WHAT DO WE REALLY KNOW ABOUT SPIRAL GALAXY MORPHOLOGY?

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Abstract: Astronomers have long learned to classify spirals in terms of their morphological features, primarily their bulges, discs, and bars. In addition other properties of discs are used in classification, notably spiral arms, warps and truncations. In this paper we show how with modern techniques parts of the basis of these standard classifications are shown to be unsatisfactory, even misleading. In particular we will look carefully at bulges and at truncations, and explain how on purely morphological grounds we need to make basic changes in our concepts. We will put in question the traditional view of the spheroidal bulge and will also show that the majority of galaxy discs are not in fact truncated.

1 When is a bulge not a bulge? (When it's a pseudo-bulge).

The standard basic structural division of galaxies is that of spheroidal bulges, and exponential discs. A bulge is a structure which, observed in two dimensions, shows a surface brightness law varying with radius to the one quarter (de Vaucouleurs Law) and a disc is a structure whose radial surface brightness falls off exponentially. Early type spirals have large bulges, and spirals in general are characterized by their bulge to disc ratios. As early as the 1980's [1] and [2] argued that at least some "bulges", at least in late type spirals, are really discs. They argued this on the basis of a number of types of evidence:

- Their surface brightness profiles are exponential, not spheroidal.
- Their stellar populations appear young, as in discs rather than bulges.
- They have spirals, rings and even bars within them, features characteristic of discs.

Where it is possible to determine their geometry out of the plane, they appear to be flattened rather than spheroidal.Their measured kinematics shows rotational support rather than the pressure support normal in bulges. These features, which are bulge-like in showing strongly increased stellar density towards the centre of the galaxy, have been termed “pseudo-bulges” and their properties have been described in some detail in a recent review by [3]. The hypothesis which appears to give the best explanation of the difference between a bulge and a pseudo-bulge is that the former mark an initial phase of rapid collapse prior to the formation of a disc, while the latter mark the secular movement of stars from an existing disc towards the centre of the galaxy due to long term vertical disc instability, often mediated by a bar structure. However this distinction has not been made in the past and ignoring it will lead to missclassification of galaxies and incorrect interpretation of their dynamic properties.

2 How can we recognize pseudo-bulges?

There are two complementary ways to identify a pseudo-bulge: photometrically and spectroscopically. Photometrically the distinction is in the surface brightness profile. A true spheroidal bulge, seen more or less face on, shows a classical de Vaucouleurs surface brightness profile, falling off radially with galactocentric distance as $R^{1/4}$. A pseudo-bulge on the other hand has a Sersic profile with index between 2 and 3. Figure 1 shows a photometric profile analysis of two galaxies which we will use as template examples in this article. We can see that they show classical exponential outer discs, and more steeply rising inner profiles which would traditionally have been considered as bulges. We will look at these profiles again below, to show that both of the galaxies in fact have pseudo-bulges.This photometric decomposition is a valid way to work when using face-on or nearly face-on objects, which is the cleanest presentation of a galaxy for bulge-disc decomposition and other structural analysis. However the alternative method for picking out pseudo-bulges uses kinematic criteria and for these to be applied together with photometry the ideal inclination angle is 45 degrees. The spectroscopic method of identifying pseudo-bulges relies on the fact that the stars in a true bulge move on essentially radial orbits. This means that if we look at the width of an absorption line formed via a bulge it will be widened due to the combined effect of the radial motions. This is conventionally called a “hot” profile,by analogy with the random motions of a gas. For a disc, however, the stars rotate in quasi-circular orbits.If we see the disc face on, and there is only a small vertical component, we would see the collective stellar absorption lines virtually unbroadenned by motion. A disc is called a dynamically cool system for this reason. A pseudo-bulge which is really a disc will have disc kinematics,

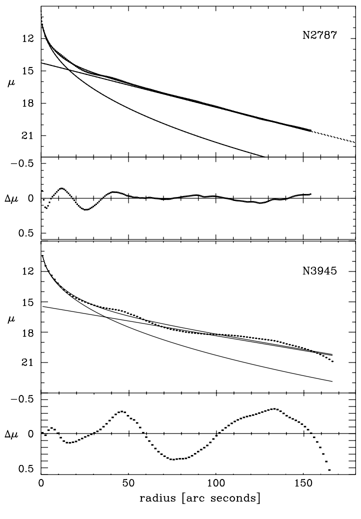

Figure 1: Simple bulge-disc decomposition for NGC 2787 and NGC 3945. Both galaxies were previously classified as S0. The “bulge” dominates the central parts of the profiles of each object, but kinematic evidence suggests that these bulges are not as simple as they appear (see text for more details).

but a pseudo-bulge which is a mixed system, part bulge part inner disc, will show mixed kinematic behaviour. To systematize this [1, 2, 3] suggested that a useful diagnostic diagram would be a plot of the ratio of the maximum velocity of the galaxy’s rotation curve to the width of the central dispersion velocity, against the observed bulge ellipticity. He gave a criterion for a bulge-like object to be pseudo-bulge, which is that the maximum rotational velocity of a galaxy should be twice its velocity dispersion, i.e. the disc-like motion within the “bulge” should predominate over bulge like motion. When the effect of the inclination of the galaxy on the observed velocities is taken into account this gives the solid curve in Figure 2, based on a model for an obliquely rotating galaxy by [4] Galaxies which show points above the curve are candidates for kinematically inferred pseudo-bulges. If a candidate also shows the photometric signature of a pseudo-bulge as typified in Figure 3 we can be reasonably confident that a pseudo-bulge is present.

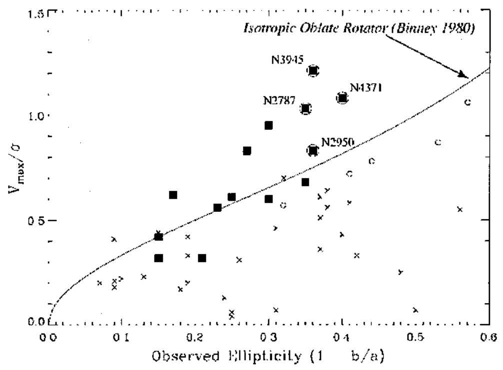

Figure 2: Kinematic diagnostic diagram for pseudo-bulges. The continuous curve separates those objects whose ratio of maximum circular velocity to velocity dispersion in the central region is greater than or less than 2. Galaxies above the line are candidates for pseudo-bulge systems. Named galaxies have probable pseudo-bulges. Filled squares = barred S0 galaxies, encircled filled squares = composite pseudo-bulges, crosses = ellipticals [5], circles = edge-on bulges [1, 6, 7].

It is important to point out that galaxies which have been identified as having pseudo-bulges in fact fall into two categories. Some of them do not have a classical bulge at all; the whole of what had been identified as a bulge is found instead to be an inner disc. However some (and without a full statistical study it is not easy to say what fraction but probably a majority) of the pseudo-bulges are composite. They do have true bulges, but these are much smaller than had been previously derived when they were classified, and the rest of the "bulge" is an thick inner disc. This is well illustrated in Figure 3 where a careful photometric decomposition of the two galaxies reveals that what were previously considered bulges in fact comprise much smaller spheroidal bulges at the centre together with thick discs extending to the outer radius of the previously derived bulge. One of the two objects has a very small bulge which makes the reclassification of considerable dynamical importance. In fact both of these galaxies were suspected of having pseudo-bulges from a careful photometric analysis and this was confirmed using the kinematic test based on spectra [5]. In Figure 2 we can see that of the small sample of early type spiral galaxies presented rather a high fraction are candidates for pseudo-bulges. There has as yet not been an exhaustive study in the literature, but it would be fair to say that maybe one half of the S0 galaxies which have been examined with photometric care show

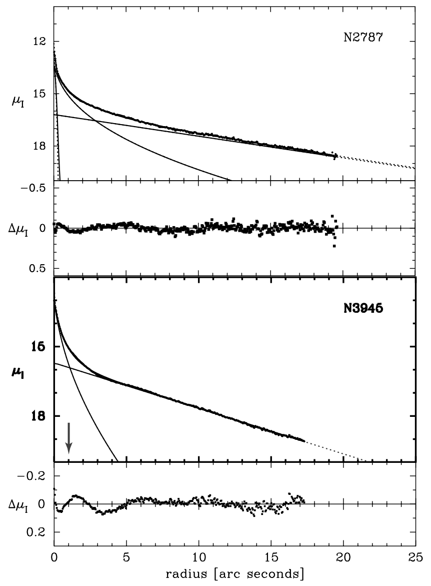

Figure 3: Bulge-disc decomposition for NGC 2787 and NGC 3945, where the structure of the central zone into small bulge and larger inner disc (instead of a large single bulge) is shown for each . For NGC 2787 the central bulge luminosity is only 0.1 times that of the inner disc, while for NGC 3945 the ratio is 0.4.

the pseudo-bulge phenomenon. Further observational work is needed.

3 What is the importance of pseudo-bulges?

The importance of the discovery that many galactic bulges in early type spirals do not in fact have a bulge-like spheroidal geometry has repercussions on our concepts of galactic evolution. Firstly the baryonic mass distribution in these galaxies is different from what had been assumed, which leads to variations in the derived distributions of the dark matter components of these objects as inferred from their rotation curves. Secondly, and more important it implies a different scenario for bulge formation in these objects. The two standard ways of modelling bulge formation were, until recently, the classical model of [6] in which the bulge of a galaxy forms during a rapid radial collapse at the beginning of the galaxy's lifetime, and the merger model in which the bulge of a spiral forms essentially in the same way as do ellipticals in that scenario, by the merger of two smaller galaxies in an interaction which leaves a bulge as a result of gravitational funneling of gas into the centre followed by a relatively short period of strong star forming activity (for a review see [7]). However the discovery that bulges often have completely different radial mass distributions is consistent with recent work in which the secular evolution of galaxies over their lifetimes is being given its due importance. The best general overview of current ideas on secular evolution is given in [3]. It is not possible even to summarize all of the detailed content of that review, but a key point is that one way for galaxies to evolve is by the formation of bars due to disc instabilities, but followed by the concentration of stellar mass towards the centre of the galaxy impelled by buckling instabilities in the bars themselves. In this scenario an inner disc could be formed as a result of this type of processes, in a galaxy without a previous bulge or with a very small initial bulge. The scenario is interesting not primarily because of this consequence but because it offers an overall line of galaxy evolution by internal rearrangement supported by steady unspecular accretion of stars and/or gas which is different from either simple monolithic or merger driven evolutionary scenarios. The discovery of the wide presence of pseudo-bulges is therefore important because it gives very useful support to this scenario. However the specific version of the scenario in which the bar is responsible for the pseudo-bulge predicts that this should not be larger in radius than the bar of the galaxy, and several pseudo-bulges are known which are in fact larger than their bars. So as usual in astrophysics the unknowns lead to the need for more refined studies which will either reinforce the scenario or lead to its eventual replacement.

4 The outer zones of galaxy discs: truncated brightness profiles

Freeman [8] first showed systematically that the surface brightness of the stellar component in galactic discs shows a radially exponential fall-off, and this is a basic property of all galactic discs. However [9] and [10] showed from studies of edge-on galaxies that these exponential discs often, and maybe always, are terminated radially by a sharp, almost instantaneous cut-off in surface brightness, a "truncation". Ever since then the truncation phenomenon has been considered as an important constraint on any model of the formation and evolution of discs. In their early work [10, 11] estimated the radius of the cut-off as 4.2 times the disc scale length. More modern measurements using CCD's instead of the photo- multipliers available to van der Kruit and Searle [cambiar] have been made, starting with [15] and continuing in studies which steadily augmented the numbers of galaxies, by [16, 17] and [18]. A value of 3.6 seems to be the best summary value of the ratio of the truncation radius to the disc scale length as a result of these studies of edge-on galaxies, but more relevant here the concept of truncation suffered a change when more precise photometry was brought to bear. [19] showed convincingly that a truncation should best be described not as a sharp cut-off but as a second exponential for the outer radial brightness profile, considerably steeper than that of the inner disc. However the difficulty of establishing clear photometric criteria for radial brightness profiles from edge-on galaxies (in order to do this one has to make a 3-dimensional transformation to derive what would have been derive from a face-on measurement and this is badly affected by dust or just by noise in the low brightness outer profile) eventually led [20] to use face-on galaxies for this profile work, in spite of the fact that the signal in the outermost parts of face-on galaxies is always very low. They found that the radial profiles in the discs of their objects showed a double exponential fall off, more gradual in the inner part of the disc, and blending smoothly into a steeper exponential in the outer part. The radius at which this occurs and the ratios of the inner and outer exponential slopes can be used to define the properties of the truncation. The difference in the type of results on truncations found using edge-on and face-on galaxies is illustrated in Figure 4.

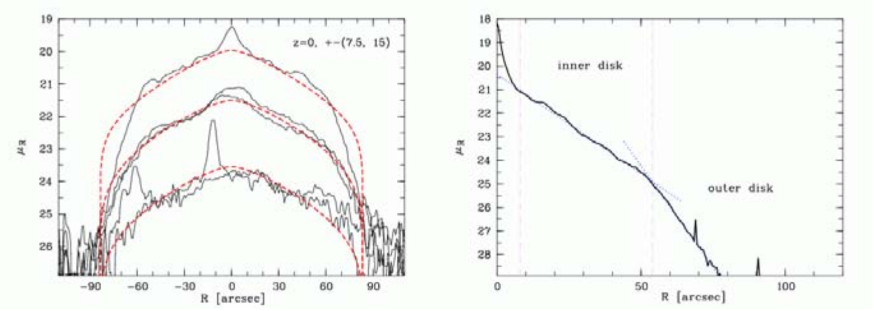

Figure 4: Illustration of the difference entailed in using edge-on or face-on galaxies to derive the radial profiles from which truncations are inferred. The best fits to the outer profiles of NGC 522 (left panel), which is edge-on, show a steep cut-off at the edge. For the face-on galaxy NGC 5923 the outer profile is an exponential with a steeper decline than that of the inner disc, but not an abrupt cut-off. It is very difficult to get round the effects of fore-shortening in the first case, and it is now generally agreed that it is easier to obtain reliable outer profiles from face-on galaxies.

However the key point to deal with here is whether most, or even all discs are truncated. In his thesis [19] found that 79% of his sample of galaxies showed truncations. We should note, though, that these were late type galaxies measured edge-on. Most of the remaining 21% had either obviously disturbed discs due to an interaction with a nearby galaxy, or had poor S:N ratio. [21] came to a similar conclusion from a similar sample. We will see below that these conclusions are not reproduced in face-on samples and will comment on this point in detail. In the meantime we will take a brief look at models which have been proposed to explain the truncation phenomenon.

5 Possible causes for truncations

There are two favored scenarios which can give rise to galaxy truncations: the threshold model and the collapse model. The collapse model relates the presence of a truncation to basic processes during the formation of the galaxy disc. In this model, as proposed by [22] the truncation is a result of the maximum angular momentum in the protogalactic cloud and is therefore independent of the subsequent history of the disc, e.g. by hierarchical merging. The threshold model stems from an original idea by [23] elaborated by [24] and recently addressed by [25]. In this scenario there is a critical threshold column density of gas for star formation which depends on the dynamical parameters of the thin disc under consideration. If this threshold remains close to constant for a sufficient time there will be a critical radius beyond which star formation will be sharply curtailed, and this will give rise to the truncation in surface brightness of the integrated stellar component. Variants on this have been produced in which the authors have recognized that a truncation is not an abrupt cut-off but shows a two-sloped exponential. In fact Schaye's [25] models give these results, and a series of evolutionary models by [26] also produced double exponentials with quite clean breaks, but these authors stated that their breaks represented initial conditions in the gas and would tend to smear out with time as the galaxy evolves. It is of interest to note that [27] propose a mechanism for truncations due to the presence of large scale galactic magnetic fields. While this has controversial aspects, since it also predicts flat rotation curves without the presence of dark matter, it is capable of making definite quantitative predictions, such as that of the variation of the break radius (in unit of disc scale length) as a function of morphological type and rotational velocity. Finally the possibility that interactions, the gravitational effects of a neightbour galaxy on the disc, might induce truncations cannot be ruled out, and at first glance appears a reasonable mechanism to investigate. However [28] showed, using simulations of satellite mergers, that interactions are more likely to produce radial spreading, in direct contradiction to any idea of a cut-off. In the light of recent observational results which we will discuss below, these results are plausible, but up to date and more comprehensive simulations would contribute significantly to our understanding of the possible effects of interactions on the outer parts of galaxy discs.

6 How common are truncations?

One of the points of this article is to show how recent observational work with the availability of improved detectors on large telescopes with excellent seeing has given rise to new data which tends to change our global view of the phenomenon concerned. In sections 1, 2 and 3 we showed how this is changing our concept of galactic bulges, with the consequent impact on our understanding of galactic evolution. Here we will discuss the equivalent story for truncations. A useful reference point here is the overall classification of radial disc profiles introduced by [8] who used the notation "type I" to refer to a profile which showed just a simple single exponential slope, and "type II" to refer to a profile which showed two slopes, a flatter inner slope and a steeper outer slope. Freemans original definitions were designed to take into account not the increased slopes in outer discs (i.e. truncations), but flattened slopes in some inner discs,i.e. a "deficit" of light in the inner disc between the main outer disc profile and the bulge. However the two categories are a good enough way to classify profiles with steeper outer slopes, i.e. with truncations, and as we will see the truncation phenomenon seen this way is more complex than had been thought. In addition as we will show in more detail below, galaxies have been observed in which the outer slope of the radial photometric profile is LESS steep than the inner slope. Although at first we thought that these were rare, it turns out that they are common, and need the introduction of a third category, type III profiles, in which the outer disc slope is flatter than that of the inner disc. Classical examples of types I, II, and III are given in Figure 5. In [29] we named the type III profiles "anti-truncations" and this gives a reasonable idea of how they behave.

At this point I will have to take some short cuts in order to avoid an unduly complex and lengthy article, but will try to discuss the three types of profiles and also their implications where relevant. Type I profiles showing a single exponential fall off in the disc with no hint of a truncation have now been found by a number of observers. We show here two examples, first in Figure 6. the profile of NGC 300 by Bland-Hawthorn et al. (2005), which falls off unchanged out to 10 scale lengths, and second in Figure 7 that of NGC 4596 from [29] which is compared with the truncated, type II, profile, of NGC 2273). These are illustrations, but they show (as do many other examples observed by our group and by

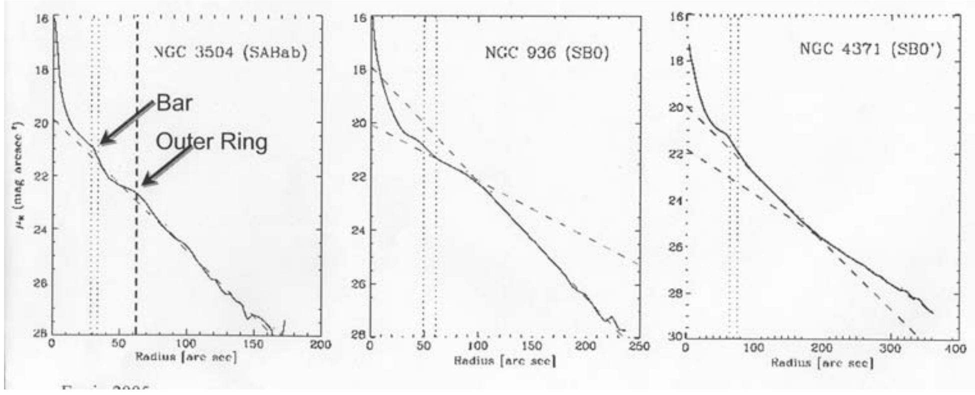

Figure 5: Three classes of radial profiles for disc galaxies. *Left:* Freeman types I (continuous single exponential decline). *Centre:* Type II (shallower inner exponential and steeper outer exponential) can be considered examples of Freemans (1970) original classification. *Right:* Type III (steeper inner exponential and shallower outer exponential) is a new class first defined in [29].

others) that both types of profiles are genuine, and not due to problems in the data reduction, e.g. to inadequate sky subtraction. In Figure 7, for example, both galaxies were observed and analyzed in exactly the same way, and the break in the profile of NGC 2273 is found at a signal level an order of magnitude higher than a 3-sigma limit imposed by the sky background noise. Many type I profiles are now known, and I will present a preliminary statistic after briefly discussing the other types.

Type II profiles, as mentioned above, were first classified in this way to include galaxies with an inner defect in their single exponential profiles rather than an outer steepening of the profile. In fact in our groups detailed studies we find that even for conventional truncations the steepening break occurs at a range of radii depending on the individual galaxy. In this rather complex picture we have picked out two phenomena as rather frequent, and characteristic of two different modes of producing truncations. Firstly there are “classical” truncations where a well-defined break occurs at between three and four disc scale lengths, which we have termed type IIo. Hypotheses for their formation have been outlined in section 5. But there are also truncations where the break occurs much closer to the centre of the galaxy, which we have termed type IIi. These latter occur in barred galaxies, and the break radius occurs just inside the outer limit of the bar. Our hypothesis is that these truncations are resonance phenomena in which

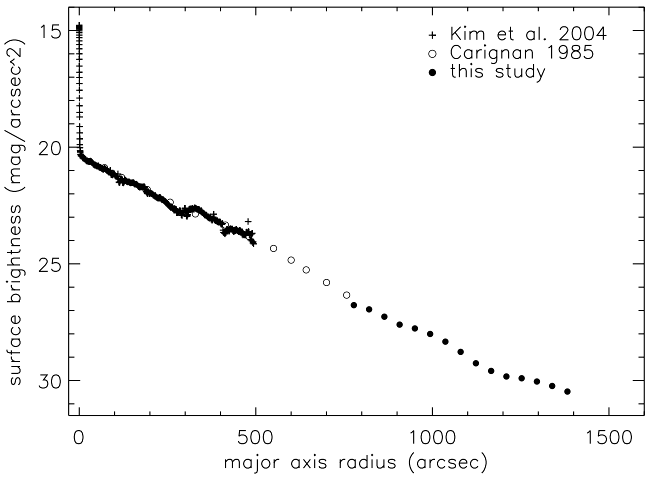

Figure 6: A very clean case of a type I profile, NGC 300 (from [30]).

star forming material converges on the break radius, flowing inwards from the outside and outwards from the inside, with the net result that the outer disc forms fewer stars and its light profile falls off more steeply. They are brought about by the presence of the bar and should not occur in unbarred or weakly barred galaxies. Preliminary results seem to confirm this.

The type III profiles are the most interesting result thrown up in recent work. Although they had been detected previously, their frequency was first pointed out in [29]. Figure 8 taken from that article shows a set of twelve type III profiles, and also shows an interesting division in their properties. The majority, 8 out of 12, show sharp breaks between clearly exponential profiles, changing from steeper to shallower slopes at a well defined radius. The other four, however, show a gradual transition from an exponential inner disc slope to a slope which gets continually shallower over a range of radii, but does not settle to a simple exponential form. There is a highly probable explanation for this. If we examine the isophotes of the galaxies which show the second type of photometric curves, we find that they become less elliptical as the slope decreases outwards, whereas galaxies showing the sharper breaks retain the ellipticity of their isophotes at large radii, where the shallower slope prevails. Examples are shown in Figure 9. The explanation is that the profiles showing the gradual slope change are

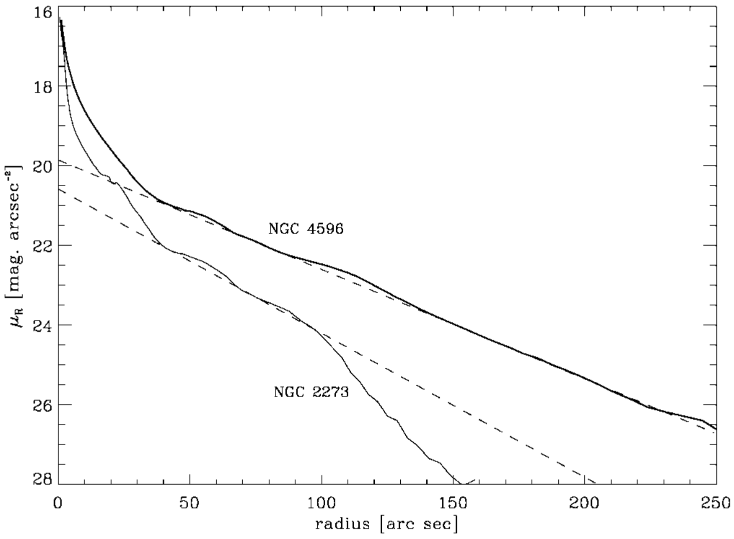

Figure 7: Examples of a class I profile, NGC 4596 (SB0), and a class II profile which shows a classical truncation, NGC 2273 (Sba), from our own studies [29].

those where a stellar halo, geometrically concentric with the bulge, dominates the light from the outermost part of the galaxy. The outer light profiles shows the change from the geometry of the disc, where the profile is exponential, to the rounder geometry of the halo where there is a continuous slope change but not an exponential profile. We term these profiles type IIIh. The others do not show any change of isophote ellipticity corresponding to the change in profiles slope. The outer shallower profiles correspond to a disc with the same geometry as the inner disc. These are indeed antitruncations, as the photometric and geometrical behaviour is the same as that of a truncated disc, but with a sign change in the difference between the slopes of the inner and outer disc, positive instead of negative for a normal truncation. We have termed these profiles type IIId.

The question asked at the beginning of this section, 'how common are truncations?', cannot yet be given a definitive answer because a number of surveys with relatively larger data sets than those published to date are now in the process of analysis. However an indicative answer is shown in Figure 10 based on a limited survey of mainly barred galaxies. We can see that the number of classical disc truncations in the early type galaxies is really low, of order 10% of the total sample, but that in late types this fraction jumps sharply to something around 40%.

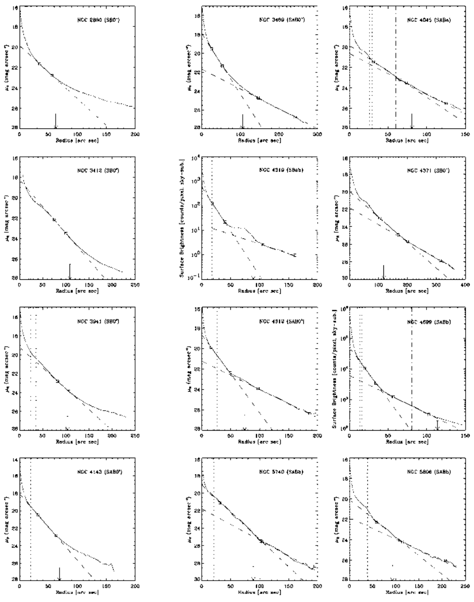

Figure 8: A set of twelve type III profiles, showing anti-truncations, from [29]. The four profiles in the first column show a gradual curved transit ion outwards characteristic of galaxies whose outer profile is dominated by their faint stellar halos. The remaining eight profiles in the second and third column s show a sharp transition from an inner steeper slope to a shallower outer slope, chara cteristic of galaxies where the outer profile is due to a disc component.

In the Figure we have used the nomenclature type II for those profiles which show a transition to a steeper slope, but not at the outer disc limit, rather they do this at radii related to the bar radius (above I called these type IIi, and the classical transitions type IIo; there is as yet no generally accepted nomenclature so I apologize for this inconsistency). If we are "generous" and put both of these categories together we find that some 40% of early type galaxies could be considered to have some sort of disc cut- off while for later types this figure is a little higher, closer to 50%. All of the sample shown here are barred. We can also see from Figure 10 that in the early types we appear to have more type III profiles (antitruncations) than type I (single exponentials without any detectable slope change) while for the late type sample the numbers appear to be the other way. However for both early types and late types the non-truncated galaxies are more

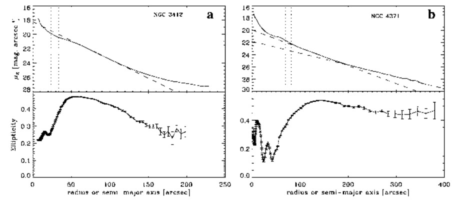

Figure 9: Radial plots of ellipticity and position angle for two type III galaxies which differ in their outer profiles as described in Figure 8. NGC 3412, which shows a gradual transition from exponential to shallow slope also shows outer isophotes which are steadily less elliptical than those of the inner disc, implying that the outer profile is due to a spheroidal stellar distribution. NGC 4371 has a sharp transition to a shallow exponential in the outer disc profile and the ellipticity in the outer disc retains the value found in the inner disc.

numerous than the truncated ones.

So we are left now with two questions. Firstly what causes truncations,(maybe there is more than one cause as we seem to have identified two parametrically separate sets of objects which might previously have been designated truncated) and secondly what factors prevent truncations from forming in the majority of galaxies? Although the numbers can vary as bigger samples of objects are chosen I can already say that from the much larger samples analyzed in [31]and in [32], the overall conclusions reported here will not be qualitatively different. We now have to wonder not why truncations are caused, but how so many galaxies do not present truncations. This is a progress report and interested readers are welcome to ask the authors for further details and/or for the results of more recent analyses.

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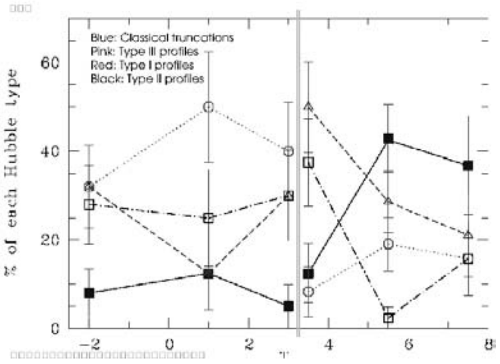

Figure 10: Proportions of profiles of different types found in samples of a few tens of galaxies in two ranges of morphological classes. To the left of the diagram early types and to the right late types. In early type galaxies not only are truncations a minority, but the single most representative type is type III, i.e. galaxies with anti-truncations. In the late types there are more truncations, but even here the sum of the type Is (single exponential without truncation) and type IIs is comparable in numbers to the truncated profiles. Further work with extended samples is in progress. Triangles: type I, open squares: type II, open circles: type III, and filled squares: classical truncations.

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