The General Assembly of Galaxy Halos: Structure, Origin and Evolution
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Direct imaging of haloes and truncations in face-on nearby galaxies

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Abstract. We use ultra-deep imaging from the IAC Stripe 82 Legacy Project to study the surface photometry of 22 nearby, face-on to moderately inclined spiral galaxies. The reprocessed and co-added SDSS/Stripe 82 imaging allows us to probe down to $29-30\,r'$-mag/arcsec^2 and thus reach into the very faint outskirts of the galaxies. We find extended stellar haloes in over half of our sample galaxies, and truncations in three of them. The presence of stellar haloes and truncations is mutually exclusive, and we argue that the presence of a stellar halo can hide a truncation. We find that the onset of the halo and the truncation scales tightly with galaxy size. We highlight the importance of a proper analysis of the extended wings of the point spread function (PSF), finding that around half the light at the faintest levels is from the inner regions of a galaxy, though not the nucleus, re-distributed to the outskirts by the PSF. We discuss implications of this effect for future deep imaging surveys, such as with the LSST.

Keywords. Galaxies: spiral, Galaxies: haloes, Galaxies: structure

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1. Introduction

The expected surface brightness levels of haloes in face-on galaxies are similar to those of truncations. Truncations were discovered in edge-on stellar disks by van der Kruit (1979), who noticed that in successively deeper photographic exposures the radial extent of edge-on galaxies does not grow, in contrast to their vertical extent (see Fig. 10 in van der Kruit & Freeman 2011 for an illustration). We now know that truncations occur in most edge-on galaxies, are sharp with scalelengths of less than 1 kpc, and typically occur at $4-5$ times the exponential scalelength of the inner disk. They seem to be fundamental features of disks, and as the evolutionary timescales in the outer regons of galaxies are relatively long, studying truncations can have immediate impact on our understanding of the early evolution of disks.

The face-on counterparts of the truncations observed in most edge-on galaxies have remained elusive. Mostly because of the shorter line-of-sight integration through face-on disks, the surface brightness where truncations might be expected is faint, at around 27 mag/arcsec^2. Some face-on truncations have been reported as such in the literature but van der Kruit (2008) has argued that these are in fact breaks in the inner disk similar to those found by Freeman (1970)—a plausible interpretation in light of the view

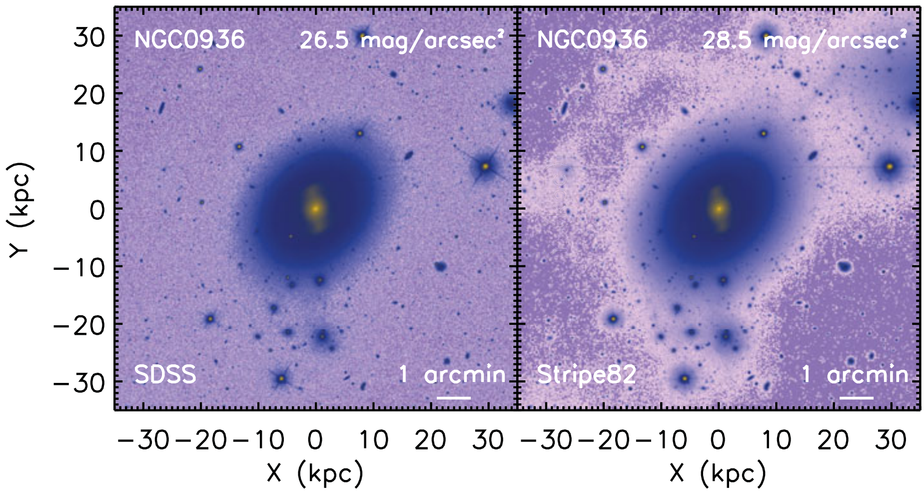

Figure 1. Standard SDSS (left) and re-reduced Stripe 82 (right) r'-band images of NGC 936, highlighting the faintest surface brightness levels. From Fliri & Trujillo (2016).

presented by Martín-Navarro *et al.* (2012) of breaks and truncations as well separated common features in disks.

We have used deep images of relatively face-on galaxies to look for truncations at surface brightness levels of 27 or below (see Peters *et al.* 2016 for full details of our study, which is only summarised in the present paper). These levels are most interesting in the context of the subject of the current Symposium, because stellar haloes are expected to become visible at roughly similar surface brightnesses. Such stellar haloes are the remants of the merger process now thought to be the dominant process shaping galaxies in ΛCDM cosmology.

As reported in detail elsewhere in these proceedings, the faint stellar haloes around galaxies can be studied in the most nearby galaxies by observing their resolved stars. In order to study haloes also beyond the nearest galaxies, and in many more objects, one needs to image the haloes directly in integrated light. Our images allow us to do this, as described below. We will also discuss to what extent light redistributed by the point spread function (PSF) can contaminate these imaged haloes, and how this informs us of difficulties ahead in future deep imaging studies.

2. Data and Analysis

We use imaging from the Stripe 82 subset of the Sloan Digital Sky Survey (SDSS), as reprocessed by us in the context of the IAC Stripe 82 Legacy Project (Fliri & Trujillo 2016). We selected a sample of 22 galaxies from the Stripe 82 area, with a diameter larger than 1 minute of arc, face-on or moderately inclined, and without signs of distortions, mergers or nearby foreground objects which might cause problems with the photometry.

The Stripe 82 images allow us to reach surface brightness levels down to $29 - 30\,r'$-mag/arcsec^2, a few magnitudes deeper than standard SDSS images. This is illustrated in Fig. 1 for one of our galaxies, NGC 936, as a comparison of a standard SDSS and a new Stripe 82 image. For our sample of 22 galaxies, we added g, r' and i images, destroying all colour information but gaining another half a magnitude in depth. We then used various techniques to identify truncations, as explained in detail in Peters *et al.* (2016). Here, we concentrate on the results obtained from standard ellipse fitting to derive radial surface brightness profiles. We inspected those profiles by eye and identified truncations as increases and haloes as decreases of the steepness of the exponential profiles (see Peters *et al.* 2016), and measured the radial distance and the surface brightness levels at which these changes, indicating the onset of the truncation or halo, occur. We also identify breaks in the profiles occurring well within the disk.

3. Effects of the PSF

Before continuing with a description of our results, we first consider whether the effects of an extended PSF can artificially flatten a radial profile, mimicking a halo signature. A PSF describes the response of an imaging system to a point source, and can be either modelled or empirically derived. We do the latter, to quantify the extent to which extended wings to a PSF, often of Gaussian shape or similar, can redistribute light from the central regions of a galaxy to the outskirts.

For the faint outer regions we are interested in, we need to combine the observed profiles of relatively faint stars in the Stripe 82 area (which yield a good representation of the central part of the PSF) with those of the very brightest stars in the area. These latter show large saturated cores, but are the only ones which allow to characterise the PSF at distances of tens of arcsec from the point source, and thus where we observe our faint structure.

After combining the PSFs from all these stars, we create a combined PSF with which we can then convolve a model of our galaxy. The results are shown for the galaxy IC 1515, a rather typical case, in Fig. 2, in terms of original and convolved models to components of the light of the galaxy, namely the central, bulge, component, and a double exponential which describes the disk. From our PSF modelling we can draw the following most interesting conclusions. (1) Indeed light from the central regions of a galaxy can be redistributed by the PSF and add to the surface brightness at levels of below 27 mag/arcsec^2, and at radial distances from the centre of the galaxy of over one minute of arc. (2) This PSF component contributes typically a few tens of per cent (some 50% in the example of Fig. 2) but is not enough to explain the flattening of the profile. We thus claim that we indeed detect haloes (see next Section). (3) The bulk of the redistributed light adding to the outer regions does *not* originate in the nuclear point source or even the central bulge component, but in the spiral arm region of the disk of a galaxy.

4. Results

Having established that the flattening observed in many of our radial surface brightness profiles at levels of $26-28$ mag/arcsec^2 is indeed indicative of a halo component, we then proceed to characterise the profile shapes. The two main results are that we indeed detect truncations in face-on or moderately inclined disk galaxies, and that we detect the halo component in most other galaxies. In particular, we find truncations in three of our 22 sample galaxies, and haloes in 15 of them (see Peters *et al.* 2016 for full details). We also find breaks in the inner disk region in most of our galaxies.

Truncations and haloes are mutually exclusive, in the sense that we either observe a truncation, or a halo, but never both in the same galaxy (some galaxies have neither). This is easily understandable, but does imply that a truncation can only be observed if a halo is either absent, or very faint. We have studied the three galaxies in which we found this to occur, but could not find any parameter that might cause such a faint or absent halo (Peters *et al.* 2016). Most galaxies do have a halo, and we can image that directly using our very deep Stripe 82 data.

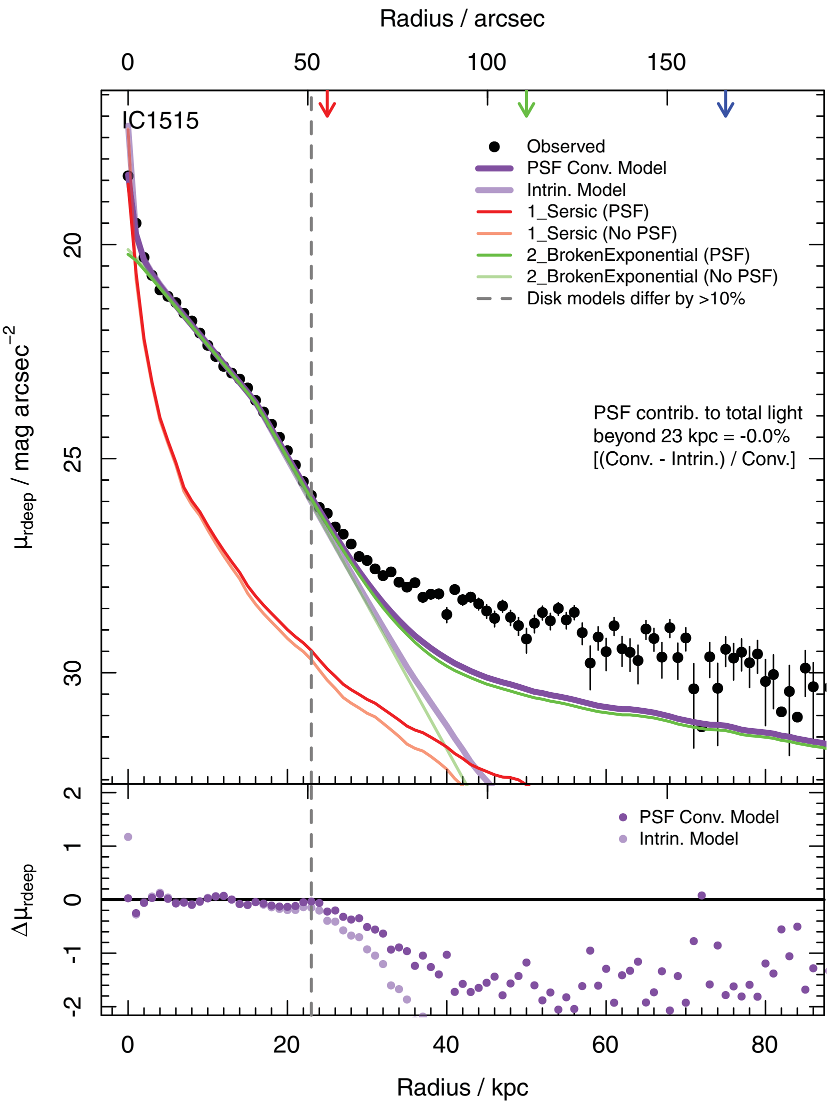

Figure 2. Graphical description of modelling whether the PSF can create an artificial halo, showing radial surface brightness profiles for IC 1515. The red curves depict a Sersic fit to the inner galaxy, corresponding to the bulge, the green curves a broken exponential, and the purple curves the sum of the two. Black dots denote the observations. In all cases, the light curves are before and the darker ones after the convolution with the PSF model. The lower panel shows the differences between the observations and the PSF-convolved and intrinsic models. The conclusion is that half the light at large radii can be PSF-scattered light, but that a halo is indeed observed. From Peters *et al.* (2016).

The physical sizes of the various features truncation, halo, and break correlate rather well with the size of their host galaxy. This is shown in Fig. 3 where we plot the radius of the onset of the feature (location for the breaks) versus the size of the galaxy, and contains some surprising aspects. First, the break radius correlates with the size of the galaxy. As the break seems to be related to the zones where spiral arms occur and bars may end (e.g., Martín-Navarro *et al.* 2012) this is probably related to structural components of galaxies being related to their host galaxy.

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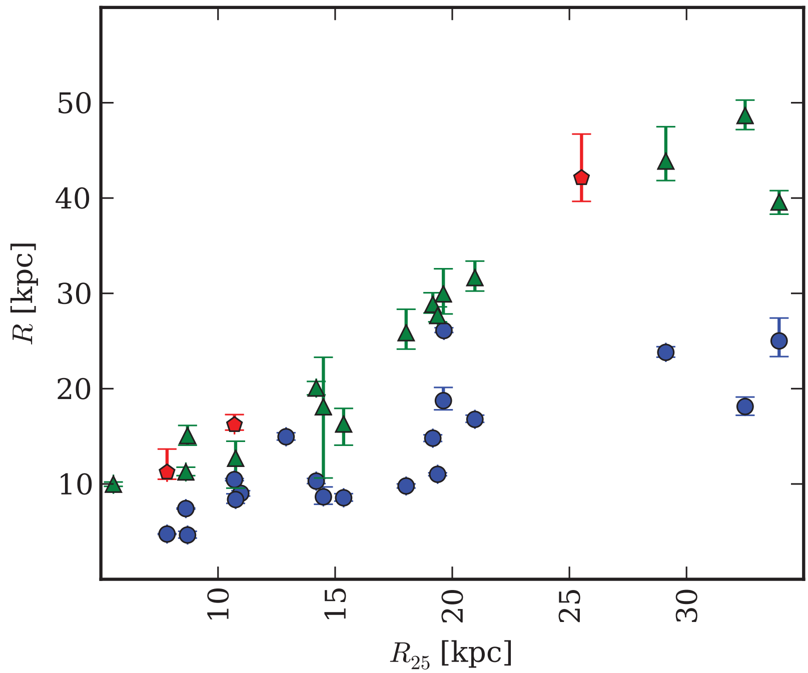

Figure 3. The correlation of R_{25}, indicative of the size of a galaxy, with the radii R of the various features. Red pentagons represent the truncations, blue circles the breaks, and green triangles the haloes. From Peters *et al.* (2016).

We also see in Fig. 3 how the onset of both truncations and haloes is tightly correlated with host galaxy size, but, in fact, following the exact same correlation. So not only do truncations and halo know about the size of their host galaxy, also do they occur (or start to become apparent) at exactly the same relative location. Correlations between other parameters of breaks, truncations, or haloes and a variety of parameters of the galaxy or its bulge or disk are not statistically significant (Peters *et al.* 2016).

5. Implications for future studies

Perhaps surprisingly to many workers in the field, the effects of the PSF extend to the faint outer regions of relatively nearby galaxies (see also Sandin 2014, 2015 for a detailed analysis). As we show here (and in Peters *et al.* 2016, see also L. Kelvin, I. Trujillo & J. Fliri, in prep.), light from the inner disk of a galaxy which has been redistributed by the PSF can contribute up to half of the light which we identify here as originating in a halo component. For the purpose of our study, and going down to some $29 - 30\,\mathrm{mag/arcsec^2}$, this cannot fully explain the observed flattening of the profile, allowing us to claim the successful detection of the halo component in 15 galaxies. But in deeper imaging the problem will become worse.

The extended wings of the PSF are primarily caused by turbulence in the atmosphere, and are also time-variable. Space-based imaging is less affected by PSF wings, and they are easier to model thanks to the lack of the varying atmosphere component. But all ground-based imaging will be affected, and the deeper one goes the more pronounced the effect. In particular surveys such as those with the LSST (Large Synoptic Survey Telescope) will be affected. Stacking multiple images will allow one, in principle, to reach limits in surface brightness of around $33\,\mathrm{mag/arcsec^2}$, but whether faint extended structure in galaxies can be detected and believed at those depths critically depends on the ability to model the PSF.

Another problem with such deep imaging is background subtraction. As described in detail in Peters *et al.* (2016, see also Fliri & Trujillo 2016) significant modelling and subsequent subtraction of the residual background was necessary before we could use our Stripe 82 images. This involves extrapolating over the area of the galaxy. But a typical Virgo galaxy such as NGC 4321 (at a distance of some 17 Mpc) will have a diameter of 50 arcmin (240 kpc) at a depth of 33 mag/arcsec^2, extrapolating the profile of its exponential disk. In the presence of a flatter halo profile, it will become even larger. So the background modelling will not only have to be done outside this huge region, but will then have to be extrapolated across the galaxy. These are serious challenges that must be overcome before the far outer regions of galaxies can be imaged to such extreme depth.

6. Conclusions

We report on our detection of truncations in three relatively face-on galaxies, found in a sample of 22 galaxies for which we analysed deep Stripe 82 images. In another 15 galaxies, we found a flattening of the radial surface brightness profile which we interpret as the direct detection of a stellar halo. The presence of a truncation or a halo is mutually exclusive. Light from the inner galaxy which has been redistributed to the outskirts by the PSF can add up to half the light in the outer, halo, regions, but the remaining excess light (above an extrapolated exponential profile) is due to a stellar halo. We caution that the combined difficulties in modelling the PSF and modelling and subtracting the background will make deeper direct imaging of outer regions of galaxies extremely challenging. This is particularly true for ground-based imaging, including stacked images from the LSST.

7. Acknowledgments

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