Section A: PROJECT SUMMARY

Overview:

Intellectual Merit:

Broader Impact:

PROJECT DESCRIPTION
Collaborative Proposal: XXX

1 Dwarf Irregular Galaxies Stress the Paradigms

Stellar exponential disks are ubiquitous in the nearby universe and have been observed for over 40 years. The usual interpretations for this structure, such as specific angular momentum conservation during cosmic collapse (Freeman 1970), stellar scattering in bars (Hohl 1971, Debattista et al. 2006, Foyle et al. 2008), and star formation at the viscous rate (Lin & Pringle 1987, Yoshii & Sommer-Larsen 1989, Firmani et al. 1996, Ferguson & Clarke 2001, Wang et al. 2009), are getting more difficult to accept as the number of scale lengths over which exponential disks are observed increases beyond ~ 6 (Efstathiou 2000). Even non-barred, spiral-free galaxies with little shear, such as half the local dwarf irregulars (dIrrs), have exponential disks that can exceed 10 scale lengths in spite of an irregular structure and a sporadic star formation history (SFH; LMC: Saha et al. 2010; see also Hunter et al. 2011, Bellazzini et al. 2014). How do they produce and maintain such structures? Elmegreen & Struck (2013) proposed that stellar scattering from bars, spirals, and clumps could be the general cause, with clumps being more important in both the early universe (Bournaud et al. 2007b) and today's dwarfs.

Dwarfs are *not* just little spirals. Dwarfs also differ from spirals in their color profiles. Zhang et al. (2012a) found that dwarfs are older in their outer parts, suggesting outside-in growth, outside-in quenching, or stellar scattering from inner star-forming regions to outer quiescent regions. Spirals with down-bending outer exponentials (Freeman Type II) have U-shaped color profiles, suggesting a decrease in age with radius (inside-out growth; Mu noz-Mateos et al. 2007) until the break radius where the outer profile begins to steepen. Beyond this, the age increases presumably because of old scattered stars (Bakos et al. 2008; Roškar et al. 2008). Cosmic accretion may also have an inside-out pattern (Pichon et al. 2011).

Star formation in dIrrs is difficult to understand anyway, particularly in the outer parts where the gas densities are very low. There, the Toomre (1964) gravitational instability parameter for the gas, identified by Kennicutt (1989) as an important parameter for star formation, predicts that the gas is highly stable ($Q > 5$; Hunter et al. 2011). Yet, we detect FUV and Hα emission, signposts of recent star formation, even into the outer disks. Outer disk gas sometimes has large irregularities, however, especially in Blue Compact Dwarfs (BCDs) that we have mapped with both the VLA and GBT. Thus, interaction-triggered star formation may be important in some, but not all, dwarfs.

In this proposal we attack the problem of how dIrr galaxies are built and evolve, using a large sample of galaxies with extensive data from our existing surveys. We especially target *outer* disks of dIrrs as sensitive probes of external influences and galaxy evolutionary processes and stress-tests of star formation models. We will observe the extreme far-outer parts of dIrrs in optical light, observe star-forming regions at low metallicity with CO using accepted and future ALMA programs, and run models for dwarf formation in both a cosmological setting and with highly-resolved stellar scattering in the presence of realistic gas clumps. At the end of 5 years, we will have determined the SFHs in the extreme outer disks of dIrrs, tested crucial candidates for large-scale drivers of star formation including accretion, examined what happens at the breaks in the stellar surface brightness/mass profiles where the exponential changes abruptly in slope, and determined the effects of low metallicity on star formation, the life-force of galaxy evolution. In the process, we will have pushed the current paradigms of disk evolution and star formation to the benefit of our understanding of all disk galaxies.

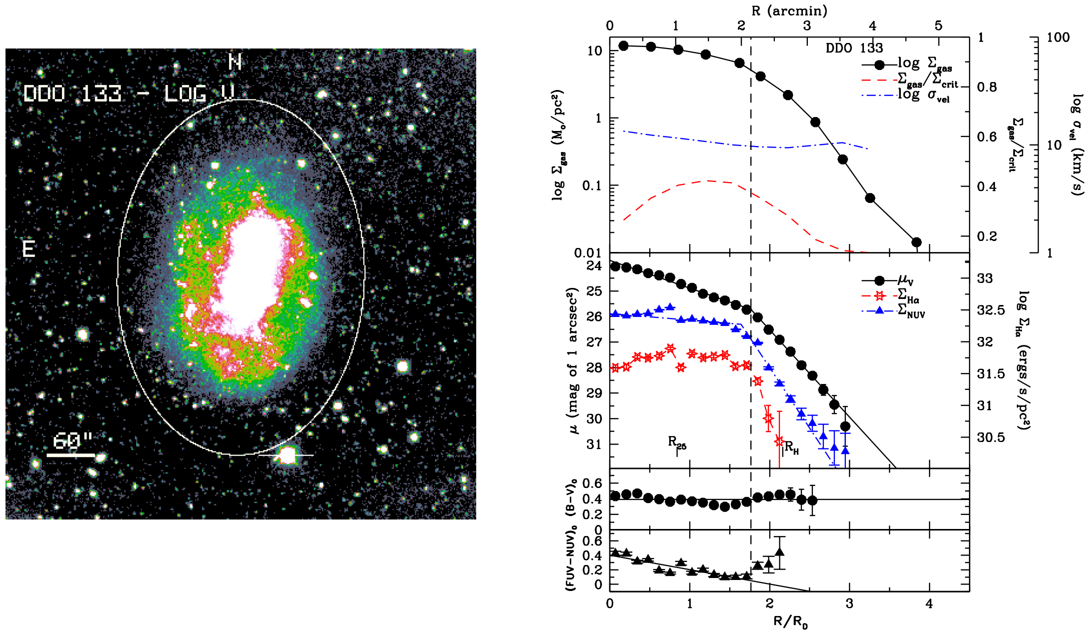


Figure 1: *Left:* V-band image of DDO 133, with a logarithmic stretch to enhance faint features. The ellipse denotes $\mu_V = 29.5$ mag/arcsec^2, the furthest we trace the disk. *Right:* Top panel: Gas density Σ_{gas}, velocity dispersion σ_{vel}, and ratio of gas density to Toomre critical density Σ_{crit} as a function of radius normalized to the disk scale length R_D. Middle panel: V, Hα, and NUV surface brightness profiles. We trace the disk into the regime of very low gas density, and we see a break in the stellar profile at $R/R_D \sim 2$ (vertical dashed line, Hunter et al. 2011). Bottom two panels: Radial profiles of the $B-V$ and FUV-NUV *GALEX* colors. The $B-V$ color is nearly constant.

2 Determining How Dwarf Disks are Assembled and Evolve

We attack the issue of dIrr disk evolution through four questions:

What is the star formation history and structure in outer stellar disks? In a pilot project, we obtained deep V and *GALEX* FUV images of 4 dIrr galaxies and one BCD and B images for 3 of the dIrrs (Hunter et al. 2011). We traced the stellar disks in these images to $\mu_V = 29.5$ mag/arcsec^2. We found that the stellar surface brightness in V and FUV continue as far out as we can measure (Fig. 1). Also, the gas surface density is significantly less than the Toomre (1964) threshold for instability, which means that the gas should be stable against spontaneous gravitational collapse. This led to two conclusions. First, exponential stellar disks are extraordinarily regular in spite of the fact that dIrr galaxies are clumpy with sporadic star formation. Second, there is a continuity of star formation with the same exponential profile even though the outer gas is stable.

We propose to build on this study by ultra-deep imaging of the extreme outer stellar disks of the LITTLE THINGS dIrrs (see §3) in $UBVI$. With multiple filters, we will measure photometric properties and fit SEDs to stellar populations and SFHs (as in Zhang et al. 2012a). The SFHs as a function of radius are the record of the disk growth, so with ultra-deep images and SFHs we will be able to test ideas on the assembly history of dIrr disks.

We will go 2.5 mag/arcsec^2 deeper than our existing images, which doubles the observable length of the outer disk, where very little is known about star formation, dynamical processes, or environmental influences. The additional depth also corresponds to an increase in the observable stellar area by a factor of ~ 2, increasing the probability we will find evidence for new dynamical

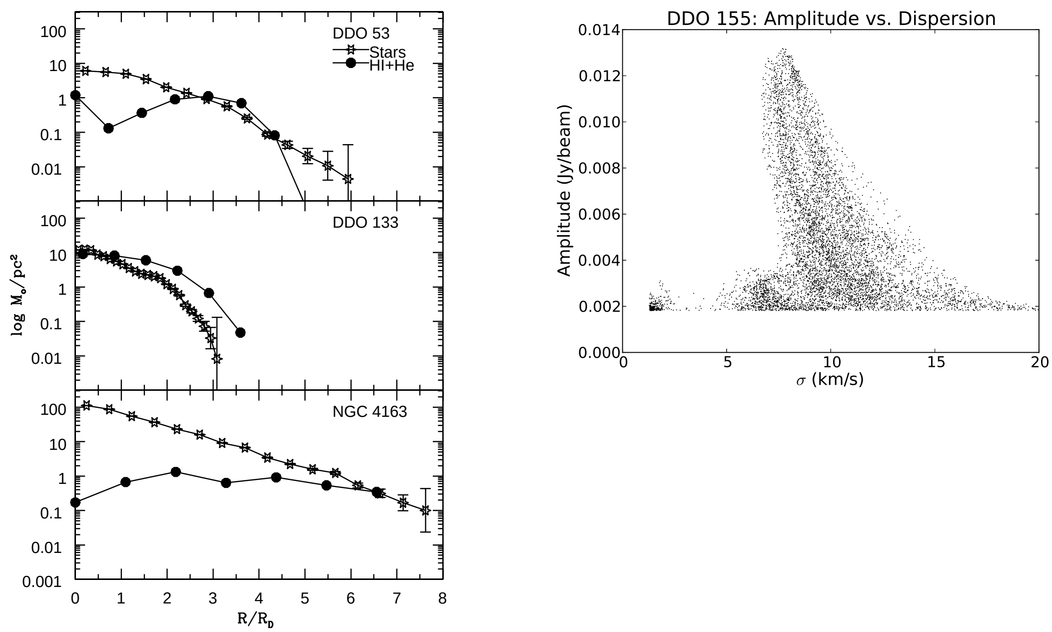


Figure 2: *Left:* Mass column densities from ultra-deep imaging of 3 dIrrs (Hunter et al. 2011), plotted as a function of radius normalized to the disk scale length. *Right:* Anticorrelation of H I amplitude with velocity dispersion of the gas in DDO 155 from our maps (Cigan et al., in prep), indicating cooler or more quiescent gas in regions of high column density.

processes, such as perturbations by dark companions, stellar responses to extragalactic H I clouds, or accretion of primordial gas.

What are the large scale drivers of star formation? Star formation is a primary force in the evolution of galaxies. Star formation in inner regions of spirals is predicted because the gas is marginally gravitationally unstable ($Q \sim$ 1-2; Toomre 1964, Kennicutt 1989), but in dwarfs Q is 2-3$\times$ too high for these instabilities (Hunter & Plummer 1996; Meurer et al. 1996; van Zee et al. 1997; Hunter et al. 2011). Yet, the outer disks of dIrrs and spirals are even more extreme and one of the fundamental questions in disk evolution today is how star formation takes place in such extreme environments (e.g., Bland-Hawthorn et al. 2005, Thilker et al. 2005).

Figure 2 shows mass column densities corresponding to the stellar surface brightness and the gas surface density in 3 of the galaxies in the deep imaging pilot project discussed above. The stars go down to 0.01 $M_\odot$ pc^{-2} in two cases and 0.1 $M_\odot$ pc^{-2} in a third, and the H I gas goes to values $\sim$ 10 times higher in each case. These stellar surface densities are extraordinarily low: the average star formation rate (SFR) over the last 10 Gyr would have been 10^{-6} $M_\odot$ yr^{-1} kpc^{-2} if the outer disk was populated by star formation (as the FUV suggests). This value is 0.0005 times the SFR at the H I-molecule threshold (e.g., $\Sigma_{\rm gas} \sim 10$ $M_\odot$ pc^{-2}) in typical galaxies found by Bigiel et al. (2008). Even though CO has been detected below the H I-molecule threshold by another factor of 10 using stacking techniques (Schruba et al. 2012), and the SFR there is also a factor of 10 lower than this threshold, the outer disks of the dwarfs we studied go yet another factor of 200 lower. The question is not just how molecular clouds form at such low densities, but how they know to do it as part of a continuous exponential profile as shown by the FUV light?

We are proposing to test the importance of accretion, turbulence and non-rotational gas dynamics, environmental conditions, and stellar feedback to star formation in dIrrs. Accretion of primordial gas flowing onto galaxies from the cosmic web is currently believed to be *the* driver for on-going star formation in spiral galaxies (e.g., Finlator & Davé 2008, Forbes et al. 2014;

see review Sánchez Almeida et al. 2014a). This process is also proposed to explain chemical inhomogeneities in tadpole galaxies and BCDs, the starbursts in BCDs, and possibly the unusual H I structures around the starburst IC 10 (Ashley et al. 2014, Sánchez Almeida et al. 2013, 2014b, Verbeke et al. 2014), but observational evidence of this as a common phenomenon driving normal dIrr evolution does not exist. We will use high sensitivity large-scale optical and H I maps around the LITTLE THINGS dIrrs to search for signs of accretion.

What changes at the breaks in exponential profiles? In $20-60\%$ of dwarfs and spirals there is a break in the exponential profile with a steeper exponential (Type II) extending beyond that for at least several more scale lengths (de Grijs et al. 2001; Kregel et al. 2002; Pohlen et al. 2002; Kregel & van der Kruit 2004; Hunter & Elmegreen 2006; Pohlen & Trujillo 2006; Erwin et al. 2008; Herrmann et al. 2012). In some cases the second exponential is shallower (Type III).

Herrmann et al. (2013) analyzed the surface brightness profiles of the 141 galaxies in our large dwarf survey (§3). She identified breaks, where the exponential fall-off changes slope, in a semi-automated fashion and classified their type in up to 11 passbands. Remarkably, spiral and dwarf breaks occur at about the same stellar mass density, so something fundamental is happening at these breaks, but we do not yet know what. In spiral galaxies, Bakos et al. (2008) found that Type II breaks nearly disappear in stellar surface *mass* density profiles. However, we find that the breaks in dIrrs are often present in the mass density profiles too (Herrmann et al., in prep).

We will investigate the cause of the profile breaks by looking for empirical correlations and by comparison with predictions from current models.

What affect does low metallicity have on star formation? According to Filho et al. (2013), nearby extremely metal-poor galaxies are chemically primordial-like objects (see also Richards et al. 2014). At extremely low metallicities, star formation should be very difficult (Spaans & Norman 1977). Increasing metallicity enhances atomic and molecular cooling; increasing dust content absorbs part of the stellar radiation field and boosts H_2. This thirst for metals should have critical consequences to the SFH of galaxies (Kuhlen et al. 2012). As star formation gains a foothold, the on-going evolution of disk galaxies is driven by the interplay between star formation and the transition from atomic to molecular gas, which depends on metallicity (Fumagalli et al. 2010, Walch et al. 2011, Genzel et al. 2012, Tassis et al. 2012). Clearly, metallicity is not a passive result of galaxy evolution, but a crucial *driver*.

A result of low metallicity is poor shielding of molecular clouds. As a consequence it is expected that the structure of the molecular cloud itself will change as the metallicity drops: the CO core shrinks and the photodissociation shell (PDR) grows (Maloney & Black 1988, Bolatto et al. 1999, 2011, Röllig et al. 2006). In fact, it is possible that in galaxies with metallicities below a few percent of solar, star formation will proceed in cold *atomic* gas (Krumholz 2012). We need to understand the role of molecules in the star formation process at low metallicities where young galaxies began their stellar buildup. We also need to determine if metallicity-related changes in the chemical structure of clouds have an affect on star formation, such as the formation of bound vs. unbound clusters. The shrinking CO core with declining metallicity has meant that molecular gas has been hard to detect at metallicities below 20% of solar (Taylor et al. 1998, Wong et al. 2009, Schruba et al. 2012). However, we have broken this metallicity barrier (Elmegreen et al. 2013) and now have the data to show directly the molecular structure down to 5% solar abundance (Figure 3). We will also examine the basic properties of the GMCs we find and determine the environmental conditions important in forming star-forming molecular clouds at low metallicities.

Our proposal We are proposing to obtain ultra-deep multi-wavelength optical imaging that we will use to obtain SFHs as a function of radius to extraordinary low stellar surface densities. We will also search for young star clusters as signposts of in situ star formation and look for unusual

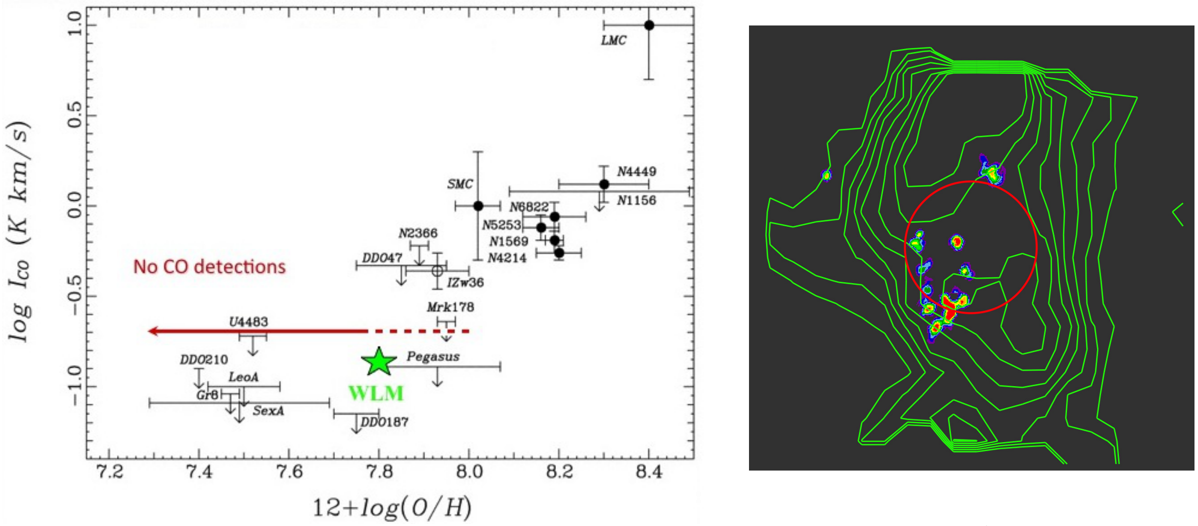


Figure 3: *Left:* I_{CO} as a function of galaxy oxygen abundance at low metallicity (Tacconi & Young 1987, Taylor et al. 1988; plot courtesy of M. Rubio). Only the solid black circles and the green star marking WLM are detections. Our measurement of CO 3-2 in WLM with APEX extends the detections to 13% of solar metallicity (Elmegreen et al. 2013). *Right:* False-color ALMA map of CO 1-0 in a region in WLM (Rubio et al., in prep). The red circle is the APEX beam (18″ diameter) where we first detected CO 3-2, and the green contours are of the *Herschel* [CII] emission. For the first time we can see directly the structure of the molecular cloud at 13% solar abundance!

stellar structures. We will use large-scale, high sensitivity optical and H I images to look for stellar and gas structures around our dIrrs that could be indications of past interactions or accretion of primordial gas. We will use our existing H I maps to look for connections between the large-scale structures and local peculiar kinematics. We will examine turbulence and environmental factors of potential importance in triggering or regulating star formation. We will examine changes in SFR, H I gas structures and kinematics, and disk flaring at the breaks in stellar exponential profiles and test several current predictions for the cause of the breaks. We will determine the molecular cloud structure and properties as a function of metallicity to 5% of solar abundance and examine the environments in which these clouds have formed and their relationship to the star forming units. Finally, we will use numerical simulations to test the viability and significance of star scattering into the outer disks of dIrrs, and we will conduct numerical simulations of the formation and evolution of dIrrs.

At the end of this effort, we will have tested ideas on the assembly history, mechanisms, and timescales of dIrr disks, determined the extent and nature of in situ star formation vs scattering of stars in building and maintaining the outer exponential disk, modeled their cosmological evolution, and determined the overall relative importance of environmental factors versus internal processes on the evolution of dIrrs. We will also have examined the likely large-scale drivers of star formation in dIrrs, learned of the importance of accretion of primordial gas in controlling the evolution of dIrrs, and tested various internal processes such as gas dynamics, regulation by existing stars, and internal local environmental factors determining properties of star-forming regions. We will have examined empirical correlations and predictions of models to understand the breaks in exponential profiles, a fundamental feature of most exponential disks. And, finally, we will have determined the effects of low metallicity on the structure of star-forming clouds and on star formation. We will then have a comprehensive understanding of how dIrr galaxies are built and evolve.

3 The Observational Foundations

The proposed work outlined below builds on our multi-wavelength survey of 96 dIrr and 26 BCD galaxies that are relatively nearby, contain abundant gas, and cover a large range in properties, including SFR and M_V. We obtained *UBVJHK*, Hα, *GALEX* FUV and NUV images, and *Spitzer* IR images of these galaxies (Hunter & Elmegreen 2004, 2006; Hunter et al. 2010), and used these data to trace the stellar populations and ages (Zhang et al. 2012a). A sub-sample of 37 dIrrs and 4 BCDs were chosen for the LITTLE THINGS survey that was granted ∼376 hours with the VLA to obtain H I data on 21 galaxies (Hunter et al. 2012, see Fig. 4). We added 20 dwarfs from the archives. The H I data are of high sensitivity ($\leq$ 1.1 mJy beam^{-1} channel^{-1}), high spectral resolution ($\leq$2.6 km s^{-1}), and high spatial resolution (6″, 110 pc at 3.7 Mpc). We use these data to trace the atomic gas distribution, morphology, and kinematics. We have targeted a sub-sample of the LITTLE THINGS galaxies for detailed studies of the non-atomic ISM: CO using APEX and ALMA, *Herschel* maps of the fine-structure lines of PDRs, *Herschel* dust FIR continuum maps, and cold dust maps at 870μm using APEX. In the radio continuum, we mapped several galaxies with the JVLA in a multi-frequency pilot project (Heesen et al. 2011, 2014), and obtained time for a larger 6-cm survey. We have also mapped H I in a 2° FOV around all LITTLE THINGS galaxies with the GBT, looking for gas-rich companions and streams (c.f. Johnson 2013), and we are searching for stellar companions using amateur astronomer partners.

To this rich dataset, we will add new observations motivated by the science questions, as described in the next section. We also initiate several new modeling efforts.

4 Specific Projects

We propose here specific experiments aimed at answering the 4 questions in §2 that are necessary to understand how dIrr galaxy disks have assembled and evolve with time.

4.1 Ultra-Deep Imaging of Outer Stellar Disks

Our deep *UBVI* imaging will use the Large Monolithic Imager (LMI) on Lowell's new 4.3-m Discovery Channel Telescope (DCT). The technical specifications of LMI were set to reach to $\mu_V \geq$ 30 mag/arcsec^2. This means there is very low scattered light and a large FOV (12.5′) to sample sky. It also uses the largest single CCD that can currently be built. By avoiding the dithering necessary to fill gaps in mosaics, the sky-brightness can be determined very accurately, which is necessary in obtaining low surface brightness measurements. The DCT is performing extraordinarily well and is now entering full science observations. Lowell Observatory has guaranteed Hunter the 100 nights needed for this NSF project if it is funded. Our deep imaging approach differs from that of ANGST (Dalcanton et al. 2009), which is complementary to ours and uses color magnitude diagrams of individual stars on *HST* images to give resolved SFHs. Here we can probe much further out in the disk and cover the entire disk all at once.

With these data we will determine the relative proportions of stars with different ages as a function of radius, binned by age within factors of 10. This will extend into the extreme outer disk the SED fitting of our previous data on 34 dIrrs by Zhang et al. (2012). We found that in systems with baryonic masses $< 10^8$ M/solar , the SFR in the outer disk has been declining with time, while in the more massive dwarfs the SFRs have been more uniform over radius and time. In the LMC also, Meschin et al. (2013) found outside-in star formation. This is contrary to the current paradigm that spiral stellar disks grow from the inside-out (c.f., Mu noz-Mateos et al. 2007), with

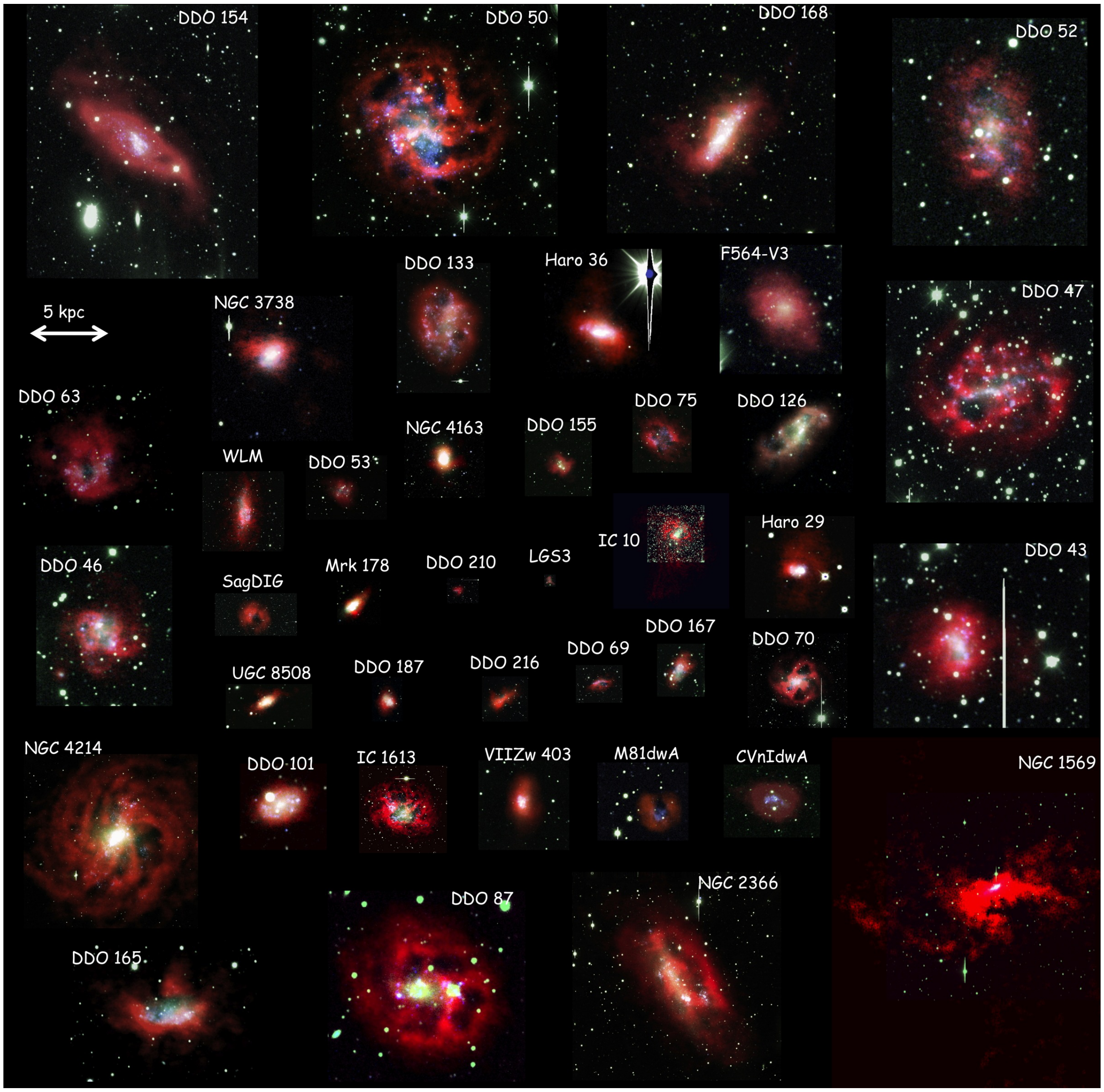


Figure 4: LITTLE THINGS dwarf galaxy sample: Red is H I, green is V, blue is FUV. Images are to same relative size.

scattered stars (Rŏskar et al. 2008) and perhaps recent cosmic accretion (references in Sánchez Almeida et al. 2014a) in the far outer parts. A consistent picture of the stellar populations and ages over the disks of dIrrs is a necessary first step to determining their assembly history.

But are outer disks populated primarily through stars scattered from the inside out or from in situ star formation? In spiral galaxies, numerical simulations show that spiral arms are capable of scattering stars into the outer disks (Rŏskar et al. 2008) and this could be a significant source of the stellar populations there. However, dIrrs do not have spiral arms. We will run 2D and 3D test particle models to determine if scattering of stars is a viable mechanism to populate outer disks in dwarfs (Elmegreen & Struck 2013). Scattering centers are added in the form of clumps representing a range of objects from star-forming regions to small companions. The scattering model may explain exponential disk profiles in the absence of bars and spirals. These models will predict stellar kinematics or populations that may allow us to tell the difference observationally between scattering of old inner stars and a lack of star formation for a long time.

On the other hand, if the outer disk of dIrrs is forming stars in situ, there should be young stars. We have detected clusters and associations to a radius of a few disk scale lengths (Hunter et al. 2011). Here we will use our proposed deep U-band images to identify young clusters much further out. If they exist, we will be able to find them. Then we will determine if such clusters change their properties or disappear altogether in the far outer regions, and if there is a change, we will determine the H I and stellar column densities where the change occurs for comparison with possible models of cluster formation (e.g., Kruijssen et al. 2011). We will also determine the gas, stellar, and kinematic environments in which the clusters formed. This will be a stringent test for in situ star formation in extreme outer disks of dIrrs.

The results from these investigations will tell us whether dIrr disks grow from the outside-in and on what time scales, the importance of star scattering versus in situ star formation in building and maintaining the outer exponential disk, and whether there are changes in the cluster formation properties in the outer disk. These will be important constraints on cosmological evolutionary models of dwarfs.

4.2 Large-scale drivers of star formation

The process of turning gas into stars is a key process that causes galaxies to evolve. Yet, we do not know what the crucial processes are that drive star formation in dIrrs. Here we look at the major forces that are currently proposed to make star-forming clouds or regulate SFRs: accretion, turbulence and non-circular gas motions, and feedback from older stars.

4.2.1 Accretion

Accretion of primordial gas is proposed as the major driver for on-going star formation in spirals, but what about the average dwarf galaxy? We propose to look for evidence of accretion through wide FOV imaging to reveal large-scale optical and gas structures around the LITTLE THINGS dIrrs and through comparison to gas kinematics and the SFH of the disk.

Dragonfly, an innovative, multi-lens array designed for ultra-low surface brightness imaging over a 2.6° FOV (Abraham & van Dokkum 2014), has proven an ability to reveal extraordinary, faint structure in the far outer disks of spiral galaxies. R. Abraham, one of the co-inventors of Dragonfly, has agreed to obtain images in g-band of several of the LITTLE THINGS dIrrs as tests to see if similar structures are found around dwarfs. The Dragonfly data are low angular resolution (2.8″ pixels) and will be taken in only one filter, but they are of unparalleled sensitivity over a large FOV and will complement the multi-wavelength, high angular resolution imaging of the galaxy disk with DCT. For large-scale gas structures we have GBT observations over a 2° FOV around all of the LITTLE THINGS dwarfs. Besides possible sign posts of accretion, these data could also reveal indications of tidal interactions, spiral structures, blobs, or disk holes.

Oh et al. (in prep) has deconvolved the VLA H I kinematics of LITTLE THINGS galaxies into its main components: ordered rotation and non-ordered motions. Using the maps of peculiar gas motions, we will look for a physical correspondence between non-ordered motions and large-scale optical structures found by Dragonfly or large-scale H I structures found with GBT. These could be the signature of accretion, where the large-scale becomes local. We will determine the total angular momentum of the non-ordered motion gas and therefore the preferred scale length after settling, compare the before and after radii and the surface density, and determine the in-plane disk accretion rate ($\Sigma \times 2\pi\Delta R$/adjustmenttime) and compare that to the observed SFR.

Finding accretion signatures would relieve the stress on star formation models that are hard pressed to form stars in dIrrs through internal processes. It would mean that the evolution of dIrrs, like spirals, are controlled by outside factors and, thus, disk growth can continue indefinitely.

4.2.2 Turbulence and gas kinematics

An internal process for creating star-forming clouds is compression of gas in a supersonically turbulent medium (MacLow & Klessen 2004), and this has been predicted to be particularly important for star formation in outer disks (Elmegreen & Hunter 2006). There is extensive evidence for interstellar turbulence, but the energy content and source of this turbulence has been difficult to quantify. The LITTLE THINGS survey of H I in dIrr galaxies also shows considerable kinematic structure in the gas, including non-ordered and streaming motions, varied velocity dispersions, and possible warps. Oh et al.'s (in prep) deconvolutions of rotational motions and non-ordered motions and LITTLE THINGS team member Cigan's code to construct 2D maps of the FWHM of the velocity components will serve as starting points for examining the importance of gas kinematics and its relationship to star formation.

Burkhart et al. studied the turbulence in the SMC through analysis of higher order moment maps (skewness and kurtosis) of the H I column density distributions, and we are following their analysis for the LITTLE THINGS galaxies (begun summer 2014 by an undergraduate). We are determining kurtosis values globally, radially, and locally (region size is limited by statistics of H I beams). We will look for variations of kurtosis with radius, proximity to clumps, and proximity to star-forming regions. Burkhart et al. found no correlation between the turbulent Mach number and the local SFR, but a clear correlation between Mach number and the bar. Similar analyses for our galaxies might confirm the implication of this study that considerable turbulent energy comes from galactic dynamics, rather than stellar feedback. This would be consistent with observations (Block et al. 2010) and modeling (Bournaud et al. 2010) of two-step power law Fourier Transform power spectra in the LMC. We will also look at an anti-correlation we found before (Hunter et al. 2001, 2011) between the velocity dispersion σ_{vel} and surface density of H I Σ_{HI} (c.f., Fig. 2, *right*) which suggests turbulent pressure equilibrium on large scales (e.g., Piontek & Ostriker 2005).

Ultimately we want 2D maps of the turbulent energy density. We can produce these by removing the thermal parts of local H I line profiles. Determining the thermal part requires estimates of the state of the ISM as a function of radius. There are no extensive data on this for dIrrs, but we can use the results of Zhang et al. (2012b) from H I Fourier Transform power spectra as a guide to the relative fractions of cool and warm H I. We will then compare the turbulent energy density with H I surface densities, SFR profiles and locations of star-forming regions, and star formation models.

Other gas kinematics that are not, strictly speaking, turbulence, such as streaming motions around bars, could also play important roles in star formation. We will identify such kinematic structures and determine their impact on star formation in the LITTLE THINGS galaxies. Together, these projects will tell us of the importance of internal gas dynamics on dIrrs.

4.2.3 Stellar feedback

The strongest correlation with SFR is the stellar mass density of stars (Shi et al. 2011), but we do not know what this means. One possibility is that feedback from older stars is crucial in triggering or regulating the next generation of stars. We know "sequential triggering" takes place since we see specific examples of it (e.g. Constellation III in the LMC, Dopita et al. 1985). In this process the winds and supernova explosions from concentrations of young massive stars blow holes in the gas of a galaxy, producing a higher density shell that fragments into star-forming clouds. However, a consequence is an ISM full of holes where star formation is halted and the path length for UV photons that can heat the gas increases. Once disrupted, holes in the ISM can last a long time because there's little shear in these primarily solid-body, slowly rotating systems. Another explanation for the correlation of old and young stars is that, averaged over some suitable time scale, the conditions in a given part of a galaxy always produce the same SFR and hence build a stellar population that is proportional to the SFR over the lifetime of the galaxy. If so, we don't know what the crucial environmental conditions are. Here we examine several aspects of these explanations for the relationship between old stars and new.

One of the PhD dissertations being done under LITTLE THINGS uses the VLA H I cubes to catalog the holes in the gas in our dIrrs, and these data will then be used to determine the fraction of current star formation taking place in the shells around these holes, potentially a result of sequential triggering. In this proposal, we will take this study further and use the catalogues of holes to determine the porosity of the ISM as a function of radius in dIrrs. With this fundamental characteristic of each galaxy, we will then examine the consequences by looking for correlations with underlying stellar populations and with current star formation. We will test Silk's (1997) prediction that at a given surface density the SFR should anti-correlate with porosity.

Stars can also regulate star formation in other ways. In the model of Ostriker et al. (2010), star formation adjusts to provide the needed FUV heating to balance cooling and, thus, to match the thermal pressure to that of the mid plane pressure set by the vertical gravitational field. In this model star formation continues, although with decreasing efficiency, to large radii, and there is no sharp cutoff caused by a $\Sigma_{\rm HI}$ limit. So this model may provide a way to understand stellar disks that go on and on into highly sub-critical gas densities. On the other hand, in a comparison we made for a small sample of dIrrs, the relationship between $\Sigma_{\rm SFR}$ predicted by this model with FUV surface photometry is not very good. Here we will tune the parameters of this model to better fit dIrrs and compare its SFR(R) predictions against our observations of dIrrs.

If local environmental effects are important in driving star formation, we might see this in the products of the star formation process. We will compare the characteristics of young star-forming regions or star clusters to environmental factors, and if there are correlations, look for radial trends. For example, is there a relationship between the mass or density of clusters and gas structure, kinematics, or disk pressure in that part of the galaxy?

From these experiments we will learn of the consequences of holes blown in the gas, of stars as regulatory agents of star formation, and of environmental factors in determining properties of star-forming regions. With this and our projects aimed at accretion and gas dynamics, we will determine the relative importance of various internal and external processes in driving star formation in dIrrs.

4.3 Breaks in exponential profiles

We will investigate the cause of the breaks in the stellar surface brightness profiles by looking for empirical correlations and by comparison with model predictions. We will examine the SFR interior and exterior to the profile breaks to see if there is a change in the normalized star formation at the break. We will do this both in dIrrs and in a sample of spirals for comparison. We will determine the relationship between the breaks and the gas surface density profile for the LITTLE THINGS sub-sample. Are there breaks in the H I where there are breaks in the stellar mass profiles? Does the outer H I (and perhaps star formation tracers too) drop off faster than the stellar mass, as might be expected from scattering? Is there a relationship between the break-type (downward bending or upward bending) and bar or external disturbances that are either observed directly in our deep images or inferred from H I velocity perturbations in the LITTLE THINGS subsample? Are there asymmetries and faint stellar structures that are possibly related to the breaks in our deep images? Is there a relationship with scale-heights, ratio of gas to stellar mass, or star formation drivers?

A correlation between disk flaring and breaks has been seen in M94 (Herrmann & Ciardullo 2009) and the Milky Way (Benjamin, private communication), perhaps by the effect of the flaring on the star formation process. Disk thickness affects star formation through the stellar contribution to the gravitational force on the gas, and therefore to the weight, pressure, and molecular fraction in the gas layer. Here we will identify flaring in dIrrs by using Planetary Nebulae (PNe) to determine stellar velocity dispersions of stars combined with disk surface mass densities from photometry. PNe velocities could also indicate non-circular motions (e.g., from line-of-sight velocities on the minor axis) which could be relevant to stellar scattering into the outer regions. PNe are extremely bright in [OIII], relatively easy to distinguish from HII regions (via the [OIII]-Hα ratio; Ciardullo et al. 2002), abundant to $\gtrsim 5$ scale lengths and present in all stellar populations with ages between 0.1 to 10 Gyr. We have identified $\sim$150 PNe in two dwarfs from Hα and [OIII]λ5007 imaging with DCT, and have submitted a proposal to use Hydra on WIYN to obtain the velocities. Four more LITTLE THINGS dwarfs are bright enough that large populations of PNe are expected (c.f. Gonçalves et al. 2012), and we will use DCT imaging to identify them and high resolution spectrographs to determine the kinematics.

There are several models that predict what happens at the exponential break, and we can test these. Elmegreen & Hunter (2006) show that a change from star formation dominated by the gravitational instability in the central regions to star formation dominated by turbulence compression in the outer disk produces a sharp change in slope of the SFR profile. Furthermore, this model predicts that the break should occur about twice as close in to the center in dwarfs as in spirals, as is observed. Schaye (2004), on the other hand, argues that the break occurs where the average gas density drops below a threshold of 3-10$\times10^{20}$/cm^2. Another mechanism for producing local density enhancements is the magnetorotational instability, where the angular velocity decreases outward and magnetic fields are present. Piontek & Ostriker (2005) predict that turbulent velocity dispersions go up, reaching a quasi-steady plateau, as the average gas density goes down. This results in departures from thermal equilibrium and local density variations that might be particularly useful in outer disks. Roškar et al. (2008) suggest that the break forms in a (spiral) disk within 1 Gyr and that the break moves outward as the gas cools. The break in their model corresponds to a rapid drop in the SFR associated with a drop in the cool gas surface density relative to the Toomre critical density. We will test the predictions of what happens at the breaks in each of these models against the observed properties of the galaxies.

The results of these studies will be an understanding of a fundamental feature of most exponential disks and may help to explain what forms and maintains exponential disks.

4.4 Star formation at low metallicity

We are determining the molecular cloud structures (PDR shells plus CO cores) in 4 dwarfs that trace a metallicity sequence of 13% to 5% of solar. This became possible when we used the single-dish telescope APEX to detect ^{12}CO 3-2 in two pointings in WLM, a local dwarf with a metallicity 13% solar (Elmegreen et al. 2013). This broke the "metallicity barrier" of 20% that was believed to be the limit of CO detections (Fig. 3). We also obtained *Herschel* spectroscopy that maps the PDR fine-structure lines in one of the WLM pointings and in 4 other LITTLE THINGS galaxies to 5$\times$ lower metallicity than had been done before. The APEX beam where we detected CO in WLM fits like a baseball in the glove of the PDR [CII] emission. We have since obtained ALMA Cycle 1 ^{12}CO 1-0 maps at 2″ angular resolution of both of the WLM regions, and for the first time we have an *image* of a molecular cloud structure at 13% solar abundance! We find that the CO cores are very tiny indeed (Rubio et al., in prep; Fig. 3). We have also been granted Cycle 2 time to obtain CO maps of 3 of the other dwarfs we observed with *Herschel*. At the end we will have pictures of the PDR shells plus CO cores of 4 dwarfs spanning abundances down to 5% of solar.

We can then examine the basic properties of the GMCs: their sizes and luminosities, the luminosity distribution function for CO clouds, the overall SFR/molecule ratio, and Larson's (1981) laws – velocity dispersion is proportional to cloud size and mass and cloud size is inversely proportional to density. To do some of these things, we need to estimate the H_2 mass. To do that we use dust masses estimated from our *Herschel* FIR images (angular resolutions of 3.2″ at 110 μm to 36″ at 500 μm, 5 passbands) supplemented with *Spitzer* data, a metallicity-scaled dust-to-gas ratio (c.f. Elmegreen et al. 2013), and H I masses from LITTLE THINGS (angular resolutions ∼7″). We will compare the properties of the molecular clouds to the star formation in the regions: Are the sizes and numbers of star forming regions like those of the CO knots? We will use our H I and stellar data to determine the context of their formation: density, turbulent speeds, H I morphology, the warm and cool (broad and narrow) components of the H I, and the ages and distributions of nearby stellar populations. We will also use numerical and analytical models of H_2 and CO formation and its connection to star formation to better understand the chemistry, extinction, molecule formation, CO excitation and other processes in these low-metallicity galaxies (c.f. Sternberg 2007, Sternberg et al. 2011, Genzel et al. 2012). With these, we will answer: What environment is necessary to form molecular clouds at low metallicities?

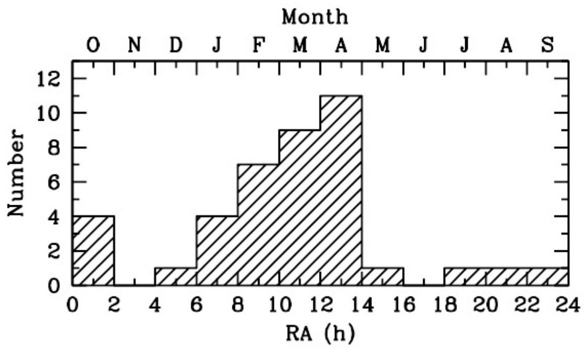
4.5 Numerical simulations of the formation and evolution of dIrrs

We will use high-resolution, cosmological SPH+N-body simulations to model the formation and evolution of dIrrs and compare these with our observations. These simulations are some of the highest resolution simulations ever run with gas dynamics (spatial resolution <100 pc) all the way to $z = 0$, and include a physically motivated treatment of the gas, star formation, and energetic feedback processes (Zolotov et al. 2009). These simulations will resolve the high density regions, comparable to GMCs, where stars form, and probe the formation and evolution of exponential disks and disk breaks in dwarfs. They will have enough particles to resolve the Jeans length and minimize particle noise heating in the outer disk. Using these simulations, we will study the impact of environmental effects (mergers and tidal interactions) versus internal processes (disk instability and clump-driven migration) on the morphology and disk properties of dwarf galaxies. These models will tell us the overall relative importance of environmental factors versus internal processes on the evolution of dIrrs, and they will be global models against which to test our cumulative paradigm of dIrr disk assembly and formation.

5 Personnel and Activity Plan

Outer disks

Hunter will be responsible for the imaging with DCT: observations, data reduction, surface photometry, finding and characterizing structures and star clusters and their environments. The timeline of observations is shown in Fig. 5. Zhang (unfunded collaborator) will carry out the SED fitting to determine SFHs from surface photometry and masses and ages of individual star clusters. Struck and Elmegreen will run 2D and 3D test particle models to determine if scattering



	Q1	Q2	Q3	Q4
2014	-	-	-	11.5
2015	15	15	7.5	1
2016	15	15	-	mop-up
2017	15	mop-up		-
2018	5			

Figure 5: *Left:* RA distribution of our sample galaxies. *Right:* Requested DCT observing profile in nights per quarter. Red is Y1, blue Y2, and green Y3.

of stars is a viable mechanism to populate outer disks. Hunter will guide the LARI project (§6).

Large-scale drivers of star formation

Accretion: Johnson (unfunded collaborator) will map and analyze the GBT images of large-scale H I structures. Simpson will analyze the relationship between structures found by Dragonfly or GBT with properties seen in stellar and gas imaging and kinematics. Elmegreen will connect the observations with cosmological and accretion constraints and peripheral observations.

Turbulence and non-circular motions in the gas: Simpson will compare the non-circular motion H I maps produced by Oh (unfunded collaborator) with star formation patterns and other properties of the galaxies. Levine will provide dynamical analyses. Hunter will continue a student project examining ISM turbulence through kurtosis of H I density profiles and Probability Density Functions, and another project looking at the anti-correlation between H I column density and velocity dispersion. Simpson will use H I profile deconvolution maps to construct turbulence maps. She will compare this to star formation patterns and radial trends and look for turbulence patterns as a function of distance from star forming regions.

Stellar feedback: Simpson will use catalogues of holes in the H I to explore the effects of porosity on star formation. Elmegreen will test the Ostriker et al. (2010) model predictions of SFR(R) on the LITTLE THINGS dIrrs. Hunter will examine the relationship of star-forming region characteristics to environmental conditions and produce azimuthal-profiles around star-forming regions of gas, stars, mass, colors, and pressure.

Exponential profile breaks

Herrmann will compare the location of the breaks to H I profiles, scale-heights, and star formation drivers, search for asymmetries in the 2D images, and explore models to reproduce profile breaks. Herrmann will also reduce and analyze the PNe imaging, carry out the spectroscopy of PNe candidates, analyze their kinematics, and compare the breaks to flaring in outer disks. Simpson will determine how H I structures in outer disks compare to those in inner disks. Hunter will determine the normalized SFR interior and exterior to the breaks in dwarfs and spirals. Elmegreen will test models for what happens at the breaks.

Effects of metallicity on star formation

Rubio (unfunded collaborator) will coordinate ALMA and APEX data reductions and map making. Hunter will use the ALMA and *Herschel* data to analyze molecular cloud structure, evaluate the consequences to star formation, and examine the environmental context in which the clouds formed. Sternberg (unfunded collaborator) will provide theoretical work on the HI-to-H_2 transition at low metallicity. Elmegreen will connect the observations with star formation theory at low metallicity (c.f. Sánchez Almeida et al. 2013, 2014a, 2014b; Fiho et 2013). Young will

Table 1: Project Timeline and Effort

Grant-Date	Activity	Effort (months)	Lead People
Y1–Mid 2015	Outer disks: DCT observations, reduction procedures	12	DH
	Outer disks: Numerical modeling of stellar scattering	6	CSt,BE
	Outer disks: LARI observing continues	1	DH
	Accretion: Dragonfly observations	3	(RA)
	Accretion: GBT H I maps made, paper	3	MJ
	Turbulence: Kurtosis and PDFs of H I densities, paper	6	DH
	SF-Stars: SFing regions and environment, analysis	6	DH
	SF-Stars: Test Ostriker et al. (2010) model	6	BE
	SF-Stars: Explore the effects of porosity	6	CSi
	Breaks: PNe spectroscopy, imaging	6	KH
	Breaks: Comparison to H I, paper	12	KH
	Breaks: H I structures in outer vs inner disk, paper	12	CSi
	Metallicity: ALMA C2 observations, analysis and paper	6	MR,DH
	Metallicity: Cool H I and star formation, analysis and paper	6	LY
	Metallicity: HI-H_2 at low Z theory begins	6	AS
	Context: Simulations of dwarf evolution begins	12	AZ
Y2–Mid 2016	Outer disks: DCT observations, reductions	12	DH
	Outer disks: Stellar scattering, paper	6	CSt,BE
	Outer disks: LARI observing continues	1	DH
	Accretion: Analysis of Dragonfly and GBT data begins	12	CSi,MJ
	Turbulence: Analysis of non-circular gas motions	12	CSi,SL,SO
	Turbulence: Anti-correlation Σ_{HI}-σ_{vel}, paper	6	DH
	SF-Stars: Explore the effects of porosity, paper	6	CSi
	SF-Stars: SFing regions and environment, paper	6	DH
	SF-Stars: Test Ostriker et al. (2010) model, paper	6	BE
	Breaks: PNe spectroscopy, imaging	6	KH
	Breaks: 2D images, modeling, paper	12	KH
	Breaks: SFR interior and exterior to breaks, paper	6	DH
	Metallicity: HI-H_2 at low Z theory, paper	6	AS
	Context: Simulations of dwarf evolution continues	12	AZ
Y3–Mid 2017	Outer disks: DCT reductions finish, SED fitting	12	DH, HZ
	Outer disks: LARI paper	1	DH
	Accretion: Analysis of Dragonfly and GBT data, paper	12	CSi,MJ
	Turbulence: Analysis of non-circular gas motions	12	CSi,SL,SO
	Turbulence: maps made	12	CSi
	SF-Stars: SFing region azimuthal-profiles, analysis	12	DH
	Breaks: PNe spectroscopy, imaging	3	KH
	Breaks: Relationship to external structures, paper	12	KH
	Metallicity: Environments of clouds, paper	12	DH
	Metallicity: HI-H_2 at low Z compare with observations, paper	6	BE,AS
	Context: Simulations of dwarf evolution continues, paper	12	AZ

Table 2: Project Timeline and Effort (continued)

Grant-Date	Activity	Effort (months)	Lead People
Y4–Mid 2018	Outer disks: SFH analysis, paper	12	DH,HZ ,BE
	Outer disks: Search for young regions	12	DH
	Accretion: Cosmological context of Dragonfly and GBT, paper	6	BE,CSi
	Turbulence: Non-circular gas motions, paper	12	CSi,SL,SO
	Turbulence: Compare to star formation, paper	12	CSi
	SF-Stars: Azimuthal-profiles around SFing regions, paper	6	DH
	Breaks: PNe paper	6	KH
	Breaks: Sersic fitting scheme, paper	12	KH
	Metallicity: Affect of metallicity on star formation, paper	12	DH
	Context: Compare simulations with obs, paper	12	BE,AZ
Y5–Mid 2019	Outer disks: SFH and broader picture, paper	12	BE,DH,HZ,AZ
	Outer disks: Analysis of young regions, paper	12	DH
	Turbulence: Radial trends around SFing regions, paper	12	CSi
	Breaks: Test models for breaks, paper	12	BE
	Papers Answering the Big Questions	6	BE
Mid 2020	End		

examine the distribution of the cool atomic gas and its relationship to star formation.

Broader context

Zolotov will perform numerical simulations of dwarf galaxy formation and evolution in a cosmological context. Elmegreen will provide direction for specific activities, theoretical interpretations, and a wider context for our results.

6 Broader Impact

We will make a broad impact on science literacy in our communities as follows:

Involving high school students and undergraduates in our research

Elmegreen has a collaboration with local high schools that enable him to work with students. He has worked with 7, who have submitted their projects to the Siemens Competition in Math, Science & Technology and to the Intel Science Talent Search. At Penn State, Herrmann plans to begin involving undergraduates from her astronomy and physics classes in research projects. Lowell Observatory is involved in an NSF-funded summer REU program through Northern Arizona University (NAU). Occasionally Hunter also has winter interns through the MIT-Lowell Field Camp each January or through other connections. Hunter has worked with 26 undergraduates this way. The students work on substantial projects, carrying them to completion, publication, and dissemination at AAS meetings. Struck has a long history of working with undergraduate research students, and is currently working with a study-abroad student.

Promoting the participation of minorities in science

Most of the young people who have participated in our research are women, and some are also ethnic minorities. We expect this pattern to continue.

The Lowell Observatory Navajo-Hopi Astronomy Outreach Program, described below, shows

Native American students that science is done by people and that they too can consider science as a career. Hunter also participates in "Scientist in the Classroom" in a local middle school.

Florida International University is classified as a Hispanic Serving Institution with a total of 54,000 students. The Physics Department attracts a high percentage of underrepresented groups which puts it in an ideal position to increase the participation of minorities in the sciences. A departmental effort has led to a 2,300% increase in the number of majors (now at ∼180) as well as a 950% increase in the number of graduates (∼15/year). To achieve these results, the department launched a systematic approach to reforming the undergraduate experience, including introductory course transformations and establishing a nationally renowned Physics Education Research (PER) group. In 2007, they received funding to develop and implement the Learning Assistant (LA) program (Otero et al. 2010). Promising undergraduates are recruited and trained in interactive teaching methods, and then are hired to work in labs and classes to assist the instructor and work with the students. This peer-teaching model enhances the learning of students in the classroom, but just as importantly, it enhances the learning of the LAs as well (Goertzen et al. 2011), and increases their retention in STEM disciplines. In 2012, Simpson was awarded a Fellowship through FIU's Howard Hughes Medical Institute grant to implement interactive inquiry-based pedagogical methods into her introductory astronomy courses for non-science majors. This provided funding to incorporate two undergraduate LAs, both Physics majors pursuing Astronomy minors, in her introductory astronomy for non-science majors classroom. Mentored and guided in and outside of class by Simpson, the LAs assisted the students during in-class team-based tutorial exercises and provided outside-of-class tutoring via office hours. Pre- and post-tests were administered, and common exam questions from previous semesters (taught with traditional teaching methods) were used to measure the effect of the change in pedagogy. Analysis of the learning gains in her reformed classes is in progress. To continue this research into astronomy education, funding for support of LAs for introductory astronomy classes is requested in this proposal.

Involving amateur astronomers in our research

The"Lowell Amateur Research Initiative" (LARI) pairs amateur astronomers with Lowell astronomers in collaborative research projects. Several amateurs are working with Hunter to obtain deep white-light imaging of the LITTLE THINGS galaxies over a wide field of view in order to search for very faint companions (c.f. Martínez-Delgado et al. 2012). Seventeen systems have now been imaged, and the data have ruled out external companions currently affecting the star formation activity of those galaxies. Herrmann is involved in a local amateur astronomy club.

K-12 education

Hunter runs the Lowell Observatory Navajo-Hopi Astronomy Outreach Program, now in its 19th year, that pairs astronomers with 5th-8th grade teachers on the Navajo and Hopi Nations. They also hold bi-annual teacher workshops that introduce teachers to classroom activities and enhances their understanding of astronomy. Teachers go away energized and excited to bring astronomy to their classrooms. The 2014 AAS Education Award was granted, in part, for this program. Often pre-docs and post-docs at Lowell participate in this program, and it is likely that some funded from this proposal will join Hunter in this program. Johnson is involved in an outreach program in Sydney that is similar to the Navajo-Hopi program. She partners with a 3rd grade teacher and makes classroom visits once a month to do astronomy activities.

Sharing the excitement of our work with the public

We are all called on frequently to give talks to public groups, and we expect this to continue. For example, Hunter will be giving talks to two Girl Scout groups and to the public in Nov 2014 alone. When she was at Lowell, Herrmann frequently helped with public evenings and she is now instituting star parties at Penn State-Mont Alto. Struck also regularly gives talks to local amateur astronomy groups, including one to a multi-state gathering at the Whiterock (dark sky) Conservancy in western Iowa. A few years ago Struck published a general science book and has given a couple of outreach talks on that, including to the local community via the university library.

In addition, Discovery Communications, a global media giant, has partnered with Lowell Observatory in building the 4.3-m DCT. Discovery owns no share of DCT nor directs research done; it only uses the work done at DCT to bring science to the public, principally through the online elements of Discovery Education and the Science Channel. An interview of Hunter titled "Exploring Dwarf Galaxy Mysteries: DCT Science" appeared in online Discovery News in July 2012. There have been webcasts from regional and national science teacher conferences, as well as to Discovery Education Network schools from the telescope itself. We will exploit further opportunities as they arise.

RESULTS FROM PRIOR NSF SUPPORT

LITTLE THINGS

AST-0707563 ($1,398,638) to Hunter, AST–0707426 ($122,845) to Elmegreen, AST-0707468 ($462,807) to Simpson, and AST-0707835 ($79,975) to Young funded "Collaborative Research: Star Formation in Subcritical Environments" June 2007-May 2012.

Intellectual Merit

We have 11 published refereed articles: Elmegreen & Hunter 2010, Heesen et al. 2011, Elmegreen et al. 2012, 2013, Zhang et al. 2012a, 2012b, Hunter et al. 2012, Johnson et al. 2012, Johnson 2013, Herrmann et al. 2013, Ashley et al. 2013. Three more are in press (Ashley et al. 2014, Heesen et al. 2014, Kitchener et al. 2014), one is in the refereeing stage (Johnson et al. 2014), and 8 more are close to being submitted, as well as 3 PhD dissertations nearing completion (Ficut-Vicas, Kitchener, Cigan). These products cover a large variety of science, but include the following results: 1) Even tiny irregular galaxies have formed regular stellar exponential disks to very low stellar surface brightness levels ($\mu_V = 29.5$ mag/arcsec^2). However, abrupt changes in the slope of the exponential stellar surface brightness profiles are common, but the breaks are found on average twice as close to the center in radius as in spirals. The breaks in both dwarfs and spirals occur at the same V-band surface brightness, suggesting common evolutionary processes. Surprisingly, star-formation in most dIrr galaxies appear to be shrinking in radius with time, opposite to the inside-out growth of spirals (see §1). 2) We detected CO in a galaxy with 13% of solar abundance, and in doing so, broke the metallicity barrier to CO detections. 3) Inner disks have proportionally more cooler H I than outer disks. 4) Either non-stellar power sources are playing a fundamental role in driving ISM turbulence in dIrrs or the nonlinear development of turbulent structures has little to do with the driving sources. 5) BCDs are likely the result of interactions or dwarf-dwarf mergers. NGC 1569 appears to have been hit by a giant gas cloud. The giant star-forming clumps in BCDs are high enough that dynamical friction should bring them and other gas into the center in about 1 Gyr. This can produce the observed central concentration and feed a long-lived starburst. 6) Magnetic field in dIrrs lacks a strong large-scale component.

Broader Impact

LITTLE THINGS involved 8 senior astronomers, 3 graduate students currently doing dissertations (Cigan, Ficut-Vicas, Kitchener), 3 completed PhD dissertations (Ashley, Johnson, Zhang), and 3 post-docs (Heesen, Herrmann, Oh). Nine undergraduates and two high school students were involved in related research projects. Of these people, 14 (48%) are women, a minority in astronomy; 2 (7%) are ethnic minorities.

We produced a first-class data set that is timeless in its usefulness. We invested 4.25 years resolving problems in the data reduction and producing H I maps, and we shared this knowledge with other teams: 1) aliasing into the lower 500 kHz of the bandpass caused by the mixture of VLA and EVLA technology, and 2) using Multi-Scale CLEAN for imaging as first-generation users. We made the final map cubes, moment maps, and ancillary imaging available to the public February 2012 on an NRAO web site. Higher level analysis products will also populate the site.

At the Jan 2012 AAS meeting we held an oral and poster Special Session "The LITTLE THINGS Survey." In June 2012 Lowell Observatory hosted a workshop "Star Formation in Dwarf Galaxies" attended by 81 astronomers from around the world. The team presented 31 talks and 25 posters at international meetings and US institutions. We gave 16 public talks, and many more that were not LITTLE THINGS specific. Hunter, Herrmann, and Johnson participated in the Lowell Observatory Navajo-Hopi Astronomy Outreach Program. Simpson gave a talk on unconscious biases in hiring practices at the Jan 2012 AAS meeting. PhD dissertations were completed by Johnson (Georgia State Univ and Lowell Obs, Aug 2011), Zhang (Purple Mountain Obs and Lowell Obs, May 2012), and Ashley (Florida International University, May 2014).

STRUCK

AST-1311935 ($133,715) to B. J. Smith funded "Beads, Knots, and Gems: Star Formation Processes in Interacting Galaxies" 9/1/2013 - 8/31/2016.

Intellectual Merit

Struck is an unpaid collaborator who will work on semi-analytic models of the interacting galaxy sample. He will also help to understand the star formation morphology and history.

Broader Impact

Mergers and interactions are one of the most important processes in galaxy evolution. Understanding how star formation is generated in interactions, is relevant to a wide range of problems in astrophysical cosmology.

Section D: REFERENCES CITED

Abraham, R. G., & van Dokkum, P. 2014, "Ultra Low Surface Brightness Imaging with the Dragonfly Telephoto Array, " PASP, in press
http://arxiv.org/abs/1401.5473

Ashley, T., Elmegreen, B. G., Megan, J., Nidever, D. L., Simpson, C. E., & Pokhrel, N. J., 2014, "The HI Chronicles of LITTLE THINGS BCDs II: The Origin of IC 10's HI Structure," AJ, in press
http://adsabs.harvard.edu/abs/2014arXiv1409.5406A

Ashley, T., Simpson, C. E., & Elmegreen, B. G. 2013, "The H I Chronicles of LITTLE THINGS BCDs: Evidence for External Perturbations in the Morphology and Kinematics of Haro 29 and Haro 36," AJ, 146, 42, 17 pp.
http://adsabs.harvard.edu/abs/2013AJ....146...42A

Bakos, J., Trujillo, I., & Pohlen, M. 2008, ApJ, 683, L103-L106.
http://adsabs.harvard.edu/abs/2008ApJ...683L.103B

Barker, M. K., Ferguson, A. M. N., Irwin, M. J., Arimoto, N., & Jablonka, P. 2012, "Quantifying the faint structure of galaxies: the late-type spiral NGC 2403," MNRAS, 419, 1489-1506. http://adsabs.harvard.edu/abs/2012MNRAS.419.1489B

Barton, I. J., & Thompson, L. A. 1997, "Deep Surface Photometry of Spiral Galaxy NGC 5383: Observational Techniques and Halo Constraints," AJ, 114, 655-668.
http://adsabs.harvard.edu/abs/1997AJ....114..655B

Bell, E. F., & de Jong, R. S. 2001, "Stellar Mass-to-Light Ratios and the Tully-Fisher Relation," ApJ, 550, 212-229. http://iopscience.iop.org/0004-637X/550/1/212/

Bigiel, F., Leroy, A., Walter, F., Brinks, E., de Blok, W. J. G., Madore, B., & Thornley, M. D. 2008, "The Star Formation Law in Nearby Galaxies on Sub-Kpc Scales," AJ, 136, 2846-2871. http://adsabs.harvard.edu/abs/2008AJ....136.2846B

Billett, O. H., Hunter, D. A., & Elmegreen, B. G. 2002, "Compact Star Clusters in Nearby Irregular Galaxies," AJ, 123, 1454-1475.
http://adsabs.harvard.edu/abs/2002AJ....123.1454B

Binggeli, B., & Popescu, C. C. 1995, "Dwarf galaxies in the Virgo cluster III. Flattening distributions," A&A, 298, 63-76

Bland-Hawthorn, J., Vlajić, M., Freeman, K. C., & Draine, B. T. 2005, "NGC 300: An Extremely Faint, Outer Stellar Disk Observed to 10 Scale Lengths." ApJ, 629, 239-249. http://adsabs.harvard.edu/abs/2005ApJ...629..239B

Bolatto, A. D., Leroy, A. K., Jameson, K., Ostriker, E., Gordon, K., Lawton, B., Stanimirović, S., Israel, F. P., Madden, S. C., Hony, S., Sandstrom, K. M., Bot, C., Rubio, M., Winkler, P. F., Roman-Duval, J., van Loon, J. Th., Oliveira, J. M., & Indebetouw, R. 2011, "The State of the Gas and the Relation between Gas and Star Formation at Low Metallicity: The Small Magellanic Cloud," ApJ, 741, 12-30

Bournaud, F., Elmegreen, B. G., & Elmegreen, D. M. 2007b, "Rapid Formation of Exponential Disks and Bulges at High Redshift from the Dynamical Evolution of Clump-Cluster and Chain Galaxies," ApJ, 670, 237-248.
http://adsabs.harvard.edu/abs/2007ApJ...670..237B

Ciardullo, R., Feldmeier, J. J., Jacoby, G. H., Kuzio de Naray, R., Laychak, M. B., & Durrell, P. R. 2002, "Planetary Nebulae as Standard Candles. XII. Connecting the Population I and Population II Distance Scales," ApJ, 577, 31-50

Dalcanton, J. J., Williams, B. F., Seth, A. C., Dolphin, A., Holtzman, J., Rosema, K.,

Skillman, E. D., Cole, A., Giradi, L., Gogarten, S. M., Karachentsev, I. D., Olsen, K., Weisz, D., Christensen, C., Freeman, K., Gilbert, K., Gallart, C., Harris, J., Hodge, P., de Jong, R. S., Karachentseva, V., Mateo, M., Stetson, P. B., Tavarez, M., Zaritsky, D., Governato, F., & Quinn, T. 2009, ApJS, 183, 67-108.
http://adsabs.harvard.edu/abs/2009ApJS..183...67D

Debattista V. P., Mayer L., Carollo C. M., Moore B., Wadsley J., & Quinn T., 2006, "The Secular Evolution of Disk Structural Parameters," ApJ, 645, 209-227.
http://adsabs.harvard.edu/abs/2006ApJ...645..209D

Dohm-Palmer, R. C., Skillman, E. D., Gallagher, J., Tolstoy, E., Mateo, M., Dufour, R. J., Saha, A., Hoessel, J., & Chiosi, C. 1998, "The Recent Star Formation History of GR 8 from Hubble Space Telescope Photometry of the Resolved Stars," AJ, 116, 1227-1243.
http://adsabs.harvard.edu/abs/1998AJ....116.1227D

Efstathiou, G. 2000, "A model of supernova feedback in galaxy formation," MNRAS, 317, 697-719.
http://adsabs.harvard.edu/abs/2000MNRAS.317..697E

Einasto, J., Saar, E., Kaasik, A., & Chernin, A. D. 1974, "Missing mass around galaxies - Morphological evidence," Nature, 252, 111-113.
http://adsabs.harvard.edu/abs/1974Natur.252..111E

Elmegreen, B. G., & Hunter, D. A. 2010, "On the Disruption of Star Clusters in a Hierarchical Interstellar Medium," ApJ, 712, 604-623.
http://adsabs.harvard.edu/abs/2010ApJ...712..604E

Elmegreen, B. G. & Hurst, R. 2013, "A Density Dependence for Protostellar Mass in Class I Sources," ApJL, submitted October 2013

Elmegreen, B. G., Rubio, M., Hunter, D. A., Verdugo, C., & Brinks, E. 2013, "Carbon Monoxide in the WLM Galaxy: Breaking the Metallicity Barrier," Nature, 495, 487-489. http://adsabs.harvard.edu/abs/2013Natur.495..487E

Elmegreen, B. G. & Struck, C. 2013, "Exponential Galaxy Disks from Stellar Scattering," ApJ, 775, L35, 5 pp. http://adsabs.harvard.edu/abs/2013ApJ...775L..35E

Elmegreen, B. G., Zhang, H.-X., & Hunter, D. A. 2012, "In-spiraling Clumps in Blue Compact Dwarf Galaxies," ApJ, 746, 105, 9 pp.

Ferguson, A. M. N., & Clarke, C. J. 2001, "The evolution of stellar exponential discs," MNRAS, 325, 781-791.
http://adsabs.harvard.edu/abs/2001MNRAS.325..781F

Filho, M. E., Winkel, B., Sánchez Almeida, J., Aguerri, J. A., Amorín, R., Ascasibar, Y., Elmegreen, B. G., Elmegreen, D. M., Gomes, J. M., Humphrey, A., Lagos, P., Morales-Luis, A. B., Muñoz-Tuñón, C., Papaderos, P., & Vílchez, J. M. 2013, "Extremely metal-poor galaxies: The H I content," A&A, 558, 18, 30 pp.
http://adsabs.harvard.edu/abs/2013A%26A...558A..18F

Finlator, K., & Davé, R. 2008, "The origin of the galaxy mass-metallicity region and implications for galactic outflows," MNRAS, 2181-2204.
http://adsabs.harvard.edu/abs/2008MNRAS.385.2181F

Firmani, C., Hernandez, X., & Gallagher, J. 1996, "Viscous models for slowly evolving galactic disks," A&A, 308, 403-414.
http://adsabs.harvard.edu/abs/1996A%26A...308..403F

Forbes, J. C., Krumholz, M. R., Burkert, A., & Dekel, A. 2014, "Balance among gravitational instability, star formation and accretion determines the structure and evolution of disc galaxies," MNRAS, 438, 1552-1576

http://adsabs.harvard.edu/abs/2014MNRAS.438.1552F
Foyle, K., Courteau, S., & Thacker, R. J. 2008, "An N-body/SPH study of isolated galaxy mass density profiles," MNRAS, 386, 1821-1844.
http://adsabs.harvard.edu/abs/2008MNRAS.386.1821F
Freeman, K. C. 1970, "On the Disks of Spiral and so Galaxies," ApJ, 160, 811-830.
http://adsabs.harvard.edu/abs/1970ApJ...160..811F
Geha, M., Willman, B., Simon, J. D., Strigari, L. E., Kirby, E. N., Law, D. R., & Strader, J. 2009, "The Least-Luminous Galaxy: Spectroscopy of the Milky Way Satellite Segue 1," ApJ, 692, 1464-1475. http://adsabs.harvard.edu/abs/2009ApJ...692.1464G
Goertzen, R. M., Brewe, E., Kramer, L. Hl, Wells, L., & Jones, D. 2011, "Moving toward change: Institutionalizing Reform through Implementation of the Learning Assistant Model and Open Source Tutorials," Physical Review Special Topics-Physics Education Research, 7, 020105, 9 pp., DOI:10.1103/PhysRevSTPER.7.020105
Gonçalves, D. R., Teodorescu, A. M., Alves-Brito, A., Méndez, R. H., & Magrini, L. 2012, "A kinematic study of planetary nebulae in the dwarf irregular galaxy IC10," MNRAS, 425, 2557-2566
Grogin, N. A., & Geller, M. J. 2000, "An Imaging and Spectroscopic Survey of Galaxies within Prominent Nearby Voids. II. Morphologies, Star Formation, and Faint Companions," AJ, 119, 32-43. http://adsabs.harvard.edu/abs/2000AJ....119...32G
Grossi, M., Hwang, N., Corbelli, E., Giovanardi, C., Okamoto, S., & Arimoto, N. 2011, "Stellar structures in the outer regions of M 33," A&A, 533, 91,13 pp.
http://adsabs.harvard.edu/abs/2011A%26A...533A..91G
Heesen, V., Rau, U., Rupen, M. P., Brinks, E., & Hunter, D. A. 2011, "Deep Radio Continuum Imaging of the Dwarf Irregular Galaxy IC 10: Tracing Star Formation and Magnetic Fields," ApJL, 739, L23, 5 pp.
http://adsabs.harvard.edu/abs/2011ApJ...739L..23H
Heesen, V., Brinks, E., Krause, M. G. H., Harwood, J. J., Rau, U., Rupen, M. P., Hunter, D. A., Chyży, K. T., & Kitchener, G. 2014, "The non-thermal superbubble in IC 10: the generation of Cosmic Ray electrons caught in the act," MNRAS, in press
Herrmann, K. A., & Ciardullo, R. 2009, "Planetary Nebulae in Face-On Spiral Galaxies. III. Planetary Nebula Kinematics and Disk Mass," ApJ, 705, 1686-1703
Herrmann, K. A., Hunter, D. A., & Elmegreen, B. G. 2013, "Surface Brightness Profiles of Dwarf Galaxies: I. Profiles and Statistics," AJ, 146, 104, 24 pp.
http://adsabs.harvard.edu/abs/2013AJ....146..104H
Hodge, P. W., & Hitchcock, J. L. 1966, "The Three-Dimensional Shape of Irregular Galaxies," PASP, 78, 79-80
Hohl, F. 1971, "Numerical Experiments with a Disk of Stars," ApJ, 168, 343-359.
http://adsabs.harvard.edu/abs/1971ApJ...168..343H
Hunter, D. A., & Elmegreen, B. G. 2004, "Star formation properties of a large sample of irregular galaxies," AJ, 128, 2170-2205.
http://adsabs.harvard.edu/abs/2004AJ....128.2170H
Hunter, D. A., & Elmegreen, B. G. 2006, "Broad-Band Imaging of a Large Sample of Irregular Galaxies," ApJS, 162, 49-79. http://adsabs.harvard.edu/abs/2006ApJS..162...49H
Hunter, D. A., Elmegreen, B. G., & Baker, A. L. 1998, "The Relationship between Gas, Stars, and Star Formation in Irregular Galaxies: A Test of Simple Models," ApJ, 493, 595-612. http://adsabs.harvard.edu/abs/1998ApJ...493..595H
Hunter, D. A., & Elmegreen, B. G., & Ludka, B. C. 2010, "*GALEX* ultaviolet imaging of

dwarf galaxies and star formation rates," AJ, 139, 447-475.
http://adsabs.harvard.edu/abs/2010AJ....139..447H

Hunter, D. A., Elmegreen, B. G., & Martin, E. 2006, "Mid-Infrared Images of Stars and Dust in Irregular Galaxies," AJ, 132, 801-818.
http://adsabs.harvard.edu/abs/2006AJ....132..801H

Hunter, D. A., Elmegreen, B. G., Oh, S.-H., Anderson, E., Nordgren, T. E., Massey, P., Wilsey, N., & Riabokin, M. 2011, "The Outer Disks of Dwarf Irregular Galaxies," AJ, 142, 121, 26 pp. http://adsabs.harvard.edu/abs/2011AJ....142..121H

Hunter, D. A., Elmegreen, B. G., Rubin, V. C., Ashburn, A., Wright, T., Józsa, G. I. G., & Struve, C. 2013, "Star Formation in Two Luminous Spiral Galaxies," AJ, 2013, 146, 92, 15 pp. http://adsabs.harvard.edu/abs/2013AJ....146...92H

Hunter, D. A., Ficut-Vicas, D., Ashley, T., Brinks, E., Cigan, P., Elmegreen, B. G., Heesen, V., Herrmann, K. A., Johnson, M., Oh, S.-H., Rupen, M. P., Schruba, A., Simpson. C. E., Walter, F., Westpfahl, D. J., Young, L. M., & Zhang, H.-X. 2012, "LITTLE THINGS," AJ, 144, 134, 29 pp.
http://iopscience.iop.org/1538-3881/144/5/134/pdf/1538-3881_144_5_134.pdf

Johnson, M. 2013, "Determining the Nature of the Extended H I Structure around LITTLE THINGS Dwarf Galaxy NGC 1569," AJ, 145, 146, 16pp.
http://adsabs.harvard.edu/abs/2013AJ....145..146J

Johnson, M., Hunter, D. A., Oh, S.-H., Zhang, H.-X., Elmegreen, B. G., Brinks, E., Tollerud, E., & Herrmann, K. A. 2012, "The Stellar and Gas Kinematics of the LITTLE THINGS Dwarf Irregular Galaxy NGC 1569," AJ, 144, 152, 22 pp.
http://iopscience.iop.org/1538-3881/144/5/152/

Johnson, M., Hunter, D., Wood, S., Oh, S.-H., Zhang, H.-X., Herrmann, K. A., & Levine, S. E. 2014, "The shape of LITTLE THINGS dwarf galaxies DDO 46 and DDO 168: Understanding the stellar and gas kinematics," AJ, submitted

Kennicutt, R. C., Jr. 1989, "The star formation law in galactic disks," ApJ, 344, 685-703

Kruijssen, J. M. D., Pelupessy, F. I., Lamers, H. J. G. L. M., Portegies Zwart, S. F., & Icke, V. 2011, "Modelling the formation and evolution of star cluster populations in galaxy simulations," MNRAS, 414, 1339-1364.
http://adsabs.harvard.edu/abs/2011MNRAS.414.1339K

Krumholz, M. R. 2012, "Star Formation in Atomic Gas," ApJ, 759, 9, 9 pp.
http://adsabs.harvard.edu/abs/2012ApJ...759....9K

Larson, R. B. 1981, "Turbulence and star formation in molecular clouds," MNRAS, 194, 809-826.
http://adsabs.harvard.edu/abs/1981MNRAS.194..809L

Lee, J. C., Kennicutt, R. C., Funes, S. J., José G., Sakai, S., & Akiyama, S. 2007, "The Star Formation Demographics of Galaxies in the Local Volume," ApJ, 671, L113-L116

Lin D. N. C., & Pringle J. E., 1987, "The formation of the exponential disk in spiral galaxies," ApJL, 320, L87-L91. http://adsabs.harvard.edu/abs/1987ApJ...320L..87L

Minchev, I., Famaey, B., Quillen, A.C., Di Matteo, P. Combes, F., Vlajić, M., Erwin, P., & Bland-Hawthorn, J. 2012, "Evolution of galactic discs: multiple patterns, radial migration, and disc outskirts," A&A, 548, 126, 24 pp
http://adsabs.harvard.edu/abs/2012A%26A...548A.126M

Martínez-Delgado, D., Romanowsky, A. J., Gabany, R. J., Annibali, F., Arnold, J.b A., Fliri, J., Zibetti, S., van der Marel, R. P., Rix, H.-W., Chonis, T. S., Carballo-Bello, J. A., Aloisi, A., Macciò, A. V., Gallego-Laborda, J., Brodie, J. P., & Merrifield, M. R. 2012, “Dwarfs Gobbling Dwarfs: A Stellar Tidal Stream around NGC 4449 and Hierarchical Galaxy Formation on Small Scales,” ApLJ, 748, L24, 6pp. http://adsabs.harvard.edu/abs/2012ApJ...748L..24M

Mayer, L., Kazantzidis, S., Mastropietro, C., Wadsley, J. 2007, “Early gas stripping as the origin of the darkest galaxies in the Universe,” Nature, 445, 738-740. http://adsabs.harvard.edu/abs/2007Natur.445..738M

McConnachie, A. W., Ferguson, A. M. N.,, Irwin, M. J., Dubinski, J., Widrow, L. M., Dotter, A., Ibata, R., & Lewis, G. F. 2010, “The Photometric Properties of a Vast Stellar Substructure in the Outskirts of M33,” ApJ, 723, 1038-1052. http://adsabs.harvard.edu/abs/2010ApJ...723.1038M

McQuinn, K. B. W., Skillman, E. D., Cannon, J. M., Dalcanton, J., Dolphin, A., Hidalgo-Rodríguez, S., Holtzman, J., Stark, D., Weisz, D., & Williams, B. 2010, “The Nature of Starbursts. II. The Duration of Starbursts in Dwarf Galaxies,” ApJ, 724, 49-58. http://adsabs.harvard.edu/abs/2010ApJ...724...49M

Melena, N. W., Elmegreen, B. G., Hunter, D. A., & Zernow, L. 2009, “Bright Ultraviolet Regions and Star Formation Characteristics in Nearby Dwarf Galaxies,” AJ, 138, 1203-1229. http://adsabs.harvard.edu/abs/2009AJ....138.1203M

Nidever, D., Ashley, T., Slater, C. T., Ott, J., Johnson, M., Bell, E. F., Stanimirović S., Putman, M., Majewski, S. R., Simpson, C., Burton, W. B. 2013 “Evidence for an Interaction in the Nearest Starbursting Dwarf Irregular Galaxy IC 10,” ApJL, submitted

Oh, S.-H., Brook, C., Governato, F., Brinks, E., Mayer, L., de Blok, W. J. G., Brooks, A., & Walter, F. 2011, “The Central Slope of Dark Matter Cores in Dwarf Galaxies: Simulations versus THINGS,” AJ, 142, 24, 12 pp. http://adsabs.harvard.edu/abs/2011AJ....142...24O

Oosterloo, T. A., Heald, G. H., & de Blok, W. J. G. 2013, “Is GBT 1355+5439 a dark galaxy?,” A&A, 555, L7, 4 pp. http://adsabs.harvard.edu/abs/2013A%26A...555L...7O

Ostriker, E.C., McKee, C.F., & Leroy, A.K. 2010, “Regulation of Star Formation Rates in Multiphase Galactic Disks: A Thermal/Dynamical Equilibrium Model,” ApJ, 721, 975-994. http://adsabs.harvard.edu/abs/2010ApJ...721..975O

Otero, V., Pollock, S., & Finkelstein, N. 2010, “A Physics Departments Role in Preparing Physics Teachers: The Colorado Learning Assistant Model,” American Journal of Physics, 78, 1218, http://dx.doi.org/10.1119/1.3471291

Pichon, C., Pogosyan, D., Kimm, T., Slyz, A., Devriendt, J., & Dubois, Y. 2011, “Rigging dark haloes: why is hierarchical galaxy formation consistent with the inside-out build-up of thin discs?” MNRAS, 418, 2493-2507. http://adsabs.harvard.edu/abs/2011MNRAS.418.2493P

Piontek, R. A., & Ostriker, E. C. 2005, “Saturated-state Turbulence and Structure from Thermal and Magnetorotational Instability in the ISM: Three-Dimensional Numerical Simulations,” ApJ, 629, 849-864

Pustilnik, S. A., Kniazev, A. Y., Lipovetsky, V. A., & Ugryumov, A. V. 2001, “Environment status of blue compact galaxies and trigger of star formation,” A&A, 373, 24-37. http://adsabs.harvard.edu/abs/2001A%26A...373...24P

Radburn-Smith, D. J., Roškar, R., Debattista, V. P., Dalcanton, J. J., Streich, D., de Jong, R. S., Vlajić, M., Holwerda, B. W., Purcell, C. W., Dolphin, A. E., & Zucker, D. B. 2012, “Outer-disk Populations in NGC 7793: Evidence for Stellar Radial Migration,” ApJ, 753, 138, 8 pp. http://adsabs.harvard.edu/abs/2012ApJ...753..138R

Reid, W. A., & Parker, Q. A. 2013, "A New Population of Planetary Nebulae Discovered in the Large Magellanic Cloud (IV): The Outer LMC," 2013, MNRAS, 436, 604-624. http://adsabs.harvard.edu/abs/2013MNRAS.436..604R

Richards, S. N. Schaefer, A. L., López-Sánchez, Á. R., Croom, S. M., Bryant, J. J., Sweet, S. M., Konstantopoulos, I. S., Allen, J. T., Bland-Hawthorn, J., Bloom, J. V., Brough, S., Fogarty, L. M. R., Goodwin, M., Green, A. W., Ho, I.-T., Kewley, L. J., Koribalski, B. S., Lawrence, J. S., Owers, M. S., Sadler, E. M., & Sharp, R. 2014, "The SAMI Galaxy Survey: the discovery of a luminous, low-metallicity H II complex in the dwarf galaxy GAMA J141103.98-003242.3," MNRAS, 445, 1104-1113. http://adsabs.harvard.edu/abs/2014MNRAS.445.1104R

Roškar, R., Debattista, V. P., Quinn, T. R., Stinson, G. S., & Wadsley, J. 2008, ApJ, 684, L79-L82. http://adsabs.harvard.edu/abs/2008ApJ...684L..79R

Saha, A., Olszewski, E. W., Brondel, B., Olsen, K., Knezek, P., Harris, J., Smith, C., Subramaniam, A., Claver, J., Rest, A. Seitzer, P., Cook, K. H., Minniti, D., & Suntzeff, N. B. 2010, "First Results from the NOAO Survey of the Outer Limits of the Magellanic Clouds," AJ, 140, 1719-1738

Sánchez Almeida, J., Elmegreen, B. G., Muñoz-Tuñón, C., Elmegreen, D. M. 2014a, "Star formation sustained by gas accretion," A&AR, 22, 71 http://adsabs.harvard.edu/abs/2014A%26ARv..22...71S

Sánchez Almeida, J., Morales-Luis, A.B., Muñoz-Tu nón, C., Elmegreen, D. M., Elmegreen, B.G., Méndez-Abreu. J. 2014b, "Metallicity Inhomogeneities in Local Star-forming Galaxies as a Sign of Recent Metal-poor Gas Accretion," ApJ 783, 45, 9 pp. http://adsabs.harvard.edu/abs/2014ApJ...783...45S

Sánchez Almeida, J., Muñoz-Tuñón, C., Elmegreen, D. M., Elmegreen, B. G., & Méndez-Abreu, J. 2013, " Local Tadpole Galaxies: Dynamics and Metallicity," ApJ, 767, 74, 15 pp. http://adsabs.harvard.edu/abs/2013ApJ...767...74S

Schaye, J. 2004, "Star Formation Thresholds and Galaxy Edges: Why and Where," ApJ, 609, 667-682

Schruba, A., Leroy, A. K., Walter, F., Bigiel, F., Brinks, E., de Blok, W. J. G., Kramer, C., Rosolowsky, E., Sandstrom, K., Schuster, K., Usero, A., Weiss, A., & Wiesemeyer, H. 2012, "Low CO Luminosities in Dwarf Galaxies," AJ, 143, 138, 18 pp. http://adsabs.harvard.edu/abs/2012AJ....143..138S

Sellwood, J. A., & Binney, J. J. 2002, "Radial mixing in galactic discs," MNRAS, 336, 785-796. http://adsabs.harvard.edu/abs/2002MNRAS.336..785S

Shi, Y., Helou, G., Yan, L., Armus, L., Wu, Y., Papovich, C., & Stierwalt, S. 2011, "Extended Schmidt Law: Role of Existing Stars in Current Star Formation," ApJ, 733, 87, 15 pp. http://adsabs.harvard.edu/abs/2011ApJ...733...87S

Steinmetz, M., & Navarro, J. F. 2002, "The hierarchical origin of galaxy morphologies," New Astronomy, 7, 155-160. http://www.sciencedirect.com/science/article/pii/S1384107602001021

Sung, E.-C., Han, C., Ryden, B. S., Patterson, R. J., Chun, M.-S., Kim, H.-I., Lee, W.-B., & Kim, D.-J. 1998, "The Intrinsic Shapes of Low Surface Brightness Dwarf Irregular Galaxies and Comparison to Other Types of Dwarf Galaxies," ApJ, 505, 199-206. http://adsabs.harvard.edu/abs/1998ApJ...505..199S

Thilker, D. A., Bianchi, L., Boissier, S., Gil de Paz, A., Madore, B. F., Martin, D. C., Meurer,

G. R., Neff, S. G., Rich, R. M., Schiminovich, D., Seibert, M., Wyder, T. K., Barlow, T. A., Byun, Y.-I., Donas, J., Forster, K., Friedman, P. G., Heckman, T.M., Jelinsky, P. N., Lee, Y.-W., Malina, R. F., Milliard, B., Morrissey, P., Siegmund, O. H. W., Small, T., Szalay, A. S., Welsh, B. Y. 2005, "Recent Star Formation in the Extreme Outer Disk of M83," ApJ, 619, L79-L82
http://adsabs.harvard.edu/abs/2005ApJ...619L..79T

Toomre, A. 1964, "On the gravitational stability of a disk of stars," ApJ, 139, 1217-1238.
http://adsabs.harvard.edu/abs/1964ApJ...139.1217T

van den Bergh, S. 1988, "Inclinations and axial ratios of spiral and irregular galaxies," PASP, 100, 344-345

Verbeke, R., De Rijcke, S., Koleva, M., Cloet-Osselaer, A., Vandenbroucke, B., & Schroyen, J. 2014, "Gaseous infall triggering starbursts in simulated dwarf galaxies," MNRAS, 442, 1830-1843.
http://adsabs.harvard.edu/abs/2014MNRAS.442.1830V

Vlajić, M., Bland-Hawthorn, J., & Freeman, K. C. 2011, "The Structure and Metallicity Gradient in the Extreme Outer Disk of NGC 7793," ApJ, 732, 7, 10 pp.
http://adsabs.harvard.edu/abs/2011ApJ...732....7V

Walter, F., Brinks, E., de Blok, W. J. G., Bigiel, F., Kennicutt, R. C., Jr., Thornley, M. D., & Leroy, A. 2008, "THINGS: The H I Nearby Galaxy Survey," AJ, 136, 2463-2647

Wang, J.-M., Yan, C.-S., Li, Y.-R., Chen, Y.-M., Xiang, F., Hu, C., Ge, J.-Q., & Zhang, S. 2009, "Evolution of Gaseous Disk Viscosity Driven by Supernova Explosions in Star-Forming Galaxies at High Redshift," ApJL, 701, L7-L11.
http://adsabs.harvard.edu/abs/2009ApJ...701L...7W

Weiner, B. J., Williams, T. B., van Gorkom, J. H., & Sellwood, J. A. 2001, "The Disk and Dark Halo Mass of the Barred Galaxy NGC 4123. I. Observations," ApJ, 546, 916-930.
http://adsabs.harvard.edu/abs/2001ApJ...546..916W

Weisz, D. R., Zucker, D. B., Dolphin, A. E., Martin, N. F., de Jong, J. T. A., Holtzman, J. A., Dalcanton, J. J., Gilbert, K. M., Williams, B. F., Bell, E. F., Belokurov, V., & Evans, N. W. 2012, "The Star Formation History of Leo T from *Hubble Space Telescope* Imaging," ApJ, 748, 88, 6 pp. http://iopscience.iop.org/0004-637X/748/2/88

Wilcots, E. M., & Miller, B. W. 1998, "The Kinematics and Distribution of H I in IC 10," AJ, 116, 2363-2394.
http://adsabs.harvard.edu/abs/1998AJ....116.2363W

Yoachim, P., Roökar, R., Debattista, V.P. 2012, "Spatially Resolved Spectroscopic Star Formation Histories of nearby Disks: Hints of Stellar Migration," ApJ, 752, 97, 21 pp.
http://adsabs.harvard.edu/abs/2012ApJ...752...97Y

Yoshii, Y., & Sommer-Larsen, J. 1989, "On the formation of exponential discs," MNRAS, 236, 779-799.
http://adsabs.harvard.edu/abs/1989MNRAS.236..779Y

Younger, J. D., Cox, T. J., Seth, A. C., & Hernquist, L. 2007, "Antitruncated Stellar Disks via Minor Mergers," ApJ, 670, 269-278.
http://adsabs.harvard.edu/abs/2007ApJ...670..269Y

Zaritsky, D., Salo, H., Laurikainen, E., Elmegreen, D., Athanassoula, E., Bosma, A., Comerón, S., Erroz-Ferrer, S., Elmegreen, B., Gadotti, D. A., Gil de Paz, A., Hinz, J. L., Ho, L. C., Holwerda, B. W., Kim, T., Knapen, J. H., Laine, J., Laine, S., Madore, B. F., Meidt, S., Menendez-Delmestre, K., Mizusawa, T., Muoz-Mateos, J. C., Regan, M. W., Seibert, M., Sheth, K. 2013, "On the Origin of Lopsidedness in Galaxies as

Determined from the Spitzer Survey of Stellar Structure in Galaxies (S4G)," ApJ, 772, 135, 16 pp. http://adsabs.harvard.edu/abs/2013ApJ...772..135Z

Zhang, H.-X., Hunter, D. A., Elmegreen, B. G., Gao, Y., & Schruba, A. 2012a, "Outside-In shrinking of the star-forming disk of dwarf irregular galaxies," AJ, 143, 47, 27 pp, http://iopscience.iop.org/1538-3881/143/2/47/pdf/aj_143_2_47.pdf

Zhang, H.-X., Hunter, D. A., & Elmegreen, B. G. 2012b, "H I Power Spectra and the Turbulent Interstellar Medium of Dwarf Irregular Galaxies," ApJ, 754, 29, 14 pp, http://iopscience.iop.org/0004-637X/754/1/29/pdf/apj_754_1_29.pdf

Zolotov, A., Brooks, A.M., Willman, B., Governato, F., Pontzen, A., Christensen, C., Dekel, A., Quinn, T., Shen, S., & Wadsley, J. 2012, "Baryons Matter: Why Luminous Satellite Galaxies Have Reduced Central Masses," ApJ, 761, 71, 13 pp. http://adsabs.harvard.edu/abs/2012ApJ...761...71Z

Zolotov, A., Willman, B., Brooks, A. M., Governato, F., Brook, C. B., Hogg, D. W., Quinn, T., & Stinson, G. 2009, "The Dual Origin of Stellar Halos," ApJ, 702, 1058-1067. http://adsabs.harvard.edu/abs/2009ApJ...702.1058Z