Section A: PROJECT SUMMARY

Overview:

Intellectual Merit:

Broader Impact:

PROJECT DESCRIPTION
RIDDLE: Revealing Irregular Dwarf Disks at Luminosity Extremes

1 Dwarf Irregular Galaxies Stress the Paradigms

Stellar exponential disks are ubiquitous in the nearby universe. The usual interpretations for this structure, such as specific angular momentum conservation during cosmic collapse, stellar scattering in bars, and star formation at the viscous rate (e.g. Freeman 1970, Hohl 1971, Foyle et al. 2008, Lin & Pringle 1987, 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). How do they produce and maintain such extended 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. 2007) and today's dwarfs.

However, dwarfs are not just little spirals. Dwarfs differ from spirals in their color profiles. We 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 (Zhang et al. 2012a; also Meschin et al. 2014). This is in contrast to spirals with down-bending outer exponentials (Type II), which decrease in age with radius until the break radius (inside-out growth; Muñoz-Mateos et al. 2007). Beyond the break radius, the age increases presumably because of old scattered stars (Bakos et al. 2008, Roškar et al. 2008a).

Also, star formation in general in dIrrs is difficult to understand, but this is particularly true 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 (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, especially in Blue Compact Dwarfs (BCDs) that we have mapped with both the Very Large Array (VLA, pre-JVLA) and Green Bank Telescope (GBT; e.g. Johnson 2013, Ashley et al. 2014). Thus, interaction-triggered star formation may be important in some, but not all, dwarfs (Stierwalt et al. 2014, Verbeke et al. 2014).

In this proposal we tackle the problem of how dIrr disks 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 obtain new data on 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 break the current paradigms of disk evolution and star formation to the benefit of our understanding of all disk galaxies.

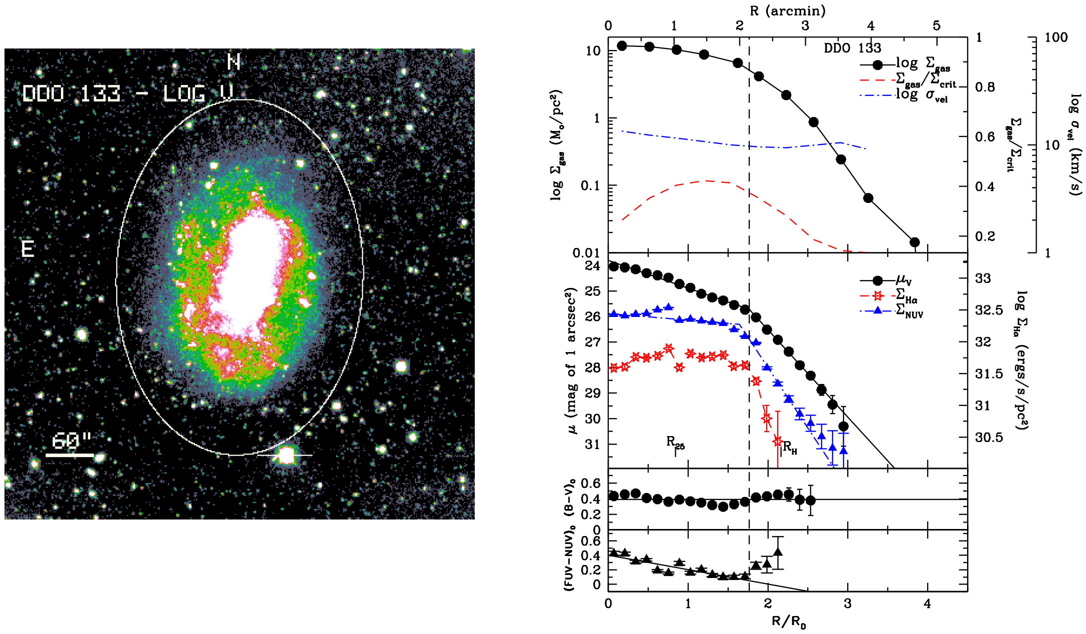

Figure 1: *Left:* V-band image of DDO 133. The ellipse denotes the furthest we trace the disk. *Right:* Top: Gas density Σ_{gas}, velocity dispersion σ_{vel}, and ratio of gas density to Toomre critical density Σ_{crit} by radius normalized to the disk scale length. Middle: V, Hα, and NUV surface brightness. We trace the disk into the regime of very low gas density, and we see a break in the stellar profile (vertical line). Bottom: Radial profiles of the $B-V$ and FUV-NUV colors. $B-V$ is roughly constant. From Hunter et al. (2011).

2 Determining How Dwarf Disks are Assembled and Evolve

To understand dIrr disk evolution, we address the following four questions and describe a proposal for action.

1. What is the star formation history and structure in outer stellar disks? In a pilot project, we obtained deep V and *GALEX* UV images of 4 dIrr galaxies and one BCD and B images for 3 of the dIrrs (Hunter et al. 2011). We traced stellar disks in these images to $\mu_V \sim 30$ mag/arcsec^2. We found that the stellar surface brightness in V and FUV continue exponentially as far out as we can measure (Fig. 1, also Bellazzini et al. 2014). However, 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 in the conventional model (Kennicutt 1989). This led to two conclusions: 1) Exponential stellar disks are extraordinarily regular in spite of the fact that dIrr galaxies are clumpy with sporadic star formation. 2) There is a continuity of star formation with the same exponential profile even though the outer gas is stable.

We will build on this study by ultra-deep imaging of the extreme outer stellar disks of the LITTLE THINGS dIrrs (§3). With multiple filters ($UBVI$), we will measure photometric properties and fit SEDs to stellar populations and SFHs (as we did in Zhang et al. 2012a). The SFHs as a function of radius are the record of the disk growth and radial migrations, 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 survey images (to $\mu_V = 30$ mag/arcsec^2), which doubles the observable length of the outer disk, where very little is known about star formation, dynamical processes, or environmental influences. This increases the observable stellar area by a factor of $\sim$ 3, increasing the probability we will find evidence for new dynamical processes, such as perturbations by faint companions or extragalactic clouds, stellar streams, or star formation in hotspots triggered by accretion (e.g. Sánchez Almeida et al. 2013, 2014b).

Are outer disks populated primarily through stars scattered from the inside out or from 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. On the other hand, if the outer disk of dIrrs is forming stars, there should be young stars. We have detected clusters and associations to a radius of a few disk scale lengths (Melena et al. 2009), and as members of the *HST* LEGUS project we are using UV data to learn more about clusters in bright star-forming dwarfs. Here we propose to explore models for star scattering and search for young star clusters in the far outer disks of our dIrr sample. Since scattering takes longer than the ages of young clusters, this will be a stringent test for star formation in extreme outer disks of dIrrs.

2. What are the large scale drivers of star formation? Star formation is a primary force in the evolution of galaxies. It is predicted in the inner regions of spirals because the gas is nearly gravitationally unstable ($Q \sim$ 1-2; Kennicutt 1989), but in dwarfs Q is too high for this instability (Fig. 2, *lower right*). 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 (Bland-Hawthorn et al. 2005, Gil de Paz et al. 2005, Thilker et al. 2005).

Fig. 2 (*left*) shows stellar mass column densities and gas surface densities 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. 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 2000 times lower than the SFR at the H I-molecule threshold ($\Sigma_{\rm gas} \sim 10$ $M_\odot$ pc^{-2}) in typical galaxies found by Bigiel et al. (2008), and 200 times lower than the SFR at the CO detection limit from stacking techniques (Schruba et al. 2012). The question is not just how molecular clouds form at such low densities, but why they do it as part of a continuous exponential profile as shown by the FUV?

We are proposing to test the importance of the major forces that are currently suggested to make star-forming clouds or regulate SFRs: accretion, turbulence and non-circular gas motions, and stellar feedback. Accretion of gas flowing onto galaxies from the cosmic web is currently believed to be the driver for on-going star formation in spirals (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, the starbursts in BCDs, and possibly the unusual H I structures around the starburst IC 10 by our group (Ashley et al. 2014, Sánchez Almeida et al. 2013, 2014b) and 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 our sample of dIrrs to search for signs of accretion.

An *internal* process for creating star-forming clouds is compression of gas in a supersonically turbulent medium (MacLow & Klessen 2004), and we have predicted this 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 (Stilp et al. 2013). Our LITTLE THINGS survey of H I in dIrr galaxies (§3) also shows considerable kinematic structure in the gas, including non-ordered and streaming motions, varied velocity dispersions, and possible warps. Our deconvolutions of rotational motions and non-ordered motions and 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. (2010) studied turbulence in the SMC through analysis of higher

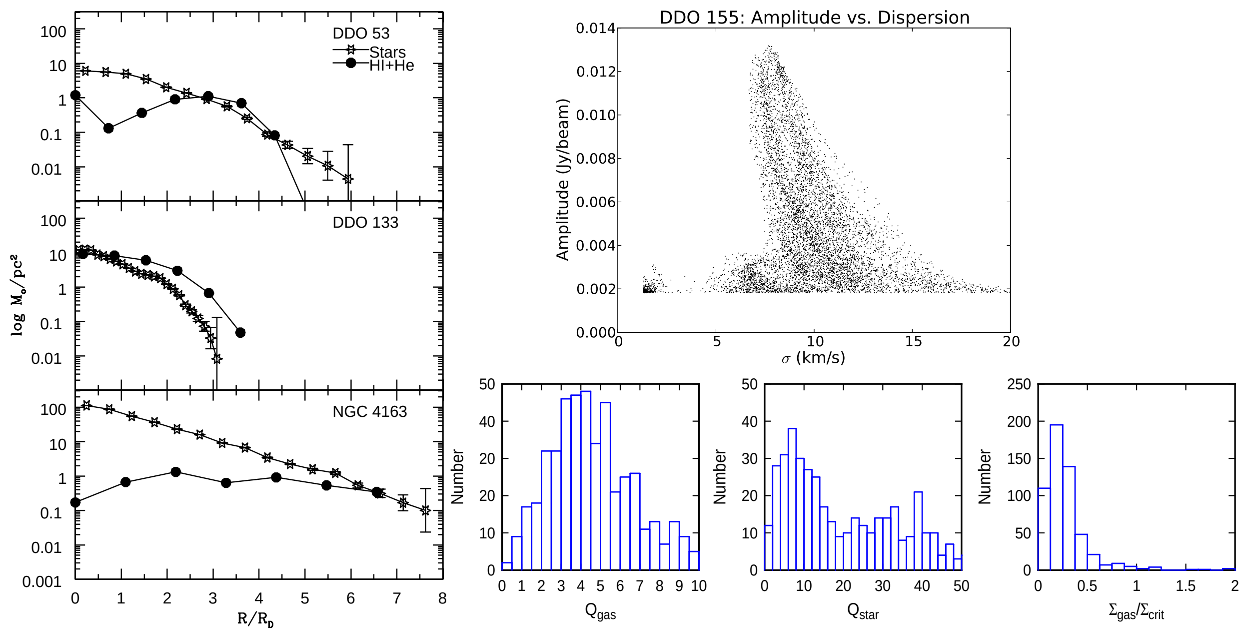

Figure 2: *Left:* Mass column densities from deep imaging of 3 dIrrs as a function of radius normalized to the disk scale length (Hunter et al. 2011). *Right, top:* Anticorrelation of H I amplitude with velocity dispersion of the gas in DDO 155 from our maps, indicating cooler or more quiescent gas in regions of high column density. *Right, bottom:* Histograms of Q_{gas}, Q_{star}, and the ratio of the gas column density to the conventional Toomre critical column density evaluated in radial intervals for 20 LITTLE THINGS galaxies. The values of Q are high, as is an effective two-fluid Q ($\sim 1/Q_{gas} + 1/Q_{star}$), and the observed column densities are sub-critical, even though there is star formation in these annulii and the average profile in FUV and Hα is exponential (Elmegreen et al., in prep).

order moment maps (skewness and kurtosis) of the Σ_{HI} distributions. They found no correlation between the turbulent Mach number and local SFR, but a clear correlation between Mach number and the bar (also Block et al. 2010, Bournaud et al. 2010).

Shi et al. (2011) found a correlation between the SFR and the stellar mass surface density of stars, but we do not know what this means. One possibility is that feedback from older stars triggers or regulates 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 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 in the holes and the path length for UV photons that can heat the gas increases. Once formed, holes in the ISM can last a long time because there's little shear in these solid-body, slowly rotating systems. Stars can also regulate star formation in other ways. In the model of Ostriker et al. (2010, see also Krumholz 2013), 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.

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 time. If so, we don't know what the crucial environmental conditions are.

3. 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 (e.g. de Grijs et al. 2001; Hunter & Elmegreen 2006; Pohlen & Trujillo 2006; Erwin et al. 2008). In some cases the second exponential is shallower (Type III). We analyzed the surface brightness profiles of the 141 galaxies in our large dwarf and Sm survey (§3, Herrmann et al. 2013). We 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 Type II breaks occur at about the same stellar mass density, so something fundamental is happening at these breaks, but we do not yet know what.

Several models predict what happens at the break. We showed that a change from star formation dominated by gravitational instability in the central regions to star formation dominated by turbulence and spiral wave compression in the outer disk produces a sharp change in slope of the SFR profile (Elmegreen & Hunter 2006). 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. Local density enhancements can also be produced by 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, resulting in departures from thermal equilibrium and local density variations. Roškar et al. (2008b) suggest that the break in a spiral disk moves outward as the gas cools. The break 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 have also seen a correlation between disk flaring and breaks in M94 (Herrmann & Ciardullo 2009) and the Milky Way (Benjamin, private communication), perhaps from the effect of flaring on the star formation process (Barnes et al. 2012).

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

4. What effect does low metallicity have on star formation? At metallicities $< 0.02Z_\odot$, star formation should be different than at solar metallicity (e.g. Spaans & Norman 1977). Increasing metallicity enhances atomic and molecular cooling; increasing dust content absorbs part of the stellar radiation and boosts H_2. Once star formation begins, 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 (e.g. Fumagalli et al. 2010, 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 dust shielding of molecular gas. As a consequence we expect 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 proposed 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 changes in the chemical structure of clouds affects 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% 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 (Fig. 3). Here we propose to examine the basic properties of the GMCs and determine the environmental conditions

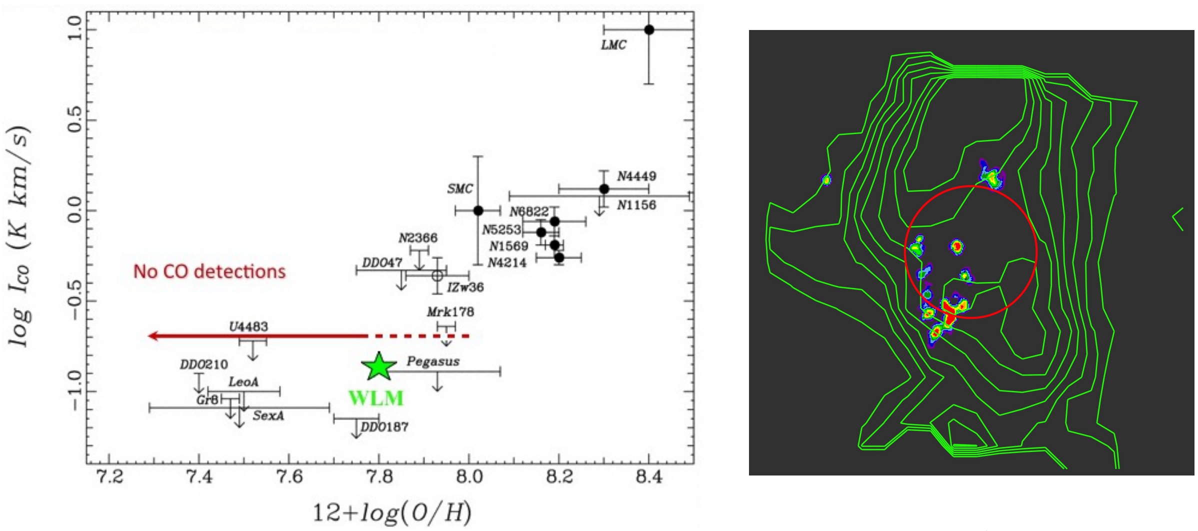

Figure 3: *Left:* I_{CO} as a function of galaxy oxygen abundance at low metallicity (Tacconi & Young 1987, Taylor et al. 1998; plot courtesy of M. Rubio). Only the solid black circles and the green star marking WLM are detections. Our measurement of CO 3-2 in WLM with APEX extends the detections to 13% of solar metallicity (Elmegreen et al. 2013). *Right:* Our 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! Another region in WLM observed by ALMA shows similar CO structure

important in making star-forming molecular clouds at low metallicities (Sternberg et al. 2014).

Our proposal

In section §3 we give our current data and in §4 we give details on our plan. 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 star formation versus scattering of stars in building and maintaining the outer exponential disk, modeled their cosmological evolution, and investigated the overall relative importance of environmental factors versus internal processes on the evolution of dIrrs in our sample. 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 gained important insights into 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 current SFR (0 to starburst) and M_V (−9 to −19). We obtained *UBVJHK*, Hα, *GALEX* FUV and NUV, and *Spitzer* IR images of these galaxies (Hunter & Elmegreen 2004, 2006; Hunter et al. 2006, 2010), and used the data to trace stellar populations and ages (Zhang et al. 2012a). A sub-sample of 37 dIrrs and 4 BCDs were chosen for the LITTLE THINGS

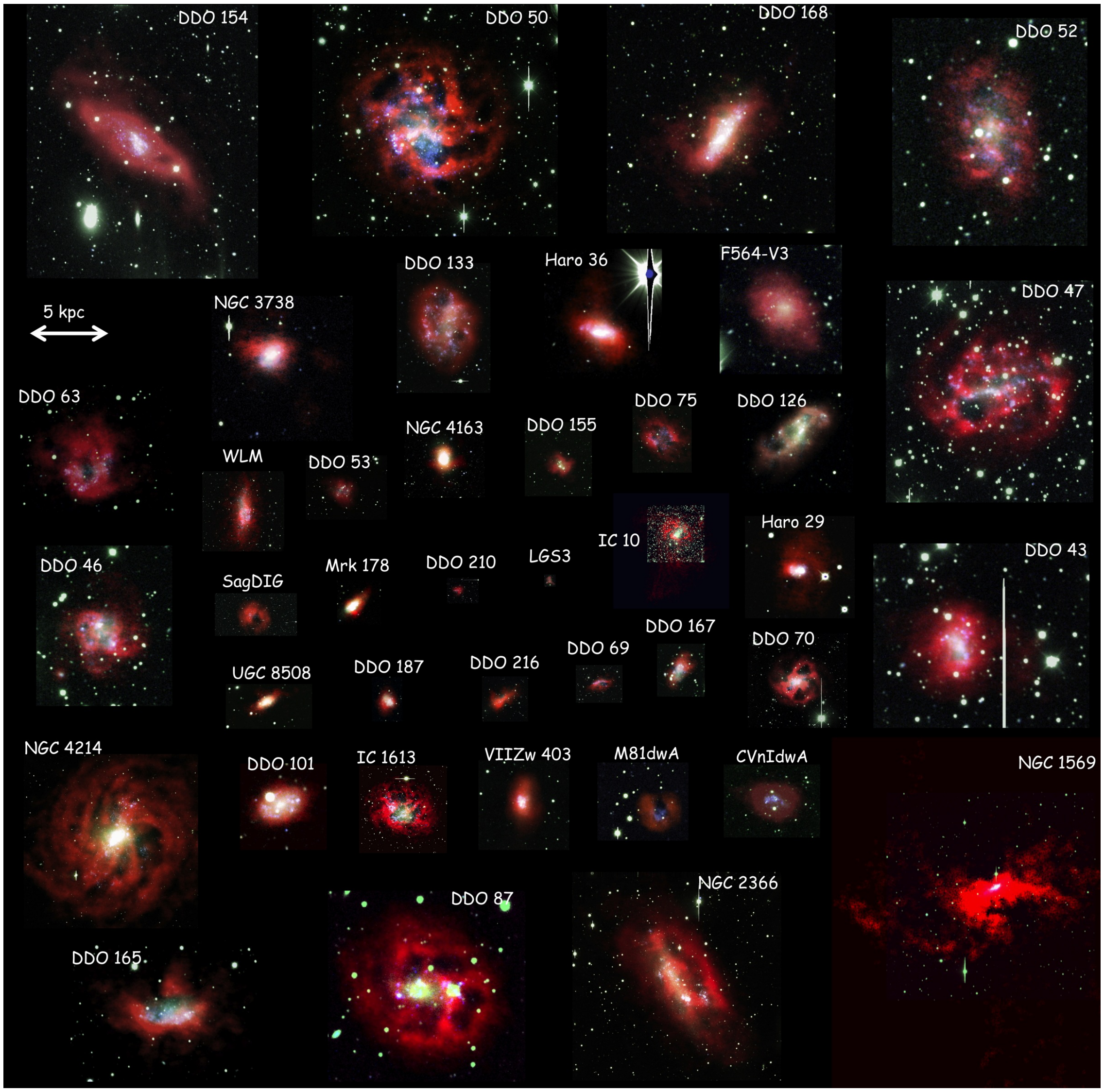

Figure 4: LITTLE THINGS dwarfs: Red is H I, green is V, blue is FUV. Images are to same relative size.

survey (<10.3 Mpc) that was granted ∼376 hr with the VLA to obtain H I data on 21 galaxies (Hunter et al. 2012; 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 angular resolution (6″, 110 pc at 3.7 Mpc). These data trace the H I distribution 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 870 μm 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 observed H I in a 2° field around 40 LITTLE THINGS galaxies with the GBT to look for gas-rich companions and streams (c.f. Johnson 2013), and we are searching for stellar companions using amateur astronomer partners (§6). Scientific results from LITTLE THINGS are summarized in §7.

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

4.1 Addressing question 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). LMI was designed for this project: low scattered light, large field of view (12.5′) to sample sky, 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 to reach low surface brightness ($\mu_V \geq 30$ mag/arcsec^2). The telescope is performing extraordinarily well, routinely achieving 0.8″ image quality, and is now entering full science observations. Lowell Observatory has guaranteed Hunter the 100 nights needed for this 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 SFHs. Here we can probe much further out in the disk and observe more extreme, but more distant, objects. Our project also complements the FIR survey of Madden et al. (2013) and the coarse resolution survey of GAMA (Driver et al. 2009).

With these data we will determine the relative proportions of stars with different ages as a function of radius; our broad-band data are sensitive to ages of order 10 Myrs, 1 Gyr, and 10 Gyr. This will extend into the extreme outer disk the SED fitting of our previous data on 34 dIrrs (Zhang et al. 2012a). A consistent picture of the stellar populations and ages over the disks of dIrrs is a necessary first step to determining their assembly history.

To determine if scattering of stars is a viable mechanism to populate outer disks in dwarfs, we will run 2D and 3D test particle models (Elmegreen & Struck 2013). Scattering centers are added in the form of clumps representing a range of objects from star-forming regions to small companions. These models will predict stellar kinematics and populations that should allow us to tell the difference observationally between scattering of old inner stars and a lack of star formation for a long time. For example, strong clump scattering makes eccentric orbits which should broaden the stellar velocity dispersion on the minor axis that we might see in PNe motions (§4.3).

To look for evidence of star formation, we will use our proposed deep U-band images to identify young clusters much further out than anyone has seen them in dIrrs before. Then we will determine if such clusters change their properties 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.

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 vs 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 dIrrs.

4.2 Addressing question 2: Large-scale drivers of star formation

Accretion We propose to look for evidence of accretion through wide field of view imaging to reveal large-scale optical and gas structures around the LITTLE THINGS dIrrs. Dragonfly, an innovative, multi-lens array designed for ultra-low surface brightness imaging over a 2.6° field (Abraham & van Dokkum 2014), has proven an ability to reveal extraordinary, faint structure in the far outer disks of spirals. R. Abraham, one of the co-inventors of Dragonfly, has agreed to obtain images of several of the LITTLE THINGS dIrrs as tests to see if similar structures are found around dwarfs. For large-scale gas structures we have GBT observations over a 2° field around 40 of the LITTLE THINGS dwarfs. Maps have been made from these observations for a few of the galaxies (e.g. Johnson 2013, Ashley et al. 2013), and the rest will be mapped under this grant. Besides possible signposts of accretion, these data could also reveal indications of tidal interactions, spiral structures, blobs, or disk holes.

We have deconvolved the VLA H I kinematics of LITTLE THINGS galaxies into its main components: ordered rotation and non-ordered motions (Oh et al. 2011; in prep). Using the maps of peculiar gas motions, we will look for a physical correspondence between non-ordered motions and any large-scale optical or H I structures we find. 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 ($\Sigma \times 2\pi\Delta R$/adjustment time) 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.

Turbulence and gas kinematics We will apply the analysis in Burkhart et al. (2010) to the LITTLE THINGS galaxies. We will determine kurtosis values globally, radially, and locally (limited by statistics of H I beams). We will look for variations of kurtosis with radius and proximity to clumps and star-forming regions. We will also look at an anti-correlation we found between the velocity dispersion σ_{vel} and Σ_{HI} (Hunter et al. 2001, 2011; Fig. 2, *top right*) that suggests turbulent pressure equilibrium on large scales (Piontek & Ostriker 2005).

We will produce 2D maps of the turbulent energy density 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 our results from H I Fourier Transform power spectra as a guide to the relative fractions of cool and warm H I (Zhang et al. 2012b) and our devonvolutions of multiple component H I velocity profiles. 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 by colliding clouds. 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 galactic dynamical processes on the gas dynamics and star formation in dIrrs.

Stellar feedback A PhD thesis in progress uses our H I cubes to catalog holes in the gas of our dIrrs and 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. 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. We will also tune the parameters of the Ostriker et al. (2010) model to fit dIrrs and compare its SFR(R) predictions against our observations.

If local environmental effects are important in driving star formation, we might see this in the star formation products. 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. Is there a relationship between the mass or density of clusters and the gas structure (e.g., clump mass, filaments versus clumps), kinematics (HI line widths or shear), or disk pressure (determined from gas and stellar column densities) in that part of the galaxy? As LEGUS team members, we are testing this idea on the LEGUS dwarfs, but here will extend this project to more typical dIrrs.

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 the projects outlined in this section, we will determine the relative importance of various internal and external processes in driving star formation in dIrrs.

4.3 Addressing question 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 star formation normalized to the V-band starlight at the break. We will do this both in dIrrs and a sample of spirals for comparison. (The 9 Sa-Sd spirals have FUV images and were imaged in V-band by an MIT Field Camp student at Lowell Observatory and are now being reduced by a NAU Space Grant student.) We will determine the relationship between the break radius and Σ_{HI} for the LITTLE THINGS sub-sample. Are there changes in the H I profiles where there are breaks in the stellar mass profiles? Is there a relationship between the break-type (downward bending or upward bending) and bar or external disturbances, as suggested by M94 (Herrmann & Ciardullo 2009), that are either observed directly in our deep images or inferred from H I velocity perturbations? Are there asymmetries and faint stellar structures in our deep images, such as we saw in DDO 86 in our pilot project (§2; Hunter et al. 2011), that possibly produce breaks in azimuthal averages? Is there a change in H I hole properties or porosity at the break?

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 ∼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.

We will test the predictions of what happens at the breaks by the models discussed in §2 against our observed properties. 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 them.

4.4 Addressing question 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%, 10%, 6%, and 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). 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× 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 (Fig. 3, *right*). 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, *right*). We have been granted Cycle 2 time to obtain CO maps of 3 more dwarfs we observed with *Herschel*. At the end we will have pictures of the PDR+CO cores of 4 dwarfs down to 5% solar.

For this proposal, we will 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 are inversely proportional to density. To do some of these things, we need estimates of 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 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 H I warm and cool (broad and narrow) components, 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 at low-metallicity (c.f. Sternberg 2007, Sternberg et al. 2011, 2014, 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. They will have enough particles to resolve the Jeans length and minimize particle noise heating in the outer disk. We will then study the impact of environmental effects (mergers, tidal interactions) versus internal processes (disk instability, clump-driven migration) on the morphology and disk properties of dIrrs. These models will tell us the overall relative importance of environmental factors versus internal processes on the evolution of dIrrs and will be global models against which to test our cumulative paradigm of dIrr disk assembly and formation.

5 Personnel and Activity Plan

In addition to unique observational and theoretical resources, we have brought together an international team with the experience and expertise to make the most of these resources. In Fig. 6 we show the different projects, color-coded by lead people, but crucial roles will also be played by non-lead members. Hunter will be responsible for organizing, coordinating, and leading the team.

Outer disks Hunter will be responsible for DCT imaging, surface photometry, and finding and characterizing structures and star clusters and their environments (Fig. 5). Zhang (unfunded collaborator) will carry out the SED fitting to determine SFHs from surface photometry and

	Q1	Q2	Q3	Q4
2014	-	-	-	11.5
2015	15	15	7.5	1
2016	15	15	-	mop-up
2017	15	mop-up		-
2018	5	-	-	-
2019	mop-up			

Figure 5: Expected DCT observing profile in nights per quarter: Pre-grant is black, Y1 is red, Y2 is blue, Y3 is green, and Y4 is purple. Q4 2014 observations are in progress; the Q1 2015 request has been submitted.

masses and ages of star clusters. Struck and Elmegreen will run 2D and 3D test particle models to determine if scattering of stars is viable. Hunter will guide the LARI project (§6).

Large-scale drivers of star formation

Accretion: Johnson, Ashley, and Brinks (unfunded collaborators) will make maps from the GBT H I observations and analyze them. Simpson and Brinks 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.

Turbulence and non-circular motions in the gas: Simpson and Oh (unfunded collaborator) will compare the non-circular motion H I maps with star formation patterns and other properties. Levine will provide dynamical analyses. Hunter will examine kurtosis of H I density profiles and Probability Density Functions and the anti-correlation between Σ_{HI} and σ_{vel}. 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 around star forming regions.

Stellar feedback: Simpson will explore the effects of porosity on star formation. Elmegreen will test model predictions of SFR(R). 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 break radius to H I profiles, scale-heights, and star formation drivers, search for asymmetries in the 2D images, and explore models to reproduce profile breaks. She will also carry out the PNe kinematic study and compare the breaks to flaring in outer disks. Simpson will determine how H I holes and porosity in outer disks compare to those in inner disks. Hunter will determine the SFR interior and exterior to the breaks in dwarfs and spirals. Elmegreen will test models for what happens at the breaks.

Effects of metallicity Rubio (unfunded collaborator) will lead ALMA and APEX data reductions and map making. Hunter will analyze molecular cloud structure, evaluate consequences to star formation, and examine the environmental context of clouds. 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 (Sánchez Almeida et al. 2013, 2014a, 2014b; Fiho et 2013). Hunter will examine the distribution of the cool atomic gas.

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: science literacy in our communities

Involving high school students and undergraduates in our research

Elmegreen has a collaboration with local high schools that enable him to work with students. The 7 he has worked with have submitted their projects to the Siemens Competition in Math, Science & Technology and to the Intel Science Talent Search. At Penn State, Herrmann will begin

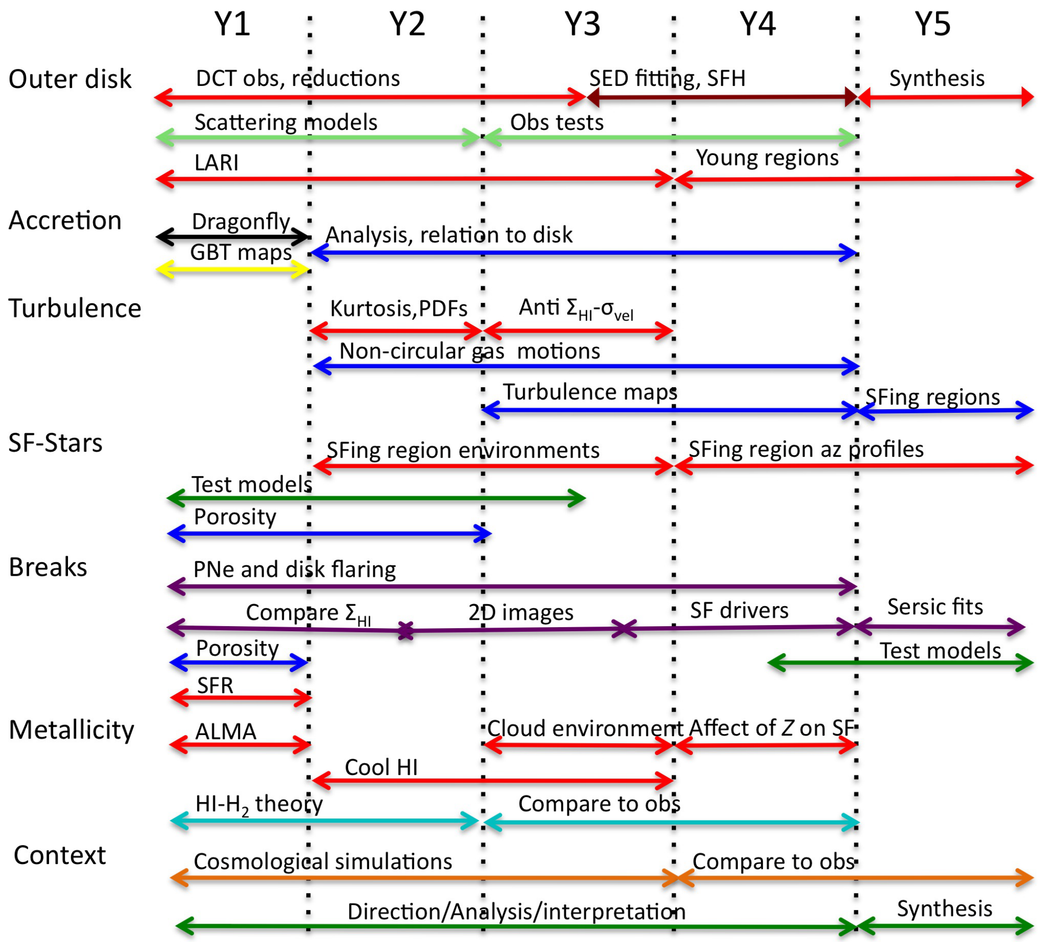

Figure 6: Timeline of projects. Color codes lead person: red - Hunter, blue - Simpson, dark green - Elmegreen, light green - Struck, purple - Herrmann, yellow - Johnson, turquoise - Sternberg, dark red - Zhang, and orange - Zolotov.

involving undergraduates from her astronomy and physics classes in research projects. Hunter works with undergraduates through a summer REU program with Northern Arizona University (NAU) and the MIT-Lowell Field Camp each January. 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 students.

Promoting the participation of women and minorities in science

The majority of 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 they too can consider science as a career. Hunter participates in middle school "Scientist in the Classroom".

Florida International University is classified as a Hispanic Serving Institution with 54,000 students. The Physics Department attracts a high percentage of underrepresented groups and a departmental effort led to a 2,300% increase in the number of majors (now ~180) as well as a 950% increase in the number of graduates (~15/year). To achieve this, the department reformed the undergraduate experience, including introductory courses, and established a nationally renowned Physics Education Research (PER) group. In 2007, PER 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 hired to assist the instructor and work with the students. This peer-teaching model enhances the learning of students in the classroom, but also increases the retention of the LAs in STEM disciplines (Goertzen et al. 2011). In 2012 Simpson was awarded a Fellowship 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 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 traditionally) were used to measure the effect of the change. Simpson's budget includes funding for support of LAs for her introductory astronomy classes in order to continue this program.

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. 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 as well. Johnson is involved in an outreach program in Sydney in which she partners with a 3rd grade teacher and makes classroom visits once a month.

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. 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. A few years ago Struck published a general science book and gives talks on that.

In addition, Discovery Communications, a global media giant, has partnered with Lowell Observatory to build the 4.3-m DCT. Discovery 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. We will exploit further opportunities as they arise.

7 Results from Prior NSF Support

1. 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 published 12 refereed articles: Elmegreen & Hunter 2010, Heesen et al. 2011, 2014, 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. More are in press (Ashley et al. 2014, Kitchener et al. 2014), one is in the refereeing stage (Johnson et al. 2014), and 8 are nearing submission. These products cover a 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. Abrupt changes in the slope of the exponential 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. 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 thus 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 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. Giant star-forming clumps in BCDs are massive 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 fields in dIrrs lacks a strong large-scale component.

Broader Impact

Three PhD theses are in progress (Cigan, Ficut-Vicas, Kitchener). Three PhD theses were completed: Johnson (Georgia State Univ and Lowell Obs, Aug 2011), Zhang (Purple Mountain Obs and Lowell Obs, May 2012), Ashley (Florida International Univ, May 2014). We employed 3 post-docs (Heesen, Herrmann, Oh). Nine undergraduates and two high school students were involved in research projects. Of these people, 14 (48%) are women; 2 (7%) are ethnic minorities.

We produced a first-class data set that is timeless in its usefulness. We invested 4 years resolving problems in the data reduction and map making, including aliasing caused by the mixture of VLA and EVLA technology and being first-generation users of Multi-Scale CLEAN for imaging. We shared our knowledge with other teams. We made the final map cubes, moment maps, and ancillary imaging available to the public February 2012 on an NRAO web 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. The team gave 31 talks and 25 posters at meetings and colloquia. We gave 16 public talks and 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 at the Jan 2012 AAS meeting.

2. STRUCK

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

Intellectual Merit Mergers and interactions are one of the most important processes in galaxy evolution. Struck is developing semi-analytic models and helping to understand star formation morphology and history of the galaxy sample.

Broader Impact Understanding how star formation is generated in interactions is relevant to a wide range of problems in astrophysical cosmology.

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