

• It offers an alternative to the cosmologic look-back-time approach to study galaxy evolution, by tracing the complete evolution of particular objects.

Furthermore, it is indeed a feasible task. From the observational point of view, we have the means of gathering the necessary observations. For the nearest objects, the dSph satellites of the Milky Way and the Magellanic Clouds, we have excellent wide-field CCDs on ground-based telescopes. Observations of this kind
have already revealed in amazing detail the varied SFHs of these galaxies, and we will be able to reach the same level of detail for the remaining Local Group galaxies using the Advanced Camera for Surveys (ACS) on the HST. Further improvements in optical capabilities on space (e.g. NGST) or the ground (e.g. adaptive optic systems) will be important to pursue the same kind of studies, with similar precision to larger distances. From the theoretical point of view, and hand in hand with increasing computational power, we are seeing important improvement on stellar evolution models (through e.g. more realistic treatments of convection or rotation, or improved opacities), and on the accurate modeling of synthetic CMDs with realistic simulations of observational errors.

There is three main levels of information in the CMD depending on the magnitude limit of the available data: the one we obtain when we reach the oldest MS turnoffs, the one provided by reaching the horizontal branch (HB) level, and when we only observe a couple of magnitudes below the tip of the red-giant branch (RGB); see Figure 1. I will discuss them separately below.

2. A quantitative method of deriving SFHs: synthetic CMDs

The comparison of the observed CMDs with synthetic CMDs computed using stellar evolution models is a fundamental tool that is becoming widely used to quantitatively retrieve the SFH from the CMD. With this technique, a number of synthetic -or model- CMDs are computed assuming possible scenarios for the SFH, which can be reasonably decomposed in a number of simpler functions: the instantaneous star formation rate, $SFR(t)$, the chemical enrichment law, $Z(t)$, the initial mass function, IMF, and a function $\beta(f,q)$ controlling the fraction $f$ and mass ratio distribution $q$ of binary stars (Aparicio 1998; Gallart et al. 1999b). This basic approach has been followed, with variation in the details, by a number of groups (Bertelli et al. 1992; Gallart et al. 1996a; Tolstoy & Saha 1996; Dolphin 1997; Hernández, Valls-Gabaud & Gilmore 1998; Hurley-Keller, Mateo & Nemec 1998; Ng 1998), and it has proven particularly successful, and leading to basically unique results when applied to data reaching the oldest MS turnoffs (Gallart et al. 1999b). In the following, I will comment on the application of this method to CMDs of different magnitude limits.

3. The best case: when the CMD reaches the oldest MS turnoffs

During the last decade, our conception of the evolution of the dSph galaxies satellites of the Milky Way, has changed dramatically from the idea that they were predominantly old systems, to our current knowledge of their varied SFHs. Indeed, we find almost every imaginable evolutionary history in this sample of galaxies, from the extreme case of Leo I (Gallart et al. 1999a,b), which has formed over 80% of its stars from 6 to 1 Gyr ago, to intermediate cases like Carina (Smecker-Hane et al. 1996; Hurley-Keller et al. 1998) and Fornax (Stetson, Hesser & Smecker-Hane 1997; Buonanno et al. 1999), with prominent intermediate-age populations, to predominantly old ($\simeq 10$ Gyr old) systems like Sculptor (Hurley-Keller, Mateo & Grebel 1999), Draco (Aparicio, Carrera & Martínez-Delgado 2000), Ursa Minor (Martínez-Delgado & Aparicio 1998) or Leo II (Mighell & Rich 1996). Studies of the LMC SFH have also benefited of
CMDs of this quality (e.g. Holtzman et al. 1999). This clear and extremely interesting picture has only been obtained when CMDs reaching the oldest MS turnoffs, and covering a substantial fraction of the galaxy have been available.

Even though CMDs of this kind offer qualitative first glance SFHs (e.g. in the case of Carina, the most emblematic example, one can see, just by comparing the CMD with isochrones, that there has been three major events of star formation), a quantitative determination of the SFH requires a detailed comparison of the distribution of stars in the CMD with that predicted by model CMDs. With CMDs reaching the old MS turnoffs, there is the advantage that the stellar evolution involved (that of MS and subgiant-branch stars) is relatively well known, and there is less intrinsic degeneracy age-metallicity. Indeed, we have shown that, with this method, it is possible to break the classical age-metallicity degeneracy in stellar populations (Gallart et al. 1999b). This is so because detailed information on the age distribution of the stars is gained from their distribution along the MS and subgiant branches. Once this is determined, the possibilities for metallicity distributions are relatively unique in order to fit the detailed distribution of stars in the CMD. Admittedly, the position of the stars in the MS and subgiant branches also depends on metallicity, but, in practice, only narrow combinations of $Z(t)$, SFR$(t)$ and $\beta(f,q)$ can reproduce the distribution of stars in the CMD.
4. How well can we do with CMDs not reaching the oldest MS turnoffs?

Here I will distinguish two cases depending on the information they provide: when the CMD reaches below the HB level, $M_I \simeq 1$, and when only 2-3 magnitudes below the tip of the RGB are observed, $M_I \simeq -2$ (see Figure 1). In both cases, the CMD is populated by stars of all ages, and therefore, it must be possible, in principle, to retrieve information about the complete SFH. As before, the analysis of the CMD using synthetic CMDs is potentially the best method to derive quantitative information. However, the detail with which the SFH can be retrieved is necessarily smaller than in the previous case.

We are undertaking a project, using CTIO MOSAIC data of the LMC, to quantify the maximum amount of information on the SFH that one should aim to retrieve from CMDs with different magnitude limits. Thanks to its proximity, the LMC is ideal for this project because one can obtain wide field, good precision old MS turnoff photometry from the ground. Photometry over large areas is necessary to obtain good statistics of stars in short lived evolutionary phases, which are key in the analysis of shallower CMDs. The aim is to independently retrieve the SFH from CMDs of different limiting magnitudes, to learn both about the information we loose at each step and about possible strategies to help make the most of the available data. Such test is important because we can potentially obtain HB and particularly, RGB photometry out to distances like those of the nearest clusters of galaxies, and we must know how confidently we can derive SFHs there. A similar project, to compare SFHs obtained through CMD analysis and integrated spectroscopy is underway together with several participants in this conference (Alloin, Demarque, Fritze von-Alvensleben, Hardy et al.)

4.1. CMDs reaching the HB level

The main age markers here are the (blue and red) HB and the red-clump (RC) of core He-burning stars. The presence and appearance of these features, and in particular that of the HB depends on both age and metallicity, although other factors, particularly the amount of mass loss during the RGB phase, may also play a role (Lee 1993). Very old, low metallicity stars distribute along the HB during the core He-burning phase and, generally speaking, produce a red HB when the core He burners are not so old, or more metal rich, or both. A RC well populated and extended in luminosity (like that of Leo I in Figure 1) denotes the presence of a large intermediate-age population. In addition, the vertical RC (Zaritsky & Lin 1997) is populated by few hundred Myr old stars that don’t undergo the He-flash (Beaulieu & Sackett 1998; Gallart 1998).

One should aim at retrieving old and intermediate-age star formation rates, integrated over intervals of a few Gyr, by fitting the number of stars in the HB, the RC and the RGB using synthetic CMDs. In spite of the uncertainties in the modeling of these advanced stellar evolution phases, the comparison of the models with the CMDs and luminosity functions of star clusters (see Maeder & Renzini 1983; Renzini & Fusi Pecci 1988; Chiosi, Bertelli & Bressan 1992) show reasonable agreement, (e.g. Zoccali & Piotto 2000) even though some parameters in the models are still uncertain (e.g. the He content, the $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ or the details of the mixing processes, see Zoccali et al. 2000).
HST has provided HB-RC CMDs for a sample of Local Group galaxies outside the Milky Way system. The M31 dSph satellites have been studied by Da Costa et al. (1996, 2000), while the remaining M31 satellites have been studied by a variety of authors (e.g., M32: Grillmair et al. 1996; NGC147: Han et al. 1997; NGC185 and NGC205: Geisler et al. 1998). Similar data have been analyzed for some of the dIrr (Leo A: Tolstoy et al. 1998; Pegasus: Gallagher et al. 1998; IC1613: Cole et al. 1999; WLM: Dolphin 2000; Sextans A: Dohm-Palmer et al. 1997). Also VLT is starting to produce results in this regard (Tolstoy et al. 2000; Held et al. 2000). It is beyond the scope of this paper to summarize the results of these works, and I would just like to comment on very general aspects. In the case of the M31 companions, the main general conclusion may be the diversity of their SFHs, much like among the Milky Way satellites (Da Costa et al. 2000). For the dIrr, it has been possible to retrieve in detail the SFH up to about 1 Gyr ago using MS and blue-loop stars (Dohm-Palmer et al. 1997), and to reveal a prominent intermediate-age star formation. However, the positional overlap of the blue HB with the generally well populated \( \approx 1 \) Gyr old MS in the CMD difficults the characterization of the old population, and therefore, additional constraints on the old stars, like studies of RR Lyrae variables, are important. As for the Milky Way satellites, CMDs reaching the oldest MS turnoffs of dwarf galaxies through the Local Group would reveal the detail of their SFHs and would allow us to study the early evolution of isolated dwarf galaxies, as well as dwarfs in a different satellite system like that of M31. And they would provide us, again and very likely, with fundamental surprises. This will become technically feasible for the first time with ACS on HST.

Finally, I would like to mention other potentially very useful stellar population markers in the HB-RC area of the CMD, namely the RGB-bump, the AGB-bump (Gallart 1998) and the vertical structure of the RC (Piatti et al. 1999). These structures are produced by very short-lived phases of stellar evolution, and they have only become evident in the CMDs of composite stellar populations when very densely populated CMDs have been available. While the RGB and AGB-bumps are produced by stellar populations of basically any age, and their structure depends on both age and metallicity, the vertical structure is predicted to be produced by relatively metal rich stars (\( Z \geq 0.004 \)) in a very narrow range of masses and ages around 1 Gyr (Girardi 1999).

### 4.2. CMDs reaching just below the tip of the RGB

Gallart et al. (1996a,b) and Aparicio, Gallart & Bertelli (1997a,b) used synthetic CMDs to constrain the SFHs of the dIrr galaxies NGC6822, Pegasus and LGS3 using this kind of data. Only star formation rates averaged over relatively long periods of time can be obtained in this way (see also Aparicio 1998), but it was also possible to conclude that star formation began in these galaxies at an early epoch (\( \approx 15 - 10 \) Gyr ago), and that they contained a relatively prominent old population. In addition, some constraints on the chemical enrichment history were obtained by including different parameterizations of \( Z(t) \) in the models.

The position and width of the RGB have been widely used to derive the mean metallicity and metallicity dispersion of the stars in dwarf galaxies (Da Costa & Armandroff 1990; Lee, Freedman & Madore 1993; Saviane et al. 2000). This method, however, assumes that the contribution of the dispersion in age
to the width of the RGB is basically negligible, and it has to be used with care when there is a substantial intermediate-age population since, in this case, and specially for low metallicity systems, a substantial fraction of the RGB width may be contributed by age. Finally, AGB stars are useful tracers of intermediate-age star formation (Gallart et al. 1994).

CMDs of this kind are available for basically all Local Group dwarf galaxies. Besides the ones referenced above, good examples among those not yet superseded by published deeper data are the following. Phoenix: Martínez-Delgado, Gallart & Aparicio, 1999; NGC3109: Minniti & Zijlstra 1997; DDO210: Lee et al. 2000; Sag DIG: Karachentsev, Aparicio & Makarova 1999; Antlia: Piersimoni et al. 1999; And VI: Armandroff, Jacoby & Davies 1999; Grebel & Guhatakurta 1999; Gallart et al. 1998). CMDs for very distant galaxies, of types not represented in the Local Group have been obtained using HST (e.g. Schulte-Ladbeck et al. 1999; Harris, Harris & Poole 1999).

5. Summary and concluding remarks

Deep CMDs, in particular those reaching the oldest MS turnoffs, are our most valuable tools to retrieve in detail the SFH of nearby galaxies. Spectroscopy is a very useful complement, but, on its own, it is not well suited to derive SFR(t), or even Z(t) directly; instead, the temporal information is beautifully laid out in the CMD. Even if possible for a very limited volume of the Universe, I have argued that this is a worthwhile task, key to understand galaxy formation and evolution in general, because we have representatives of most types of galaxies in our neighborhood, and because using nearby objects, we can learn what can be obtained, and trusted, from integrated properties. And most importantly, it is a really feasible task using the latest generations of telescopes and instruments, particularly HST (specially with ACS) and the new generations of 8–10m class telescopes, equipped with some kind of adaptive optics capability.

But still a lot remains to be done. Even for some of the nearest galaxies (the satellites of the Milky Way) for which beautiful CMDs exist, analysis using the full power of current modeling techniques are still lacking. For the most distant galaxies, the optimal data does not yet exist, but is under reach of current instrumentation. Representations of the SFHs of the more distant LG galaxies like those presented by Mateo (1998) or Grebel (1998) provide an useful, qualitative view of the SFH of these systems as inferred from different stellar tracers but should not be taken literally: we still don’t know, in any level of detail, the evolutionary histories of Local Group galaxies outside the Milky Way neighborhood, and reliable population boxes (Hodge 1989) for these systems in such a level of detail will only be available when deeper data (reaching at least the HB level, and preferably the old MS turnoffs) will be quantitatively analyzed. But we are getting there. And we will get there faster if we can persuade our colleagues on TAC’s that this type of study is a key path and ingredient in our quest for the global understanding of galaxy formation and evolution.

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