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The star formation history from resolved stellar populations

State of the art and future perspectives

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Abstract. We present a new method to solve the star formation history (SFH) of a complex stellar population system from the analysis of the color-magnitude diagram (CMD). The SFH is obtained in four steps: i) computing a synthetic CMD, ii) simulating observational effects, iii) parametrization and sampling of the synthetic and observed CMDs, and iv) solving and averaging the solutions. The consistency and stability of the method have been tested using a mock stellar population. The method has been used to solve the SFH of a set of six isolated Local Group dwarf galaxies observed with HST. The main goal is to probe the effects of cosmological processes, such as the reionization in the early star formation or the ability of SNe feedback to remove gas in small halos, in dwarf galaxies free from environmental effects due to the strong interaction with the host galaxy.

Key words. Hertzsprung-Russell diagram, galaxies: stellar content, Local Group, methods: numerical

1. Introduction

A quantitative star formation histories (SFHs) is a very important tool to cast light on the formation and evolution of galaxies. Depending on the type of observations, two different approach has been used to obtain SFHs. For unresolved stars, galaxy spectra and populations synthesis is commonly used, while the color-magnitude diagram (CMD) and stellar population fitting for resolved stars. Although both methods focus in the same type of object, it is clear that deal with different type of data. As a consequence, the requisites of using one or other method and the characteristics of the results may differ slightly. For example, it is clear that stellar population fitting can be used only in the nearest galaxies while population synthesis is used at larger distances. The first method has no needs for an estimation of the spectral energy distribution to obtain an absolute SFH, while it is necessary in the second one. Age resolution is usually better in the CMD fitting method when it is compared with age resolution from population synthesis. This work is devoted to the SFHs obtained from resolved stellar populations.

The capabilities to obtain reliable SFHs have been linked to three developments: increasing image quality in depth and accuracy, the improvement of stellar evolution libraries, and the development of computation codes for deriving SFHs. Better image quality has produced deep CMDs, reaching the main sequence turn-offs of the oldest stars with good accuracy. The improvement in the calculation of advanced phases of the horizontal-branch (HB) or the AGB phases in the evolution of stars and a wider range coverage in age an metallicity of the models have been essential for deriving reliable SFHs. Finally, code computations have been improved for searching solutions involving multiple stellar components, which requires a large parameter space and more computing capabilities.

The CMD is the best tool to derive the SFH of resolved galaxies. If the CMD is deep enough stars born all over the life-time of the galaxy can be observed. However, deciphering an accurate SFH in a complex stellar population system requires some relatively sophisticated technique.

We present a procedure and a set of algorithms designed for this task. The main code we present here is based in the same principle as that used by (Aparicio et al. 1997) for the solution convergence. Applied in the most general way it derives the SFR as a function of both time and metallicity of a system from the comparison of its CMD star distribution with the star distribution in a synthetic CMD. This method has been applied to accurate CMDs to obtain the onset of the star formation in a set of dwarf galaxies of the Local Group.

2. Basic concepts and definitions

We will adopt here the following approach: considering that time and metallicity are the most important variables in the problem, we define the SFH as a function $\psi(t, z)$ such that $\psi(t, z)\mathrm{d}t\mathrm{d}z$ is the number of stars formed at time t' in the interval $t < t' \leq t + \mathrm{d}t$ and with metallicity z' in the interval $z < z' \leq z + \mathrm{d}z$, per unit time and metallicity. $\psi(t, z)$ is a distribution function and can be identified with the usual SFR, but as a function both of time and metallicity.

There are several other functions and parameters related to the SFH, that we will consider here as auxiliary. The initial mass function (IMF), $\phi(m)$ and a function accounting for the frequency and relative mass distribution of binary stars, $\beta(f, q)$ are the main ones. The solution found for the SFH depends on the assumptions made for these functions. The method we present here uses several choices of both with the aim of setting constraints for them.

Other parameters affecting the solution of $\psi(t, z)$ are distance and reddening, including differential reddening. But the strongest limitation on the observational information is produced by the *observational effects*. These include all the factors affecting and distorting the observational material, namely the signal-to-noise limitations, the defects of the detector and the crowding and blending among stars. The consequences are loss of stars, changes in measured stellar colors and magnitudes, and external errors larger and more difficult to control than internal ones.

3. Running the algorithms

The method is designed to obtain a SFH in four steps, each one, handled by an algorithm:

- Generating one (o several) global synthetic stellar population which serves as a model (algorithm: IAC-star).
- Simulating observational effects on the model (obsersin).
- Parametrization and sampling the model and data (minniac).
- Solving the equations (IAC-pop).

3.1. IAC-star

IAC-star (Aparicio & Gallart 2004) is a code for synthetic CMD computation. In short, the algorithm is intended to be as general as possible and allows a variety of inputs for the initial mass function (IMF), star formation rate, metallicity law, and binarity. IAC-star is used to generate a global synthetic stellar population with a large number of stars with ages and metallicities with a constant distribution over the full interval of variation of $\psi(t, z)$ in time and metallicity. If functions $\phi(m)$, $\beta(f, q)$ are to be explored, a global synthetic stellar population must be generated for each choice of $\phi(m)$ and $\beta(f, q)$, as mentioned before. Among other quantities, IAC-star provides magnitudes in several filters, age, and metallicity for each synthetic star, and the integral of the SFH (i.e. total mass ever formed in the model), used to normalize the solutions. Synthetic magnitudes are used to plot the CMD (sCMD) associated to the global synthetic population.

3.2. Obsersin

Once the sCMD is generated, observational effects must be simulated. This is done by *obsersin* which makes use of the results of previously done completeness tests. The completeness tests are done by injecting a list of false stars in the observed images and recovering them using the same photometric procedure used for the photometry of real stars. From the list of the unrecovered stars and the differences between the injected (m_i) and recovered magnitudes (m_r) obsersin uses the following procedure to simulate the observational effects: for any star from sCMD (called synthetic star) with magnitude m_s a list of false stars with $|m_i - m_s| \leq \epsilon$ is created for each filter, being ϵ a free input searching interval. From the stars in common to both filters, a single false star is selected by a simple random sampling. If m'_i and m'_r are the injected and recovered magnitudes of the selected false star in a given filter, then $m^e_s = m_s + m'_i - m'_r$ will be the magnitude of the synthetic star with observational effects simulated. The same is done for both filters.

With the procedure described above, the observational effects are simulated in sCMD star by star. The number of injected stars in the completeness tests in comparison with the number of synthetic stars in sCMD determines the quality of the observational effects simulation.

3.3. Minniac

IAC-pop uses a method to solve the SFH introduced by (Aparicio et al. 1997). The method assumes that any SFH can be given as linear combination of simple populations (see §3.4). We define a simple stellar population by a number of stars with ages and metallicities within small intervals. Each simple population has an associated CMD that we call partial model CMD (pCMD). With this definition, sCMD is formed by the sum of all pCMD. To compare pCMD with the observed CMD (oCMD) we create a set of boxes and counting stars in them. This process repeated for all the pCMD included in sCMD gives the arrays M_i^j, containing the number of stars from partial model i populating the pCMD box j, and O^j, containing the number of observed stars in box j.

To minimize the dependency of the results on the selection of simple populations and size and position of the boxes, the process is repeated by introducing offsets in age and metallicity bins which define the simple populations. The age and metallicity interval for each simple population is fixed. For each new set of simple populations, the boxes can change in size and position.

Beside this, minniac can introduce for each set of simple populations and/or size and position of the sampling boxes an offset in color and magnitude in oCMD. For each new color-magnitude point, the process described above is repeated. This produces a manifold of input files which are used by IAC-pop (see below) to solve the SFH. We call *model parametrization* to each set of simple populations, position and size of boxes, and color-magnitude point. Each model parametrization have the arrays defined above M_i^j and O^j associated.

3.4. IAC-pop

With the information provided by minniac, the distribution of stars in the CMDs can be calculated for any model SFH as a linear combination of the M_i^j calculated above:

$$M^j = A \sum_i \alpha_i M_i^j \qquad (1)$$

It should be noted that $\alpha_i \geq 0$. A is a scaling constant.

The best SFH matching the distribution, O^j, of the observational CMD can be found using a merit function. In particular Mighell's χ^2_γ (Mighell 1999) is used:

$$\chi^2_\gamma = \sum_j \frac{(O^j + min(O^j, 1) - M^j)^2}{O^j + 1} \qquad (2)$$

We will use $\chi^2_\nu = \chi^2_\gamma/\nu$, where ν is the number of freedom degrees. In our case $\nu = k - 1$, where k is the number of boxes defined in the CMD. Minimization of χ^2_ν provides the best solution as a set of α_i values. IAC-pop makes use of a genetic algorithm (Charbonneau 1995) for an efficient searching of the χ^2_ν minimum.

The solution SFH can be written as:

$$\psi(t, z) = A \sum_i \alpha_i \psi_i \qquad (3)$$

where ψ_i refers to partial model i, with i taking values from 1 to $n \times m$, and A is a scaling constant.

All solutions given by IAC-pop for the same color-magnitude point are averaged. The solutions obtained for different color-magnitude points are used to calculate external uncertainties. To find the color-magnitude offset which gives the best χ^2_ν several choices of color-magnitude points must be explored. This procedure minimize the impact of the uncertainties from the reddening and distance determination and the differences between the evolutionary models and data.

4. Consistency test

To test the consistency and stability of the method, a mock stellar population has been computed using IAC-star and analyzed with the procedure described in §3 to obtain its SFH as if it were a real one. Results have been compared with the input used to compute the mock population. The IAC-star input parameters used to compute the mock population were as follows. The BaSTI stellar evolution library (Pietrinferni et al. 2004) and the (Castelli & Kurucz 2003) bolometric correction library were used. The number of stars in the associated mock CMD (mCMD) were 10^5. The star formation ranges from 14 Gyr ago to date with a constant SFR, $\psi(t)$, for that period. The metallicity increases with time, with initial and final metallicities $z_0 = 0.0001$ and $z_f = 0.008$ and some metallicity dispersion at each time. Finally, no binary stars were considered and the IMF by (Kroupa et al. 1993) was used. The integral of $\psi(t, z)$ (i.e. the total mass ever transformed into stars) for this system is $\Psi_T = 2.02 \times 10^6 M_\odot$. The SFH $\psi(t, z)$ of the mock population is shown in Figure 1. The volume below the curved surface and over the age-metallicity plane gives the mass that has been ever transformed into stars within the considered age-metallicity interval. The SFR as a function of time only, $\psi(t)$, and of metallicity only, $\psi(z)$, are also shown. The associated mCMD is shown in Figure 2.

Figure 3 shows the $\psi(t, z)$ solution for the mock population given in Figure 1. Agreement is good, being the differences between input and solution within the error bars, showing the algorithms robustness against observational effects. Figure 4 shows the CMD corresponding to the solution.

Table 1 summarizes the consistency test. Column 1 identifies the CMD. Column 2 gives the χ^2_ν value of the solution. Columns 3, 4 and 5 give, respectively, the total mass (M_T), mean age ($< age >$), and mean metallicity ($< z >$) of the stars in the mock population (first row) and the solutions. Agreement on integral and average values between mock population and solution is good in all the cases.

5. SFHs of the LCID project

The procedure described in the previous sections have been applied to LCID (Local Cosmology from Isolated Dwarfs) project. LCID was granted 110 orbits on the HST@ACS to obtain deep photometry of five Local Group isolated dwarf galaxies of different level of current star formation activity and gas fraction: IC1613, Leo A, Tucana, LGS-3 and Cetus. Phoenix dwarf galaxy was observed previously with the HST@WFPC2 over 24 orbits and also added to the LCID sample. The final objective is to analyze how

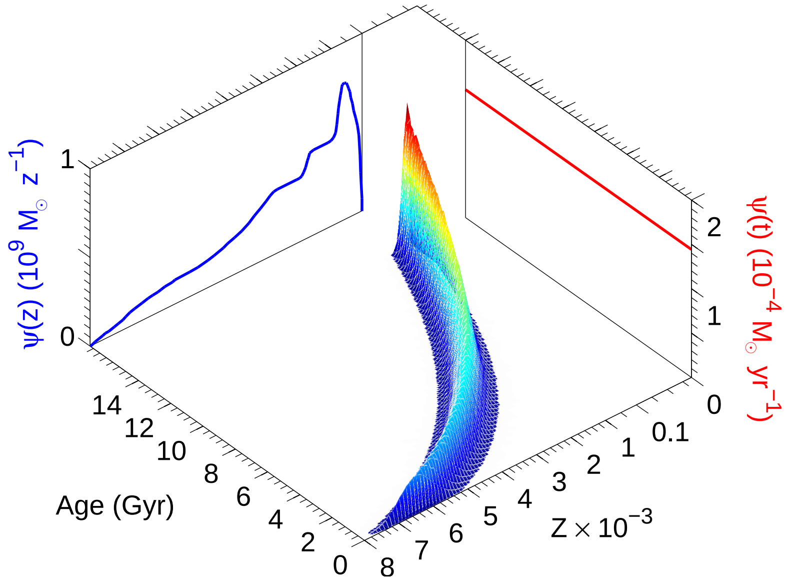

Fig. 1. The SFH $\psi(t,z)$ of the mock population. Age and metallicity are given in the horizontal axis. The volume below the curved surface and over the age-metallicity plane gives the mass that has been ever transformed into stars within the considered age-metallicity interval. The mono-dimensional $\psi(t)$ and $\psi(z)$ are shown on the ψ-age plane (in red in the paper electronic version) and on the ψ-metallicity plane (in blue in the paper electronic version) respectively.

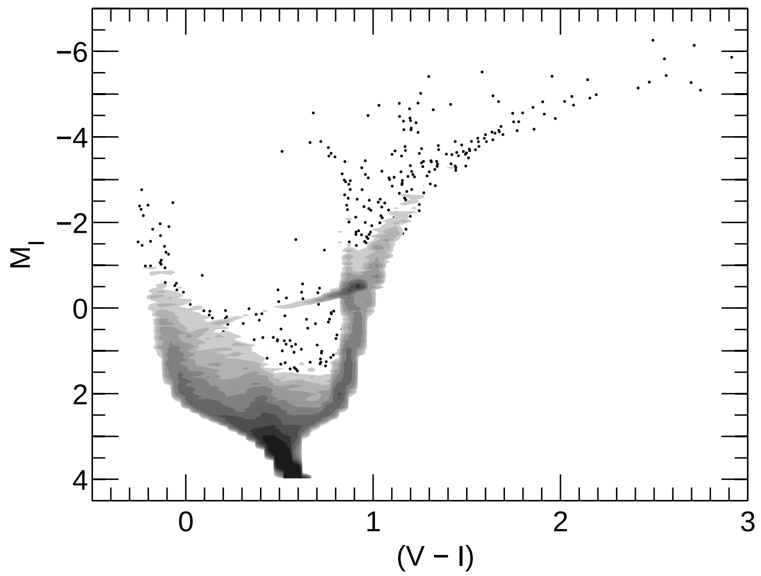

Fig. 2. The CMD of the mock population (mCMD) associated to the SFH shown in Figure 1. Grey levels show the density of stars. A factor of two in density exists between each two successive gray levels.

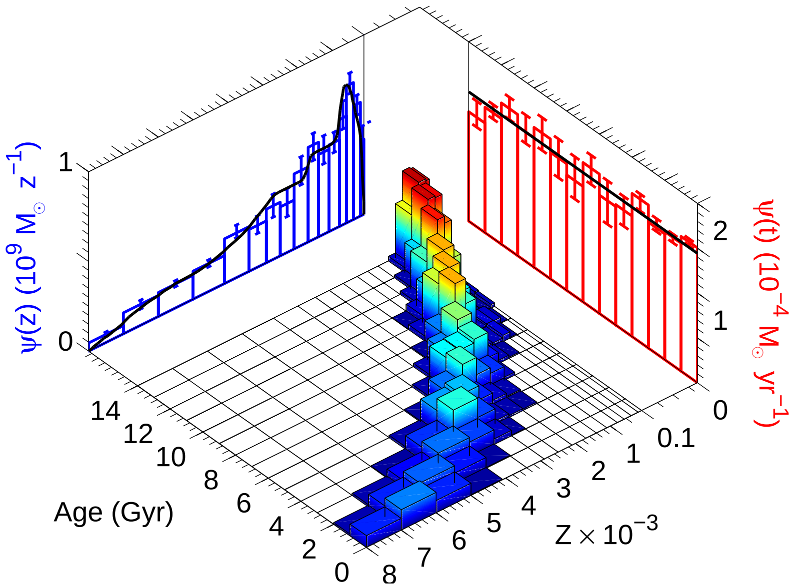

Fig. 3. Solution of $\psi(t, z)$ obtained for the mock population. The caption is the same as in Figure 1.

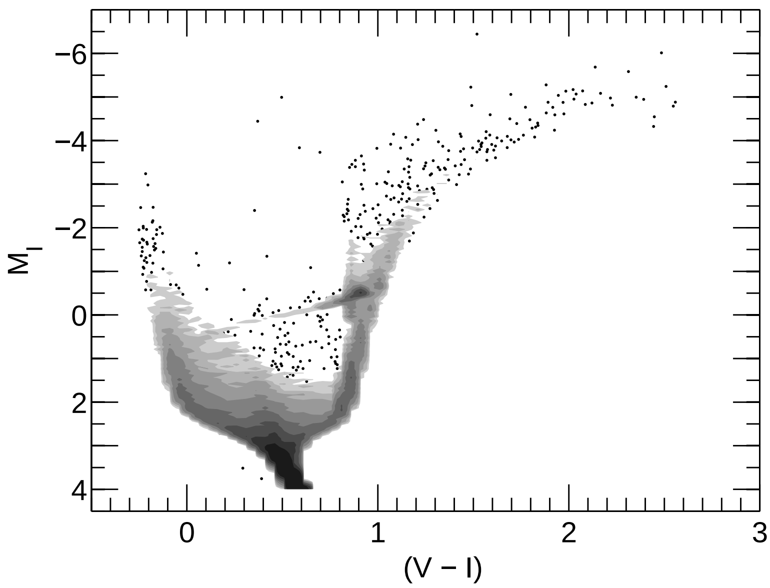

Fig. 4. The CMD corresponding to the solution shown in Figure 3. To be compared with the mCMD shown in Figure 2.

Table 1. Results for the self-consistency test

CMD	χ^2_ν	M_T ($10^6 M_\odot$)	$< age >$ (Gyr)	$< z >$
Mock		2.02	7.00	0.0026
Solution	0.9	2.00 ± 0.02	6.91 ± 1.10	0.0026 ± 0.0005

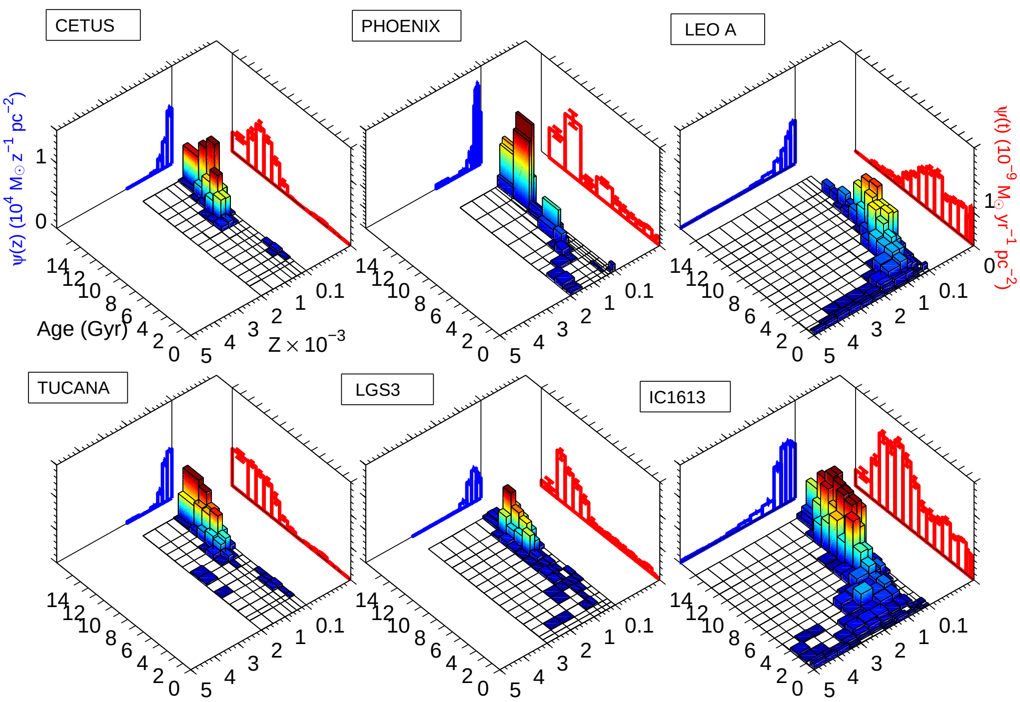

Fig. 5. SFHs obtained for the six galaxies of the LCID project. The caption is the same as in Figure 1.

the star formation has proceed in isolated dwarfs free of strong tidal effects.

The galaxies were observed in F475W and F814W ACS filters (except Phoenix which was observed in F555W and F814W WFPC2 filters). The photometry list was obtained using DOLPHOT (Dolphin 2000) [photometry of Phoenix was obtained using DAOPHOT/ALLFRAME, Stetson, P. B. (1994)]. The process described in this paper was used to obtain the preliminary SFHs of all galaxies, which are shown in Figure 5. Preliminary results show that all galaxies except LeoA have old (> 10 Gyr) star formation. The first star formation even seems to be stronger in Tucana and Cetus than the other galaxies. LeoA shows a delay in the first star formation event. However, in the case of LeoA, our results show that the SFR for stars older than 10 Gyr depends on the distance and reddening assumed.

6. Conclusions

We have presented several algorithms which have been shown to be an useful tool to obtain the SFH from the CMD of resolved stellar systems. The procedure has been run through a consistency test showing the robustness of the method against the effects introduced by realistic observational effects.

The method has been applied to obtain the SFHs of a set of six Local Group dwarf galaxies form the LCID project.

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