Discovery of disc truncations above the galaxies’ mid-plane in Milky Way-like galaxies

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ABSTRACT

Disc truncations are the closest feature to an edge that galaxies have, but the nature of this phenomena is not yet understood. In this paper we explore the truncations in two nearby (D ∼ 15 Mpc) Milky Way-like galaxies: NGC 4565 and NGC 5907. We cover a wide wavelength range from the NUV and optical, to 3.6 μm. We find that the radius of the truncation (26 ± 0.5 kpc) is independent of wavelength. Surprisingly, we identify (at all wavelengths) the truncation at altitudes as high as 3 kpc above the mid-plane, which implies that the thin disc in those outer regions has a width of at least this value. We find the characteristic U-shape radial colour profile associated with a star formation threshold at the location of the truncation. Further supporting such an origin, the stellar mass density at the position of the truncation is ∼1-2 M⊙ pc−2, in good agreement with the critical gas density for transforming gas into stars. Beyond the truncation, the stellar mass in the mid-plane of the disc drops to just 0.1-0.2% of the total stellar mass of the galaxies. The detection of the truncation at high altitude in combination with the U-shape of the radial colour profile allow us to establish, for the first time, an upper limit to the present-day growth rate of galactic discs. We find that, if the disc of the galaxies are growing inside-out, their growth rate is less than 0.6-0.9 kpc Gyr−1.

Key words: galaxies: evolution – galaxies: formation – galaxies: structure – galaxies: stellar content – galaxies: individual: NGC 4565 and NGC 5907 – galaxies: spiral

1 INTRODUCTION

Many discs of spiral galaxies have a well-defined feature in their periphery called truncation. Truncations are found in three out of four galaxy thin discs (van der Kruit & Freeman 2011; Comerón et al. 2012) and typically occur at radial distances of four or five times the exponential scale length of the inner disc. Truncations should not be confused with the surface brightness breaks in Type II surface brightness profiles found at smaller radii (Pohlen & Trujillo 2006; Martín-Navarro et al. 2012). Beyond the truncation the light distribution declines rapidly (van der Kruit 1979; van der Kruit & Searle 1981a,b). The origin of this effective frontier for disc galaxies is yet unclear. Some authors suggest it could be linked to a threshold in star formation (Kennicutt 1989; Roškar et al. 2008b,a), for others, the truncation reflects the location of those stars with the largest angular momentum at the moment of the collapse of the protogalaxy (van der Kruit 1987). Other alternatives in the literature to explain the origin of breaks in the surface brightness distribution of the discs include bar angular momentum distribution (Debattista et al. 2006), or any other driver such as density waves, heating and stripping of stars by bombardment of dark matter subhaloes (e.g., Laurikainen & Salo 2001; de Jong et al. 2007). In order to probe the nature of this edge, we explore whether its location depends on either the wavelength at which it is measured or the height above the galaxy mid-plane (see e.g., de Jong et al. 2007). The truncation of discs can be seen at any galaxy orientation but, due to its location in the outer disc (and consequently at low surface brightness), an edge-on orientation is the most favoured one (see discussion in Martín-Navarro et al. 2012).

If a truncation is connected with an inside-out propagation of the star formation in the disc, the expectation is that the location of this feature changes as cosmic time progresses (such cosmic evolution has been observed for the location of type II breaks in disc galaxies since z ∼ 1, Trujillo & Pohlen 2005; Azzollini et al. 2008b). If this were the
case, the younger populations would be expected to show a truncation at larger radial distances than older populations. Similarly, due to the time delay for the stellar populations originated in the plane of the disc to reach a given distance above the galaxy mid-plane, the location of the truncation at large heights would be expected to occur at smaller radial distances than for stars at the mid-plane. Consequently, one could use the location of the radial truncation of discs to measure ongoing growth (if any) of disc galaxies. We explore these ideas in this paper.

Galaxies grow at different speed depending on their mass (see e.g., Trujillo et al. 2004, 2006). In this sense, to facilitate the interpretation of the data, we have explored two edge-on disc galaxies with masses similar to the Milky-Way: NGC 4565 and NGC 5907 (\(v_{\text{rot}} \approx 230\ \text{km/s}\)). To probe the ongoing growth of the galaxies it is necessary to have enough spatial and time resolution. The closer the galaxies are, the better the spatial resolution to explore the locations of the truncation as a function of wavelength and/or height. For this reason, we have taken two galaxies which are at a distance less than 20 Mpc. At the typical 1 arcsec resolution from ground-based data, this implies that the minimum difference in spatial location we can resolve is \(\sim 100\ \text{pc}\). To probe whether the truncation is moving (i.e., to measure its radial velocity), it is also necessary to have a time estimator. Throughout this work, we will use two different clocks. For the first approach, we use as a proxy to measure time the change in the NUV-r colour of recently formed stellar populations. We will show that intervals of time of just a few hundred Myr can produce variations of such a colour of \(\sim 1\ \text{mag}\). The other time indicator we will use is the time that it takes for a star originated in the disc plane to reach a certain height. We will show that at the radial distance of the truncation, the time that a star needs to arrive a few kpc above the disc is (again) around few hundred Myr. These two time indicators, together with our spatial resolution, allow us to measure growth rates with an accuracy better than \(0.5\ \text{kpc/Gyr}\).

Finally, in addition to measuring the growth rate of the disc, finding disc truncations at different heights above the galaxy mid-plane can help to measure the “thickness” of the thin disc. Although the origin of the truncation is not clear, if indeed it is related to a star formation threshold, then the truncation is expected to be a phenomenon linked exclusively with the thin disc. In this sense, if the truncations are clearly visible up to a given height, we could claim with some confidence that at such radial location the thin disc is still present. Consequently, the highest location at which the disc truncation can be measured can be used as a measure of the thickness of the thin disc.

The paper is structured as follows. In Sect. 2 we present our sample, selection criteria, and data. Then, we describe in detail the method and how the profiles are extracted (Sect. 3). The results are shown in Sect. 4 and analysed in Sections 5, 6 and 7. All magnitudes are provided in the AB system.

2 TARGET SELECTION AND DATA

We study the position of the truncation as a function of the height above the mid-plane in the two well-known highly inclined nearby galaxies NGC 4565 and NGC 5907 (see Fig. 1). We cover a wide wavelength range, from the near ultraviolet (NUV) and optical, to the infrared (IR). Table 1 summarizes the general information and physical parameters of both galaxies. For each object, the Hubble type was taken from the Spitzer Survey of Stellar Structure in Galaxies (S^3G, Sheth et al. 2010) morphology classification of Buta et al. (2015) and the distance was obtained from most recent values in the NASA/IPAC Extragalactic Database\(^1\) (NED). The other properties were taken from the HyperLeda\(^2\) database (Makarov et al. 2014).

2.1 Selection criteria

The galaxies were selected based on the apparent size, the mass, the inclination, the galaxy type and on the availability of images in the wide spectral range considered. In particular, we need galaxies with large apparent sizes \(d_{55} \gtrsim 10\ \text{arcmin}\) in order to reach good physical spatial resolution. We also want very inclined galaxies \(\text{incl} \gtrsim 85\ \text{deg}\) to ensure that our analysis is done in the vertical direction of the object. We choose Milky Way-like galaxies in terms of rotational velocity \(v_{\text{rot}} \sim 230\ \text{km/s}\) (Bland-Hawthorn & Gerhard 2016) but with different morphology (see Table 1). The main reason is that several N-body simulations have shown relations between the sources of internal secular vertical heating and galaxy morphology, such as spiral arms or bars (e.g., Sellwood & Carlberg 1984; Mincev & Quillen 2006; Grand et al. 2016). In this case, the main difference is the presence of a bar in NGC 4565 but not in NGC 5907 (Buta et al. 2015). Finally, we checked Sloan Digital Sky Survey Data Release 12 (SDSS DR12) images ( Alam et al. 2015) to avoid galaxies with bright foreground stars or very strong dust lanes. These selection criteria allow us to select discs that are sufficiently well visible and with enough spatial resolution to derive radial and vertical surface brightness profiles.

2.2 GALEX NUV data

The ultraviolet data were taken from the Galaxy Evolution Explorer (GALEX, Martin et al. 2005; Morrissey et al. 2007) Guest Investigator Program (GIP, PI V. Buat; NGC 4565: G16-049003, NGC 5907: G16-049002) in the NUV band (1750-2800 \(\AA\), 2267 effective wavelength). GALEX images have a circular field of view (FOV) of 1.2 degrees. GALEX data have a spatial resolution (FWHM) of 5.3 arcsec in the NUV channel sampled with a pixel size of 1.5 arcsec. The exposure times of our images are 12050.15 seconds in fourteen visits for NGC 4565 and 15118.45 seconds in eleven visits for NGC 5907, which gives a surface brightness limit of \(\mu_{AB} \sim 30.5\ \text{mag arcsec}^{-2}\) (1σ). To convert intensities to magnitudes, we used the GALEX zero point magnitude from Morrissey et al. (2007), \(m_{0,\text{NUV}} = 20.96\).

2.3 SDSS optical data

We use optical data from the SDSS DR12 (Alam et al. 2015) in the \(g\), \(r\) and \(i\) bands. As we are studying extended objects,

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1. http://ned.ipac.caltech.edu/
2. http://leda.univ-lyon1.fr/
3 METHODOLOGY

3.1 Masking process

We used the SDSS mosaic tool\(^3\), which stitches together the corrected frames in a selected region to form coherent images over larger patches of the sky. These mosaics were created using the SWARP (Bertin et al. 2002) utility. The resulting images were calibrated and sky-subtracted just as the corrected frames themselves are, but we also estimate our sky background independently (see Sect. 3.2 for more details).

The SDSS survey images have a pixel size of 0.396 arcsec and a mean PSF FWHM value in r-band of 1.3 arcsec. The exposure time for all the images is 53.9 seconds. Taking into account that we combine the three g, r, and i bands by adding them all together, in order to reach a deeper surface brightness limit, it is possible to extract reliable surface brightness profiles down to \( \mu \sim 27.0 \) mag arcsec\(^{-2} \) (1\( \sigma \) uncertainty less than 0.2 mag, Pohlen & Trujillo 2006), with a fixed zero point value of \( m_{0,gr} = 20.49 \). The combined gri profile is roughly equivalent to the r-band profile. We did not find any departure of the gri combined data from the r-band larger than 0.1 mag along the entire radial profile in the region where the photometric uncertainty is negligible.

\(^3\) http://dr12.sdss.org/mosaics/

Table 1. Properties and physical parameters of NGC 4565 and NGC 5907. Columns represent: (1) galaxy ID; (2) morphological type from Buta et al. (2015); (3) distance in Mpc from the average of the most recent values (since 2010) in the NED; (4) major axis position angle (North Eastwards) from the HyperLeda database (Makarov et al. 2014); (5) absolute B-band magnitude (HyperLeda, Makarov et al. 2014); (6) maximum rotational velocity corrected for inclination (HyperLeda, Makarov et al. 2014); (7) galaxy diameter in arcmin at the isophotal level 25 mag arcsec\(^{-2} \) in the B-band corrected for galactic extinction (HyperLeda, Makarov et al. 2014); and finally, (8) inclination to the line-of-sight in degrees obtained by the authors of this work assuming that the most dense part of the dust lanes of the galaxies are located in the mid-plane.

| Galaxy ID | Morph. type | \( D \) [Mpc] | PA [deg.] | \( M_{abs} \) [B-mag] | \( v_{rot} \) [km/s] | \( d_{25} \) [arcmin] | Incl. [deg.] |
|-----------|-------------|---------------|-----------|-----------------|-----------------|-----------------|--------------|
| NGC 4565  | SB(r)gb spw | 13.1 ± 0.5    | 135.2     | -21.44 ± 0.24   | 243.6 ± 4.7    | 16.6 ± 0.1     | 88.5 ± 0.5   |
| NGC 5907  | SA:nd)c spw | 16.9 ± 0.3    | 155.6     | -21.48 ± 0.14   | 226.6 ± 4.3    | 11.2 ± 0.1     | 87.5 ± 0.5   |

Figure 1. Images of NGC 5907 (left) and NGC 4565 (right) in SDSS gri combined light (roughly equivalent to a deep r-band image). For illustrative purposes, a colour image obtained with the same telescope has been inserted atop the saturated disc region of the galaxy. Panels in the first row show the observed data and the second row are the PSF deconvolved models for each galaxy (see Sect. 3.4 for details). Overplotted on all the images are the surface brightness contours (red lines) corresponding to 27 mag arcsec\(^{-2} \).

2.4 Infrared S\(^4\)G data

The S\(^4\)G project (Sheth et al. 2010) obtained 3.6 and 4.5 \( \mu \)m images of 2352 nearby galaxies (\( D < 40 \) Mpc) using the Infrared Array Camera (IRAC, Fazio et al. 2004). We are particularly interested in the 3.6 \( \mu \)m band (IRAC channel 1) because it is a reasonably good tracer of stellar mass density and the images are less affected by dust. This is a key point when dealing with edge-on galaxies as there is a lot of dust along the line of sight. The S\(^4\)G team have reduced all the data by using their pipelines (Muñoz-Mateos et al. 2015; Querejeta et al. 2015; Salo et al. 2015).

The S\(^4\)G IRAC 3.6\( \mu \)m images have a pixel size of 0.75 arcsec and each galaxy was observed for 240 seconds. The limit in the surface brightness profiles is \( \mu \sim 27.0 \) mag arcsec\(^{-2} \) (1\( \sigma \)) using a zero point of \( m_{0,SG} = 20.472 \).

3 METHODOLOGY

3.1 Masking process

Dealing with deep imaging of the outskirts of galaxies requires careful treatment to remove the light from foreground...
and background objects (see e.g., Trujillo & Fliri 2016). The goal of the masking process is to keep only the flux from the sources we want to analyse, avoiding contamination in their fainter parts. Thus, we mask every fore-and background emission source using a semi-automatic code (see an example in Fig. 2).

First, using SExtractor (Bertin & Arnouts 1996), the code detects the sources in the whole image, and builds a mask with all of them. Then, we use Python-based routines to unmask the galaxy under study. To do that, we create a code to convert all the masked areas (but the target) provided from SExtractor in masked pixels. The target is identified by comparing its coordinates with those of the SExtractor masked regions. Finally, we check visually whether the extent of the mask covers all undesirable flux. For better inspection, we smooth the images and adjust the contrast to the background limit. This allows us to see if the size of the individual masks is big enough to cover all light from sources which are not our target. If not, we increase each masked area in steps of three pixel dilation to completely avoid all the non-desirable flux. By repeating this process, we are able to remove the background sources from the image. However, some objects that SExtractor has problems to detect can remain visible around the galaxy under study, in its outskirts and even within it (e.g., stars from our Galaxy). To get rid of these, we add masks manually with Python.

This is a common method for all bands, except for the S^4G data, where the masks were supplied by the S^4G team (details in Sheth et al. 2010). In this case, we increase the masked areas using the same method than above to cover all foreground and background objects flux when adjusting the contrast to the background limit.

### 3.2 Sky subtraction and background treatment

We used background-subtracted images from each of the telescopes. However, once the images were masked (see Sect. 3.1), we performed non-aggressive sky subtraction by measuring the background level as in Pohlen & Trujillo (2006). We determined the gradient of a very extended radial surface brightness profile of each galaxy (∼1.5 times the size of the galaxy), convolved with a one-dimensional Gaussian kernel (1 pixel standard deviation). The mean sky level of each image is the mean value of the most extended part (∼80 arcsec length) of the radial surface brightness profile in the corresponding flattest region of its gradient function for each galaxy, and this is subtracted from the whole image. As we obtain the sky value from our region of interest through very extended radial surface brightness profiles, this method allow us to identify clearly where a galaxy ends and, consequently, where a profile starts to be dominated by the sky background component. Note that our data was free of large scale gradients in the sky background emission, so the procedures in Peters et al. (2017) are not considered here.

### 3.3 Profile extraction and truncation position

The galaxy surface brightness profiles in the radial direction were extracted by calculating the flux values along a slit of constant width. The width of the slit was determined in terms of the physical distance (kpc) in the galaxy, depending on its apparent size and distance. The methodology followed to obtain the profiles is the same for all the wavelength ranges. The first step was to rotate the masked and sky-subtracted galaxy image in order to have horizontal major axes.

To obtain the radial surface brightness profiles, we started with a central profile in the galactic plane using a slit of 0.5 kpc width (see Fig. 3). We calculated the right-
and left-band side surface brightness profiles separately, by dividing the slit into radial logarithmic scale bins, from the centre of the galaxy to the outer regions. The logarithmic bins allow us to increase the signal to noise ratio (S/N) in the outskirts. For each bin, we calculated the surface brightness correcting by $A_\lambda$, the Galactic extinction coefficient at each wavelength, presented as the total absorption in magnitudes in the NED. The final surface brightness profile distribution was obtained by averaging the left and right radial logarithmic bins at the same distance from the centre of the galaxy. Despite small asymmetries in the radial direction, we combine the two sides to explore the surface brightness profiles down to very faint levels (below $\mu = 27.0$ mag arcsec$^{-2}$).

After producing the central radial profile, we obtained the shifted radial surface brightness profiles at a given height above and below the galaxy mid-plane. We proceed in a similar manner to the mid-plane profile, but averaging the right and left radial logarithmic bins of the profile above and below the galaxy mid-plane. The first shifted radial surface brightness profile is obtained at $|z| = 0.5$ kpc above and below the galaxy mid-plane with a height (vertical box) also equal to 0.5 kpc. Then, by repeating the same procedure we go up/down in steps in height of 0.5 kpc up to where we start to lose S/N. We consider low S/N when the mean size of the error bars is larger than the intrinsic oscillations in the profile due to the galaxy structure (i.e., spiral arms, regions of star formation, etc), and we recover the S/N by increasing the vertical box height. As our two galaxies are different in terms of apparent size and distance, the steps in height above (and below) the mid-plane of the galaxy were as follows (see also Fig. 3): for NGC 4565, boxes with 0.5 kpc height up to 3 kpc, and then steps of 1.0, 1.5 and 2.0 kpc at 4.0, 5.5 and 7.5 kpc altitude, respectively; in the case of NGC 5907, 0.5 kpc boxes up to $|z| = 2.5$ kpc, followed by boxes of 0.7, 1.5 and 2.5 kpc at altitudes of 3.2, 4.7 and 6.7 kpc above the mid-plane, respectively. As we are combining boxes which are above and below the galaxy mid-plane we explored whether there are any significant differences between these two regions of the galaxy (see Appendix B). We do not find any significant difference between the two sides of the galaxies except slightly different ($\Delta \mu_{gri} \sim 0.3$ mag arcsec$^{-2}$ for NGC 4565 and $\Delta \mu_{gri} \sim 0.1$ mag arcsec$^{-2}$ for NGC 5907) surface brightnesses, expected from the fact that the galaxies are not perfectly edge-on (particularly NGC 5907).

The uncertainties in each bin of the profiles were for all cases defined as:

$$\sigma_{\text{bin}}^2 = \sigma_{\text{Poisson,bin}}^2 + \sigma_{\text{sky,bin}}^2,$$

which is the result of the quadratic sum of the Poissonian error of the bin ($\sigma_{\text{Poisson,bin}}$) and its associated sky error value ($\sigma_{\text{sky,bin}}$). The first is the contribution of the Poissonian error in the determination of the signal in each bin of the profile:

$$\sigma_{\text{Poisson,bin}} = \text{RMS}(\bar{I}_{\text{bin}} - f_{\text{pix}})/\sqrt{N_{\text{bin}}},$$

where $f_{\text{pix}}$ is the intensity value of a given pixel inside the bin; $\bar{I}_{\text{bin}}$ is the mean intensity value of all the pixels in the bin; RMS is the root mean square of the expression in brackets; and $N_{\text{bin}}$ is the number of pixels along the bin area. The second source of error is the uncertainty in the determination of the sky due to fluctuations at the bin area scale. It can be written as:

$$\sigma_{\text{sky,bin}} = \text{RMS}_{\text{sky}}/\sqrt{N_{\text{bin}}}.$$
estimate of the RMS per pixel and the confidence in the mean for each region by using the Python package scipy.stats.bayes_mvs (Oliphant 2006). The uncertainty of the RMS was based on the average confidence limit for the mean.

The last part of this process was to determine the position of the truncation, which we define as the sharp edge of a highly-inclined galaxy. We consider that the slope change at the position of the intersection between the prolongations of two exponential components in a surface brightness profile. For an unbiased measurement of the truncation radius, we followed the steps of Pohlen & Trujillo (2006). We took the derivative of a rebinned and smoothed version of the profile (i.e., smoothing by a Gaussian with $\sigma = 1$ pixel) at each bin around the truncation radius. Hence, we obtained two regions with nearly constant but different scale lengths together with a downward bend (i.e., a downbending) in the profile. A characteristic scale length value was taken as the median of this distribution to avoid a bias towards the more extended region. The truncation position is the radius where that median value cuts the derivative profile. We defined an inner and outer boundary of the truncation region where the profile (starting from the truncation) reaches a value within two standard deviations away from the mean calculated for the inner/outer region separately. The derived truncation radii are almost always consistent with those derived by eye.

### 3.4 The effect of the PSF on the surface brightness profiles

Before starting the analysis of our findings it is necessary to explore whether the effect of the point spread function (PSF) can alter the location of the truncation. Although this may appear unlikely in the mid-plane of the galaxies, it is worth exploring whether any potential truncation feature above the mid-plane could be the result of a PSF effect. Another issue to explore is whether the addition of extra light by the PSF in the outer (beyond the mid-plane) regions of the galaxies can affect the location of this feature at high altitudes.

The PSF effect is stronger in edge-on than in face-on galaxies (e.g., de Jong 2008; Sandin 2014, 2015) due to the departure from the circular symmetry in the edge-on configuration (see a quantification of the effect of the ellipticity on the PSF effect in Trujillo et al. 2001a,b). This has been explored in previous work (e.g., Zibetti et al. 2004; Sandin 2014; Trujillo & Fliri 2016; Peters et al. 2017; Comerón et al. 2017) which showed that the properties of stellar haloes and faint outskirts of galactic discs can be influenced significantly by the wings of the PSF.

To check how the faint wings of the PSF are affecting our measurements, we used an extended SDSS r-band PSF ($R = 13.2$ arcmin), built by combining very bright (saturated) and fainter stars (following the same procedure as in Fliri & Trujillo 2016). We then used IMFIT (Erwin 2015) to perform a 2D fit of a truncated exponential disc for each galaxy, producing PSF-convolved and -deconvolved models. We made a two-disc fit (thin and thick disc) with a bulge and a bar component (the latter only for NGC 4565) to properly reproduce both galaxies. In the two cases, we needed a thin disc truncated at the same distance as the data and a pure exponential thick disc. Fig. 1 shows how our galaxy images are affected by removing the PSF.

In order to quantify the effect of the PSF on the surface brightness profiles, we extract the surface brightness profiles from the deconvolved images following exactly the same slit configurations as in the original dataset. Fig. 4 shows that the position of the truncation is not affected by the PSF: its value is exactly the same as in the original data (see Sect. 4). In Fig. 4 we also see the truncation up to $z = 3$ kpc, but it is not more prominent than in the data (see details in Figs. A4 and A8). Thus, the truncation position is not affected by the PSF in terms of the height above the galaxy mid-plane where it is detectable, nor in terms of its visibility.

We have explicitly checked the effect of the PSF only on the optical bands and assume that the effect of the PSF is also negligible in the other bands. The reason is that (as we will see in Sect. 4) the location of the truncations is the same (within the error bars) from NUV to IR (infrared). As the position of the truncation is independent on the wavelength (which implies different telescopes and cameras with both, different PSFs and spatial resolutions). Occam’s razor justifies the assumption that the location of this feature is essentially unaffected by the effect of the PSF.

### 4 RESULTS

#### 4.1 Truncations from NUV to IR

In Fig. 5 we plot the radial surface brightness profiles along the mid-plane of NGC 4565 and NGC 5907 in our three wavelength ranges: GALEX NUV, SDSS gri combined band and Spitzer 3.6 µm. The profiles were obtained as described in Sect. 3.3, where the slit width is 0.5 kpc and the radial bin size changes logarithmically.

In both galaxies, a truncation is clearly observed. The change in slope between the inner region of the disc ($R < R_{\text{trun}}$) and the outer region ($R > R_{\text{trun}}$) is more prominent in bluer bands, and the truncation is more prominent in the NIR band. It is least pronounced, but still clearly present in the IR. The main difference in the shape of the surface brightness profiles is in the flux inside the truncation. The effect of dust in this region severely affects the NUV and the optical profile, producing a much flatter distribution than in the NIR regime (see a review of dust extinction in Mathis 1990). It is worth observing that, beyond the truncation, the shapes of the surface brightness profiles in all the bands are quite similar, highlighting that beyond this feature the dust has a smaller (if any) effect than in the inner parts.

Figure 5 shows that the stellar mass density (traced by the IR band) in both galaxies has a peak near the centre because of the bulge (more prominent in NGC 4565), afterwards it decreases slowly until the truncation, after which it falls. If we assume the difference between the IR and optical profiles to be predominantly due to dust, we deduce that the fraction of dust in total local mass density is roughly constant from the centre up to ~10 kpc in both galaxies, and then it diminishes until the position of the truncation. The similar slope after the truncation for all bands suggest that

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4 See the approximately constant gri-3.6µm–2 mag colour inside 10 kpc in both galaxies in Fig. 7.
there is essentially no dust in that region. This finding is extremely interesting as it suggests that star formation after the truncation has a low SFR (star formation rate). Finally, in the NUV band we see the discs strongly affected by dust extinction (see also Fig. 2, lower panel) so the distribution is mainly flat with some fluctuations due to either star formation activity peaks or less dust extinction from ∼10 kpc up to the truncation position, for both galaxies. Beyond that position, the profiles decrease sharply.

### 4.2 Radial SB profiles: truncation position is independent of colour

Figure 6 shows another noteworthy feature in common between the two galaxies: the radial location of the truncation is the same (within the error bands) in all the three wavelength ranges, NUV (GALEX), SDSS gri combined band, and the IRAC/Spitzer 3.6 μm. We obtained a mean value for the three wavelengths at the galaxies mid-plane of 26.7 ± 0.4 kpc for NGC 4565 (26.3 ± 0.4 kpc for NUV, 27.0 ± 0.4 kpc in optical and 26.9 ± 0.4 kpc in NIR), and 26.2 ± 0.2 kpc for NGC 5907 (26.0 ± 0.2 kpc in NUV, 26.0 ± 0.1 kpc in optical and 26.6 ± 0.2 kpc for the NIR), although these values in physical units are affected by uncertainties in the distance (see Sect. 2 and Table 1). The independence of the location of the truncation on wavelength suggests that the truncation is a robust feature of the galaxies. This is because the truncation is observed in profiles as different as the one that traces the stellar mass density (i.e., 3.6 μm) and the one connected with star formation activity (i.e., NUV). As we will explore later, this makes the truncation ideal to measure the sizes of the discs as well as to explore the ongoing growth of the galaxies.

Interestingly, although we do not know whether this is just by chance or physically connected to the fact that our two galaxies have the same maximum rotational velocity (i.e., ∼230 km/s), the surface brightness and the radial position of the truncations are very similar in both objects (i.e., μ3.6μm ∼23 mag/arcsec² and R_{trun} ∼ 26.5 kpc).

### 4.3 Comparison with previous studies

NGC 4565 and NGC 5907 were the first galaxies in which a truncation was detected and analysed via surface photometry from photographic plates (van der Kruit 1979; van der Kruit & Searle 1981a,b). They defined the truncation location as a cut-off radius, R_{max}, just after a sharp cut-off with an exponential folding of ≤ 1 kpc (see Figs. 5 and 11 from van der Kruit & Searle 1981a). Their values for R_{max} were 32.6 kpc for NGC 4565 (assumed distance 10 Mpc) and 29.6 kpc for NGC 5907 (for a distance modulus of 11 Mpc). These values were later confirmed with excellent precision using CCD photometry by Morrison et al. (1994) for NGC 5907, and by Wu et al. (2002) for NGC 4565. There is also good agreement with our results if we consider the discrepancies in the truncation definition between these works and...
our study (we set the truncation position at the cut-off of the exponential folding), as well as the different distance values.

Comparing with other results recently published in the literature, we find that our estimates of the positions of the truncation are in good agreement. Martín-Navarro et al. (2012) obtained surface brightness profiles for 34 highly inclined spiral galaxies from the S$^4$G, including NGC 5907. They find that NGC 5907 is a type II galaxy (truncated) with its truncation position located at $R \sim 26.0$ kpc, in agreement with our result taking into account that their assumed distance to the object (16.3 Mpc) is slightly different from ours (16.9 Mpc).

Seventy S$^4$G edge-on galaxies were studied in Comerón et al. (2012), and later in Comerón et al. (2017). From 1D surface brightness profile fitting of NGC 4565 for the whole disc, but also for each component (thin and thick disc) separately, Comerón et al. showed that NGC 4565 is a type II+II galaxy, i.e., with two truncations along the disc. The second truncation (in which we are interested) is located at $R \sim 26.0$ kpc, in agreement with our result taking into account that their assumed distance to the object (16.3 Mpc) is slightly different from ours (16.9 Mpc).

Figure 5. Surface brightness profiles along the disc mid-plane of NGC 4565 (up) and NGC 5907 (down) in the three wavelength ranges (UV/optical/NIR).

Figure 6. Truncation position at each wavelength, measured from the SB profiles along the disc plane (above) and at different heights in the SDSS-$gri$ combined band (bottom). In both cases the dashed lines represent the mean value of the points in the corresponding colour.

4.4 Truncation position is constant above the mid-plane

In order to study the vertical behaviour of the position of the truncation, we derived radial surface brightness profiles at different altitudes above (and below) the galactic mid-plane in the two galaxies, as explained in Sect. 3.3. In Appendix A, we show the set of surface brightness profiles: Figs. A1, A2 and A3 show the results for NGC 4565 in the NUV, $gri$ and
3.6\mu m bands, respectively, while Figs. A5, A6 and A7 show the results of NGC 5907.

In Fig. 6 we summarise this by showing all the positions of the truncation values along the vertical axis in the case of the SDSS gri combined band, for both galaxies. The position of the truncation of NGC 4565 is practically constant up to a height of $z \sim 3$ kpc. Above that value, we are unable to explore the truncation and the profiles become compatible with pure exponentials, considering the poor S/N. For NGC 5907, we observe the same behaviour, but up to $z \sim 3.2$ kpc. Figures in Appendix A show that the position of the truncation is roughly the same for the whole wave-length range, up to those altitudes, in both galaxies. It is important to note that the truncation is always sharpest in the mid-plane and becomes less prominent at larger heights.

The values that we derive for the position of the truncation for both galaxies in the optical and at different altitudes are shown in Fig. 6. The average truncation values for all the heights (indicated in Fig. 6 with dashed lines for the optical) are: 26.2\pm0.4 kpc (NUV), 26.6\pm0.4 kpc (optical) and 26.3\pm0.4 kpc (NIR) for NGC 4565 and 26.1\pm0.2 kpc (NUV), 26.1\pm0.2 kpc (optical) and 26.1\pm0.3 kpc (NIR) for NGC 5907.

The independence of the location of the truncation with height has been also found in a previous study; de Jong et al. (2007) showed that the truncation (they call it break) occurs at the same radius independent of the height above the disc up to $z \sim 1.5$ kpc in the low-mass ($v_{\text{esc}} = 98$ km/s; $M_{\text{dyn,B}} = -18.4$) edge-on galaxy NGC 4244. This study is based on resolved stellar populations of NGC 4244 by counting stars in both F606W and F814W bands of the HST Advanced Camera for Surveys (ACS). They also found that the truncation is sharpest in the mid-plane and nearly disappears at large heights, also in concordance with our results.

In further agreement, Comerón et al. (2012, 2017) found that beyond 3 kpc above the mid-plane, the surface brightness profiles of NGC 4565 do not show any evidence for truncation. In particular, they explored the region from $z \sim 42$ arcsec (2.7 kpc) up to $z \sim 110$ arcsec (7.0 kpc) above the galaxy mid-plane.

It is noteworthy that our truncation position values are affected by the spatial resolution of the surface brightness profiles. In NGC 4565, the corresponding surface brightness profile width is equal to 0.5 kpc. In the case of NGC 5907, as its absolute magnitude is similar to NGC 4565 but the distance to the object is higher (see Table 1), the S/N is lower at such altitudes. Consequently, the last profile where we detect the truncation is 0.7 kpc wide. In this way, a more conservative statement would be that the location of the truncation is the same at all heights up to $z \sim 3$ kpc in both galaxies. Above 3 kpc, this feature is not visible, either (1) because it is where the truncation actually ends and/or (2) the light coming from the thick disc or from the stellar halo outshine the thin disc.

Finally, we stress again that the location of the truncation as visible up to 3 kpc in both galaxies occurs at a similar position. As previously stated, this may either be a consequence of the similar characteristics of the galaxies or simply a coincidence.

4.5 Radial colour profiles

From the radial surface brightness profiles in the three wave-length ranges, we can obtain radial colour profiles. In Fig. 7 we show the $gri$-3.6\mu m and the NUV-$gri$ radial colour profiles for both galaxies along the mid-plane, at 1.5 kpc and at 3 kpc height above/below it. The colours are similar (though bluer in the mid-plane) at the truncation radii for the three altitudes in all cases. Inward of the truncation, the colours show a negative gradient (less clear for NUV-$gri$ in NGC 5907) with a very similar behaviour between the radial profiles at 1.5 kpc and 3 kpc height above/below the mid-plane. The mid-plane profiles are strongly affected by dust, mainly in the inner parts of both galaxies. Beyond the truncation, in the NUV-$gri$ mid-plane colour, we can observe an increase in the colour values for the two galaxies\(^5\). This U-shape around the truncation resembles the behaviour found at the break position in previous works (see e.g., Azzollini et al. 2008a; Bakos et al. 2008). We will take advantage of this feature below to explore the ongoing growth of these galaxies.

4.6 The vertical extent of the thin disc

Our analysis of the surface brightness profiles above the galaxy mid-plane shows that it is possible to identify the truncation up to at least 3 kpc above/below the disc plane. Moreover, the location of the truncation, within the uncertainty in determining this position, is the same independently of the altitude above the disc. It is difficult to understand this without invoking a similar physical origin for the truncation in both the galactic plane and at higher altitudes. The obvious conclusion is then that the thin disc extends up to at least 3 kpc in height. Thus, we can use the maximum height where the truncation has been identified to provide a lower limit to the vertical extent of the thin disc.

The above result does not imply that there is no need for a thick disc in our two galaxies - our result only suggests that the brightness of any thick disc component is not enough to outshine the truncation feature from the thin disc up to at least 3 kpc height. In this sense, we can make a direct comparison of our results with Comerón et al. (2017), who found that the ratio of thick to thin disc mass is a declining function of the total mass of the galaxy as measured by the circular maximum velocity. In the galaxy we have in common, NGC 4565, Comerón et al. (2017) quote a mass ratio between the two disc components of 14%. In addition, they provide the surface brightness profiles of both the thin and thick component (see their Appendix). At the location of the truncation, they report $\Sigma_T(0)/\Sigma_0(0)=0.04$, and scale heights $h_t=7.1$ arcsec (0.45 kpc) and $h_T=49.3$ arcsec (3.15 kpc) for the thin and thick discs, respectively. If we assume an exponential decay for both disc components in the vertical direction: $\Sigma(z) = \Sigma_0(0) \times \exp(-z/h_t)$ (thin disc) and $\Sigma_T(z) = \Sigma_T(0) \times \exp(-z/h_T)$ (thick disc), these numbers imply that the thick disc starts to dominate the light of the thin disc at $z = 1.7$ kpc. However, making reasonable assumptions on the dilution of the thin disc truncation by\(^5\) There is a hint that the same behaviour could also happen in the $gri$-3.6\mu m colour, although the trend is not so obvious as in the NUV-$gri$ colour.
Figure 7. Radial colour profiles for both galaxies along their mid-plane, at 1.5 kpc and at 3 kpc height (NGC 5907 at left and NGC 4565 at right). The rows show the different colours: gri - 3.6µm in the top row and NUV - gri in the bottom. The vertical dark grey regions of each galaxy represent the mean position of the truncations for all the heights in the SDSS-gri combined band, plus/minus the standard deviation of that distribution of truncation positions: 26.1±0.2 kpc for NGC 5907 and 26.6±0.4 kpc for NGC 4565.

thick disc light (i.e. the thin disc 10 times fainter than the thick disc), we can estimate that the truncation can be observed up to $z \sim 2.9$ kpc, in very nice agreement with our observed result. Thus, our data show that we are able to detect the truncation of the thin disc at altitudes as high as 3 kpc. In future work, we will use deeper data (with better S/N) of NGC 4565 to discuss whether the truncation can be detected at even higher distances above the mid-plane.

5 THE ONGOING GROWTH OF GALACTIC DISCS

In this section we will discuss two methods to measure the ongoing growth of galactic discs. In the first, we will use the location of the truncation at different heights above the mid-plane. The second method analyses the shape of the radial colour profiles beyond the truncation.
the location of the truncation in the mid-plane moves a radial distance \( \Delta R \). In this particular example, we use \( z = 3 \) kpc to illustrate this idea.

### 5.1 First approach: offsets in the location of the truncation at different heights

Stars move (in a movement called migration; see for a review Sellwood 2014; Debattista et al. 2017) both in the radial and vertical directions. Stars currently being formed in the mid-plane at the truncation position will take some time to reach a given height above the mid-plane of the galaxy. For this reason, considering a propagation of the star formation from inside-out, the location of the truncation at a high location should be closer to the galactic center than that in the mid-plane. We illustrate this with a cartoon in Fig. 8.

We call \( v_{\text{growth}} \) the speed at which the location of the truncation moves radially outwards in the mid-plane. Given an amount of time \( \Delta t \), the position of the truncation in the mid-plane moves a radial distance \( \Delta R \). As stars born at the truncation in the mid-plane take a time to reach a given height \( z \), we can use the different position of the truncation at height \( z \) compared to the mid-plane to measure the speed of galaxy growth. The key element is then to know how much time it takes a typical star to reach a certain height \( z \) at a given radial distance \( R \). Once this is known, \( v_{\text{growth}} \) will be simply:

\[
v_{\text{growth}} = \frac{\Delta R}{\Delta t}.
\]

In order to estimate \( v_{\text{growth}} \), we estimate how long it takes for a given star in the disc mid-plane to reach a height of 3 kpc (i.e., we calculate \( \Delta t \)). We use \( z = 3 \) kpc as this is approximately the maximum height at which we are able to measure the truncation above the mid-plane for both galaxies. To estimate \( \Delta t \), we calculate the difference in gravitational potential between a star located at a radial position \( R \) and \( z = 0 \), and a star at the same radial distance \( R \) and \( z = 3 \) kpc. This way, we can estimate the initial vertical velocity \( v_z \) that a star needs to reach a height \( z \) starting from the mid-plane \( v_z \).

The gravitational potential for an infinitely thin disc is given by Toomre (1963):

\[
\Phi(R, z) = -2\pi G \int dk \exp(-k|z|)J_0(kR)S(k),
\]

where \( S(k) = \int dR \Sigma(R)RJ_0(kR) \) is the Hankel transform of \( \Sigma(R) \), and \( J_0(kR) \) is the zero-order first-kind Bessel function.

We consider an exponential disc with surface density:

\[
\Sigma(R) = \frac{\alpha^2 M}{2\pi R_0} e^{-\alpha R},
\]

where \( M \) is the total disc mass and \( \alpha \) is the inverse of the disc scale length (\( h \)). Thus, if we call \( \Sigma = \alpha^2 M/2\pi \), the resulting gravitational potential as a function of \( R \) and \( z \) is:

\[
\Phi(R, z) = -\frac{2\pi G \Sigma_0}{\alpha^2} \int_0^{\infty} dk \frac{J_0(kR)e^{-k|z|}}{[1 + k^2\alpha^2]}.
\]

As our galaxies are similar to the Milky Way, we use for a rough estimate of \( v_z \) the structural properties of the disc of our Galaxy. In other words, we replace the galaxy physical parameters by those of the Milky Way from Bland-Hawthorn & Gerhard (2016):

\[
M = 3.6 \times 10^{10} M_\odot; \quad h = 2.6 \text{kpc}.
\]

We solve numerically the integral of the gravitational potential and we then assume that the corresponding potential energy at \( R = 25 \) kpc and \( z = 3 \) kpc is equal to the kinetic energy at the same radial distance but \( z = 0 \) kpc. Hence, taking the values above, we find \( v_z = 10.8 \text{kpc/Myr} \) (i.e., \( v_z \sim \frac{10.6 \text{km/Myr}}{10} \) at \( R = 25 \) kpc.

Once we have the gravitational potential distribution along the disc, the gravitational acceleration at any \((R, z)\) position is given by:

\[
g(R, z) = -\nabla \Phi(R, z).
\]

Having \( v_z \), we are now ready to estimate \( \Delta t \). We divide the trajectory of the star from \( z = 0 \) to \( z = 3 \) kpc in steps of 0.1 kpc. This simplifies our measurement, as we can assume constant acceleration in such small vertical steps and we can use the motion equations for a particle under uniform acceleration. With the above \( v_z \), the amount of time a star at \( R = 25 \) kpc needs to reach \( z = 3 \) kpc is \( \sim 0.45 \text{Gyr} \).

These give us now the possibility to estimate \( v_{\text{growth}} \). In reality, as we are unable to measure \( \Delta t \) with our current uncertainties, we use those uncertainties to provide an upper limit to the maximum growth speed of the discs in our two galaxies. For NGC 4565 we use \( \Delta R < 0.25 \text{kpc} \) and for NGC 5907 \( \Delta R < 0.4 \text{kpc} \). With such values, the maximum speed for the growth of our galaxies is: \( v_{\text{growth}} < 0.9 \text{Gyr}^{-1} \) for NGC 4565 and \( v_{\text{growth}} < 0.6 \text{Gyr}^{-1} \) for NGC 5907.

It is worth stressing the approximations that have been used in our estimate of \( v_{\text{growth}} \). The most relevant one is that we have neglected the effect of the gravitational potential of both the bulge component and the dark matter halo of these galaxies. This is justified as we have only explored the difference in gravitational potential in a region very close to the galactic disc (i.e., \( z = 3 \) kpc) and at a large distance from the center (\( R = 25 \) kpc). At such location, the difference in radial distance from a star in the mid-plane with a star at \( z = 3 \) kpc is just 0.2 kpc. Consequently, the gravitational potential of the bulge is basically the same in both locations. Similarly, assuming a spherical dark matter halo, the small difference
in the radial position with respect to the galactic center implies that the variation of the gravitational potential for such structure is small. In this sense, the main component responsible for the difference in gravitational potential is the disc. Another source of uncertainty in our estimate is the use of the stellar mass and radial scale length of the MW to model these two galaxies. We base this approximation on the fact that their rotational velocities are similar to the one in our Galaxy.

We now discuss how reasonable is the value of \( v_z \) we have estimated. To do this we use the fact that we know the surface brightness at the location of the truncation, both at \( z=0 \) and \( z=3 \) kpc; at \( z=0 \): \( \mu_{3.6\mu m} \sim 23 \) mag/arcsec\(^2\). The same estimate at \( z=3 \) kpc, yields \( \mu_{3.6\mu m} \sim 26 \) mag/arcsec\(^2\). Consequently, the difference in stellar mass density, assuming a similar \( M/L \) for both locations, is a factor of 16. In other words, stars are 16 times more abundant in the disc mid-plane than at 3 kpc height at the location of the truncation. We assume now that the vertical velocity distribution of stars at the location of the truncation is Gaussian. If this were the case we can estimate what would be the velocity dispersion \( \sigma_z \) of such a distribution, in which the density of the stars at 3 kpc were a factor of 16 smaller than at \( z=0 \) kpc. Under this hypothesis we find typical values of \( v_z \sim 11 \) km s\(^{-1}\), which will correspond to stars with \( -2.4 \sigma_z \). In other words, the vertical velocity dispersion should be \( \sigma_z=4.5 \pm 0.3 \) km s\(^{-1}\). Unfortunately, there are no measurements of the vertical velocity dispersion of the stars at radial distances as large as \( R=25 \) kpc. We can only compare this number with the typical vertical velocity dispersion of the thin disc at the radial location of the Sun (\( R=8.2 \pm 0.1 \) kpc): \( \sigma_z^2=25 \pm 5 \) km s\(^{-1}\) (Bland-Hawthorn & Gerhard 2016). As expected, the estimated velocity dispersion at \( R=25 \) kpc is significantly smaller than at \( R=8 \) kpc. As the velocity dispersion is expected to decrease as the square root of the mass density, the mass density at the Solar position will then be \( (25/4.5)^2=31 \) times larger than at the truncation. The local mass surface density at the Solar position is \( 70 \pm 5 \) \( M_\odot \) pc\(^{-2}\) (Bland-Hawthorn & Gerhard 2016). The prediction is then that the local mass surface density at the truncation should be \( \sim 2.3 \) \( M_\odot \) pc\(^{-2}\). Using both the NUV-\( r \) and \( g-r \) colours at the truncation, as well as the surface brightness in \( g-r \) and \( \mu_{3.6\mu m} \) corrected by the effect of inclination (which is around 2 mag; Martín-Navarro et al. 2014) we can estimate whether \( \sim 2 \) \( M_\odot \) pc\(^{-2}\) is in agreement with our data. We use the model by Vazdekis et al. (2016) assuming a bimodal IMF (initial mass function) and Solar metallicity, to reach the following estimate of the stellar mass densities at the truncation position: \( 1.4-2.4 \) \( M_\odot \) pc\(^{-2}\) (NGC 4565) and \( 0.4-1.4 \) \( M_\odot \) pc\(^{-2}\) (NGC 5097). These numbers show that, even the results do seem to be consistent though we are using simple approximations.

5.2 Second approach: the shape of the radial colour profile beyond the truncation

Another way to measure the growth speed of the galaxies is by exploring the shape of the radial colour profile beyond the truncation. The main assumption that we make in this approach is the following: beyond the truncation there is negligible new star formation. This seems to be a very good approximation, considering the sharp decline in all the surface brightness profiles, particularly in the NUV, after the truncation. If our hypothesis is correct then we can interpret the gradual reddening colour of the stars beyond the truncation as purely driven by the passive aging of their stellar populations. We also assume that beyond the truncation the dust obscuration is not playing any role, in agreement with the idea that there is no star formation beyond this point. In this sense, the stars that we observe there will be the result of migration from the regions of the disc inside the truncation towards the outer parts.

In order to estimate the growth speed of the disc \( v_{growth} \) we follow the scheme presented in Fig. 10. We use the NUV-\( r \) radial colour profile\(^6\) as a proxy for measuring the time interval \( \Delta t \). We use this colour profile as this combination of bands is very sensitive to recent star formation and consequently allows us to measure intervals of time of the order of 100 Myr. In our scheme, stars are born at a radial position \( R \) (which coincides with the initial location of the truncation at the beginning of the time interval). After a given time \( \Delta t \), the stars have moved outward a radial distance \( v_{stars} \times \Delta t \). At the same time, the truncation has also moved outwards by \( v_{growth} \times \Delta t \). It is then straightforward to show that:

\[
\Delta R = v_{stars} \Delta t + v_{growth} \Delta t .
\]

The values \( \Delta R \) and \( \Delta t \) can be inferred directly from the data. This last interval, \( \Delta t \), is measured using \( \Delta(NUV-gri) \). In Fig. 9 we highlight the location of the truncation region for our two galaxies.

We use the following positions in the colour-radial distance plane to measure \( \Delta R \) and \( \Delta t \). For the galaxy NGC 4565: (27.6±0.2 kpc, 1.9±0.1 mag) and (28.3±0.2 kpc, 26.9±0.2 mag).

\(^6\) Actually, we use the colour profile NUV-gri to gain S/N in the outer regions of the galaxies. We have confirmed that the combined gri surface brightness profile is equivalent to the \( r \)-band to a level below 0.1 mag along the entire profile of the galaxies.
Truncations above the galaxies’ mid-plane

6 A COMPARISON WITH THE COSMOLOGICAL GROWTH OF DISCS

Although it would be extremely interesting to measure, to the best of our knowledge no one has probed how the radial location of the truncation is moving with cosmic time. The most closely related approach was by Trujillo & Pohlen (2005), later expanded by Azzollini et al. (2008b). In those works, the type II breaks of galaxies were incorrectly called truncations. Nowadays, we know that the type II breaks correspond to a feature in galaxy discs at closer radial distances than the truncations (see a full discussion on this issue in Martín-Navarro et al. 2012). While acknowledging that the origin of the breaks and the truncation could be different, we can nevertheless use the growth of the discs inferred from the movement of the position of the type II breaks to put our current measurements of the speed of the truncation into a context. According to Fig. 8 in Azzollini et al. (2008b), present-day MW-like galaxies ($M_\odot \sim 5 \times 10^{10}$) would have their break at $R_{\text{break}} \sim 11$ kpc. At redshift $z \sim 1$, objects with the same stellar mass would typically have $R_{\text{break}} \sim 8$ kpc. However, a galaxy like the MW had a lower stellar mass 8 Gyr ago. This means that we can expect $R_{\text{break}}$ to be smaller than 8 kpc for the progenitor of the MW at redshift $z \sim 1$. Consequently, the 3 kpc increase in the location of the position of the break in the last 8 Gyr must be considered a lower limit for their speed. In other words, the average cosmic speed for the location of the break for MW-like galaxies was $>0.4$ kpc Gyr$^{-1}$, and probably not larger than 0.5 kpc Gyr$^{-1}$ assuming that the progenitor of the MW at redshift $z \sim 1$ was two times less massive than it is now. In this sense, if the current growth speed of the truncation were comparable with the cosmic growth in the location of the break, we would not expect velocities larger than 0.5 kpc Gyr$^{-1}$. This number is in nice agreement with our upper limits for the speed of the truncation found above.

7 WHAT IS THE PHYSICAL ORIGIN OF THE TRUNCATION?

Multiple ideas have been discussed in the literature to understand the origin of the truncation of galaxy discs. The two main concepts have been that the position of the truncation reflects the maximum angular momentum of the protogalactic cloud at the moment of collapse (van der Kruit 1987) or, alternatively, that the location of the truncation reflects the location of the disc where there is a threshold in the star formation activity (Kennicutt 1989). In both scenarios, the presence of stars beyond the truncation can be understood if there is a mechanism of radial migration (see

Figure 10. A cartoon illustrating how to use the shape of the radial colour profile beyond the truncation to estimate the growth speed $v_{\text{growth}}$ of a disc. The observables in the radial colour profile beyond the truncation are $\Delta$ and $\Delta R$. In this particular example we use the colour NUV-$r$ (vertical left axis) as a proxy to measure the interval of time (vertical right axis). The yellow dot indicates the birth location of a star in the colour-radial distance plane. The green dot is the current position of the star born at the yellow dot location. The red dot is the position of the truncation.

2.2±0.2 mag), and for the galaxy NGC 5907: (26.9±0.1 kpc, 1.5±0.2 mag) and (27.4±0.1 kpc, 1.9±0.2 mag). This corresponds to the following intervals: $\Delta R=0.6\pm0.2$ kpc and $\Delta t=0.1\pm0.01$ Gyr for NGC 4565 and $\Delta R=0.6\pm0.1$ kpc and $\Delta t=0.09\pm0.01$ Gyr for NGC 5907. The transformation from NUV-$gri$ colour to age has been done using the Vazdekis et al. (2016) model, assuming a Solar metallicity and a bimodal IMF. Consequently, for both galaxies we have $\Delta R/\Delta t \sim 6 \pm 2$ kpc Gyr$^{-1}$. Unfortunately, there are no measurements of this value at such locations in galaxies like ours. We can use the ratio of velocity dispersions at the solar location $\sigma^2/\sigma^2 = 35/25$ (Bland-Hawthorn & Gerhard 2016) and assume that this ratio is the same at the location of the truncation. This assumption is quite uncertain, but we can use such a value to illustrate the method. If the above assumption is reasonable, and taking $\sigma^2 = 4.5$ km s$^{-1}$ from Section 5.1, then the typical velocity dispersion at the radial position of the truncation would be $\sigma_R^2 = 7/5 \times \sigma^2 = 7/5 \times 4.5$ km s$^{-1} \sim v_{\text{stars}}$. This value is very similar to the quantity $\Delta R/\Delta t$ we have estimated above, indicating that $v_{\text{growth}}$ should be small (i.e., $v_{\text{growth}} < 0.5$ kpc Gyr$^{-1}$). We acknowledge that this estimate is strongly dependent on the exact value of $v_{\text{stars}}$ used, which is unfortunately not known.

Compared to the approach shown in the previous section, the colour-based method to measure $v_{\text{growth}}$ is much more uncertain and depends strongly on the assumptions we have made. For example, our measurement of $\Delta t$ is based on the inference of age associated to the colour NUV-$gri$ which depends on the properties of the stellar population model used. As a way to test the robustness of measuring $\Delta t$ from the colour NUV-$gri$, we can compare the predictions for such an interval of time based on a completely different stellar population model (Han et al. 2007) which accounts for the binary population. According to this model, NUV-$r=1.5$ mag corresponds to 0.14 Gyr, NUV-$r=1.9$ mag to 0.21 Gyr and NUV-$r=2.2$ mag to 0.28 Gyr, implying $\Delta t=0.07$ Gyr for NGC 4565 and $\Delta t=0.07$ Gyr for NGC 5907. These values are similar to the ones inferred using the Vazdekis et al. (2016) model (i.e., $\sim 0.1$ Gyr). We conclude that, as we have stated before, the weakest point in this approach is the estimate of $v_{\text{stars}}$. 
for a review Sellwood 2014; Debattista et al. 2017). In this sense, even if originally the angular momentum distribution of the stars were reflecting the angular momentum distribution of the protogalaxy, a substantial redistribution of the angular momentum is expected to take place due to secular evolution processes. For example, bars may play an important role in such a redistribution, as suggested by Debattista et al. (2006) and Erwin et al. (2008). Additionally, transient spiral arms cause greater angular momentum changes to stars at co-rotation than to those at the Lindblad resonances (Sellwood & Binney 2002) and can thus move co-rotating stars radially without heating the disc. Roskær et al. (2008b) showed that this mechanism is the one responsible for the largest amounts of redistribution because it is very efficient and can operate on relatively short timescales.

The analysis of the properties of truncations that we have made in this paper can shine some light on the physical processes that are taking place at such locations in galaxies. The first thing to note is that we have detected for the first time a U-shaped colour at the location of the truncation. This feature (found previously at the location of breaks in Type II galaxies, Azzollini et al. 2008a; Bakos et al. 2008) is considered to be associated to a star formation threshold followed by a migration of stars to the outer regions (Roskær et al. 2008b,a). For this reason, it seems that the truncation in the two MW-like galaxies we have analysed can be closely related to a star formation threshold. It is worth noting that the surface brightness at the position of the truncation is significantly lower than the typical brightness of the breaks in Type II galaxies. In fact, the average surface brightness of the break in the r-band is $22\, \text{mag/arcsec}^2$ for galaxies with the brightness of our objects (see Fig. 9 in Pohlen & Trujillo 2006) whereas here we find for the truncation (after deprojecting the brightness by the effect of the inclination) $25.5\, \text{mag/arcsec}^2$. This corresponds to a factor of $\sim 25$ less in stellar mass density for the truncation with respect to the break. Using the NUV-r and g-r colours at the location of the truncation we get a stellar mass density of $\sim 1-2 \, M_\odot\, \text{pc}^{-2}$. This stellar mass density is at the bottom edge for the critical gas density value assumed to trigger the star formation (within the spatial uncertainties) at at least up to a height of $3\, \text{kpc}$, indicating an efficiency of $\sim 30\%$.

Both the stellar mass density at the location of the truncation and the U-shaped colour profile at this position suggest that the truncation is linked to a star formation threshold. The presence, however, of the truncation up to a height of $3-4\, \text{kpc}$, where the density is much lower than in the mid-plane, seems to be difficult to explain as the result of a threshold of star formation at such an altitude. In fact, the characteristic U-shape is not observed at high altitudes (see Fig. 7). This indicates that truncations seen at high altitudes are the result of migration of stars form the mid-plane to higher altitudes.

Another interesting number to consider is the number of stars beyond the truncation in the mid-plane of the galaxies. Using the mid-plane 3.6$\mu$m surface brightness profile (a good proxy for the stellar mass density which is barely affected by the dust) we find fractions of $0.2\%$ (NGC 4565) and $0.1\%$ (NGC 5907). We can make a crude estimate to see whether such an amount of stars is compatible with the idea of radial migration from the region of the truncation to the outer part of the disc. As we have said before, we expect a radial velocity for the stars at the radial position of the truncation of $\sim 6\times 2$ kpc Gyr$^{-1}$. In practical terms this means that the stars produced at the location of the truncation can fill very quickly the outer regions of the galaxies (beyond the truncation). Considering $v_{\text{growth}} \sim 0.5$ kpc Gyr$^{-1}$ and a typical stellar mass density of $\sim 1 \, M_\odot\, \text{pc}^{-2}$, the total mass of stars in an annulus around the truncation (i.e., inner radius $R_i = 26\, \text{kpc}$ and outer radius $R_o = 26.5\, \text{kpc}$) is $\sim 0.8\times 10^8 \, M_\odot$. This represents, assuming the total stellar mass of a typical MW galaxy of $5\times 10^{10} \, M_\odot$, a fraction of $\sim 0.15\%$. These crude numbers show that there are enough stars at the location of the truncation to fill the outer parts of the discs, simply by the process of migration.

Finally, it is worth discussing whether a star formation threshold origin for the truncation could be in contradiction with the presence of a profile break in galaxies, which has also been related to star formation activity. One of the most important results by Martín-Navarro et al. (2012) is that, for galaxies with rotational velocities above $v_c > 100\, \text{km s}^{-1}$ (see their Fig. 13), the ratio between the location of the truncation and the break is quite constant and around $\sim 1.8$. This could indicate that both features could be linked with different resonances produced by the same phenomena. The fact that both features correlate strongly with the rotational velocities of galaxies reinforces this view.

To summarize, our observational results, together with other evidence from the literature, points to a scenario where the location of the truncation is directly linked to a threshold in the star formation activity. This threshold is due to the gas density at such a location which ultimately is connected to the angular velocity of rotation at that radial distance in the galaxy. Migration of stars from their birthplace leads both to the truncation observed well above and below the disc mid-plane, and to the small but significant quantity of stars observed beyond the truncation radius.

8 CONCLUSIONS

We have explored the nature of the disc truncations in two edge-on nearby MW-like galaxies: NGC 4565 and NGC 5907. We have used GALEX, SDSS and Spitzer S4G imaging to extract radial surface brightness profiles in and above the galaxies’ mid-plane. We have found the following results:

- The truncations are observed at the same spatial location ($\sim 26\pm 0.5\, \text{kpc}$ within the spatial uncertainties) at all the wavelength ranges (NUV, optical and 3.6 $\mu$m).
- The truncations are observed at the same spatial location (within the spatial uncertainties) at least up to a vertical location above the mid-planes as high as 3 kpc.
- At the location of the truncation, the NUV-r colour radial profile shows the characteristic U-shape associated to a star formation threshold, followed by migration of stars to the outer regions of the galaxies.
- The stellar mass density at the location of the truncation is $\sim 1 - 2 \, M_\odot\, \text{pc}^{-2}$. This number is very close to the critical gas density necessary to transform gas into stars $\sim 3 - 10 \, M_\odot\, \text{pc}^{-2}$, indicating an efficiency of $\sim 30\%$ for this process at the radial location of the truncation.
Truncations above the galaxies’ mid-plane

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APPENDIX A: SURFACE BRIGHTNESS PROFILES

In the following figures, we plot the radial surface brightness profiles for each galaxy, in each wavelength range and at different heights above/below the galaxy mid-plane. We plot all the surface brightness profiles of a galaxy, in a given band, together, so as to highlight the variations of the truncation position along the vertical axis. Then, we show the same kind of plot but for a PSF deconvolved model of each galaxy in the optical SDSS-\textit{gri} combined band.

In all panels of each figure, the black line shows the mid-plane surface brightness profile. The vertical dark grey region always represents the mean position of the truncation for all the heights in the wavelength range, plus/minus the standard deviation of that distribution of truncation positions. From top to bottom and from left to right, the panels show in red the surface brightness profile at a given altitude above the galaxy mid-plane (indicated in the legend) and, in light grey, the surface brightness profiles plotted in the previous panels.
Figure A1. Vertical development of the radial surface brightness profiles in the NUV band for NGC 4565. The mean of the truncation position distribution is equal to 26.2 kpc and the standard deviation is 0.4 kpc.
Figure A2. As in Fig. A1, now for the gri combined band. The mean of the truncation position distribution is 26.6 kpc and the standard deviation is 0.4 kpc.
Figure A3. As in Fig. A1, now in 3.6µm. The mean of the truncation position distribution is 26.3 kpc and the standard deviation is 0.4 kpc.
Figure A4. As in Fig. A1, but for the NGC 4565 PSF deconvolved model in gri. The mean of the truncation position distribution is the same as in A2.
Figure A5. As in Fig. A1, now for NGC 5907 in NUV band. The mean of the truncation position distribution is 26.1 kpc and the standard deviation is equal to 0.2 kpc.
Figure A6. As in Fig. A1, now for NGC 5907 in the gri combined band. The mean of the truncation position distribution is equal to 26.1 kpc and the standard deviation is 0.2 kpc.
Figure A7. As in Fig. A1, but for NGC 5907 in 3.6 µm. The mean of the truncation position distribution is 26.1 kpc and the standard deviation is 0.3 kpc.
Figure A8. As in Fig. A1, but for the PSF deconvolved model of NGC 5907 in $gri$. The mean of the truncation position distribution is the same as in A6.
In the next figure, we plot radial surface brightness profiles for each galaxy, in the gri band, at three different heights: along the galaxy mid-plane, at 1.5 kpc and at 3 kpc. In each case, we show the surface brightness profiles obtained above the mid-plane of the galaxies (northeastwards, NE), below it (southwesterly, SW) and the mean of both, which is the actual surface brightness profile we show in all the plots of this paper. Here we see that the truncation position is the same in both sides of the galaxies, so using the mean profile in our analysis is a reasonable approach. Note that the main difference is a slight brightness offset between the above and below mid-plane profiles caused by departures from a perfect edge-on inclination of the galaxies. This is more clearly visible in the case of NGC 5907.
Figure B1. Radial surface brightness profiles in the $gri$ combined band for both galaxies along the mid-plane, at 1.5 kpc and 3 kpc above/below the mid-plane. In the two panels of the figure, the purple solid curves show the mean surface brightness profile at each height (in the case of the mid-plane profile is the only possibility). The orange dashed curves represent the profiles above the mid-plane of the galaxies (north-eastwards, NE) and the green dotted lines are the profiles below the mid-plane (south-westerly, SW). The height of each set of surface brightness profiles is indicated with the light grey boxes. The vertical dark grey region always represents the mean position of the truncation for all the heights in the wavelength range, plus/minus the standard deviation of that distribution of truncation positions.
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