THE EDGE-ON PERSPECTIVE OF BULGELESS, SIMPLE DISK GALAXIES

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ABSTRACT

This review focuses on flat and superthin galaxies. These are edge-on bulgeless galaxies, which are composed of a simple, stellar disk. The properties of these simple disks are at the end of a continuum that extends smoothly from bulge-dominated disk galaxies to the pure disks. On average, simple disks are low-mass galaxies with low surface brightnesses, blue colors, and slow rotational velocities. Widely-accepted cosmological models of galaxy formation and evolution were challenged by a relatively large observed fraction of pure disk galaxies, and only very recent models can explain the existence of simple disk galaxies. This makes simple disks an optimal galaxy type for the study of galaxy formation in a hierarchical Universe. They enable us to analyze the environmental and internal influence on galaxy evolution, to study the stability of the disks, and to explain the nature and distribution of dark matter in galaxies. This review summarizes the current status of edge-on simple disk galaxies in the Universe.

Subject headings: Galaxies, IYA Review

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1. INTRODUCTION AND HISTORY

After the Great Debate in 1920 (Trimble 1995), it became evident that many of the known nebulae were extragalactic systems. Hubble (1926) introduced a classification scheme for extragalactic nebulae that is still the most powerful tool today to categorize galaxy morphology (see also van den Bergh 2007). In this scheme, galaxies of different morphologies can be reduced into two basic geometric manifestations: stellar spheroidal ellipsoid or stellar disk. All other morphologies represent a combination of spheroidal components centered in disks, and span a continuum from the spheroid-dominated early-type galaxies (E, S0, Sa) to the disky late-type galaxies (Sb, Sc, Sd, Sm, Im, Irr). Peculiar and distorted morphologies are considered to be the result of interaction processes (Pfleiderer 1963; Toomre 1977).

In the 1960s, a special type of a thin and elongated galaxy was found in various galaxy surveys. Ogorodnikov (1957, 1958) and Vorontsov-Vel'yaminov (1967, 1974) were among the first scientists who studied these needle-shaped galaxies. Fujimoto (1968) suggested that these systems are very elongated, prolate ellipsoids. However, the needles would be gravitationally and kinematically unstable systems. It later became evident that these objects are bulgeless "simple disk" galaxies seen edge-on (Heidmann et al. (1972), see also Caimmi (2007)). Figure 1 shows an example of an edge-on simple disk galaxy in contrast to a disk galaxy with bulge.

Because of their appearance, these galaxies are frequently called flat galaxies (e.g., Karachentsev 1989; Karachentsev et al. 1993). Flat galaxies are edge-on disks that are defined to have axial ratios of the semi-major to semi-minor axis of ≥ 7 on blue photographic plates (Karachentsev et al. 1993, 1999); for instance, M33 would be a flat galaxy when seen edge-on. Almost all flat galaxies are bulgeless disks. Objects with even larger ax-

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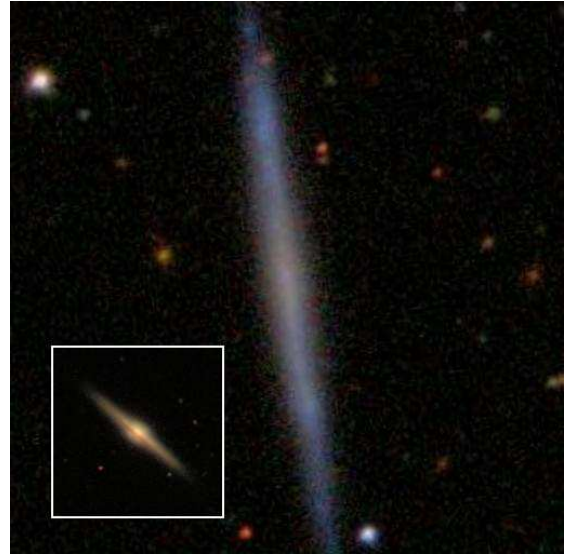

FIG. 1.— The late-type, bulgeless edge-on galaxy J214439.43-064122.5, an Sd(f) class galaxy, is an example of a simple disk. For contrast, the inlay shows a typical disk galaxy (J111146.36+364442.3) with a bulge of type Sa(f). Note the typical dust lane in the Sa(f) galaxy which is absent in the simple disk galaxy. Both images are taken from the SDSS and shown in Kautsch (2009a). The angular size of the images is 100 arcsec^2.

ial ratios ($\frac{a}{b} \geq 10$) are called superthin galaxies and represent a subset of bulgeless flat galaxies with very small disk scale heights (Goad & Roberts 1979, 1981). Flat bulgeless and superthin galaxies are part of the class of simple disk galaxies, which ranges from thin, late-type galaxies of morphological Hubble class ∼Scd and later without a bulge component[2] to the thicker, puffy disks of bulgeless irregular disks. The Large Magellanic Cloud, LMC, represents a prototype for a non edge-on irregular and puffed bulgeless disk (Wyse et al. 1997). This review focuses on the properties and challenges related to

[2] Not all late-type spirals are bulgeless (Böker et al. 2003a; Graham & Worley 2008).

bulgeless flat and superthin galaxies as an integral part of the class of simple disk galaxies.

2. FORMATION

The formation of disk galaxies in general is believed to be the result of the collapse of a gaseous protogalaxy within a dark halo (Eggen et al. 1962; White & Rees 1978; Fall & Efstathiou 1980). Chemodynamical and analytical models of disk evolution within a slowly growing dark matter (DM) halo can reproduce many properties of disk galaxies like the Milky Way (Samland & Gerhard 2003; Hernandez & Cervantes-Sodi 2006; Dutton 2009). In these models, a Gaussian distribution of initial conditions leads to either a massive disk galaxy after an efficient collapse of a low angular momentum protogalaxy or to a low surface-brightness (LSB) exponential disk out of an inefficient cooling protogalaxy with high angular momentum and/or lower mass (Sandage et al. 1970; Dalcanton et al. 1997).

Cosmological, numerical simulations of galaxy formation are challenged in forming bulgeless galaxies, known as the angular momentum problem (or angular momentum catastrophe) (Navarro & Benz 1991). The simulated galaxies are too dense, too small, too centrally concentrated, and have lower angular momentum than observed because subhalos in a DM halo cool too fast, which causes angular-momentum loss by dynamical friction and merging of these clumps (D'Onghia & Burkert 2004; Piontek & Steinmetz 2009a). Feedback processes can suppress dramatic cooling and loss of angular momentum (Sommer-Larsen et al. 2003; Okamoto et al. 2005; Robertson et al. 2006; Mayer et al. 2008; Scannapieco et al. 2008). Modern cosmological simulations show that it is possible to form exponential disk galaxies that are comparable to observations by using realistic models of feedback (Mayer et al. 2008; Piontek & Steinmetz 2009b; Governato et al. 2010). However, other studies claim that neither different kinds of feedback (D'Onghia & Burkert 2004; D'Onghia et al. 2006) nor increased numerical resolution (Köckert & Steinmetz 2007; Piontek & Steinmetz 2009a) can resolve the angular momentum problem completely. Therefore, the formation of simple disk galaxies in a cosmological framework is not yet well understood (Burkert 2008; Mayer et al. 2008), and a detailed understanding of this topic is just at the beginning.

3. EVOLUTION

In the current Λ cold DM (ΛCDM) framework of structure formation and evolution, galaxies in DM halos grow hierarchically by the absorption of smaller substructures in sub halos (Searle & Zinn 1978; White & Rees 1978; Blumenthal et al. 1984). This means that disk galaxies have always been subject to merging and interaction. Almost all galaxies with present halo mass comparable to the Milky Way ($M_{DM} \sim 10^{13} M_\odot$, $M_{stars} \sim 10^{11} M_\odot$, Dutton (2009)) are believed to have experienced a major merger (i.e., a merger with a similar mass partner) (Stewart et al. 2008; Wang & Kauffmann 2008; Stewart et al. 2009).[3] Major mergers cause dra-

matic morphological transformations of disk galaxies. At the upper limit, a merger may cause the total destruction of the disk and the formation of a spheroidal, elliptical galaxy (e.g., Toomre 1977; Barnes 1992; Gardner 2001; Cox & Loeb 2008). Massive disks can then be rebuilt from gas deposited in a gas-rich (major) merger (Hammer et al. 2009; Robertson & Bullock 2009; Yang et al. 2009) supported by the additional accretion of cold gas (Dekel & Birnboim 2006). However, these so-called rebuilt scenarios assume that disks will be reformed around preexisting spheroidal bulges (Steinmetz 2003; Springel & Hernquist 2005). In less violent cases of major mergers, spheroidal bulges can formed by dynamically heated disk stars and accreted material (Aceves et al. 2006; Bournaud et al. 2007; Khochfar 2009). In addition, new bulge stars can be formed from disk gas that lost its angular momentum by non-axisymmetric distortions due to galaxy-galaxy interactions (Noguchi 2001; Benson et al. 2004; Hopkins et al. 2009a; Koda et al. 2009).

Simple disk galaxies are low-mass systems (comparable to M33 with $M_{DM} \sim 10^{11.5} M_\odot$, $M_{stars} \sim 10^{10} M_\odot$, Dutton (2009)) that are not subject to frequent major merging events (Stewart et al. 2008; Wang & Kauffmann 2008). However, multiple minor mergers (with partners of mass ratios $\leq \frac{1}{3}$) are common for low massive galaxies at low redshifts (Bournaud et al. 2007; Bullock et al. 2008; Jogee et al. 2009; Stewart et al. 2009). Minor mergers heat the thin disks (e.g., Bullock et al. 2008; Kazantzidis et al. 2008, 2009; Purcell et al. 2009), let bulges grow (e.g., Naab & Burkert 2003; D'Onghia et al. 2006; Bournaud et al. 2007; Khochfar 2009) and could also form an elliptical galaxy (Bournaud et al. 2007; Combes 2009). According to these model predictions, not many simple disks should have survived the cosmological evolution. Several recent studies (Robertson et al. 2006; Mayer et al. 2008; Hopkins et al. 2009a,b; Koda et al. 2009; Weinzirl et al. 2009) targeted this challenge and found that low-mass and gas-rich disk galaxies—such as simple disks—in combination with feedback processes can prevent substantial damage during mergers. In these models, the large amount of collisional gas suppresses violent relaxation of the angular momentum in the merger and subsequently conserves the disk structure of these galaxies.

However, several observations of simple disk galaxies show signatures of galaxy-galaxy interactions. For example, many simple disk galaxies show warps, a possible indicator of ongoing morphological transformations (Reshetnikov 1995; Uson & Matthews 2003; Matthews & Uson 2004). It is also observed that some simple disks host a faint and diffuse thick stellar disk component (Yoachim & Dalcanton 2006, see also Section 6). These thick disks can be formed during merging events and contain large fractions of the stellar mass in such galaxies (Yoachim & Dalcanton 2008).

Another explanation of the observed frequency of simple disks is that they are exceptionally stable. Massive spheroidal components like bulges and DM halos can stabilize disks against external influence (Samland & Gerhard 2003; Sotnikova & Rodionov 2006;

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[3] Strictly speaking, the model of hierarchical clustering (HCM) implies that every structure has experienced a major merger when its history is followed far enough in the past (Khochfar & Burkert 2001).

Kazantzidis et al. 2009). Simple disks have dominant, non-baryonic DM halos, see Section 5.[4] Moreover, the disk thickness (Karachentsev et al. 1997) of flat galaxies also is related to the dark halo. Zasov et al. (2002), Kregel et al. (2005), and Mosenkov et al. (2010) used samples of edge-on disk galaxies including simple disks and found a correlation of the relative thickness of a stellar disk and the relative mass of the spheroidal component including the DM halo. Nevertheless, disk galaxy evolution remains hotly debated and future papers will contain exciting insights in this field.

Disk galaxies can be also transformed via internal, secular evolution. We are currently in a cosmological transition era where secular evolution is becoming an important process (Kormendy & Fisher 2005). Non-axisymmetric structures like bars and oval disks support internal disk instabilities and transport gaseous material to the disk center (Kormendy (1983); Kormendy & Kennicutt (2004), see also Combes et al. (1990)). Subsequent central star formation forms a pseudobulge with disk-like properties such as disky isophotes when seen edge-on, exponential surface brightness profiles, and low velocity dispersion (Kormendy & Fisher 2005; Fisher & Drory 2008). Bars are frequently detected in bulgeless galaxies (Matthews & Gallagher 1997; Barazza et al. 2008), making simple disks potential candidates for secular evolution. Flat and superthin galaxies are ideal for studying the predictions of secular evolution and the growth of pseudobulges because we do not know how many low-mass disks are affected by this internal evolution and if it is a common phenomenon in these objects.

4. FRACTIONS OF SIMPLE DISKS

Bulgeless simple disk galaxies are common in the local Universe (Matthews & Gallagher 1997; Böker et al. 2002; Goto et al. 2003; Barazza et al. 2008; Cameron et al. 2009). The first comprehensive search for disk-dominated and bulgeless galaxies was initiated by Karachentsev (1989) in order to map cosmic flows. Karachentsev used a simple but effective method to classify these galaxies by selecting only edge-on disks where bulges can be easily detected and the vertical structure can be studied. This work resulted in the "Flat Galaxy Catalog" (FGC, Karachentsev et al. 1993) and the "Revised Flat Galaxy Catalog" (RFGC, Karachentsev et al. 1999). These optical all-sky surveys are supplemented by the near-infrared "The 2MASS-selected Flat Galaxy Catalog" (Mitronova et al. 2004). Follow-up optical and HI radio observations for FGC and RFGC galaxies are collected in Giovanelli et al. (1997), Dalcanton & Bernstein (2000), Matthews & van Driel (2000), Makarov et al. (2001), Mitronova et al. (2005), and Huchtmeier et al. (2005).

Kautsch et al. (2006a) used the first data release of the Sloan Digital Sky Survey (SDSS DR1, Abazajian et al. 2003) in order to collect a uniform and homogeneous catalog of edge-on disk galaxies. Similar to the FGC

and RFGC, Kautsch et al. (2006a,b) selected the objects based on axial ratio ($\frac{a}{b} > 3$), angular diameter ($a > 30''$), and apparent magnitude ($m < 20$ mag in the SDSS g band) within a certain color range. The galaxies were then separated into a morphological sequence ranging from objects with bulges to bulgeless simple disks and irregulars: Sa(f), Sb(f), Sc(f), Scd(f), Sd(f) and Irr(f); (f) indicates that the galaxies contain flat disks seen edge-on. This automated classification is based on bulge size and disk flatness. The bulge size is represented by the light concentration index in the SDSS r band. This concentration index is the ratio of the Petrosian radii given in the SDSS for each object that contains 90% and 50% of the Petrosian flux in the same band, respectively (see Stoughton et al. 2002, for the definition of the Petrosian parameters in the SDSS). The disk flatness parameter, e, is the luminosity weighted mean ellipticity of the elliptical isophotes in the SDSS r band fitted to each catalog galaxy (Kautsch et al. 2006a).[5]

The fraction of the simple disk class Sd(f) is 16% among the disk galaxies in the Kautsch et al. (2006a) catalog. This fraction increases to 32% if the seemingly bulgeless (but less strictly defined) Scd(f) types are included. Kautsch (2009a,b) confirmed these fractions by using the SDSS DR6 (Adelman-McCarthy et al. 2008). Kautsch (2009a) also compared the fraction of simple disks in the local Universe with other recent studies (Karachentsev et al. 1999, 2004; Allen et al. 2006; Kautsch et al. 2006a; Barazza et al. 2008; Koda et al. 2009) and found a simple disk fraction of 16±3% on average among disk galaxies. This frequency shows that bulgeless galaxies comprise a non-negligible fraction of spiral galaxy systems. It is possible that small and compact bulges are obscured due to dust extinction (Tuffs et al. 2004; Driver et al. 2008). However, this is unlikely in a majority of simple disks because they are observed to be transparent and these bulges would have different properties to those of classical bulges predicted by theoretical models (Cameron et al. 2009). Field studies show that the number density of large bulgeless galaxies is constant (maybe slightly increasing) at redshifts $0 \leq z \leq 1$ whereas the number of galaxies with bulges decreases at larger distances (Sargent et al. 2007; Domínguez-Palmero & Balcells 2009).

Bulgeless galaxies are located in all environments, ranging from low to high density (Kautsch et al. 2005, 2009). The majority of these galaxies are weakly associated with galaxy clusters and can be found in more isolated environments comparable to galaxy groups and the field (Kudrya et al. 1997; Karachentsev 1999b; Kautsch et al. 2009). Because of the low relative velocities of group galaxies, merging and morphological processes that transform late-type galaxies into bulge-dominated and spheroidal galaxies are common in the group environment (e.g., Barnes 1985; Kautsch et al. 2008; Tran et al. 2008). This implies that simple disks either have to be stable against morphological preprocessing or are located in this environment due to recent infall.

5. GLOBAL PROPERTIES OF SIMPLE DISKS

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[4] The structure of simple disks is determined by a rotation-supported, cold extended stellar disk; a dominant, spheroidal, non-baryonic DM halo (see Section 5); and no bulge. On the opposite end of the morphological spectrum are the ellipticals with a dominant, hot stellar spheroid but almost without a cold disk and DM halo (Napolitano et al. 2009).
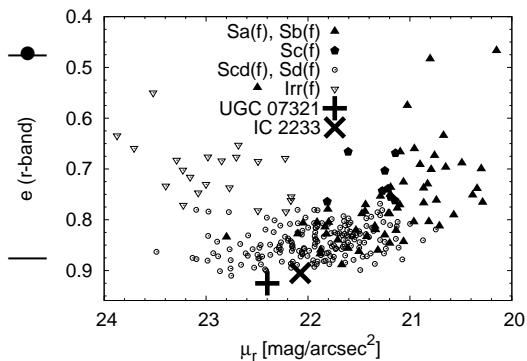
[5] Kautsch (2009a) found that e can also be directly derived from the image moments available in the SDSS archive.

FIG. 2.— This figure shows the total surface brightness, μ, versus the disk flatness, e, for a random sample of the Kautsch (2009a) edge-on galaxies. See text for a description of the parameters. The symbols above and below the y-axis label illustrate the increasing bulge size of the galaxies along this axis. The bulgeless galaxies, Scd(f), Sd(f), and Irr(f), exhibit lower total surface brightnesses compared to the disk galaxies with bulges.

Simple disks are not a separate morphological class, but rather at the end of a smooth continuum without a well-defined boundary (Matthews & Gallagher 1997; Kautsch et al. 2006a). The continuum ranges from massive, stellar disk galaxies with substantial bulges and with high surface brightnesses to the bulgeless galaxies with lower masses and surface brightnesses (e.g., Schombert et al. 1992; Karachentsev et al. 1993; Matthews et al. 1999; Dutton 2009; Ganda et al. 2009).

Figures 2−6 illustrate these properties for different edge-on galaxies. Two prototypical superthin galaxies, UGC 07321 and IC 2233,[6] are highlighted with large cross symbols. The objects in all figures represent a randomly selected subsample (in order to avoid making the plots too crowded) from the SDSS DR6 edge-on disk galaxy collection by Kautsch (2009a). These galaxies are matched with the Giovanelli et al. (1997) and Huchtmeier et al. (2005) catalogs in order to obtain their rotational velocities, except for UGC 07321 and IC 2233 for which the kinematic information was collected from Matthews et al. (1999) and Matthews & Uson (2008a), respectively. The numbers of the objects slightly vary between the diagrams because some SDSS parameters or kinematics are not provided for every individual galaxy.

Figure 2 shows the lower total surface brightnesses of simple disks compared to disks with bulges. However, this does not mean that every simple disk is an LSB galaxy (Kautsch et al. 2006a) nor that every LSB galaxy is bulgeless (Bizyaev & Kajsin 2004). The previously discussed flatness parameter e in the Figures 2−4 is derived from the SDSS image moments as shown in Kautsch (2009a). The SDSS does not contain image moments for IC 2233 because of a nearby, saturated projected star, therefore I use its isophotal ellipticity as given in the archive as a proxy for e. The total surface brightness of each galaxy in Figure 2 is derived by using the parameters $\mu = $ `petroMag`+`rho`, which are given in the SDSS archive (Stoughton et al. 2002). `rho` is five times the logarithm of the Petrosian radius. No correction for inclination and extinction in the individual objects is applied.

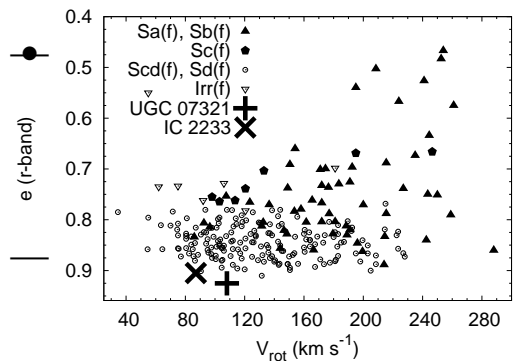On average, bulgeless disks rotate slower than galax-

[6] IC 2233 = UGC 04278

FIG. 3.— This figure shows the rotational velocity, v_{rot}, versus the disk flatness, e, for the same random sample of Fig. 2. Galaxies with bulges rotate faster on average compared to disk-dominated and bulgeless systems.
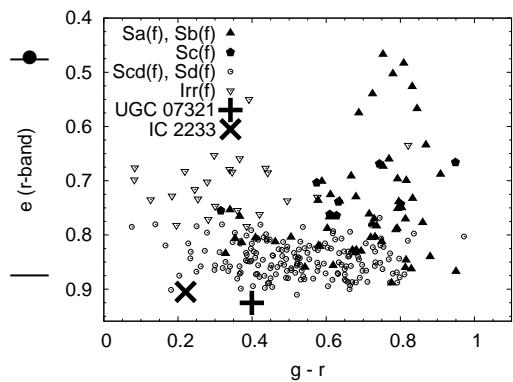

FIG. 4.— This figure shows the $g-r$ color versus the disk flatness, e, for the same random sample of Fig. 2. Galaxies with bulges are redder on average compared to disk-dominated and bulgeless systems.

ies with bulges as shown in Figure 3. The HI line width at 50% peak flux ($W_{50,c}$) from Giovanelli et al. (1997) and Huchtmeier et al. (2005) is used to derive the rotational velocities for the sample galaxies ($v_{rot} = W_{50,c}/2$, Dalcanton & Bernstein 2002). Considering the rotational velocity as a proxy for the total mass of the objects, the figure implies that flat galaxies are low-mass systems.

Only a few edge-on simple disks have been studied in detail so far. Therefore I will focus on studies of LSB superthin simple disks such as UGC 07321 and IC 2233 in this and the next section. The results from these prototypes are presumably valid for most of the simple disks. Generally, simple disks have low metallicities and blue global colors (Matthews & Gallagher 1997; Matthews & Uson 2008a; Cameron et al. 2009) which places them in the blue cloud of galaxies (Strateva et al. 2001; Baldry et al. 2004). Figure 4 shows the apparent colors for different edge-on disk galaxy types. The colors are derived from the Galactic extinction corrected Petrosian g and r magnitudes from the SDSS archive (Stoughton et al. 2002). Although no inclination correction is applied, edge-on galaxies with bulges appear to be redder compared to the average color of simple disks. The color range of bulgeless disks can represent variations of the recent star-formation rates (Lee at al. 2009;

West et al. 2009). Variations in metallicities and reddening due to different dust content also can cause differences in colors, but these effects are considered to be small because simple disks host only small amounts of interstellar dust, discussed later in this section.

Simple disks are not necessarily young. Many contain old stellar populations (≤ 10 Gyrs, Bergvall & Rönnback 1995; de Blok et al. 1995). Matthews et al. (1999) and Matthews & Uson (2008a) also find radial color gradients in edge-on superthins with a central mix of stellar populations of different ages and a very young population in the outer disk. Additionally, they find a population of redder, older stars at higher scaleheights. This suggests that the objects formed slowly in time from the inside out and experienced vertical dynamical heating.

These studies also show signatures of ongoing, localized star formation such as HII regions, OB associations, and candidate supergiant populations (Bergvall & Rönnback 1995; Matthews et al. 1999; Matthews & Uson 2008a). The global star formation rates of the prototypical superthins are: UGC 07321, $SFR_{IRAS} \sim 0.006 \ M_\odot yr^{-1}$ (Matthews & Wood 2003; Uson & Matthews 2003); and IC 2233, $SFR_{IRAS} \sim 0.02 \ M_\odot yr^{-1}$ (Matthews & Uson 2008a). These estimates are at the low end of observed star formation rates for Sd spirals (Kewley et al. 2002). Therefore, Matthews and coworkers conclude that the superthin galaxies are underevolved systems in the sense of star formation (e.g., Matthews et al. 1999; Matthews & Uson 2008a). The low global star formation rates can be explained by the HI surface density being too low to efficiently form stars (e.g., van der Hulst et al. 1993; Schombert et al. 2001) and a high velocity dispersion of the gas that makes the disks stable against star formation (Banerjee et al. 2010). Interesting future work could be done concerning the star formation rate per area, or star-formation rates, normalized to the physical sizes of the galaxies (cf., Hunter & Elmegreen 2004). The specific star formation rates of the superthins might be also higher than the global star formation when considering the low stellar masses (e.g., Dutton 2009) of these bulgeless systems.

Bulgeless galaxies contain large amounts of atomic, neutral HI gas (Karachentsev et al. 1999c; Matthews & van Driel 2000; Makarov et al. 2001; Matthews & Uson 2008a). The gas is extended throughout the stellar disk (Matthews et al. 1999; Matthews & Uson 2008a). Also hot, ionized HII gas—distributed in clumps—exists in simple disks (Matthews et al. 1999). Molecular H_2 gas as traced by carbon monoxide, CO, is weakly detected in late-type spirals and edge-on simple disks (Young & Knezek 1989; Matthews & Gao 2001; Böker et al. 2003b; Matthews et al. 2005).

The amount of dust is generally low (Matthews & Wood 2001; Stevens et al. 2005) as implied by the transparency of the edge-on simple disks (Matthews et al. 1999; Matthews & Wood 2001; Karachentsev et al. 2002; Matthews & Uson 2008b). In contrast to the organized dust lanes in edge-on spiral galaxies with bulges, simple disks show a clumpy and diffuse distribution of dust (Matthews et al. 1999; Matthews 2000; Matthews & Wood 2001). Dalcanton et al. (2004) found that organized dust
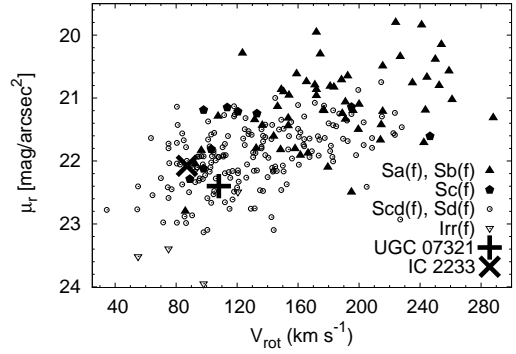

FIG. 5.— This figure shows the rotational velocity, v_{rot}, versus total surface brightness, μ, for the same random sample of Fig. 2. Bulgeless and disk-dominated systems rotate slower and have lower surface brightnesses compared to galaxies with bulges.
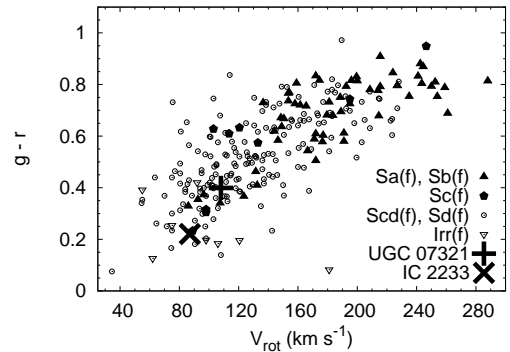

FIG. 6.— This figure shows the rotational velocity, v_{rot}, versus the $g - r$ color for the same random sample of Fig. 2. Bulgeless and disk-dominated systems have bluer colors and are slow rotators compared to galaxies with bulges.

lanes appear only in edge-on galaxies with bulges and relative fast rotational velocities. These authors suggest that the galaxies with organized dust lanes are more gravitationally unstable, which leads to fragmentation and gravitational collapse along spiral arms and subsequently smaller gas scaleheights, pronounced dust lanes, star formation, and high surface brightnesses. In contrast, the distribution of dust in edge-on simple disks is clumpy if their rotational velocity is below $v_{rot} = 120$ km s^{-1}. In this case the dust has not settled into a thin lane and therefore appears patchy and diffuse because the simple disks are gravitationally stable and have low star-formation rates, which also implies lower metallicities and lower mass. This explains the lower total surface brightnesses and slower rotation of simple disk galaxies compared to galaxies with bulges as shown in Figure 5. The ideas from Dalcanton et al. (2004) are then also visible in Figure 6: more massive galaxies as indicated by their larger rotational velocities form more stars at earlier times and have redder present day colors. In contrast, slow rotators tend to have thicker gas disks and thus less efficient star formation and therefore spread their star formation out over a longer time (see also Banerjee et al. 2010). In this way they can remain blue for longer times.

According to the ideas in Dalcanton et al. (2004), Fig-

ure 6 suggests that the rotational velocity (determined by the baryonic mass and DM) regulates the average star formation history (cf., Kennicutt 1998). While bulges become more common at large v_{rot}, their presence is not necessarily related to a red galaxy color because bulgeless galaxies can also have red colors. In other words, if a galaxy has a high rotational velocity, it forms stars quickly (Dalcanton et al. 2004) and so has red colors; and it is also more likely to produce a bulge. Both characteristics are tied to the rotational velocity but it remains unclear whether a red color and the presence of a bulge are correlated independent of v_{rot}. The lower surface brightnesses of simple disks indicate that the probability for bulge formation depends on the mass and v_{rot} of the host galaxy. As suggested by Kautsch et al. (2006a), this correlation can be linked to the models where internal, secular disk instabilities are responsible for forming bulges through the dependence of the Toomre Q-parameter on disk surface density (e.g., Immeli et al. 2004).

The rotation curves of edge-on simple disk galaxies are generally flat and slowly rising throughout their stellar disk (Matthews et al. 1999; Mendelowitz et al. 2000; Makarov et al. 2001; van der Kruit et al. 2001; Zackrisson et al. 2006), see also Zasov & Khoperskov (2003). These solid-body rotation curves are typical for late-type irregular galaxies, making simple disks the simplest dynamical type of disk galaxies. The rotation curves and axial ratios indicate that these galaxies are completely DM dominated, even in their centers, and are surrounded by a spherical dark halo (Karachentsev & Xu 1991; Mendelowitz et al. 2000; Zasov et al. 2002; Uson & Matthews 2003; Zackrisson et al. 2006; Banerjee et al. 2010). These rotation curves are also useful to probe DM profiles in disk galaxies. Numerical N-body simulations of ΛCDM predict central dark halo mass densities significantly larger and cuspier than observed in LSB simple disks ("core/cusp problem," see Navarro et al. 1997, and references therein). In contrast to the models, the observations show nearly constant density cores (Zackrisson et al. 2006; McGaugh et al. 2007; Kuzio de Naray et al. 2009).

The Tully-Fisher relation of edge-on simple disks can be used for estimations of distances, luminosities, diameters, and other parameters (e.g., Karachentsev 1991; Kudrya et al. 1997; Karachentsev et al. 1999c, 2002). The dust corrected Tully-Fisher relation for faint and bulgeless LSB galaxies indicates that their absolute magnitudes appear to be fainter than for spirals with bulges for a fixed HI line width, i.e., faint LSB simple disks rotate faster for a predicted luminosity (Kudrya et al. 1997; Matthews & Wood 2001).

The far end of the continuous sequence of properties is occupied with bulgeless irregulars, see Figures 2−6. The main difference is their thicker appearance. The underlying reason for this structural difference may be of kinematical origin, where turbulent motion can compete with ordered rotation because of low rotational velocities in irregulars (Seiden & Gerola 1979; Sung et a. 1998). This in turn leads to low surface brightnesses because more stellar material is distributed over a wide range of disk scale heights, which produces low stellar surface densities (Schombert 2006). This trend is visible in Figure 5, although the sample of irregulars is small in the present study because of the lack of available kinematic information for the presented objects. Schombert (2006) concludes that the random gas motion leads to stochastic and slow star formation compared to coherent patterns of star formation in flatter disks (see also Banerjee et al. 2010). However, the difference between flat disks and puffy irregulars is not understood in detail, considering that Irr(f) objects and flat disks can have similar values of their rotational velocity (Fig. 3).

6. STRUCTURES IN SIMPLE DISKS

The radial surface brightness profiles of edge-on simple disks are close to projected exponentials, as they are also for simple disks at other, less inclined viewing angles (Matthews et al. 1999; Böker et al. 2003a; Dutton 2009). The profiles in some bulgeless LSB galaxies decrease from an exponential fit in the central regions but it is unknown whether a strong DM dominance in the centers of the galaxies is responsible for the deficit of the stellar densities (Zackrisson et al. 2006).

The vertical stellar structure of edge-on simple disks can be fit with a variety of profiles (isothermal $sech^2$, sech, or exponential profiles) which differ only at small heights (Matthews 2000, and references therein). At large scaleheights, single profiles sometimes deviate from one-component fits which could be explained by a second, thick stellar disk component (Yoachim & Dalcanton 2006). These thick disks appear to be older than the thin disk and have distinct, slower kinematics, even counterrotation (Matthews 2000; Mould 2005; Yoachim & Dalcanton 2008). Whereas internal or external heating via dynamical friction can be responsible for the thick disk, current studies favor direct accretion of the thick-disk material during minor mergers (Yoachim & Dalcanton 2008). The sample studied so far is very small. Using larger samples, edge-on simple disks may be an excellent tool to test the different thick-disk formation theories.

Ferrarese & Merritt (2000) and Gebhardt et al. (2000) (see also Ganda et al. (2009)) found a tight relation between the mass of supermassive black holes and the velocity dispersion of bulges in disk galaxies. This relation can be explained in a hierarchical universe where bulge and black hole growth is a consequence of merging galaxies (Peng 2007; Wang & Kauffmann 2008). In this respect, simple disk galaxies are expected to be black hole free. However, there is growing evidence that this is not always true; for example: NGC 1042, Shields et al. (2008); NGC 3621, Satyapal et al. (2007), (Gliozzi et al. 2009); or NGC 4395, Filippenko & Ho (2003), among other simple disks. Nuclear star clusters are also often found in bulgeless galaxies (Böker et al. 2002; Walcher et al. 2005, 2006; Rossa et al. 2006).

7. OUTLOOK

We need studies focused on edge-on bulgeless galaxies independent of their surface brightnesses and other selection criteria to investigate the properties and the formation and evolution of simple disks. Large surveys already contain much of the needed material for such future investigations. Interesting work could be performed by tracing the frequency and properties of simple disks in different environments and redshifts in order to paint

a picture of their evolution history and progenitor systems (cf., Elmegreen et al. 2004). A census about the total halo, stellar, and gas masses would shed light on the stability of the disks and eventually on the mystery of the dark matter.

Simple disk galaxies are ideal objects to test current cosmological theories of the formation, evolution, and morphological transformations of galaxies; to explore unknown properties of these objects; and to fascinate people in the International Year of Astronomy and beyond.

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