Edge-on disk galaxies in the SDSS DR6: Fractions of bulgeless and other disk galaxies

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The aim of this study is to determine the fractions of different spiral galaxy types, especially bulgeless disks, from a complete and homogeneous sample of 15127 edge-on disk galaxies extracted from the sixth data release from the Sloan Digital Sky Survey. The sample is divided in broad morphological classes and sub types consisting of galaxies with bulges, intermediate types and galaxies which appear bulgeless. A small fraction of disky irregulars is also detected. The morphological separation is based on automated classification criteria which resemble the bulge sizes and the flatness of the disks. Each of these broad classes contains about 1/3 of the total sample. Using strict criteria for selecting pure bulgeless galaxies leads to a fraction of 15% of simple disk galaxies. We compare this fraction to other galaxy catalogs and find an excellent agreement of the observed frequency of bulgeless galaxies. Although the fraction of simple disk galaxies in this study does not represent a “cosmic” fraction of bulgeless galaxies, it shows that the relative abundance of pure disks is comparable to other studies and offers a profound value of the frequency of simple disks in the local Universe. This fraction of simple disks emphasizes the challenge for formation and evolution models of disk galaxies since these models are hard pressed to explain the observed frequency of these objects.

1 Introduction

Simple disk galaxies are flat, late-type disk galaxies of the morphological Hubble class ~Sd and later without a bulge component (e.g., Goad & Roberts 1979, 1980; Karachentsev 1989; Karachentsev et al. 1992; Kautsch et al. 2005b). The formation and evolution of such thin galaxies is not yet well understood in the framework of Λ cold dark matter models. Simulations have difficulties in producing disk-dominated and bulgeless galaxies. The simulated disks are smaller, denser and have lower angular momentum than observed, known as the angular momentum problem. Adding feedback processes to the simulations can improve the creation of disk galaxies to some extent (e.g., Okamoto et al. 2005; Scannapieco et al. 2008), but D’Onghia & Burkett (2004), D’Onghia et al. (2006), Köckert & Steinmetz (2007) and Piontek & Steinmetz (2008) show that producing the observed structural and kinematical properties of disk-dominated galaxies and simple disks cannot be improved by adding feedback processes and by increasing the numerical resolution of the simulations. Therefore, the formation mechanisms of simple disks remain enigmatic.

During and after their formation, disk-dominated galaxies and simple disks are very sensitive to various processes that are responsible for transforming those objects into bulge-dominated galaxies or even destroy the disks. The majority of disk-dominated and simple disk galaxies are located in group and low-density environment (Kautsch, Gallagher & Grebel 2008). Hence, this type of environment should preserve the bulgeless shape of those galaxies. The contrary is observed as mergers are the dominant interaction process in groups (Barnes 1985) and the group environment is effective in transforming morphologies (Kautsch et al. 2008b; Tran et al. 2008). Minor mergers already lead to bulge growth (e.g., D’Onghia et al. 2006; Cox et al. 2008b; Kazantzidis et al. 2008) and the heating of the thin, stellar disk (Purcell, Kazantzidis & Bullock 2008). Near equal mass mergers can take place across all different galaxy environments where disk-dominated and simple disk galaxies reside (Karachentsev, Karachentseva & Parnovskij 1993; Kautsch, Grebel & Gallagher 2005) and affect the overwhelming majority of Milky Way-sized halos as shown in merger-tree statistics within ΛCDM N-body simulations (Stewart et al. 2008). It is assumed that ~70% of these Milky Way-sized halos contain disk-dominated galaxies and ~11% of the halos are the hosts of simple disks (Stewart et al. 2007, and referenced therein). Undergoing such a merger event is basically infaust for a disk-dominated galaxy and especially simple disks, i.e., N-body simulations of mergers exhibit that the stellar disk can be – but is not always (Koda, Milosavljevic & Shapiro 2007; Hopkins et al. 2008) – completely disrupted and morphologically transformed into an early-type galaxy (e.g., Toomre 1977; Steinmetz 2003; Cox & Loeb 2008).

So called “pseudobulges” can grow due to internal disk instabilities. In this secular evolution model gas sinks into
the disk center and the stars from a subsequent central star-formation period form a bulge (Kormendy & Kennicutt 2004; Kormendy & Fisher 2005). Galactic bars support the gas flow towards the galactic centers and thus are important for secular evolution. Bars are frequently detected in bulgeless galaxies (Barazza, Jogee & Marinova 2008), making simple disk galaxies potential candidates for ongoing secular evolution.

The first comprehensive catalog of edge-on disk-dominated galaxies is the “Flat Galaxy Catalog” (FGC, Karachentsev et al. 1993) and its extension, the “Revised Flat Galaxy Catalog” (RFGC, Karachentsev et al. 1999). FGC and RFGC are optical all-sky surveys. RFGC contains 4236 visually selected “flat” galaxies. A collection of disk-dominated galaxies in the near-infrared is gathered in “The 2MASS-selected Flat Galaxy Catalog” (Mitronova et al. 2004).

In order to contribute to a better characterization of flat galaxies, Kautsch et al. (2005b; 2006a) carried out a work which compiled a uniform sample of disk-dominated galaxies in the optical wavelengths from the Sloan Digital Sky Survey (SDSS, York et al. 2000). The SDSS is ideal for the identification of such galaxies with its deep, multi-wavelength, homogeneous and large-area coverage. They analyzed SDSS data from the Data Release 1 (DR1, Abazajian et al. 2003) and compiled a catalog of 3169 galaxies with prominent edge-on stellar disks (Kautsch et al. 2006a, hereafter “the catalog,” which is accessible online1 and Kautsch et al. 2006b). Using an automated algorithm, galaxies in the catalog are divided into galaxies with bulges, intermediate types and simple disk galaxies and subclasses. 15.8% of the catalog galaxies are found to be simple disks. This demonstrates that bulgeless galaxies are frequent, especially among intermediate-mass star-forming galaxies (Matthews & Gallagher 1997). This frequency increases up to 1/3 of the catalog galaxies when puffy disks are included. The boundaries between the galaxy types in the catalog are not sharp, suggesting simple disks are the faint end in a continuum of disk galaxy properties, e.g., surface brightness.

Since DR1, SDSS has undergone significant changes. DR1 provides a survey area of 2099 deg² of imaging data. The data releases DR2 (Abazajian et al. 2004), DR3 (Abazajian et al. 2005), DR4 (Adelman-McCarthy et al. 2006), DR5 (Adelman-McCarthy et al. 2007) and DR6 (Adelman-McCarthy et al. 2008) are now available. DR6 covers 9583 deg² of imaging in total and has an r-band depth of approximately 22.2 mag. Hence, DR6 contains more than four times the footprint area of DR1. In addition, changes were made between DR1 and DR2 concerning the deblending of overlapping objects. This correction should improve the detection of individual galaxies.

In this study we collect edge-on disk galaxies as done in the catalog (Kautsch et al. 2006a) but use the larger and newer database of the SDSS DR6 and we apply improved morphological separation criteria. This allows us to study the fractions of different edge-on disks in a more robust statistical manner. The galaxies in this new sample are also divided into morphological classes using a new approach compared to the catalog. The improved object detection and especially the much larger coverage area in the sky should provide updated statistics, accuracy and homogeneity of the fractions of disk-dominated galaxies in the local Universe. In addition, we provide a unique comparison of fractions of bulgeless disk galaxies from several catalogs and derive a robust estimation of the frequency of simple disks among spirals in the local Universe. The knowledge of this fraction is crucial for studies about the formation, evolution and survival of disk-dominated galaxies. Therefore, this work delivers useful statistical results for several follow-up studies such as the fraction of simple disk galaxies at high redshifts.

This article has the following structure: in Sect. 2 we describe how edge-on disk galaxies were selected in previous works and in this present study. The quantified morphological classification of galaxies with and without bulges is discussed in Sect. 3. The results of this study in terms of numbers and fractions and a comparison to the fractions of recently published studies are shown in Sect. 4. In Sect. 5 we summarize the results.

2 Data acquisition

In the catalog, edge-on disk galaxies were selected based on selection criteria that are similar to those of the original approach by Karachentsev et al.’s catalogs FGC and RFGC. The original object selection by Karachentsev et al. (1993; 1999) is based on the visual identification of galaxies with an axial ratio a/b ≥ 7 and a major axis diameter of 40′′ in the blue band POSS-I copies and ESO/SERC photographic plates. In order to come as close as possible to these original values, a training set of RFGC galaxies that were recovered in the SDSS DR1 was analyzed in the catalog with respect to their sizes, magnitudes and color distribution. This allowed Kautsch et al. (2006a) to translate the original object selection from the RFGC into a query that selects all galaxies brighter than m_g = 20 from the DR1 “Best Galaxy Table” with axial ratios >3 and a major axis diameter >30″ within certain broad color limits. For the details of this query, please consult Kautsch et al. (2006a; 2006b). Our intention now is to collect edge-on galaxies from the DR6 in the same reproducible fashion. Therefore we apply the SDSS CasJobs on the SDSS Context DR6 to the “Galaxy Table”. CasJobs² is an online interface that performs queries on various SDSS datasets using the “Structured Query Language” (SQL) and the “Galaxy Table” is the table of the SDSS data archive that contains all parameters for objects selected as galaxies in DR6 with the highest quality at the time of the data release. The query used in the catalog and in this study selects all galaxies with: i) an axial ratio a/b > 3

1 http://vizier.cfa.harvard.edu/viz-bin/VizieR?-source=J/A+A/445/765
2 http://casjobs.sdss.org/CasJobs
(a major axis, b minor axis) in the g-band, ii) an angular major axis diameter a > 30′′ in the g-band, iii) colors in the range of -0.5 < g - r < 2 and -0.5 < r - i < 2, iv) a magnitude limit in the g-band < 20 mag. These selection criteria have the following form in SQL:

```
SELECT * into mydb.edge_on_dr6_catalog from Galaxy as G
WHERE G.petroMag < 20
and (G.isoA_g/G.isoB_g) > 3
and G.isoA_g > 37.8 pixel this corresponds to an angular radius of 15′′
and (G.dered_g - G.dered_r) between -0.5 and 2
and (G.dered_r - G.dered_i) between -0.5 and 2
```

This query leads to a sample of 27,308 objects. A visual inspection shows a non-negligible number of contaminants. The contaminants are mostly stellar refraction spikes and artifacts such as satellite/meteor tracks, empty images as well as face-on galaxies where elongated structures (e.g., bars, spiral arms) simulate an edge-on disk appearance. In addition, some of the galaxies are also affected by “shredding” (Abazajian et al. 2004). This means that a single object has more than one unique detection and therefore multiple entries in the SDSS database. In the catalog, these contaminants were removed manually. Because of the large numbers in the present sample, this approach is inefficient and should be quantified. We find that the majority of the contaminants are automatically removed by excluding the objects flagged with the following DR6 PhotoFlags:

- “edge” indicates galaxies truncated on the survey borders;
- “saturated” indicates saturated pixels;
- “notchecked” indicates that SDSS deblending may be unreliable;
- “too few good detections” indicates objects with no good centroid found in all bands;
- “petroMagErr” > 0.3 in g, r, i indicates the magnitude errors.

This leads to a DR6 sample of 15,176 objects. We exclude also the objects that do not have Petrosian radii, “petroR50” and “petroR90.” The final DR6 edge-on galaxy sample contains 15,127 objects.

We select various large random samples in order to estimate the remaining contribution of contaminants in this final sample. We find a rate of 5% of false detections for the whole sample, mainly due to shredded galaxies, elongated HII regions in disks, projected objects in spiral arms, empty images, projected objects in halos of saturated stars and rarely, stellar spikes that are still present in the sample.

3 These flags are associated with every unique object in the database and contain important information of the quality of the object: http://www.sdss.org/dr6/products/catalogs/flags.html.

Fig. 1 This figure shows the relation between the luminosity weighted mean ellipticity ε (ordinate) and the adaptive ellipticity e (abscissa) for all galaxies in the catalog in the SDSS r-band. Early-type disk galaxies are plotted in the left part and late-type disks in the right part of this figure. The scatter plots are presented in the lower section of the figure. The fine solid lines in the upper diagrams indicate the linear relation with a slope of one. The solid lines in the bottom diagrams show the location of ε - e = 0. The dashed line in the scatter plot for the late disks (bottom right) indicates the derived mean offset between ε and e.

3 Morphological separation

In the catalog we used an automated morphological classification in order to define six types of edge-on disk galaxies. These are galaxies with bulges (Sa(f), Sb(f)); simple disk galaxies (Sd(f)); and disk-dominated intermediate types (Sc(f), Scd(f)) as well as disky edge-on irregulars (Irr(f)). We follow the terminology by de Vaucouleurs (1959) where spiral galaxies are flagged with a letter associated with the shape of the spiral arms (ring-shaped galaxies have an “r” and s-shaped galaxies have an “s”). We instead are using an “f” in brackets in order to indicate that the galaxies contain flat disks seen edge on.

The morphological separation in the catalog is based on the concentration index (CI) and the luminosity-weighted mean ellipticity of the elliptical isophotes (ε), both in the SDSS r-band. The CI is a measure of the bulge size for edge-on galaxies and is defined as the ratio of the Petrosian radii that contain 90% and 50% of the Petrosian flux in the same band in a circular aperture. We used the Petrosian radii that are listed in the “Galaxy Table.” The CI separation values divide the early (Sa(f), Sb(f)) from the late types (Sc(f), Scd(f)) as well as disky edge-on irregulars (Irr(f)). In addition, low CI values separate the Irr(f) class from the late types. We use the same CI separation criteria as in the catalog because the Petrosian radii did not undergo changes between DR1 and DR6.

ε is a discriminator of the flatness of edge-on disks and was measured directly on the individual galaxy images of the galaxies in the catalog. This measurement was performed with the MIDAS surfphot package. We fit elliptical isophotes to the galaxies and derived ε as the weighted mean ellipticity of all isophote levels of an individual galaxy.
We replace the method finding $\varepsilon$ by using variables offered directly from the SDSS tables. The new method offers consistency within the SDSS parameters. In addition, with this method it is simple to reproduce our morphological separation criteria in a fast and efficient way. Disk flatness can be expressed through the adaptive moments provided in the DR6 “Galaxy Table.” The moments are measured from the ellipticity and size of the objects within the SDSS pipeline\(^4\). The adaptive second moments from the SDSS ($m_{E1}$ and $m_{E2}$),

\begin{align}
 e_{+} &= m_{E1}, \\
 e_{\times} &= m_{E2},
\end{align}

(1)\hspace{1cm}(2)

can be converted into an “adaptive” ellipticity ($e$), using $a$ and $b$ as major and minor axis, respectively (c.f., Vincent & Ryden 2005):

\begin{equation}
 e = 1 - \frac{b}{a} = 1 - \sqrt{\frac{1 - \sqrt{e_{+}^2 + e_{\times}^2}}{1 + \sqrt{e_{+}^2 + e_{\times}^2}}}. 
\end{equation}

(3)

We now compare $\varepsilon$ with $e$ for all galaxies from the catalog. The upper part of Fig. 1 shows the relation between $\varepsilon$ and $e$ for the early-disk types (left) and the late types (right). The diagrams on the bottom of Fig. 1 show the scatter plots. Early disks (Sa(f), Sb(f)) (on the left side of this plot) tend to have a rounder shape (i.e., lower ellipticity values) of $\varepsilon$ compared to $e$. In contrast, late disk types Sc(f), Scd(f), Sd(f) and Irr(f) (shown in the right part of the figure) are flatter using $e$ instead of $\varepsilon$. We also see some late-type outliers having significantly lower $\varepsilon$ compared to $e$. A visual inspection of the outliers exhibits that many of these points belong to misclassified Irr(f) types in the catalog.

The limiting values of $\varepsilon$ in Table 1 in the catalog must be recalculated in order to separate the galaxies into different morphologies based on $e$. The late types are constantly shifted from a simple linear relation with a slope of one between $\varepsilon$ and $e$ as shown in the right bottom part of Fig. 1. We derive a mean offset of $\varepsilon - e = -0.016$, indicated as dashed line in Fig. 1. Because the late disks are flatter in $e$, the offset must be added to $\varepsilon$ in order to resemble the limiting values of the catalog. We emphasize that the main intention of this investigation is to study the fractions of disk-dominated galaxies. Therefore, early-type disks (classified as Sa(f) and Sb(f)) are less important for this purpose. However, we use a histogram of the number distribution of $e$ for the galaxies classified as Sa(f) and Sb(f) in the catalog. With the aid of this histogram (Fig. 2) we define a value of $e = 0.4$ as the best separation value that resembles the dividing limit between Sa(f) and Sb(f). The limiting values for CI and $e$ are collected in Table 1.

\(^{4}\) http://www.sdss.org/dr6/algorithms/adaptive.html

\(^{5}\) http://cas.sdss.org/dr6/en/tools/chart/list.asp

4 Results

4.1 Fractions of different types of edge-on galaxies

We apply the new limiting values from Table 1 to the new DR6 edge-on galaxy sample. Figures 3, 4, 5, 6, 7, and 8 show example images of galaxies with types Sa(f), Sb(f), Sc(f), Scd(f), Sd(f) and Irr(f), respectively. These images have an angular size of 100 square arcsec and north is to the top, east to the left. The images are downloaded from the SDSS Image List Tool\(^5\). The number results are shown in Table 2. In this table we also reprint the numbers of the classes found in the catalog on the right side. The largest difference between the catalog and this study is the fraction of Irr(f). Their increased number in the present study is due to the contamination of misclassified objects, as revealed in a visual inspection of randomly selected Irr(f) types. Aside from this, the fractions of the different types are almost the same. For completeness considerations of the classes we refer to Sect. 6 in the catalog.
The galaxy classes and their fractions are shown in this table. The absolute numbers of galaxies in the main morphological classes (Col. 2) and their percentages (Col. 3) are listed in this table. For comparison the numbers and percentages of the catalog are given inCols. 4 and 5.

| General Class | SDSS DR6 | SDSS DR1 |
|---------------|----------|----------|
| Sa(f)         | 966      | 6        | 222      | 7        |
| Sb(f)         | 3993     | 26       | 843      | 26       |
| Sc(f)         | 4835     | 32       | 1005     | 32       |
| Scd(f)        | 2257     | 15       | 503      | 16       |
| Sd(f)         | 2220     | 15       | 501      | 16       |
| Irr(f)        | 856      | 6        | 95       | 3        |
| Total         | 15127    | 100      | 3169     | 100      |

The limiting values for Sd(f) of the catalog are based on fairly conservative separation criteria in order to minimize possible contamination from other classes. So the fraction of simple disks is 15% in the present study. In the catalog we show that it is also possible to include the Scd(f) types in an extended bulgeless disk class. The fraction of this extended bulgeless disk class (Scd(f) and Sd(f)) is 30% of the total DR6 sample. This value is similar to the value of 32% of the catalog. Therefore, the fraction of the extended bulgeless disk class in this work and the catalog corresponds to roughly 1/3 of the total sample of edge-on disk galaxies. However, the contamination by other types is larger than with the more rigorous defined limits for simple disks.

4.2 Comparison with other studies

It is generally known that disk galaxies of late Hubble morphologies are often bulgeless (e.g., Hubble 1936; Böker et al. 2002; Kormendy & Kennicutt 2004). However, accurate number statistics of the fraction of simple disk galaxies are rare, probably due to the lack of large samples.

Barazza et al. (2008) studied the fraction of bars in disk galaxies and they also analyzed the fraction of bulgeless galaxies based upon visual inspection. The fraction of bulgeless disks is ∼20% in their sample. The sample they used is selected from the SDSS with −18.5 ≤ M_g ≤ −22 and redshifts between 0.01 < z < 0.03. Disk galaxies are selected using a color cut, and galaxies with inclinations larger than 60° are omitted. Their fraction of bulgeless galaxies is close to that of the simple disks (Sd(f)) found here. The ∼5% difference can be explained by considering that Barazza et al. (2008) used a color cut for the disk galaxy selection. This could exclude red spiral types and therefore slightly offset their sample towards bluer and later disk types.

Koda et al. (2007) used the “Tully Galaxy Catalog” in order to select galaxies with morphological information given in that catalog. The fraction of Sd galaxies is 11%. Considering the restriction to local (dist < 20 h^−1, −17 < M_B < −20) galaxies, their fraction is similar to ours. The small difference of ∼4% is probably an effect of visual classification: The “Tully Galaxy Catalog” is not restricted to edge-on galaxies. Less inclined objects can exhibit central light concentrations from nuclei (e.g., Walcher et al. 2006) which are not seen edge-on. For this reason, some Sd would have been classified as earlier types.

In Allen et al. (2006), 10095 galaxies with m_B < 20 from the “Millennium Galaxy Catalog” (Liske et al. 2003) were morphologically analyzed using two component Sersic spheroid + exponential disk decomposition (GIM2D, Simard et al. 2002, 2008). The fraction of pure exponential disks is 14% and comparable to the fraction of simple disks in our sample.

The Neighboring Galaxy Catalog (Karachentsev et al. 2004) contains 77 disk-like objects among 451 galaxies with a magnitude limit of M_B ≥ −12 and a distance ≤ 10 Mpc. This study exhibits an Sd fraction of 21 ± 5%. This catalog includes low-luminosity galaxies and this increases the completeness of the fraction of simple disks at the faint end. Therefore, the simple disk fraction is larger compared to the DR6 sample.

By comparing the simple disk fractions of this study with its progenitor catalogs, the catalog (Kautsch et al. 2006a) (16%) and the RFGC (Karachentsev et al. 1999) (17%), also reveal an excellent agreement of the fractions.

This comparison shows a good agreement of the fractions of simple disk galaxies (Sd types) between different studies which are using large numbers of analyzed galaxies. The results of this comparison are summarized in Table 3. Although these studies use different luminosity, distance, inclination and morphological selection criteria, the average fraction of simple disks is 16.2% ± 3.2% among late-type galaxies.

5 Summary and discussion

This study presents the fractions of disk-dominated galaxies and other edge-on disk galaxy types selected from the SDSS DR6. Using a quantitative method that measures the disk flatness and the bulge size, this sample is divided into morphological classes of galaxies with bulges, intermediate
type and apparently bulgeless objects. Each of these broad types contains roughly 1/3 of the total sample. Further sub-
division is applied to these types and allows us to define the 
fraction of simple disk galaxies, Sd(f), to be 15% of the to-
tal disk galaxy sample. The fractions of other morphological 
Hubble types of disk galaxies are also presented and com-
pared to the catalog of edge-on disk galaxies (Kautsch et al.
2006a).

We also present a comparison of the frequency of sim-
ple disk galaxies from various galaxy catalogs and find a 
simple disk fraction of \(\sim 16\% \pm 3\%\) on average. The frac-
tions are a robust result because of the excellent agreement 
between the studies, although various criteria were used to 
select the galaxies. Small differences of the Sd fractions can 
be explained qualitatively. We conclude that simple disks 
are a common galaxy type, although formation and evolu-
tion models are challenged by explaining bulgeless galax-
ies. Hence, a comprehensive description of simple disks re-
 mains to be explored.

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