Star formation histories of resolved stellar populations: in and beyond the Local Group

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**Abstract.** The exploitation of the power and the spatial resolution of HST and new generation ground-based telescopes allows to measure with good precision the individual stars of galaxies in and beyond the Local Group. This leads to very successful studies of the star formation histories of galaxies of different morphological types. Our current knowledge of the star formation history of galaxies within 10-20 Mpc, as derived from the colour-magnitude diagrams of their resolved stellar populations, is reviewed here.

1. Introduction

The research field of star formation histories (SFHs) in resolved galaxies is one of those which have advanced the most in the last 15 – 20 years. In 1986, Alan Sandage presented his enlightening view of how the star formation rate (SFR) varies with time in galaxies of different morphological type (Fig.1). From a collection of heterogeneous indicators (chemical abundances, line emissions, colors, etc.), he understood that the star formation (SF) activity is very strong and concentrated at the earliest epochs in the earliest-type galaxies and has lower and lower intensity, but longer and longer timescale going toward later morphological types. Magellanic irregulars may even have, on the long term, an average SFR increasing with time.

The best tool to trace the SFH of a galactic region is the colour-magnitude diagram (CMD) of its resolved stellar populations, where the signatures of all their evolutionary properties (age, metallicity, initial mass function - IMF) remain imprinted. When Sandage (1986) presented his perspective view of the SFH, the available telescopes and instruments had only recently attained photometric performances adequate to resolve individual stars in nearby galaxies. A few people were already working at the development of the procedures that are now known as the synthetic CMD method to derive the SFH, whose results are summarized in the next sections. We were pioneers, with few tools at our disposal and we should all be grateful to Cesare Chiosi for his contribution to the advance of this field and for the fundamental tools his group has made available, such as the Padova sets of homogeneous stellar evolution tracks covering all masses from 0.6 to 120 M\(_\odot\) and several initial metallicities.
Figure 1. Star formation rate as a function of time in galaxies of different morphological type, from Sandage (1986).

2. The synthetic CMD method

The method allows to derive the SFH parameters (epoch and duration of the SF episodes and of the quiescent phases, SFRs, IMF) of a stellar system from its observational CMDs. It is based on the comparison of the observational CMDs with theoretical CMDs created via Monte Carlo extractions on stellar evolution tracks, or isochrones, for a variety of SFHs, IMFs, and age-metallicity relations (for details, see e.g. Tosi et al. 1991; Greggio et al. 1998; Aparicio & Gallart 2004). The synthetic CMDs take into account the number of stars of the observational CMD (or portions of it), photometric errors, incompleteness and blending factors. Hence, a combination of assumed parameters is acceptable only if the resulting synthetic CMD reproduces all the features of the observational one: morphology, colours, luminosity functions, number of stars in specific evolutionary phases. Since this is a statistical approach, the method does not provide unique solutions for the SFH of the examined region, but strongly reduces the range of possible scenarios.

The observational CMDs obtainable 15 years ago from the existing instrumentation nowadays don’t look very appealing; yet the first applications of the synthetic CMD method immediately proved its power and its capability of providing interesting new perspectives (Ferraro et al. 1989; Tosi et al. 1991; Bertelli et al. 1992; Gallart et al. 1996; Tolstoy 1996). We found that the SFH differs significantly from one region to another, even in tiny galaxies such as the Local Group (LG) dwarf irregular (dIrr) WLM (Ferraro et al. 1989), and that the SF activity in late-type dwarfs usually occurs in long episodes of moderate intensity, separated by short quiescent phases, rather than in short episodes of strong intensity, separated by long quiescent intervals, contrary to what peo-
ple used to think of the active dwarfs. In other words a gasping rather than a bursting regime (Marconi et al. 1995).

Then HST became available and boosted a tremendous interest in the SFH research field. HST provided such tight and deep CMDs that many more groups became interested in the synthetic CMD method and developed their own procedures to derive the SFHs. Already in 2001, when Carme Gallart organized the famous experiment in Coimbra (Portugal) to compare with each other the results from the synthetic CMD methods of different groups, ten groups participated to the experiment (Skillman & Gallart 2002, and references therein). The importance of that initiative is that it allowed to find out strengths and weaknesses of the different procedures and showed that, within the uncertainties, most procedures provided consistent results. The experiment consisted in deriving the SFH of a region of the LMC bar from Smecker-Hane et al. (2002) HST/WFPC2 data, and we all found for that region a fairly continuous SF activity, although with variable strength. The inferred SFH of the LMC bar turned out to be quite different from that of the LMC clusters (e.g. Pagel & Tautvaišienė 1998), as shown in the bottom-right panel of Fig.5, where the empty histograms refer to the clusters and the filled ones to our (Tosi et al. 2002) results on the Coimbra experiment.

3. Resolved stellar populations in and beyond the Local Group

Nowadays, it is possible to resolve individual faint/old stars in galaxies of the LG and its immediate vicinities, and we can thus infer their SFHs over long lookback times (up to the Hubble time), with an average time resolution around 10% of the lookback time. The high spatial resolution of new generation imagers (the HST cameras in primis) also allows us to spatially resolve the SFH not only in the Milky Way satellites but in all nearby galaxies. For instance Dohm-Palmer et al. (1998) and Dohm-Palmer et al. (2002) have resolved and measured the SF activity over the last 0.5 Gyr in the various sub-regions of the dIrrs Gr8 and Sextans A, close to the borders of the LG. The resulting space/time distribution of the SF, with lightening and fading of adjacent cells, is intriguingly reminiscent of the predictions of the stochastic self-propagating SF theory proposed by Seiden, Schulman, & Gerola (1979) almost 30 years ago.

The HST/ACS provides spectacularly deep and spatially resolved images, such as those of the star forming region NGC346 in the SMC, where Nota et al. (2006) and Sabbi et al. (2007) have been able to measure 85000 stars, from very old to very young ones, including for the first time pre-main-sequence objects of mass from 3 to 0.6 \( M_\odot \). The impressive CMD obtained from HST/ACS images of M31 by Brown et al. (2003) has opened the way to accurate studies of the resolved stellar populations of other spiral galaxies (see also A. Ferguson and T. Smecker-Hane, this volume, for M31 and M33).

In galaxies beyond the LG, distance makes crowding more severe, and even HST cannot resolve stars as faint as the main-sequence turn-off (MS-TO) of old populations. The higher the distance, the worse the crowding conditions, and the shorter the lookback time reachable even with the deepest, highest resolution photometry. Depending on distance and intrinsic crowding, the reachable lookback time in galaxies more than 1 Mpc away ranges from several Gyrs
(in the best cases, when the red giant branch or even the horizontal branch are clearly identified), to several hundreds Myr (when asymptotic giant branch stars are recognized), to a few tens Myr (when only the brightest supergiants are resolved).

The effect of distance on the capability of resolving individual stars and therefore on the reachable lookback time is shown in Fig. 2, where the CMDs obtained from HST/WFPC2 photometries of three late-type galaxies are shown: the LMC bar (Smecker-Hane et al. 2002), with a distance of 50 kpc and a CMD reaching a few mags below the old MS-TO, i.e. a lookback time of 13 Gyr; NGC1705 (Tosi et al. 2001), with distance 5.1 Mpc and a CMD reaching a few mags below the tip of the red giant branch (RGB), i.e. a lookback time of more than 2 Gyr; and IZw18 (Aloisi, Tosi, & Greggio 1999), with a very uncertain distance (here assumed at the lowest limit of 10 Mpc) where we reached only the asymptotic giant branch (AGB), i.e. stars at least 0.4 Gyr old.

The problem is that not all kinds of galaxies are present in the LG, with the unfortunate circumstance that missing are systems representative of the most extreme morphological types, ellipticals and blue compact dwarfs (BCDs). We must then deal with the higher uncertainties and study the SFH of galaxies also outside the LG. The existing instrumentation currently allows to resolve AGB stars and, often, RGB stars in galaxies within 15 - 20 Mpc. For example, Fig. 3 shows the CMDs from HST/ACS photometry of two of the three most metal-poor BCDs ever discovered: IZw18 (Tosi et al. 2006) and SBS1415+437 (Aloisi et al. 2005), both more distant than 10 Mpc.

In the case of SBS1415+437 (central panel in Fig. 3) a prominent RGB is clearly measured, demonstrating that the galaxy contains stars older than about 2 Gyr. The luminosity of the RGB tip implies a distance of 13.6 Mpc.
Figure 3. CMDs of the most metal-poor BCDs resolved with HST/ACS: I Zw18 and SBS1415+437 (left and central panel, respectively). The righthand panel shows [Girardi et al. (2002)] Z=0.001 isochrones, shifted at the distance of SBS1415+437. See text for details and references.

By comparing the CMD with the Padova isochrones of appropriate metallicity (Z=0.001), shifted at that distance, it is apparent that SBS1415+437 also contains intermediate age AGB stars (including the thermally pulsing phase and carbon stars) and young massive stars. This leads to the important conclusion that, although very blue, currently active, metal poor, and gas rich, this system has not started only recently to form stars but has managed to sustain a significant star formation activity over more than 2 Gyr.

The case of I Zw18 (left-hand panel in Fig. 3 from [Tosi et al. 2006]) is more complicated, because crowding is more severe and the distance may be higher. Yet we do see in its CMD an increase in the stellar density along the red branch below $I \approx 27.5$, which is most likely due to the appearance of the RGB, specially once we consider that photometric incompleteness is increasingly affecting the faintest magnitudes (see also [Momany et al. 2005]). New HST/ACS time series observations, suitable for the derivation of Cepheids light-curves (Aloisi et al. in preparation) are providing an independent estimate of the galaxy distance and confirming the detection of the RGB. These results show that, contrary to previous claims (e.g. [Izotov & Thuan 2004]), even the most metal-poor star forming galaxy ever discovered cannot be considered a genuinely young system and is instead active since at least a couple of Gyr. Moreover, its extremely low metallicity (Z=0.0004 for the youngest stars, presumably less for the older ones) significantly reduces the age-metallicity degeneracy on the RGB, and its colour extension therefore traces a significant age spread, suggesting that the onset of the SF activity in I Zw18 has occurred several Gyrs ago.

4. Star formation histories

The SFHs of LG galaxies derived from their resolved stellar populations were extensively described by [Grebel 1998] and [Mateo 1998]. Since then, many other studies have been performed, applying the synthetic CMD method to a large fraction of the LG dwarf galaxies, both of late and early-type. Very interesting results on the SFH are expected from the ACS images of M31 (A.
Ferguson, this volume), M33 (T. Smecker-Hane, this volume) and a number of selected dwarfs of various types (e.g. C. Gallart, this volume). Many other groups have worked on the SFHs of nearby dwarf and giant galaxies, but it is unfortunately impossible to cite them all here.

Figure 4. The CMDs of concentric regions of the BCD NGC1705 (Tosi et al. 2001) are plotted in the left-hand panels, where the photometric errors and the number of resolved stars are indicated. Regions from 7 through 0 span from the galactic center to the outskirts. The right-hand panels show the corresponding SFH (SFR density vs age), and the different line-types refer to alternative scenarios (see Annibali et al. 2003, for details).

Not many groups have embarked in the more challenging application of the synthetic CMD method beyond 1 Mpc, and most of them have concentrated their efforts on the understanding of late-type dwarfs (e.g. Vallenari & Bomans 1996; Lynds et al. 1998; Schulte-Ladbeck et al. 2001; Cannon et al. 2003; Vallenari et al. 2005), with notable exceptions, such as the study of the recent SFH in the elliptical galaxy NGC5128 (Rejkuba, Greggio, & Zoccali 2004). Our group has studied some of the most active dwarfs outside the LG: the dIrr NGC1569 and the BCDs NGC1705, IZw18 and SBS1415+437.

Fig.4 shows the case of NGC1705, a very active BCD at 5.1 Mpc, with evidence of galactic winds. The most central region is very crowded and only young and intermediate-age stars can be resolved, but elsewhere RGB stars are easily resolved and become the most prominent CMD feature in the outer regions. We can then derive the SFH of most regions back to several Gyr ago, as shown in the right-hand panel of Fig.4. It is immediately apparent that in this BCD we are not seeing a bursting regime, with short episodes of SF activity separated by long periods of quiescence. It is also interesting to notice that the strong SF episode of 15 Myr ago coincides with the epoch of both the formation of the central super star cluster and the onset of the galactic wind. The wind is probably the cause of the sudden halt of the SF activity everywhere in NGC1705.
The gas, however, must have been quick in cooling and falling down, since only 6-7 Myr later another, stronger, SF burst appears to occur in all the galaxy.

Figure 5. SFHs in late-type galaxies derived with the synthetic CMD method. The thin vertical line in each panel indicates the reached lookback time. See text for references.

Fig. 5 summarizes the SFHs derived for six late-type galaxies, all, but the LMC, more than 1 Mpc away: the LMC bar (Tosi et al. 2002), the dIrr NGC1569 (Greggio et al. 1998; Angeretti et al. 2005), the BCDs NGC1705 (Annibali et al. 2003), I Zw36 (Schulte-Ladbeck et al. 2001) and Mrk187 (Schulte-Ladbeck et al. 2000), and the LSB UGC5889 (Vallenari et al. 2005). The most important result is that all of them were already active at the reached lookback time. All of them present a recent SF activity, which is what let people discover them in spite of the distance. None of them exhibits long quiescent phases within the reached lookback time. On the other hand, the SFR differs significantly from one galaxy to the other, independently of the attributed morphological type. It is true that the least active object is the LSB galaxy, as expected, but the most active one is by far the dIrr NGC1569. Of the BCDs, two have SFRs comparable to that of the LMC bar, and the third doesn’t reach the SFR level of NGC1569.

The statistics is still poor, but we can already draw some general results from all the SFHs derived so far:

1. Evidence of long interruptions in the SF activity is found only in early-type galaxies;
2. No galaxy currently at its first SF episode has been found yet;
3. No frequent evidence of strong SF bursts is found in late-type dwarfs;
4. There is no significant difference in the SFH of dIrrs and BCDs, except for the current SFR.

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