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The puzzle about the radial cut-off in galactic disks

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Abstract. The stellar disk in a spiral galaxy is believed to be truncated physically because the disk surface brightness is observed to fall faster than that for an exponential in the outer, faint regions. We review the literature associated with this phenomenon and find that a number of recent observations contradict the truncation picture. Hence we question the very existence of a physical outer cut-off in stellar disks. We show, in this paper, that the observed drop in the surface brightness profiles in fact corresponds to a negligible decrease in intensity, and that this minor change at the faint end appears to be exaggerated on a log-normal plot. Since minor deviations from a perfect exponential are common throughout the disk, we suggest that such a deviation at the faint end could easily give rise to the observed sharp drop.

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

1. Introduction

One of the important results from the early work on surface photometry of several edge-on galaxies by van der Kruit & Searle (1981) was the apparent sudden drop in the surface brightness at a radius of about four disk scale-lengths. The radius at which this occurs was defined by them to be $R_{\rm max}$, or also called $R_{\rm cut-off}$ in subsequent work in the literature. They argued that this drop represents a physical truncation of the stellar disk.

This effect was later also observed in many galaxies by a number of observational groups, both in edge-on galaxies (Jensen & Thuan 1982; Sasaki 1987; Fry et al. 1999; Barteldrees & Dettmar 1994; Pohlen et al. 2000a; de Grijs et al. 2001; Kregel et al. 2002), and also in face-on galaxies (Pompei & Natali 1997; Pohlen et al. 2002). For a recent summary of this topic, see van der Kruit (2001). The truncation picture proposed by van der Kruit & Searle (1981) is generally accepted, though initially it was questioned (see e.g., van der Kruit 1989, and the discussion thereafter). Some recent observations have raised doubts about its validity. Also, there is no clear physical understanding of the origin of truncation, although a number of theoretical models have been proposed for it (Sect. 2.3).

On looking at the observational data in the literature carefully we find that the observed drop in intensity need not imply a physical or mass truncation of the disk. The various observational points, questioning the validity of physical truncation are discussed in Sect. 2. Some possible solutions are discussed in Sect. 3 and Sect. 4 gives a brief summary of our conclusions.

2. Doubts about outer cut-off

2.1. Questions about the deduction of R_{max}

1. Deduction of $R_{\rm max}$ based on Log-Normal plot: The existence of the cut-off radius $R_{\rm max}$ was first noticed by van der Kruit & Searle (1981) using the data for the intensity versus radius plotted on a log-normal plot. The use of a log-normal plot is a standard practice in the literature and is done for convenience so that several orders of drop in intensity can be covered with a greater ease. The logarithm of intensity, measured as surface brightness is given in units of magnitude per arcsec^{-2}. We note that this mode of plotting accentuates any small deviation in the intensity from an exponential disk at large radii. This is because $d(\log I)/dR$ which is equal to $(1/I)\,(dI/dR)$ appears to be very sharp at low values of surface brightness. This point is further illustrated next.

The observed intensity in a typical face-on spiral galactic disk is known to obey the following exponential law (Freeman 1970):

$$I \;=\; I_0 \;\exp\,(-\,R/\,h_{\rm R}) \tag{1}$$

where I_0 is the central extrapolated intensity and $h_{\rm R}$ is the radial disk scalelength.

The intensity profile for an infinite exponential disk viewed edge-on, $I_{\rm edge-on} = (I_0)_{\rm edge-on}\,(R/h_{\rm R})\,K_1(R/h_{\rm R})$ (van der Kruit & Searle 1981), where K_1 is the modifed Bessel function of the second kind. For $R >> h_{\rm R}$, this reduces to:

$$I_{\rm edge-on} \sim\; (I_0)_{\rm edge-on}\,(\pi R/2h_{\rm R})^{1/2}\,\exp(-R/h_{\rm R}). \tag{2}$$

Using a constant mass-to-light ratio this gives the expression for the edge-on column mass density. To derive this, the central

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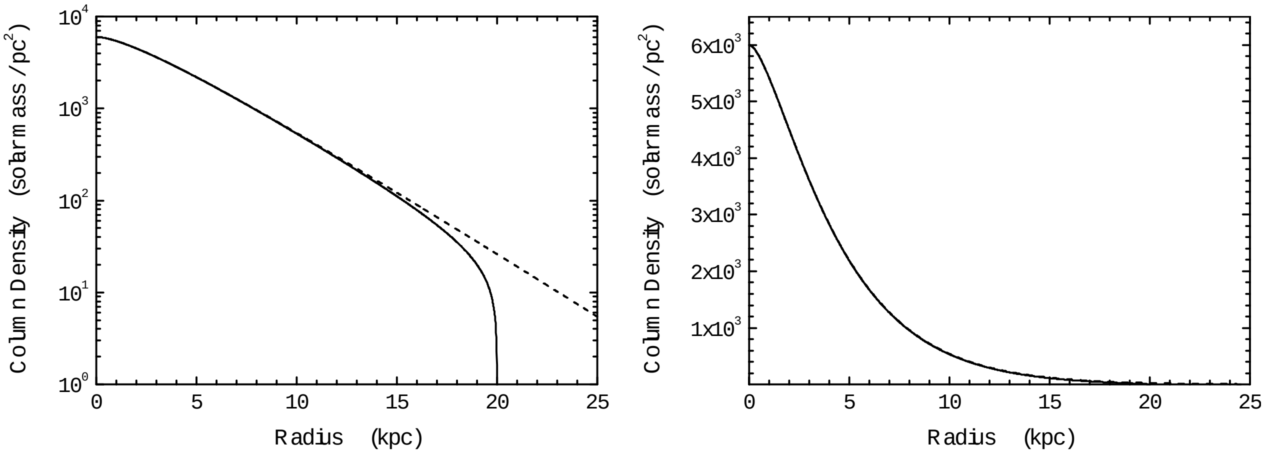

(a) (b)

Fig. 1. a) A plot of edge-on column mass density (in $M_\odot$pc^{-2}) versus radius (in kpc) for an infinite exponential disk (dashed line), and for an exponential disk truncated at a radius of 20 kpc (solid line), both plotted on a log-normal plot. The deviation of the latter from an infinite disk in regions of low surface density case is accentuated in this mode of plotting. It is such deviation, and the subsequent sharp drop, that is generally taken to indicate the existence of an outer cut-off in the disk. **b)** The same data as in Fig. 1a, except here the curves are plotted on a linear plot. The two curves nearly overlap and the difference between them is not discernible. Hence, from this plot the existence of an outer cut-off cannot be deduced.

disk surface density is taken to be 650 $M_\odot$ pc^{-2} as in our Galaxy (from Mera et al. 1998).

Figure 1 shows the column density versus radius for an edge-on infinite exponential disk, and that for a finite disk with a physical truncation at a radius of 20 kpc. Figure 1a shows these two curves plotted on a standard log-normal plot while Fig. 1b shows the same data on a linear plot. The difference in the two figures is striking, and clearly shows that the deduction of $R_{\rm max}$ would not have been possible if the data were to be plotted on a linear plot. Note that the value of intensity at 20 kpc (for an infinite disk) is already very small, $\sim 4 \times 10^{-3}$ times the central value. Physically, this means that the actual values of the intensity and hence the column mass density would not be substantially different at large radii whether the galactic disk is taken to be an infinite exponential disk or whether it has a physical truncation at an outer radius of $R_{\rm max}$. Hence it is not meaningful to even define a physical truncation in a galactic disk.

2. The ratio of $R_{\rm max}/h_{\rm R}$: The observed profiles for the edge-on galaxies were converted into the face-on ones using the exponential disk model (van der Kruit & Searle 1981; Sasaki 1987), and the observed ratio of $R_{\rm max}/h_{\rm R}$, where $h_{\rm R}$ is the exponential disk scalelength, was found to be typically ∼4. Now, the central intensity I_0 (see Eq. (1)) is observed to be remarkably constant for several galaxies (Freeman 1970; van der Kruit 1987; Bosma & Freeman 1993), and is equal to 21.65 mag arcsec^{-2}. Thus the Holmberg radius, set by detection limit to be at 26.5 mag arcsec^{-2}, will be equal to ∼4.5 in units of $h_{\rm R}$ as can be obtained from Eq. (1). This is too uncomfortably close to the observed range of values for the ratio of $R_{\rm max}/h_{\rm R}$. Hence a simple explanation for the observed $R_{\rm max}$ is that the intensity is too low to be detected beyond this point, so that $R_{\rm max}$ does not imply a physical or mass cut-off.

Despite their higher sensitivity, modern observations give comparable or even smaller values, in the range of 2–5 for the ratio $R_{\rm max}/h_{\rm R}$ (Barteldrees & Dettmar 1994; Pohlen et al. 2000b; de Grijs et al. 2001). This puzzling point has been commented upon by Barteldrees & Dettmar (1994). Thus, the above two points show that contrary to the general belief, $R_{\rm max}$ does not appear to be a fundamental parameter of the disk (see Sect. 2.3).

2.2. Observational evidence against truncation

1. Dependence of $R_{\rm max}$ on sensitivity: The size as inferred by the last detectable point or the last iso-intensity contour of galactic disks is seen to increase when observed with a greater sensitivity telescope (Bosma & Freeman 1993). This was shown to be true for nearly half of the sample of 222 galaxies seen in both the Palomar Sky Survey (with a limiting magnitude, $\mu_{\rm lim}$ = 24.6 mag arcsec^{-2}) and the SRC-J survey ($\mu_{\rm lim}$ = 25.6 mag arcsec^{-2}). The fact that the observed size of a galaxy or equivalently the value of $R_{\rm max}$ increases for a fainter detection limit implies that the outer limit is an artefact of the detection and does not indicate a genuine physical cut-off in the disk. If the truncation were truly a physical one, the size should not vary with the sensitivity.

2. $R_{\rm max}$ for the Galaxy: An outer cut-off radius of 15(± 2) kpc has been deduced for the Galaxy by modeling the DENIS star-count data by Ruphy et al. (1996). In contrast, the more recent work by Lopez-Corredoira et al. (2002) based on the modeling of 2MASS star-counts data in 820 regions has shown that there is no abrupt cut-off in the stellar disk at least to within a radius of 15 kpc studied by them.

This last conclusion agrees with our theoretical result (Narayan & Jog 2003) based on a different method. In that paper, we have argued that the variation in the scaleheight with radius for the atomic hydrogen data allows us to convincingly rule out a physical cut-off in our Galaxy upto 20 kpc. Since the Galactic disk scalelength, $h_{\rm R}$, is ∼3.2 kpc (Mera et al. 1998), this means that the stellar disk shows no signs of a cut-off till about 6 disk scalelengths.

3. Face-on galaxies: The integrated column density or surface brightness is slightly larger (by a factor of $R^{1/2}$) for an edge-on galaxy than for a face-on galaxy – compare Eqs. (1) and (2). However, it is this small difference which allows an easier detection of the faint, outer regions. This is the reason why the edge-on galaxies were first chosen for photometric studies by van der Kruit & Searle (1981). Theoretically, following the same steps as in Sect. 2.1, we find that a truncation is also seen in a face-on galaxy. Some face-on galaxies (Shostak & van der Kruit 1984; Pompei & Natali 1997; Pohlen et al. 2002) do show evidence for a radial cut-off *well beyond* four disk scale-lengths. Hence, it is not clear why a much larger sample of 86 face-on spiral galaxies studied by de Jong & van der Kruit (1994) do not show a cut-off.

4. Rate of decrease of surface brightness: The drop in the surface brightness leading to the determination of $R_{\max}$ does not seem to show a uniform well-defined behaviour in all the cases where it is observed. The rate of fall in intensity is high (>1 mag arcsec^{-2} kpc^{-1}) in some galaxies (Florido et al. 2001; Barteldrees & Dettmar 1994) which thus show a sharp cut-off, whereas the rate of fall is rather low (<1 mag arcsec^{-2} kpc^{-1}) in most other galaxies (van der Kruit & Searle 1981; Pohlen et al. 2002; Kregel et al. 2002). The drop in surface brightness in the outer radii in galaxies has over the years been also modeled as a double exponential (e.g. Pohlen et al. 2002). There has been no attempt so far to relate this variation to either the disk formation process or any theoretical truncation model.

2.3. Theoretical models for R_{max}

The origin of the physical truncation in a disk is not clearly understood yet. Some ideas proposed so far include: critical density for star formation (e.g., Kennicutt 89; van den Bosch 2001), the maximum angular momentum per unit mass in a protogalaxy (van der Kruit 1989), incomplete disk formation, expulsion of stars controlled by magnetic field (Battaner et al. 2002), etc. The ratio $R_{\max}/h_R$ forms an important parameter in these models. However, viscous evolution, which is the currently accepted scenario for the disk formation, does not lead to the existence of $R_{\max}$ *naturally* (Saiz et al. 2001). But, unfortunately, despite its uncertain status, mass truncation has been artificially introduced by both theorists (Casertano 1983; van den Bosch 2001; Bell 2002) and observers (Bottema 1996; Fry et al. 1999; Pohlen et al. 2000a; de Grijs et al. 2001) alike to match their models with obervations. The physical truncation has even been applied to explain the observed decrease in the rotation curve near the $R_{\max}$ region for two galaxies (Casertano 1983; Bottema 1996).

3. Alternative solutions and implications

As shown in Sect. 2.1, what is seen as a major deviation in a surface brightness profile far from the centre is in fact a very small difference in the intensity profile. In this section we discuss two possibilities other than truncation that can explain this drop.

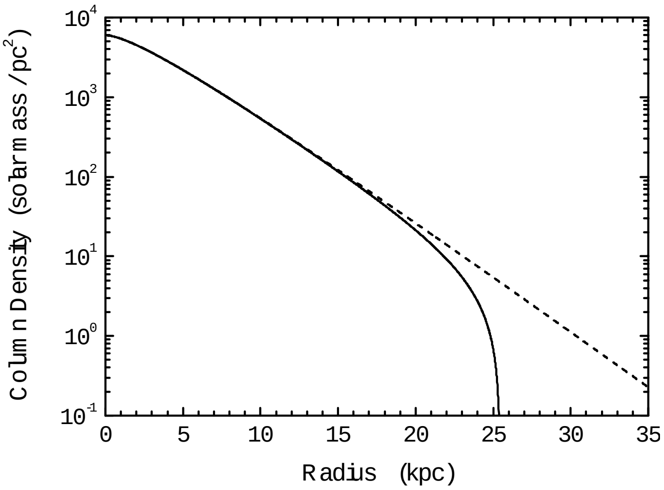

Fig. 2. The column density is plotted against the radius for an infinite exponential disk seen edge-on. The dashed line is the result of subtraction of correctly estimated sky background while the solid line is the result of a slight (0.5%) overestimation. The slight overestimate could easily be misinterpreted as a physical cut-off (compare with Fig. 1a). Thus, this figure illustrates the importance of the correct sky background estimation in bringing out the true profile of a galaxy.

(a) Background sky subtraction: First, we consider the simplest possible reason, namely, whether the sharp fall-off could result during the process of data reduction- as say by an overestimate of sky brightness during background sky subtraction (see e.g., Binney & Merrifield 1998). We illustrate this point quantitatively in Fig. 2 to show how $R_{\max}$ can arise artificially during the sky subtraction process. In Fig. 2, we plot the column density versus radius for an infinite exponential disk. The column density can be converted to surface brightness using standard techniques. The dashed line is the result of subtraction of correctly estimated background and the solid line results when a slightly over-estimated background (by 0.5%) has been subtracted. Although the overestimated sky background is subtracted from raw data at all points, the reduction is more important in the outer, fainter regions. The resulting distribution is strikingly similar to the theoretical profile with physical truncation (Fig. 1a) and to an observed profile from which physical truncation was deduced by van der Kruit & Searle (1981). Thus the observed drop can be easily explained as arising due to the inaccurate subtraction of the sky brightness, rather than due to physical truncation. A smaller overestimate of 0.1% would shift the location of drop to a larger radius of ~30 kpc, while conversely a larger overestimate of 2.5% is needed to give a cut-off at 20 kpc seen in Fig. 1a.

We find that the observers are aware of this possibility and take utmost care in the estimation of the true background – see Barteldrees & Dettmar (1994) for a detailed discussion on this. In the past, some arguments against the role of sky subtraction in causing a drop have been raised. First, in a few galaxies the deviation from the exponential happens much before the sky brightness errors can affect the profile (van der Kruit & Searle 1981; Barteldrees & Dettmar 1994). However, this need not be true for all galaxies. Second, it has been argued that if $R_{\max}$ arises due to errors in sky subtraction then we should see a similar cut-off in other luminosity distributions like the vertical profiles of disks, which is not seen (de Grijs et al. 2001; Barteldrees & Dettmar 1994). Note, however, that the intensity falls much faster along the z-axis than along R-axis for a thin galactic disk. For example, for the galaxy ESO 187-G08 (Barteldrees & Dettmar 1994), the rate of decrease is 2.63 mag arcsec^{-2} kpc^{-1} along z-axis as opposed to a change of 0.35 mag arcsec^{-2} kpc^{-1} radially, that is, about 7 times higher. This natural rapid fall in intensity can easily hide an artificial cut-off along z-axis, if any. Thus, we have argued that the role of sky subtraction in causing truncation cannot yet be ruled out.

We would like to point out that the surface brightness profiles for the low-luminosity elliptical galaxies also show curves going downwards away from the typical $R^{1/4}$ de Vaucouleurs law at all radii (Binney & Merrifield 1998), also see (Binggeli et al. 1984; Prugniel et al. 1993). It is well-known that even some giant elliptical galaxies such as NGC 4472 are better fitted by a truncated King's profile rather than by a de Vaucouleurs profile (Mihalas & Binney 1981). To our knowledge, the topic of radial cut-off in elliptical galaxies has not been studied systematically in the literature, unlike the truncation in spiral galaxies.

(b) Intrinsic variation in disk intensity: The second possibility for the observed cut-off comes from the intrinsic nature of the distribution of light in the disk itself. It is well known that galactic disks are not perfectly exponential in nature as seen in many studies involving large samples, and minor deviations from the exponential (of the order of 0.1–0.5 mag arcsec^{-2}) are commonly seen (e.g., Boroson 1981; Kodaira et al. 1986). Departures from the exponential could be due to recent star formation or oval distortions, bars, spiral arms etc falling along the line of sight (Boroson 1981). In the outer regions, the more likely reason is the presence of clumpy star formation, spiral arms, or ring-like features, beyond which there could be an abrupt drop in surface brightness. We point out that this aspect, though probably as important as the uncertainty in the sky brightness subtraction as a possible cause of the spurious cut-off, seems to have been ignored in the literature.

This approach also explains the following related observation. In face-on galaxies, the surface brightness profiles are generally azimuthally averaged (de Jong & van der Kruit 1994) thus minimising the deviations, which could explain why $R_{\max}$ is not commonly seen in face-on galaxies.

4. Conclusions

The aim of this paper is to point out that there is no conclusive evidence for the existence of a physical cut-off in the stellar disk in the outer galactic disks. Some recent observations rule out the abrupt mass truncation both in our Galaxy as well as in external galaxies. Instead, we argue that the observed drop in surface brightness appears more significant than it is because of the use of a log-normal plot used routinely in the literature. We discuss two probable causes: a small error (of <1%) in sky brightness subtraction, or the genuine wiggly nature of light distribution in galactic disks, which can give rise to a spurious drop in surface brightness. This topic deserves further study. This paper also shows that the various theoretical models proposed so far to explain the origin of truncation are not necessary since the existence of the phenomenon itself is in doubt. Thus we have here the proverbial "emperor's clothes" problem on hand.

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