Mem. S.A.It. Suppl. Vol. 25, 21

Memorie della
Supplementi

The outskirts of spiral galaxies: touching stellar halos at z∼0 and z∼1

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Abstract. Taking advantage of ultra-deep imaging of SDSS *Stripe82* and the Hubble Ultra Deep Field by HST, we explore the properties of stellar halos at two relevant epochs of cosmic history. At z∼0 we find that the radial surface brightness profiles of disks have a smooth continuation into the stellar halo that starts to affect the surface brightness profiles at $\mu_{r'}\sim$28 mag arcsec^{-2}, and at a radial distance of $\gtrsim$4-10 inner scale-lengths. The light contribution of the stellar halo to the total galaxy light varies from ∼1% to ∼5%, but in case of ongoing mergers, the halo light fraction can be as high as ∼10%. The integrated $(g' - r')$ color of the stellar halo of our galaxies range from ∼0.4 to ∼1.2. By confronting these colors with model predictions, these halos can be attributed to moderately aged and metal-poor populations, however the extreme red colors (∼1) cannot be explained by populations of conventional IMFs. Very red halo colors can be attributed to stellar populations dominated by very low mass stars of low to intermediate metallicity produced by bottom-heavy IMFs. At z∼1 stellar halos appear to be ∼2 magnitudes brighter than their local counterparts, meanwhile they exhibit bluer colors ((g'-r')$\lesssim$0.3 mag), as well. The stellar populations corresponding to these colors are compatible with having ages $\lesssim$1 Gyr. This latter observation strongly suggests the possibility that these halos were formed between z∼1 and z∼2. This result matches very well the theoretical predictions that locate most of the formation of the stellar halos at those early epochs. A pure passive evolutionary scenario, where the stellar populations of our high-z haloes simply fade to match the stellar halo properties found in the local universe, is consistent with our data.

Key words. Galaxies: Evolution, Galaxies: Formation, Galaxies: Spiral, Galaxies: Structure Galaxies: Photometry, Galaxies: Stellar Halos

1. Introduction

The detection of stellar halos is a major observational challange. The surface brightness levels that are required to explore the distribution of stars inside the disks are relatively bright ($\mu_{r'}\lesssim$27 mag arcsec^{-2}), making it possible to carry out photometric studies of disks to large distances (even to intermediate redshifts) on statistically representative samples. The stellar halos of spiral galaxies, however, are so faint that to observe them it is necessary to go ∼10 magnitudes below the night sky level (to reach ∼30 mag arcsec^{-2}). This renders stellar halo observations extremely difficult. Hitherto only a few *integrated* photometric studies can be found in the literature that have attempted

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to reach the surface brightness of stellar halos (e.g. Zibetti et al. 2004; Jablonka et al. 2010, and references therein). Most studies of stellar halos have been achieved by using resolved star technique (e.g. Mouhcine et al. 2005; Ibata et al. 2009; Radburn-Smith et al. 2011) or by extremely deep integrated photometry observations able to detect low surface brightness features (Sackett et al. 1994; Shang et al. 1998; Martínez-Delgado et al. 2008, 2009; Jablonka et al. 2010). Zibetti et al. (2004, see also Bergvall et al. 2010), stacking 1047 galaxies, were able to observe the properties of stellar halos up to z~0.05 (~200 Mpc in distance). Finally, Zibetti et al. (2004), using the Hubble Ultra Deep Field (HUDF; Beckwith et al. 2006), detected the stellar halo of a disk galaxy at z=0.32. Before this study, this last observation was the farthest detection of these faint components of galaxies.

One of the expectations of the current cosmological paradigm is that the properties of stellar halos (e.g. metallicity) correlate with the properties of their host galaxy (e.g. Brook et al. 2004; Bullock & Johnston 2005) at z~0. Although, these correlations might be hidden due to stochastic variations in the merger/accretion history. For this reason, only observing a great number of galaxies down to very low surface brightness levels would help us to discern the dominant mechanism that shape stellar halos and spiral galaxies. Another prediction of these cosmological simulations is that most of the stellar halo mass would be assembled before z∼1, and we would expect a passive evolution of the stellar populations of these halos towards the present (e.g. Cooper et al. 2010; Font et al. 2011). Hence, a cosmic epoch worth exploring is z∼1. In this paper, we attempt to combine observations done at these two particular epochs (z~0 and z∼1) of cosmic evolution (Trujillo & Bakos 2012).

2. Data and analysis

2.1. Stellar halos in the local volume

2.1.1. SDSS *Stripe82* data

Our imaging data come from the Sloan Digital Sky Survey (SDSS) *Stripe82* (Abazajian et al. 2009). This stripe covers about ~270 square degrees of the sky and has been observed in all SDSS bands multiple, often more than 80, times. This implies that after stacking the data are $\gtrsim$2 magnitudes deeper than the regular SDSS imaging (that has a depth of ~27 mag arcsec^{-2}; PT06). This makes *Stripe82* presently the largest deep sky survey in the optical regime.

For our purposes, as to explore very low surface brightness features of disk galaxies ($\mu_{r'}$~30 mag arcsec^{-2}) we assembled high-quality stacks from the *Stripe82* observations. (Details in Bakos & Trujillo 2012).

2.1.2. Sample selection

The local galaxies were selected according to the criteria by PT06 from the Hyperleda[1] online catalog, constraining the galaxy type to late-type spirals and close-to face on inclination to mitigate problems due to dust extinction. In total, we studied the following 7 spiral galaxies found in *Stripe82*: NGC 0450, NGC 0941, NGC 1068, NGC 1087, NGC 7716, UGC 02081, and UGC 02311.

2.2. Stellar halos at z∼1

2.2.1. Data

To study such faint features like stellar halos at z∼1, we needed the currently best imaging available: the ACS, NICMOS and WFC3 imaging of the HUDF. The ACS imaging (`http://archive.stsci.edu/pub/hlsp/udf/acs-wfc/`) provides the optical part of the spectrum. The WFC3 (`http://archive.stsci.edu/prepds/hudf09/`) and NICMOS (`http://archive.stsci.edu/pub/hlsp/udf/nicmos-treasury/`) imaging are both done in the near-infrared. Although, the WFC3 data are deeper and of higher resolution than that of NICMOS, but WFC3 do not cover the entire HUDF. For these reasons, we used both data sets. (Details in Trujillo & Bakos 2012).

[1] `http://leda.univ-lyon1.fr/`

2.2.2. Sample selection

We used the Rainbow Cosmological Database[2] published by Pérez-González et al. (2008, see also Barro et al. 2011a,b), to create a sample of MW-like galaxies at z$\sim$1. We selected objects with spectroscopic redshifts within 0.8<z<1.2 and $M_\star > 5\times10^9 M_\odot$ (Kroupa 2001 IMF). We carried out a visual inspection of the images using the ACS z-band to select galaxies to match our criteria of being *bona fide* spirals with low inclination. Only 2 galaxies met these criteria: UDF3372 & UDF5417.

2.3. Surface brightness profiles and stellar population

Our aim was to study the light and stellar population distribution in our galaxies with a special attention to the stellar halo. In order to do that, first we masked all sources that do not belong to the galaxy. Then, we extracted the radial surface brightness profiles in elliptical apertures in all observing bands. In case of the local galaxies, we used the r'-band surface brightness profiles to decompose the galaxy into different components, such as bulge, a double-exponential disk and stellar halo. These components were fitted simultaneously by characterizing the stellar halo with a n=0.5 Sérsic-function. We used the same method to decompose the high-z galaxies into its components.

The stellar population content was explored by means of color profiles. The (g'-r') color proved to be a good proxy to trace how stellar populations change in the disk and stellar halo. To be able to make a direct comparison of the stellar population content in the high-z galaxies with the local sample, we had to build rest frame (g'-r') color profiles. These are built from rest frame surface brightness profiles that are obtained from the SEDs by linear interpolation, and are corrected for the cosmological dimming ($\sim$3 mag arcsec^{-2}). (More details in Trujillo & Bakos 2012).

[2] https://rainbowx.fis.ucm.es/

3. Results and conclusions

We find that the stellar halo component appears below $\mu_{r'}\sim$28 mag arcsec^{-2} in local galaxies. A very similar behavior of the surface brightness profiles is seen in the z$\sim$1 galaxies. Once corrected for the cosmological dimming, it becomes evident that stellar halos (along with their host galaxies) were brighter than their local counterparts. This is subsequently due to a higher star formation rate occurring at higher redshifts. Stellar halos also appear bluer than the ones found around local spirals. (See Figure 1) Both in local and high-z stellar halos the fraction of light contained in stellar halos is $\sim$4%. From this we can deduce the following: whatever complex mechanisms evolve galaxies, presumably separately from stellar halos, these processes should produce a simultaneous fading in both structures, in order to preserve the fraction of light constant with time.

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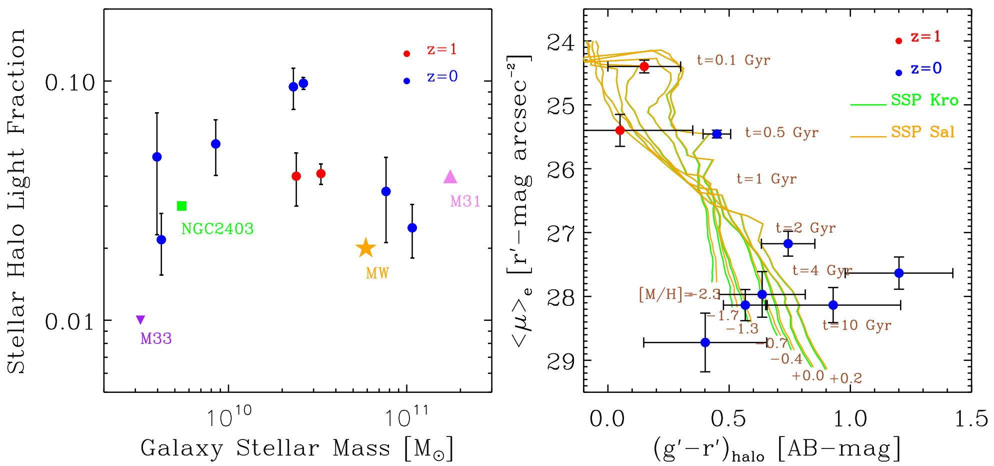

Fig. 1. Left panel: Fraction of the stellar halo light in the r-band (L_{halo}/L_{total}) vs. the total galaxy mass. The stellar halo light is estimated by fitting a n=0.5 Sérsic-model to the region of the stellar halo of the galaxies, meanwhile to obtain the total galaxy light we integrated the observed profile. The red points are the galaxies at z∼1 and the blue points represent the local sample. The stellar halo light fraction observed in the Milky Way (Carollo et al. 2010), M31 (Courteau et al. 2011), M33 (McConnachie et al. 2010) and NGC 2403 (Barker et al. 2012) are also overplotted. The light contribution of the stellar halo to the total galaxy light varies from 1% to 5%, but in case of ongoing mergers (the two most extreme cases in the local reference sample) the stellar halo light fraction can be as high as 10%. *Right panel*: Mean effective surface brightness of the stellar halo vs. the (g'-r') color of the stellar halo. Overplotted are the color and surface brightness tracks predictions using the Vazdekis et al. (2010) models for Single Stellar Populations (SSPs) with two different IMFs (Salpeter 1955; Kroupa 2001).

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