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Local Cosmology from Isolated Dwarfs: the derivation of star formation histories

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Abstract. The color-magnitude diagram (CMD) is the most powerful tool to derive quantitative star formation histories (SFHs) of complex stellar systems which host populations with different ages and chemical compositions. We present some results from the LCID project, based on the analysis of deep HST/ACS CMDs reaching the oldest Main Sequence (MS) Turn Off (TO) to derive the SFH of isolated dwarf galaxies of the Local Group (LG). In particular, we focus on Tucana, one of the few isolated dwarf spheroidal galaxies. The method applied for this work relies on the packages IAC-star and IAC-pop. A few aspects of the quantitative estimate of SFHs using this method are presented and discussed.

Key words. (galaxies:) Local Group – galaxies: photometry, techniques: photometric – galaxies: individual (Tucana)

1. Introduction

In the last twenty years the advent of CCD cameras, together with the 8-m class telescopes and the HST, has pushed the studies of stellar populations to more and more distant objects. During Cycle 14, taking advantage of the unique capabilities of the ACS onboard of the HST, we observed five isolated dwarf galaxies of the Local Group to well below the old MSTO (*LCID project, Local Cosmology from Isolated Dwarfs*). The importance of these objects relies on the fact that they are likely approaching the LG for the first time, and therefore they spent most of their life free from the influence of giant galaxies. These objects are ideal candidates to study the first stages of their formation and evolution, and can provide key insight in the cold dark matter scenery.

The SFH of resolved stellar systems can be accurately recovered through sophisticated modeling of their CMD diagram. In particular, the most reliable constraints can be derived if the MSTO is measured with high signal-to-noise (Gallart et al. 1999). We present here results concerning the SFH of the Tucana dSph, based on the application of the IAC-star and IAC-pop codes. The latter makes use of a genetic algorithm to derive the star formation rate (SFR) and the chemical evolution law of a stellar system, comparing the observed and model CMDs. We also discuss here a few technical aspects of the method (a complete description can be found in Aparicio & Gallart 2004 and in Aparicio & Hidalgo 2008).

2. Recovering SFHs with IAC-pop

The basic idea of IAC-pop is that any SFH is mainly driven by two parameters, the age and

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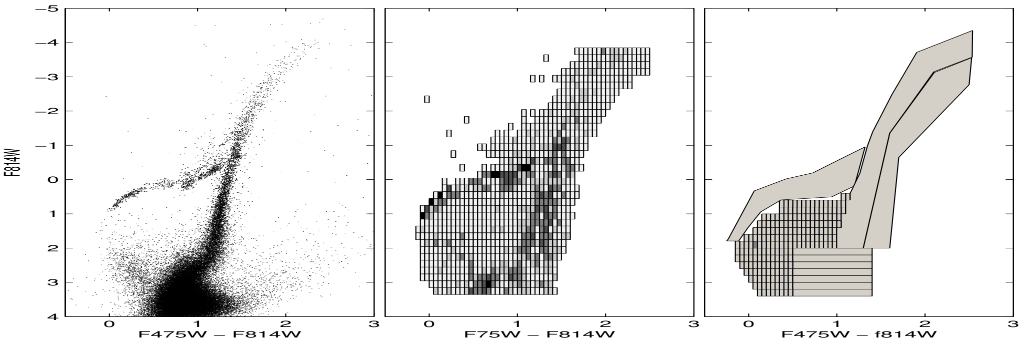

Fig. 1. CMD of Tucana (*left*) and two examples of parametrization of the CMD, homogenous grid (*center*) and "*à la carte*" (*right*). The color code represents the contribution of each box to the overall χ^2. Darker boxes indicate that the number of stars resulting from the derived SFH present the greater discrepancy with the observed number of stars in that region of the CMD.

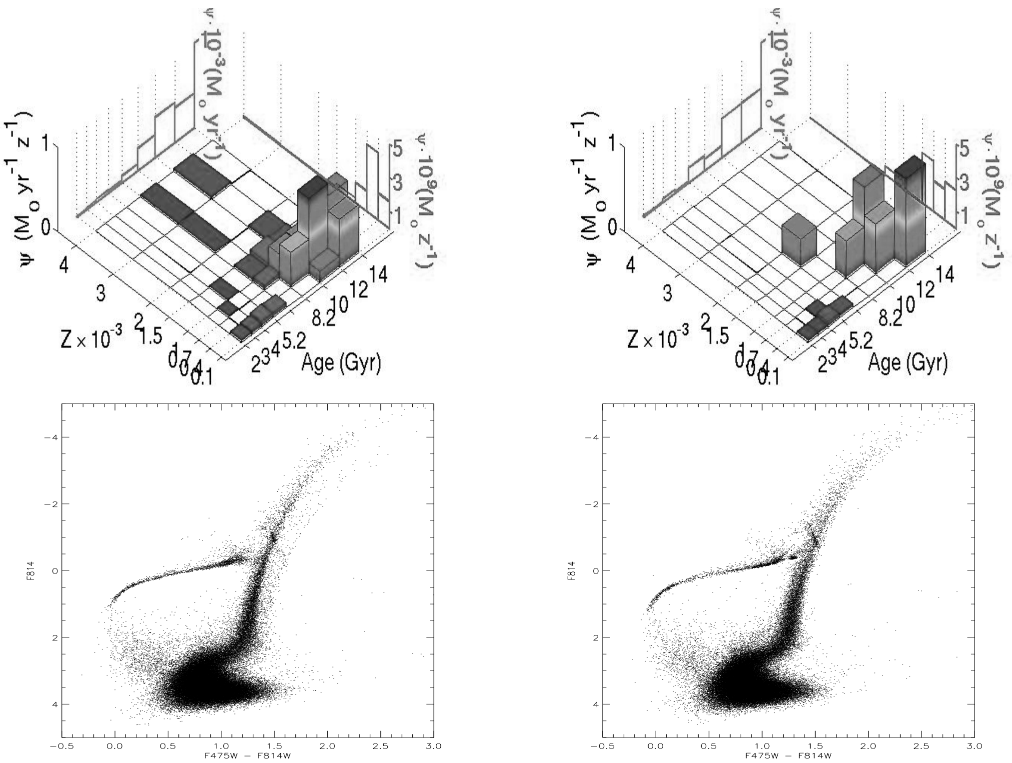

Fig. 2. The SFHs *top* and the CMDs (*bottom*) derived using the grid (*left*) and à la carte (*right*) sets of boxes. There is an overall good agreement between the two solutions, the SFH of Tucana being peaked at old epochs, with some hint of SFH at intermediate ages.

the metallicity of the system. The SFH, $\Psi(t,z)$, is therefore a function described as the combination of *single populations*, defined as the ensembles of stars formed per unit of time and metallicity, and can be expressed as:

$$\Psi(t,z) = A \sum_i \alpha_i \psi_i \tag{1}$$

where $\Psi(t,z)$ is the global SFH, ψ_i are the contributions of the single populations, and A the normalization constant. In this representation, the weights α_i give a quantitative estimate of the mass of gas transformed into star at that particular age and with that particular metallicity. From a practical point of view, the single populations are identified using a discrete set of time and metallicity bins. The values adopted in this work are the following: [14, 12, 10, 8.2, 6.6, 5.2, 3, 2] Gyr, Z=[0.0001, 0.0004, 0.0007, 0.001, 0.0015, 0.002, 0.003, 0.004].

The model CMD is generated using the IAC-star simulator, and requires a number of different ingredients:

- a set of theoretical stellar evolution libraries. Here we used the BaSTI (Pietrinferni et al. 2004) and Padova (Bertelli et al. 1994) models;
- the SFR, which we set constant at any age;
- the metallicity law, Z(t), which we define such the metallicity of stars of any age is uniformly distributed in the range 0.0001<Z<0.004;
- the initial mass function (IMF), taken from Kroupa (2001);
- the binary fraction, β, and the relative mass distribution q, the default values being β=50%, q >0.5.

Other auxiliary but fundamental information is necessary to compare the model with the observations. First, an independent estimate of the distance modulus (DM) and the extinction E(B-V) are mandatory to shift the theoretical and observed diagrams in the same magnitude system. Second, the observational errors (crowding, blending, incompleteness, photometric errors, ...) have to be properly simulated in the model CMD (Aparicio & Gallart 1995).

The observable that is used to compare the data with the model is the number of stars, using a χ^2 merit function (Mighell 1999). A key point of the method is that the CMD has to be parametrized in order to perform the star count. This is made defining a set of boxes covering the CMDs (see Fig. 1). The problem that the algorithm solves can be represented with:

$$M_o^j = A \sum_i \alpha_i M_i^j \tag{2}$$

where the number of observed stars in the box j, M_o^j, is the combination all of the partial models M_i, weighted by the coefficients α_i which are the unknowns.

3. Applications the the Tucana dSph

Fig. 1 shows the CMD of Tucana and two examples of parametrization, a homogenous *grid* and "*à la carte*" set. The advantages of the *grid* approach are manyfold: • it homogeneously samples the entire color and magnitude ranges of the CMD; • is the most neutral and objective approach; • is easy to calculate. However, Fig. 1 also illustrates the main drawback of this method. The color code (central and right panels) represents the contribution of each box to the global χ^2 of the solution, the higher the darker. Therefore, darker boxes mean a greater discrepancy between the number of stars in the observed CDM and the number of stars that the derived SFH predicts for that particular box. The five levels of grey adopted correspond to χ^2 <2.5, 2.5< χ^2 <10, 10< χ^2 <40, 40< χ^2 <100, χ^2 >100. The analysis of the distribution of these residuals shows that the HB is the region with the highest χ^2, in particular with few values >100. We interpret this as a consequence of the high sensitivity of the grid to uncertainties of stellar evolution and color-temperature transformations. In this particular case, a small difference in the HB luminosity level between the observed and the model CMDs causes the stars in the model to migrate from one box to another nearby, increasing the overall χ^2. In this sense, using *à la carte* boxes is more efficient to take full advantage of our knowledge of stellar evolution. The right panel

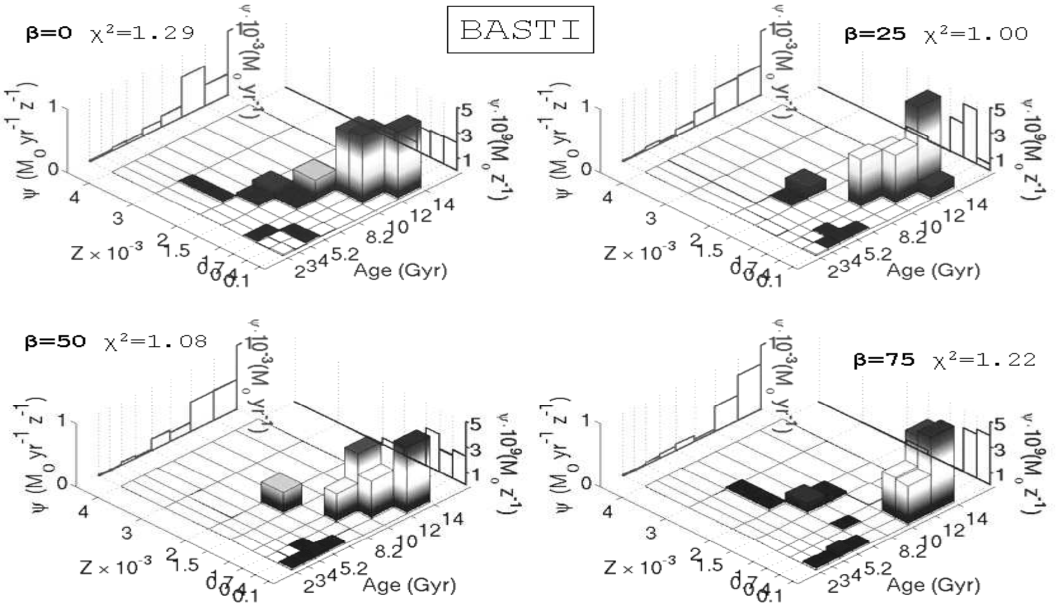

Fig. 3. SFH recovered using the BaSTI library and adopting four different values for the binary content.

of Fig. 1 shows that a different choice of boxes, with lower resolution in a few critical regions, gives a better global χ^2.

Fig. 2 shows the derived SFHs and the CMDs corresponding to the two solutions. The top panels show a 3D representation of the SFH. The height of each bin is proportional to the coefficient α_i corresponding to that interval of age and metallicity. The χ^2 corresponding to these two solutions are significantly different, 7.52 and 1.08 for the grid and *à la carte* set, respectively. However, the two solutions agree quite well in their general behavior. The SFR(t), represented in the left vertical projection as the integration of the SFH with the metallicity, looks very similar in the two cases. The SFH of Tucana appears peaked at old ages, predominantly older than 10 Gyr. However, there are hints of the presence of a slightly younger and/or more metal-rich population, corresponding to an episode occurred ≈7-8 Gyr ago.

In this respect, the grid solution appears more "blurry", in the sense that the star formation seems broader in both age and metallicity, while the *à la carte* SFH is sharper and more confined. This reflects in the corresponding CMDs (lower panels), where the more extended SFH in the case of the grid causes a wider red giant branch. However, the overall agreement is good, all the main features of the observed CDM are well represented: the morphology of the MSTO, the slope and width of the RGB, including the luminosity of the RGB Bump. It is interesting to note that the blue plume of relatively bright objects is well explained by both solutions. In particular, it corresponds to a young metal-poor population, t<6Gyr, Z<0.0004. The very low metallicity supports the idea that Tucana hosts a sizable population of Blue Stragglers rather than a genuine young MS.

To verify the stability of the solutions, we performed many tests using different inputs for the model CMD. We adopt the *à la carte* set, because of its smaller χ^2. Fig. 3 and 4 show the SFH obtained using BaSTI and Padova libraries. The four panels correspond to the four labeled percentages of binaries: 0, 25, 50 and 75%. First, we note that there is a mild trend of the SFR with the binary content: the higher the binary fraction adopted in the model, the

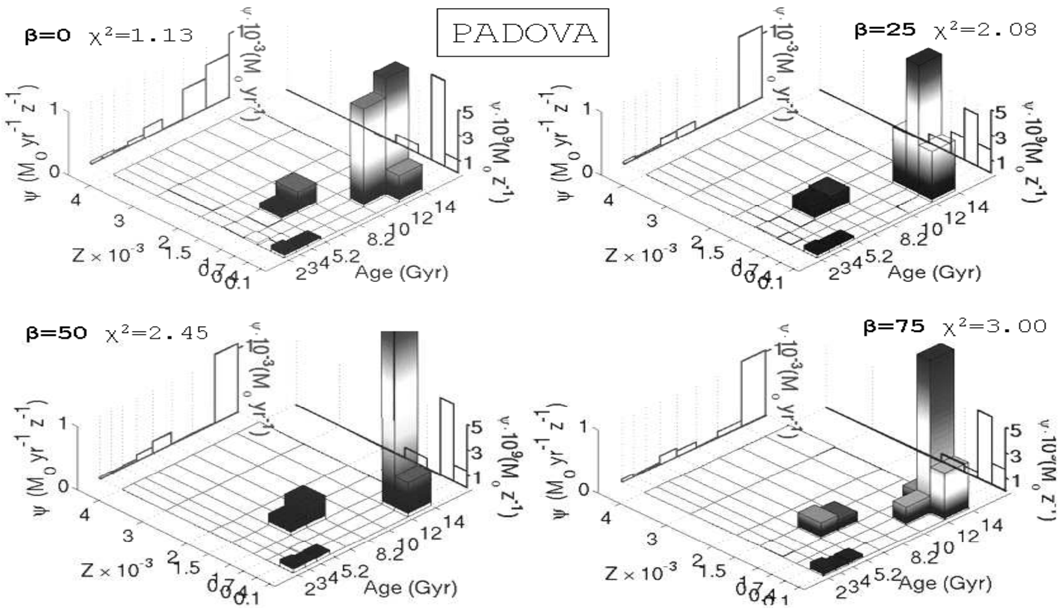

Fig. 4. Same as Fig 3, but using the Padova set of stellar evolution tracks.

more the SFH is peaked to older epochs. This happens because the position of old binaries along the MS is similar to the region occupied by younger single stars. Therefore, the lack of binaries in the model CMD is compensated by the use of slightly younger stars. However, we note that these small changes do not significantly alter the χ^2 of the solution, and therefore we cannot put firm constraints on the amount of binaries in this system.

Second, Fig. 3 and 4 show a systematic difference when adopting the two libraries. The SFH recovered using the Padova library are systematically sharper, and peaked toward older ages, while the SFH recovered with BaSTI are more extended in time toward intermediate-age epochs. It is also interesting to note that in all the solution there is evidence of intermediate-age SFH, and the young metal-poor population of candidates Blue Stragglers always appears.

4. Conclusions

We presented a short summary of the IAC-pop method to recover the SFH of resolved stellar systems. We discussed two different parametrizations of the CMD, and how different inputs of the model CMD influence the solution. However, all the tests we performed suggest the Tucana dSph galaxy experienced most of its SF events in the first few Gyrs of its life, with possibly some star formation at intermediate-age epochs, around 7 Gyr ago.

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