The resolved stellar populations of M32
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Chapter 3

The star formation history of M32


Abstract

We use deep HST ACS/HRC observations of two fields, one near M32 (F1) and another control field in M31 (F2), to determine the star formation history (SFH) of the elliptical M32 for the first time from its resolved stellar populations. We find that 2–5 Gyr old stars contribute \( \sim 40\% \) of M32’s mass while \( \sim 55\% \) of M32’s mass comes from stars older than 5 Gyr in F1. The mean mass-weighted age and metallicity of M32 at F1 are \( \langle \text{Age} \rangle = 6.8 \pm 1.5 \text{ Gyr} \) and \( \langle [\text{M/H}] \rangle = -0.01 \pm 0.08 \text{ dex} \), respectively. The presence of young (< 2 Gyr old), metal-poor stars in the derived SFH suggests that blue straggler stars (BSS) are present in M32 and that they contribute \( \sim 2\% \) of the mass in F1. This may represent the first direct evidence of BSS in M32. Our inferred SFH of M32, and in particular the substantial population of 2–5 Gyr old stars at F1, does not seem to agree with models of formation that suggest a spiral galaxy as M32’s progenitor. Instead, we favor the idea that M32 is a low-luminosity, small elliptical galaxy that has had a dissipative merger event.

The inferred SFH of the M31 background field F2 reveals that the majority of its stars are old, with 95% of its mass already acquired 5–14 Gyr ago, and is composed of two dominant populations: \( \sim 40\% \) of its mass in a 5–8 Gyr old population and \( \sim 50\% \) of the mass in a 8–14 Gyr old population. Its mean mass-weighted age and metallicity are \( \langle \text{Age} \rangle = 8.72 \pm 1.21 \text{ Gyr} \) and \( \langle [\text{M/H}] \rangle = -0.15 \pm 0.10 \text{ dex} \), respectively. Our results suggest that the inner disk and spheroid populations of M31 are indistinguishable from those of the outer disk and spheroid. Assuming the mean age of M31’s disk at F2 (~ 1 disk scale length) to be between \( \sim 5 \) to \( \sim 8 \) Gyr, our
results agree with an inside-out disk formation scenario for M31’s disk. Of course, these are the results of one field in the inner regions of M31 and we need more observations and statistics to either confirm or rule out what we suggest.

3.1 Introduction

Messier 32 (M32) is today a compact, low-luminosity elliptical galaxy, satellite of our neighbour M31. Due to its proximity, we can study M32 with great detail not only from its integrated light but also from its individual, resolved stars in a way that is impossible for most of the elliptical galaxies, given their greater distances and high densities. M32 is thus a vital laboratory to test the applicability of stellar population models used to decipher the star formation history (SFH) of elliptical galaxies in general. However, M32’s SFH, and therefore its origin, is still controversial. The different scenarios proposed to explain its origins and formation process extend from a true elliptical galaxy at the lower extreme of the mass sequence (e.g., Faber 1973, Nieto & Prugniel 1987) formed through merger events (Kormendy et al. 2009) to an spiral galaxy which, as a consequence of tidal interactions with M31, lost most of its outer disk and only its bulge survived (e.g., Bekki et al. 2001, Chilingarian et al. 2009).

The only way to accurately determine the age, and thus the SFH, of a galaxy is by directly observing its oldest main-sequence turnoff (MSTO). With this goal in mind, we were awarded 64 orbits with HST ACS/HRC to observe two fields near M32, F1 and F2 (see Fig. 2.1 in Chapter 2), in order to detect the oldest MSTOs of this galaxy.

In Chapter 2 we introduced our observations and presented the deepest HST color-magnitude diagram (CMD) of M32 yet obtained, reaching more than 2 mag fainter than the RC and fully resolving the RGB and the AGB. Chapter 2 significantly improved our knowledge on the stellar populations of M32. We have found that M32 is dominated by intermediate-age and old (8–10 Gyr old), metal-rich ([Fe/H] $\sim -0.2$) stars and it contains some old (> 10 Gyr), metal-poor stars ([Fe/H] $\sim -1.6$) as well as possible young populations (0.5 – 2 Gyr old stars). These conclusions were provided by our qualitatively analysis of the CMD of M32, which showed a red clump (RC), a red giant branch (RGB), a RGB bump (RGBb), AGB bump (AGBb), and a blue plume (BP), as main features (see Figure 2.12 of Chapter 2). The analysis presented in Chapter 2 helped to constrain the ages and metallicities of M32 at F1 and M31 at F2. However, a quantitative determination of the mix of ages and metallicities in these fields, which will provide the most detailed information about their SFHs, requires a deeper analysis.

In this Chapter, we derive the detailed young and intermediate-age SFH of M32 at $\sim 2'$ from its center and of M31 at our background field’s location, from a more sophisticated analysis of the CMDs presented in Chapter 2. We note here that whereas in Chapter 2 we mainly based our analysis and conclusions on the RC, RGB, and bump (RGBb and AGBb) features, in this Chapter we mostly probe the regions of the CMD where the brighter MSTOs are observed. We therefore provide
quantitative information about the younger population of M32. We find that our field in M32 has a substantial population of 2–5 Gyr old stars contributing to $\sim 42\%$ of its mass, an unexpectedly large population of young stars for an elliptical galaxy at such a large distance from its center.

The Chapter is organized as follows. In Section 3.2 we briefly describe our observations and photometry. Section 3.3 describes the method used to derive the SFH. We present the results of the SFH analysis obtained for F1, F2 and M32 in Section 3.4. In Section 3.5 we provide a detailed and complete SFH of M32 and discuss its implications on M32’s origins. In Section 3.6 we discuss the SFH of the inner regions of M31. Finally, we summarize our results and present our conclusions in Section 3.7.

### 3.2 Observations and Photometry

The field selection and observational strategy, as well as the image reduction, are described in Chapter 2 and we refer the reader there for details. Briefly, HST ACS/HRC images of two fields near M32 were observed during Cycle 14 (Program GO-10572, PI: Lauer). The M32 HRC field (F1) was centered on a location $110''$ south (the anti-M31 direction) of the M32 nucleus. The background field (F2) was located $327''$ from the M32 nucleus, roughly along its minor axis, at the same isophotal level in M31 as F1. The field locations are shown in Fig. 2.1 of Chapter 2.

Stellar photometry was performed on deconvolved combined images. A detailed description of the deconvolution process is explained in Chapter 2. Figure 3.1 shows the CMDs derived for F1 (left panel) and F2 (right panel) from the deconvolved photometry, calibrated onto the VEGAmag system. They contain 58143 and 27963 stars, respectively, as indicated in Table 3.1.

Note the difference between the CMD of F1 and F2 at magnitudes between $F555W \sim 27$ and 28 (cyan boxes in Figure 3.1). The number of stars in this region, where the brighter MSTOs are located, is larger in F1 than F2. This suggests that there is a bigger contribution of intermediate-age stars in F1 than in F2. We can better appreciate this difference in Figure 2.21 of Chapter 2, where we showed a Hess subtraction of the normalized F1 CMD to the F2 CMD.

#### Table 3.1: Deconvolved photometry

<table>
<thead>
<tr>
<th>Field</th>
<th>Detections$^a$</th>
<th>$R_{PSF}^{F435W}b$</th>
<th>$R_{PSF}^{F555W}b$</th>
<th>$AC_{F435W}c$</th>
<th>$AC_{F555W}c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>F1</td>
<td>58,143</td>
<td>5</td>
<td>5</td>
<td>−0.25</td>
<td>−0.22</td>
</tr>
<tr>
<td>F2</td>
<td>27,963</td>
<td>6</td>
<td>16</td>
<td>−0.22</td>
<td>−0.10</td>
</tr>
</tbody>
</table>

Notes.

$^a$ Final number of stars detected and used to derive CMDs.

$^b$ PSF radius in HRC original pixels.

$^c$ Aperture correction.
3.2.1 Crowding tests

We performed artificial star tests (ASTs) to assess the completeness level and quantify the photometric errors of our data. This is a crucial step for the derivation of the SFH. The distribution of stars in the observed CMD is modified from the actual distribution due to the observational errors, particularly at the fainter magnitudes where most of the information from the older star formation is encoded. The ASTs are used to simulate the observational errors in the synthetic CMDs that are then compared with the observed CMDs in the analysis described below.

The procedure and results of the ASTs are presented in Chapter 2 and we refer to it for further details. The results obtained from these ASTs indicate that the limiting magnitudes of the F1 and F2 CMDs are $F^5_{555W} \sim 28$ and $\sim 28.5$, respectively, nearly independent of color. The CMD of F2 is therefore slightly deeper than that of F1 (cf. Figs. 2.8 and 2.9 of Chapter 2). The 50% completeness level as well as the photometric errors derived from the ASTs for F1 and F2 are indicated in Figure 3.1.

3.3 The IAC Method to resolve the SFH

To extract the detailed SFH of F1 and F2 we use the well-known method of fitting synthetic CMDs to the data (see e.g., Tosi et al. [1991]; Bertelli et al. [1992]; Tolstoy & Saha [1996]; Aparicio et al. [1997]). There are currently different approaches to derive the SFH of galaxies (e.g., StarFISH: Harris & Zaritsky [2001]; MATCH: Dolphin [2002]; IAC-pop/MinnIAC: Aparicio & Hidalgo [2009]; Hidalgo et al. [2011]) as well as different stellar libraries (e.g., BaSTI: Pietrinferni et al. [2004]; Padova/Girardi: Girardi et al. [2000]; Marigo et al. [2008]) available to compute the required synthetic CMDs. We use the IAC-pop/MinnIAC method and adopt the BaSTI and Padova stellar libraries. The IAC-pop code (Aparicio & Hidalgo [2009]) uses a modified $\chi^2$ merit-function (Mighell [1999]) to compare the observed and synthetic star counts in different boxes (see below) of the CMDs. A genetic algorithm (Charbonneau [1995]) is adopted to minimize $\chi^2$. An important characteristic of the code is that it solves the SFH simultaneously for age and metallicity distributions. It thus provides the SFH of a stellar system as a linear combination of simple populations, i.e. small ranges of age and metallicity. We refer the reader to Aparicio & Hidalgo (2009) and Hidalgo et al. (2011) for more details about this method.

It is important to emphasize that, for the current analysis, we have mainly used information from the extended MS, MSTO and SGB regions of the CMDs, as we will see below. We have excluded the RC and most of the RGB regions, which were the main features analyzed in Chapter 2 and from which we obtained estimates on the age and metallicity of M32. This is because the physics governing these phases are more uncertain than those on the MS and SGB, and differences between stellar libraries are more severe (Gallart et al. [2005]). For instance, the morphology and number of stars occupying the HB/RC evolutionary phases depend on unknown issues, like mass loss on the RGB or He-core mass. Small differences in the adopted physics can significantly vary the number of stars and morphology of these CMD
3.3. THE IAC METHOD TO RESOLVE THE SFH

Figure 3.1: \((F_{435W} - F_{555W}, F_{555W})\) CMDs of field F1 (left-hand panel) and F2 (right-hand panel) obtained using deconvolved images. These contain 58143 and 27963 stars respectively, and are calibrated onto the VEGAmag HST system. Note the difference between the CMDs in the region highlighted with cyan boxes. The larger number of stars in F1 indicate the presence of a more significant intermediate-age population in this field compared to F2. This region of the CMD is the one we use to obtain most of the information about the SFH of both fields. See Section 3.4.1 for more details. The blue line indicates the 50% completeness level of our data in each field and the photometric errors from ASTs refer to color \((F_{435W} - F_{555W}) = 1\).
regions. The CMD regions that we probe in this Chapter allow us to obtain detailed information about the young and intermediate-age populations of M32, which we could not solve in Chapter 2, but conversely, we are unable to analyze the older populations as we qualitatively did in Chapter 2.

In what follows we describe the steps carried out to obtain the SFH of F1 and F2.

1. **Synthetic CMD.** We first generate a synthetic CMD using IAC-STAR code (Aparicio & Gallart 2004). The bolometric corrections applied to both libraries are those of Origlia & Leitherer (2000) which transform the theoretical tracks into the ACS/HRC photometric system. We assume a constant star formation rate (SFR) from 0 to 14 Gyr and metallicities \(0.0001 < Z < 0.04\) \((-2.3 < [\text{M/H}] < 0.3)\) uniformly distributed at all ages. Note that there is no assumed age-metallicity relation as input, and the selected age and \([\text{M/H}]\) ranges are broader than those expected for the solution. This allows the code to find the SFH solution with minimum constraints and ensures no lost information. We adopted a Kroupa (2002) initial mass function (IMF) from \(0.1\) to \(100 M_\odot\). The IMF has a slope of 1.3 for stars with masses lower than \(0.5 M_\odot\) and 2.3 for stars with higher masses. We assume a 35% binary fraction with a relative mass ratio distribution of \(>0.5\) (the impact of different binary fractions on the solution is discussed in subsection 3.4.1). The created synthetic CMD, shown in the top panel of Figure 3.2, contains \(5 \times 10^6\) stars and its faintest magnitude is \(\sim 2\) magnitudes fainter than the 50% completeness level of our data. The observational errors (incompleteness and photometric errors) are simulated using the information obtained from the ASTs described in a previous section (see Hidalgo et al. 2011, and references therein for a detailed description of this procedure). The bottom panel of Figure 3.2 shows the synthetic CMD after observational errors are simulated. We call it a “model CMD” following Aparicio et al. (1997)’s notation. The model CMD is the one to be compared with the observed CMD for the derivation of the SFH of our fields.

2. **Parametrization of the CMDs.** This is the main input of the IAC-pop code and it was done using MinnIAC (Hidalgo et al. 2011), a set of routines specially designed for this purpose. We first define the “simple populations”, the age and metallicity bins in which the model CMD is to be divided. These simple populations of course represent the bins in which the SFH is to be determined. The boundaries of the bins that we used are \([0, 0.5, 1, 2, 5, 14]\) in age and \([0.01, 0.04, 0.10, 0.20, 0.40, 0.60, 0.80, 1.00, 2.00, 4.00]\) in \(Z\), corresponding to \([\text{M/H}] \approx [-2.20, -1.60, -1.27, -1.00, -0.67, -0.50, -0.35, -0.25, 0.25, 0.32]\), assuming \(Z_\odot = 0.019\). These constitute \(5 \times 9 = 45\) simple populations. The resolution in age and metallicity was selected after several mock experiments as the optimal choice for our data given the observational uncertainties. Note that the bin width in age increases significantly for older populations. This is due to the limits imposed by the crowding; we cannot extract more detailed information about the oldest stars.
3.3. THE IAC METHOD TO RESOLVE THE SFH

Figure 3.2: Top panel: Hess representation of the synthetic CMD generated using IAC-STAR code for a range of age between 0 and 14 Gyr and metallicities uniformly distributed at all ages between 0.0001 and 0.04. It contains $5 \times 10^6$ stars. Bottom panel: Hess representation of the model CMD, i.e. the synthetic CMD after the observational errors have been simulated. It contains $\sim 2 \times 10^6$ stars. This model CMD is the one to be compared with the observed CMD to derive the SFH.
Figure 3.3: CMD of field F1 in absolute magnitudes, assuming a distance \( \mu_0 = 24.53 \) and \( E(B-V) = 0.08 \), with the location of the bundles superimposed. Each bundle is subdivided into boxes with sizes that vary from one bundle to another (see Table 3.2). This allows each CMD region used for the analysis to have different weights on the extracted SFH. Note that most of the RGB and RC regions are excluded of our SFH analysis. Uncertainties in the physics governing that evolutionary phases are larger than those in the MS and SGB region.
3.3. THE IAC METHOD TO RESOLVE THE SFH

We then define six “bundles”, macro-regions of the CMDs used for the fitting. We show in Figure 3.3 the CMD of F1 with the selected bundles superimposed. The bundles are subdivided into boxes, whose sizes vary from bundle to bundle. The bundles and boxes are equally sampled in the observed and model CMDs. Since the number of stars in each box is the information provided to the IAC-pop code, the different bundle subdivisions provide the weights a given CMD region has on the derived SFH. For instance, CMD regions well-populated and/or where the input physics is better understood (e.g., bundle 1) have smaller boxes than CMD regions where either the number of stars is smaller or the uncertainties in the input physics significantly affect its modeling (e.g., bundle 6). The properties of the boxes for each bundle are specified in Table 3.2. Note, in Figure 3.3, that only stars brighter than the 50% completeness level were considered to extract the SFH. Below this region, most of the information is lost and results obtained from lower-completeness regions are unreliable (see also the bottom panel of Fig. 3.2). Also, as mentioned above, we did not use most of the RGB and RC. Adding bundles in those regions did not modify the solution significantly but increased $\chi^2$ from $\sim 2$ to $\sim 5$. Bundles 5 and 6 were only adopted to constrain the metallicity of the system and the number of RGB stars, respectively (see Figure 3.3).

### Table 3.2: CMD regions used for the fitting

<table>
<thead>
<tr>
<th>Bundle</th>
<th># of boxes</th>
<th>Size of boxes (color; mag)</th>
<th>CMD region sampled</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>500</td>
<td>(0.01, 0.20)</td>
<td>lower MS</td>
</tr>
<tr>
<td>2</td>
<td>150</td>
<td>(0.03, 0.30)</td>
<td>upper MS</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>(0.50, 0.40)</td>
<td>SGB</td>
</tr>
<tr>
<td>4</td>
<td>7</td>
<td>(0.50, 0.50)</td>
<td>left of the MS</td>
</tr>
<tr>
<td>5</td>
<td>5</td>
<td>(0.50, 0.90)</td>
<td>Right of the RGB</td>
</tr>
<tr>
<td>6</td>
<td>9</td>
<td>(0.20, 0.60)</td>
<td>Upper RGB</td>
</tr>
</tbody>
</table>

3. **Solution.** For a given parametrization, i.e., box sizes and simple population boundaries, MinnIAC counts the stars in each of the boxes for both the observed and model CMDs. The number of stars in each box is the input information to run IAC-pop code. IAC-pop compares the observed and model star counts in each box using a modified $\chi^2$ merit-function (Mighell 1999), calculating which combination of simple populations best reproduces the observed CMD. A SFH solution is obtained as a linear combination of the simple populations. Thus, IAC-pop solves the SFH considering the age and metallicity as independent variables.

4. **Uncertainties and stability of the solution.** To minimize biases in the solution due to the sampling, MinnIAC allows slight changes in the input parameters. The simple populations (the age and metallicity bins) are shifted 12 times, and for each of these shifts, the boxes are shifted three times. These 36 sets of parameters are used to generate 36 individual solutions. The final
SFH solution is the average of these. This “dithering” process significantly reduces fluctuations in the solution associated with the sampling (Hidalgo et al. 2011). The standard deviation of the “dithers” provides a measurement of the uncertainties on the solution (see Aparicio & Hidalgo 2009 for further discussion of uncertainties in the solution).

To take into account uncertainties in the distance modulus (±0.14: Chapter 2), reddening (±0.03: Burstein & Heiles 1982), aperture corrections (Chapter 2), and other systematics possibly affecting the zero points of our photometry, we allow the observed CMD (not the model) to shift in both color and magnitude. The observed CMD is shifted four times in magnitude and three times in color.

MinnIAC repeats the entire process of generating the input information and averages the 36 individual solutions generated by IAC-pop, for each of the positions in a magnitude–color grid. The grid has 35 nodes, where the shifts in magnitude are (−0.14, −0.07, 0, 0.07, 0.14), and the shifts in color are (−0.12, −0.09, −0.06, −0.03, 0, 0.03, 0.06). In total we generate 36 × 35 = 1260 individual solutions for each field (F1 and F2) and library (BaSTI and Padova/Girardi) combination.

5. Final best solution. After the observed CMD-shifting and “dithering” process, we have 35 averaged solutions, one for each color-magnitude node. Among the 35 mean solutions, the one with least $\chi^2_{\nu}$ is chosen to be the final solution that best reproduces our observed CMD.

3.4 Results of the SFH Analysis

Table 3.3 indicates the $\chi^2_{\nu,\text{min}}$ values reached for F1 and F2, using both BaSTI and Padova/Girardi libraries, for the 35% binary fraction adopted. As previously mentioned, for each shift in color and magnitude of the observed CMD, we average the 36 individual solutions as well as its corresponding $\chi^2_{\nu}$. The nodes at which the mean minimum $\chi^2_{\nu}$, i.e. $\chi^2_{\nu,\text{min}}$ was reached are also indicated in Table 3.3. We consider the averaged solution corresponding to $\chi^2_{\nu,\text{min}}$ as the one that best reproduces our observations. For F1 this was found at $(\delta(F435W - F555W)_0, \delta M_{F555W}) = (-0.09, 0.07)$ with $\chi^2_{\nu,\text{min}} = 2.08$ and for F2 $(\delta(F435W - F555W)_0, \delta M_{F555W}) = (-0.06, 0.0)$ with $\chi^2_{\nu,\text{min}} = 2.29$. We emphasize here that the shifts in the observed CMD at which we obtained the best solution do not represent corrections to the distance or reddening estimates, since photometric corrections and model systematics are also present.

The $\chi^2_{\nu,\text{min}}$ values suggest that the BaSTI isochrones fit the data better than the Padova/Girardi isochrones for both fields. Nevertheless, the solutions obtained with both libraries are very similar, with the Padova/Girardi isochrones generating a best-fit mean solution slightly more metal-rich than BaSTI. For simplicity, we consider the solutions obtained using the BaSTI isochrones for most of the following analysis.
3.4. RESULTS OF THE SFH ANALYSIS

Table 3.3: $\chi^2_{\nu,\text{min}}$ values for the different assumptions considered

<table>
<thead>
<tr>
<th>Field</th>
<th>Binary %</th>
<th>$(\delta_{\text{color}}, \delta_{\text{mag}})^a$</th>
<th>$\chi^2_{\nu,\text{min}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>BaSTI</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F1</td>
<td>0</td>
<td>(-0.09, 0.14)</td>
<td>2.04</td>
</tr>
<tr>
<td></td>
<td>35</td>
<td>(-0.09, 0.07)</td>
<td>2.08</td>
</tr>
<tr>
<td></td>
<td>70</td>
<td>(-0.09, 0.07)</td>
<td>2.02</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>(-0.09, 0.14)</td>
<td>1.98</td>
</tr>
<tr>
<td>F2</td>
<td>0</td>
<td>(-0.03, 0.00)</td>
<td>2.28</td>
</tr>
<tr>
<td></td>
<td>35</td>
<td>(-0.06, 0.00)</td>
<td>2.28</td>
</tr>
<tr>
<td></td>
<td>70</td>
<td>(-0.03, 0.00)</td>
<td>2.28</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>(-0.03, 0.00)</td>
<td>2.26</td>
</tr>
<tr>
<td><strong>Padova/Girardi</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F1</td>
<td>0</td>
<td>(0.00, 0.00)</td>
<td>4.07</td>
</tr>
<tr>
<td></td>
<td>35</td>
<td>(0.00, 0.07)</td>
<td>3.07</td>
</tr>
<tr>
<td></td>
<td>70</td>
<td>(0.00, 0.07)</td>
<td>3.49</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>(0.00, 0.07)</td>
<td>3.35</td>
</tr>
<tr>
<td>F2</td>
<td>0</td>
<td>(-0.09, -0.07)</td>
<td>2.62</td>
</tr>
<tr>
<td></td>
<td>35</td>
<td>(0.03, 0.00)</td>
<td>2.82</td>
</tr>
<tr>
<td></td>
<td>70</td>
<td>(-0.12, 0.00)</td>
<td>2.58</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>(-0.09, -0.07)</td>
<td>2.53</td>
</tr>
</tbody>
</table>

**Notes.**

$^a$ Color and magnitude shifts of the observed CMD at which the $\chi^2_{\nu,\text{min}}$ value is reached.

3.4.1 The SFH of F1 and F2

We show in Figures 3.4 and 3.5 the best-fit mean SFH $= \Psi(t, Z)$ solution for F1 and F2 in a 3D-histogram representation, respectively, as well as the two projections $\Psi(t)$ (red line) and $\Psi(Z)$ (blue line). $\Psi(t)$ is the SFR as a function of time or age distribution, i.e. the $= \Psi(t, Z)$ integrated over metallicity, and $\Psi(Z)$ is the metallicity distribution function, i.e., the $= \Psi(t, Z)$ integrated over time. Both distributions are normalized by the area in pc$^2$. Recall that field F2 has $\sim 1/3$ the amount of stars as F1.

The most striking feature of Figure 3.4 is the significant burst of star formation in F1 that occurred 2–5 Gyr ago. F2 is predominantly old, with some contribution of young and intermediate-age stars from 0.5 to 5 Gyr ago, but its 2–5 Gyr old population is not as prominent as that of F1. We emphasize here that differences in the intermediate-age population between the fields were expected (see Chapter 2 and Fig. 3.1). However, the significant SFR in the 2–5 Gyr bin in F1 compared with F2 is rather surprising. As F1 has contributions from both M32 and M31 stars and F2 is expected to have a negligible contribution from M32, the derived SFHs suggest that the burst of stars 2–5 Gyr ago in F1 is associated almost entirely with
Figure 3.4: SFH = $\Psi(t, Z)$ of F1 obtained using BaSTI models and assuming a 35% binary fraction. The blue and red lines are the two SFH projections: metallicity distribution $\Psi(Z)$ and age distribution $\Psi(t)$, respectively. Note that $\Psi(Z)$ does not represent metallicity evolution, as it is integrated over age, and thus should not be compared with panel (d) of Figure 3.6 which shows $Z$ as a function of age. The solution is calculated by averaging the 36 solutions at the $\chi^2_{\nu, \text{min}}$ in the $\delta\text{mag} - \delta\text{color}$ grid. $\chi^2_{\nu, \text{min}}$ is 2.08. Note the prominent stellar population with ages 2–5 Gyr present in F1 but nearly absent in F2 (see Figure 3.5). Although differences were expected (note the different number of stars inside the cyan box in Figure 3.1 and the results in Chapter 2), the significant different SFRs in the 2–5 Gyr bin between the two fields is surprising.
3.4. RESULTS OF THE SFH ANALYSIS

Figure 3.5: SFH = Ψ(t, Z) of F2 obtained using BaSTI models and assuming a 35% binary fraction. The blue and red lines are the two SFH projections: metallicity distribution Ψ(Z) and age distribution Ψ(t), respectively. Note that Ψ(Z) does not represents metallicity evolution, as it is integrated over age, and thus should not be compared with panel (d) of Figure 3.7, which shows Z as a function of age. The solution is calculated by averaging the 36 solutions at the $\chi^2_{\nu,\text{min}}$ in the $\delta$mag – $\delta$color grid. $\chi^2_{\nu,\text{min}}$ is 2.28. Recall that the number of stars in F2 is $\sim 1/3$ of that in F1 (see Figure 3.4). F2 is predominantly old, with nearly absent stars younger than 5 Gyr. The significant different SFRs in the 2–5 Gyr bin between the fields F1 and F2 is surprising.
Table 3.4: Integrated quantities derived from the SFHs

<table>
<thead>
<tr>
<th>Field</th>
<th>⟨Age⟩ (Gyr)</th>
<th>⟨[M/H]⟩ (dex)</th>
<th>int(SFH) (10^6 M☉)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BaSTI library</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F1</td>
<td>7.95 ± 1.35</td>
<td>−0.07 ± 0.10</td>
<td>5.19 ± 0.50</td>
</tr>
<tr>
<td>F2</td>
<td>9.12 ± 0.80</td>
<td>−0.15 ± 0.10</td>
<td>2.59 ± 0.24</td>
</tr>
<tr>
<td>M32 (F1-F2)</td>
<td>6.80 ± 1.50</td>
<td>−0.01 ± 0.08</td>
<td>2.60 ± 0.50</td>
</tr>
<tr>
<td>F2a</td>
<td>8.72 ± 1.27</td>
<td>−0.15 ± 0.10</td>
<td>2.40 ± 0.18</td>
</tr>
<tr>
<td>Padova/Girardi library</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F1</td>
<td>7.99 ± 1.33</td>
<td>0.01 ± 0.10</td>
<td>5.88 ± 0.76</td>
</tr>
<tr>
<td>F2</td>
<td>9.03 ± 0.85</td>
<td>−0.07 ± 0.10</td>
<td>2.81 ± 0.29</td>
</tr>
<tr>
<td>M32 (F1-F2)</td>
<td>7.03 ± 1.50</td>
<td>0.06 ± 0.10</td>
<td>3.07 ± 0.75</td>
</tr>
</tbody>
</table>

Notes.

SFH of F2 was derived using BaSTI library with an extra age bin, from 5–8 Gyr.

M32. We discuss this further in the next section.

Figures 3.6 and 3.7 display the main results projected from the extracted SFHs of F1 and F2, respectively. We find that:

- F1 acquired 75% of its stellar mass between 5 and 14 Gyr ago. Stars with ages of 2–5 Gyr contribute 23% of the mass in F1. The remaining 2% of mass in F1 is constituted by stars younger than 2 Gyr.

- F1 is metal-rich with an almost constant age–metallicity relation.

- F1’s mass-weighted mean age is 7.95 ± 1.35 Gyr and its mass-weighted metallicity is [M/H] = −0.07 ± 0.10 dex (Table 3.4).

- F2 is predominantly old, with 95% of its mass already formed 5–14 Gyr ago. There is a small contribution of mass to the system after that, and it stopped forming stars ~ 0.5 Gyr ago.

- F2 is also quite metal-rich, but is marginally more metal-poor than F1, with a slight age–metallicity relation showing a small increase in metallicity at younger ages.

- F2’s mass-weighted mean age is 9.12 ± 0.80 Gyr and its mass-weighted metallicity is [M/H] = −0.15 ± 0.10 dex (Table 3.4).

The integrated quantities derived for the SFHs of F1 and F2 using Padova/Girardi Library are also indicated in Table 3.4.

Figures 3.6 and 3.7 show comparisons between the observed (left) and calculated CMD (middle) as well as the Hess diagram of the residuals in units of the Poisson uncertainties (right), for F1 and F2 respectively. The calculated CMDs have been obtained by randomly extracting stars from the synthetic CMDs in such
3.4. RESULTS OF THE SFH ANALYSIS

Figure 3.6: The SFH of F1. (a) SFR as a function of time; (b) cumulative mass-weighted age distribution; (c) mass as a function of metallicity; (d) age–metallicity relation; and (e) comparison between the observed, calculated CMDs and a Hess representation of the residuals. The Hess diagram of the residuals is shown in units of the Poisson uncertainties. The vertical solid line in panel (b) represents the mean age (∼ 8 Gyr) of the system, and the dashed lines indicate the 1σ deviation of that value.
Figure 3.7: As in Figure 3.6 for F2. The mass in F2 is $\sim$ half of that in F1.
3.4. RESULTS OF THE SFH ANALYSIS

a way that the resulting star distribution follows the best calculated SFHs. For both F1 and F2, the model CMD shows reasonable agreement with the observed CMD throughout most evolutionary phases, which is also reflected in the residual Hess diagrams. The RC regions, however, show significant discrepancies. This is not surprising; due to uncertainties in, e.g., the mass loss during the RGB or the He content of the stars, that particular evolutionary stage is not well-modeled—but we have not used this region in deriving the solutions. There is also some discrepancies for magnitudes fainter than the 50% completeness level, but this region was also not used for the derivation of the SFHs.

Effect of binaries

The results presented in the previous subsection were obtained assuming a 35% binary fraction in the synthetic CMD. To investigate how much this assumption might affect our solution, we have repeated the entire process of deriving the best mean SFH of F1 and F2 assuming not only 35% but also 0%, 70% and 100% binary fractions in the synthetic CMD. The mass ratios between the components of the binaries were set to be uniformly distributed between 0.5 and 1.

Table 3.3 shows the values of the $\chi^2_{\nu,\text{min}}$ as a function of the assumed binary fraction for F1 and F2, and using the stellar libraries BaSTI and Padova/Girardi. We can see that, for F1, the goodness of fit does not significantly improve when varying the binary fraction if we use the stellar library BaSTI. However, Girardi/Padova models finds the best fit to the observed CMD in F1 when the fraction of binaries is 35%. For F2, the $\chi^2_{\nu,\text{min}}$ as a function of binary fraction is nearly constant, regardless the stellar library used. Note that BaSTI isochrones always recover a better fit, i.e. lower $\chi^2_{\nu,\text{min}}$ than Girardi/Padova ones for both F1 and F2 observed CMDs. The position in the $(\delta(\text{color}), \delta(\text{magnitude}))$ grid at which $\chi^2_{\nu,\text{min}}$ is reached for F1 is nearly insensitive to changes in the model binary fraction. This is not the case for F2, which reflects the fact that its CMD is deeper than that of F1.

Figure 3.8 shows the comparison of the derived SFHs. The SFR as a function of time for F1 (left panel) and F2 (right panel) indicates that the calculated solution does not change significantly but becomes older as the number of binaries increases in the model CMD. This is expected: the larger the number of binaries in a system, the more luminous the effective (that is, observed) MS and the brighter and redder the effective MSTO of its CMD.

3.4.2 Uniqueness of the SFH solution

The IAC method does not introduce any systematic error to the SFH solution, provided that the age and metallicity bins used to extract the SFH are appropriate to the observed CMD. This has been verified by several mock experiments performed at Instituto de Astrofísica de Canarias in which the SFH of mock galaxies of known SFH have been recovered rather accurately (see Aparicio & Hidalgo 2009; Hidalgo et al. 2009, 2011). In this work, we have also performed several mock experiments
Figure 3.8: Comparison of the SFRs as a function of age for different assumed binary fractions in the synthetic CMD. The left panel shows the results for F1 and the right panel shows the results for F2. The solution becomes older as we increase the number of binaries in the model. This can be clearly seen in the first two bins of the SFR in F1 (left panel), which represent ages of $\sim 10$ and $\sim 4$ Gyr, respectively. This reflects the fact that as we increase the number of binaries of the model CMD, its effective MS becomes more luminous and its effective MSTO becomes brighter and redder.

to find the appropriate resolution at which, according to our observed CMDs, we recover the SFH of mock galaxies reasonably well.

Thus, each SFH solution obtained is “unique,” by which we mean that combinations of simple populations within the error bars of the SFH will produce CMDs indistinguishable from the best fit CMD. Any other SFH which is combination of simple populations significantly different that those of the final SFH (i.e., not possible within the error bars of our solution) will produce a CMD significantly different than the best-fit CMD and, therefore, than the observed one.

3.4.3 The SFH of M32 as revealed by the IAC method

To calculate the SFH of M32, we make use of the derived SFHs of F1 and F2. These are represented as linear combinations of the same input simple populations, i.e., the same age and metallicity intervals. Only the weights of each simple population (see Aparicio & Hidalgo 2009) differ from one SFH to the other. Given this fact, and assuming that the SFH of M31 in F1 and in F2 is identical, calculating the SFH of M32 is straightforward: we simply subtract the values of the weights of each simple population in the F2 SFH from those in the F1 SFH.

* We would ideally need a deep CMD composed solely of M32 stars to derive the SFH of M32, which we attempted to derive in Chapter 2. Under the assumption that the M31 stellar populations in F1 and F2 are statistically the same, we subtracted the stars of the F2 CMD from the CMD of F1 taking into account the difference in crowding of the fields. This produced the deepest CMD of M32 yet obtained. However, the use of such CMD to extract the SFH of M32 would introduce uncertainties associated with the decontamination process.
Figure 3.9: SFH of M32 obtained after subtracting the calculated SFH of F2 from that of F1. We find two dominant populations contributing to the SFH of M32. One is 2–5 Gyr old and contributes \( \sim 40\% \) of the total mass of M32 at F1. The population older than 5 Gyr contributes \( \sim 55\% \) of the total M32’s mass at F1. Note that some of the stars younger than 2 Gyr are quite metal-poor compared to the nearly solar mean metallicity of M32. This suggests that these are BSS and may be the first direct evidence of such a population in M32.
Figure 3.10: The SFH of M32. (a) SFR as a function of time, clearly indicating the two dominant populations: at $\sim 8$ Gyr and $\sim 4$ Gyr; (b) cumulative mass-weighted age distribution which shows how much each population contributes to the total mass of M32 at F2; (c) mass as a function of metallicity, indicates the mean metallicity of the system, roughly solar; and (d) age–metallicity relation, nearly constant. The vertical lines in panel (b) represent the mean age ($\sim 6.8$ Gyr) of M32 in F1. The dashed lines indicate the $1\sigma$ deviation of this value. Note in panel (c) that the mass value contributing to the metallicity bin at $[M/H] \approx -1.1$ is negative. This is of course not real and indicates that the SFH of M32 as derived from the SFHs of F1 and F2 is an approximation; however, it is the closest that we can obtain for the SFH of M32.
3.4. RESULTS OF THE SFH ANALYSIS

Figure 3.9 shows the inferred SFH of M32 for the first time calculated from its resolved stellar population. We used the F1 and F2 SFHs shown in Figures 3.4 and 3.5, inferred using the BaSTI isochrones and a 35% binary fraction. We can see that a major burst of star formation occurred in M32 2–5 Gyr ago, responsible for \( \sim 40\% \) of M32’s current mass at F1’s location. This can be seen from the cumulative mass function, shown in panel (b) of Figure 3.10. Stars older than 5 Gyr contribute \( \sim 55\% \) of the total mass of M32 in this field. From this CMD-fitting analysis, however, due to the limitations imposed by the crowding of our fields, we cannot specify when the star formation started, whether it was constant over the 5–14 Gyr period, or if it peaked at some age. Integrated quantities derived from the calculated M32 SFH are indicated in Table 3.4. Note that the estimated mean age and metallicity of M32, \( \sim 6.8 \) Gyr and \( \sim -0.01 \) dex, respectively, are younger and more metal-rich than the mean age and metallicity of F1, because M31’s mean age and metallicity in F2 is older and more metal-poor than M32 in F1.

The age–metallicity relation for M32 is basically constant (Fig. 3.10d) although it seems to show a mild increase at \( \sim 5 \) Gyr followed by a small decrease at \( \sim 2 \) Gyr. We note that an almost constant age–metallicity relation appears to suggest that M32 has not experienced any metal enrichment. However, the lack of resolution in age means that we cannot extract detailed information on stars older than 5 Gyr. Most of the chemical evolution of the system has likely occurred during that 5–14 Gyr period. M32’s mass-weighted peak in metallicity is at \([\text{M}/\text{H}] \sim 0.2 \) dex (Fig. 3.10c). Note that the mass reaches negative values for the metallicity bin between \(-1\) and \(-1.2\), which can also be seen in the metallicity projection of Figure 3.9. This is of course not real and indicates that the SFH derived from F1–F2 is not exactly the SFH of M32 but is an approximation of the real SFH.

We show in the top panel of Figure 3.11 the calculated CMD of M32, with its stars color-coded according to age. The CMD was obtained by randomly extracting stars from the model CMD, in such a manner that their star distribution follows the calculated SFH. This figure provides explicit information of the age interval that populates each region of the CMD as well as it shows how the various ages combine. We see, for example, that stars of different ages contribute to the RC. Younger stars populate the brighter bluer portion of the RC while older stars populate the fainter, redder portion of the RC. The BP is only populated by stars younger than 2 Gyr. The bottom panel shows the CMDs produced by each age interval considered in the extraction of the SFH. We can appreciate in detail the differences between each CMD as the ages vary, from only an extended main sequence (bottom left panel, ages \( \sim 0.5 \) Gyr) to a CMD with well-populated RGB, RC and AGB evolutionary phases (bottom right panel, ages of 5–14 Gyr). Note the presence of only few BHB stars in the bottom right panel, as expected for systems as metal-rich as M32; in the composite CMD (top panel), these few BHB stars are mixed with young, blue stars in the extended MS.
Figure 3.11: Top panel: Calculated CMD of M32, obtained by randomly extracting stars from the model CMD in such a way that they follow the derived SFH of M32. The stars are color-coded according to age. Note how the various ages fit together and the age interval that populates each region of the CMD. Bottom panel: Each CMD is composed by stars of a different age interval. From an only extended main sequence (left panel, ages $\sim 0.5$ Gyr) to a CMD with well populated RGB, RC and AGB evolutionary phases (right panel, ages of 5–14 Gyr). Note the differences in the MSTO region and fainter MS in the last two CMDs. The MSTOs for the younger population (2–5 Gyr) are brighter and bluer than the ones for the 5–14 Gyr old population.
3.5. THE STAR FORMATION HISTORY OF M32

**Young population (Ages < 2 Gyr) vs. Blue Stragglers**

In Chapter 2, we discussed the possibility that the fainter stars in the BP of M32 could be old BSS rather than a young stellar population with ages < 2 Gyr. However, the analysis presented in Chapter 2 did not allow us to confirm or rule out either case. BSS are stars hotter, bluer and brighter than the MSTOs in a CMD, thus generating a blue plume. Given their locations on the CMD, they are burning hydrogen in their cores with masses larger than the turn-off mass, which indicates that some sort of mechanism rejuvenated their inner layers. Although such a mechanism is still a matter of debate, there are currently two theoretical possible scenarios to explain the BSS origin: they are the result of either a collision between stars (e.g., Sigurdsson et al. 1994) or mass-transfer in a binary system (e.g., McCrea 1964; Carney et al. 2001).

We investigate the nature of these stars from the SFH presented here. Stars younger than 2 Gyr constitute ~4% of the total mass of M32 at F1. Figure 3.9 shows that some of the young stars, produced by a very low SFR event at Lookback time < 2 Gyr, are rather metal poor ([M/H] ~ −0.7) in comparison with the mean metallicity of M32 ([M/H] ~ 0.0). Given the almost constant age–metallicity relation for M32 and the presence of intermediate-age stars (2–5 Gyr old) of solar or even higher metallicity, it is unlikely that M32 contains at the same time younger stars with significantly sub-solar metallicities. The most plausible explanation is that these stars are BSS belonging to an old metal-poor population. BSS are found in open and globular clusters (Ferraro et al. 2004; Mapelli et al. 2004, 2006; Piotto et al. 2004; de Marchi et al. 2006), dwarf spheroidal galaxies (Hurley-Keller et al. 1999; Carrera et al. 2002; Momany et al. 2007; Mapelli et al. 2009; Monelli et al. 2010), and even in the Milky Way halo field population (Preston & Sneden 2000). Therefore, it seems natural to consider that they can also be found in an elliptical galaxy. These stars represent ~2% of the mass of M32 in F1 and might be the first direct evidence of BSS in this galaxy. An alternative explanation could be that these young and metal-poor stars were generated by an episode of late infall of metal-poor gas. However, if we assume that M32 is interacting with M31, we would not expect M32 to accrete gas, but instead to lose gas to M31 through stripping.

The other ~2% of stars with ages < 2 Gyr that we find in the SFH inferred for M32 may indeed represent a young metal-rich population in M32 at F1.

### 3.5 The Star formation history of M32

By combining the results in the present work with the analysis in Chapter 2, we can finally provide a detailed and complete SFH of M32. We conclude that M32 has had an extended SFH and is composed of two main dominant populations at F1: ~40% of the mass in a 2–5 Gyr old, metal-rich population and ~56% of the mass in stars older than 5 Gyr; with slightly subsolar metallicities. From the RC, RGB bump and AGB bump analyzed in Chapter 2, the bulk of the old population is 8–10 Gyr old. We therefore do not expect a significant contribution from stars older than 10
CHAPTER 3. THE STAR FORMATION HISTORY OF M32

Gyr in M32 at F1. Nevertheless, there are a few ancient metal-poor stars present in M32, as revealed by the detection of RR Lyrae belonging to M32 at F1. The \( \sim 4\% \) of the rest of the mass is roughly equally divided between a young metal-rich population and a young metal-poor population. We associate the latter with blue straggler stars belonging to an old (likely metal-poor) population. We confirm the existence of the younger (< 5 Gyr) stars through the presence of bright AGB stars observed in Paper I, with the appropriate ages.

The age–metallicity relation for M32 is basically constant, although there is a small increase in metallicity at younger ages. The mean mass-weighted metallicity of M32 \([\text{M/H}] \sim -0.01 \text{ dex} \) with its peak is at \([\text{M/H}] \sim 0.02 \text{ dex}\). We emphasize here again that an almost constant age–metallicity relation appears to suggest that M32 has not experienced metal enrichment; but as in F1, this is due to the poor age resolution and does not imply the lack of an age–metallicity relation. Stars with metallicities lower than \([\text{M/H}] \lesssim -1 \text{ dex} \) only contribute \( \sim 5\% \) of the total mass of M32 at \( \sim 2' \) from its center. This is consistent with the photometric metallicity function (MDF) of M32 derived in Paper I, which shows that the majority of the stars has a slightly sub-solar metallicity at \([\text{M/H}] \sim -0.2 \text{ dex}\). The MDF also indicated that metal-poor stars with \([\text{M/H}] < -1.2 \) contribute very little, at most 6% of the total V-light to M32 or 4.5% of the total mass in F1, implying that the enrichment process largely avoided the metal poor stage.

3.5.1 On the formation of M32

Certainly, the most striking result of this work is the substantial contribution of 2–5 Gyr old metal-rich stars to the total mass of M32 at F1. How has an elliptical galaxy like M32 formed such a young population of stars? What is the origin of this population? In this section we attempt to address these questions and discuss, in particular, the most popular proposed formation scenarios for M32.

A formation scenario for M32 has been proposed by Kormendy et al. (2009, hereafter K09), in which M32 is a normal, low-luminosity elliptical galaxy. K09 find that both central and global parameter correlations from recent accurate photometry of galaxies in the Virgo cluster place M32 as a normal, low-luminosity elliptical galaxy in all regards. K09 fit a Sersic profile to the SB of M32 with \( n = 2.8 \), in agreement with Sersic indices of other low-luminosity ellipticals studied by K09. They interpret the light at the center of M32 that was not fit by their Sersic profile as a signature of formation in dissipative mergers (Mihos & Hernquist 1994). Extra central light is a general feature of coreless galaxies and is observed in all the other low-luminosity ellipticals of K09’s sample.

An alternative scenario for the formation of M32 has been proposed by Bekki et al. (2001, hereafter B01), who assumed that M32 is the result of a low-luminosity spiral galaxy, whose bulge, unlike most of its outer disk, survived its interactions with M31\( ^* \). In their N-body/smoothed particle hydrodynamics simulations, B01 con-

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\* The idea that M32, as well as other small high-surface brightness galaxies, is a tidally truncated galaxy has been discussed several decades before B01 models. In, for example, Faber (1973), the original truncated galaxy was a more massive elliptical galaxy, from which only the tightly bound
considered a gas-rich low-mass disk galaxy with a bulge orbiting a massive disk galaxy like M31. Due to the interactions of the spiral with M31, the disk gradually loses most of its outer regions (from 2 kpc to 5 kpc) and only keeps $\approx 40\%$ of its initial mass in stars initially located in the central regions, i.e., within 2 kpc of the center. On the other hand, the bulge is only weakly affected by tidal interactions with M31 due to its compactness, and only $\approx 19\%$ of its mass is lost. At $\sim 0.5$ Gyr after the interactions have started, the outer stellar disk of the spiral galaxy is stripped away and only a compact bulge can be seen. New star formation is triggered by the interaction of the gas-rich spiral with M31. At the end of their simulations, there is a fractional disk, bulge, and new stars mass ratio of $\approx 49\%$, $\approx 42\%$, and $\approx 0.9\%$, respectively, within 2 Kpc of the remnant compact galaxy. Our field F1 is located at 110", i.e. $\sim 0.5$ kpc from the galactic center; at M32’s distance. Within this scenario, the $\approx 40\%$ of 2–5 Gyr old stars that we find could be in principle disk stars of the original spiral galaxy; the $\approx 55\%$ of stars older than 5 Gyr would be a mix of stars mostly of the original bulge and partly of the original inner disk. In addition, our finding of $\approx 2\%$ metal-rich stars younger than 1 Gyr would be the result of the centralized star formation in M32, triggered by the tidal field of M31. However, according to B01 scenario, only the stars initially in the inner regions of the disk survive. Thus we should be observing disk stars with ages 8–10 Gyr, assuming either an inside-out or outside-in formation scenario for the disk (see e.g., [Sommer-Larsen et al. 2003], and discussion in Section [3.6]) and considering that we are looking at a $\approx 0.5 R_d$, where $R_d = 0.9$ kpc is the scale length radius of B01’s disk. In short, B01 model would imply that M32 contains only the old bulge and very inner disk populations of an spiral galaxy, with only $\sim 1\%$ of its mass composed by new $\sim 0.5$ Gyr old stars. This is difficult to reconcile with our results, given the substantial 2–5 Gyr old intermediate-age population detected in this work.

Based on the results obtained in a small fraction of the galaxy at 110" from the galactic center, we interpret M32 as a normal low-luminosity elliptical galaxy, as proposed by K09. Its substantial population of metal-rich 2–5 Gyr old stars contributing to $\approx 40\%$ of M32’s mass at F1 is likely the result of a dissipative merger event that shape the galaxy and are intrinsic to the formation process of M32. The galaxies that hypothetically merged to form M32 as we see it today must have had gas to form those stars. If, on the contrary, a dry merger was the responsible of the formation of M32, then the 2–5 Gyr old stars should have been already formed in the galaxies that merged together and, moreover, the merging galaxies would not have gas left available to form stars. Thus, the merger should have occurred $\sim 1$ Gyr ago, but the properties of M32 indicate that this galaxy is relatively relaxed.

Our results, on the other hand, represent the first evidence of the existence of such a young population (2–5 Gyr old) in an elliptical galaxy at a radial distance from its center as far away as $\approx 2.7$ effective radii.
3.6 The disk and spheroid population of M31 in F2

In Chapter 2, we compared our findings in F2, in particular its metallicity distribution function (MDF), with several previous works on the disk and bulge of M31 (e.g. Williams 2002; Worthey et al. 2005; Olsen et al. 2006; Brown et al. 2006). We found in general a reasonably good agreement with most studies. In this section we discuss our new, quantitative results on the stellar populations at F2 and their implications on the formation of the M31’s disk. M31 seems to have formed most of its stars between 5–14 Gyr ago at F2. As mentioned above, we cannot precisely indicate when the star formation started in either F1 nor F2 but we can see that M31 is older than M32 in F1.

Brown et al. (2006, hereafter B06) analyzed three CMDs of different regions of M31: the spheroid, stream and outer disk. These CMDs reached well below the oldest MSTOs, and B06 derived SFHs at each field in great detail. Differences between these SFHs were mainly found in the age and metallicity distributions of stars older than 5 Gyr. Within this age range (5–14 Gyr) we do not have the resolution required to inspect different bursts of star formation in F2 in detail, given the SFH extracted in Section 3.4.1. We can, nevertheless study the SFH of F2 in more detail than what is presented in Section 3.4.1. As we show in Figure 3.1, the CMD of F2 is ∼ 0.5 mag deeper than the one of F1, which allows us to obtain information of fainter, i.e. older, MSTOs at F2. We therefore extracted again the SFH of F2 following the steps indicated in Section 3, but with an extra bin in the age, from 5 to 8 Gyr, for the simple populations considered. The boundaries of the bins in age are in this case [0, 0.5, 1, 2, 5, 8, 14]. The inferred best-fit mean SFH of F2 with this new resolution in age was found at $(\delta(F'435W - F'555W)_0, \delta M_{F'555W}) = (-0.06, -0.07)$ with $\chi^2_{\nu,\text{min}} = 2.23$, which is in fact slightly lower than the one obtained in the previous section. Figure 3.12 shows a 3D-histogram representation of the new SFH solution for F2. We can now distinguish two main populations that contribute substantially to our background field F2, instead of only one old population: ≈ 40% of the total mass in F2 is composed of a 5–8 Gyr old sub-solar metallicity, but still rather metal-rich, population and ≈ 55% of the mass is composed of a 8–14 Gyr old, metal-poor population. An age–metallicity relation shows a slightly steeper slope from an old metal-poorer population to younger metal-richer ones than before, as shown in Figure 3.13. We are still not able to answer when the star formation started in F2. Nevertheless, our results for the mean age and metallicity for F2, 8.72 ± 1.21 Gyr and −0.15 ± 0.10 dex respectively, are in good agreement with B06 results for their outer disk field, which are 8.5 Gyr and −0.4 dex, respectively. In addition, young stars, with ages between 0.3 and 1 Gyr, that populate the BP in the CMD of F2 do not contribute significantly to the total mass, which is also in agreement with B06’s results. Interestingly, kinematic data in our field imply that

* The previous selection of age and metallicity bins to derive the SFHs was strictly based on the resolution imposed by the CMD of F1. In order to subtract the SFH of F2 from that of F1, we required the simple populations considered be exactly the same.

† The cited values correspond to the results obtained by B06 when a 40% binary fraction was assumed.
both the disk and spheroid of M31 contribute to the populations in F2 (K. Howley, 2010, priv. commm). This was also the case for the outer disk field of B06. B06, however, attempted to disentangle both populations assuming that their spheroid field was representative of the spheroid population present in their outer disk field. By subtracting the spheroid population, they obtained a younger mean age for the outer disk of M31—but still older than 5 Gyr.

Given the resolution allowed by the depth of our data, the inner disk and spheroid populations of M31 (at 5 kpc from its center) seem to be indistinguishable from the outer disk and spheroid ones (at 25 kpc from M31 galactic center, B06). Even though we are unable to subtract the spheroid population that contributes to our field F2, most likely the mean age of M31’s disk at F2 is younger than 8.72 Gyr and older than 5 Gyr, given the negligible contribution of stars younger than 5 Gyr. This result supports the inside-out disk formation models by e.g., Abadi et al. (2003a,b); Sommer-Larsen et al. (2003). Abadi et al. find a mean age of 8-10 at 2 kpc, which radially decreases to 6-8 at 20 kpc. Sommer-Larsen et al. simulated two spiral galaxies, with two different scenarios of disk formation: inside-out and outside-in. Our expected mean age for the disk of M31 at F2 agree with both scenarios within their uncertainties, assuming a stellar disk scale length of ≈ 5 kpc (e.g., Walterbos & Kennicutt 1988; Worthey et al. 2005). They find that, at 1 disk scale length, the mean ages of both simulated disks are ∼ 6–8 Gyr. However, the significant fraction of stars younger than 5 Gyr predicted by their outside-in model at F2 is not supported by our data. Thus, we favor their inside-out model. Furthermore, the inside-out formation model of Sommer-Larsen et al. (2003) predicts that the disk has almost no age gradient which, although surprising, is also in agreement with the comparison of our and B06 results at different disk locations. They explain that this prediction is a consequence of the non linear dependence of the SFR on the cold gas density, which makes the SFR rather low in the outer disk at late times, thus the average outer disk stellar age is quite high. An alternative scenario for the absence of an age gradient, found when comparing our results with those of B06, is the radial migration of stars seen in recent simulations of isolated disk formation and evolution (Roškar et al. 2008; Minchev et al. 2011). In these simulations, inside-out disk growth yields to a negative age gradient within the break radius (2–3 disk scale length), after which there is a positive age gradient due to the secular redistribution of stars, given their interactions with transient spiral density waves. Of course, what we presented here are the results of one field in the inner regions of M31 and we need more observations and statistics to either confirm or rule out what we suggest. The multi-cycle Panchromatic Hubble Andromeda Treasury (PHAT) project, e.g., which will cover 1/3 of M31 with HST WFC3 and ACS observations, will resolve the SFH of the disk of M31.

3.7 Summary and Conclusions

We used deep HST ACS/HRC observations to derive the SFH of M32 for the first time from a detailed modelling of its CMDs. The two fields observed, one closer to
Figure 3.12: A more detailed SFH of F2 in a 3d-histogram representation than that shown in Figure 3.5. This SFH of F2 was constructed this time with an extra bin in age covering 5–8 Gyr. We now find two dominant populations of M31 at F2: An old metal-poor population, older than 8 Gyr, and an intermediate-age more metal-rich population, 5–8 Gyr old. Stars younger than 5 Gyr old only contribute $\sim 5\%$ of the mass of M31 at F2.
M32 (F1) and a background M31 field (F2), were introduced and used in Chapter 2 to construct deep CMDs of F1 and F2, and the deepest optical CMD of M32 yet obtained. The IAC-POP/MinnIAC method was used here to compare the distribution of stars in the observed CMDs of F1 and F2 with that of a model CMD. We obtained the SFH of M32 by linearly subtracting the SFHs of F2 from that of F1. The use of different stellar evolutionary libraries (BaSTI and Padova/Girardi) and assumptions of binary fractions (0, 0.35, 0.7, and 1) did not significantly modify the solutions obtained, indicating that our results are robust.

The results of the present analysis combined with those of Chapter 2 provide an unprecedented census of the stellar content of M32. The main finding of this work is that M32 is composed of two main dominant populations at F1: \( \sim 40\% \) of the mass in a 2–5 Gyr old, metal-rich population and \( \sim 56\% \) of the total mass in stars older than 5 Gyr, with slightly subsolar metallicities. Its mean mass-weighted age and metallicity are \( \langle \text{Age} \rangle = 6.8 \pm 1.5 \text{ Gyr} \) and \( \langle [\text{M/H}] \rangle = -0.1 \pm 0.08 \text{ dex} \), respectively. Even though we are unable to specify when the star formation started in M32 at
F1, we make use of the analysis of Chapter 2 to constrain the older population. We know from the RC, RGB and AGB bumps that the bulk of the population is 8–10 Gyr old. Thus, we do not expect a significant contribution from stars older than 10 Gyr in M32. There are, however, a few ancient metal-poor stars present in M32, as revealed by the detection of RR Lyrae belonging to M32 at F1. The ∼ 4% of the rest of the mass is distributed in genuine young metal-rich stars (∼ 2%) and young metal-poor stars (∼ 2%) which we associate with blue straggler stars belonging to an old metal-poor population.

The detailed SFH of a small fraction of M32 at F1 sheds light on the origins of M32. Our results, and in particular the substantial population of 2–5 Gyr old stars at F1, do not agree with models of M32’s formation that suggest an spiral galaxy as progenitor. Instead, we favor the idea that M32 is a low-luminosity elliptical galaxy that has had a dissipative merger event that shape the galaxy.

On the other hand, the inferred SFH for F2 shows that the stellar populations of the inner regions of the disk and spheroidal components of M31 are older and more metal-poor than M32. Its mean mass-weighted age and metallicity are \( \langle \text{Age} \rangle = 8.72 \pm 1.21 \) Gyr and \( \langle [\text{M/H}] \rangle = -0.15 \pm 0.10 \) dex, respectively. F2 has two main components: 55% of the mass composed by a 8–14 Gyr old metal-poor population and 40% of the mass in more-metal rich stars of 5–8 Gyr old. There is a small contribution from stars younger to 5 Gyr to the total mass. The inner disk and spheroidal stellar populations seem to be indistinguishable from those of the outer disk and spheroid. Assuming that M31’s disk at F2 (∼ 1 disk scale length) has a mean age between ∼ 5 and 8 Gyr, our results are in agreement with inside-out disk formation models. But of course, we need more observations and statistics to confirm or rule out this suggestion.

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