Formation and Evolution of Galaxy Outskirts
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The observed peripheral growth of disc galaxies from $z \sim 1$

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Abstract. Using images from the Hubble Space Telescope and Sloan Digital Sky Survey, we have computed both parametric and non-parametric measures, and examined the evolution in size, concentration, stellar mass, effective stellar mass density and asymmetry for a sample of 600 disc galaxies from $z \sim 1$ till $z \sim 0$. We find that disc galaxies have gained more than 50 per cent of their present stellar mass over the last 8 Gyr. Also, the increase in disc size is found to be peripheral. While the average total (Petrosian) radius almost doubles from $z \sim 1$ to $z \sim 0$, the average effective (half-light) radius undergoes a marginal increase in comparison. This indicates that galaxies grow more substantially in their outskirts, and is consistent with the inside-out growth picture. The substantial increase in mass and size indicates that accretion of external material has been a dominant mode of galaxy growth, where the circumgalactic environment plays a significant role.

Keywords. galaxies: evolution; galaxies: formation; galaxies: fundamental parameters; galaxies: spiral; galaxies: structure

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The goal of this work is to understand how some fundamental properties of massive, disc-dominated galaxies evolved in the past $\sim$ 8 Gyr. With this aim, the first step is to produce suitable samples spanning different redshift ranges. We have thus separated three samples of galaxies brighter than rest frame $M_B = -21$, and with global Sérsic indices less than 2.5, statistically ensuring that they are indeed disc-dominated. A local sample was defined using the New York University Value-Added Galaxy Catalog (Blanton *et al.* 2005) and the corresponding Sloan Digital Sky Survey (SDSS) images. We also defined two distant samples at higher redshifts occupying equal co-moving volumes. These galaxies are all in the Chandra Deep Field South, with accurate photometric redshifts from COMBO-17 (Wolf *et al.* 2004) and images from the Advanced Camera for Surveys onboard the Hubble Space Telescope (for the GOODS survey, Giavalisco *et al.* 2004; Great Observatories Origins Deep Survey). We thus have:

- 263 galaxies @ $0.77 < z < 1.00$,
- 203 galaxies @ $0.40 < z < 0.77$, and
- 101 galaxies @ $0.02 < z < 0.05$.

In the next step, for all galaxies in these samples, we derived the effective (half-light) radius, the Petrosian radius (as a proxy for galaxy size), concentration, asymmetry, total stellar mass, and effective stellar mass surface density (i.e. the density within the half-light radius), using standard techniques (see Sachdeva 2013 and Sachdeva *et al.* 2015). This was done using the images mentioned above, always corresponding to rest-frame B band.

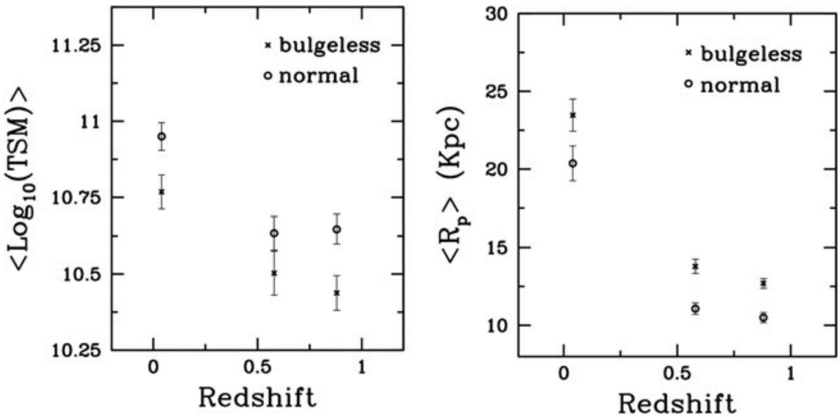

Figure 1. Evolution of total stellar mass (left) and Petrosian radius (right) from redshift one to zero. The increase in both parameters is over a factor two. The error bars correspond to the 1σ error on the mean.

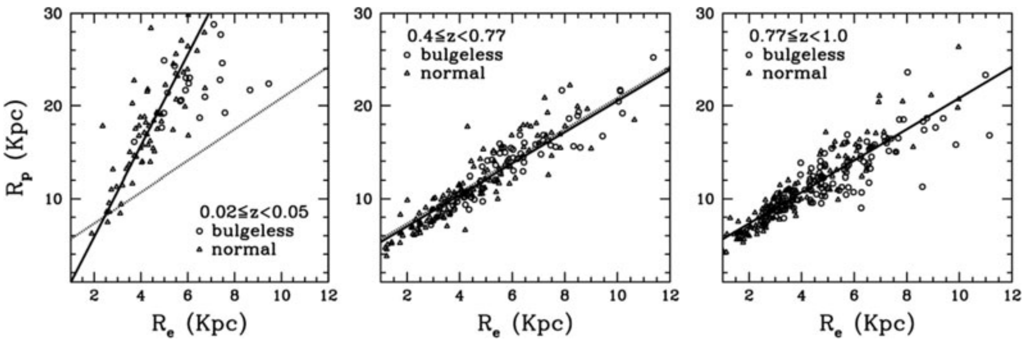

Figure 2. Evolution of the correlation between Petrosian radius and effective (half-light) radius for the three redshift bins as indicated. Fits are shown with solid lines; the dashed line indicates the fit for the highest redshift bin. The uncertainty in the Petrosian radius scales with its value and is in the range of $\pm 5\%$. For the effective radius the typical uncertainty is of ± 0.2 kpc. From redshift one to 0.5 there is no evolution, whereas from redshift 0.5 to zero the Petrosian radius increases more significantly than the effective radius. This indicates a more important growth in the outskirts of galaxies rather than their central regions.

We find that the stellar mass grows from $M_\star = 3 \times 10^{10}\, \mathrm{M}_\odot$ to $M_\star = 8 \times 10^{10}\, \mathrm{M}_\odot$, on average, from redshift one to zero. For the three redshift bins, the average Petrosian radius increases from 10.6 kpc to 11.1 kpc to 22.0 kpc, from higher to lower redshifts (see Fig. 1). The average effective radius also grows, but less significantly so: from 4.5 kpc to 5.2 kpc to 5.8 kpc, from higher to lower redshifts (see Fig. 2). Therefore, over time, the Petrosian radius grows much more significantly than the effective radius, which implies that the observed factor two growth in stellar mass corresponds to a very substantial growth in the outskirts of galaxies, much more than in their central regions.

This is corroborated by the observed little increase in the average concentration, from $C \approx 2.75$ to $C \approx 2.95$, and effective density, from $3 \times 10^8\, \mathrm{M}_\odot\, \mathrm{kpc}^{-2}$ to $4 \times 10^8\, \mathrm{M}_\odot\, \mathrm{kpc}^{-2}$, over the same redshift range (Fig. 3). Figure 3 also shows how galaxies become more symmetric with time, with the average asymmetry parameter evolving from 0.70 to 0.62 to 0.36 for our three redshift bins, from higher to lower redshifts.

It is important to note that the sensitivity of the GOODS images, as compared to that of the SDSS images, is more than enough to account for cosmological surface brightness

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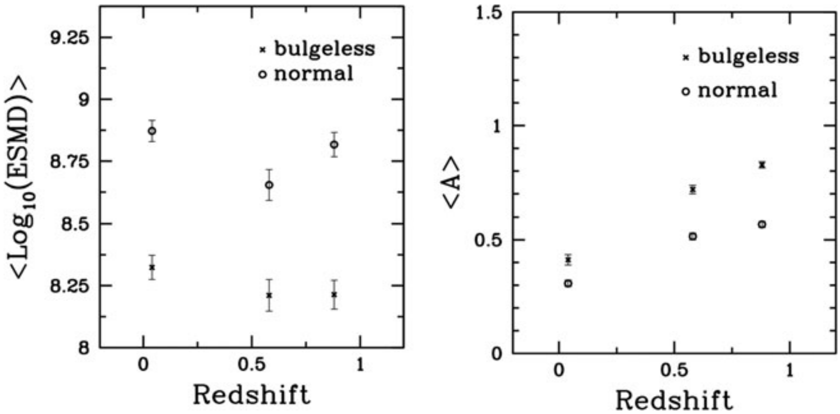

Figure 3. Evolution of the effective stellar mass surface density (i.e. the density within the half-light radius – left) and asymmetry (right) from redshift one to zero. The error bars correspond to the 1σ error on the mean. There is little relative increase in effective density as compared to e.g. the total stellar mass (see Fig. 1). On the other hand, galaxies clearly become more symmetric with time.

dimming, ensuring that the comparisons made here for our different samples are robust. Cosmological effects imply a dimming of ≈ 3 mag arcsec^{-2} from $z \sim 0$ to $z \sim 1$, but the sensitivities of the g, V, I and z images used are, respectively, 23.3, 27.8, 27.1 and 26.6 mag (see York *et al.* 2000 and Giavalisco *et al.* 2004). This implies that there are no systematic effects that could result in the remarkable difference we observe in the evolutions of the Petrosian and effective radii. A bright type 1 active galactic nucleus can harm the estimate of the Petrosian radius, but all galaxies in our samples were visually inspected and we thus verified that such an effect in this study should be minimal, if present at all. In terms of physical spatial resolution, the match between SDSS images at $z \sim 0$ and GOODS images at $z \sim 1$ is also excellent. At $z = 0.035$, $1''$ corresponds to ≈ 0.7 kpc whereas $1''$ corresponds to ≈ 8 kpc at $z \sim 1$, but the typical PSF FWHM of SDSS and GOODS is, respectively, $1.4''$ and $0.125''$. These assessments reinforce the robustness of our conclusions. Further details are extensively described in our main paper (Sachdeva *et al.* 2015).

The growth of massive, disc-dominated galaxies in the past ~ 8 Gyr is remarkable, with an increase in both stellar mass and size of factors around two. We show that most of this mass increase is indeed amassed at the outer disc, consistent with an inside-out picture for disc formation, where the accretion of external material plays a major role.

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