

Outskirts of Nearby Disk Galaxies: Star Formation and Stellar Populations

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Abstract The properties and star formation processes in the far-outer disks of nearby spiral and dwarf irregular galaxies are reviewed. The origin and structure of the generally exponential profiles in stellar disks is considered to result from cosmological infall combined with a non-linear star formation law and a history of stellar migration and scattering from spirals, bars, and random collisions with interstellar clouds. In both spirals and dwarfs, the far-outer disks tend to be older, redder and thicker than the inner disks, with the overall radial profiles suggesting inside-out star formation plus stellar scattering in spirals, and outside-in star formation with a possible contribution from scattering in dwarfs. Dwarf irregulars and the far-outer parts of spirals both tend to be gas dominated, and the gas radial profile is often non-exponential although still decreasing with radius. The ratio of $H\alpha$ to far-UV flux tends to decrease with lower surface brightness in these regions, suggesting either a change in the initial stellar mass function or the sampling of that function, or a possible loss of $H\alpha$ photons.

1 Introduction

The outer parts of galaxies represent a new frontier in observational astronomy at the limits of faint surface brightness. We know little about these regions except that galaxies viewed deeply enough can usually be traced out to 10 stellar scale lengths or more, without any evident edge. We do not know in detail how the stars and gas got there and whether stars actually formed there or just scattered from

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the inner parts. Neither do we know as much as we'd like about the properties, elemental abundances, scale heights and kinematics of outer disk stars except for a limited view in the Milky Way (e.g., Bovy et al 2016) and the Andromeda galaxy (Dalcanton et al 2012). Yet the outer parts of disks are expected to be where galaxy growth is occurring today, and where the left-over and recycled cosmological gas accretes or gets stored for later conversion into stars in the inner disk (Lemonias et al 2011, Moffett et al 2012). The outer parts should also show the history of a galaxy's interactions with other galaxies, as the orbital time is relatively long. A high fraction of outer disks are lopsided too, correlating with the stellar mass fraction in the outer parts (i.e., the ratio of the stellar mass to the total from the rotation curve; Zaritsky et al 2013), perhaps because of uneven accretion, interactions, or halo sloshing (Ghosh et al 2016). This chapter reviews disk structure, star formation and stellar populations in the outer parts of nearby galaxies. General properties of these outer disks are in Sect. 2 to 7, and a focus on dwarf irregular galaxies (dIrrs) is in Sect. 8. The observational difficulties in observing the faint outer parts of disks are discussed in other chapters in this volume.

2 Outer disk Structure from Collapse Models of Galaxy Formation

A fundamental property of galaxy disks is their exponential or piece-wise exponential radial light profile (de Vaucouleurs 1959). Freeman (1970) noted that this profile gives a distribution of cumulative angular momentum versus radius that matches that of a flattened uniformly rotating sphere (Mestel 1963), but this match is only good for about four disk scale lengths. The problem is that an exponential disk has very little mass and a lot of angular momentum in the far-outer parts, unlike a power-law halo which has both mass and angular momentum increasing with radius in proportion (Efstathiou 2000). Nevertheless, observations show some disks with 8 to 10 scale lengths (Weiner et al 2001, Bland-Hawthorn et al 2005, Grossi et al 2011, Hunter et al 2011, Radburn-Smith et al 2012, Vlajić et al 2011, Barker et al 2012, Hunter et al 2013, Mihos et al 2013, van Dokkum et al 2014). These large extents compared to the predicted four scale lengths from pure collapse models need to be explained (Ferguson and Clarke 2001).

Thus we have a problem: if the halo collapses to about four scale lengths in a disk, then how can we get the observed eight or more scale lengths in the stars that eventually form? The answer may lie with the conversion of incoming gas into stars. In a purely gaseous medium, interstellar collapse proceeds at a rate per unit area that is proportional to the square of the mass column density, Σ_{gas} (Elmegreen 2015). One factor of Σ_{gas} accounts for the amount of fuel available for star formation and the other factor accounts for the rate of conversion of this fuel into stars. This squared Kennicutt-Schmidt law converts four scale lengths of primordial gas into eight scale lengths of stars after they form (Sect. 7). Stellar scattering from

clouds and other irregularities could extend or smooth out this exponential further (Elmegreen and Struck 2013, Elmegreen and Struck 2016).

There is an additional observation in Wang et al (2014) that in local gas-rich galaxies, the outer gas radial profiles are all about the same when scaled to the radius where $\Sigma_{\text{HI}} = 1 M_{\odot} \text{pc}^{-2}$. Bigiel and Blitz (2012) found a similar universality to the gas profile when normalized to R_{25} , the radius at 25 magnitudes per square arcsec in the V band. Wang et al (2014) found that the ratio of the radius at $1 M_{\odot} \text{pc}^{-2}$ to the gaseous scale length in the outer disk is about four, the same as the maximum number of scale lengths in a pure halo collapse. This similarity may not be a coincidence (Sect. 7).

Cosmological simulations now have a high enough resolution to form individual galaxies with reasonable properties (Vogelsberger et al 2014, Schaye et al 2015). Zoom-in models in a cosmological environment show stellar exponential radial profiles in these galaxies (Robertson et al 2004) even though specific angular momentum is not preserved during the collapse and feedback moves substantial amounts of gas around, especially for low-mass galaxies (El-Badry et al 2016). For example, Aumer and White (2013) ran models with rotating halo gas aligned in various ways with respect to the dark matter symmetry axis. They found broken exponential disks with a break radius related to the maximum angular momentum of the gas in the halo, increasing with time as the outer disk cooled and formed stars. Star formation is from the inside-out. Angular momentum was redistributed through halo torques, but still the disks were approximately exponential. Aumer et al (2013) further studied 16 simulated galaxies with various masses. All of them produced near-exponential disks.

In a systematic study of angular momentum, Herpich et al (2015) found a transition from exponentials with up-bending outer profiles (Type III—Sect. 3) at low specific angular momentum (λ) to Type I (single exponential) and Type II (down-bending outer parts) at higher λ . An intermediate value of $\lambda = 0.035$, similar to what has been expected theoretically (Mo et al 1998), corresponded to the pure exponential Type I. The reason for this change of structure with λ was that collapse at low spin parameter produces a high disk density in a small initial radius, and this leads to significant stellar scattering and a large redistribution of mass to the outer disk, making the up-bending Type III. Conversely, large λ produces a large and low-density initial disk, which does not scatter much and nearly preserves the initial down-bending profile of Type II.

3 Outer Disk Structure: Three Exponential Types

Galaxy radial profiles are often classified as exponential Types I, II or III according to whether the outer parts continue with the same scale length as the inner parts, continue with a shorter scale length (i.e., bend down a little) or continue with a larger scale length (bend up a little), respectively (Fig. 1). The Sersic profile with $n = 1$ corresponds to Type I; the other types do not have a constant Sersic index. For

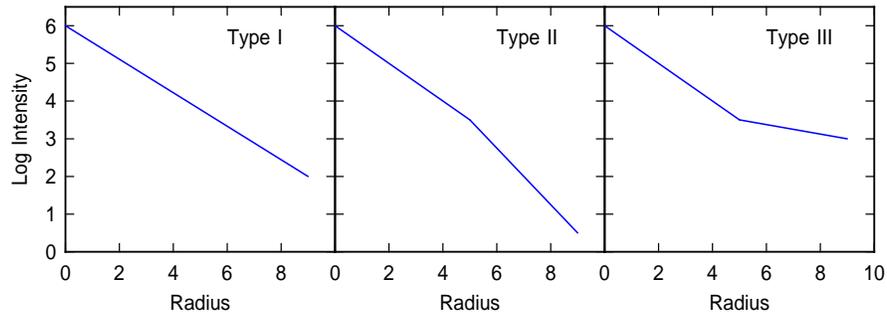


Fig. 1 Three types of exponential or piece-wise exponential profiles

a review, see van der Kruit (2001), and for early surveys, see Pohlen and Trujillo (2006) and Erwin et al (2008).

Gutiérrez et al (2011) determined the proportion of the three exponential profile types for barred and non-barred galaxies of various Hubble types, including 183 large local face-on galaxies from three separate studies. For S0 and earlier, the three profile types are nearly evenly divided. For Sab to Sbc, Types II and III are about equal and Type I becomes relatively rare (10%). For Scd to Sdm, Type II dominates with $\sim 80\%$ of the total. Herrmann et al (2013) continued this study to dIrrs and blue compact dwarfs (BCDs, see also Sect. 8.4). dIrr galaxies are dominated (80%) by Type IIs, while BCDs have steep inner parts from a starburst and are usually Type III.

A general caution should be mentioned about possible contamination at faint light levels from scattered light. Sandin (2015) showed R and I band radial profiles for NGC 4102 that were fit to a single exponential model with a broad point spread function from the instrument. The usual Type III profile for this galaxy turned into a Type I when the outer excess was corrected for the instrumental profile.

4 Outer Disk Stellar Populations: Colour and Age Gradients

Radial profiles become more complex when changes in stellar colours and ages are considered. Bakos et al (2008) noted that Type II light profiles tend to correspond to U-shaped $B - V$ colour profiles, which means that the inner part of the disk gets bluer with radius at first, and then the outer part of the disk gets red again. This colour change presumably corresponds to a change in the mass-to-light ratio, with large ratios in the outer parts. Then the down-bending Type II in a light profile tends to straighten out and become Type I in a mass profile. That is, the outer red trend gives an increasing mass-to-light ratio, causing an increasing conversion factor from surface brightness to mass surface density. The red outer parts could be from old stars that scattered there from the inner regions (Roškar et al 2008), as distinct from the common model of inside-out growth for spiral galaxies. A larger survey recently

confirmed this result. Zheng et al (2015) included 700 galaxies using deep images from the Pan-STARRS survey. The average g -band (peak at 5150 \AA) light profile was the down-bending Type II for low-mass galaxies ($< 10^{10} M_{\odot}$) and slightly less bent for high mass galaxies ($< 10^{10.5} M_{\odot}$), as usual, and the average $g - i$ colour profiles (i band peaks at 7490 \AA) were U-shaped to various degrees, so the average mass profile became Type I for all galaxy masses. Muñoz-Mateos et al (2015) made average radial profiles separated into eight mass bins for ~ 2400 galaxies using $3.6 \mu\text{m}$ emission from the *Spitzer* Survey of Stellar Structure in Galaxies. Such long wavelength emission is a nearly direct probe of galaxy mass, although there is some PAH emission from dust in it too. All masses showed Type II profiles on average, with a straighter trend like Type I from a central bulge in the more massive galaxies. This suggests that the mass profile for most galaxies is not exactly Type I, but still tapers off more steeply in the outer parts, beyond 1 kpc for low mass galaxies ($< 10^9 M_{\odot}$) and beyond 10 kpc for high mass galaxies ($> 10^{10.5} M_{\odot}$).

The most telling observations are of stellar age gradients because colour gradients can be from a mixture of age gradients and metallicity gradients. Roediger et al (2012) determined radial age profiles from photometry and stellar population models of 64 Virgo cluster disk galaxies. They found U-shaped age profiles in 15% of Type I's, and also in 36% of both Types II and III. In one-third of all exponential types, the age increased steadily with radius. Yoachim et al (2012) found about the same mixture of age profiles, measuring ages from spectra in 12 galaxies. Dale et al (2016) determined star formation histories for 15 nearby galaxies with masses in the range $10^8 M_{\odot}$ to $10^{11} M_{\odot}$ using ultraviolet and infrared data; they also found U-shaped age profiles. These results imply that outer disks generally have old stars, although most also still have some star formation.

A recent integral field unit survey of 44 nearby spiral galaxies (CALIFA) by Ruiz-Lara et al (2016) also found U-shaped age profiles in Types I and II when the stars were weighted by brightness, as would be the case from integrated spectra or photometry. This is in agreement with the previous surveys mentioned above. The galaxies were observed beyond their break radii or for at least three scale lengths. In contrast, Ruiz-Lara et al (2016) found constant age profiles when the stars were weighted by mass. They suggested that the entire disk formed early with star formation stopping in the inner parts first, and then quenching from inside-out. This is unlike cosmological simulations that have the outer disk form more slowly than the inner disk, and also unlike models where the outer disk stars migrate there from the inner disk.

Watkins et al (2016) viewed three nearby spirals with very deep images, covering a range of about 10 magnitudes in surface brightness for B band. They found smooth and red stellar distributions with no spiral arms in the far-outer disks. For the typical colour of $B - V \sim 0.8$ mag in the outer parts, and from a lack of FUV light, they concluded that the star formation rate (SFR) had to be less than $3 - 5 \times 10^{-5} M_{\odot} \text{ pc}^{-2} \text{ Myr}^{-1}$. This seemed to be too low for continuous star formation and disk building, suggesting some radial migration. However, the lack of spiral arms makes the usually invoked churning mechanism (Sellwood and Binney 2002; Roškar et al 2008; Berrier and Sellwood 2015) inoperable. Churning is a process of

stellar migration back and forth around corotation. Perhaps stellar scattering off local gas irregularities makes the outer exponential structure (Elmegreen and Struck 2013).

5 Mono-age Structure of Stellar Populations

Age profiles in galaxy disks can be viewed in another way too. A series of galaxy simulations have looked at the distributions of stars of various ages in the final model. For example, Bird et al (2013) did a simulation of the Milky Way and found that older stars in the present-day disk have shorter radial scale lengths and thicker perpendicular scale heights than younger stars. Other mono-age population studies of simulated disks are in Sánchez-Blázquez et al (2009), Stinson et al (2013), Martig et al (2014), Minchev et al (2015) and Athanassoula et al (2016), giving the same result.

Bovy et al (2016) found structure related to this in the Milky Way using 14700 red clump stars. Higher metallicity populations are more centrally concentrated than lower metallicity populations (not considering the α -enhanced “thick disk” component). Each narrow metallicity range tends to have a maximum surface density of stars at a particular radius where the disk has that average metallicity. Plus, each mono-metallicity population has a perpendicular scale height that increases with radius, producing a flare.

The correspondence between metallicity and peak surface density for a population of stars suggests that star formation, feedback, halo recycling, and other processes establish an equilibrium metallicity in a region that depends primarily on local conditions, such as the local mass surface density (Bovy et al 2016). Stellar migration then broadens this distribution to produce the observed total profiles. This local equilibrium concept is consistent with the results of Rosales-Ortega et al (2012), who found for 2000 HII regions in nearby galaxies that metallicity depends mostly on stellar mass surface density, as determined from photometry. Bresolin and Kennicutt (2015) present a similar result: that the metallicity gradients in galaxies are all the same when expressed in units of the disk scale length.

6 Outer Disk Structure: Environmental Effects and the Role of Bulges and Bars

Environment may also affect outer disk structure. Younger et al (2007) showed that prograde minor mergers can drive mass inward and outward, creating a Type III profile. Borlaff et al (2014) also suggested that Type III S0 galaxies can result from a merger. This is consistent with observations in Erwin et al (2012) that S0 galaxies in Virgo have proportionally more Types I and III, suggesting that interactions or mergers have been important. Erwin et al. also found that bars have little effect on

the proportion of exponential types. Athanassoula et al (2016) simulated a gas-rich major merger and showed that it formed an exponential disk in the final system.

On the other hand, Maltby et al (2012) measured the V -band radial profiles of 330 galaxies observed with *Hubble Space Telescope* over a half-degree field surrounding a galaxy supercluster at redshift 0.165. They found no dependence on environment, cluster versus field, for the ratio of the outer to the inner disk scale length or the outer scale length itself. Head et al (2015) got a similar result looking at S0 galaxies in the Coma cluster; using a profile decomposition algorithm to remove the bulge, they found that bars are important for disk structure, correlating with Types II and III (contrast this with the Erwin et al 2012 result above), but that location in the cluster is not important. According to Head et al (2015), the relative proportion of Types I, II, and III is the same in the core, at intermediate radii, and in the outskirts of Coma (in fact, most of the S0 galaxies were Type I).

Some of the appearance of Type III could be from a bright halo or extended bulge and not from stars in the disk (Erwin et al 2005). Maltby et al (2015) suggested that half of the S0 Type III structures in various environments come from extended bulge light, although this fraction is only 15% in later Hubble type spirals. This implies that disk fading can make an S0 from a spiral, preserving the scale length. Simulations by Cooper et al (2013) also found that the outer stellar structure can be in a halo and not a disk, as a result of mergers.

Bars and spirals seem to be important in determining the break radius for down-bending (Type II) exponentials. Muñoz-Mateos et al (2013) suggested that the break radius for Type II's is either at the outer Lindblad resonance (OLR) of a bar or the OLR of a spiral that is outside of a bar. The spiral and bar are assumed to have their pattern speeds in a resonance with the inner 4:1 resonance of the spiral at the corotation radius of the bar (see Pohlen and Trujillo 2006 and Erwin et al 2008). Laine et al (2014) also found that bars and spirals are important: 94% of Type II breaks are associated with some type of feature; 48% are in early type galaxies with an outer ring or pseudoring; 8% are with a lens, assumed to be the OLR of a bar, and if there is no outer ring, then the breaks are at 2 times the radius of an inner ring (this being the ratio of radii for outer and inner ring resonances); 14% are in late type galaxies associated with an end to strong star formation, and 24% are at the radius where the spiral arms end. For Type III breaks studied by Laine et al (2014), 30% are associated with inner or outer lenses or outer rings.

7 Outer Disk Structure: Star Formation Models

The outer disks of spiral galaxies and most dIrrs are dominated by gas in an atomic form, and not stars. Because stars form in molecular gas, it is difficult to observe directly how stars form in these regions. Moreover, outer disks and dIrrs tend to be stable by the Toomre Q condition (Elmegreen and Hunter 2015). Nevertheless, star formation usually looks normal there, forming clusters and associations at low

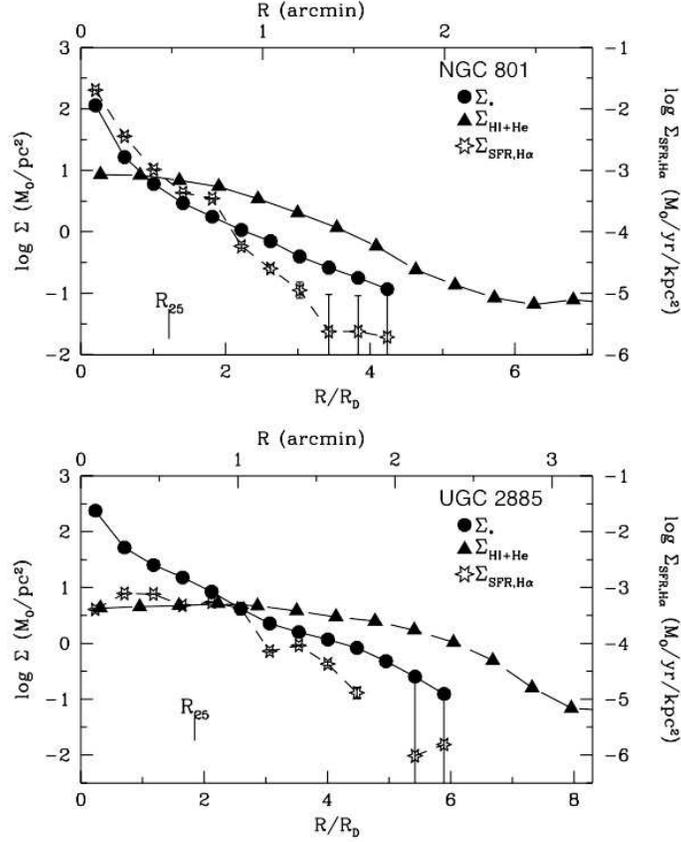


Fig. 2 Stellar mass surface density Σ_* , HI+He surface density $\Sigma_{\text{HI+He}}$, and SFR density $\Sigma_{\text{SFR,H}\alpha}$ plotted as a function of radius for two very luminous ($M_V = -22$ to -23) Sc-type spiral galaxies, NGC 801 and UGC 2885. The radius is normalized to the optical V-band disk scale length R_D . The gas and stellar mass surface densities have been corrected to face-on. The logarithmic interval is the same for all three quantities, but the SFR zero point is different. Adapted from Hunter et al (2013)

density (Melena et al 2009; Hunter et al 2016a), although it may stop short of the full extent of the gas disk (see, for example, Fig. 2.)

Krumholz (2013) formulated a model for star formation in these conditions that considers the existence of a two-phase atomic medium (i.e., a warm neutral medium in pressure equilibrium with a cool neutral medium) and the molecular fraction in such a medium. He then assumed that star formation occurs in the molecular medium at a rate given by an efficiency per unit free fall time, $\epsilon_{\text{ff}} \sim 0.01$, times the molecular mass divided by the free fall time in the molecular gas:

$$\Sigma_{\text{SFR}} = \epsilon_{\text{ff}} \Sigma_{\text{mol}} / t_{\text{ff,mol}}. \quad (1)$$

The free fall time depends on the molecular cloud density, which for outer disks in their model, depends on the molecular cloud mass and a fiducial value of the molecular cloud surface density, $\Sigma_{\text{GMC}} = 85 M_{\odot} \text{pc}^{-2}$. The molecular cloud mass was taken to be the turbulent Jeans mass in the interstellar medium (ISM), $M_{\text{GMC}} = \sigma^4 / (G \Sigma_{\text{gas}})$ for turbulent speed σ and average ISM gas surface density Σ_{gas} . For inner disks, the free fall time was taken to be the value for an average disk density where the Toomre Q parameter equals unity. To span the inner and outer regions, the minimum of these two free fall times was used.

One uncertainty in the Krumholz (2013) model is the assumption that a two-phase medium is present, because it need not be present everywhere in the outer disk. But this assumption seems reasonable for star formation because cool gas greatly facilitates cloud formation (Elmegreen and Parravano 1994, Schaye 2004, Forbes et al 2016). A second assumption is that the SFR is given only by the molecular gas mass and density, and that this is related to the total density by the molecular fraction, which depends on the ratio of the radiation field to the cool cloud density. In this model, molecule formation is calculated separately as a precursor to star formation, and then whatever is calculated for molecules is used to determine the SFR.

Another model considers that the average SFR is determined by the average ISM dynamics and that molecule formation is incidental, i.e., molecule formation happens along the way but it is not a limiting factor. Star formation in predominantly atomic gas has been predicted by Glover and Clark (2012) and Krumholz (2012) and suggested by observations in Michałowski et al (2015) and Elmegreen et al (2016). In this model, the gas mass available for star formation is the total gas mass in all forms, even atomic gas, and the free fall rate of this gas is given by the average midplane density, regardless of molecular content (Elmegreen 2015). Cool clouds are still required so the ISM cannot be purely warm phase. Also, because molecular hydrogen is slow to form at low density (Mac Low and Glover 2012), there could be a substantial fraction of H_2 in stagnant, diffuse clouds without significant CO emission and with little connection to star formation (Elmegreen and Hunter 2015). Such a diffuse H_2 medium was found in simulations by Hu et al (2016) and Safraneck-Shrader et al (2016) but has not been observed yet. These diffuse H_2 clouds, along with more atom-rich clouds, would presumably come together during localized ISM collapse as a precursor to star formation. In this model the SFR per unit area is given by

$$\Sigma_{\text{SFR}} = \varepsilon_{\text{ff}} \Sigma_{\text{gas}} / t_{\text{ff, gas}} \quad (2)$$

for midplane free-fall time t_{ff} at the density $\rho = \Sigma_{\text{gas}} / (2H)$ and scale height $H = \sigma^2 / (\pi G \Sigma_{\text{gas}})$. The result is (Elmegreen 2015)

$$\Sigma_{\text{SFR}} = \varepsilon_{\text{ff}} (4/3)^{1/2} (G/\sigma) \Sigma_{\text{gas}}^2 = 1.7 \times 10^{-5} (\Sigma_{\text{gas}} / [1 M_{\odot} / \text{pc}^2])^2 (\sigma / 6 \text{ km s}^{-1})^{-1} \quad (3)$$

where σ is the gas velocity dispersion and $\varepsilon_{\text{ff}} \sim 1\%$ is the efficiency of star formation per unit free fall time.

Both of the above models compare well with observations (Krumholz 2013, Elmegreen 2015).

Hu et al (2016) simulated dwarf galaxies with a chemical model to form H_2 , CO and other molecules, cloud self-shielding from radiation, and a SFR given by Eq. (2) at a threshold density of 100 cm^{-3} and a temperature less than 100 K. They found that Σ_{SFR} decreases faster than Σ_{gas} but not because of a flare (the extra Σ_{gas} factor in Eq. 3). Rather, Σ_{SFR} follows the cold gas with a rate that scales directly with the cold gas fraction, i.e., a linear law, and this cold gas fraction decreases with radius. The linear law in their model is because of the assumed constant threshold density. Most star-forming gas is close to this fixed density, so the characteristic dynamical time is the fixed value at this density.

This point about a fixed density is similar to the explanation for the linear star formation law in Elmegreen (2015), where it was pointed out that if CO, HCN, and other star formation tracers emit mostly at their fixed excitation density, as determined by the Einstein A coefficient, then the effective free fall time is the fixed value at this density. The SFR then scales only with the amount of gas at or above this observationally selected density. The fixed density in this case is not because of an assumption about a star formation threshold, as there is no threshold in the Elmegreen (2015) model. There is just a continuous collapse of ISM gas at a rate given by the midplane density, and a feedback return of the dense gas to a low density form.

The existence of a fixed threshold density for star formation is something to be tested observationally. Elmegreen (2015) suggest there is no threshold density because clouds are strongly self gravitating when $\pi G \Sigma_{\text{cloud}}^2 > P_{\text{ISM}}$ for cloud surface density Σ_{cloud} and ambient pressure P . Because the interstellar pressure varies with the square of the total surface density of gas and stars inside the gas layer, there is a large range in pressure over several exponential scale lengths in a galaxy disk—a range that may exceed a factor of 100 for dIrrs, and 1000 for spirals. Thus if there is a threshold for star formation, the above equation suggests that it might be

$$\Sigma_{\text{cloud}} > (P/\pi G)^{1/2}, \quad (4)$$

in which case it should vary with radius.

We return to a point made in Sect. 1 about the gas surface density profile in the far-outer regions of gas-rich galaxies. Wang et al (2014) noted that the gas exponential scale length beyond the radius R_1 , where $\Sigma_{\text{gas}} = 1 M_{\odot} \text{ pc}^{-2}$, is always about 0.25 times this radius. We can see this here also from Eq. (3), which states that

$$\Sigma_{\text{SFR}} = 2 \times 10^{-5} M_{\odot} \text{ pc}^{-2} \text{ Myr}^{-1} \text{ at } \Sigma_{\text{gas}} = 1 M_{\odot} \text{ pc}^{-2}. \quad (5)$$

After a Hubble Time of 10^4 Myr , Σ_{stars} is approximately $0.2 M_{\odot} \text{ pc}^{-2}$. According to the average disk mass profiles in Zheng et al (2015), this outer stellar surface density is lower than that at the disk centre by $10^{-3.5}$ on average, which represents eight scale lengths in stars. But eight scale lengths in stars is four scale lengths in gas for Eq. (3). Thus the radius at $1 M_{\odot} \text{ pc}^{-2}$ is about four times the scale length in the gas, as observed further out by Wang et al (2014).

8 The Disks of Dwarf Irregular Galaxies

Dwarf irregular galaxies are like the outer parts of spiral galaxies in terms of gas surface density, SFR, and gas consumption time. Tiny dIrrs have extended exponential disks as well. For example, Saha et al (2010) traced the Large Magellanic Cloud (LMC) to $12 R_D$, an effective surface brightness of $34 \text{ mag arcsec}^{-2}$ in I , and Sanna et al (2010) found stars in IC 10 to $\sim 10 R_D$. Bellazzini et al (2014) detected stars associated with Sextans A and Sextans B to $6 R_D$, and Hunter et al. (2011) measured surface brightness profiles in four nearby dIrrs and one BCD to $29.5 \text{ mag arcsec}^{-2}$ in V , corresponding to $3 - 8 R_D$. These extended stellar disks represent extreme galactic environments for star formation and are potentially sensitive probes of galaxy evolutionary processes, and yet they are relatively unexplored. In this Section we examine what is known about outer disks of dIrr galaxies.

8.1 Radial Trends

8.1.1 The Gas Disk

The H I gas often dominates the stellar component of dIrr galaxies, both in extent and mass. How much further the gas extends compared to the stars was demonstrated by Krumm and Burstein (1984) for DDO 154 where the H I was traced to $8 R_{25}$ at a column density of $2 \times 10^{19} \text{ atoms cm}^{-2}$ ($0.22 M_\odot \text{ pc}^{-2}$). In the LITTLE THINGS sample of 41 nearby ($< 10.3 \text{ Mpc}$), relatively isolated dIrrs (Hunter et al 2012), most systems have gas extending to $2 - 4 R_{25}$ or $3 - 7 R_D$ at that same (face-on) column density. Some spiral galaxies also have extended H I; Portas (2010) found that the Sbc galaxy NGC 765, for example, has gas extending to $4 R_{25}$. Large holes (up to 2.3 kpc diameter) are also sometimes found in the gas beyond $2 R_D$ (Dopita et al 1985, R.N. Pokhrel, in preparation).

In most dIrrs, the galaxy is gas-dominated and becomes increasingly gas-rich with radius (Fig. 3). This implies a decreasing large-scale star formation efficiency (Leroy et al 2008, Bigiel et al 2010). The lack of sharp transitions in the star-to-gas ratio, including at breaks in the optical exponential surface brightness profiles, suggests that the factors dominating the drop in star formation with radius are changing relatively steadily.

The gas surface density drops off with radius usually in a non-exponential fashion. In Sect. 2 – 7, we have approximated the radial gas profiles of spiral galaxies as exponentials. However, especially in dIrrs, the gas profiles are rarely pure exponentials, and since dIrrs are gas-dominated, the shape of the gas profile is crucial. Note, however, that in dIrrs, the radial *stellar* profiles are usually exponential in shape. In a sub-sample of the THINGS spirals (Walter et al 2008), Portas (2010) found that the gas is approximately constant at $5 - 10 \times 10^{20} \text{ atoms cm}^{-2}$ and then drops off rapidly. A Sersic function fits the profiles with indices of $n = 0.14 - 0.22$. For comparison, an exponential disk has an n of 1.0. In five THINGS dIrrs the gas density

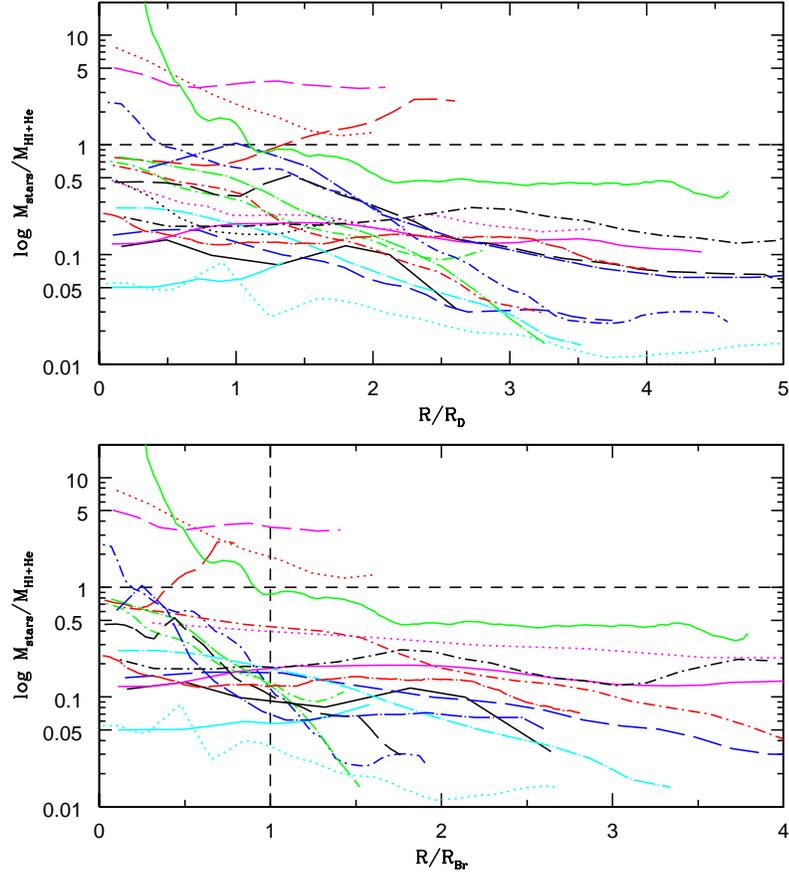


Fig. 3 Azimuthally averaged stellar mass to gas mass ratios as a function of radius normalized to the disk scale length (*top*) and radius at which the *V*-band surface brightness profile changes slope R_{Br} (*bottom*). These galaxies are from the LITTLE THINGS sample with stellar mass profiles determined by Zhang et al (2012) and gas mass profiles from Hunter et al. (2012)

dropped more shallowly with radius, and the distribution of n peaked around 0.3. For the LITTLE THINGS sample of dwarfs, the shape of the HI radial profiles varied from galaxy to galaxy, and n varied from 0.2 to 1.65 with most having values 0.2 – 0.8. The lack of correlations between the HI profile index n and characteristics of the stellar disk suggest that the role of the gas distribution in determining the stellar disk properties is complex.

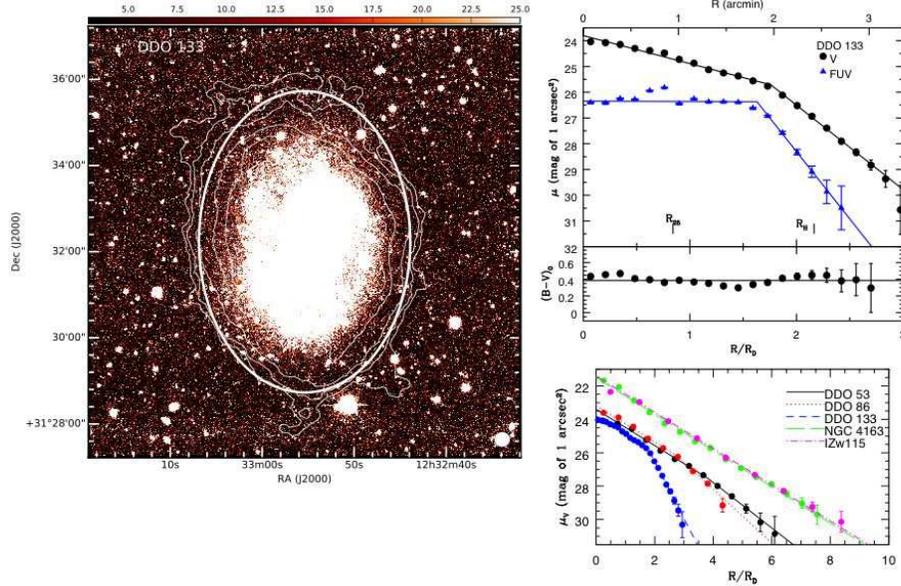


Fig. 4 *Left*: V -band image of DDO 133 from Hunter et al (2011). The white ellipse marks the extent of the galaxy measured to $29.5 \text{ mag arcsec}^{-2}$. The white contours trace column densities of 5, 30, 100, 300, 500, 1000, and $3000 \times 10^{18} \text{ atoms cm}^{-2}$ in H I (Hunter et al. 2012). *Top right*: Surface photometry in V , FUV, and $B - V$ as a function of radius normalized to the disk scale length R_D . *Bottom right*: V -band surface photometry of all five galaxies from Hunter et al (2011). IZw 115 is a BCD; the rest are dIrrs

8.1.2 The Stellar Disk

Zhang et al (2012) performed spectral energy distribution fitting to azimuthally-averaged surface photometry of the LITTLE THINGS galaxies. The fitting included up to 11 passbands from the FUV to the NIR. From these fits they constructed SFRs as a function of radius over three broad timescales: 100 Myr, 1 Gyr, and galaxy lifetime. Zhang et al found that the bulk star formation activity has been shrinking with radius over the lifetime of dwarf galaxies, and they adopted the term “outside-in” disk growth. Although Zhang et al found that “outside-in” disk growth applied primarily to dIrrs with baryonic masses $< 10^8 M_\odot$, Gallart et al (2008) and Meschin et al (2014) found the same phenomenon in the LMC, a more massive irregular galaxy. Similarly, Pan et al (2015) suggested from colour profiles that the same process is occurring in a large sample of Sloan Digital Sky Survey galaxies with stellar masses up to $10^{10} M_\odot$. This outside-in disk growth is in contrast to the inside-out disk growth identified in spirals (White and Frenk 1991, Mo et al 1998, Muñoz-Mateos et al 2007, Williams et al 2009, but see Ruiz-Lara et al 2016).

Hunter et al (2011) carried out an ultra-deep imaging program on four nearby dIrrs and one BCD. They measured surface photometry in this sample to 29.5 mag

arcsec⁻² in V , and also obtained deep B images of three of the galaxies and deep FUV and NUV images with the *Galaxy Evolution Explorer* (*GALEX*, Martin et al 2005). Fig. 4 shows the V -band image and photometry of DDO 133, illustrating what they found. What does a surface brightness of 29.5 mag arcsec⁻² mean? In DDO 133, that is a factor of ~ 160 down in brightness from the centre. A 1 kpc-wide annulus at 29.5 mag arcsec⁻² corresponds to a SFR of $0.0004 M_{\odot} \text{ yr}^{-1}$, assuming a mass-to-light ratio from the $B - V$ colour and a constant SFR for 12 Gyr. This is roughly seven Orion nebulae every 10 Myr.

In their five dwarfs, Hunter et al (2011) found that the stellar surface brightnesses in V and FUV continue exponentially as far as could be measured. Furthermore, the stellar disk profiles are exponential and extraordinarily regular in spite of the fact that dIrr galaxies are clumpy in gas and SFR and star formation is sporadic. Saha et al (2010) found the same thing for the LMC, and Bellazzini et al (2014), for Sextans B. However, Bellazzini et al. also found that, by contrast, Sextans A has a very complex surface brightness profile and suggested that that is the consequence of past outside perturbations, assuming that a regular profile is “normal” for an isolated galaxy.

8.2 Star Formation in Dwarfs

The deep FUV surface photometry of Hunter et al (2011) also shows that there is a continuity of star formation with radius. The Toomre (1964) model, in which star formation is driven by two-dimensional gravitational instabilities in the gas, predicts a precipitous end to star formation where the gas surface density drops below a critical level. Nevertheless, these data show that young stars extend into the realm where the gas is a few percent of the critical gas density and should be stable against spontaneous gravitational collapse (Kennicutt 1989). Models suggest that dIrrs need to be treated as three-dimensional systems, in which case the Q parameter is not a good measure of total stability. Also, the dynamical time at the mid-plane density is more important than the growth time of a two-dimensional instability, which is more closely related to spiral arms than star formation (Elmegreen 2015, Elmegreen and Hunter 2015).

The presence of FUV emission in outer disks poses a stringent test of star formation models by extending measures of star formation activity to the regime of low gas densities. How low can the gas density get and still have star formation? HII regions have been found in the far-outer disks of spirals (Ferguson et al 1998), and *GALEX* has found FUV-bright regions out to 2 – 3 times the optical radius of the spiral (Gil de Paz et al 2005, Thilker et al 2007). Bush et al (2008) proposed that these FUV regions could be due to spiral density waves from the inner disk propagating into the outer disk and raising local gas regions above a threshold for star formation. In fact, Barnes et al (2012) found evidence for greater instability in outer disk spirals compared to inner disk spirals in eight nearby spiral galaxies. Dwarf irregular galaxies, however, do not have spiral density waves, and neither do the

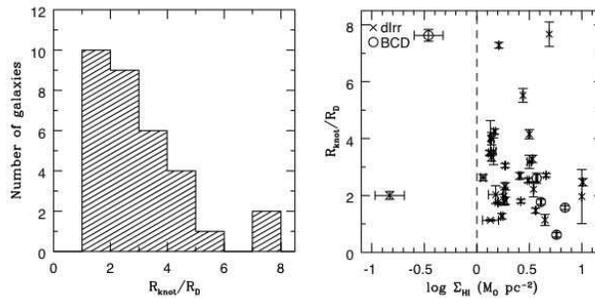


Fig. 5 *Left*: Histogram of the distance from the centre to the furthest knot of FUV emission in the LITTLE THINGS dIrrs relative to the disk scale length R_D (Hunter et al 2016a). *Right*: Distance from the galaxy centre to the FUV knot vs average HI surface density at the radius of the knot. The Σ_{HI} have been corrected for a scaling error as described in Hunter et al (2016b)

far-outer parts of the galaxies observed by Watkins et al (2016), so the problem still remains of how stars form in or get scattered to extreme outer disks.

Recently, *GALEX* images have been used to identify FUV-bright knots in the outer disks of dIrrs in order to determine how far-out young star clusters are formed *in situ* and the nature of the star clusters found there. Hunter et al (2016a) identified the furthest-out FUV knot of emission in the LITTLE THINGS galaxies, and found knots at radii of $1 - 8R_D$ (see Fig. 5). Most of these outermost regions are found intermittently where the HI surface density is $\sim 2M_\odot \text{pc}^{-2}$, although both the HI and dispersed old stars go out much further (also true of some spiral galaxies; e.g., Grossi et al 2011). In a sample of 11 of the LITTLE THINGS dwarfs within 3.6 Mpc, Melena et al (2009) identified all of the FUV knots and modelled their UV, optical, and NIR colours to determine masses and ages. They found no radial gradients in region masses and ages (see Fig. 6 for an example), even beyond the realm of $\text{H}\alpha$ emission, although there is an exponential decrease in the luminosity density and number density of the regions with radius. In other words, young objects in outer disks cover the same range of masses and ages as inner disk star clusters.

8.3 The $\text{H}\alpha/\text{FUV}$ Ratio

$\text{H}\alpha$ and FUV emission are often used to trace star formation in galaxies, including dwarfs. However, commonly the $\text{H}\alpha$ emission drops off faster than, and ends before, the FUV emission as one traces star formation into the outer disk (for example, Hunter et al 2010, and Fig. 2 here). In addition global ratios of $\text{H}\alpha/\text{FUV}$ have been found to be a function of galactic surface brightness (for example, Meurer et al 2009, Treyer et al 2011). Lee et al (2009), for example, find that the $\text{H}\alpha/\text{FUV}$ ratio is lower than expected by a factor of $2 - 10$ in the nearby 11HUGS galaxies with the lowest SFRs ($< 0.003M_\odot \text{yr}^{-1}$).

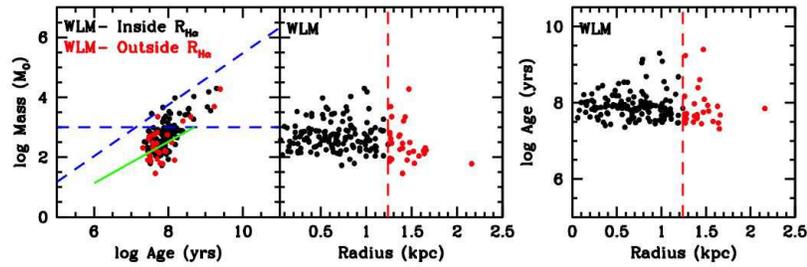


Fig. 6 Plots of mass vs. age, mass vs. galactocentric radius, and age vs. radius for WLM, one of the galaxies from Fig. 3 of Melena et al (2009). The radius corresponding to the extent of $H\alpha$ is marked with a vertical dashed red line, and the regions outside the $H\alpha$ extent are in red. The horizontal dashed line in the *left* panel is the mass limit for completeness to an age of 500 Myr. The slanted dashed line is a fit by eye to the upper envelope of the cluster distribution. The slanted solid line shows the slope for a fading relationship in which the minimum observable mass scales as $\log \text{mass} \propto 0.69 \log \text{age}$

The decline of the ratio $H\alpha/FUV$ with radius in galaxies and variations between galaxies have been the subject of much debate. Causes that have been considered include variations in (Meurer et al 2009, Bruzzone et al 2015) or sampling issues with (Fumagalli et al 2011, da Silva et al 2014) the stellar initial mass function. Other explanations include variations in star formation history, loss of ionizing photons from the galaxy, and undetectability of diffuse $H\alpha$ emission in outer disks (for example, Hunter et al 2010, Hunter et al 2011, Lee et al 2011, Eldridge 2012, Relaño et al 2012, Weisz et al 2012).

Since escape of ionizing photons from galaxies, and preferentially from small galaxies, is believed to have been responsible for the epoch of re-ionization in the early Universe, measuring the amount of leakage has been an important motivation for observations of Lyman continuum emission around galaxies in the nearby and more distant Universe. These observations give us the opportunity to see if leakage of ionizing photons from galaxies or outer disks could explain low $H\alpha/FUV$ ratios. Lyman continuum escape fractions have been measured of order 6% – 13% in compact star-forming galaxies at $z \sim 0.3$ and $Ly\alpha$ escape fractions of order 20% – 40% (Izotov et al 2016b). Rutkowski et al (2016) have placed a limit of $\leq 2.1\%$ on the Lyman continuum escape fraction of a sample of most star-forming dwarf galaxies at $z \sim 1$, and Izotov et al (2016a) measured an escape fraction of order 8% in a relatively low-mass star-forming galaxy at $z \sim 0.3$. In a sample of four nearby galaxies, Leitert et al (2013) detected Lyman continuum in one, yielding an escape fraction of 2.4%, but Zastrow et al (2013) mapped $[SIII]/[SII]$ in six nearby dwarf starburst galaxies and found that the fraction of emission that escapes may depend on the orientation of the galaxy to the observer, the morphology of the ISM, and the age and concentration of the starburst producing the emission. Nevertheless, we see that escape fractions are not high enough to explain the lowest ratios of $H\alpha/FUV$. On the other hand, Hunter et al (2013), in a study of two luminous spirals, suggest

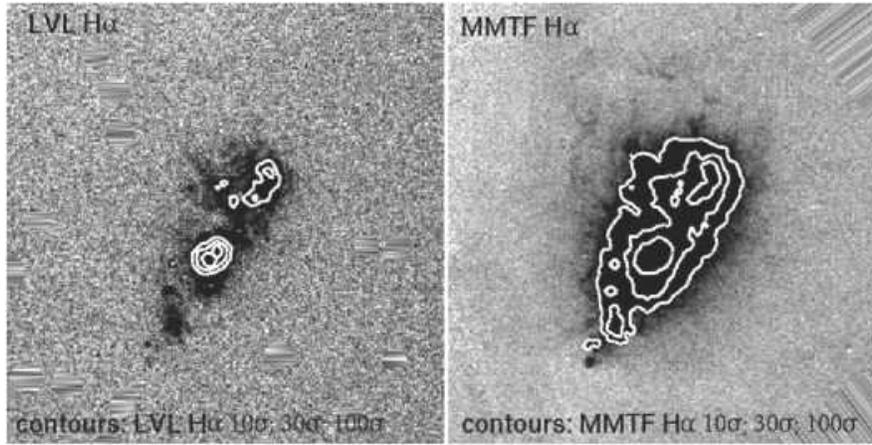


Fig. 7 $H\alpha$ images of UGC 5456 displayed on a linear scale to emphasize emission from diffuse ionized gas. Contours are at 10σ , 30σ , and 100σ above the background. On the *left* is the standard continuum subtracted narrow band image from the 11HUGS/LVL survey (Kennicutt et al 2008) and on the *right* is the deeper image from Lee et al (2016). Reproduced from Lee et al (2016) with permission from the AAS

that the drop in $H\alpha$ emission with radius is due to low gas densities in outer disks and the resulting loss of Lyman continuum photons from the vicinity of star forming regions, making them undetectable in $H\alpha$, and not from a loss of photons out of the galaxy altogether.

Could we instead be under-estimating the amount of $H\alpha$ emission that is actually there? To test the idea that significant amounts of $H\alpha$ emission have been missed in outer disks, Lee et al (2016) performed very deep imaging in $H\alpha$ of three nearby dwarf galaxies, reaching flux limits of order 10 times lower than that of the 11HUGS/LVL survey (Kennicutt et al 2008). Their new images (Fig. 7) do show emission extending up to 2.5 times further than the previous survey data, but this additional emission only contributes $\sim 5\%$ more $H\alpha$ flux. Therefore, the additional emission found in these deep images does not account for the radial trend in $H\alpha/FUV$.

The emission measure of individual HII regions in outer disks can be very low, however, because of the extremely low average density. Following Hunter et al (2011), one can consider the possible values for emission measure if the far-outer disks in Fig. 2 are completely ionized. The limits of the stellar disks in these galaxies correspond to radii of 60 kpc in NGC 801 ($R/R_D = 4.2$ in the figure) and 71 kpc in UGC 2885 ($R/R_D = 5.9$). The total surface densities at these radii can be used to determine the gas disk thicknesses assuming a velocity dispersion of 10 km s^{-1} . These thicknesses are $T = 26.2 \text{ kpc}$ and 11.4 kpc , respectively, if we consider thickness to be two isothermal scale heights. When combined with the HI surface densities, the corresponding average densities are only $n = 0.00052 \text{ cm}^{-3}$ and 0.0031 cm^{-3} . If the entire disk thicknesses were ionized at these densities, then the emission measures

would be $n^2T = 0.0069 \text{ cm}^{-6} \text{ pc}$ and $0.11 \text{ cm}^{-6} \text{ pc}$. We convert emission measure to surface brightness as $\Sigma_{\text{H}\alpha}(\text{erg s}^{-1} \text{ pc}^{-2}) = 7.7 \times 10^{30} \text{EM}(\text{cm}^{-6} \text{ pc})$. Converting this to intensity units, we get $I_{\text{H}\alpha}(\text{erg s}^{-1} \text{ cm}^{-2} \text{ arcsec}^{-2}) = 1.5 \times 10^{-18} \text{EM}(\text{cm}^{-6} \text{ pc})$. The limit of detection in the very deep survey by Lee et al (2016) was $8 \times 10^{-18} \text{erg s}^{-1} \text{ cm}^{-2} \text{ arcsec}^{-2}$, which is still too high to see the fully ionized far-outer disks in Figure 2 by a factor of ~ 50 or more.

8.4 Breaks in Radial Profiles in dIrr Galaxies

Figure 8 (right) illustrates another common feature of outer dIrr disks: abrupt breaks in azimuthally-averaged surface brightness profiles (Herrmann et al 2013). Most often the profile drops in brightness into the outer disk more steeply than in the inner disk (Type II profiles; Sect. 3) but occasionally it drops less steeply (Type III). Surface brightness profiles without breaks (Type I) are relatively rare. Radial profile breaks are common in spirals as well and were first discovered there (van der Kruit and Shostak 1982, Shostak and van der Kruit 1984, de Grijs et al 2001, Kregel et al 2002, Pohlen et al 2002, MacArthur et al 2003, Kregel and van der Kruit 2004, Erwin et al 2005, Pohlen and Trujillo 2006, Erwin et al 2008, Gutiérrez et al 2011). They are also found in high redshift disks (Pérez 2004). Bakos et al (2008) and Ruiz-Lara et al (2016) found that the Type II downturn at mid-radius decreases significantly in spirals when stellar mass profiles are considered instead of surface brightness. However, this is not the case for most dIrrs, as found by Herrmann et al (2016). Thus, R_{Br} appears to represent a change in stellar population in spirals but a change in stellar surface mass density, at least in part, in dwarfs.

Herrmann et al (2013) examined the surface brightness profiles of 141 dwarfs in up to 11 passbands, and typical Type II and Type III profiles are sketched in Fig. 8 (left). Herrmann et al (2016) further examined the colour and mass surface density trends. They found that, although brighter galaxies tend to have larger R_{Br} , the surface brightness in V , μ_V , at R_{Br} is about $24 \pm 1 \text{ mag arcsec}^{-2}$, independent of M_B and independent of galaxy type. The $B - V$ colour at R_{Br} is also nearly constant. However, when surface photometry is converted to stellar mass surface density for Type II profiles, values for dwarfs are a factor of ~ 6 lower than those for spirals (Herrmann et al 2016, Bakos et al 2008). When separated by radially averaged colour trends, Type II profiles with reddening colour trends (IIR) have a larger fraction of their stellar mass beyond R_{Br} than Type IIs with a bluing colour trend (IIB) or Type IIIs (Herrmann et al 2016; Fig. 8, right).

What is happening at R_{Br} ? Simulations of spirals by Roškar et al (2008), Martínez-Serrano et al (2009), Bakos et al (2011), and Minchev et al (2012) suggest that the break radius R_{Br} grows with time and that for Type II profiles stars formed inside R_{Br} migrate outward beyond R_{Br} as a result of secular processes involving bar potentials or spiral arms (see observations by Radburn-Smith et al 2012). However, scattering of stars from spiral arms is not applicable to dIrrs and observations of some spirals are inconsistent with this scenario as well (Yoachim et al 2012). Another possibil-

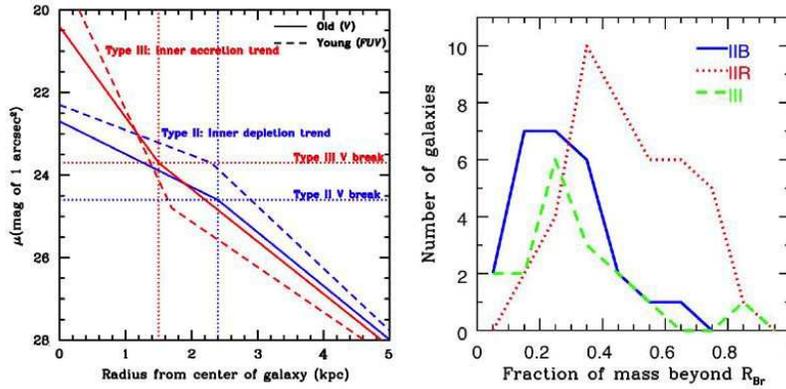


Fig. 8 *Left*: Representative V and FUV Type II and III surface brightness profiles with parameters for $M_B = -16$ from Herrmann et al (2013). V highlights older stars, and FUV reveals younger stars. The steep FUV slope of the Type III profile interior to R_{Br} implies an inner accretion trend. The steeper FUV slope in the Type II outskirts is evidence of outside-in shrinking of star formation activity. *Right*: Number of galaxies with the given fraction of the stellar mass beyond R_{Br} . Type II profiles with bluing colour trends with radius (IIB) and with reddening colour trends with radius (IIR) are shown separately. Type IIR profiles have a larger fraction of their stellar mass beyond R_{Br} than Type IIB or Type III

ity is that there is a change in the dominate star formation process or efficiency at R_{Br} (e.g., Schaye 2004, Piontek and Ostriker 2005, Elmegreen and Hunter 2006, Barnes et al 2012; but for models of star formation without a sharp change with radius see Ostriker et al 2010 and Krumholz 2013). Roškar et al (2008) suggest that, for spirals, it is a combination of a radial star formation cutoff and stellar mass redistribution (see also Zheng et al 2015). The different radial surface brightness and colour profiles in dwarfs can be understood empirically as the result of different evolutionary histories (Fig. 8, left): Type III galaxies are building their centres, perhaps through accretion of gas, while in Type IIR galaxies star formation is retreating to the inner regions of the galaxy (outside-in disk growth as suggested by Zhang et al 2012) and Type IIB galaxies may be systems in which star formation in the inner regions is winding down. Regardless, the near-constant surface brightness and colour at R_{Br} in dwarfs and spirals argue that whatever is happening at R_{Br} is common to both types of disk galaxies.

9 Summary

The outer parts of spiral and dwarf irregular galaxies usually have a regular structure with an exponentially declining surface brightness in FUV, optical, and near-infrared passbands, somewhat flatter or irregular radial profiles in atomic gas, and frequent evidence for azimuthal asymmetries. Models suggest that these outer parts form by

a combination of gas accretion from the halo or beyond, *in situ* star formation, and stellar scattering from the inner disk. The exponential shape is not well understood, but cosmological simulations get close to exponential shapes by approximate angular momentum conservation. Wet mergers also get exponentials after the combined stellar systems relax, and stellar scattering from gas irregularities and spiral arm corotation resonances get exponentials too, all probably for different reasons.

Star formation persists in far outer disks without any qualitative change in the properties of individual star-forming regions. This happens even though the gas density is very low, $H\alpha$ is often too weak to see, and the dynamical time is long. Gas also tends to dominate stars by mass in the outer parts, but the gas appears to be mostly atomic, making star formation difficult to understand in comparison to inner disks, where it is confined to molecular clouds.

Colour and age gradients suggest that most spiral galaxies have their earliest star formation in the inner disk, with a scale length that increases in time and an outward progress of gas depletion or quenching too. The result is a tendency for spirals to get bluer with increasing radius. Eventually the blue trend stops and spirals get redder after that. This gradient change occurs in all types of spiral galaxies, regardless of the exponential shapes of their radial profiles, and suggests a different process for the formation of inner and outer stellar disks. Most likely stellar scattering from the inner disk to the outer disk is part of the explanation, including stellar scattering from bars and spirals, but there could be other processes at work too, including minor mergers and interactions with other galaxies. Colour gradients in dIrrs are usually the opposite of those in spiral galaxies. Dwarfs tend to get systematically redder with radius in what looks like outside-in star formation. This could reflect an enhanced role for stellar scattering with the first star formation still near the centre, as for spirals, or it could result from radial gas accretion or other truly outside-in processes.

The advent of new surveys that probe galaxies to very faint stellar surface brightnesses, combined with new maps of atomic and molecular emission from the far-outer regions of galaxies, should help us to better understand the origin and evolution of galaxy disks.

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