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Footprints of the early Universe in the SFHs of dwarf galaxies

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Abstract. We present the star formation histories (SFHs) as a function of galactocentric radius of four isolated dwarf galaxies, Cetus, Tucana, LGS-3, and Phoenix. Our results suggest that beyond some distance from the center, there are no significative differences in fundamental properties of these galaxies. In the innermost regions, dwarf galaxies appear to have formed stars during time intervals which duration varies from galaxy to galaxy. This extended star formation produces the dichotomy between dwarf spheroidal (dSph) and dwarf Transition (dTr) galaxy types. This behavior is compatible with a scenario in which global reionization stops the star formation in the outer galaxy regions and self-shielding allows extended star formation in the inner regions.

Key words. galaxies:dwarf – galaxies:evolution – galaxies:photometry – galaxies:stellar content – galaxies:structure

1. Introduction

One of the mechanisms proposed to account for the missing satellite problem is related to the radiative feedback produced by the cosmic UV-background. This mechanisms suggests that by the end of the epoch of reionization ($z \sim 6$) the Universe was fully reionized by UV photons from the first generation of stars. This UV-background suppressed the star formation in low mass dark matter halos (Susa & Umemura 2004; Sawala et al. 2010) which should host dwarf galaxies close or below observable level. Internal SN-feedback may have played a role by heating and diluting the gas prior to the epoch of reionization, increasing the limit mass of dark matter halos in which the reionization stopped the star formation.

Although several of the dwarf galaxies observed in the Local Group show evidences of a complex SFH lasting a Hubble time, radiative feedback mechanisms may have also affected to the star formation in these galaxies. The reason is that the interplay between the UV radiation and SN-feedback may result in the formation of a self-shielded envelop in the innermost regions of the galaxies (Sawala et al. 2010). Self-shielding has been proposed as a mechanism to maintain the star formation at least in the inner regions of dwarf galaxies, protecting the gas in the denser inner regions from being heated by the UV-background. If this were the case, radiative feedback must have affected differently to the star formation according to the galactocentric radius and thus, to the spatial distribution of the stellar populations. In this sense, the cosmic UV radiation at the EoR may have not stopped the star formation in the internal regions of the dwarf galaxies but only in the external ones. This could be a key factor to explain why some dwarf galaxies have been forming stars continuously in the center but not in the outskirts.

We have selected a subsample of the dwarf galaxies of the LCID project (Local Cosmology form Isolated Dwarfs) to obtain the SFH as a function of radius. The subsample contains two dSph galaxies, Cetus and Tucana, and two transition (dTr) galaxies, LGS-3 and Phoenix.

2. The SFH at a function of radius

We have obtained the SFR as a function of age at different galactocentric radius for the four galaxies. Four regions were selected in each galaxy to compare the results. The three innermost ones are such that their equivalent radii approximately correspond to α_ψ, $1.5\alpha_\psi$, and $2\alpha_\psi$ where α_ψ is the scale length of the stellar mass distribution of each galaxy. The fourth region corresponds to the area outer of $2\alpha_\psi$. This fourth area has not been used in Phoenix due to the low number of stars observed in it (less than 3% of the total). Hereafter we will denote these regions, from the central to the outer ones, as R_1, R_2, R_3, and R_4.

We have used IAC-star/IAC-pop/MinnIAC to obtain the SFHs as described in Aparicio & Hidalgo (2009) and Hidalgo et al. (2011). In short, IAC-star (Aparicio & Gallart 2004) is used to create a synthetic CMD, which star distribution is compared with that in the observed CMD, after suitable simulation of observational effects. This comparison is carried out using the IAC-pop/MinnIAC algorithms which finally give the SFH: mass of gas converted into stars in the galaxy as a function of age and metallicity. This technique does not assume any age-metallicity relation (AMR) for the stars and explore possible variations in the values of the photometric zero points, distance modulus, and reddening from the adopted ones, thus minimizing the impact of the uncertainties in these parameters on the final SFH.

Figure 1 shows the star formation rate as a function of time, $\psi(t)$, of Cetus, Tucana, LGS-3, and Phoenix obtained for the four regions defined above. In the case of Phoenix, due to the low statistic numbers, the $\psi(t)$ has been obtained only for the three inner regions. The $\psi(t)$ has been normalized to its time integral for each region. There is star formation activity in all galaxies for ages $\gtrsim$ 10 Gyr, regardless of distance to the center. Interestingly, in the outermost area (R_4) the three normalized $\psi(t)$ are almost indistinguishable within error bars. However, $\psi(t)$ gradually decreases outwards for ages $\lesssim$ 9 Gyr. Few stars younger than this age exist in the R_4 regions, though some stars can still be observed at $\sim$ 3.5 Gyr for Cetus and Tucana and at $\sim$ 1.5 Gyr for LGS-3. These stars have been identified as a population of Blue-straggler stars (BSS) in Cetus and Tucana by Monelli et al. (2012b). In the case of LGS-3, the expected BSSs may be mixed with some young and intermediate age stellar population, which produces the bump at 1.5 Gyr in $\psi(t)$.

3. The age radial gradient of the galaxies

The age of the stars as a function of radius can be obtained by calculating the age corresponding to certain percentiles of $\psi(t)$. We define the age of the p-th percentile (e_p) of $\psi(t)$ as the age at which $\Psi(t) = p/100 \times \Psi(T)$, where $\Psi(t)$ is the cumulative mass function. We have used the age of the 10th (e_{10}) and 95th (e_{95}) percentiles, which we consider representative of the age of the first and last star formation event, respectively.

Figure 2 shows e_{10} and e_{95} as a function of galactocentric radius. The e_{10} is, within uncertainties, flat for all the galaxies. The weighted mean age of e_{10} is 12.8 ± 0.2 Gyr for dTrs and 13.1 ± 0.2 Gyr for dSphs. The dispersion associated to e_{10} (σ = 0.2 Gyr) is indicative of the variation of the age of the first star formation event with radius. This means that within a time period of $\sim$ 0.4 Gyr (i.e. 2σ), the star formation was concurrent at all radii for all the

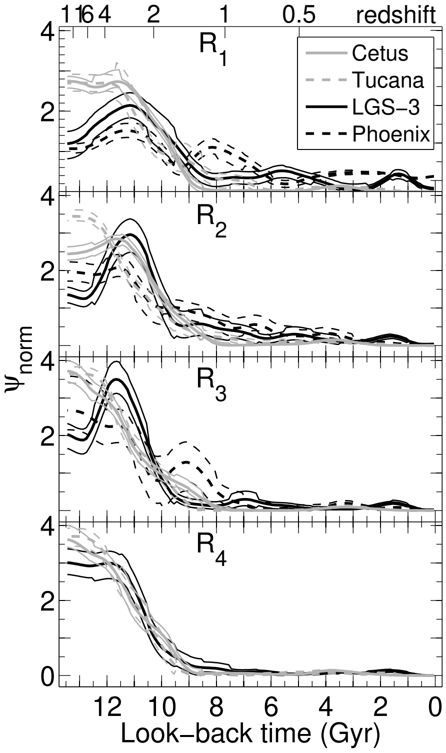

Fig. 1. Normalized SFRs as a function of galactocentric radius. Dashed lines represent 1σ confidence intervals of each solution.

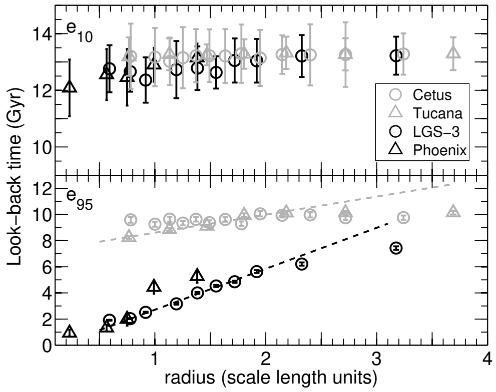

Fig. 2. The age of the 10th (top panel) and 95th (bottom panel) percentiles of the cumulative mass function of Cetus, Tucana, LGS-3, and Phoenix as a function of radius. Two straight lines have been fitted to the inner points of e_{95} ($0.75\alpha_\psi \leq r \leq 2\alpha_\psi$) for Tucana (gray dashed-line) and LGS-3 (black solid-line).

galaxies producing a coeval star formation onset.

Focusing now on the last star formation event, Cetus shows e_{95} centered at 9.6 ± 0.3 Gyr with no dependency with radius. In the case of Tucana e_{95} shows a small gradient of ~ 1.5 Gyr per scale length unit for stars with $r \lesssim 2\alpha_\psi$. This result shows that in Cetus the star formation lasted about 3.5 Gyr ($e_{10} - e_{95}$) and it stopped at the same time (within the ~ 0.3 Gyr of dispersion of e_{95}) in the whole galaxy. The same result can be extended also to Tucana for radii larger than about two scale lengths. However e_{95} decreases toward younger ages for $r \lesssim 2\alpha_\psi$, pointing to a star formation which lasted longer ($\sim$ 1.5 Gyr) in the inner regions of Tucana. This is in fair agreement with the results obtained by Bernard et al. (2008), Bernard et al. (2009), and Monelli et al. (2012a) using RR-Lyrae stars which suggest that the early evolution of these two galaxies was different.

For LGS-3 and Phoenix, e_{95} shows a clear stellar population age gradient of about $\sim$ 4 Gyr per scale length unit in the range $r \gtrsim 0.75\alpha_\psi$. It is also interesting to note that Tucana and LGS-3 show a change in the profile of e_{95}. This change is produced at about two scale lengths for both galaxies and corresponds to ages $\sim$ 10 Gyr for Tucana and $\sim$ 6 Gyr for LGS-3.

4. The effect of the cosmic UV-background in the SFHS of the galaxies

We have preformed several test with mock stellar populations to elucidate whether the SFHs of our galaxies hold some signature of the EoR at some galactocentric radius. We have followed the procedure described in Monelli et al. (2010a,b) and Hidalgo et al. (2011). In short, it consists in built a synthetic CMD corresponding to a star burst. Observational effects are simulated in the synthetic CMD and the corresponding SFH is recovered in the same way as the observed CMDs. Assuming a flat

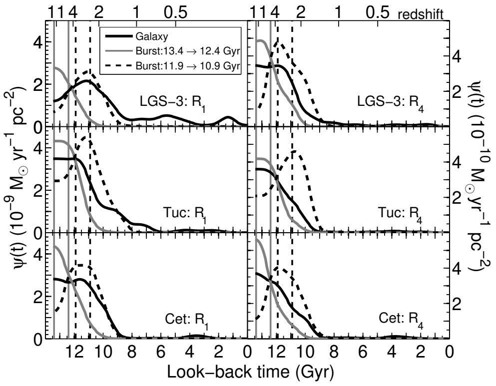

Fig. 3. Input (vertical lines) and recovered SFHs for two mock bursts placed before (gray solid-line) and after (black dashed-line) the EoR. Two regions were selected: an inner one with $r \leq \alpha_\psi$ (left panels) and an outer one with $r > 2\alpha_\psi$ (right panels). The SFHs of the galaxies are over-plotted (black solid-line).

Einstein-de Sitter Universe and using the 5-years WMAP data (Komatsu et al. 2009), the age of the EoR ($z = 6$) is 12.7 Gyr (Loeb & Barkana 2001; Becker et al. 2001). We will assume this as the age in which the Universe is fully reionized.

We show the results of two of our tests in Fig. 3: one for a star burst produced before the EoR, between 13.4 and 12.4 Gyr ago, and another for a burst produced after the EoR, between 11.9 and 10.9 Gyr ago. We have performed this analysis at two distances from the center of the galaxies: for stars with $r \leq \alpha_\psi$ and $r \geq 2\alpha_\psi$. The results show that for $r \leq \alpha_\psi$, the model with all stars formed before the EoR is inconsistent with the SFHs of all the galaxies for both radii. Indeed, the best model for the inner region of LGS-3 is that with all stars formed after the EoR. Only for the case of the outer region of Tucana there is some agreement between the results and the model in which all stars are formed before the EoR, but even in this case the agreement do not seem good enough.

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