Stellar haloes outshine disc truncations in low-inclined spirals

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ABSTRACT

The absence of stellar disc truncations in low-inclined spiral galaxies has been a matter of debate in the last decade. Disc truncations are often observed in highly inclined galaxies but no obvious detection of this feature has so far been made in face-on spirals. Here we show, using a simple exponential disc plus stellar halo model based on current observational constraints, that truncations in face-on projections occur at surface brightness levels comparable to the brightness of stellar haloes at the same radial distance. In this sense, stellar haloes outshine the galaxy disc at the expected position of the truncations, forcing their studies only in highly inclined (edge-on) orientations.

Key words: galaxies: formation – galaxies: fundamental parameters – galaxies: photometry – galaxies: spiral – galaxies: structure.

1 INTRODUCTION

Since truncations in the surface brightness profiles of edge-on galaxies were first noticed by van der Kruit (1979) and van der Kruit & Searle (1981, 1982), it has been clear that the radial light distribution of spiral galaxies does not decline following an exponential law along the whole disc as proposed in the earliest photometric studies (Patterson 1940; de Vaucouleurs 1958; Freeman 1970). However, over the last decade, numerous works have revealed a dichotomy in the observational framework while comparing truncations in the surface brightness profiles of edge-on and face-on spirals. In edge-on galaxies, these truncations are usually found at radial distances of four to five times the exponential scalelength of the disc (e.g. Barteldrees & Dettmar 1994; Bottema 1995; de Grijs, Kregel & Wesson 2001; Kregel, van der Kruit & de Grijs 2002; van der Kruit 2007), whereas face-on galaxies show downbending breaks closer to the galactic centre, typically at around two or three disc scalelengths (Erwin, Beckman & Pohlen 2005; Pohlen & Trujillo 2006; Erwin, Pohlen & Beckman 2008). Moreover, the way in which the surface brightness profile changes depends on the orientation of the galaxy with respect to the line of sight (LOS): edge-on galaxies exhibit a sharp truncation in the radial light distribution, as opposed to a smoother break observed in face-on spirals.

The strong observational difference between edge-on and face-on galaxies is reflected in the proposed explanations for the formation of such breaks and truncations. Two main mechanisms have been proposed. On the one hand, van der Kruit (1987, 1988) suggested that truncations could be related to the maximum angular momentum of the protogalactic cloud. In this scenario, it is expected that the truncation happens at a radius of four or five times the exponential scalelength, which is in good agreement with the edge-on observational results. On the other hand, a threshold in the star formation of the galaxy can also explain the presence of a break in the surface brightness profiles of spiral galaxies (e.g. Fall & Efstathiou 1980; Kennicutt 1989; Elmegreen & Parravano 1994; Schaye 2004; Elmegreen & Hunter 2006). This threshold in the star formation would lead to a change in the stellar population around the break radius, as both photometric (Azzollini, Trujillo & Beckman 2008; Bakos, Trujillo & Pohlen 2008; Bakos & Trujillo 2012) and resolved stellar population (de Jong et al. 2007; Radburn-Smith et al. 2012) studies of face-on galaxies appear to confirm. Numerical simulations tend to support the idea of the breaks being caused by a threshold in the star formation of the galaxy (Debattista et al. 2006; Roškar et al. 2008; Martínez-Serrano et al. 2009; Sánchez-Blázquez et al. 2009). In addition, these numerical simulations place the break at radial distances which fit the face-on measurements quite well, e.g. Roškar et al. (2008) find the break radius at 2.6h, whereas the average break in Pohlen & Trujillo (2006) occurs at 2.5h, (h is the exponential scalelength of the inner disc before the appearance of the break).

The access to deep and high-quality imaging from both the Sloan Digital Sky Survey (SDSS) Data Release 7 (Abazajian et al. 2009) and the Spitzer Survey of Stellar Structure in Galaxies (S^3G) (Sheth et al. 2010) has allowed to shed more light on the break–truncation dichotomy. Thanks to these surveys, Martín-Navarro et al. (2012)
and Comerón et al. (2012) have shown that both breaks and truncations can be observed simultaneously in edge-on galaxies. Consequently, there is growing consensus that truncations, usually observed in edge-on galaxies, and breaks, initially measured in face-on systems, are not the same phenomenon. However, an unavoidable question remains unanswered: Why are we able to detect both breaks and truncations in edge-on galaxies but only the former in face-on orientations?

To complete the observational picture of the radial light distribution of spiral galaxies it is necessary to take into account the stellar halo. Only a few photometric studies (e.g. Zibetti & Ferguson 2004; Zibetti, White & Brinkmann 2004; Jablonka et al. 2010; Bakos & Trujillo 2012; Zackrisson, de Jong & Micheva 2012; Trujillo & Bakos 2013; Peters et al., in preparation) have been able to reach surface brightnesses \( \mu_r \sim 30 \text{ mag arcsec}^{-2} \), deep enough to study the stellar halo properties. Although the formation and evolution of stellar haloes around spiral galaxies remains an open question, most observations point to old and moderately metal-poor stars as the main component of these stellar haloes, probably assembled in merger/accretion events at redshifts \( z > 1 \) (Zibetti et al. 2004; Bakos & Trujillo 2012; Trujillo & Bakos 2013).

Trying to reconcile all the previous observational results, we have built a three-dimensional (3D) disc galaxy model using an exponential disc plus stellar halo. Our model comfortably fits the current observational constraints on the photometrical structure of spiral galaxies. We show how this simple model is able to explain why different disc orientations prevent the general detection of truncations in low-inclined galaxies. Basically, the expected surface brightness of the stellar disc at the position of the truncation in a face-on orientation is so faint that this feature is outshone by the brightness of the stellar halo at that radial distance.

In Section 2 we present a compilation of observational results of face-on and edge-on galaxies; in Section 3 we describe the model and finally, in Section 4 we derive the main conclusions of this work.

2 OBSERVATIONAL CONSTRAINTS TO THE MODEL

To introduce the observational framework regarding breaks, truncations and stellar haloes in spiral galaxies, we compile in this section the current observational constraints that describe these features.

2.1 Breaks

Pohlen & Trujillo (2006) found in their sample of 85 low-inclined galaxies that downbending breaks appear, on average, at a radial distance of \( 2.5 \pm 0.6h_{\text{in}} \), where \( h_{\text{in}} \) is the exponential scalelength before the break radius. Yoachim, Roškar & Debattista (2012) measured a quite similar value of \( 2.5 \pm 0.2h_{\text{in}} \) for the break radius among a sample of 12 nearby galaxies, while Erwin et al. (2008) and Gutiérrez et al. (2011) found slightly lower values (1.8 ± 0.2\( h_{\text{in}} \) and \( 2.1 \pm 0.5h_{\text{in}} \), respectively) for the break radius of early-type galaxy discs (with morphological types from S0 to SB). Pohlen & Trujillo (2006) also found that the radial distance where the break occurs in a given galaxy depends on its absolute magnitude, ranging from \( r_B \sim 1.5h_{\text{in}} \) for galaxies with \( M_B \sim -19 \) to \( r_B \sim 4.5h_{\text{in}} \) if the absolute magnitude of the galaxy is close to \( M_B \sim -21 \). Breaks also present a characteristic ratio between the exponential scale-length before and after the break radius (\( h_{\text{in}}/h_{\text{out}} \)). In this sense, low-inclined spiral galaxies show a value for \( h_{\text{in}}/h_{\text{out}} \sim 2 \), with values typically varying from \( h_{\text{in}}/h_{\text{out}} = 2.6 \pm 0.3 \) (Erwin et al. 2008) to 1.7 ± 0.1 (Gutiérrez et al. 2011). This scatter lies within the measurements of Pohlen & Trujillo (2006) who found a mildly peaked distribution ranging between \( h_{\text{in}}/h_{\text{out}} = 1.3 \) and 3.6.

2.2 Truncations

The first results of van der Kruit & Searle (1982) placed the truncation radius at a radial distance of \( 4.2 \pm 0.6h_{\text{in}} \), significantly larger than the break radius. Barteldrees & Dettmar (1994) proposed a truncation radius of \( 3.7 \pm 1.0h_{\text{in}} \) which is compatible also with the results of Pohlen, Dettmar & Lüticke (2000), who found an averaged truncation radius of \( 2.9 \pm 0.7h_{\text{in}} \). As discussed in Section 1, truncations are principally detected in edge-on galaxies. Nevertheless, Martín-Navarro et al. (2012) and Comerón et al. (2012) have shown that edge-on galaxies can simultaneously host breaks too. Thus, if no distinction is made between breaks and truncations while studying edge-on systems, the measurements can be confusing both features (breaks and truncations). This could be the reason for the large scatter in the values of the truncation radii found in the literature. For the ratio \( h_{\text{in}}/h_{\text{out}} \) between the exponential scale-lengths before and after the truncation radius, Martín-Navarro et al. (2012) found a mean value of \( 1.9 \pm 0.4 \), very similar to the observed change in the exponential scalelength around the break radius. This measurement is in agreement with Comerón et al. (2012) who did not find significant differences between the \( h_{\text{in}}/h_{\text{out}} \) distributions for breaks and truncations.

2.3 Stellar haloes

The current observational constraints on stellar haloes are not as strong as those on breaks and truncations because of the very low surface brightnesses where these haloes start to be visible, typically below \( \mu_r \sim 28 \text{ mag arcsec}^{-2} \) in the \( R \) band. Stellar haloes are usually detected as an excess of light with respect to the exponential decline of the discs in the outer parts of spiral galaxies (\( R \gtrsim 15 \text{ kpc} \)) and they are observed not only in images (e.g. Bakos & Trujillo 2012; Trujillo & Bakos 2013; Peters et al., in preparation), but also in particular using star-counting techniques (e.g. Ferguson et al. 2002, 2007; Mouhcine et al. 2005; Ibata, Mouhcine & Rejkuba 2009; Jablonka et al. 2010). The shape and the surface brightness of the stellar haloes are the same in edge-on and face-on galaxies. For example, Bakos & Trujillo (2012) found them at around \( R \sim 20 \text{ kpc} \), with a typical surface brightness in the SDSS \( r' \) band of \( \mu_{r'} \sim 28 \text{ mag arcsec}^{-2} \) in a sample of low-inclined disc galaxies. In the edge-on galaxy NGC 3957, Jablonka et al. (2010) measured the stellar halo above 20 kpc above the galactic plane, at a surface brightness of \( \mu_R = 28.5 \text{ mag arcsec}^{-2} \). Wu et al. (2002) detected the stellar halo of the edge-on spiral NGC 4565 at 22 kpc measured along the minor axis, having a surface brightness of \( H_{6660} = 27.5 \text{ mag arcsec}^{-2} \).

3 MODEL

To explain the proposed model in a clear way, this section is split into two parts. In the first subsection we describe the mathematical formulation of the model, along with the required information regarding the vertical distribution of the disc and the dust component. In the second part, we use this same model to reproduce the observed characteristics of two galaxies with similar properties in the \( r' \) band, one seen with a low inclination (UGC 00929) and the other one observed in an edge-on orientation (UGC 00507).
3.1 Mathematical description

The disc component of our model is parametrized as an exponential function in both the radial (Freeman 1970; van der Kruit 1988; Pohlen et al. 2007) and the vertical direction (Wainscoat, Freeman & Hyland 1989; de Grijs, Peletier & van der Kruit 1997; de Grijs et al. 2001). Although the vertical exponential scalelength can vary with galactocentric distance (see de Grijs & Peletier 1997), for simplicity, we assume it is constant along the whole disc (van der Kruit & Searle 1981, 1982; Shaw & Gilmore 1990). In the radial direction, the model is characterized by two changes (a break and a truncation) in the exponential behaviour. Thus, the 3D light distribution of our synthetic galaxy can be expressed in cylindrical coordinates \((R, z)\) as

\[
L(R, z) = L_0 L(R) e^{-|z|/h_z},
\]

where \(L_0\) is the luminosity at the centre of the disc and the radial light distribution is given by

\[
L(R) = e^{-R/h_R} \Pi_{0,R} + e^{-R/h_R} \Pi_{R,B} + e^{-R/h_R} \Pi_{R,\infty}.
\]

As mentioned before, equation (2) shows two changes in the exponential behaviour: the first one (break) is located at a radial distance \(R = R_B\), while the second change (truncation) occurs at \(R = R_T\). The light distribution is parametrized by the vertical exponential scalelength \((h_R)\) and also by the radial exponential scalelength before the break radius \((h_B)\), after the break radius \((h_B)\) and after the truncation radius \((h_T)\). The boxcar function \(\Pi_{a,b}\) is defined as

\[
\Pi_{a,b} = \begin{cases} C_{a,b} & \text{if } a \leq R < b, \\ 0 & \text{otherwise,} \end{cases}
\]

where \(C_{a,b}\) is constant, and \(L(R)\) is continuous over the whole domain.

Although a certain level of clumpiness is expected in the dust distribution, we have only considered the diffuse component for the dust attenuation, parametrizing the extinction with a continuous spatial exponential function (Xilouris et al. 1997, 1998). This exponential approach has properly described the dust distribution in edge-on galaxies (Xilouris et al. 1999; Misiriotis et al. 2001) and a very careful description can be found in Popescu et al. (2011, section 2.1). The extinction of the dust disc can be written as

\[
\tau(\xi, \lambda) = \int_{\text{LOS}} \kappa_{\text{dust}}(\lambda, R, z) d\xi,
\]

where the optical depth \(\tau(\xi, \lambda)\) is given by

\[
\tau(\xi, \lambda) = \int_{\text{LOS}} \kappa_{\text{dust}}(\lambda, R, z) d\xi.
\]

3.2 Comparison with the data

The above model can simultaneously reproduce the typical surface brightness profiles of low and highly inclined spiral galaxies. In order to do illustrate this, we have selected two galaxies, UGC 00929 (low inclined) and UGC 00507 (highly inclined), from the SDSS Stripe 82. The SDSS Stripe 82 is a very deep photometric survey covering 275 deg\(^2\) around the celestial equator and reaching ~2 mag deeper than the standard SDSS survey. These ultradeep data are crucial to constrain the model since, as mentioned in Section 2.3, the stellar halo starts to dominate the surface brightness distribution at around \(\mu_r \sim 28\) mag arcsec\(^{-2}\). Table 1 summarizes the basic information about these two objects, found in the HyperLeda data base (Patoule et al. 2003).

| Galaxy  | \(M_{\text{ds}}\) | Morph. type | Incl. |
|---------|-------------------|-------------|-------|
| UGC 00507 | −20.34 | Scd | 80.0 |
| UGC 00929 | −20.60 | SABc | 24.7 |

Table 1. Global parameters of the two galaxies analysed in this paper (from the HyperLeda data base).

where \(I_{\text{eff}}\) is the intensity at the effective radius \(R_{\text{eff}}\), \(n\) is the so-called Sérsic index and \(b_0\) is a function of the Sérsic index that, in good approximation, is given by \(b_0 \sim 2n - 0.324\) (e.g. Trujillo, Graham & Caon 2001). We fixed the Sérsic index of the stellar halo to \(n = 1\) and that of the bulge to \(n = 0.5\). Keeping the Sérsic index fixed does not have a major impact on our claim since the bulge is only relevant in the very central region and the shape of the stellar halo is not well constrained because of its low surface brightness (see Section 3.2).

Equations (1)–(4) completely define the 3D light distribution in our model. The observed surface brightness profile is given by the integration along the LOS of equation (1), attenuated by the dust component following equation (3) plus the contribution of the bulge and the stellar halo in equation (4). Thus, the radial surface brightness profile of our synthetic galaxy, observed in an arbitrary orientation, can be written as

\[
I_{\text{obs}}(R) = I_{\text{halo}}(R) + \int_{\text{LOS}} L(R, z) e^{-\tau(\xi, \lambda)} d\xi,
\]

where the optical depth \(\tau(\xi, \lambda)\) is given by

\[
\tau(\xi, \lambda) = \int_{\text{LOS}} \kappa_{\text{dust}}(\lambda, R, z) d\xi.
\]

An extensive explanation on the surface brightness profile calculation process can be found in these two papers.
contribution to the total surface brightness profile of the galaxy just starts to be important. To address this problem and complete the edge-on galaxy profile below μ_v ≳ 27 mag arcsec^{-2}, we measured the stellar halo of UGC 00507 by using elliptical apertures centred on the galaxy. Since the intrinsic ellipticity of the stellar halo is unknown, we calculated a set of possible stellar halo profiles by using elliptical apertures with an axis ratio ranging from 1 (circular case) to 0.6, which is typically found in nearby spiral galaxies (Chiba & Beers 2000; Zibetti et al. 2004; Bell et al. 2008). The large uncertainties associated with the set of halo profiles prevent us from attempting any further fit beyond the n = 1 approximation described in Section 3.1. Note, however, that providing a precise characterization of the halo shape is beyond the scope of this work and does not affect the main idea of this paper.

Apart from these radial surface brightness profiles, additional information about the vertical light distribution and about the dust was required to fully constrain our model. Typically, the vertical exponential scalelength is found to be h_z ≃ 1/10h_r (van der Kruit & Searle 1982; de Grijs & van der Kruit 1996). For the dust distribution we followed Xilouris et al. (1999), assuming a characteristic vertical scalelength h_r dust ≃ 1/20h_r and a radial scalelength h_G dust ≃ 2h_r.

Once the surface brightness profiles for the two galaxies were obtained, we built up two synthetic galaxies that reproduce both the face-on and the edge-on surface brightness distributions. The structural parameter set that defines our synthetic galaxy models is listed in Table 2.

In Fig. 1 we show how our simple model is able to reproduce the surface brightness profiles of low and highly inclined galaxies. The structural parameters listed in Table 2 were not obtained by a systematized fitting process of the data showed in Fig. 1 since providing a precise characterization of the observed data is not in the scope of the present paper. Following a simplified approach, we tuned the free parameters in our model (see Section 3.1) to obtain a reasonable representation of the data, taking into account the observational constraints detailed in Section 2. That is the reason why no uncertainties are given for the structural parameters showed in Table 2.

### 4 DISCUSSION AND CONCLUSIONS

We present in Fig. 2, qualitatively, the main idea of this paper: truncations in the surface brightness profile of low-inclined spiral galaxies are outshone by the light of the stellar halo component. The explanation for the lack of observational evidence of truncations in the radial light distribution of low-inclined galaxies is based on the different response that the stellar disc and the stellar halo have to the LOS integration. Whereas the surface brightness profile of a highly symmetric stellar halo is almost independent of orientation with respect to the observer, we expect from the model that the stellar disc is ≃ 2 mag arcsec^{-2} dimmer in a face-on than in an edge-on projection. It is the absence of contrast between the stellar disc and the stellar halo which prevents us from detecting truncations in the surface brightness profiles of low-inclined spiral galaxies.

However, our model does not necessary imply that truncations cannot be studied in face-on galaxies. The contribution of the stellar halo to the total light of a galaxy depends on the galaxy mass (see fig. 10 of Courteau et al. 2011). The lower the mass of the galaxy, the weaker the contribution of the stellar halo to the total light is. Low-mass spirals are then the most suitable candidates to distinguish between truncations and stellar haloes in face-on disc galaxies. Another option to detect truncations in low-inclined systems could be through the decomposition of the surface brightness profiles in separate components: bulge, thin and thick discs, stellar halo, etc. However, since we do not yet have a complete characterization of the radial light distribution of stellar haloes, the subtraction of such component from the observed surface brightness distribution of a galaxy may lead to misleading conclusions. Interestingly, the break in the surface brightness profile of UGC 00929 (see Fig. 1) happens at a large radial distance, 4.1h_r, where a confusion between breaks and truncations for a galaxy of this mass is still a possibility. Hence, this break could also be interpreted as a truncation in a face-on galaxy. This result does not invalid our conclusions, but rather invites to further explore more complex scenarios.

The properties of the underlying stellar population could be also a tool to study the mechanism behind the formation of breaks and truncations in face-on spiral galaxies, without the inherent problems associated with the edge-on projection (e.g. dust attenuation and the mixing of stellar properties because of the LOS integration). The stellar disc and the stellar halo are expected to have very different kinematical properties and that can be used to spectroscopically differentiate the two components. Also, since truncations are thought to be related to the total angular momentum of the protogalactic cloud (van der Kruit 1987, 1988), a detailed study of the kinematics around the truncation radii might bring precious information about the angular momentum distribution when galaxies were formed. In addition, in terms of α-element overabundance, age and metallicity, stellar discs and stellar haloes might show significant differences (Radburn-Smith et al. 2012), with the stars in the stellar halo probably being older, more metal poor and more α-enhanced than the stars in the stellar disc. Deep enough resolved spectroscopic surveys such as Calar Alto Legacy Integral Field Area (CALIFA; Sánchez et al. 2012) and Mapping Nearby Galaxies at APO (MaNGA)3 might help to separately study truncations and stellar haloes. Finally the next generation of space- (Gaia, James Webb Space Telescope) and ground-based telescopes (European Extremely Large Telescope) will allow us to perform resolved stellar population analysis in the Milky Way and beyond the Local Group, opening the door to very detailed star-counting studies of breaks and truncation up to the distance of the Virgo cluster.

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3 http://www.sdss3.org/future/manga.php

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**Table 2.** Modeled structural parameters of the galaxies used in this paper. The listed quantities are those expected for the face-on projection of the synthetic galaxy.

| Parameter | UGC 00929 | UGC 00507 |
|-----------|-----------|-----------|
| μ_v^break | 24.7 (mag arcsec^{-2}) | 24.0 (mag arcsec^{-2}) |
| r_B | 4.1 (h_r) | 3.0 (h_r) |
| h_B | 1/1.7 (h_r) | 1/2.1 (h_r) |
| r_T | 6.0 (h_r) | 4.5 (h_r) |
| h_T | 1/3.4 (h_r) | 1/3.6 (h_r) |

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Figure 1. Surface brightness distributions of a face-on (UGC 00929) and an edge-on (UGC 00507) spiral galaxy. Our model fits to the surface brightness distribution are overplotted (green solid lines). We also show the different contributions to the final surface brightness profiles: blue dashed line for the disc, red dashed line for the stellar halo and purple dashed line for the bulge. Because of the LOS integration, the observed radial surface brightness profile of the edge-on galaxy is brighter, allowing us to measure the truncation in the radial light distribution of the stellar disc above the stellar halo contribution. However, the halo brightness outshines the truncation in the face-on case since the surface brightness of the stellar disc and the halo is similar at the radial distance where the truncation happens. For UGC 00507, the stellar halo profile is represented as a set of all possible radial surface brightness profiles, assuming axis ratios from 1 to 0.6. This set reflects our lack of knowledge about the actual shape of the stellar halo and, since it was obtained using elliptical apertures, in its innermost region the stellar halo, the disc and the bulge contribute to the observed profile.

Figure 2. Schematic representation of the observed surface brightness profiles of a face-on and an edge-on disc galaxy according to our interpretation. The surface brightness profile of the stellar halo component is the same in both cases since it is assumed to be spherically symmetric. The surface brightness profile of the edge-on galaxy is 2 mag brighter than the face-on counterpart because of the LOS integration. This LOS integration brings the brightness of the galaxy at the truncation radius well above the stellar halo contribution, allowing us to detect it. In the face-on case, the truncation in the stellar disc is completely outshone by the brightness of the stellar halo.

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