REVISITING THE SCALE LENGTH–$\mu_0$ PLANE AND THE FREEMAN LAW IN THE LOCAL UNIVERSE

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ABSTRACT

We have used Virtual Observatory technology to analyze the disk scale length $r_d$ and central surface brightness $\mu_0$ for a sample of 29,955 bright disk galaxies from the Sloan Digital Sky Survey. We use the results in the $r$ band and revisit the relation between these parameters and the galaxy morphology, and find the average value $\langle \mu_0 \rangle = 20.2 \pm 0.7$ mag arcsec$^{-2}$. We confirm that late-type spirals populate the lower left corner of the $r_d$–$\mu_0$ plane and that the early and intermediate spirals are mixed in this diagram, with disky ellipticals at the top left corner. We further investigate the Freeman Law and confirm that it indeed defines an upper limit for $\mu_0$ in bright disk galaxies with $r_{\text{mag}} < 17.0$, and that disks in late-type spirals ($T \geq 6$) have fainter central surface brightness. Our results are based on a volume-corrected sample of galaxies in the local universe ($z < 0.3$) that is two orders of magnitudes larger than any sample previously studied and deliver statistically significant implications that provide a comprehensive test bed for future theoretical studies and numerical simulations of galaxy formation and evolution.

Key words: galaxies: evolution – galaxies: formation – galaxies: structure

Online-only material: color figures

1. INTRODUCTION

The current mainstream galaxy formation paradigm states that galaxy disks form within dark matter halos and that there is an intimate relation between the scale length $r_d$ of the disk and that of the halo. The mass distribution of the disk is entirely set by the $r_d$ and, for example, in the exponential case, 60% of its total mass is confined within two scale lengths and 90% within four scale lengths. Moreover, the angular momentum of the disk is set by $r_d$ and the mass distribution of its host halo, and the fact that the angular momentum vectors are aligned suggests that there is a physical relation between the two. During the formation process, galaxy mergers and associated star formation and feedback processes play a crucial role in the resulting structure, however, the observed sizes of disks suggest that the combination of these physical processes indicate that galactic disks have not lost much of the original angular momentum acquired from cosmological torques (e.g., White & Rees 1978; Fall & Efstathiou 1980). The hierarchical and infall models predict comparable $r_d$, and in a cold collapse scenario (Vand 1959) since angular momentum is conserved, immediately after the collapse the gas is supported by rotation so that it quickly collects in the region where a disk forms with substantially higher rotation velocity than the halo is to form. A large $r_d$ disk forms when the disk mass is smaller than the halo mass over the disk region, and vice versa: a small $r_d$ disk forms when the mass of the disk dominates the mass of the halo in any part of the disk. The self-gravitating disk will also modify the shape of the rotation curve near the center of a galaxy (Gelato & Sommer-Larsen 1999) and the disk is then set to undergo secular evolution. The natural implication of this scenario is that the $r_d$ dictates the life of a disk, and consequently, is a prime factor which determines the position of a galaxy on the Hubble sequence.

One prominent indicator for a smooth transition from spiral toward S0 and disky ellipticals is provided by the $r_d$–$\mu_0$ diagram, where $\mu_0$ is the central surface brightness of the disk, where spirals and S0s are mixed and disky ellipticals populate the upper left corner of this diagram (Kent 1985; Scorza & Bender 1995). Another instructive relation is the Freeman Law (Freeman 1970) which relates $\mu_0$ to the galaxy morphological type. Although, some studies have found that the Freeman Law is an artifact due to selection effects (e.g., Disney 1976; Bothun 1981; Scorza & van den Bosch 1998), recent work has shown that proper consideration of selection effects can be combined with kinematic studies to explore an evolutionary sequence (e.g., van der Kruit 1987, 2002; de Jong 1996; Koda et al. 2000).

In the comparison between theory and observations, two issues complicate matters. On the theory side, mapping between initial halo angular momentum and $r_d$ is not trivial, partly due to the fact that commonly the initial specific angular momentum distribution of the visible and dark component favors disks that are more centrally concentrated than exponential (e.g., de Jong & Lacey 2000; van den Bosch 2001). Observationally, comprehensive samples have yet not been studied, and the mixture of different species such as low and high surface brightness galaxies complicate the measurements of disk parameters (McGaugh et al. 1995; Graham & de Blok 2001).

Here, we analyze the $r_d$ and $\mu_0$ from an unprecedentedly large sample of bright disk galaxies in the nearby universe ($z < 0.3$) using the Sloan Digital Sky Survey (SDSS) Data Release 6 (York et al. 2000; Adelman-McCarthy et al. 2008). As detailed in Fathi et al. (2010), both parameters were robustly determined for 30,374 galaxies in the $r$ band (only 29,955 used here as described in Section 2), whereas in other SDSS bands, the derived parameters are valid only for subsets of this sample. In the $g$, $i$, and $z$ bands ($\approx 27,000–30,000$ galaxies), the sample sizes are comparable to the one presented here. In the $u$ band, $r_d$ and $\mu_0$ were robustly derived for a few hundred objects and therefore, not considered here. Throughout this Letter, unless otherwise stated, we use disk parameters in the $r$ band and investigate the two relations mentioned above, in order to provide a comprehensive test bed for forthcoming cosmological simulations (or analytic/semi-analytic models) of galaxy formation and evolution.
2. THE DERIVED PARAMETERS AND SAMPLE CORRECTION

The derivation of \( r_d \) and \( \mu_0 \) for the SDSS sample is detailed in F10, and testing the code with standard IRAF routines delivered fully consistent results. Comparing disk parameters with those from several published samples (de Jong 1996; Graham 2003; Anderson et al. 2004; Koopmann et al. 2006; Balcells et al. 2007) failed to deliver any objects in common. However, cross matching with the multi-band image fitting and multi-component (disk, bar, bulge, and central source) profile decomposition of nearly 1000 galaxies based on SDSS (Gadotti 2009) returned 322 disk galaxies for which we derived comparable values (see Figure 1). As outlined in F10, we made use of the SkyView services to obtain cut outs from the SDSS tiles, with the galaxy counts derived in the reference frame of the tile that is at the center of the SkyView cutout. The disk central surface brightness can thus be derived using the procedure provided by the SDSS services. Applying pixel area correction and Tolman cosmological dimming correction \((z + 1)^4\), we were able to obtain the \( \mu_0 \) in correct units of mag arcsec\(^{-2}\). The longitudes provided by the SDSS services show that for our sample \( \|b\| > 20^\circ \), and we use the standard extinction correction law of Giovanelli et al. (1994) to correct for this effect. Following the description in Valentijn (1990) and de Jong (1996), we use a range of internal extinction parameters (0 for optically thick galaxies to 1 for transparent galaxies) for every diagram to quantify this effect throughout our analysis, but present diagrams calculated with the extinction parameter of 0.26 (de Jong 1996).

We also derived the asymmetry parameter and the calculation of the inverse concentration parameter (F10). By examining a small subset of galaxies for which reliable morphological classifications are available from the LEDA catalog (Paturel et al. 2003), we assert that the stellar velocity dispersion, classifications are available from the LEDA catalog (Paturel et al. 2003), we assert that the stellar velocity dispersion, asymmetry, and concentration can be used with caution as indicators of the position of a galaxy along the Hubble sequence. We stress, however, that the data points have large spread and at best have a correlation coefficient of determination \( R^2 = 0.31 \), well below 1\( \sigma \) level (see F10 for details).

Our derived \( r_d \) and \( \mu_0 \) for the SDSS sample will have to be corrected for the frequency of galaxies with a certain property in a volume to be included in the sample. The volume over which we can detect low-luminosity galaxies is smaller than the volume over which we can detect high-luminosity galaxies. In order to calculate the number density contribution of each galaxy, we calculate the maximum volume over which it is observable \( V_{\text{max}} \). We follow the volume weighting recipe described in van der Kruit (e.g., 1987) and de Jong (e.g., 1996), and weight each galaxy by the calculated \( V_{\text{tot}}/V_{\text{max}} \), where \( V_{\text{tot}} \) is the volume contained within the distance to the faintest galaxy in the sample (e.g., Davies 1990; Blanton et al. 2003). To calculate the volumes, we assume a \( \Lambda \)CDM universe with the Hubble parameter \( H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1} \), \( \Omega_L = 0.7 \), and \( \Omega_M = 0.3 \), and for this calculation use g-band luminosities to calculate luminosity distances as these are more representative of B-band values. Changing the cosmology has no significant effect on the analysis carried out here.

This method has the disadvantage that if the near part of the sample is overdense, where a magnitude-limited survey is most sensitive to low-luminosity galaxies, then the \( V_{\text{tot}}/V_{\text{max}} \) will become very large for the faintest objects. To avoid this problem, we make a cut in the sample by removing galaxies with unreasonably large weights (\( > 10,000 \)). This leaves us with 29,955 galaxies at \( z < 0.3 \) and \( r_{\text{mag}} < 17.0 \), for which we obtain volume-corrected parameter distributions (see, e.g., Figure 2).

3. THE \( r_d-\mu_0 \) PLANE

Figure 2 shows that the derived \( r_d \) and \( \mu_0 \) follow the linear trend previously discussed in the context of the formation and evolution of disks (de Jong 1996; Courteau 1996; van den Bosch 1998; Graham & de Blok 2001). We find that \( \mu_0 \) has a Gaussian distribution with \( \langle \mu_0 \rangle = 20.1 \pm 0.7 \) mag arcsec\(^{-2} \) with a linear trend seen in Figure 2 (applying different internal extinction parameters changes this mean value by 0.2 mag arcsec\(^{-2} \)). The top right corner is enclosed by the constant disk luminosity line, void of objects. The top right corner is also the region where the disk luminosity exceeds \( 3 L^* \), thus the absence of galaxies in this region cannot be a selection effect since bright galaxies cannot be missed in our diameter-selected sample. However, it is clear that selection effect plays a role in populating the lower left corner of this diagram. Analogous to the \( r_d-\mu_0 \) plane, the
Figure 3. Four-dimensional parameter space of $r_d$, $\mu_0$, morphological type $T$, and total stellar mass. Three different views are illustrated here, the $\mu_0$ values are given in mag arcsec$^{-2}$, and $r_d$ and mass are given in decimal logarithm of parsecs and solar masses, respectively. (A color version of this figure is available in the online journal.)

Figure 4. $r_d$–$\mu_0$ plane color coded by asymmetry (top), concentration parameter (middle), and velocity dispersion $\sigma$ (bottom), where the ranges have been chosen to amplify the effects discussed here. (A color version of this figure is available in the online journal.)
Figure 5. Volume-corrected distribution of disk central surface brightness $\mu_0$ vs. morphological type $T$, asymmetry, concentration parameters, and stellar velocity dispersion. The red dots illustrate the 282 galaxies for which robust morphological types were given in the LEDA catalog (type error smaller than 0.5), and the open circles show the average $\mu_0$ for each type.

(A color version of this figure is available in the online journal.)
Tully–Fisher relation implies lines of constant maximum speed a disk can reach.

The type dependency of the $r_d-\mu_0$ plane was previously presented by Graham & de Blok (2001) who used 120 high and low surface brightness galaxies to explore the type dependency of the diagram. Our 282 well-classified galaxies (illustrated with colored dots in Figure 2) follow the results of Graham & de Blok (2001) and Gadotti (2009). Disks of intermediate- and early-type spirals have higher $\mu_0$ while the late-type spirals have lower $\mu_0$, and they populate the lower left corner of the diagram. The $r_d$, on the other hand, does not vary as a function of morphological type (F10).

Figure 3 shows that a forth quantity is equally important in this analysis. The total galaxy mass obtained from Kauffmann et al. (2003) and Brinchmann et al. (2004), separates the data along lines parallel to the dashed lines drawn in Figure 2. This is indeed also confirmed by the Tully–Fisher relation. Moreover, we validate that the lower mass galaxies are those with type $\geq 6$.

Our data also show the expected trends: asymmetry and concentration increase for later types, and central stellar velocity dispersion decrease for later type spiral galaxies, however, we note that these correlations are well below 1σ confidence level (see end of Section 2 and F10). In Figure 4, we illustrate $r_d-\mu_0$ plane where the data points have been color coded by asymmetry, concentration, and velocity dispersion as a rough indication of the galaxies in different types.

The top panel of Figure 4 indicates that the higher asymmetry galaxies populate a region more extended toward the bottom right corner with respect to the high asymmetry galaxies. The middle panel shows an opposite trend, and the bottom panel shows that larger velocity dispersion has the same effect as asymmetry. In full agreement with Graham & de Blok (2001), Figure 4 confirms that galaxies with early and intermediate morphologies are mixed along a linear slope of 2.5 in the $r_d-\mu_0$ plane, coinciding with the region populated by S0s as shown by Kent (1985) and disky ellipticals shown by Scorza & Bender (1995).

4. THE FREEMAN LAW

We plot the Freeman (1970) diagram, where the density plot indicates that disks have constant surface brightness put to Scd galaxies (types $T = 5$, top panel of Figure 5). The volume-corrected density plot also shows that the vast majority of the sample is of morphological type earlier than 5, thus introducing a bias in the observed trend. When we consider only the galaxies with robust morphological classification (red dots in the top panel of Figure 5), we note that $\mu_0$ drops for galaxies of $T \geq 6$ (cf. Figure 3 of de Jong 1996) with the significant advantage that our sample contains five times more galaxies than the number of late-type spirals of de Jong (1996). Furthermore, using the entire sample of 29,955 galaxies, we confirm that the Freeman Law indeed defines an upper limit for $\mu_0$ in bright disk galaxies at $z < 0.3$ (low surface brightness galaxies are not present in our sample). Combined with our previous results, i.e., that $r_d$ varies by two orders of magnitude independent of morphological type, this result implies that disks with large scale lengths (and typically higher mass) not necessarily have higher $\mu_0$.

We use the asymmetry, concentration, and stellar velocity dispersion as indicators of morphological type. The lower three panels of Figure 5 illustrate that the density plots for the entire sample and the galaxies. None of the trends are statistically significant in exploring these parameters against the Freeman diagram. The lack of strong correlation may well be attributed to the fact that three parameters that we have used here do not correlate strongly with morphological type. The concentration parameter is further complicated by the nature of the bulges (Gadotti 2009). We conclude that these parameters cannot be used to further explore the Freeman Law.

5. CONCLUSIONS

We have derived and analyzed $r_d$ and $\mu_0$ in the r band from SDSS images of the largest ever volume-corrected sample of disk galaxies in the local universe ($z < 0.3$ and $r_{mag} < 17.0$). We confirm that early- and intermediate-type spirals are mixed in the $r_d-\mu_0$ plane and late-type spirals ($T \geq 6$) populate the lower left corner of this plane. Varying the internal extinction value does not change the trends found here, and the average value ($\mu_0 = 20.1 \pm 0.7$ mag arcsec$^{-2}$ only varies slightly. Moreover, the Freeman Law defines an upper limit for $\mu_0$, where disk galaxies of type $T \geq 6$ have fainter $\mu_0$.

These results in the $r$ band are comparable with those in other SDSS bands, and the average $\mu_0$ in other bands are: $g$ band$-20.3 \pm 0.7$ mag arcsec$^{-2}$; $i$ band$-20.1 \pm 0.7$ mag arcsec$^{-2}$ and fully consistent with the median value from Gadotti (2009); and $z$ band$-21.6 \pm 0.7$ mag arcsec$^{-2}$. Given the intrinsic scatter in each band, we do not find these differences significant to interpret the effects of dust and/or stellar populations (cf. Peletier et al. 1994), moreover that presented in F10. Furthermore, our results imply that disks with large scale lengths (and typically higher mass) not necessarily have brighter $\mu_0$.

As earlier discussed by, e.g., Kent (1985), van der Kruit (1987), Scorza & Bender (1995), van der Kruit (2002), and many others, selection effects could cause artificially tight or incorrect correlations. In the two relations analyzed here, we find typically larger scatter than previous analyses, and although our sample represents bright disks, the sample size adds credibility to our findings. These results are fully consistent with the common understanding of the $r_d-\mu_0$ plane and the Freeman Law, and they contribute to past results since they are based on a sample that is two orders of magnitude greater than any previous study, with more than five times more late-type spiral galaxies than any previous analysis.

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