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Outskirts of spiral galaxies: result of a secular evolution process?

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Abstract. We present our recent results on the properties of the outskirts of disk galaxies. In particular, we focus on spiral galaxies with stellar disk truncations in their radial surface brightness profiles. Using SDSS, UDF and GOODS 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 ± 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 redshift 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 constrain 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.

Key words. galaxies: evolution – galaxies: formation – galaxies: high-redshift – galaxies: photometry – galaxies: spiral – galaxies: structure

1. Introduction

Multiband observations (Gil De Paz et al. 2005; Pohlen & Trujillo 2006; Erwin et al. 2008) show evidence of a large number of stars being present in the outer regions of spiral galaxy disks. However, current star formation theories do not support easily the idea of stars forming in those regions, because the environment is not dense enough to provide the conditions of star formation, e.g., gas surface mass density is too low ($\leq 10\,M_{\odot}\,pc^{-2}$, Kennicutt 1989). This fact creates a so-far not answered question: what is the origin of these stars? We approach this problem by means of investigating the structural and stellar population properties of the (outskirts) spiral galaxy disks.

Early studies of the disks of spiral galaxies (Patterson 1940; de Vaucouleurs 1958; 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 (van der Kruit 1979) of the stellar population at large radii, typically 2–4 exponential scale-

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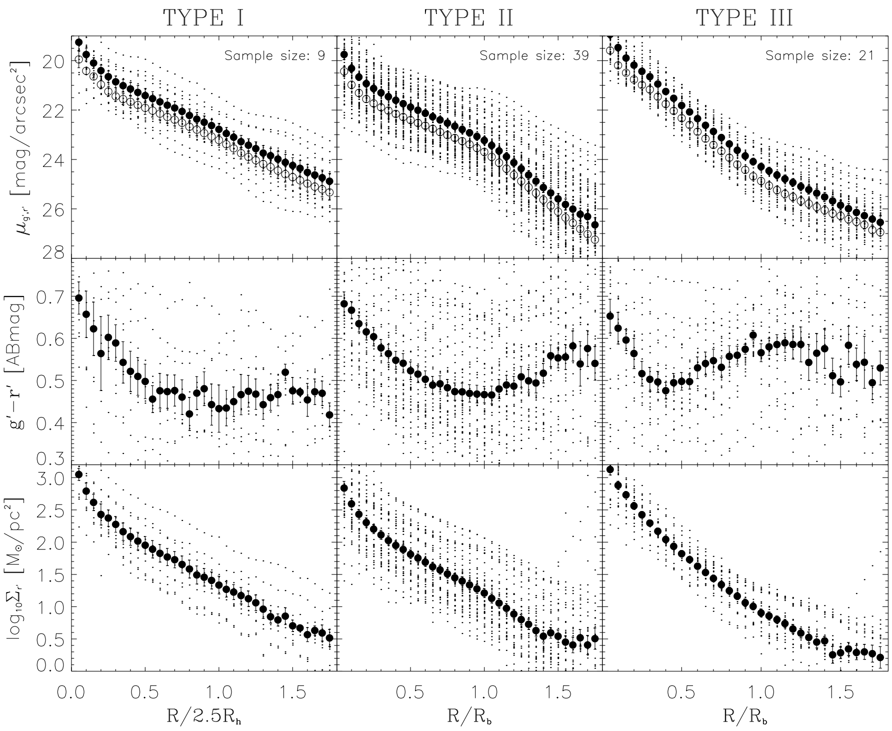

Fig. 1. Upper panels: Averaged, scaled radial surface brightness profiles of 9 Type I (pure exponential profiles), 39 Type II (truncated galaxies), and 21 Type III (antitruncated) galaxies. The filled circles correspond to the r'-band mean surface brightness, the open circles to the mean g'-band data (Pohlen & Trujillo 2006). The small dots are the individual galaxy profiles in both bands. The surface brightness is corrected for Galactic extinction. Middle panels: $(g' - r')$ 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 ± 0.02 mag at the break position. The mean color profile of Type III has a redder value of about 0.57 ± 0.02 mag at the break. Bottom panels: r'-band surface mass density profiles obtained using the color to M/L conversion of Bell et al. (2003), and using Kroupa-IMF (Kroupa 2001). Note how the significance of the break almost disappears for the Type II (truncated galaxies) case.

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, 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). Magnetic fields have been also considered (Battaner et al. 2002) as responsible of the truncations. More recent models using collisionless N-body simulations, such as those by Debattista et al. (2006), demonstrated that the redistribution of angular momentum by spirals during bar

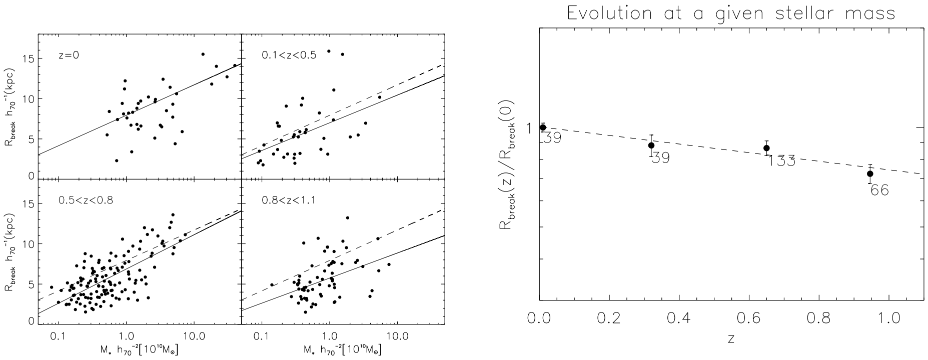

Fig. 2. Left: Break radius of 'truncated' galaxies as a function of stellar mass, for 4 ranges of redshift. Local data are from Pohlen & Trujillo (2006) (g'-band results). Right: Size evolution at a given stellar mass of the break radius as a function of redshift. We have found a growth of a factor 1.3 ± 0.1 between $z = 1$ and $z = 0$. The numbers below each point in the right panel indicate the size of the sample.

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, 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. (2008b,a) and Bakos et al. (2008). Throughout, we assume a flat Λ-dominated cosmology ($\Omega_m = 0.30$, $\Omega_\Lambda = 0.70$, and $H_0 = 70$ km s^{-1} Mpc^{-1}).

2. Color profiles of 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 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, exhibiting either 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 $(g' - r') = 0.47 \pm 0.02$ mag at the position of the break radius, this minimum is followed by a reddening outwards (see the middle panels in Fig. 1). The antitruncated galaxies reveal a different behavior. At the position of the break radius (obtained from the light profiles) now resides a plateau region of the color profile with a value about $(g' - r') = 0.57 \pm 0.02$.

2.1. Stellar surface mass density profiles

Using the $(g' - r')$ color (Bell et al. 2003) it is possible calculate mass-to-light (M/L) ratios along the radius of the disks. Converting the (M/L) into stellar surface mass density reveals a surprising result. The breaks, well established in the light profiles of the Type II galaxies, are almost gone (in case of several individual galaxies, e.g., NGC 5300, the break is completely gone). The mass profiles resembles now those of the pure exponential Type I galaxies (see the bottom panels 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 the ingredients of the stellar population than being associated to an actual drop in the distribution of mass. The antitruncated galaxies, on the other hand, show clear mass-excess in the outer regions on the stellar mass density profiles, which could have been accumulated from an external (possibly satellite) origin.

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 ± 1.6 $M_\odot\,pc^{-2}$) and the same parameter for the antitruncated (Type III) galaxies (9.9 ± 1.3 $M_\odot\,pc^{-2}$). 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.

3. Stellar disk truncation along the Hubble-time

In Azzollini et al. (2008b), 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 ± 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 ~ 8 Gyr. In the same period of time, the surface brightness level in the rest-frame B-band at which the break takes place has increased by 3.3 ± 0.2 mag arcsec^{-2} (a decrease in brightness by a factor of 20.9 ± 4.2, see Fig. 3).

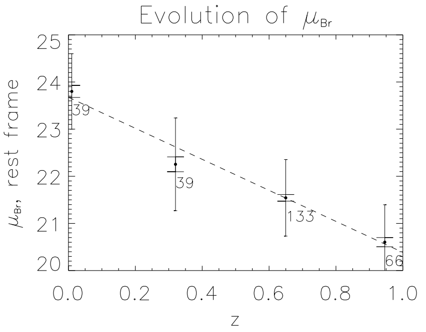

Fig. 3. Evolution of the surface brightness at the break for Type II galaxies with redshift. We show the median surface brightness at the break for the distribution of our galaxies. The larger error bars represent the standard deviation of the distributions, while the shorter ones give the error in the median values. (The numbers below each point give the size of the sample at that redshift bin.)

In Azzollini et al. (2008b) 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

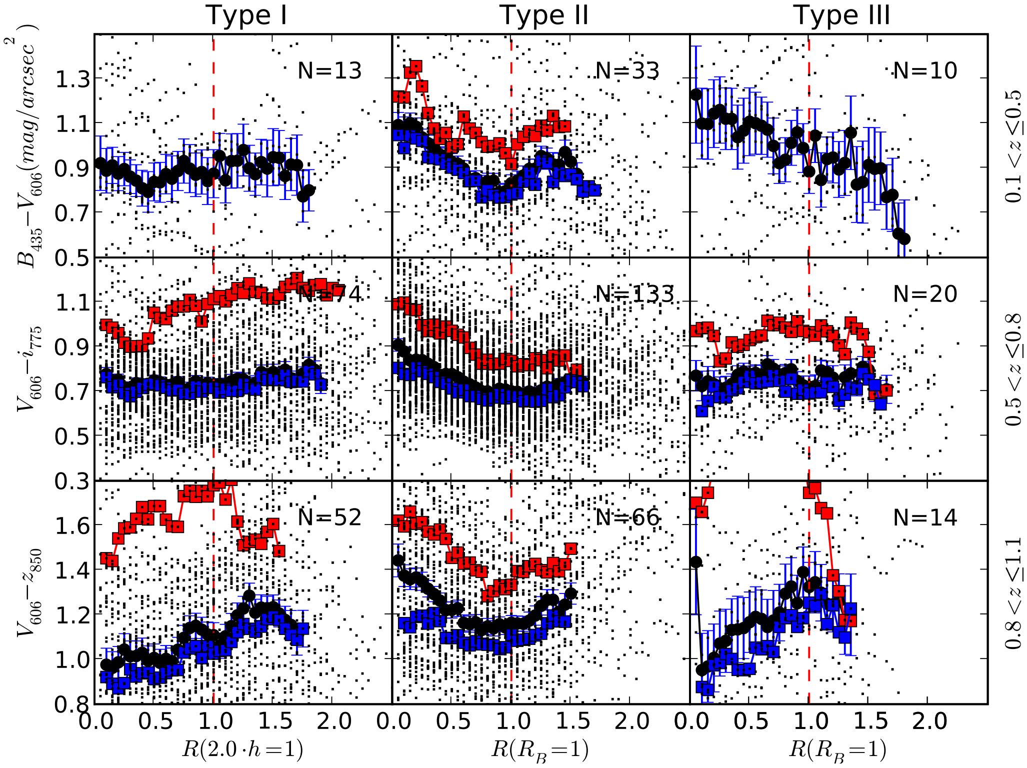

Fig. 4. Color profiles of the 415 galaxies under study in Azzollini et al. (2008a). The sample is divided in subsamples according to surface brightness profile type (I or pure exponential profiles, II or truncated galaxies, III or antitruncated, in columns, from left to right) and redshift range (low, 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 $M_\star > 10^{10}$ M$_\odot$, while the blue squares give the same for objects with $M_\star \leq 10^{10}$ M$_\odot$.

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 of the position of the break in spiral galaxies, it 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. (2008a) 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 (see, Fig. 4). We find that objects which show a truncation in their stellar disk (type II objects) usually show a minimum in their color profile at the break, or very near to it, with a maximum to minimum amplitude in color of ≤ 0.2 mag arcsec^{-2}, a feature which is persistent through the explored range of redshifts (i.e., in the last ∼ 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).

5. Discussion

Our results on the color profiles fit qualitatively with the particular prediction of Roškar et al. (2008), 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. (2008a) 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 ∼ 8 Gyr.

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