Probing the Stellar Populations in the Outskirts of Spiral Galaxies

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Abstract. We present our results on the stellar population 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 data we show color gradients. We find that the color radial profile exhibits a “U’-shape”, showing a minimum at the position of the break of the surface brightness profile. We obtain stellar surface mass density profiles of truncated galaxies as well, these show a peculiar behaviour: they follow very closely an exponential decrement. This suggests the idea that the observed properties of truncated galaxies are not caused by a drop in the mass distribution but by a different stellar population in the outer regions of the disks. Confronting this with current theoretical scenarios we find that this is likely to be a result of secular evolution, in which scenario stars are being formed inside the break and then being motioned outwards which would result in an inverted age gradient corresponding to the observed color profiles. Having maintained this idea, using multiwave-length data from GALEX, SDSS, UKIDSS and SPITZER we showed a dependence of the inner-outer scale-length ratio of truncated disks. Our results suggest that there is an existing general trend of the scale-length ratio: from bluer to redder bands the scale-length ratio decreases, which is in accordance with the stellar disk being dominated by an older stellar population in the outer disk.

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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 the idea of stars being created 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, 1979) 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 surface brightness 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). 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 that by Debbatista 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 optical color profiles of the galaxies. Another approach is to use fully cosmological simulations of disk galaxy formation. The latest models (Sáchez-Blázquez et al. 2009; Martínez-Serrano et al. 2009) are able to explain all the observational phenomenology and predict the break to be a consequence of the appearance of warp at the truncation radius. This warp will decrease the gas density beyond the break decreasing the star formation and consequently producing a break in the surface brightness profile. A prediction of these models is that there should be an increase in the gas velocity dispersion beyond the break. This is explored in great detail in Trujillo & Bakos (2010, in prep.). Furthermore, exploring multiwave-length data in order to study how the break properties change depending on the observing wavelength can prove to be important in our study of the dominant stellar population inside the disks.

Here we summarize the results of Bakos, Trujillo & Pohlen, 2008 (BTP08, later on) and Bakos & Trujillo, 2010 (in prep).

2. Color Profiles of Local Galaxies

In order to constrain the outer disk formation models, in BTP08 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 $g^\prime$- and $r^\prime$-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 $(g^\prime - r^\prime) = 0.47 \pm 0.02$ 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. 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 $(g^\prime - r^\prime) = 0.57 \pm 0.02$.

2.1. Stellar Surface Mass Density Profiles

Using the $(g^\prime - r^\prime)$ color it is possible calculate mass-to-light ($M/L$) ratios along the radius of the disks (Bell et al., 2003). 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., NGC5300, the break is completely gone). The mass profiles resembles 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.
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 (PT06). 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), and using Kroupa-IMF (Kroupa, 2001). Note how the significance of the break almost disappears for the Type II (truncated galaxies) case.

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 ($13.6 \pm 1.6 \, M_\odot pc^{-2}$) and the same parameter for the antitruncated (Type III) galaxies ($9.9 \pm 1.3 \, M_\odot pc^{-2}$). 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 is found beyond the measured break radii in the light profiles.
Figure 2. The dependence of the scale-length ratio on wavelength in case of NGC0450. The decrease on the ratio towards redder wavelength is quite dramatic. Errorbars are propagated errors coming from the errors on the fit. We fitted the surface brightness profiles by using robust linefitting method.

3. Multi-wavelength characterization of a truncated disk

To further investigate the origin of the surface brightness break, we have chosen galaxies with full wavelength coverage (from UV to IRAC) from the PT06 sample. Here we show an example of NGC0450. We have obtained the radial surface brightness profiles in all bands using fixed isophotes of the ellipticity and position angle, see Fig. 3. We first masked the stars and other background objects on the galaxy image, the objects were identified by SExtractor (Bertin & Arnouts, 1996). After masking we calculated the moments of the light distribution of the galaxy in r'-band, which is sufficiently smooth enough to derive the correct position angle and ellipticity of the galaxy. The break radius of this galaxy is independent of the wavelength and it is located at ∼ 80 arcseconds. (See PT06, and Bakos & Trujillo (2010, in prep).)

We characterize the outer disk by means of calculating the ratio of the inner and outer scale-lengths. We use profiles which are deep enough to obtain reliable fit beyond the break. We find that the scale-length ratio decreases towards redder wavelengths. (See Fig. 2.)

4. 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 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.
Nevertheless, the fact that the stellar mass density of the break for Type II galaxies with ∼ 13M⊙ pc−2 is so close to the gas density threshold prediction of ∼ 10M⊙ pc−2 makes the case for a stellar population origin for the surface brightness break even stronger (with a 100% efficiency of transforming gas to stars).

Our results on the dependence of the inner-outer scale.length ratio on the observing wavelength suggests that indeed this is the case: from bluer to redder bands the scale-length ratio decreases, which is in accordance with the stellar disk being dominated by an older stellar population in the outer disk.

Evidence for the same color phenomenology for Type II galaxies also at high redshift is presented by Azzollini et al. (2008). They have shown that a similar minimum in the color profile can be found, at least, up to z∼1 and that the main source of the scatter of the color profiles is caused by the different stellar mass (in our case absolute magnitude) of the galaxies in their sample. Following these findings, we can conclude that once the absolute magnitude of a galaxy is fixed, the color profiles within a given Type (I, II or III) of galaxy, are strikingly similar.

Combining the results found in Azzollini et al. (2008b) and BTP08 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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Figure 3. Radial surface brightness profiles of NGC0450 obtained from UV to IRAC. The profiles are shown down to the surface brightness limit of a given filter.