

# Cosmic evolution of stellar disk truncations: from $z = 1$ to the Local Universe

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**Abstract.** We present our recent results on the cosmic evolution of the outskirts of disk galaxies. In particular we focus on disk-like galaxies with stellar disk truncations. Using UDF, GOODS and SDSS data we show how the position of the break (i.e. a direct estimator of the size of the stellar disk) evolves with time since  $z \sim 1$ . Our findings agree with an evolution on the radial position of the break by a factor of  $1.3 \pm 0.1$  in the last 8 Gyr for galaxies with similar stellar masses. We also present radial color gradients and how they evolve with time. At all redshifts we find a radial inside-out bluing reaching a minimum at the position of the break radius, this minimum is followed by a reddening outwards. Our results constraint several galaxy disk formation models and favour a scenario where stars are formed inside the break radius and are relocated in the outskirts of galaxies through secular processes.

**Keywords.** galaxies: evolution - galaxies: high-redshift - galaxies: structure - galaxies: formation - galaxies: spiral - galaxies: photometry

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## 1. Introduction

Early studies of the disks of spiral galaxies (Patterson 1940, de Vaucouleurs 1959, Freeman 1970) showed that this component generally follows an exponential radial surface-brightness profile, with a certain scale length, usually taken as the characteristic size of the disk. Freeman (1970) pointed out, though, that not all disks follow this simple exponential law. In fact, a repeatedly reported feature of disks for a representative fraction of the spiral galaxies is that of a truncation of the stellar population at large radii, typically 2-4 exponential scale lengths (see e.g. the review by Pohlen *et al.* 2004).

Several possible break-forming mechanisms have been investigated to explain the truncations. There have been ideas based on maximum angular momentum distribution: van der Kruit (1987) proposed that angular momentum conservation in a collapsing, uniformly rotating cloud naturally gives rise to disk breaks at roughly 4.5 scale radii. van den Bosch (2001) suggested that the breaks are due to angular momentum cut-offs of the cooled gas. On the other hand, breaks have also been attributed to a threshold for star formation (SF), due to changes in the gas density Kennicutt (1989), or to an absence of equilibrium in the cool Interstellar Medium phase (Elmegreen & Parravano 1994, Schaye 2004). More recent models using collisionless N-body simulations, such as that by Debattista *et al.* (2006), demonstrated that the redistribution of angular momentum by spirals during bar formation also produces realistic breaks. In a further elaboration of this idea, Roškar *et al.* (2008) have performed high resolution simulations of the formation of a galaxy embedded in a dark matter halo. In these models, breaks are the result

of the interplay between a radial star formation cut-off and redistribution of stellar mass by secular processes. A natural prediction of these models is that the stellar populations present an age minimum in the break position. This prediction could be probed by exploring the color profiles of the galaxies.

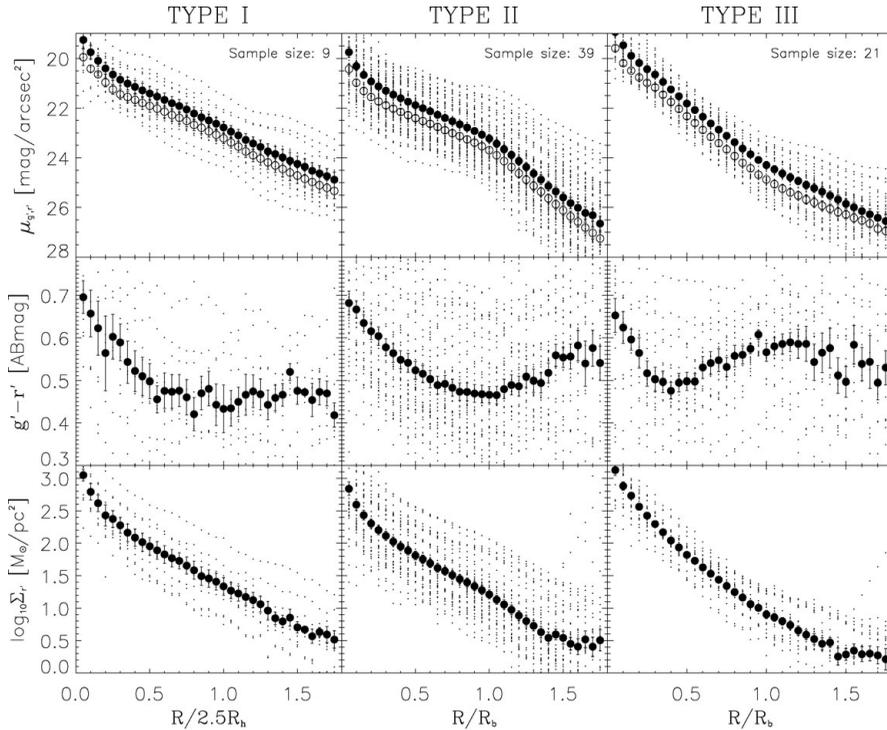
Furthermore, addressing the question of how the radial truncation evolves with  $z$  is strongly linked to our understanding of how the galactic disks grow and where star formation takes place. Pérez (2004) showed that it is possible to detect stellar truncations even out to  $z \sim 1$ . Using the radial position of the truncation as a direct estimator of the size of the stellar disk, Trujillo & Pohlen (2005) inferred a moderate ( $\sim 25\%$ ) inside-out growth of disk galaxies since  $z \sim 1$ . An important point, however was missing in the previous analyses: the evolution with redshift of the radial position of the break at a given stellar mass. The stellar mass is a much better parameter to explore the growth of galaxies, since the luminosity evolution of the stellar populations can mimic a size evolution (Trujillo *et al.* 2004, Trujillo *et al.* 2006). We present in this contribution a quick summary of our recent findings on the stellar disk truncation origin and its evolution with redshift. The results presented here are based on the following publications: Azzollini *et al.* (2008a), Azzollini *et al.* (2008b) and Bakos *et al.* (2008). Throughout, we assume a flat  $\Lambda$ -dominated cosmology ( $\Omega_M = 0.30$ ,  $\Omega_\Lambda = 0.70$ , and  $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$ ).

## 2. Color profiles in Local Galaxies

In order to constrain the outer disk formation models, in Bakos *et al.* (2008), we have explored radial color and stellar surface mass density profiles for a sample of 85 late-type spiral galaxies with available deep (down to  $\sim 27 \text{ mag/arcsec}^2$ ) SDSS  $g'$  and  $r'$  band surface brightness profiles (Pohlen & Trujillo 2006). About 90% of the light profiles have been classified as broken exponentials, either exhibiting truncations (Type II galaxies) or antitruncations (Type III galaxies). Their associated color profiles show a significantly different behavior. For the truncated galaxies a radial inside-out bluing reaches a minimum of  $(g' - r') = 0.47 \pm 0.02 \text{ mag}$  at the position of the break radius, this minimum is followed by a reddening outwards (see middle row in Fig. 1). The antitruncated galaxies reveal a different behavior. Their break in the light profile resides in a plateau region of the color profile at about  $(g' - r') = 0.57 \pm 0.02$ .

Using the  $(g' - r')$  color (Bell *et al.* 2003) to calculate the stellar surface mass density profiles reveals a surprising result. The breaks, well established in the light profiles of the Type II galaxies, are almost gone, and the mass profiles resemble now those of the pure exponential Type I galaxies (see bottom row in Fig. 1). This result suggests that the origin of the break in Type II galaxies is more likely due to a radial change in stellar population than being associated to an actual drop in the distribution of mass. The antitruncated galaxies on the other hand preserve to some extent their shape in the stellar mass density profiles.

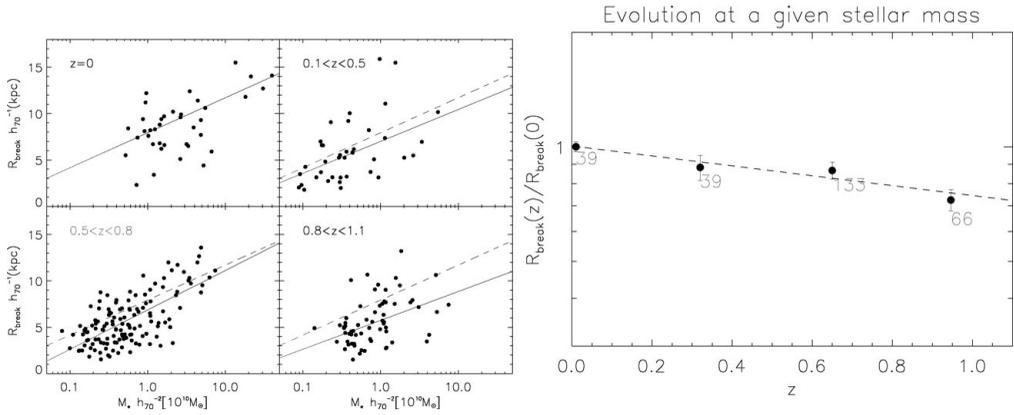
There are other structural parameters that can be computed to constrain the different formation scenarios. Among these we have estimated the stellar surface mass density at the break for truncated (Type II) galaxies ( $13.6 \pm 1.6 \text{ M}_\odot \text{ pc}^{-2}$ ) and the same parameter for the antitruncated (Type III) galaxies ( $9.9 \pm 1.3 \text{ M}_\odot \text{ pc}^{-2}$ ). Finally, we have measured that  $\sim 15\%$  of the total stellar mass in case of truncated galaxies and  $\sim 9\%$  in case of antitruncated galaxies are to be found beyond the measured break radii in the light profiles.



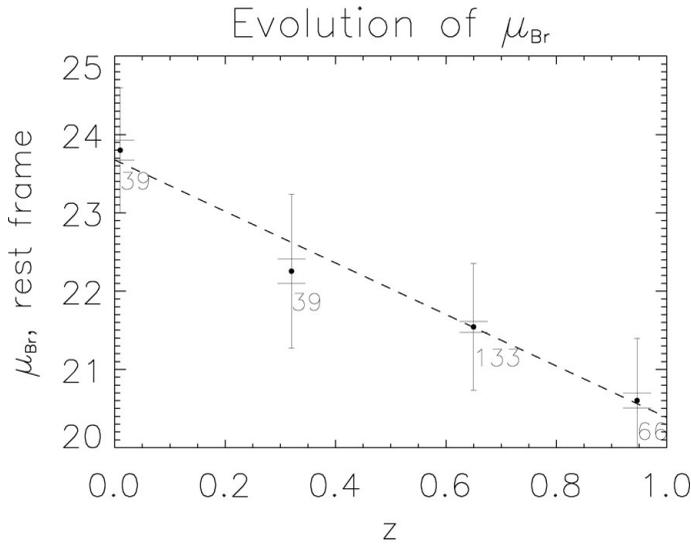
**Figure 1.** *Upper row:* Averaged, scaled radial surface brightness profiles of 9 Type I (pure exponential profiles), 39 Type II (truncated galaxies) and 21 Type III (antitruncated) galaxies. The filled circles correspond to the  $r'$  band mean surface brightness, the open circles to the mean  $g'$  band data (Pohlen & Trujillo 2006). The small dots are the individual galaxy profiles in both bands. The surface brightness is corrected for Galactic extinction. — *Middle row:*  $(g' - r')$  color gradients. The averaged profile of Type I reaches an asymptotic color value of  $\sim 0.46$  mag being rather constant outwards. Type II profiles have a minimum color of  $0.47 \pm 0.02$  mag at the break position. The mean color profile of Type III has a redder value of about  $0.57 \pm 0.02$  mag at the break. — *Bottom row:*  $r'$  band surface mass density profiles obtained using the color to M/L conversion of Bell *et al.* (2003). Note how the significance of the break almost disappears for the Type II (truncated galaxies) case.

### 3. Stellar disk truncation evolution

In Azzollini *et al.* (2008a), we have conducted the largest systematic search so far for stellar disk truncations in disk-like galaxies at intermediate redshift ( $z < 1.1$ ), using the Great Observatories Origins Deep Survey South (GOODS-S) data from the *Hubble Space Telescope* - ACS. Focusing on Type II galaxies (i.e. downbending profiles) we explore whether the position of the break in the rest-frame  $B$ -band radial surface brightness profile (a direct estimator of the extent of the disk where most of the massive star formation is taking place), evolves with time. The number of galaxies under analysis (238 of a total of 505) is an order of magnitude larger than in previous studies. For the first time, we probe the evolution of the break radius for a given stellar mass (a parameter well suited to address evolutionary studies). Our results suggest that, for a given stellar mass, the radial position of the break has increased with cosmic time by a factor  $1.3 \pm 0.1$  between  $z \sim 1$  and  $z \sim 0$  (see Fig. 2). This is in agreement with a moderate inside-out growth of the disk galaxies in the last  $\sim 8$  Gyr. In the same period of time,



**Figure 2.** Left: Break Radius of “truncated” galaxies as a function of stellar mass, for 4 ranges of redshift. Local data are from Pohlen & Trujillo (2006) (*g'*-band results). Right: Size evolution at a given stellar mass of the break radius as a function of redshift. We have found a growth of a factor  $1.3 \pm 0.1$  between  $z = 1$  and  $z = 0$ . The numbers accompanying each point in the right panel give the population of objects which they represent.



**Figure 3.** Evolution of the surface brightness at the break for Type II galaxies with redshift. We show the median surface brightness at the break for the distribution of our galaxies. The larger error bars represent the standard deviation of the distributions, while the shorter ones give the error in the median values. The numbers accompanying each point in the right panel give the population of objects which they represent.

the surface brightness level in the rest-frame *B*-band at which the break takes place has increased by  $3.3 \pm 0.2$  mag/arcsec<sup>2</sup> (a decrease in brightness by a factor of  $20.9 \pm 4.2$ ).

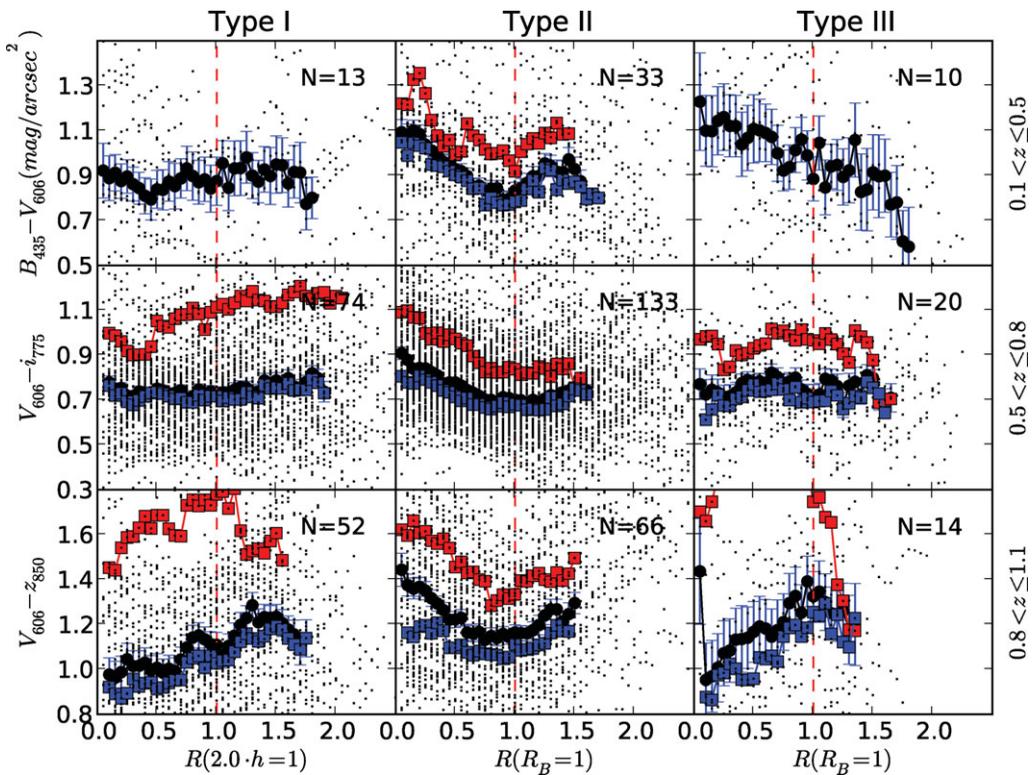
In Azzollini *et al.* (2008a) we also find that at a given stellar mass, the scale lengths of the disk in the part inner to the “break” were on average somewhat larger in the past, and have remained more or less constant until recently. This phenomenon could be related to the spatial distribution of star formation, which seems to be rather spread over the disks in the images. So disk galaxies had profiles with a flatter brightness distribution

in the inner part of the disk, which has grown in extension, while becoming fainter and “steeper” over time. This is consistent with at least some versions of the inside-out formation scenario for disks.

#### 4. Color profiles in intermediate redshift galaxies

In addition to the evolution on the position of the break in spiral galaxies is important to explore how the color of the surface brightness profiles has evolved with time. This kind of analysis sheds light on when stars formed in different parts of the disk of galaxies, thus giving hints on the stellar mass buildup process.

In Azzollini *et al.* (2008b) we present deep color profiles for a sample of 415 disk galaxies within the redshift range  $0.1 \leq z \leq 1.1$ , and contained in HST ACS imaging of the GOODS-South field. For each galaxy, passband combinations are chosen to obtain, at each redshift, the best possible approximation to the rest-frame  $u - g$  color. We find that objects which show a truncation in their stellar disk (type II objects) usually show a



**Figure 4.** Color profiles of the 415 galaxies under study in Azzollini *et al.* (2008b). The sample is divided in subsamples according to surface brightness profile type (I or pure exponential profiles, II or truncated galaxies, III or antitruncated, in columns, from left to right) and redshift range (low, mid, or high, in rows, from top to bottom). The colors ( $B_{435} - V_{606}$ ,  $V_{606} - i_{775}$ ,  $V_{606} - z_{850}$ ) are chosen as the best proxies to the rest-frame  $u - g$  color in each redshift bin. The radii are scaled to the scale radius,  $R_s$ , whose definition depends on profile type:  $R_s = 2h$  for type I, where  $h$  is the scale length of the disk, and it is equal to the break radius,  $R_s = R_B$ , for types II and III. Small points are individual color profiles. Large black dots are the median color profiles for each subsample, and the error bars give the error in those estimations. The red squares give the median color profile for objects with stellar mass  $M_* > 10^{10} M_\odot$ , while the blue squares give the same for objects with  $M_* \leq 10^{10} M_\odot$ .

minimum in their color profile at the break, or very near to it, with a maximum to minimum amplitude in color of  $\leq 0.2$  mag/arcsec<sup>2</sup>, a feature which is persistent through the explored range of redshifts (i.e., in the last  $\sim 8$  Gyr and that it is also found in our local sample for comparison (Bakos *et al.* 2008)). This color structure is in qualitative agreement with recent model expectations where the break of the surface brightness profiles is the result of the interplay between a radial star formation cutoff and a redistribution of stellar mass by secular processes (Roškar *et al.* 2008). Our results fit qualitatively their prediction that the youngest stellar population should be found at the break radius, and older (redder) stars must be located beyond that radius. It is not easy to understand how “angular momentum” or “star formation threshold”/“ISM phases” models alone could explain our results. Thus they pose a difficult challenge for these models. However, it will also be necessary to check whether the Roškar *et al.* (2008) models (as well as other available models in the literature like those of Bournaud *et al.* 2007 and Foyle *et al.* 2008) are able to reproduce quantitatively the results shown here.

Combining the results found in Azzollini *et al.* (2008b) and Bakos *et al.* (2008) one is tempted to claim that both the existence of the break in Type II galaxies, as well as the shape of their color profiles, are long lived features in the galaxy evolution. Because it would be hard to imagine how the above features could be continuously destroyed and re-created maintaining the same properties over the last  $\sim 8$  Gyr.

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