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Evolution of $z \sim 0$ Luminous Compact Blue Galaxies

Katherine Rabidoux

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Evolution of $z \sim 0$ Luminous Compact Blue Galaxies

Katie Rabidoux

Dissertation submitted to the
Eberly College of Arts and Sciences
at West Virginia University
in partial fulfillment of the requirements
for the degree of

Doctor of Philosophy
in
Physics

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Morgantown, West Virginia
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ABSTRACT

Evolution of $z \sim 0$ Luminous Compact Blue Galaxies

Katie Rabidoux

Luminous compact blue galaxies (LCBGs) are bright ($M_B \leq -18.5$), blue ($B - V \leq 0.6$), massive ($M_* \sim 10^9 M_\odot$) star-forming galaxies with high B-band surface brightnesses ($S_{\text{Be}}(B) \leq 21.0$) that were common at $z \sim 1$ when the Universe was half of its current age, but are rare in the local Universe. In this thesis, I have conducted studies of the atomic neutral hydrogen (H I) and global star formation properties of a group of the rare $z \sim 0$ analogs to the common $z \sim 1$ LCBGs to better understand how this class of galaxies evolves. I have first conducted a pilot study of the global star-formation properties of a heterogeneous group of local star-forming galaxies using observations at 33 GHz with the Green Bank Telescope. In this study, we made the first detections at 33 GHz for 22 of the 27 galaxies we observed. We fit spectral energy distributions (SEDs) to the galaxies' radio continuum emission from ~ 1 GHz – 40 GHz and quantified the relative contributions of thermal free-free emission from massive, short-lived stars and non-thermal synchrotron emission from supernovae. We found that these galaxies followed the radio-far-infrared correlation at 33 GHz, and that the thermal fraction at 33 GHz, spectral index from 1.4 GHz to 33 GHz, and ratio of radio continuum emission at 33 GHz to total far-infrared emission together give an estimate of the relative ages of the most recent episodes of star formation in these galaxies. In the second study, we analyzed resolved H I observations of nine $z \sim 0$ LCBGs. We found that the LCBGs have a variety of H I morphologies, are rotationally-supported at all radii, and are unlikely to be forming large S0-type bulges. We also found that the disks of LCBGs are stable on average with respect to gravitational instabilities, but may have the potential to form instabilities at large radii. In addition, the LCBGs in our sample had the lowest ratios of ordered rotation to disordered motions in the centers of their disks, supporting the idea of these galaxies forming a small central bulge or bar. Finally, we applied the techniques we used in our study of the global star-formation properties of a heterogeneous sample of galaxies to investigate a sample of 42 local ($D < 80$ Mpc) LCBGs. We found that LCBGs all have evidence of ongoing star formation, though the ages of their most recent episodes of star formation are varied. We also saw that LCBGs without star-forming clumps appeared to have relatively young star formation ages ($\lesssim 30$ Myr), while clumpy LCBGs could have a range of ages, from very young to ~ 100 Myr or more. We conclude that there are likely to be at least two broad causes of star formation in LCBGs, and that their evolutionary paths are likely to be diverse.

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Chapter 1

Introduction

1.1 The evolution of galaxies since $z \sim 2$

The visual appearances of the galaxies we observe, from our own Milky Way to the most distant galaxies we can see, are strongly influenced by whether or not they are actively forming stars. In galaxies that are making new stars, the bright, blue, hot, short-lived stars that are associated with star-forming regions will give the galaxies a blue appearance where the stars are being formed. If a galaxy is no longer actively forming stars, it will look red due to evolved lower-mass stars dominating its light. At higher redshifts, where we observe light from galaxies that was emitted when the Universe was much younger, blue galaxies were more common than they are in the local Universe (e.g. Tyson 1988). This evolution in color implies that star-forming galaxies were once more common. While blue galaxies cannot continue making new stars forever, and will transition to have red appearances when their star formation ceases, it is not obvious how this evolution proceeds, and how long it takes for galaxies to stop forming stars.

While individual galaxies evolve on too long of a timescale for astronomers to watch them change, we can watch the evolution of star-forming galaxies over cosmic timescales by observing many galaxies at a range of redshifts. It has been shown by combining the results of large surveys of galaxies at a variety of redshift

ranges that the Universe’s average star formation rate (SFR) density peaked at $z \sim 2$ (~ 10 Gyr ago), and has been declining ever since (for a review, including illustrative figures, see Madau & Dickinson 2014). At $z \sim 2$, many star-forming galaxies have blue, compact, clumpy appearances in rest-frame ultraviolet (observed-frame optical) images (Elmegreen et al. 2009), quite unlike the spiral and elliptical galaxies familiar in the local Universe. While the trend of a declining average star formation rate since $z \sim 2$ is well-measured, the path from a Universe full of clumpy star-forming galaxies to one that has more quiescent galaxies on average is not obvious.

The average star formation rate density of local galaxies is almost an order of magnitude lower than it was 6-10 Gyr ago (Guzmán et al. 1997; Madau & Dickinson 2014). When average star formation rate densities are calculated using both rest-frame UV luminosities and rest-frame IR luminosities at a range of redshifts, the Universe shows a declining star formation rate density with decreasing redshift for $z < 2$ (see Figure 9 of Madau & Dickinson 2014). Because of this change, there has been an effort to identify a population of galaxies that are present at all redshifts from $z \sim 0$ to $z \sim 2$, but decrease in number density between $z \sim 2$ and the present day. Such galaxies may be candidates for contributing to the overall evolution of galaxies. Koo et al. (1994) used the Hubble Space Telescope to image some of the compact sources found in optical surveys of quasars from $0.1 \lesssim z \lesssim 0.7$ that appeared to have emission lines consistent with star formation, and found that a subset of them were luminous, compact, and very blue. Phillips et al. (1997) and Guzmán et al. (1997) identified a sample of compact star-forming galaxies in the Hubble Deep Field from $0.4 \lesssim z \lesssim 1$. They estimated that these galaxies comprise 20% of the

number density, but contribute $\sim 45\%$ of the star formation rate density of galaxies at this redshift range. They also found that even though the galaxies had relatively constant star formation rates normalized by their masses at all redshifts, the higher-redshift galaxies in their sample have higher masses than the lower-redshift galaxies, implying not only an evolution in star formation rate, but also in the typical mass of star-forming galaxies at this redshift range. This is consistent with the picture of “downsizing” in galaxy formation (Cowie et al. 1996; Juneau et al. 2005), where more massive galaxies formed at higher redshifts.

The evolution of $z \sim 1$ compact star-forming galaxies, and the nature of their descendants among the galaxies in the local Universe, has been a subject of debate for the two decades since these galaxies were first identified. Some authors have argued that their high velocity dispersions, along with their relatively high stellar masses compared to local blue compact dwarf galaxies, make it likely that they are either galaxies undergoing their final starburst that will fade to become dwarf elliptical galaxies once their star formation stops, or are the compact, bright central bulges of larger galaxies with faint disks that are difficult to detect in surveys of galaxies at higher redshifts (e.g. Koo et al. 1994; Guzman et al. 1996; Hammer et al. 2001; Barton & van Zee 2001). Other authors have argued that these galaxies are more like low-mass spiral or irregular galaxies undergoing a period of intense star formation, and are the progenitors of more quiescent versions of such galaxies in the local Universe (e.g. Noeske et al. 2006). Recently, Tollerud et al. (2010) and Garland et al. (2015) have argued that $z \sim 0$ luminous, compact, blue galaxies (LCBGs) are similar to the clumpy galaxies that Elmegreen et al. (2009) identified at $z \sim 2$, and have blue

clumpy appearances due to the accretion of gas from companions, cluster potentials, or cosmic filaments.

In order to better understand how star-forming galaxies have evolved since $z \sim 1$, it is important to identify nearby examples of these galaxies to study in more detail than is possible at very large distances. Local ($z \sim 0$) LCBGs have been selected as possible links to the types of galaxies that contributed up to 45% of the star formation rate density at $z \sim 1$. Werk et al. (2004) outlined a set of criteria to select for local galaxies that are similar to the bright, blue, compact star-forming galaxies first seen in higher-redshift surveys. They found that intermediate-redshift LCBGs tend to have B-V colors bluer than 0.6 magnitude, absolute B band magnitudes less than -18.5, and B-band surface brightnesses less than 21.0 magnitudes per square arcsecond. We adopt this classification for LCBGs in Chapters 3 and 4 of this thesis.

Studies of $z \sim 0$ LCBGs that have the optical properties outlined by Werk et al. (2004) have characterized some of their physical properties to better understand how their star formation is triggered, sustained, and quenched. Garland et al. (2004) studied a sample of $z \sim 0$ galaxies with these properties and found that they are rich in atomic neutral hydrogen (H I) and relatively massive ($M_{\text{HI}} \sim 10^9 M_{\odot}$, $M_{\text{dyn}} \sim 10^{10} M_{\odot}$). Garland et al. (2005) found that these local LCBGs have average interstellar medium (ISM) properties traced by their molecular gas that are consistent with those of individual star-forming regions in the Milky Way, and that if they continue to form stars at their current rate, LCBGs will use up their molecular gas in $\lesssim 200$ Myr. Garland et al. (2007) found that the H I in LCBGs is often asymmetrically distributed. Pérez-Gallego et al. (2010) and Pérez-Gallego et al. (2011) found

that the ionized gas in nearby LCBGs also tends to be asymmetric, and that approximately half of the local LCBGs that they observed have either perturbed rotation or complex kinematics, which they interpret as evidence for recent interactions that could trigger their star formation. Recently, Garland et al. (2015) found that LCBGs can be both clumpy, like the galaxies common at $z \sim 2$, or non-clumpy and that these two broad categories of LCBGs have different average masses, sizes, star formation rates, metallicities, and colors, leading them to conclude that the causes of star formation in the two types of galaxies are likely to be different. All of the above authors found local LCBGs to be a heterogeneous group of galaxies, and hypothesize that their evolutionary paths are likely varied.

The overarching motivation for the projects in my thesis, especially those in Chapters 3 and 4, was to study in-depth the physical properties of local LCBGs to better understand how these galaxies have evolved since $z \sim 1$, and what their future evolutionary paths will be. In order to conclusively determine whether these galaxies are rotationally-supported disk galaxies undergoing a temporarily elevated episode of star formation as hypothesized by Noeske et al. (2006), or dispersion-dominated galaxies that could be undergoing their final episode of star formation before fading to become dwarf ellipticals as hypothesized by Koo et al. (1994), my collaborators and I have conducted a resolved study of H I in nine local LCBGs. In addition, to characterize the star formation properties of LCBGs and constrain the ages of their current episodes of star formation, I apply methods from my work studying the global star formation properties of a heterogeneous sample of local star-forming galaxies (presented in Chapter 2) to a local sample of 42 LCBGs to conduct the most

comprehensive examination so far of extinction-free star formation tracers in LCBGs. These studies paint a picture of the current state of low-redshift LCBGs and suggest future evolutionary paths for these galaxies.

1.2 Useful derivations

In the following subsections, I show how the quantities used in our analysis in this thesis are derived from observable quantities. Readers may skip these derivations without loss of understanding of the science discussed in subsequent chapters.

1.2.1 Gravitational instabilities in star-forming galaxies

One of the explanations proposed for why $z \sim 2$ galaxies have such high SFRs concentrated in clumps is due to gravitational instabilities caused by the accretion of primordial gas onto the galaxies' disks (e.g. Elmegreen et al. 2009). This gas forms local overdensities in galaxies, and if the kinematic conditions are right within the galaxy, the overdensities can become unstable and condense into gas clumps that form stars. The condition required for gravitational instabilities is that the Toomre parameter, $Q = \sigma\kappa/(\pi G\Sigma)$, is less than unity (Toomre 1964). In this parameter, σ is the velocity dispersion, κ is the epicyclic frequency and is defined as $\kappa = \sqrt{2GM_{total}/R^3}$, and Σ is the mass surface density. In this thesis, we address the H I component of LCBGs' disks, so we investigate the stability of the H I using $Q_{gas} = \sigma_{gas}\kappa/(\pi G\Sigma_{gas})$ where $\Sigma_{gas} = M_{gas}/\pi R^2$, assuming that the gas is in a flat, thin disk (Romeo & Wiegert (2011) showed that adding a stellar component,

$Q_* = \sigma_* \kappa / (\pi G \Sigma_*)$, results in a total stability parameter of $Q_{tot}^{-1} = W Q_*^{-1} + Q_{gas}^{-1}$ for $Q_* \geq Q_{gas}$ or $Q_{tot}^{-1} = Q_*^{-1} + W Q_{gas}^{-1}$ for $Q_* \leq Q_{gas}$ where $W = 2\sigma_* \sigma_{gas} / [\sigma_*^2 + \sigma_{gas}^2]$. Since Garland et al. (2005) found that molecular gas does not contribute significantly to LCBGs' gas masses, we do not consider the LCBGs' molecular gas components in this analysis.

We can then use the Q parameter to relate a rotating galaxy's gas fraction to its ratio of rotation velocity to velocity dispersion in the following way. First, we take the condition $Q_{gas} < 1$:

$$\sigma_{gas} \kappa < \pi G \Sigma_{gas}. \quad (1.1)$$

If we multiply both sides of the inequality by the galaxy's rotation velocity, then this becomes

$$\sigma_{gas} \kappa V_{rot} < \pi G \Sigma_{gas} V_{rot}. \quad (1.2)$$

Substituting $\kappa = \sqrt{2GM_{total}/R^3}$, and $V_{rot} = \sqrt{GM_{total}/R}$ on the left side of the inequality, we have

$$\sigma_{gas} \sqrt{\frac{2GM_{total}}{R^3}} \sqrt{\frac{GM_{total}}{R}} < \pi G \Sigma_{gas} V_{rot} \quad (1.3)$$

If we divide both sides by σ_{gas} , we have

$$\sqrt{\frac{2G^2 M_{total}^2}{R^4}} < \pi G \Sigma_{gas} \frac{V_{rot}}{\sigma_{gas}} \quad (1.4)$$

or

$$\sqrt{2}G\frac{M_{total}}{R^2} < \pi G\Sigma_{gas}\frac{V_{rot}}{\sigma_{gas}} \quad (1.5)$$

If we substitute $\Sigma_{gas} = M_{gas}/\pi R^2$, we have

$$\sqrt{2}G\frac{M_{total}}{R^2} < \pi G\frac{M_{gas}}{\pi R^2}\frac{V_{rot}}{\sigma_{gas}} \quad (1.6)$$

or

$$\sqrt{2}M_{total} < M_{gas}\frac{V_{rot}}{\sigma_{gas}}. \quad (1.7)$$

We can write this as

$$\sqrt{2}\frac{M_{total}}{M_{gas}} < \frac{V_{rot}}{\sigma_{gas}}. \quad (1.8)$$

In this way, we can derive a relationship for how a galaxy's total mass, gas mass, rotation velocity, and velocity dispersion of its gas are related, and use these measurable quantities to probe dynamical instabilities. We use this relationship in Chapter 3 to determine whether the disks of LCBGs have the potential to become unstable at small and large radii given their current H I properties.

I note that the relationship derived above is for a galaxy's gas (Noguchi 2000), and makes the approximation that the galaxy's total mass is equal to its dynamical mass.

1.2.2 From observables to physical properties of star-forming galaxies

To better characterize the global star formation properties of galaxies in the local Universe, it is important to be able to identify types of light that trace the formation of new stars over a range of timescales. While ultraviolet (UV) light is the most direct tracer of recent star formation, as it is emitted by massive O-type stars that live for only a short time, it is easily scattered and absorbed by interstellar dust grains. Since newly-formed stars tend to form in areas where dust is abundant, this means that a significant amount of UV light in star-forming galaxies is obscured. Instead, we must look for emission at wavelengths that are long enough that they are not affected by dust grains, but that also trace short-lived processes associated with star formation. To avoid the effects of extinction due to dust while tracing star formation on short timescales, we have chosen to our focus observations on the radio and far-infrared continuum.

We have focused on three emission components that contribute most of the emission in star-forming galaxies without active galactic nuclei (AGN) between ~ 1 GHz and ~ 5 THz ($\sim 60 \mu\text{m}$): (1) thermal free-free radio continuum emission from ionized regions around massive O-type stars, (2) nonthermal synchrotron radio continuum emission from electrons accelerated by recent supernovae, and (3) thermal blackbody far-infrared (FIR) emission from dust that absorbs stellar radiation and re-radiates that emission in the FIR. In Chapters 2 and 4 of this thesis, we use measurements of these three components to derive properties for the galaxies we observe such as star formation rates (SFRs), supernova rates, dust masses, and dust

temperatures. Since the relationship between the amount of each type of emission in a galaxy and these physical properties is not obvious, I show a short derivation of how each type of emission is used as an indicator of physical properties in a galaxy in the following subsections.

1.2.2.1 Star formation rates from thermal radio continuum emission

Thermal radio continuum photons are emitted when a free electron scatters when it encounters a free ion, causing a change in the electron's velocity. These interactions occur most frequently in dense ionized regions around massive O-type stars. Thus, this process traces very recent ($\lesssim 10$ Myr) star formation. We can derive a star formation rate from thermal emission at radio continuum frequencies by relating the thermal continuum flux at a given frequency to the emission line flux of $H\alpha$ and $H\beta$, as both the line and continuum emission components are produced by ionizing radiation from O-type stars. From Caplan & Deharveng (1986), we can write the $H\beta$ emission line flux as

$$\frac{F(H\beta)}{10^{-12}\text{erg cm}^{-2}\text{ s}^{-1}} \sim 0.28 \left(\frac{T_e}{10^4\text{ K}} \right)^{-0.52} \left(\frac{\nu}{\text{GHz}} \right)^{0.1} \left(\frac{S_{\nu,T}}{\text{mJy}} \right) \quad (1.9)$$

where T_e is the electron temperature, and $S_{\nu,T}$ is the thermal radio continuum flux at a frequency ν . The ratio between $H\alpha$ and $H\beta$ emission can be approximated as

$$\frac{F(H\alpha)}{F(H\beta)} = 2.86 \left(\frac{T_e}{10^4\text{ K}} \right)^{-0.07} \quad (1.10)$$

(Caplan & Deharveng 1986), so the relationship between $H\alpha$ and thermal radio continuum flux can be written as

$$\frac{F(H\alpha)}{10^{-12} \text{erg cm}^{-2} \text{s}^{-1}} \sim 0.8 \left(\frac{T_e}{10^4 \text{ K}} \right)^{-0.59} \left(\frac{\nu}{\text{GHz}} \right)^{0.1} \left(\frac{S_{\nu,T}}{\text{mJy}} \right). \quad (1.11)$$

We can rearrange units to arrive at

$$\frac{F(H\alpha)}{W \text{ m}^{-2}} = 8 \times 10^{13} \left(\frac{T_e}{10^4 \text{ K}} \right)^{-0.59} \left(\frac{\nu}{\text{GHz}} \right)^{0.1} \left(\frac{S_{\nu,T}}{W \text{ m}^{-2} \text{ Hz}^{-1}} \right). \quad (1.12)$$

Since $L_\nu = 4\pi D_L^2 S_\nu$ where D_L is the luminosity distance, if we multiply both sides by an arbitrary distance squared, we can convert the $H\alpha$ and thermal radio continuum fluxes to luminosities:

$$\frac{L(H\alpha)}{W} = 8 \times 10^{13} \left(\frac{T_e}{10^4 \text{ K}} \right)^{-0.59} \left(\frac{\nu}{\text{GHz}} \right)^{0.1} \left(\frac{L_{\nu,T}}{W \text{ Hz}^{-1}} \right). \quad (1.13)$$

We follow the assumption from Condon (1992) here for simplicity that $T_e = 10^4 \text{ K}$ in the star-forming regions. We can substitute the relationship between $L(H\alpha)$ and SFRs that Kennicutt (1983) derived for spiral and irregular galaxies from empirical models of $H\alpha$ equivalent widths. This relationship assumes that the Lyman continuum emission in a galaxy represents the total Lyman continuum emission from O and B stars, so that for a given initial mass function (IMF), the number of O and B stars can be computed exactly from the total Lyman continuum flux. Condon (1992)

scales this relationship to reflect star formation rates for stars larger than $5M_{\odot}$:

$$\frac{L(\text{H}\alpha)}{W} \approx 4.4 \times 10^{34} \left(\frac{\text{SFR}(M > 5M_{\odot})}{M_{\odot} \text{ yr}^{-1}} \right). \quad (1.14)$$

We can substitute the SFR for $L(\text{H}\alpha)$ in Equation 1.13 to derive Equation 23 in Condon (1992):

$$\frac{L_{\text{T}}}{W \text{ Hz}^{-1}} = 5.5 \times 10^{20} \left(\frac{\nu}{\text{GHz}} \right)^{-0.1} \left(\frac{\text{SFR}(M > 5 M_{\odot})}{M_{\odot} \text{ yr}^{-1}} \right). \quad (1.15)$$

In this way, we can use an expected line to continuum ratio, as well as a well-modeled star formation rate for $\text{H}\alpha$, to derive a relationship between extinction-free thermal radio emission from recently-formed O-type stars and the rate at which those stars are formed.

In order to derive a relationship between a galaxy's thermal radio continuum luminosity and the rate at which it is forming all stars between $0.1 M_{\odot}$ and $100 M_{\odot}$, we must multiply Equation 1.15 by a scaling factor dependent on our choice of IMF. The massive star formation rates derived in Condon (1992) and Kennicutt (1983) were found using an extended Miller-Scalo IMF (Miller & Scalo 1979), which uses a broken power law:

$$\psi(m) \propto m^{-1.4} \quad \text{for } 0.1 M_{\odot} < m < 1 M_{\odot} \quad (1.16)$$

$$\psi(m) \propto m^{-2.5} \quad \text{for } 1 M_{\odot} < m < 100 M_{\odot}. \quad (1.17)$$

In this thesis, we use a Kroupa IMF (Kroupa 2001), which has power law indices of -1.3 between $0.1 M_{\odot}$ and $0.5 M_{\odot}$ and -2.3 between $0.5 M_{\odot}$ and $100 M_{\odot}$. To scale a galaxy's rate of massive ($M > 5 M_{\odot}$) star formation calculated using an extended Miller-Scalo IMF to its total star formation rate for all stars with masses $0.1 M_{\odot} < M < 100 M_{\odot}$ calculated using a Kroupa IMF (Kroupa 2001), we can divide two integrals. For a Miller-Scalo IMF,

$$\frac{\text{SFR } (M > 5 M_{\odot})}{M_{\odot} \text{ yr}^{-1}} = \int_{5 M_{\odot}}^{100 M_{\odot}} k m m^{-2.5} dm \quad (1.18)$$

where k is a constant with units yr^{-1} . Evaluating the integral gives $\text{SFR } (M > 5 M_{\odot})/M_{\odot} \text{ yr}^{-1} = k \times 0.694 M_{\odot}$. For the same physical conditions, a Kroupa IMF would find that for all stars from $0.1 M_{\odot}$ to $100 M_{\odot}$,

$$\frac{\text{SFR } (M > 0.1 M_{\odot})}{M_{\odot} \text{ yr}^{-1}} = \int_{0.1 M_{\odot}}^{0.5 M_{\odot}} k m m^{-1.3} dm + \int_{0.5 M_{\odot}}^{100 M_{\odot}} k m m^{-2.3} dm. \quad (1.19)$$

Evaluating this integral gives $\text{SFR } (M > 0.1 M_{\odot})/M_{\odot} \text{ yr}^{-1} = k \times 3.86 M_{\odot}$. Dividing the result of the integrated Kroupa IMF by the result of the integrated Miller-Scalo IMF gives a scaling factor of 5.56 between these two SFRs. Putting all of these steps together allows us to calculate a star formation rate for stars between $0.1 M_{\odot}$ and $100 M_{\odot}$ after measuring the thermal radio continuum emission in a galaxy.

1.2.2.2 Star formation rates from nonthermal synchrotron radio continuum emission

When ultrarelativistic electrons are accelerated by magnetic field lines, these electrons emit synchrotron radiation. In galaxies without AGN, most synchrotron emission is produced by electrons in remnants of massive star (Type II) supernovae that eventually enter the more diffuse interstellar medium outside of the supernova remnants. Since all stars with $M \geq 8 M_{\odot}$ become supernovae, if the rate of supernova events can be measured for a galaxy, then the number of supernova-producing stars that have been recently formed can be estimated. Thus, a galaxy's supernova rate (the death rate of massive stars) is closely related to its star formation rate (the birth rate of all stars). Following Condon & Yin (1990) and Condon (1992), we can relate a galaxy's supernova rate to the galaxy's IMF:

$$\frac{\nu_{\text{SN}}}{\text{yr}^{-1}} = \int_{8 M_{\odot}}^{100 M_{\odot}} \psi(m) dm. \quad (1.20)$$

Using the same Miller-Scalo IMF from the previous derivation, the supernova rate becomes

$$\frac{\nu_{\text{SN}}}{\text{yr}^{-1}} = \int_{8 M_{\odot}}^{100 M_{\odot}} k m^{-2.5} dm, \quad (1.21)$$

which when evaluated yields the result $\nu_{\text{SN}}/\text{yr}^{-1} = k \times 0.029 M_{\odot}$. We can also define the star formation rate of stars with $M > 5 M_{\odot}$ as

$$\frac{\text{SFR} (M > 5 M_{\odot})}{M_{\odot} \text{ yr}^{-1}} = \int_{5 M_{\odot}}^{100 M_{\odot}} m \psi(m) dm. \quad (1.22)$$

which for the same IMF becomes

$$\frac{\text{SFR (M} > 5 \text{ M}_\odot\text{)}}{\text{M}_\odot \text{ yr}^{-1}} = \int_{8 \text{ M}_\odot}^{100 \text{ M}_\odot} k m m^{-2.5} dm. \quad (1.23)$$

Evaluating this integral gives the result $\text{SFR (M} > 5 \text{ M}_\odot\text{)}/\text{M}_\odot \text{ yr}^{-1} = k \times 0.694 \text{ M}_\odot$.

If we solve for k in both the ν_{SN} and SFR results and set the two equations equal, we can relate the supernova rate and the star formation rate in an observed region by

$$\frac{\text{SFR (M} > 5 \text{ M}_\odot\text{)}}{\text{M}_\odot \text{ yr}^{-1}} = 24.1 \frac{\nu_{SN}}{\text{yr}^{-1}}. \quad (1.24)$$

To scale the massive SFR to a total SFR from $0.1 \text{ M}_\odot$ to $100 \text{ M}_\odot$ using a Kroupa IMF rather than a Miller-Scalo IMF, we can use the scale factor we calculated by dividing Equation 1.18 by Equation 1.19 to derive the result

$$\frac{\text{SFR}}{\text{M}_\odot \text{ yr}^{-1}} = 134.1 \frac{\nu_{SN}}{\text{yr}^{-1}}. \quad (1.25)$$

While this relationship between a galaxy's star formation rate and its supernova rate is useful, the supernova rate for a galaxy is not necessarily an easily observable quantity. Instead, we observe the nonthermal synchrotron emission left over after a supernova event. Since the lifetime of this energy is $\sim 100 \text{ Myr}$ (Condon 1992), it is visible long after a supernova has occurred. We can relate the luminosity of this nonthermal emission to a galaxy's supernova rate following the observed relationship

from Condon & Yin (1990):

$$\frac{L_N}{W \text{ Hz}^{-1}} \sim 13 \times 10^{22} \left(\frac{\nu}{\text{GHz}} \right)^{\alpha_N} \left(\frac{\nu_{\text{SN}}}{\text{yr}^{-1}} \right) \quad (1.26)$$

where α_N is the synchrotron spectral index between two observed frequencies defined as

$$\alpha = \frac{\log(S_{\nu_2}/S_{\nu_1})}{\log(\nu_2/\nu_1)}. \quad (1.27)$$

In Chapter 2 and Chapter 4, we will use these relationships between the observable quantities (thermal and nonthermal fluxes), and the derived quantities (SFRs) to characterize galaxies' current episodes of star formation.

1.2.2.3 Far-infrared dust blackbody emission

In addition to the thermal and nonthermal radio continuum emission that we observe in star-forming galaxies, we also observe their far-infrared emission radiated by dust that has been heated by radiation from short-lived massive stars. These dust grains emit thermal blackbody emission at a characteristic temperature, which can be inferred using Wien's law. For a blackbody with an optical depth $\tau(\nu)$, its flux at frequency ν can be approximated as a modified Planck function:

$$S_\nu \propto (1 - e^{-\tau(\nu)}) B_\nu(T) \quad (1.28)$$

where $B_\nu(T) = \nu^3 / (e^{h\nu/kT} - 1)$. If $\tau(\nu) = (\nu/\nu_0)^\beta$ where β is the emissivity, then the flux of a region of dust at a particular frequency is

$$S_\nu \propto \frac{(1 - e^{-(\nu/\nu_0)^\beta}) \nu^3}{e^{h\nu/kT} - 1} \quad (1.29)$$

where T is the intrinsic dust temperature. β controls the slope of the Rayleigh-Jeans long-wavelength component of the blackbody curve, and can vary between 1.0 and 2.0, depending on the shape and composition of dust grains. Yang & Phillips (2007) found that β also inversely correlates with dust temperature. In this thesis, we adopt the value $\beta = 1.5$ for the galaxies in our sample, as is common practice for galaxies that do not have well-sampled long-wavelength data (e.g. Casey 2012).

Calzetti et al. (2010) found an empirical relationship between a galaxy's luminosity at $24 \mu\text{m}$ and its SFR. We use this relationship in Chapter 2. In Chapter 4, we calculate SFRs for LCBGs taking advantage of far-infrared data from a range of wavelengths, so rather than a monochromatic relationship between luminosity at a particular wavelength and a galaxy's SFR, we instead use galaxies' total IR luminosities from $8 \mu\text{m} - 1000 \mu\text{m}$. Kennicutt (1998) modeled continuous star formation using models with a Salpeter IMF ($\psi(m) \propto m^{-2.35}$ for $0.08 M_\odot < M < 100 M_\odot$) and solar metallicities developed by Leitherer & Heckman (1995) for a continuous starburst with an age of 10-100 Myr. For a starburst of this age, the dust heating is dominated by massive, short-lived stars. They found that

$$\text{SFR}(M_\odot \text{ yr}^{-1}) = 1.17 \times 10^{-10} L_{\text{TIR}} \left(1 + \sqrt{\frac{10^9}{L_{\text{TIR}}}} \right) \quad (1.30)$$

where L_{TIR} is in units of solar luminosities. Bell (2003) confirmed this relationship for galaxies with $L < 10^{11} L_{\odot}$, which is true for the galaxies we study in Chapter 4. In order to take advantage of this relationship, we must calculate the total ($8 \mu m - 1000 \mu m$) infrared luminosity of the galaxies we observe. Sanders & Mirabel (1996) approximated the total infrared flux as

$$\frac{F_{8-1000\mu m}}{W \text{ m}^{-2}} = 1.8 \times 10^{-14} (13.48S_{12\mu m} + 5.16S_{25\mu m} + 2.58S_{60\mu m} + S_{100\mu m}) \quad (1.31)$$

where the flux densities at each wavelength are in units of Janskys. We can multiply Equation 1.31 by $4\pi D^2$ to calculate L_{TIR} . Substituting L_{TIR} into Equation 1.30, and multiplying Equation 1.30 by a factor of 0.662 to scale it to a Kroupa (2001) IMF, allows us to calculate SFRs using measured mid- and far-infrared data.

Another physical property of star-forming galaxies that we can calculate from measurements of far-infrared emission is the mass of the dust in the galaxy. Following Hildebrand (1983), the flux at a given frequency from a cloud of N dust grains at a distance D is

$$F_{\nu} = N \frac{\sigma}{D^2} Q(\nu) B(\nu, T) \quad (1.32)$$

where $\sigma = \pi a^2$ is the cross section of a dust grain of radius a , $B(\nu, T)$ is the Planck function, and $Q(\nu)$ is the emissivity of the dust grains. If the total volume of the dust is $V = Nv$, where v is the volume of each dust grain, and V can also be written in terms of the dust mass and the mass density ρ , then we can write the total number

of dust grains as $N = m_d/(\rho v)$. Then the flux density of the dust cloud becomes

$$F_\nu = \frac{m_d}{\rho v} \frac{\sigma}{D^2} Q(\nu) B(\nu, T). \quad (1.33)$$

We can introduce a mass opacity of the dust grains such that

$$\kappa_\nu \rho = n_d C_{ext} \quad (1.34)$$

where C_{ext} is the total extinction cross section defined as the sum of absorption and scattering cross sections, $C_{abs} = Q_{abs}\sigma$, and $C_{sc} = Q_{sc}\sigma$. In this way we can write

$$\kappa_\nu \rho = n_d \sigma (Q_{abs} + Q_{sc}) \quad (1.35)$$

If we approximate $Q(\nu)$ as $Q_{abs} + Q_{sc}$, then we can say

$$\kappa_\nu \rho = n_d \sigma Q(\nu). \quad (1.36)$$

Substituting ρ into the flux density equation gives

$$F_\nu = \frac{m_d \kappa}{v \sigma n_d Q(\nu)} \frac{\sigma}{D^2} Q(\nu) B(\nu, T). \quad (1.37)$$

Since $n_d = N/V = 1/v$, we can cancel terms and solve for m_d :

$$m_d = \frac{F_\nu D^2}{\kappa B(\nu, T)}. \quad (1.38)$$

In this way, if we can measure or assume a dust temperature for a galaxy, we can easily determine its dust mass.

1.3 Organization of the thesis

In this thesis, I approach the study of the evolution of LCBGs in a new way. Previous studies of LCBGs' star formation have focused on their optical properties (at low redshift) or rest-frame UV properties (at high redshift), but light at these wavelengths can suffer from extinction from dust. At radio continuum and far-infrared wavelengths, we can trace recent star formation that may be obscured by dust. In addition, while previous H I studies of LCBGs measured their global H I and CO properties (Garland et al. 2004) or resolved optical spectral lines (Pérez-Gallego et al. 2010, 2011), only five LCBGs have previously been studied with resolved H I data (Garland et al. 2007). Since H I in star-forming galaxies typically extends to larger radii than CO or optical emission lines, and can thus measure both a galaxy's kinematics at large radii and its interactions with companions, our resolved H I observations of LCBGs can better characterize the motions of the gas that ultimately fuels star formation in these galaxies. In my work, I synthesize these two approaches to studying LCBGs to develop a picture of how these galaxies have evolved, and predict their future paths.

This thesis synthesizes three projects to develop an understanding of local star-forming galaxies. In Chapter 2, we use observations of a heterogeneous sample of nearby well-studied star-forming galaxies to develop a method of determining star

formation properties and ages using global measurements of the galaxies' radio continuum emission. This chapter has been published as Rabidoux et al. (2014). In Chapter 3, we use resolved H I observations of nine LCBGs to investigate their H I morphologies, kinematics, evidence of interactions, and H I mass fractions in order to determine whether these galaxies, which are analogs to higher- z star-forming galaxies, are rotationally-supported, building bulges, or strongly interacting with companions. In Chapter 4, we apply the methods we developed in Chapter 2 to investigate the star formation properties of a sample of 42 local LCBGs to determine the ages of their starbursts to better understand the triggering and quenching mechanisms of higher- z star-forming galaxies. Finally, we conclude with an assessment of what we know about LCBGs, and what their future paths may be.

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Chapter 2

Radio continuum observations of local star-forming galaxies using the Caltech Continuum Backend on the Green Bank Telescope¹

Abstract

We observed radio continuum emission in 27 local ($D < 70$ Mpc) star-forming galaxies with the Robert C. Byrd Green Bank Telescope between 26 GHz and 40 GHz using the Caltech Continuum Backend. We obtained detections for 22 of these galaxies at all four sub-bands and four more marginal detections by taking the average flux across the entire bandwidth. This is the first detection (full or marginal) at these frequencies for 22 of these galaxies. We fit spectral energy distributions (SEDs) for all of the four-sub-band detections. For 14 of the galaxies, SEDs were best fit by a combination of thermal free-free and nonthermal synchrotron components. Eight galaxies with four-sub-band detections had steep spectra that were only fit by a single nonthermal component. Using these fits, we calculated supernova rates, total number of equivalent O stars, and star formation rates within each $\sim 23''$ beam. For unresolved galaxies, these physical properties characterize the galaxies' recent star formation on a global scale. We confirm that the radio-far-infrared correlation holds for the unresolved galaxies' total 33 GHz flux regardless of their thermal fractions,

though the scatter on this correlation is larger than that at 1.4 GHz. In addition, we found that for the unresolved galaxies, there is an inverse relationship between the ratio of 33 GHz flux to total far-infrared flux and the steepness of the galaxy’s spectral index between 1.4 GHz and 33 GHz. This relationship could be an indicator of the timescale of the observed episode of star formation.

2.1 Introduction

Radio continuum emission traces star formation on timescales of up to 100 Myr (Condon 1992). Two physical processes resulting from massive star formation produce most of the radio continuum emission between 1 and 100 GHz in star-forming galaxies: (1) nonthermal synchrotron emission from relativistic electrons accelerated by magnetic fields as a result of recent supernovae and (2) thermal free-free emission from gas ionized by young massive stars (Condon 1992). The nonthermal emission is closely tied to the number of supernova-generating massive stars produced in recent episodes of star formation, while the thermal emission gives a nearly direct measure of the current equivalent number of O stars via the ionizing flux in the sampled area. Since each component traces a physical process with a well-known timescale, we can use measurements of the radio continuum to determine star formation rates and constrain the ages of recent episodes of star formation.

Recent studies of nearby star-forming galaxies with interferometers have emphasized resolving individual star-forming regions (e.g. Beck, Turner, and Kovo 2000;

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Johnson, Indebetouw, and Pisano 2003; Johnson and Kobulnicky 2003; Johnson et al. 2004; Tsai et al. 2006; Reines, Johnson, and Goss 2008; Johnson, Hunt, and Reines 2009; Aversa et al. 2011). Since radio continuum emission is not affected by extinction, it can be used to observe deeply embedded regions of current star formation that have not yet shed their surrounding material and are thus invisible at shorter wavelengths. These studies have taken advantage of interferometers’ exceptional spatial resolution to probe very young starbursts whose optical emission is obscured by dust. While these studies have been invaluable for determining star formation properties in galaxies outside of our own, the high angular resolution and missing short-spacing data of interferometers, especially at higher frequencies, “resolves out” the diffuse radio continuum emission outside of compact star-forming regions. This effect disproportionately impacts synchrotron emission, which tends to be much more diffuse than the primarily thermal emission surrounding areas of ongoing massive star formation (Johnson et al. 2009). Unlike interferometers, single dish telescopes are not plagued by missing short spacings. Therefore, these telescopes provide a way to simultaneously measure the compact thermal and diffuse non-thermal components of a galaxy’s radio continuum emission in order to characterize its *global* star formation properties.

Determining the relative contributions of the thermal and nonthermal components of the measured flux of entire galaxies can be challenging. Fortunately, each component has a distinct behavior with respect to frequency, and therefore we can model radio continuum emission with a simple two-component fit. Radio continuum flux follows a power law relation such that $S_\nu \propto \nu^\alpha$, where α is the spectral index

that is characteristic of a source’s emission. Optically thin thermal emission exhibits $\alpha = -0.1$, and nonthermal emission exhibits $\alpha \approx -0.8$ (Condon 1992). To determine a reliable fit to these parameters, observations sampling the same physical area at multiple, widely-spaced frequencies are required. If only one frequency is observed, it is impossible to determine the relative contributions of each emission process without previous knowledge of the source. Since single dish telescopes are sensitive to both compact thermal and diffuse nonthermal emission over large spatial extents, they are useful for constraining the large-scale properties of multiple components of a galaxy’s radio continuum emission, and are thus powerful probes of star formation.

The goal of this paper is to characterize the *global* star formation properties of local galaxies. Our observations were taken in four independent channels continuous in frequency across the full 26-40 GHz span of Ka band. This range in frequencies is where a typical star-forming galaxy’s global radio continuum emission would be expected to contain relatively equal amounts of flux from steep-spectrum synchrotron and flat-spectrum thermal sources (Condon 1992). Our observations are thus ideal for approximating the relative contributions of each type of emission at this “lever arm” frequency range. Using new radio continuum observations centered at 27.75 GHz, 31.25 GHz, 34.75 GHz, and 38.25 GHz, as well as archival NVSS 1.4 GHz and IRAS 60 μm and 100 μm data, we have determined these galaxies’ thermal fractions and star formation rates. We have also explored the radio-far-infrared correlation in these galaxies and its implications for their star formation timescales. We will describe the galaxy sample and our observations and data reduction in Section 2, present our

results and address the process of fitting spectral energy distributions to our data in Section 3, and finally conclude in Section 4.

2.2 Data

2.2.1 Sample Selection

We selected a heterogeneous group of 27 local ($D < 70$ Mpc), well-studied star-forming galaxies with known thermal radio continuum emission. Our sample contains galaxies spanning a variety of shapes, sizes, and environments, from blue compact dwarfs to grand-design spirals, including major and minor mergers, with members of compact groups as well as more isolated galaxies (see Table 3.1 for galaxy types). The intention was to observe as many types of star-forming galaxies as possible to probe star formation in a diverse range of environments. See Table 3.1 and Figure 2.1 for sample properties. For more information on each galaxy’s previous radio continuum observations and discussions of their properties, see the papers named in Table 3.1.

The galaxies in our sample span a range of distances (1-70 Mpc) and properties. They all have previously detected radio emission and ongoing star formation that covers three orders of magnitude in star formation rate. Thus, they are strong targets for a study of global radio continuum properties at a frequency range that probes both thermal free-free and nonthermal synchrotron star formation indicators. As seen in Figure 2.1, these galaxies are largely less massive and have higher star formation rates than the Milky Way, and have subsolar metallicities. However, their properties are not so similar that they can be considered as a single class. It would not be surprising

Figure 2.1 *Top Left:* Distribution of distances in our sample. *Top Right:* Distribution of K band optical galactic stellar masses in our sample estimated using the (B-V) color and the expression in Bell & de Jong (2001). *Bottom Left:* Metallicity distribution for our sample estimated from the B band absolute magnitude using the expression in Tremonti et al. (2004). *Bottom Right:* Star formation rate for galaxies in our sample calculated using the $25\mu\text{m}$ IRAS fluxes for our sample and the expression in Calzetti et al. (2010). Not all galaxies are represented in every histogram.

if their radio continuum properties also encompassed a range of values. Our analysis is best understood as reflecting properties of nearby star-forming galaxies, though it is beyond the scope of this paper to perform detailed analysis on each galaxy individually.

2.2.2 Observations and Data Reduction

We observed the galaxies in our sample with the Caltech Continuum Backend (CCB) on the Robert C. Byrd Green Bank Telescope (GBT)² using single pointings. The CCB is designed for the GBT’s dual-beam Ka band receiver spanning the entire range of frequencies from 26-40 GHz. The primary observing mode of the CCB is a 70 second “nod”, where each beam takes a turn as the on-source beam while the other beam is off-source. We observed 24 of the galaxies using a single nod each, while we observed eight galaxies using multiple nods, which we then averaged. Five galaxies in our sample were observed on two different nights with both of these methods; we treated these on a case-by-case basis and chose the observation(s) with the best weather and elevation conditions. We used the standard NRAO primary flux calibrators 3C 147 and 3C 48 for flux calibration, as well as nearby pointing calibrators to ensure accurate pointing. See Table 3.1 for a summary of the observations.

We reduced our data using IDL reduction routines developed by B. Mason (for details on the data reduction process, see Mason et al. 2009). Data with wind speeds over 5 m s^{-1} were excluded due to the possibility of large pointing errors. We detected 22 galaxies in all four channels. When a galaxy’s flux was lower than the 2σ level in one or more of the four channels, we combined the channels’ fluxes to produce one average flux across the entire band, centered at 33 GHz. One galaxy, Pox 4, was detected at the 5σ level after averaging the four channels. Three additional galaxies were marginally detected (between 2σ and 3σ) using this method. We report an

²The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

upper limit 33 GHz flux for one galaxy, Tol 35. The galaxies’ observed fluxes are reported in Table 2.2.

Since the angular size of a telescope’s beam is inversely proportional to the frequency observed, the beam size of the GBT varies appreciably across the 26-40 GHz range of our observations ($\sim 27''$ in the lowest-frequency sub-band versus $\sim 19''$ in the highest-frequency sub-band, see Figure 2.2 for an illustration). We followed the procedure of Murphy et al. (2010) to correct for differing beam sizes in each of the four sub-bands. First, we imaged an archival VLA radio continuum map of each galaxy (typically at frequencies of 4-10 GHz) using the AIPS task IMAGR. For these maps, we selected the archival UV data from the NRAO science data archive³ with the closest beamsizes to our Ka-band data. We explicitly imposed each of the four CCB beam sizes on these images using BMIN and BMAJ (assuming a circular beam). We determined correction factors for each beam by normalizing the flux contained in each beam area in the archival map to the flux in the 34.75 GHz port’s $\sim 21''$ beam. This procedure partially adjusts for more flux being observed at lower frequencies due to these frequencies’ intrinsically larger beam sizes. We then could approximate “beam-matched” flux measurements to determine spectral indices between 26-40 GHz (see Figure 2.3 for an illustration of the galaxies’ spectral indices before and after applying the corrections). NGC 1222 did not have available archival data, so we applied to it the average correction factors of all of the other galaxies. We emphasize that these correction factors are only approximate. In many cases, they are based on resolved archival images that may not contain all of the galaxies’ radio flux. In particular, these resolved images may contain most of the thermal emission, which tends to be

compact, but underestimate the galaxies' nonthermal emission, which tends to be diffuse. This could bias the correction factors to be closer to 1.0 than should be the case, especially in the highest-frequency (and thus highest-resolution) channel. See Table 2.3 for the beam correction factors for each galaxy.

The dominant sources of uncertainty in our beam corrections are systematic errors due to the geometries of our sources. The smallest corrections possible are for a galaxy whose most diffuse, extended flux is still contained within the smallest beam and is unresolved by the lower-frequency interferometric observations. This type of source would look identical to all four of the GBT beam sizes. In this case, the correction factors would be 1.0 for each sub-band. For a source much more extended than the beam sizes, the maximum deviations from no beam corrections in each sub-band are -36%, -19%, 0%, and +21%. Pointing offsets from the peak of radio emission can also be sources of systematic error, though the errors depend on whether the source is compact or extended, and the magnitude of the pointing offset from the central peak of radio emission. These errors are typically smaller than the maximum deviations discussed above. Since we do not know how much diffuse emission is missing in the archival data, we do not have enough information to quantify uncertainties in the beam correction factors for each galaxy.

Many of the galaxies that we observed were more extended than the $\sim 23''$ beam size of the GBT at 33 GHz. In these cases, radio continuum fluxes and star formation rates should only be interpreted as covering the inner $\sim 23''$ of the galaxies. The

³<https://archive.nrao.edu>

Figure 2.2 Largest ($\sim 27''$) and smallest ($\sim 19''$) beam sizes overlaid on SDSS g or DSS B images of each galaxy observed. The galaxies are presented in the order listed in Table 1 viewed left to right and top to bottom.

Figure 2.2 Continued.

Figure 2.3 Distribution of α_{26-40} before correcting for beam size (left) and after the corrections have been applied (right). The beam size corrections flatten α_{26-40} relative to uncorrected data.

Figure 2.4 Average CCB beamsize ($\sim 23''$, white) and circle with radius ($\sim 78''$) equal to the separation between the “on” and “off” beams (blue) overlaid on an optical (SDSS g) image of M 101. M 101 and M 51 are both larger than the beam separation, which likely results in an oversubtraction when the flux in the “off” beam is subtracted from the flux in the “on” beam.

galaxies with resolved lower-frequency archival data that was more extended than the beam size are flagged with a “1” in Table 2.4.

The CCB has a beam separation of $78''$ between the “on” and “off” beams. M 51 and M 101 are more extended than that separation in both optical images (see Figure 2.4) and in maps of their lower-frequency radio continuum emission (Klein et al. 1984; Graeve et al. 1990). In these cases, our flux measurements may be lower than the true amount of flux contained within the beam. There is likely to be radio continuum emission at the “off” positions, which would cause an oversubtraction of flux in the reduction process.

2.3 Results and Discussion

2.3.1 Fluxes

For 22 of the 27 galaxies that we observed, the fluxes we report are the first detections (either in all four sub-bands or averaged) at ~ 33 GHz. Four of the galaxies in our sample were previously observed with the CCB by Murphy et al. (2012), three of which were detected (M 101 was reported as an upper limit by Murphy et al. (2012) and is a 2.6σ marginal detection when the four sub-bands were averaged in our observations). Only one galaxy in our sample, Tol 35, was not detected when averaging four sub-bands' fluxes. Its 3σ upper-limit flux is 0.87 mJy. This galaxy was observed at a very low elevation (7.9°), so it was observed with large atmospheric extinction. See Table 2.2 for the uncorrected fluxes, and Table 2.4 for the fluxes corrected for the differing beam sizes of each frequency.

2.3.2 Spectral energy distribution fitting

We fit a spectral energy distribution (SED) for each galaxy that was detected in all four sub-bands using the four CCB fluxes and archival NRAO VLA Sky Survey (NVSS) 1.4 GHz fluxes (measured with a $45''$ aperture). We assumed a two-component fit of nonthermal emission with a spectral index $\alpha_N = -0.8$ and thermal emission with a spectral index $\alpha_T = -0.1$. These fits are plotted in Figure 4.5. Though the spectral index of nonthermal emission can vary (this phenomenon is described further in Section 3.2.1), we used this simple model because we only fit to five data points for each galaxy; our model did not include enough data to justify additional

free parameters. We do not see evidence of anomalous dust emission in the observed regions of these galaxies (for explanations of anomalous dust, see Draine & Lazarian 1998; Murphy et al. 2010). Our observations are also at frequencies low enough to have negligible contributions from the low-frequency tail of the dust blackbody. Therefore, we did not include any thermal dust emission in our fits. Our spectra also do not show the inverted structure characteristic of self-absorption or optically thick thermal emission, so we did not include either of these components. From these fits, we determined each galaxy’s thermal and nonthermal fluxes at 33 GHz.

None of the galaxies have globally flat spectra indicative of purely thermal emission, nor the inverted spectra seen in some resolved observations of very young, obscured thermal sources. Thermal emission was the primary component at 33 GHz in some galaxies, while others had less prominent or even negligible thermal components in the observed regions. In contrast to radio continuum studies done at high spatial resolution, our single dish observations detect the diffuse synchrotron emission produced by past supernovae in addition to the strong compact thermal emission from H II regions, so the spectral indices that we derive are typically much steeper than those derived only from detections of compact radio sources. Since our observations do not spatially separate regions of thermal and nonthermal emission, we cannot further distinguish the two components in that way.

Figure 2.5 NVSS 1.4 GHz and CCB 26-40 GHz points for each galaxy that was detected with all four CCB sub-bands. In most cases, the error bars are smaller than the point size. The best-fit spectral energy distribution for each galaxy is also plotted. Each SED was fit with a combination of nonthermal and thermal components (black line). The purple dashed line is the nonthermal ($\alpha_N = -0.8$) component, the blue dotted line is the thermal ($\alpha_T = -0.1$) component. When a galaxy's SED could not be fit with the inclusion of a positive thermal component, we only fit the nonthermal component (the thermal flux at 33 GHz is calculated as an upper limit in such cases). Galaxies that are resolved at 33 GHz are marked with an *.

Figure 2.5 Continued.

2.3.2.1 Galaxies with steep radio spectra

The fitted spectra for eight of the 27 galaxies (Arp 217, NGC 4449, NGC 2903, Maffei II, NGC 4038, M 51, NGC 4490, and NGC 1741) are significantly steeper than can be fit by a combination of thermal ($\alpha_T = -0.1$) and nonthermal ($\alpha_N = -0.8$) components (see Figure 4.5). When we could not fit a galaxy’s SED with both the thermal and nonthermal components at the 2σ level, we used only a single-component fit that assumed no thermal flux and a fixed nonthermal spectral index of $\alpha_N = -0.8$ for consistency. The thermal fluxes and associated properties of this group of galaxies are reported as upper limits. We used the total flux in the 34.75 GHz channel plus 3σ as a conservative upper limit to the thermal flux in these cases.

There are two possible explanations for the steep spectra that we see in some galaxies. There could be technical considerations due to imperfect beam-matching in our data, or there could be physical processes taking place within these galaxies causing their spectra to steepen at high frequencies. In order to have more accurate SED fits—and more precise star formation rates—we would need to have beam-matched observations of the same regions at many different frequencies.

The correction factors for differing beam sizes that are given in Table 2.3 are limited by being calculated using higher-resolution data that could be missing extended emission. If extended emission is missing in the archival data, the correction factors in Table 2.3 could be closer to 1.0 than is actually the case. While all of the correction factors calculated act to flatten the SED between 26 GHz and 40 GHz with respect to the uncorrected data, it is possible that they do not flatten the SED enough

if they do not reflect contributions from extended emission (as discussed in Section 2.2). In addition, we did not correct for mismatched beams between the $\sim 45''$ NVSS data and the $\sim 23''$ CCB data. This beam difference only affects resolved galaxies (those marked with a “1” in Table 2.4), which comprise 33% of our sample. It is possible that synchrotron emission is more adversely affected by the differences in beam sizes than thermal emission. More diffuse synchrotron emission could be undetected at higher frequencies (and thus smaller beam sizes) than would be expected for a smooth flux distribution observed with two apertures of different sizes. If this is the case in our observed regions, it could explain why some of our galaxies’ spectra steepen at the frequencies we observed. It is also possible that the choice of where the GBT beams were pointed within a galaxy could affect its fluxes in different beam sizes. If the beam is not centered on the galaxy (in the case of unresolved galaxies) or is not centered on a bright knot of emission (in the case of resolved galaxies), the smaller beams could contain even less flux than would be expected after corrections for the beams’ areas. NGC 1741 and NGC 4490 are likely affected by pointing offsets, as seen by comparing the GBT pointing in Table 3.1 to previous radio continuum maps in Figure 2 of Beck et al. (2000) and Figure 4 of Aversa et al. (2011). As described in Section 2.2, pointing offsets from the peak of radio continuum emission result in the need for larger beam correction factors than derived from the archival radio continuum data, the lack of which result in steep spectra at the observed frequencies.

In addition to the technical issue of mismatched beam sizes, there are possible physical explanations for steep spectra in star-forming galaxies. It is difficult to distinguish between a spectrum with a nonthermal component having $\alpha_N \approx -0.8$

coupled with a low thermal fraction from a spectrum with a steeper nonthermal component coupled with a relatively high thermal fraction (Condon 1992). Though the spectral indices that we used are typical values (Condon 1992), they can vary depending on the physical parameters of the observed regions. Thermal emission can have a positive spectral index if the emission regions are optically thick, though we do not see any evidence that this is occurring on the angular scale of our observations. Nonthermal spectral indices can be positive at low frequencies due to synchrotron self-absorption (which we do not observe), or become more negative with increasing frequency and increasing scale height from the disk due to aging cosmic ray electrons losing energy as they propagate outward from their parent supernovae (Seaquist et al. 1985; Carlstrom & Kronberg 1991; Heesen et al. 2009). Kepley et al. (2011) calculated the timescale for synchrotron losses for cosmic ray electrons in NGC 4214 to be 44 Myr at 1.4 GHz and 18 Myr at 8.5 GHz. There is also some evidence of steepening spectra at higher frequencies ($\gtrsim 10$ GHz) for luminous and ultra-luminous infrared galaxies, as well as in the post-starburst galaxy NGC 1569 (Israel & de Bruyn 1988; Lisenfeld et al. 2004; Clemens et al. 2008; Calzetti et al. 2010; Lintott et al. 2011). These authors hypothesize that winds or outflows may disperse synchrotron emission from its parent source more quickly than would be expected for simple diffusion. This rapid dispersal could cause a dearth of synchrotron emission at higher frequencies on shorter timescales than would be predicted from the timescale of energy loss. Lintott et al. (2011) also hypothesize that there could be a modified injection spectrum in galaxies where this is the case. Our sample of galaxies does not contain any LIRGs or ULIRGs, and we do not see steepening in our measurements of NGC 1569. We

are only observing the inner region of NGC 1569, while the dispersed synchrotron emission resides in its outer halo, so it is not surprising that we do not observe a steepening spectrum in this galaxy.

We suspect that the steep spectra seen in our sample are primarily a result of imperfect beam matching as discussed above. This is especially likely to be the case for the galaxies resolved by the GBT at 33 GHz, since these galaxies will have emission that is outside of the view of the GBT beam but is included in the NVSS flux. As discussed earlier, the galaxies that appear unresolved in archival maps could still have diffuse synchrotron emission that was not detected in the archival data but that is more extended than the $23''$ beam at 33 GHz. Five of the eight resolved galaxies that were detected in all sub-bands had steep spectra (four out of those five are classified as spiral galaxies), while only three of the fourteen unresolved galaxies had this feature. Two of these three are classified as SABbc galaxies, while the third is classified as peculiar. It is possible that these steep-spectrum galaxies contain emission in their spiral arms that is extended with respect to the GBT's smaller beam but is observed in the NVSS data. In Figure 4.5, most of the galaxies with steep spectra (and thus single component fits) also showed the NVSS 1.4 GHz data point being located above the best-fit line expected for purely nonthermal emission. This could be a consequence of the larger beam at 1.4 GHz sampling a larger physical area of emission. Even so, the alternative physical explanations merit consideration, especially in the case of the unresolved galaxies. In Figure 2.7, which will be discussed further in Section 4.6, the three unresolved galaxies with steep spectra (NGC 1741, NGC 2903, and Arp 217) have elevated 1.4 GHz fluxes with respect to what would

be expected from the radio-far infrared correlation. Since the 33 GHz fluxes of these galaxies are not similarly elevated with respect to their far-infrared fluxes in Figure 2.7, their steep radio spectra may indicate an internal physical process that strongly increases the amount of synchrotron emission.

2.3.3 Thermal fractions

The average thermal fraction fit by two-component models at 33 GHz was 54%, with a 1σ scatter of 24% and a range of 10%-90%. The average is consistent, albeit with large scatter, with the average global thermal fraction at 33 GHz in star-forming galaxies without active galactic nuclei following the relation

$$\frac{S}{S_T} \sim 1 + 10 \left(\frac{\nu}{\text{GHz}} \right)^{0.1+\alpha_N} \quad (2.1)$$

where $\alpha_N = -0.8$ is the nonthermal spectral index, S_T is the thermal flux at a given frequency, and S is the total flux at that frequency (Condon & Yin 1990). When a two-component fit was not possible, we report the thermal flux as the corrected flux at 34.75 GHz plus 3σ , which gives a very conservative upper limit. We expect from the galaxies' SEDs that their true thermal fractions are very low at 33 GHz, which we assume in the rest of our analysis.

2.3.3.1 Implications for star formation timescales

The large scatter in the thermal fraction is likely a consequence of our heterogeneous galaxy sample; these galaxies are at different stages of evolution and have

different star formation rates, stellar populations, and physical properties (Beck et al. 2000). Some of them may have a very recent (< 10 Myr) burst of star formation that produces a large amount of free-free emission that dominates their spectra from 1-100 GHz. Others may be in between episodes of very active star formation and instead be experiencing a more quiescent phase, which would result in a relatively low thermal fraction and steepening nonthermal component at 33 GHz due to synchrotron energy losses at high frequencies.

Thermal emission traces very recent star formation, since it comes from ionized regions around short-lived, massive stars. For a single starburst, a spectrum showing solely thermal emission requires that too few supernovae have yet occurred to detect their emission. This would constrain the starburst to be less than ~ 6 Myr old (or even younger, depending on the mass and lifetime of the most massive O stars in the starburst; Maeder & Meynet (1989) find the lifetime of a $120 M_{\odot}$ star to be 3.4 Myr). A complete absence of thermal flux implies the absence of enough massive O stars to have detectable free-free emission for a long enough period of time that the emission has dissipated from its parent region. If this was the case, the starburst is likely at least 30 Myr old (the lifetime of the least massive supernova progenitors). On the other hand, nonthermal emission probes star formation on longer timescales ($30 \text{ Myr} < \tau < 100 \text{ Myr}$). It is produced by recent supernovae of stars that can be less massive and have longer lifetimes than the O stars that produce thermal emission (see Figure 9 of Condon 1992). The presence of nonthermal emission implies that the starburst is at least 6 Myr old but younger than the timescale dictated by synchrotron energy loss for the galaxy's magnetic field (~ 100 Myr) (Condon 1992).

We note that there are limits to the amount of each component that we can detect, so the timescales quoted in the previous paragraph are only approximate. To constrain how much nonthermal emission could be present in a spectrum that appears purely thermal, we generated spectra with varying thermal fractions with fluxes at the same five frequencies as those in our data set (1.4 GHz, 27.75 GHz, 31.25 GHz, 34.75 GHz, and 38.25 GHz) and 10% errors on the fluxes. When these spectra are fit with a two-component model assuming $\alpha_T = -0.1$ and $\alpha_N = -0.8$, nonthermal emission can only be detected in the spectra for thermal fractions less than 97%. This means that the galaxy could have some nonthermal emission (up to 3% for 10% errors on the fluxes), but the emission would be undetectable and thus the starburst would appear younger than it is. Similarly, a spectrum could look like it contains no thermal emission while actually containing quite a bit. For the same spectra with 10% errors on the fluxes, thermal fractions of up to 20% resulted in undetectable thermal components. This means that a galaxy could look like its massive star formation has ceased while still having a small thermal component.

For the galaxies in our sample, this picture could be more complicated. The quoted timescales in this section are for an isolated single starburst. Since our observations measure star formation properties on large angular scales, the galaxies may have multiple overlapping generations of star formation that are not easily separated in time. We are also sampling different structures and physical scales in each galaxy. For some galaxies, we are only observing the most central region. For these galaxies, we may be missing the majority of the ongoing star formation happening in outer regions and spiral arms. For the more compact galaxies, however, we are likely

measuring the entirety of the galaxy’s star formation within the GBT beam, so our measurements characterize their global star formation properties.

2.3.4 O stars producing ionizing photons

For those galaxies whose SEDs were fit with thermal components, we used their fluxes at 33 GHz to calculate their thermal luminosities. We then used those luminosities to calculate the number of ionizing photons responsible for the thermal fluxes seen within the GBT beam following Equation 2 in Condon (1992):

$$\left(\frac{Q_{Lyc}}{s^{-1}}\right) \geq 6.3 \times 10^{52} \left(\frac{T_e}{10^4 K}\right)^{-0.45} \left(\frac{\nu}{GHz}\right)^{0.1} \left(\frac{L_T}{10^{20} WHz^{-1}}\right), \quad (2.2)$$

where Q_{Lyc} is the number of Lyman continuum photons emitted by the region on thermal emission, T_e is the electron temperature, and L_T is the thermal luminosity. The resulting values are detailed in Table 2.5 (unresolved galaxies) and Table 2.6 (resolved galaxies). We used an electron temperature of $10^4 K$, as is typical for star-forming regions (Condon 1992), and used $Q_0 = 10^{49} s^{-1}$ as the number of Lyman continuum photons emitted by an O7.5V star from Table 5 in Vacca et al. (1996). We report the total number of O7.5V stars in the galaxies that are unresolved by the GBT at 33 GHz, and the number of O7.5V stars per square kiloparsec for the resolved galaxies in Tables 2.5 and 2.6. As seen in Table 2.5, the number of O7.5V stars in each unresolved galaxy varies widely (log # O7.5V stars is between 2.42 and 4.66). This is likely due to the wide range in the unresolved galaxies’ overall star formation rates and physical areas observed.

2.3.5 Supernova rates

Since we were able to fit nonthermal components for all of our galaxies, we calculated supernova rates (ν_{SN}) for each of them following Equation 18 in Condon (1992):

$$\left(\frac{L_N}{10^{22}\text{WHz}^{-1}}\right) \sim 13 \left(\frac{\nu}{\text{GHz}}\right)^{-0.8} \left(\frac{\nu_{SN}}{\text{yr}^{-1}}\right), \quad (2.3)$$

where L_N is the nonthermal luminosity. We report the total supernova rate of the unresolved galaxies in Table 2.5, while for the resolved galaxies we report the supernova rate per square kiloparsec in Table 2.6. The supernova rates of the unresolved galaxies vary by three orders of magnitude (log SNe rate between -3.72 and -0.71), which is not surprising given the differences in star formation rates and physical areas sampled.

2.3.6 Star formation rates

We calculated massive star formation rates (SFRs) from thermal fluxes for each galaxy whose SEDs have a thermal component and from nonthermal fluxes for all of our galaxies following Equations 21 and 23 of Condon (1992):

$$\left(\frac{L_N}{\text{WHz}^{-1}}\right) \sim 5.3 \times 10^{21} \left(\frac{\nu}{\text{GHz}}\right)^{-0.8} \left(\frac{\text{SFR}_N (M \geq 5 \text{ M}_\odot)}{\text{M}_\odot\text{yr}^{-1}}\right) \quad (2.4)$$

$$\left(\frac{L_T}{\text{WHz}^{-1}}\right) \sim 5.5 \times 10^{20} \left(\frac{\nu}{\text{GHz}}\right)^{-0.1} \left(\frac{\text{SFR}_T (M \geq 5 \text{ M}_\odot)}{\text{M}_\odot\text{yr}^{-1}}\right) \quad (2.5)$$

where L_T and L_N are thermal and nonthermal luminosities, respectively, calculated from each galaxy's thermal and nonthermal fluxes, and $\nu = 33 \text{ GHz}$. These equations

are derived from Equations 2 and 18 of Condon (1992) (reproduced as Equations 2.2 and 2.3 in this chapter). Those equations were derived assuming (1) an extended Miller-Scalo IMF (Miller & Scalo 1979) with an exponent of -2.5 , (2) that all stars with masses greater than $8 M_{\odot}$ become supernovae, and (3) that dust absorption is negligible (Condon 1992). We then scaled the massive SFRs generated by each equation by a factor of 5.6 to transform them to total SFRs ($M \geq 0.1 M_{\odot}$) calculated with a Kroupa IMF (Kroupa 2001). The galaxies' SFRs calculated from their thermal and nonthermal fluxes are shown in Table 2.5 (unresolved galaxies) and Table 2.6 (resolved galaxies). We report the total massive SFRs of the unresolved galaxies, while we report the massive SFR per square kiloparsec of the resolved galaxies. All of the galaxies for which we calculated both thermal and nonthermal SFRs showed agreement between the two to within an order of magnitude, but not necessarily to within their margins of uncertainty. The disagreement correlates with the thermal fractions of each galaxy: galaxies with high thermal fractions were likely to have higher thermal SFRs than nonthermal SFRs, while galaxies with low thermal fractions showed the opposite relation. Like the differences in thermal fractions between galaxies in our sample, disagreement could be due to the different star formation timescales traced by the thermal and nonthermal fluxes. Since these two emission components are caused by physical processes that operate over differing lengths of time (as discussed in Section 3.3.1), it is possible that the discrepancies between the star formation rates could be used to infer the recent star formation histories of the observed regions.

We compared the radio continuum SFRs to monochromatic SFRs from $24\mu\text{m}$ fluxes as described in Calzetti et al. (2010). The galaxies' SFRs (for the unresolved galaxies) and SFR densities (for the resolved galaxies) derived from $24\mu\text{m}$ fluxes are listed in Table 2.5 and Table 2.6. In Figure 2.6, we compare the SFRs derived from thermal and nonthermal radio continuum fluxes of the unresolved galaxies for which we fit two-component SEDs to SFRs derived from $24\mu\text{m}$ fluxes. We find that most of the galaxies in our sample have higher radio continuum SFRs (both from thermal and nonthermal fluxes) than SFRs from $24\mu\text{m}$ data. One possible explanation for this is that extinction is lower at radio wavelengths than it is at $24\mu\text{m}$. Another possible explanation is that since radio continuum emission traces very young star formation while $24\mu\text{m}$ emission traces less recent star formation, higher SFRs calculated from radio continuum observations than from $24\mu\text{m}$ data could be another indication that our sample of galaxies is undergoing recent star formation.

2.3.7 Radio-far-infrared correlation

There is a well-established tight correlation between far-infrared (FIR) and radio flux in star-forming galaxies (e.g. Helou et al. 1985; Murphy et al. 2006, 2012). When plotted on a log-log scale, the relationship between radio continuum and FIR flux for star-forming galaxies appears linear. This correlation has been well-studied at low frequencies (~ 1.4 GHz) where synchrotron emission is the dominant component of radio emission in a star-forming galaxy. We investigated whether this correlation could also be found on a global scale at 33 GHz, where synchrotron emission is

Figure 2.6 Star formation rates calculated from nonthermal (filled symbols) and thermal (open symbols) radio continuum fluxes plotted against SFRs calculated from IRAS $25\mu\text{m}$ fluxes according to Equations 1 and 17 from Calzetti et al. (2010). The solid black line represents equal SFRs at radio and infrared wavelengths. Most galaxies have higher SFRs when calculated using radio continuum fluxes, which trace more recent star formation than infrared fluxes.

weaker than it is at 1.4 GHz and the relative contribution from thermal emission is more significant.

We limited our study of the radio-FIR correlation to the galaxies in our sample that are unresolved with the GBT beam at 33 GHz (as discussed in Section 2.2). We chose this limit to ensure that we were observing both the total area of radio emission and total area of far-infrared emission in each galaxy. This minimizes issues related to the different beam sizes of the GBT and IRAS (objects are considered point sources to IRAS if they are more compact than $1'$ at $60\text{ }\mu\text{m}$ and $2'$ at $100\text{ }\mu\text{m}$).

We fit a power law to our 33 GHz flux as a function of total FIR flux. The total FIR flux was determined by a combination of archival IRAS $100\text{ }\mu\text{m}$ and $60\text{ }\mu\text{m}$ fluxes as described in Harmanec (1988) ($S_{\text{FIR}} = 2.58S_{60\mu\text{m}} + S_{100\mu\text{m}}$). We chose to compute each galaxy's 33 GHz flux by taking the average of its fluxes in the four sub-bands. We used this measure (rather than the flux at 33 GHz inferred from the galaxies' SEDs) in order to eliminate possible uncertainties in the flux due to using assumed spectral indices in our fits. We found that the fluxes were related by $\log S_{33} = (0.88 \pm 0.01)\log S_{\text{FIR}} + \log (5.3 \times 10^{-4} \pm 6 \times 10^{-5})$. This correlation is relatively well-fit (the fractional errors of both fit parameters are small) even though our sample contains a wide range of thermal fractions. Murphy et al. (2012) found a similar correlation between 33 GHz and $24\text{ }\mu\text{m}$ fluxes for resolved nuclei and individual star-forming regions of galaxies. We find that the radio-FIR correlation at 33 GHz can be extended to global measurements of galaxies' fluxes.

As a control of the tightness of the radio-FIR correlation in our sample, we also fit a relationship between the galaxies' NVSS 1.4 GHz fluxes and their total

FIR fluxes. This relationship for the unresolved galaxies in our sample is $\log S_{1.4} = (0.85 \pm 0.01)\log S_{\text{FIR}} + \log (0.0047 \pm 0.0006)$. The fractional uncertainties on the fit parameters are similar to those of the fit at 33 GHz. We plot both correlations in Figure 2.7.

As discussed in Section 3.2, we have determined thermal fractions from SED fits assuming fixed thermal and nonthermal spectral indices. Due to the limited number of radio data points we have for each galaxy, we cannot more accurately constrain the thermal fractions at 33 GHz of the galaxies in our sample at this time. Therefore, we do not have enough information to definitively isolate thermal and nonthermal components to explore whether the radio-FIR correlation is equally tight for each. As an estimate, we have coded approximate thermal fractions in the plot. Even given these limitations, we are confident that a correlation exists between the unresolved galaxies' total radio flux at 33 GHz and total FIR flux. Murphy et al. (2012) found a similar correlation at 33 GHz for resolved nuclei and star-forming regions of galaxies.

To further constrain the radio-FIR correlation at 33 GHz in our sample, we calculated q_ν for each galaxy. q_ν is a logarithmic measure of the ratio of total far-infrared flux (S_{FIR} in Janskys) to radio continuum flux (S_ν) in units of $\text{Wm}^{-2}\text{Hz}^{-1}$ at a given frequency. It is defined in Helou et al. (1985) as

$$q_\nu = \log \left(\frac{S_{\text{FIR}} \cdot 1.26 \times 10^{-14} \text{ Wm}^{-2}}{3.75 \times 10^{12} \text{ Hz}} \right) - \log \left(\frac{S_\nu}{\text{Wm}^{-2} \text{ Hz}^{-1}} \right). \quad (2.6)$$

The average q_{33} for our sample is $q_{33} = 3.3$, with a 1σ scatter of 0.3. Condon (1992) reported that at 1.4 GHz, the average value of $q_{1.4}$ from a large sample of galaxies

Figure 2.7 Radio-far-infrared correlation for 1.4 GHz (top) and 33 GHz (bottom) fluxes vs. total far-infrared flux. The FIR flux is derived from a combination of IRAS $60\ \mu\text{m}$ and $100\ \mu\text{m}$ data. All of the galaxies unresolved with the GBT's $23''$ beam are plotted except for SBS 0335-052, which was not detected by IRAS, and Pox 4, which was not detected at $100\ \mu\text{m}$. The lines that best fit each data set are also plotted. The galaxies are coded by thermal fraction at 33 GHz. While the correlation is tighter at 1.4 GHz than it is at 33 GHz, it is still easily seen at 33 GHz. Since the galaxies with the highest thermal fractions all lie above the best-fit line at 33 GHz (but don't at 1.4 GHz), it is possible that some of the scatter in the correlation at 33 GHz is due to the increased proportion of thermal emission at higher frequencies.

is $q_{1.4} = 2.3 \pm 0.2$. The average value of q_ν at 1.4 GHz for this set of galaxies is $q_{1.4} = 2.4 \pm 0.2$, consistent with the Condon (1992) value. Since q_ν is a function of the ratio of FIR flux to radio flux at a given frequency, it makes sense that q_ν is larger using 33 GHz fluxes than it is using 1.4 GHz fluxes (star-forming galaxies are generally much brighter at 1.4 GHz than at 33 GHz). The scatter on q_ν at 33 GHz is larger than that at 1.4 GHz, which indicates that the radio-FIR correlation is not as tight at 33 GHz as at 1.4 GHz. This may be due to contamination from increased thermal flux at 33 GHz. If the correlation is solely between synchrotron and FIR emission, thermal flux at 33 GHz will increase the scatter in the correlation. However, due to our small sample size, we cannot rule out the possibility that the correlation is just as strong at 33 GHz, where thermal fractions are higher, as it is at 1.4 GHz, where nonthermal emission is typically much stronger. We note that the galaxies with the highest thermal fractions lie above the fitted correlation at 33 GHz, while the same is not true at 1.4 GHz, which supports thermal emission being the cause of increased scatter.

In addition to plotting the radio-FIR correlation, we also plot the ratio of 33 GHz flux to FIR flux, q_{33}^{-1} , against $\alpha_{1.4-33}$ for our unresolved galaxies in Figure 2.8, similar to Murphy et al. (2012). The plot shows an increasing q_{33}^{-1} for flatter values of $\alpha_{1.4-33}$. Flatter $\alpha_{1.4-33}$ values are presumably indicative of a higher proportion of thermal flux to nonthermal flux, which is reflected in the highest thermal fractions in our sample also having the flattest $\alpha_{1.4-33}$. A correlation between an elevated q_{33}^{-1} and flat values of $\alpha_{1.4-33}$ is not surprising if the radio-FIR correlation is solely dependent on synchrotron emission. If the radio-FIR correlation was independent of the type of

radio emission, q_{33}^{-1} should be relatively constant between galaxies and should not be affected by different spectral indices or thermal fractions. Our data support that the radio-FIR correlation is independent of a galaxy’s thermal emission since the addition of thermal emission results in elevated ratios of 33 GHz flux to FIR flux.

2.3.7.1 Implications for star formation timescales

When the timescales of the emission mechanisms for thermal, nonthermal, and FIR fluxes are taken into account, the observed relationship between the ratio of 33 GHz and FIR fluxes and $\alpha_{1.4-33}$ may be a way to age-date an episode of star formation. Since thermal flux is only produced by the shortest-lived ($\tau < 10$ Myr) massive stars, its presence in large quantities relative to synchrotron emission is indicative of very young star formation. Since in addition to massive stars, infrared emission also traces less massive stars ($M > 5 M_{\odot}$) that live longer than the $M > 8 M_{\odot}$ stars that produce thermal and nonthermal radio emission (Devereux & Young 1990), FIR emission is a tracer of star formation on longer timescales. Stars with these masses can live up to ~ 100 Myr, while nonthermal radio emission traces stars with lifetimes of up to ~ 30 Myr and whose emission is detectable for up to 100 Myr (for an illustrative plot of stellar lifetimes, see Figure 3 of Romano et al. 2005). In addition, infrared emission also contains a component from diffuse dust that is heated by lower-mass stars with lifetimes longer than 100 Myr. These timescales could mean that the galaxies that show both flat spectral indices and enhanced q_{33}^{-1} also host the youngest areas of ongoing star formation. This correlation could then be a method

Figure 2.8 q_{33}^{-1} vs $\alpha_{1.4-33}$ using 33 GHz fluxes for unresolved galaxies. q_{ν}^{-1} is a measure of the ratio between radio flux and total far-infrared flux at a given radio frequency. As in Figure 2.7, SBS 0335-052 and Pox 4 are not plotted. The red diamonds represent the highest thermal fraction (greater than 75%). The green squares represent galaxies with thermal fractions between 50% and 75%. The blue circles represent galaxies with thermal fractions less than 50%. The purple inverted triangles represent galaxies where we were only able to determine upper limits for their thermal fractions. The light blue triangles represent galaxies that were only marginally detected at 33 GHz, so no thermal fraction was calculated. At 33 GHz, the ratio of radio flux to total FIR flux is highest when $\alpha_{1.4-33}$ is flat and thermal fractions are high. These three properties are all indicative of recent star formation. Thus, it is possible that these properties together act as a rough measure of the timescale of the current episode of star formation.

of determining approximate ages for galaxies’ global star formation. As a simple test, we used a Starburst 99 model of a single instantaneous burst using default inputs (solar metallicity, a 2-component Kroupa IMF, and no effects of cosmic ray aging, escape, or absorption taken into account) run for 100 Myr (Leitherer et al. 1999; Vázquez & Leitherer 2005; Lacki et al. 2010). This model, depicted in Figure 2.9, shows the flattest spectral indices and highest thermal fractions at the earliest times of the starburst. Similarly, the steepest spectral indices and lowest thermal fractions were seen as the lowest-mass stars that produce supernovae were dying (at ~ 40 Myr). The starburst’s ratio of 33 GHz luminosity to FIR luminosity was also high at early times (between 3 Myr and 40 Myr) while the lowest ratios of 33 GHz luminosity to FIR luminosity were seen even later (after 40 Myr). While modeling a more robust quantitative relationship between this observed correlation and the age of each galaxy’s star-forming episode is beyond the scope of this work (the simple model we used does not take into account multiple co-existing generations of star formation), the apparent relationship between enhanced 33 GHz flux, flat spectral indices, and high thermal fractions is a promising metric for future global radio and far-infrared photometric studies of star-forming galaxies. Our simple model is not robust enough to constrain the timescales’ uncertainties, but is only meant to be illustrative of a correlation visible in our data.

Figure 2.9 Spectral index between 1.4 GHz and 33 GHz (top), thermal fraction (middle), and ratio of 33 GHz luminosity to total far-infrared luminosity (bottom) for a simple Starburst 99 model of an instantaneous starburst. The large jumps in each curve at 40 Myr are due to the supernova rate dropping to zero at that time, as all of the stars massive enough to produce supernovae (and thus nonthermal emission) have died. The flattest spectral indices and highest thermal fractions are seen at the earliest times after the beginning of the starburst (up to 3 Myr), while the steepest spectral indices and lowest thermal fractions are seen at later times as more supernovae occur, up to 40 Myr, after which the supernovae cease. Similarly, the higher ratios of 33 GHz luminosity to FIR luminosity were seen during the lifetimes of massive stars, while the lowest ratios of 33 GHz luminosity to FIR luminosity were seen after supernovae ended, though this trend is delayed with respect to the timelines in the top two panels. This model demonstrates that flat spectral indices, high thermal fractions, and elevated 33 GHz fluxes with respect to FIR fluxes are all indicative of very recent star formation.

2.4 Conclusions

We have observed 27 local, well-studied, star-forming galaxies between 26-40 GHz with the GBT and obtained the first detections at this frequency range for 22 of the galaxies. We determined the contributions of thermal free-free and nonthermal synchrotron emission to the galaxies' total radio emission. We have used these measures to derive the number of massive, short-lived O stars and the number of recent supernovae in the observed regions of each galaxy. In addition, we have calculated SFRs for each galaxy using thermal and nonthermal fluxes and explored the radio-FIR correlation for the unresolved galaxies. We found that

- None of the galaxies have spectral indices indicative of purely thermal emission; eight galaxies show spectra that are too steep to fit thermal components,
- Thermal fractions range from 10% to 90%, with a median of 55%,
- The radio-far infrared correlation holds for the unresolved galaxies at 1.4 GHz and 33 GHz, though the scatter at 33 GHz is larger due to the increased influence of thermal emission at higher frequencies, and
- Galaxies with flat $\alpha_{1.4-33}$ and high thermal fractions have enhanced radio flux at 33 GHz with respect to far-infrared flux, which identifies them as galaxies with recent star formation. This is consistent with a simple model of a single starburst.

We found that the observed regions of our galaxies had a diverse mix of radio continuum characteristics, with some galaxies' SEDs being dominated at 33 GHz

by the thermal emission indicative of ongoing massive star formation, while others have little or no detectable thermal emission. Even with this spread in the relative contributions of thermal and nonthermal emission, we saw that there is still a correlation between the global 33 GHz and far-infrared flux in the unresolved galaxies. The scatter in the correlation is larger than that at 1.4 GHz, likely due to the increased influence of thermal emission at 33 GHz. We cannot, however, rule out that the radio-FIR correlation is not solely dependent on synchrotron emission. We also found that higher ratios of 33 GHz emission to FIR emission correlated with flatter spectral indices (and higher thermal fractions) for unresolved galaxies, which is consistent with younger ages in simple starburst models. This correlation may be useful as a rough indicator of the age of the most recent episode of star formation. Future global studies of more homogeneous galaxy populations or resolved studies of individual star-forming regions will enable better modeling of star formation timescales using this metric.

In giving a broad measure of nearby galaxies' radio continuum emission, our observations complement previous studies done with interferometers in which individual star-forming regions in local galaxies were highly resolved. With the GBT, we can simultaneously observe compact and diffuse thermal and nonthermal emission and determine their relative intensities, and in doing so estimate the timescale for the current episode of star formation. Unfortunately, we cannot make stricter timescale estimates than those discussed in Section 3.3 at this time, as we do not have enough radio data points to robustly fit thermal and nonthermal flux components with vary-

ing spectral indices. Obtaining more unresolved radio fluxes at lower and higher frequencies would help this effort.

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Table 2.1. Observation summary

Source	RA ^a (J2000)	Dec (J2000)	D (Mpc)	R_{25} ^b (arcsec)	$R_{23''}$ (kpc)	Hubble Type ^c	# nods ^d	Ref code ^e
NGC 520	01:24:34.8	+03:47:29	30.5 ± 2.1	122.2 ± 3.2	1.7	Sa	2	B03
Maffei II	02:41:55.9	+59:36:14	3.11 ± 0.23	20.8 ± 4.3	0.17	SBbc	2	T94, T06
NGC 1222	03:08:56.8	-02:57:18	32.4 ± 2.3	47.5 ± 3.6	1.8	E/S0	1	B07
SBS 0335-052	03:37:44.0	-05:02:40	53.7 ± 3.8	13.8^e	3.0	BCG/starburst ^g	2	J09
IC 342	03:46:48.5	+68:05:46	3.93 ± 0.27	599 ± 3.1	0.22	SABc	1	M12, T06
NGC 1569	04:30:49.3	+64:50:52	1.39 ± 0.11	116.7 ± 3.2	0.08	IB	3	L04
VII Zw 19	04:40:47.3	+67:44:09	67.4 ± 5.5	12.8 ± 3.6	3.8	E	3	B00
NGC 1741	05:01:38.3	-04:15:24	54.6 ± 3.8	36.1 ± 3.6	3.0	Sm	1	B00

Table 2.1—Continued

Source	RA ^a (J2000)	Dec (J2000)	D (Mpc)	R_{25} ^b (arcsec)	$R_{23''}$ (kpc)	Hubble Type ^c	# nods ^d	Ref code ^e
II Zw 40	05:55:42.6	+03:23:32	11.1 ± 0.80	16.8^f	0.62	Sbc	3	B02
Mrk 8	07:29:26.3	+72:07:44	52.5 ± 3.7	26.1 ± 4.1	2.9	Sbc	1	B00
Mrk 86	08:13:14.6	+45:59:29	7.94 ± 1.5	61.3 ± 3.4	0.44	SBm	1	A11
NGC 2903	09:32:09.7	+21:30:02	7.39 ± 0.52	360.8 ± 3.1	0.41	SABb	1	T06
NGC 2997	09:45:38.7	-31:11:25	13.8 ± 0.90	307.0 ± 3.1	0.77	SABc	1	K11
Mrk 1236	09:49:54.1	+00:36:58	27.6 ± 5.1	36.1 ± 3.3	1.5	WR/HII ^g	1	B00
NGC 3077	10:03:20.2	+68:44:01	2.55 ± 0.19	157.4 ± 3.2	0.14	S?	1	M12, R05
NGC 3125	10:06:33.6	-29:56:08	13.8 ± 1.0	36.1 ± 3.3	0.77	E	1	A11

Table 2.1—Continued

Source	RA ^a (J2000)	Dec (J2000)	D (Mpc)	R_{25} ^b (arcsec)	$R_{23''}$ (kpc)	Hubble Type ^c	# nods ^d	Ref code ^e
Arp 233	10:32:31.1	+54:24:04	25.5 ± 1.8	34.4 ± 3.4	1.4	I	1	T72, B00, A11
Arp 217	10:38:45.9	+53:30:11	19.2 ± 1.3	57.2 ± 3.3	1.1	SABb	1	A11
Haro 3	10:45:22.4	+55:57:37	18.5 ± 1.3	40.5 ± 3.4	1.0	Sb	1	T72, J04, A11
Pox 4	11:51:11.7	-20:35:57	52.5 ± 3.9	19.4 ± 3.4	2.9	Sm	1	B00
NGC 4038	12:01:52.5	-18:52:02	21.5 ± 1.6	161.1 ± 3.2	1.2	SBm	1	C04
NGC 4214	12:15:39.2	+36:19:41	2.94 ± 0.27	202.8 ± 3.2	0.16	IB	1	B00
NGC 4449	12:28:10.1	+44:05:33	3.54 ± 0.25	140.3 ± 3.2	0.20	IB	1	R08
NGC 4490	12:30:36.7	+41:38:26	9.22 ± 0.65	202.8 ± 3.3	0.51	SBcd	1	A11

Table 2.1—Continued

Source	RA ^a (J2000)	Dec (J2000)	D (Mpc)	R_{25} ^b (arcsec)	$R_{23''}$ (kpc)	Hubble Type ^c	# nods ^d	Ref code ^e
Tol 35	13:27:07.2	-27:57:26	25.2 ± 1.8	43.4 ± 3.4	1.4	Sab	1	B00
M 51	13:29:52.4	+47:11:40	7.90 ± 0.85	414.1 ± 3.1	0.44	Sbc	1	M12, T94, D11
M 101	14:03:12.5	+54:20:53	6.46 ± 0.18	719.7 ± 3.1	0.36	SABc	1	M12, T94

^aRA and Dec are center positions of the beam for each observation.

^b R_{25} values are derived from average d_{25} from Hyperleda (<http://leda.univ-lyon1.fr/>).

^cHubble types from Hyperleda except where specified.

^dEach nod is 70 seconds long.

^eThese galaxies have previously published radio continuum observations. M12 denotes galaxies detected with the CCB by Murphy et al. (2012) at 33 GHz. T72 denotes galaxies that were observed, but not detected, by Tovmassian (1972) at 9.5 mm (31.6 GHz). T94 (Turner & Ho 1994), B00 (Beck et al. 2000), B02 (Bressan et al. 2002), B03 (Bell 2003), C04 (Chyży & Beck 2004), J04 (Johnson et al. 2004), L04 (Lisenfeld et al. 2004), R05 (Rosa-González 2005), T06 (Tsai et al. 2006), B 07 (Beck et al. 2007), R08 (Reines et al. 2008), J09 (Johnson et al. 2009), D11 (Dwek & Cherkneff 2011), K11 (Kodilkar et al. 2011), and A11 (Aversa et al. 2011) denote galaxies that were observed at lower frequencies. The galaxies are described in more detail in these papers.

^fNo radius data available from Hyperleda so major axis diameter from NED is reported.

^gNo Hubble type data available from Hyperleda so classification listed on NED is reported.

Table 2.2. Observed Flux

Source	27.75 GHz (mJy)	31.25 GHz (mJy)	34.75 GHz (mJy)	38.25 GHz (mJy)
Four-sub-band detections: flux in each sub-band				
NGC 520	21.77 ± 0.39	19.50 ± 0.19	17.44 ± 0.27	15.43 ± 0.43
Maffei II	23.17 ± 0.28	19.42 ± 0.16	16.36 ± 0.20	13.98 ± 0.29
NGC 1222	9.83 ± 0.53	8.57 ± 0.25	7.91 ± 0.36	7.26 ± 0.54
SBS 0335-052	0.66 ± 0.20	0.62 ± 0.12	0.69 ± 0.18	0.52 ± 0.24
IC 342	35.59 ± 3.46	31.03 ± 0.87	27.82 ± 1.08	25.25 ± 2.21
NGC 1569	28.60 ± 0.19	24.67 ± 0.12	21.31 ± 0.15	18.75 ± 0.21
VII Zw 19	3.16 ± 0.27	2.60 ± 0.14	2.26 ± 0.19	2.11 ± 0.27
NGC 1741	2.12 ± 0.31	2.07 ± 0.18	1.67 ± 0.22	0.84 ± 0.32
II Zw 40	15.09 ± 2.00	14.12 ± 0.50	12.99 ± 0.62	12.20 ± 1.28
Mrk 8	3.23 ± 0.38	2.84 ± 0.39	2.21 ± 0.33	2.53 ± 0.42
NGC 2903	14.50 ± 1.47	12.80 ± 0.52	11.15 ± 0.82	9.60 ± 1.16
NGC 2997	5.14 ± 1.12	4.77 ± 0.45	4.38 ± 0.63	3.90 ± 0.85
NGC 3077	6.94 ± 0.39	5.93 ± 0.38	5.45 ± 0.32	4.71 ± 0.43
NGC 3125	8.15 ± 1.03	7.43 ± 0.44	6.52 ± 0.58	5.92 ± 0.79

Table 2.2—Continued

Source	27.75 GHz (mJy)	31.25 GHz (mJy)	34.75 GHz (mJy)	38.25 GHz (mJy)
Arp 233	4.22 ± 0.43	4.05 ± 0.40	3.49 ± 0.31	2.93 ± 0.43
Arp 217	25.98 ± 0.43	21.65 ± 0.40	19.04 ± 0.31	16.26 ± 0.43
Haro 3	6.10 ± 0.43	5.49 ± 0.40	4.78 ± 0.31	4.35 ± 0.43
NGC 4038	7.77 ± 0.96	5.44 ± 0.42	4.64 ± 0.55	4.27 ± 0.74
NGC 4214	7.18 ± 0.93	6.22 ± 0.38	5.26 ± 0.48	4.68 ± 0.69
NGC 4449	4.37 ± 0.90	3.45 ± 0.38	2.73 ± 0.44	2.30 ± 0.65
NGC 4490	3.40 ± 0.90	2.64 ± 0.38	1.64 ± 0.46	1.33 ± 0.66
M 51	7.67 ± 0.94	5.84 ± 0.38	4.89 ± 0.47	3.65 ± 0.65
Marginal detections: average of four sub-bands' fluxes				
Mrk 86	0.42 ± 0.19			
Mrk 1236	0.99 ± 0.40			
Pox 4	1.62 ± 0.29			
Tol 35	< 0.87			
M 101 ^b	0.69 ± 0.27			

^a α_{26-40} is calculated using the 27.75 GHz and 38.25 GHz fluxes.

^bThe lower-frequency radio continuum emission of M 101 is more extended than the separation between the on-source and off-source beams (Graeve et al. 1990), so its reported flux may suffer from oversubtraction due to emission in the off-source beam.

Table 2.3. Beam correction factors for galaxies detected in all four sub-bands

Source Beamsize	27.75 GHz 26.7 "	31.25 GHz 23.7 "	34.75 GHz 21.3 "	38.25 GHz 19.4 "
NGC 520	0.99	0.99	1	1.01
Maffei II	0.89	0.95	1	1.05
NGC 1222 ^a	...	...	...	...
SBS 0335-052	0.98	0.99	1	1.01
IC 342	0.93	0.97	1	1.03
NGC 1569	0.81	0.91	1	1.09
VII Zw 19	0.97	0.99	1	1.02
NGC 1741	0.98	0.99	1	1.01
II Zw 40	0.95	0.97	1	1.03
Mrk 8	0.92	0.96	1	1.04
NGC 2903	0.96	0.98	1	1.03
NGC 2997	0.89	0.94	1	1.07
NGC 3077	0.97	0.98	1	1.02
NGC 3125	0.92	0.96	1	1.04
Arp 233	0.98	0.99	1	1.01

Table 2.3—Continued

Source	27.75 GHz	31.25 GHz	34.75 GHz	38.25 GHz
Beamsize	26.7 ''	23.7 ''	21.3 ''	19.4 ''
Arp 217	0.87	0.93	1	1.07
Haro 3	0.95	0.98	1	1.03
NGC 4038	0.83	0.94	1	1.03
NGC 4214	0.87	0.94	1	1.07
NGC 4449	0.78	0.89	1	1.11
NGC 4490	0.75	0.87	1	1.13
M 51	0.83	0.91	1	1.08
average	0.91	0.95	1	1.05
standard dev	0.07	0.04	0	0.04

^aNGC 1222 did not have archival radio data available for re-imaging, so average beam correction values were used.

Table 2.4. Corrected Flux

Source	27.75 GHz (mJy)	31.25 GHz (mJy)	34.75 GHz (mJy)	38.25 GHz (mJy)	α_{26-40} ^a	Notes ^b
Four-port detections: flux in each port						
NGC 520	21.54 ± 0.39	19.30 ± 0.19	17.44 ± 0.27	15.58 ± 0.43	-1.01 ± 0.10	
Maffei II	20.62 ± 0.28	18.45 ± 0.16	16.36 ± 0.20	14.68 ± 0.29	-1.06 ± 0.07	1
NGC 1222	8.94 ± 0.53	8.14 ± 0.25	7.91 ± 0.36	7.62 ± 0.54	-0.50 ± 0.29	2
SBS 0335-052	0.65 ± 0.20	0.61 ± 0.12	0.69 ± 0.18	0.53 ± 0.24	-0.65 ± 1.7	
IC 342	33.10 ± 3.5	30.10 ± 0.87	27.82 ± 1.1	26.01 ± 2.2	-0.75 ± 0.42	
NGC 1569	23.17 ± 0.19	22.45 ± 0.12	21.31 ± 0.15	20.44 ± 0.21	-0.39 ± 0.04	1
VII Zw 19	3.07 ± 0.27	2.54 ± 0.14	2.26 ± 0.19	2.15 ± 0.27	-1.10 ± 0.48	

Table 2.4—Continued

Source	27.75 GHz (mJy)	31.25 GHz (mJy)	34.75 GHz (mJy)	38.25 GHz (mJy)	α_{26-40} ^a	Notes ^b
NGC 1741	2.08 ± 0.31	2.05 ± 0.18	1.67 ± 0.22	0.85 ± 0.32	$-2.78^2 \pm 1.3$	
II Zw 40	14.33 ± 2.0	13.70 ± 0.50	12.99 ± 0.62	12.59 ± 1.3	-0.41 ± 0.54	
Mrk 8	2.97 ± 0.38	2.72 ± 0.39	2.21 ± 0.33	2.63 ± 0.42	-0.38 ± 0.64	
NGC 2903	13.91 ± 1.5	12.54 ± 0.52	11.15 ± 0.82	9.89 ± 1.2	-1.06 ± 0.51	
NGC 2997	4.58 ± 1.1	4.48 ± 0.45	4.38 ± 0.63	4.17 ± 0.85	-0.29 ± 0.98	1
NGC 3077	6.73 ± 0.39	5.81 ± 0.38	5.45 ± 0.32	4.80 ± 0.43	-1.05 ± 0.33	
NGC 3125	7.49 ± 1.0	7.13 ± 0.44	6.52 ± 0.58	6.15 ± 0.79	-0.62 ± 0.58	
Arp 233	4.14 ± 0.43	4.01 ± 0.40	3.49 ± 0.31	2.96 ± 0.43	-1.05 ± 0.56	

Table 2.4—Continued

Source	27.75 GHz (mJy)	31.25 GHz (mJy)	34.75 GHz (mJy)	38.25 GHz (mJy)	α_{26-40} ^a	Notes ^b
Arp 217	22.60 ± 0.43	20.14 ± 0.40	19.04 ± 0.31	17.40 ± 0.43	-0.81 ± 0.10	
Haro 3	5.79 ± 0.43	5.38 ± 0.40	4.78 ± 0.31	4.48 ± 0.43	-0.80 ± 0.38	
NGC 4038	6.45 ± 0.96	5.11 ± 0.42	4.64 ± 0.55	4.39 ± 0.74	-1.20 ± 0.70	1
NGC 4214	6.25 ± 0.93	5.84 ± 0.38	5.26 ± 0.48	5.01 ± 0.69	-0.69 ± 0.63	1
NGC 4449	3.41 ± 0.90	3.07 ± 0.38	2.73 ± 0.44	2.56 ± 0.65	-0.90 ± 1.1	1
NGC 4490	2.55 ± 0.90	2.30 ± 0.38	1.64 ± 0.46	1.50 ± 0.66	-1.65 ± 1.8	1
M 51	6.36 ± 0.94	5.32 ± 0.38	4.89 ± 0.47	3.94 ± 0.65	-1.49 ± 0.69	1,3

^a α_{26-40} is calculated using the 27.75 GHz and 38.25 GHz fluxes.

^bNotes: 1: Lower-frequency radio continuum emission is more extended than the largest beam. 2: No lower-frequency radio continuum emission available; used characteristic beam-size correction values. 3: The lower-frequency radio continuum emission of M 51 is more extended than the separation between the on-source and off-source beams (Klein et al. 1984), so its reported flux may suffer from oversubtraction due to emission in the off-source beam.

^cThough α_{26-40} for NGC 1741 is extremely steep (determining α_{26-40} via calculation and via a fit both result in $\alpha_{26-40} < -2$), its SED can be fit with a spectral index of $\alpha = -0.8$ when a 1.4 GHz data point is incorporated into the fit.

Table 2.5. Star formation properties of unresolved galaxies

Source	Thermal fraction ^a	Log max # O7.5V stars	Log SNe rate (yr^{-1})	Thermal SFR ^b ($M_{\odot}yr^{-1}$)	Nonthermal SFR ^c ($M_{\odot}yr^{-1}$)	Infrared SFR ^d ($M_{\odot}yr^{-1}$)
NGC 520	0.24 ± 0.01	4.65	-0.71	7.16 ± 0.43	26.7 ± 3.7	5.99 ± 0.94
NGC 1222	0.43 ± 0.02	4.59	-1.14	6.26 ± 0.48	9.8 ± 1.4	5.03 ± 0.79
SBS0335-052	0.79 ± 0.06	4.18	-2.25	2.43 ± 0.50	0.77 ± 0.25	...
IC 342	0.53 ± 0.02	3.41	-2.50	0.41 ± 0.03	0.43 ± 0.06	0.60 ± 0.09
VII Zw 19	0.38 ± 0.003	4.66	-0.97	7.28 ± 0.07	14.4 ± 2.3	16.6 ± 3.0
NGC 1741	< 1.00	< 4.87	-1.03	< 12.0	12.7 ± 1.8	3.80 ± 0.62
II Zw 40	0.91 ± 0.01	4.20	-2.63	2.57 ± 0.09	0.32 ± 0.05	0.46 ± 0.08
Mrk 8	0.50 ± 0.05	4.58	-1.26	6.1 ± 1.1	7.4 ± 1.2	2.19 ± 0.38
NGC 2903	< 0.94	< 3.90	-1.92	< 1.28	1.62 ± 0.23	0.31 ± 0.05

Table 2.5—Continued

Source	Thermal fraction ^a	Log max # O7.5V stars	Log SNe rate (yr^{-1})	Thermal SFR ^b ($M_{\odot}yr^{-1}$)	Nonthermal SFR ^c ($M_{\odot}yr^{-1}$)	Infrared SFR ^d ($M_{\odot}yr^{-1}$)
NGC 3077	0.66 ± 0.02	2.42	-3.72	0.042 ± 0.003	0.026 ± 0.004	0.0022 ± 0.004
NGC 3125	0.77 ± 0.02	4.03	-2.35	1.73 ± 0.11	0.61 ± 0.10	0.30 ± 0.06
Arp 233	0.71 ± 0.02	4.25	-1.99	2.89 ± 0.22	1.40 ± 0.21	1.29 ± 0.21
Arp 217	< 0.99	< 4.92	-0.92	< 13.4	16.2 ± 2.1	3.71 ± 0.61
Haro 3	0.85 ± 0.02	4.19	-2.40	2.51 ± 0.13	0.54 ± 0.10	0.65 ± 0.11
Marginal Detections						
Mrk 86	...	< 2.82	< -3.02	< 0.11	< 0.13	0.037 ± 0.015
Mrk 1236	...	< 4.25	< -1.60	< 2.88	< 3.43	0.36 ± 0.15
Pox 4	...	< 4.87	< -0.98	< 11.8	< 14.1	0.87 ± 0.27

Table 2.5—Continued

Source	Thermal fraction ^a	Log max # O7.5V stars	Log SNe rate (yr^{-1})	Thermal SFR ^b ($M_{\odot}yr^{-1}$)	Nonthermal SFR ^c ($M_{\odot}yr^{-1}$)	Infrared SFR ^d ($M_{\odot}yr^{-1}$)
Tol 35	...	< 3.99	< -1.86	< 1.57	< 1.87	...

^aThe thermal fractions of each galaxy at 33 GHz are based on two-component fits, except for the galaxies with negative fitted thermal components. In such cases, the thermal fractions are presented as 3σ upper limits.

^bThermal SFRs are calculated using thermal flux following Equation 4 scaled to a Kroupa IMF.

^cNonthermal SFRs are calculated using nonthermal flux following Equation 5 scaled to a Kroupa IMF.

^dInfrared SFRs are calculated from IRAS $24\mu m$ fluxes using Equations 1 and 17 of Calzetti et al. (2010).

Table 2.6. Star formation properties of resolved galaxies

Source	Thermal fraction ^a	Log max # O7.5V stars (kpc^{-2})	Log SNe rate ($yr^{-1}kpc^{-2}$)	Thermal SFR density ^b ($M_{\odot}yr^{-1}kpc^{-2}$)	Nonthermal SFR density ^c ($M_{\odot}yr^{-1}kpc^{-2}$)	Infrared SFR density ^d ($M_{\odot}yr^{-1}kpc^{-2}$)
MaffeiII	< 0.97	< 4.27	-1.57	< 2.99	3.69 ± 0.77	0.039 ± 0.009
NGC 1569	0.11 ± 0.03	3.41	-1.52	0.41 ± 0.15	4.06 ± 0.92	0.31 ± 0.07
NGC 2997	0.32 ± 0.01	3.19	-2.34	0.25 ± 0.04	0.63 ± 0.12	...
NGC 4038	< 0.87	< 3.84	-1.95	< 1.11	1.53 ± 0.33	...
NGC 4214	0.58 ± 0.03	3.55	-2.44	0.56 ± 0.12	0.49 ± 0.13	0.076 ± 0.022
NGC 4449	< 1.00	< 3.65	-2.25	< 0.72	0.76 ± 0.15	...
NGC 4490	< 0.92	< 3.52	-2.29	< 0.53	0.69 ± 0.15	0.16 ± 0.04
M 51	< 0.94	< 3.84	-1.98	< 1.11	1.41 ± 0.43	0.13 ± 0.04

Table 2.6—Continued

Source	Thermal fraction ^a	Log max # O7.5V stars (kpc^{-2})	Log SNe rate ($yr^{-1}kpc^{-2}$)	Thermal SFR density ^b ($M_{\odot}yr^{-1}kpc^{-2}$)	Nonthermal SFR density ^c ($M_{\odot}yr^{-1}kpc^{-2}$)	Infrared SFR density ^d ($M_{\odot}yr^{-1}kpc^{-2}$)
Marginal Detection						
M 101	...	< 2.83	< -3.02	< 0.26	< 0.32	0.015 ± 0.002

^aThe thermal fractions of each galaxy at 33 GHz are based on two-component fits, except for the galaxies with negative fitted thermal components. In such cases, the thermal fractions are presented as 3σ upper limits.

^bThermal SFR densities are calculated using thermal flux following Equation 4 and scaled to a Kroupa IMF over the area of the $23''$ GBT beam.

^cNonthermal SFR densities are calculated using nonthermal flux following Equation 5 and scaled to a Kroupa IMF over the area of the $23''$ GBT beam.

^dInfrared SFR densities are calculated from IRAS $24\mu m$ fluxes using Equations 1 and 17 of Calzetti et al. (2010) over the area of the $47''$ IRAS beam at $25\mu m$.

Table 2.7. Radio and far-infrared properties of unresolved galaxies

Source	33 GHz flux ^a (mJy)	1.4 GHz flux ^b (mJy)	Far-IR flux ^c (Jy)	$\alpha_{1.4-33}$	q_{33} ^d
NGC 520	18.5 ± 0.2	176.3 ± 5.3	129.72 ± 0.04	-0.71 ± 0.01	3.37 ± 0.004
NGC 1222	8.15 ± 0.22	61.7 ± 1.9	47.89 ± 0.01	-0.64 ± 0.01	3.30 ± 0.01
SBS 0335-052	0.62 ± 0.04	2.3 ± 0.4	...	-0.41 ± 0.06	...
IC 342	29.3 ± 1.1	190.7 ± 7.3	348.22 ± 0.03	-0.59 ± 0.02	3.60 ± 0.02
VII Zw 19	2.51 ± 0.11	20.5 ± 0.7	18.97 ± 0.03	-0.66 ± 0.02	3.40 ± 0.02
NGC 1741	1.66 ± 0.13	30.4 ± 1.6	16.13 ± 0.02	-0.92 ± 0.03	3.51 ± 0.03
II Zw 40	13.4 ± 0.6	32.5 ± 1.1	22.87 ± 0.03	-0.28 ± 0.02	2.76 ± 0.02
Mrk 8	2.63 ± 0.19	18.1 ± 1.0	348.22 ± 0.03	-0.61 ± 0.03	3.11 ± 0.03
Mrk 86	0.42 ± 0.19	10.5 ± 1.7	14.75 ± 0.03	-1.02 ± 0.15	4.07 ± 0.20
NGC 2903	11.9 ± 0.5	444.5 ± 13.9	176.93 ± 0.03	-1.14 ± 0.02	3.70 ± 0.02
Mrk 1236	0.99 ± 0.40	16.5 ± 1.8	11.03 ± 0.03	-0.89 ± 0.13	3.57 ± 0.18
NGC 3077	5.70 ± 0.19	29.0 ± 1.5	61.65 ± 0.02	-0.51 ± 0.02	3.56 ± 0.01
NGC 3125	6.82 ± 0.37	26.6 ± 1.6	19.31 ± 0.03	-0.43 ± 0.03	2.98 ± 0.02
Arp 233	3.65 ± 0.20	16.6 ± 0.6	17.84 ± 0.03	-0.48 ± 0.02	3.22 ± 0.02
Arp 217	19.8 ± 0.2	362.8 ± 12.4	127.65 ± 0.03	-0.92 ± 0.01	3.34 ± 0.004

Table 2.7—Continued

Source	33 GHz flux ^a (mJy)	1.4 GHz flux ^b (mJy)	Far-IR flux ^c (Jy)	$\alpha_{1.4-33}$	q_{33} ^d
Haro 3	5.11 ± 0.20	15.5 ± 0.9	19.51 ± 0.02	-0.35 ± 0.02	3.11 ± 0.02
Pox 4	1.62 ± 0.29	4.2 ± 0.5	...	-0.30 ± 0.07	...

^aThe 33 GHz flux is the average of the corrected fluxes in the four sub-bands.

^bThe 1.4 GHz flux is taken from the NRAO VLA Sky Survey.

^cThe far-IR flux is derived from IRAS $60\mu m$ and $100\mu m$ fluxes using $S_{FIR} = 2.58S_{60\mu m} + S_{100\mu m}$ (Harmanec 1988).

^d q_{33} is a logarithmic measure of the ratio of far-IR flux (in Jy) to 33 GHz flux (in $\text{Wm}^{-2}\text{Hz}^{-1}$).

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Chapter 3

Resolved H I observations of local analogs to $z \sim 1$ luminous compact blue galaxies: evidence for rotation-supported disks¹

Abstract

While bright, blue, compact galaxies are common at $z \sim 1$, they are relatively rare in the local universe, and their evolutionary paths are uncertain. We have obtained resolved H I observations of nine $z \sim 0$ luminous compact blue galaxies (LCBGs) using the Giant Metrewave Radio Telescope and Very Large Array in order to measure their kinematic and dynamical properties and better constrain their evolutionary possibilities. We find that the LCBGs in our sample are rotating galaxies that tend to have nearby companions, relatively high central velocity dispersions, and can have disturbed velocity fields. We compare our measurements to those previously made with single dishes and find that single dish measurements tend to overestimate LCBGs' rotation velocities and H I masses. We also compare the ratio of LCBGs' rotation velocities and velocity dispersions to those of other types of galaxies and find that LCBGs are strongly rotationally supported at large radii, similar to other types of disk galaxies, though within their half-light radii their $\text{H I } V_{\text{rot}}\sigma^{-1}$ values are comparable to stellar $V_{\text{rot}}\sigma^{-1}$ values of dwarf elliptical galaxies. We find that LCBGs'

disks on average are gravitationally stable, though conditions may be conducive to local gravitational instabilities at the largest radii. Such instabilities could lead to the formation of star-forming gas clumps in the disk, resulting eventually in a small central bulge or bar.

3.1 Introduction

3.1.1 LCBGs: Analogs to $z \sim 1$ star-forming galaxies

Luminous compact blue galaxies (LCBGs) are a morphologically heterogeneous class of star-forming galaxies that are defined by their blue colors, high blue luminosities, compact sizes, and high surface brightnesses (Werk et al. 2004). LCBGs at $z < 1$ are selected to have optical properties that are consistent with the small, bright, blue galaxies that appear in deep field observations (Koo et al. 1994; Phillips et al. 1997; Werk et al. 2004). Their strong optical emission lines and blue continua suggest that LCBGs harbor diverse stellar populations, with a current starburst involving approximately a tenth of the galaxy’s mass coexisting with older cohorts of stars of approximately solar metallicity (Hammer et al. 2001; Guzmán et al. 2003; Hoyos et al. 2007). While they are blue and compact, LCBGs are too massive ($M_* \sim 10^9 M_\odot$, Guzmán et al. 2003; Garland et al. 2004; Tollerud et al. 2010), luminous ($L_B \sim 10^9 L_\odot$, Garland et al. 2004), and have metallicities too high ($12 + \log(\text{O}/\text{H}) \sim 8.5$, Tollerud et al. 2010) to be classified as Blue Compact Dwarfs.

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LCBGs are common at intermediate redshifts. Koo et al. (1994) found that 30% of compact sources at $z \sim 0.1 - 0.7$ show strong, narrow emission lines characteristic of star formation. Guzmán et al. (1997) found that LCBGs compose 20% of the general field population of galaxies and contribute 45% of the total star formation rate density at $0.4 < z < 1$. Tollerud et al. (2010) found that LCBGs comprise $\sim 10\%$ of the total galaxy population with $M_B < -17$ and $\sim 5\%$ of the galaxies with $M_B < -16$ at a median redshift of $z = 0.49$, which they note is lower than the Guzmán et al. (1997) value likely due to the rapid evolution of LCBGs after $z \sim 1$. In contrast to their abundance at intermediate redshifts, LCBGs are a factor of ten rarer in number density in the local universe (Guzmán 2001). This discrepancy suggests that LCBGs are a progenitor population for one or more of the galaxy types prevalent at $z \sim 0$. Garland et al. (2015) recently confirmed that local LCBGs have similar morphologies, gas fractions, and specific star formation rates to higher-redshift star-forming galaxies. Following the definitions compiled by Werk et al. (2004) to select for local analogs of intermediate-redshift LCBGs, these galaxies have $B - V < 0.6$ mag, $SBe(B) < 21.0$ mag arcsec $^{-2}$, and $M_B < -18.5$ mag.

LCBGs' properties overlap with many similar types of galaxies that have been described in the literature, including Compact Galaxies (Phillips et al. 1997; Guzmán et al. 1997), Luminous Compact Galaxies (Hammer et al. 2001), and Blue Compact Galaxies (Koo et al. 1994; Guzmán 1999; Barton & van Zee 2001; Pisano et al. 2001). Cardamone et al. (2009) found that LCBGs overlap in blue luminosity, morphology, stellar mass, and metallicity with the Green Pea galaxies detected by Galaxy Zoo at $z \sim 0.1 - 0.4$. Heckman et al. (2005) found that the lower-mass examples of compact

Ultraviolet Luminous Galaxies (UVLGs), which they identify as low-redshift analogs of high-redshift Lyman Break Galaxies (LBGs), overlap in mass with the higher-mass examples of compact galaxies discussed in Phillips et al. (1997). Similarly, Guzmán et al. (2003) and Hoyos et al. (2004) point out that some LCBGs could be low-mass, lower-redshift counterparts to LBGs, and France et al. (2010) have detected fine-structure emission lines of Si II that have been previously observed in $z \sim 3$ LBGs in a $z \sim 0.04$ LCBG, which they interpret as an indication that star formation processes may be related in both types of galaxies. It is useful to study $z \sim 0$ LCBGs, then, to better understand the properties of the types of galaxies that exist at higher redshifts.

LCBGs have heterogeneous morphologies. Many LCBGs appear to be the products of mergers, especially at intermediate redshift where the spatial density of galaxies was larger and mergers were more common (Amram & Östlin 2001). In particular, irregular morphologies are more common in LCBGs than in other blue compact galaxies (Östlin et al. 2001). Many LCBGs also have companions (Garland et al. 2004; Pérez-Gallego et al. 2010; Garland et al. 2015). At $z \sim 0.2 - 1.3$, 60% of LCBGs appear to have similar properties to local H II galaxies, while 40% of LCBGs resemble local starburst disk galaxies, and 90% seem to be small galaxies with some extension, but lacking large, faint disks (Noeske et al. 2006). Garland et al. (2015) find that 40% of local LCBGs are “clumpy”, which they define to mean three or more optical clumps. Werk et al. (2004) point out that LCBGs are also not a distinct class of galaxies in parameter space. They exist at the extreme blue, bright, and compact ends of the optical properties that serve to identify them, but they are not outliers

along the continuum of observed properties for field galaxies at the redshifts at which they appear (see Figure 1 in Garland et al. 2004).

As LCBGs at $z \sim 0$ are rare compared to their number density at $z \sim 1$ (Guzmán 2001), it is likely that they evolve quickly once their current episodes of star formation end, though it is not known what types of galaxies LCBGs will subsequently become. It has been suggested that LCBGs could be undergoing their final phase of star formation, and will continue to passively evolve and fade to become today's spheroidal or dwarf elliptical galaxies (Guzmán et al. 1997; Bershadsky et al. 2005) or faint, low-mass spiral galaxies (Phillips et al. 1997). Other authors have suggested that LCBGs could be spiral galaxies undergoing a burst of star formation as they form their bulges (Barton & van Zee 2001; Hammer et al. 2001; Barton et al. 2006). It has also been asserted that LCBGs are galaxies that only appear similar in unresolved optical images at intermediate redshift and are actually a diverse enough population that their evolutionary paths and end products are widely varied (Tollerud et al. 2010). As LCBGs are visible at a large range of redshifts, they are excellent candidates for studying galaxy evolution (Hoyos et al. 2007).

3.1.2 Goals

In order to determine possible evolutionary paths for LCBGs, it is necessary to have knowledge of their H I properties. Measuring the H I mass gives an estimate of the fuel available for star formation and constrains the duration of the current starburst. The internal kinematics of the H I and evidence of past interactions give clues

regarding the starburst triggering and quenching mechanisms (Pisano et al. 2001), and can support or rule out disk or spheroid models of LCBGs' morphology. To investigate the nature of these galaxies, we have studied a selection of local analogs to intermediate-redshift LCBGs. Previously, Garland et al. (2004, 2005, 2007) surveyed the optical, H I, and CO properties of Sloan Digital Sky Survey (SDSS)- and Markarian- selected LCBGs. They took H I and CO spectra of a large sample of LCBGs using single pointings (Garland et al. 2004, 2005). For their study, they selected local LCBG analogs having the same optical properties as intermediate-redshift LCBGs as outlined by Werk et al. (2004). Garland et al. (2007) also initiated follow-up mapping observations of four Markarian galaxies and one SDSS galaxy with the Very Large Array (VLA). In this paper, we follow up the previous Garland et al. studies with Giant Metrewave Radio Telescope (GMRT) and VLA H I observations of galaxies selected from the Garland et al. (2004) sample, plus one additional local LCBG.

An overarching goal of this paper is to compare the H I properties we derive from resolved observations of nearby LCBGs to the properties derived from unresolved single pointings. Since LCBGs are most common at redshifts where resolved H I studies are not possible, it is important for us to understand what information is lost in unresolved observations of these galaxies. To accurately predict their evolution, we must first know what available observations can definitively tell us.

Previous H I studies of local LCBGs have not had the spatial resolution to distinguish the target sources from their nearby companions. Therefore, another goal of our study is to identify H I-rich companions and signatures of interacting galaxies

that were not resolved in the single-dish H I observations from Garland et al. (2004). Since H I gas traces a galaxy’s gravitational potential at a much larger radius than light from stars, our resolved H I observations could indicate locations conducive to interaction-driven star formation where it may not be obvious from optical observations. We therefore take advantage of the GMRT and VLA’s angular resolution to measure the extent of H I emission and identify signatures of rotation in order to calculate dynamical masses (M_{dyn}) for these LCBGs from measurements of rotation velocities (as opposed to estimating M_{dyn} from linewidths that could potentially be biased by the inclusion of nearby companions, tidal features, or non-rotation components). Coupled with the H I mass (M_{HI}), these measurements give us an estimate of how much gas is available for the continuation of the starburst. This constrains the evolutionary scenarios for LCBGs, as the bulge formation scenario would imply that LCBGs have higher M_{dyn} than have been sampled from the central bright cores of LCBGs at intermediate redshifts (e.g. Pisano et al. 2001), and the spheroidal/dwarf elliptical progenitor scenario requires LCBGs to undergo passive evolution after their current starburst (Guzmán 1999), which would limit their possible rotation velocities.

An additional goal of this paper is to determine whether LCBGs are rotationally-supported disk galaxies or dispersion-dominated bulges to better understand their likely future morphologies once their star formation has been quenched. Since our resolved study can also distinguish velocity dispersions from rotation velocities, we can compare their rotation velocities to their velocity dispersions and look for evidence of disklike or bulgelike behavior both at their outermost regions and their centers. We can also use the ratio of ordered to random motions and the gas fractions that we have

measured to look for evidence of disk instabilities that could trigger star formation in these galaxies. These measurements will better constrain the future evolution of local LCBGs, and have strong implications for the possible evolutionary products of their $z \sim 1$ counterparts.

In this paper, we describe our sample of LCBGs in Section 2, discuss results in Section 3, and give our conclusions in Section 4. We briefly address the properties of each LCBG in the Appendix. We assume $H_0 = 70 \text{ km s}^{-1}\text{Mpc}^{-1}$ throughout this paper.

3.2 Sample Selection, Observations, and Data Reduction

3.2.1 Sample selection

We chose nine galaxies from the SDSS- and Markarian-selected single-dish sample of LCBGs that Garland et al. (2004) observed with the Green Bank Telescope (GBT). We also included an additional SDSS galaxy (SDSS0125+0110) in our sample, selected from the single-dish sample of LCBGs that Garland et al. (in prep) observed with Arecibo. The Garland et al. samples were chosen for their blue colors, high luminosities, and compact appearances similar to properties outlined by Werk et al. (2004, see Garland et al. (2004) for a more detailed discussion of the selection criteria). We selected sources that had not been previously observed in H I emission at high resolution with interferometers. The galaxies we observed span the full range of colors of the GBT sample, but do not include the very brightest or most compact galaxies in the GBT sample that Garland et al. (2004) observed. We made sure to

include galaxies with and without companions. We show the optical properties of the galaxies in our sample in Table 3.1 calculated using SDSS Data Release 7 magnitudes and radii (DR7, Abazajian et al. 2009) using the equations in Section 2.1.2 of Garland et al. (2004). The galaxies in our sample were strong detections in single-dish H I observations (Garland et al. 2004), which makes them good candidates for interferometer observations. The galaxies in our sample have heterogeneous morphologies, including isolated spiral galaxies, galaxies with tidal tails, multiple galaxies in a common H I envelope, galaxies with distant companions, and galaxies with disturbed gas components. One source (SDSS1319+5253) contains three galaxies in a common H I envelope, one of which (SBS 1317+523B) is an LCBG. The galaxy that was not included in the original Garland et al. (2004) sample (SDSS0125+0110) is not consistent with the LCBG optical parameters defined by Werk et al. (2004) when using the photometry of DR7, though it is consistent with these optical parameters when using the photometry of SDSS Data Release 4 (DR4), which Garland et al. (2004) used to select the original local LCBG sample. As its optical properties remain close to the LCBG optical cuts described by Werk et al. (2004), are within the defined LCBG optical parameters when using the photometry of earlier SDSS data releases, and remain within optical properties of LCBGs as described by other authors (for example, Guzmán et al. 1997), we include it in our analysis. We discuss each galaxy individually in the Appendix.

3.2.2 GMRT observations and reduction

We observed eight galaxies with the GMRT near Pune, India. The GMRT is comprised of 30 antennas in a fixed Y-configuration with 14 antennas within 1 km and a maximum baseline of 25 km. We observed five galaxies (SDSS0728+3532, SDSS0934+0014, SDSS0936+0106, SDSS1319+5253, and SDSS1402+0955) in January 2006, along with three additional galaxies (SDSS0119+1452, SDSS0125+0110, and SDSS1507+5511) in January 2007. We observed each galaxy during a separate session with measurements of flux calibrators 3C48, 3C147, and/or 3C286 at the beginning and end of the observing run. We interspersed observations of a bright, unresolved, nearby phase calibrator every ~ 40 minutes that we selected from the VLA calibrator manual for a typical observing session of ~ 9 hours. We flagged and calibrated the data using the Astronomical Image Processing System (AIPS)² data reduction package using the standard procedures. For the GMRT this requires doing an initial calibration for a single, RFI-free channel before flagging and calibrating the full observing band. We made data cubes from the inner 50 channels (out of an original 128 channels with a channel width of $\sim 13.7 \text{ km s}^{-1}$) using the AIPS task IMAGR. For each galaxy, we made two different cubes: a “low-resolution” cube (typically $\sim 50'' - 60''$) made from baselines shorter than $5 \text{ k}\lambda$, and a “high-resolution” cube (typically $5'' - 20''$) made with a larger UV range (made from baselines out to $50 \text{ k}\lambda - 120 \text{ k}\lambda$). When making the high-resolution cubes, we chose robustness parameters, UV tapers, and UV ranges for each galaxy in order to maximize the resolution while maintaining a high level of signal to noise. We cleaned the data cubes using

the number of iterations necessary for the total flux of the clean components in a central channel to reach a plateau so as not to incorporate too many negative clean components. See Table 3.2 for the imaging parameters used for each galaxy.

We used the high-resolution data cubes to make Moment 0 (total intensity), Moment 1 (intensity-weighted velocity), and Moment 2 (velocity dispersion) maps for each LCBG using the AIPS task MOMNT. These moment maps are shown in Figures 3.1 - 3.8. We also made low-resolution Moment 0 maps, shown in Figure 3.10. We typically clipped the high-resolution moment maps at the $2 - 3\sigma$ level, where we measured σ from the RMS in an emission-free channel. We chose this noise cut to maximize the galaxy emission shown in the moment maps, while minimizing the noise shown. We made an effort to include companions and preserve extended structures with lower column densities when possible in order to more fully show the morphology of these galaxies.

3.2.3 VLA observation and reduction of Mrk 325

We observed the final galaxy, Mrk 325, with the VLA in the B and C configurations in December 2003 and November 2002 as part of projects AP463 and AP438, respectively. We also used data from the VLA archive taken as part of project AM361 in May 1992 and project AN62 in November 1993. In all cases, we performed flux calibration via observations of 3C48 or 3C286, and phase calibration through regular observations of J2254+247 (B2251+244). We carried out the data reduction for each configuration separately in the usual manner using AIPS. Because the pointing cen-

²aips.nrao.edu

Figure 3.1 Moment maps for SDSS0119+1452 (NGC 469) made with a $13'' \times 13''$ beam. The beam size is shown in the lower left corner. (a) Contours represent optical SDSS g intensity on an arbitrary scale overlaid on a Moment 0 grayscale. Contours were chosen to represent the positions and extent of the optical emission. (b) Contours are $2^n \times 10^{20} \text{ cm}^{-2}$ for $n = 0, 1, 2, 3$ taken from the Moment 0 map overlaid on a Moment 0 grayscale. (c) Contours are 10 km s^{-1} taken from the Moment 1 map overlaid on a Moment 0 grayscale. (d) Contours are 5 km s^{-1} from 5 km s^{-1} to 20 km s^{-1} taken from the Moment 2 map overlaid on a Moment 0 grayscale.

ter for the D configuration observations was different than the B and C configuration data, we made the data cubes by mosaicking the observations in Miriad³ (Sault et al. 1995). We made high-resolution and low-resolution moment maps for Mrk 325 in the same way as described in Section 2.2, shown in Figures 3.9 - 3.10.

³<http://carma.astro.umd.edu/miriad/>

Figure 3.2 Moment maps for SDSS0125+0110 (ARK 044) made with a $22'' \times 13''$ beam. The beam size is shown in the lower left corner. (a) Contours represent optical SDSS g intensity on an arbitrary scale overlaid on a Moment 0 grayscale. Contours were chosen to represent the positions and extent of the optical emission. (b) Contours are $2^n \times 10^{20} \text{ cm}^{-2}$ for $n = 0, 1, 2, 3$ taken from the Moment 0 map overlaid on a Moment 0 grayscale. (c) Contours are 25 km s^{-1} taken from the Moment 1 map overlaid on a Moment 0 grayscale. (d) Contours are 5 km s^{-1} from 5 km s^{-1} to 25 km s^{-1} taken from the Moment 2 map overlaid on a Moment 0 grayscale.

Figure 3.3 Moment maps for SDSS0728+3532 (ARK 134) and its companions made with a $13'' \times 8''$ beam. The beam size is shown in the lower left corner. (a) Contours represent optical SDSS g intensity on an arbitrary scale overlaid on a Moment 0 grayscale. Contours were chosen to represent the positions and extent of the optical emission. (b) Contours are $2^n \times 10^{20} \text{ cm}^{-2}$ for $n = 0, 1, 2, 3, 4, 5$ taken from the Moment 0 map overlaid on a Moment 0 grayscale. (c) Contours are 25 km s^{-1} taken from the Moment 1 map overlaid on a Moment 0 grayscale. (d) Contours are 10 km s^{-1} from 10 km s^{-1} to 40 km s^{-1} taken from the Moment 2 map overlaid on a Moment 0 grayscale.

Figure 3.4 Moment maps for SDSS0934+0014 (UGC 05097) made with a $20'' \times 20''$ beam. The beam size is shown in the lower right corner. (a) Contours represent optical SDSS g intensity on an arbitrary scale overlaid on a Moment 0 grayscale. Contours were chosen to represent the positions and extent of the optical emission. (b) Contours are $2^n \times 10^{20} \text{ cm}^{-2}$ for $n = 0, 1, 2, 3$ taken from the Moment 0 map overlaid on a Moment 0 grayscale. (c) Contours are 25 km s^{-1} taken from the Moment 1 map overlaid on a Moment 0 grayscale. (d) Contours are 10 km s^{-1} from 10 km s^{-1} to 50 km s^{-1} taken from the Moment 2 map overlaid on a Moment 0 grayscale.

Figure 3.5 Moment maps for SDSS0936+0106 (CGCG 007-009) made with a $21'' \times 11''$ beam. The beam size is shown in the lower right corner. (a) Contours represent optical SDSS g intensity on an arbitrary scale overlaid on a Moment 0 grayscale. Contours were chosen to represent the positions and extent of the optical emission. (b) Contours are $2^n \times 10^{20} \text{ cm}^{-2}$ for $n = 0, 1, 2, 3, 4, 5$ taken from the Moment 0 map overlaid on a Moment 0 grayscale. (c) Contours are 25 km s^{-1} taken from the Moment 1 map overlaid on a Moment 0 grayscale. (d) Contours are 10 km s^{-1} to 50 km s^{-1} taken from the Moment 2 map overlaid on a Moment 0 grayscale.

Figure 3.6 Moment maps for SDSS1319+5203 (SBS 1317+523B) and its companions made with a $15'' \times 12''$ beam. The beam size is shown in the lower left corner. (a) Contours represent optical SDSS g intensity on an arbitrary scale overlaid on a Moment 0 grayscale. Contours were chosen to represent the positions and extent of the optical emission. (b) Contours are $2^n \times 10^{20} \text{ cm}^{-2}$ for $n = 0, 1, 2, 3, 4, 5$ taken from the Moment 0 map overlaid on a Moment 0 grayscale. (c) Contours are 25 km s^{-1} taken from the Moment 1 map overlaid on a Moment 0 grayscale. (d) Contours are 10 km s^{-1} from 10 km s^{-1} to 70 km s^{-1} taken from the Moment 2 map overlaid on a Moment 0 grayscale.

Figure 3.7 Moment maps for SDSS1402+0955 (NGC 5414) made with a $23'' \times 14''$ beam. The beam size is shown in the lower left corner. (a) Contours represent optical SDSS g intensity on an arbitrary scale overlaid on a Moment 0 grayscale. Contours were chosen to represent the positions and extent of the optical emission. (b) Contours are $2^n \times 10^{20} \text{ cm}^{-2}$ for $n = 0, 1, 2, 3, 4$ taken from the Moment 0 map overlaid on a Moment 0 grayscale. (c) Contours are 25 km s^{-1} taken from the Moment 1 map overlaid on a Moment 0 grayscale. (d) Contours are 10 km s^{-1} from 10 km s^{-1} to 70 km s^{-1} taken from the Moment 2 map overlaid on a Moment 0 grayscale.

Figure 3.8 Moment maps for SDSS1507+5511 (UGC 09737) made with a $11'' \times 9''$ beam. The beam size is shown in the lower left corner. (a) Contours represent optical SDSS g intensity on an arbitrary scale overlaid on a Moment 0 grayscale. Contours were chosen to represent the positions and extent of the optical emission. (b) Contours are $2^n \times 10^{20} \text{ cm}^{-2}$ for $n = 0, 1, 2, 3, 4$ taken from the Moment 0 map overlaid on a Moment 0 grayscale. (c) Contours are 25 km s⁻¹ taken from the Moment 1 map overlaid on a Moment 0 grayscale. (d) Contours are 10 km s⁻¹ from 10 km s⁻¹ to 30 km s⁻¹ taken from the Moment 2 map overlaid on a Moment 0 grayscale.

Figure 3.9 Moment maps for Mrk 325 (NGC 7673) made with a $6'' \times 6''$ beam. The beam size is shown in the lower right corner. (a) Contours represent optical SDSS g intensity on an arbitrary scale overlaid on a Moment 0 grayscale. Contours were chosen to represent the positions and extent of the optical emission. (b) Contours are $2^n \times 10^{20} \text{ cm}^{-2}$ for $n = 0, 1, 2, 3, 4, 5$ taken from the Moment 0 map overlaid on a Moment 0 grayscale. (c) Contours are 10 km s^{-1} taken from the Moment 1 map overlaid on a Moment 0 grayscale. (d) Contours are 5 km s^{-1} from 5 km s^{-1} to 25 km s^{-1} taken from the Moment 2 map overlaid on a Moment 0 grayscale.

Figure 3.10 Low-resolution ($\theta \sim 1'$) Moment 0 maps of (a) SDSS 0119+1452, (b) SDSS0125+0110, (c) SDSS0728+3532, (d) SDSS0934+0014, (e) SDSS0936+0106, (f) SDSS1319+5203, (g) SDSS1402+0955, (h) SDSS1507+5511, and (i) $\theta \sim 6''$ Moment 0 map of Mrk 325. Contours are $2^n \times 10^{20} \text{ cm}^{-2}$. The fields of view were chosen to include detected companions. For a $\theta \sim 1'$ moment map of Mrk 325, see Figure 17 of Nordgren et al. (1997).

3.3 Results

3.3.1 H I intensity maps, linewidths, and masses

The high-resolution Moment 0 maps in Figures 1-9 (the top right image in each figure) show heterogeneous H I morphologies, though the LCBGs have in common that the H I emission is centrally peaked, coincides with the center of the optical emission, and extends in an envelope to a radius larger than their stellar radii. Seven (78%) of the galaxies have companions that are detected in our H I maps (see Table 3.3). In addition, seven of the LCBGs have H I gas that appears disturbed.

We measured H I profiles for each LCBG using the AIPS task ISPEC using the low-resolution data cubes in order to correct for missing short spacings. We chose spatial boundaries for ISPEC using the $2 - 3\sigma$ extent of each LCBG's H I emission in low-resolution Moment 0 maps. In the case of multiple galaxies in a common H I envelope, we measured the H I profile of the entire envelope because identifying boundaries for each galaxy while excluding H I emission associated with other galaxies or tidal features in the envelope introduced large uncertainties. We note that this means that measurements of quantities such as M_{HI} using the H I profiles of LCBGs in larger envelopes also encompass the entire envelope. We calculated an integrated flux for each galaxy by summing the flux in each channel within the first crossing at 0 mJy on each side of the peak and multiplying the sum by one channel width. We found uncertainties on the integrated fluxes by adding in quadrature the RMS flux of each galaxy's low-resolution cube and 10% of the galaxy's peak flux following the method of Chandra et al. (2004). We then calculated M_{HI} for each galaxy (or

group of galaxies, in the case of systems with multiple galaxies sharing a common H I envelope) using the equation

$$\left(\frac{M_{\text{HI}}}{M_{\odot}}\right) = 2.356 \times 10^5 \left(\frac{D_{\text{HI}}}{\text{Mpc}}\right)^2 \frac{\int S \, dv}{\text{Jy km s}^{-1}} \quad (3.1)$$

where $\int S \, dv$ is the integrated H I flux within the spectrum’s crossing of 0 mJy and D_{HI} is the galaxy’s distance derived from dividing the recession velocity by the Hubble constant. This equation assumes that a galaxy’s H I is optically thin, and that it is at low redshift. The H I profile properties for each galaxy are listed in Table 3.4.

We compare the M_{HI} we measure for the LCBGs in our sample to those measured from the integrated line profiles observed by Garland et al. (2004) for the same LCBGs using single-dish observations in Table 3.4. Many of the LCBGs that Garland et al. (2004) detected had optical companions within the GBT beam. If the companions contain H I, they will add emission to the observed H I spectrum, and thus increase the measured M_{HI} . We flag the galaxies that Garland et al. (2004) identified as having companions within the GBT beam in Table 3.4.

By contrast to previous single-dish observations, our observations can spatially resolve the LCBGs from their companions. Thus, the M_{HI} that we measure from integrating over the intensities measured in each velocity channel within the spatial boundaries of each galaxy’s H I map are more likely to reflect the true M_{HI} of the target galaxies than those measured from integrating over the H I spectrum measured with an unresolved single pointing. In addition, having unresolved companions or tidal features in the beam can act to broaden a galaxy’s observed linewidth, and thus

increase its inferred rotation velocity. Since LCBGs' possible evolutionary scenarios depend on whether they are rotation-dominated, dispersion-dominated, or show signatures of interactions, it is important to determine whether LCBGs' linewidths can be interpreted as the result of rotation. We discuss this further in Section 3.4.

3.3.2 Companions, mergers, and interactions

It has been hypothesized that LCBGs' bright, blue, strongly star-forming appearances are due to star formation triggered by major and minor mergers (Amram & Östlin 2001; Östlin et al. 2001). These authors point out that LCBGs tend to have asymmetrical stellar distributions and non-uniform rotation curves, which are suggestive of mergers and interactions. In contrast, Werk et al. (2004) find that the majority of their sample of local LCBGs have symmetric morphologies. It is known that star formation can be triggered by mergers and interactions, so it would not be surprising if LCBGs were merger-driven. However, Garland et al. (2015) found using optical data that only 20% of the galaxies in their sample of local ($D < 76$ Mpc) LCBGs are in merging systems. In our sample, two of the nine galaxies have H I gas that overlaps with the gas of another galaxy, which is consistent with the merger rate of the Garland et al. (2015) sample. The LCBGs in our sample do not seem to require mergers to trigger their star formation, which is consistent with the relatively low percentage of LCBGs in merging systems.

Even though LCBGs are not preferentially mergers, they are commonly found in denser environments where close encounters with other galaxies that disturb their

gas are more likely. Garland et al. (2015) found that in their sample, 40% of LCBGs are found in clusters. Crawford et al. (2011) found that from $0.5 < z < 1.0$, LCBGs are more likely to reside in denser environments at lower redshifts than at higher redshifts, and Cortese et al. (2014) found that LCBGs tend to reside in the outer regions of clusters. Those authors hypothesize that in intermediate-redshift clusters, LCBGs are gas-rich blue galaxies whose star formation is triggered during their first infall into the cluster (Crawford et al. 2011; Cortese et al. 2014). The LCBGs in our sample tend to have other galaxies nearby. In our sample, seven out of nine LCBGs have companions within one GBT beamwidth ($\sim 9'$ at 1.4 GHz), and three of the nine LCBGs have companions within one Arecibo beamwidth ($\sim 3'$ at 1.4 GHz). Six out of those seven LCBGs with companions have companions that we detect in our H I maps, and five of those seven have detected companions within ~ 10 times the LCBGs' H I radii (R_{HI}) and within 100 km s^{-1} of the LCBGs' systemic velocities. Seven of the nine LCBGs have disturbed gas properties that may be the result of an interaction with a companion, such as irregular morphologies, H I major axes that are offset in position angle from optical major axes, and disturbed velocity fields. Because this is not the case for every LCBG in our sample, we do not have strong evidence from this study that star formation in LCBGs *must* be triggered solely by interactions, though interactions may contribute to the star formation properties of some LCBGs. We discuss alternative scenarios for star formation in LCBGs in Section 3.6.1.

3.3.3 Velocity measurements

As is shown in the high-resolution Moment 1 maps (the bottom left images in Figures 1-8), all of the LCBGs in our sample show evidence of rotation. We measured systemic and rotation velocities (V_{rot}) for the LCBGs in our sample using the high-resolution Moment 1 maps for each LCBG both by measuring a slice of velocities along the galaxies' major axes and by fitting rotation curves to each galaxy's velocity field. We then calculated M_{dyn} for each LCBG using both of these V_{rot} using the equation

$$M_{\text{dyn}} = \frac{V_{\text{rot}}^2 \times R}{G} \quad (3.2)$$

where R is the radius at which V_{rot} is measured (and within which M_{dyn} applies).

V_{rot} is corrected for inclination by

$$V_{\text{rot}} = \frac{V_{\text{measured}}}{\sin i} \quad (3.3)$$

where i is either the optical inclination taken from Hyperleda⁴ (for V_{rot} found using a slice across the major axis, as described in Section 3.3.3.1), or the inclination fitted to the velocity field by the AIPS task GAL (for V_{rot} computed from rotation curve fitting, as described in Section 3.3.3.2).

⁴<http://atlas.obs-hp.fr/hyperleda/>

3.3.3.1 Velocities from a slice along the major axis

The most reliable method of determining V_{rot} for each LCBG was to measure the velocities corresponding to the positions along the galaxies' major axes. We determined the major axis of each galaxy using a visual inspection of their Moment 1 maps to identify features of rotation. This method produced measured, rather than fit, rotation curves from which we measured V_{rot} at the half-light radius (R_{eff}), the extent of ongoing star formation ($R_{25}(\text{B})$, the radius at which the galaxy has $\text{SBe}(\text{B}) = 25 \text{ mag arcsec}^{-2}$) and the extent of neutral hydrogen (R_{HI} , calculated as half of the galaxy's diameter across its major axis between locations with a column density of $1 \text{ M}_{\odot} \text{ pc}^{-2}$, or $N_{\text{HI}} = 1.26 \times 10^{20} \text{ cm}^{-2}$). We note that while this method produced easily measurable and reproducible values of V_{rot} , these velocities are only valid along the H I major axis. Values of V_{rot} corrected for inclination are uncertain due to using the galaxies' optical inclinations, which may not match the inclination of the galaxies' H I disks. We also calculated recession velocities as the velocity halfway between the velocities at each R_{HI} edge along the major axis, and M_{dyn} using V_{rot} at $R_{25}(\text{B})$ and R_{HI} . We report these values in Table 3.5 and display the rotation curves and major axis locations in Figure 3.11.

3.3.3.2 Rotation curve fitting

Because their Moment 1 maps all show a velocity gradient, with an identifiable major axis, it appears from the maps of the galaxies' velocity fields that all of the galaxies, with the possible exceptions of SDSS0934+0014 and Mrk 325, are domi-

Figure 3.11 (Left) Moment 0 map of each galaxy (grayscale) with Moment 1 contours (black) and major axis (thick black line) overlaid. (Right) Position-velocity plot of each galaxy along its major axis.

Figure 3.11 Continued.

Figure 3.11 Continued.

Figure 3.11 Continued.

Figure 3.11 Continued.

nated by ordered rotation. This is the case even for the galaxies with companions, interactions, tidal tails, and otherwise disturbed gas. We fit rotation curves using the AIPS task GAL to each of these LCBGs to determine their H I centers, V_{rot} , recession velocities, and inclinations. We used the high-resolution Moment 1 maps as the maps to be fit, and used the corresponding Moment 0 maps at the same resolution as weights to better identify the locations of the galaxies' centers and extents. We used the optical positions and inclinations of the galaxies, as well as the R_{HI} , H I recession velocities and rotation velocities shown in Table 3.5 as initial guesses in our fits, and did not fix any of the parameters at first. We limited the fit to R_{HI} for each galaxy.

While we were able to fit rotation curves to seven of the nine galaxies if we assumed a rotation curve shape and held some parameters fixed, it was not possible to fit well-constrained rotation curves for the galaxies that allowed the centers and extents of the galaxies to be free parameters and did not assume a rotation curve shape, even when using the Moment 0 maps as weights. It is possible that the poor

fits were due to limited spatial resolution (as LCBGs are spatially compact, even the higher-resolution moment maps that we produce have only a handful of beams across the major axis), or spectral channels that are too broad to provide a sufficient number of velocity data points to fit for galaxies that are slowly rotating or face-on. It is also difficult to distinguish between a galaxy with an intrinsically low V_{rot} and one that has a higher intrinsic V_{rot} but is face-on, so uncertainty in a galaxy’s inclination can lead to large uncertainties in V_{rot} . Since we do not have enough resolution elements, both spatially and spectrally, to fit more detailed tilted-ring rotation models to decompose the LCBGs into multiple gas components, we do not report their V_{rot} values as calculated, though we emphasize that all LCBGs in our sample show clear signs of ordered rotation.

The V_{rot} values derived from measuring along the major axis of each galaxy are less dependent on models that have systematic uncertainties than rotation curve fits, and are more easily reproduced. Thus, we use the velocities along the major axis shown in Table 3.5 when discussing V_{rot} in the remainder of the paper.

3.3.4 Comparison with single-dish results

One of the primary goals of this study was to investigate how results from single-dish observations of nearby LCBGs compare to those derived from resolved maps. Since LCBGs are unresolved at the distances at which they are common, it is important to determine whether unresolved observations of these galaxies are sufficient to describe their global properties and predict their evolutionary paths.

Seven of the LCBGs in our sample were observed with the GBT by Garland et al. (2004) at a resolution of $\sim 9'$, which is large with respect to their R_{HI} . We compare the M_{HI} of these galaxies derived from our resolved observations and the unresolved observations of Garland et al. (2004) in the last column of Table 3.4. We find that for six of the eight LCBGs common to both samples, the single dish observations generate a larger M_{HI} than what we calculate from resolved observations. We recover more H I emission for two of the LCBGs in our sample (SDSS0728+3532 and SDSS1319+5203) than was measured by Garland et al. (2004), which is likely due to those galaxies residing in H I envelopes that include other galaxies (the H I masses we report for those two LCBGs are for the entire envelope), though their H I envelopes are unresolved with the GBT beam. On average, the M_{HI} that we measure is 76% of what Garland et al. (2004) measured in their single dish observations, although there is a large dispersion (40%) between the values obtained in both measurements. In comparison, in resolved observations of five LCBGs with the VLA, Garland et al. (2007) measured values of M_{HI} that were on average 61% of the measured single dish values from Garland et al. (2004), with a similarly large dispersion. If we remove the two galaxies that reside in larger H I envelopes from consideration, we recover on average 58% of the M_{HI} that Garland et al. (2004) measured for the remaining six galaxies, with a dispersion of 24%, which is consistent with the Garland et al. (2007) result.

We also compare the V_{rot} and M_{dyn} values we derive from our velocity fields to those calculated from W_{20} corrected for inclination in the Garland et al. (2004) sample in Table 3.6 (SDSS0125+0110 is left out of this discussion because it was

not observed by Garland et al. (2004)). With the exception of SDSS1507+5511, the single-dish V_{rot} values calculated by Garland et al. (2004) using half of W_{20} corrected for inclination are larger than the V_{rot} values that we measure using a cut along the major axis ($\langle 0.5 \times W_{20}/V_{\text{rot}} \rangle = 2.6 \pm 1.6$). Since the observations of Garland et al. (2004) were made with beam sizes large enough to include contributions from companion galaxies in the case of SDSS0119+1452, SDSS0934+0014, SDSS0936+0106, SDSS1319+5203, and SDSS1402+0955, and tidal features in the case of SDSS0728+3532 and SDSS1319+5203, their measurements of W_{20} are not spatially resolved enough to distinguish the velocity contributions of the LCBGs from the contributions of their nearby companions.

When calculating M_{dyn} , Garland et al. (2004) estimated that $R_{\text{HI}} = 2 \times R_{25}$, following Broeils & van Woerden (1994), since they did not have measured values of R_{HI} . We compare the estimated and measured values of R_{HI} in Table 3.6. The R_{HI} values that we measure are on average 84% of those used in Garland et al. (2004), though the scatter is relatively large ($\langle R_{\text{HI}}^{\text{GMRT}}/R_{\text{HI}}^{\text{est.}} \rangle = 0.84 \pm 0.40$). SDSS0728+3532, SDSS0936+0106, and SDSS1319+5203 have measured R_{HI} values that are larger than those that Garland et al. (2004) estimated. We use our measured R_{HI} to calculate M_{dyn} here.

With the exception of SDSS0936+0106 and SDSS1507+5511, the M_{dyn} within the estimated R_{HI} calculated by Garland et al. (2004) are larger than those that we calculate here, owing to the larger V_{rot} and R_{HI} values estimated using single dish observations. On average, the single-dish M_{dyn} values are 16.9 times larger than M_{dyn}

measured along the galaxies' major axes, with a large scatter ($\sigma_{(M_{\text{dyn}}^{\text{GBT}}/M_{\text{dyn}}^{\text{GMRT}})} = 21.2$). We note that we used slightly different distances to calculate M_{dyn} than Garland et al. (2004) did. The recession velocities we measured, and thus the distances we calculated, were on average 8 km s^{-1} lower than those measured by Garland et al. (2004). As this translates to a difference of 0.1 Mpc, and no galaxy had a difference of more than 1 Mpc, we do not consider differences in our recession velocity measurements to be a significant source of error in our comparison.

The H I mass fractions, $f_{\text{gas}} = M_{\text{HI}}/M_{\text{dyn}}$, that we calculate using our resolved observations are on average nine times larger than those calculated from single-dish measurements, though with nearly as large of a standard deviation ($\langle f_{\text{gas}}^{\text{GMRT}}/f_{\text{gas}}^{\text{GBT}} \rangle = 9.0 \pm 8.9$). Only SDSS0936+0106 and SDSS1507+5511 have smaller f_{gas} when using resolved data than the f_{gas} values derived from single-dish observations. For two of the LCBGs, SDSS0728+3532 and SDSS1319+5203, the M_{HI} values that we calculate encompass the entire, multi-galaxy H I envelopes in which these galaxies reside, while M_{dyn} only encompasses the LCBGs. As a result, the f_{gas} that we calculate are likely much higher than the true values (for example the f_{gas} values of SDSS1319+5203 and Mrk 325 are 5.0 and 1.7, respectively, which are unrealistically high).

The major advantages that our current study has over those undertaken with single dishes are that (1) our improved spatial resolution enables us to distinguish individual galaxies from their nearby companions, (2) mapping the galaxies allows for their rotation axes to be identified and their V_{rot} to be measured rather than estimated from linewidths, and (3) mapping the galaxies also makes measuring their R_{HI} possible, enabling calculations of their M_{dyn} to be made with fewer assumptions.

We generally calculate lower M_{dyn} and higher f_{gas} than what was calculated from single-dish measurements by Garland et al. (2004). This result strengthens their assertion that LCBGs are gas-rich galaxies with smaller M_{dyn} than elliptical galaxies. We note that the V_{rot} , and thus M_{dyn} , that we calculate depend on the galaxies' inclinations. Since we do not have the spatial or velocity resolution to reliably fit rotation curves and inclination models to the LCBGs in our sample, we have not been able to accurately measure the inclinations of the galaxies' gas. We are thus restricted to the same assumption that Garland et al. (2004) made: the gas in these galaxies is inclined at the same angle with respect to our line of sight as their optical components. Thus, even though our resolved study better measures the gas properties of each LCBG, it is still limited by uncertain galaxy inclinations. Our results are consistent with the conclusions of Garland et al. (2004) that LCBGs are gas-rich and morphologically heterogeneous.

From comparing the H I properties of the LCBGs in our sample to those measured with a single dish, we find that the V_{rot} , R_{HI} , and M_{dyn} that we measure are not related by a simple scale factor to those estimated using single dish linewidths and R_{25} . See Figure 3.12 for a visual representation of the scatter in the H I properties that we measure when compared to those reported by Garland et al. (2004). We note that our sample size is small, so we cannot rule out a characteristic relationship between R_{25} and R_{HI} or between single-dish linewidths and V_{rot} in LCBGs, though we do not find such a relationship here.

Figure 3.12 R_{HI} (top), V_{rot} (middle), and M_{dyn} (bottom) using data from Garland et al. (2004) and our measurements for the LCBGs common to both samples. Garland et al. (2004) estimated R_{HI} to be $R_{\text{HI}} = 2 \times R_{25}$, and used half of the width of each galaxy’s single-dish H I spectrum corrected for inclination and random motions as V_{rot} . The dashed black lines show a 1:1 relationship between the two data sets. In some cases, error bars are smaller than point sizes.

3.3.4.1 Comparison with stellar masses

As a constraint on the M_{dyn} that we have calculated, we have also calculated stellar masses, M_* , for each LCBG using the equation $\log(M_*/L) = a_\lambda + b_\lambda \times \text{Color}$ given in Bell & de Jong (2001), where a_λ and b_λ are constants dependent on the wavelength of measured luminosity and are tabulated in Table 1 of Bell & de Jong (2001). We used the $B - V$ colors that we listed in Table 3.1, and K-band magnitudes from the Two Micron All Sky Survey (2MASS) catalog (Schmitt et al. 2006). We note that four LCBGs, SDSS0119+1452, SDSS0934+0014, SDSS1319+5302, and Mrk 325, had M_{dyn} values lower than their stellar masses. Bell & de Jong (2001) state that the scatter on their color - M_*/L relation is $\sim 10\%$, which is smaller than the difference between the M_* and M_{dyn} values for these galaxies, so it is not likely that uncertainties on the color - M_*/L relation are responsible for this unphysical result. There are two possible reasons for these four galaxies having larger M_* than M_{dyn} . First, if a galaxy is more face-on than the inclination given in Hyperleda, then we have likely underestimated its M_{dyn} due to under-correcting its rotation velocity for inclination. Since these four galaxies were the most difficult to identify axes of rotation for, it is likely that the uncertainty in their rotation velocities is higher than for the other LCBGs. Second, the equation used to calculate M_* is a relationship between M_*/L and galaxy colors determined by a model for several combinations of colors and optical and near-infrared absolute magnitudes. As was shown in Garland et al. (2004), LCBGs are more likely to have lower M/L than the average for local galaxies, and Bell & de Jong (2001) find that bluer colors correlate with lower M/L . If LCBGs

significantly deviate from the color-M/L relationship that Bell & de Jong (2001) have derived (for example, if the $B - V$ that we use in our calculations is redder than the average $B - V$ for a galaxy’s disk), we may be overestimating their stellar masses.

3.3.5 Tully-Fisher relation

The Tully-Fisher (T-F) relation (Tully & Fisher 1977) posits that for rotating galaxies, intrinsic luminosity is proportional to the galaxy’s V_{rot} raised to the fourth power. Garland et al. (2004) showed that not all of the LCBGs in their sample follow the T-F relation when they estimated V_{rot} using single-dish linewidths. It would be expected that a star-forming galaxy’s intrinsic brightness would temporarily be elevated with respect to the brightness associated with its V_{rot} on the T-F relation, and Garland et al. (2004) did see some evidence of that effect in their sample. However, they also found that some LCBGs are less intrinsically bright than their V_{rot} would suggest, which would not be expected for star-forming galaxies. Since a galaxy undergoing active star formation becomes less intrinsically bright once its star-forming episode ends, an LCBG that is fainter than would be expected for a galaxy on the T-F relation would never become bright enough to evolve onto the T-F relation. However, if a galaxy’s V_{rot} is overestimated by its single-dish linewidth, the galaxy could appear to be too faint to follow the T-F relation given its (overestimated) V_{rot} . This scenario could happen if, for example, an unresolved nearby companion or tidal feature exists whose recession velocity overlaps with the rotation velocity range of the target galaxy. For example, Garland et al. (2004) found that six of the ten LCBGs in their sample

that are too faint to follow the T-F relation have companions. Since our resolved observations enable us to measure the V_{rot} values of the LCBGs in our sample, we revisit whether LCBGs follow the T-F relation using our velocity measurements.

We have plotted the LCBGs in our sample in Figure 3.13 along a version of the T-F relation described in Tully & Pierce (2000). In this plot, we use V_{rot} as measured along the galaxies' major axes and corrected for optical inclination, as well as their M_B listed in Table 3.1. We also plotted the corresponding linewidths and M_B calculated for those LCBGs in Garland et al. (2004), with the exception of SDSS0125+0110 as it was not observed in that study. Five of the nine LCBGs in our sample appear to follow the T-F relation (within error bars), while four LCBGs are brighter than anticipated given their V_{rot} . These are the same four LCBGs that have $M_* > M_{\text{dyn}}$ as discussed in the previous subsection. None of the LCBGs in our sample have lower than expected luminosities given their V_{rot} values, while six of the LCBGs have low luminosities with respect to rotation velocities inferred from their linewidths as measured in Garland et al. (2004). Since the average V_{rot} derived from half of the galaxies' single-dish linewidths is nearly three times the V_{rot} values that we measure, we can infer that the cause of some LCBGs lying to the right of the T-F relation in single-dish measurements is likely due to uncertainties in estimating V_{rot} from single-dish linewidths.

In addition to a temporarily elevated luminosity due to ongoing star formation, one potential cause of some LCBGs being positioned to the left of the T-F relation could be disturbed H I velocity fields due to mergers or interactions. Eight of the nine LCBGs in our sample have nearby companions or show signs of disturbed gas

Figure 3.13 *Top*: A version of the Tully-Fisher relation, described in Tully & Pierce (2000). M_B for the LCBGs in our sample (filled squares) are calculated as described in Garland et al. (2004) using SDSS g and r magnitudes and distances taken from Table 3.1. Their V_{rot} values are taken from cuts across the galaxies' major axes at R_{HI} and corrected for inclination. The same LCBGs (with the exception of SDSS0125+0110) are plotted with M_B and linewidths corrected for random motions and inclinations taken from Table 1 and Table 3 of Garland et al. (2004) (open circles). The Tully-Fisher relation as described in Tully & Pierce (2000) is plotted with the black line. Four of the LCBGs in our sample are much brighter in the B band than their V_{rot} values would suggest, while six of the LCBGs in the Garland et al. (2004) sample are faint in the B band with respect to their linewidths. We find that the LCBGs in our sample either follow the Tully-Fisher relation or have the ability to evolve onto it once their star formation is quenched and their M_B subsequently fade. We interpret the galaxies lying to the right of the Tully-Fisher relation from the Garland et al. (2004) sample as having overestimated rotation velocities due to the inclusion of non-rotation H I features or companion galaxies in the beam. *Bottom*: Stellar mass Tully-Fisher relation as described in Kassin et al. (2007). M_* are calculated using K-band magnitudes and B-V colors. V_{rot} values are calculated the same way as in the top figure, both at R_{HI} (red circles) and R_{25} (blue squares). σ values are the average σ within R_{HI} and R_{25} . The same LCBGs that lie to the left of the T-F relation on the top plot also lie to the left of the stellar mass T-F relation.

morphology, though their optical morphologies remain disk-like. If a galaxy’s V_{rot} is not accurately measured by taking a cut along its major axis (but is instead underestimated), the galaxy could appear to be too luminous for its measured V_{rot} . We also note that our measured V_{rot} values include a correction for optical inclination. If a galaxy’s gas disk inclination differs from the measured optical inclination, a systematic error will occur in their corrected values of V_{rot} that we do not account for in our measurements. Since the four LCBGs that lie to the left of the T-F relation also have $M_* > M_{\text{dyn}}$, it is likely that we are underestimating their dynamical masses, and thus also underestimating their V_{rot} . We discuss this further in Section 3.3.6.

Another possible cause of deviation from the T-F relation, which does not exclude a merger scenario, could be due to the formation of a bulge or pseudobulge (Tonini et al. 2014). If LCBGs are undergoing their final major burst of star formation while they build a bulge and transition to more quiescent S0 or dE-type galaxies, we may be able to see evidence of this transformation in their H I properties. Earlier-type spiral galaxies have higher mass-to-light ratios than later-type spirals, so their T-F relations tend to be flatter than the average T-F relation for spiral galaxies (Tonini et al. 2014). None of the LCBGs in our sample appear to have higher mass to light ratios than the T-F relation would suggest (see Figure 3.13), so we do not see evidence that the LCBGs in our sample have prominent bulges like Sa-type galaxies.

As the LCBGs in our sample either follow the T-F relation or have the potential to evolve onto it once their blue luminosities fade due to decreased star formation activity, we can infer that the LCBGs in our sample are likely to be rotation-supported. An additional consideration to include in our analysis is the effect of velocity dis-

persion on the galaxies' rotation velocities. Since we measured the LCBGs' rotation velocities at the edges of the extent of the galaxies' H I, where their velocity dispersions are relatively low (see the Moment 2 maps in Figures 3.1 - 3.9), the effects of velocity dispersions on the galaxies' rotation velocities are likely to be small. It is possible that the rotation velocities measured by Garland et al. (2004) from single-dish linewidths could be affected by the inclusion of velocity dispersion. If this is the case, the additional contribution from velocity dispersion would increase the measured linewidth relative to what would be measured due to pure rotation. This increase could contribute to the data points in Figure 3.13 from Garland et al. (2004) that lie to the right of the T-F relation, where it is impossible to evolve onto the T-F relation solely due to quenching of star formation. We discuss velocity dispersions further in Section 3.6.

3.3.6 Velocity dispersions

We calculated the average intensity-weighted velocity dispersions, σ , of the LCBGs in our sample by taking the average pixel values of the Moment 2 maps at four locations: (1) within a circle bordered by the half-light radius, $R_{\text{eff}}(B)$, (2) within a circle bordered by R_{25} , (3) for the whole disk within R_{HI} , and (4) outside of region within R_{25} . We chose the R_{25} radius limit because it generally signifies the outer limit of active star formation (Tamburro et al. 2009). Thus, σ within R_{25} is a measure of the gas properties that affect and are affected by galaxies' star formation,

while σ outside of R_{25} probes the kinematics of the galaxies beyond the region where they actively form stars. These values of σ are tabulated in Table 3.7.

We find that the areas of highest σ tend to coincide with the optical centers of the LCBGs in our sample, similar to what Tamburro et al. (2009) measured for spiral galaxies. This is true not only for the relatively isolated LCBGs, but also for LCBGs with companions (even those with companions in a common H I envelope, with obvious evidence of gas interactions and disturbed morphology).

We also calculated the ratio of each LCBG’s V_{rot} (corrected for inclination) at a given radius to its average σ inside of that radius, $V_{\text{rot}}\sigma^{-1}$, to determine the relative contributions of ordered rotation and disordered motion of each galaxy’s H I emission. A galaxy’s $V_{\text{rot}}\sigma^{-1}$ values are indicative of whether it has bulge-like or disk-like behavior, with values of $V_{\text{rot}}\sigma^{-1} < 1$ signifying that random motions of the gas dominate over rotation. Such values of $V_{\text{rot}}\sigma^{-1}$ are typically present in a galaxy’s bulge, if it has one, while values of $V_{\text{rot}}\sigma^{-1} \sim 1$ can be found in “pseudobulges”, which are built up by internal processes and maintain some rotation (for a review, see Kormendy & Kennicutt 2004). We also wanted to investigate possible gravitational instabilities in the disks as a potential trigger for star formation, which can be traced by comparing $V_{\text{rot}}\sigma^{-1}$ to the amount of gas available in the disk.

Another implication of centrally-peaked σ values is that the outer parts of the galaxies’ disks have relatively low σ , which is a property associated with gas that is less dynamically hot. All nine of the LCBGs in our sample have V_{rot} values in excess of their σ values when measured at R_{HI} . In Table 3.7, we show values of $V_{\text{rot}}\sigma^{-1}$ within several radii. We find that $V_{\text{rot}}\sigma^{-1}$ increases at larger radii, with the highest

values occurring when σ is measured outside of R_{25} , and the lowest values occurring within R_{eff} .

To investigate whether the four LCBGs that lie to the left of the T-F relation, as discussed in Section 3.3.5, have kinematics that are not dominated by rotation, we plotted the LCBGs in our sample along the stellar mass T-F relation described by Kassin et al. (2007). This relationship correlates M_* with the kinematic property $S_{0.5}$, which is defined as $S_{0.5} = (0.5V_{\text{rot}}^2 + \sigma^2)^{1/2}$ (Weiner et al. 2006; Kassin et al. 2007). Since we calculated M_* using near-infrared magnitudes, which are not as sensitive to recent star formation as B-band magnitudes, the LCBGs that lie to the left of the T-F relation may lie closer to the stellar mass T-F relation if recent star formation is significantly elevating the B-band magnitudes in these galaxies. In Figure 3.13, we find that the same four LCBGs that lie to the left of the T-F relation also lie to the left of the stellar mass T-F relation when we measure V_{rot} and σ at R_{HI} , and three of those four LCBGs (SDSS1319+5203 is the exception) lie to the left of the stellar mass T-F relation at R_{25} . In addition, the five LCBGs that follow the T-F relation lie to the right of the stellar mass T-F relation. It is likely that these results indicate systematic uncertainty in our measurements of V_{rot} . Since including both ordered rotation and disordered motions in $S_{0.5}$ did not move the four LCBGs to the left of the T-F relation onto the stellar mass T-F relation, it is not likely to be the case that these four LCBGs are dominated by disordered motions at large radii. It is instead likely that we have not identified these four LCBGs' true inclinations to use to correct their rotation velocities (the LCBGs are more face-on than we have estimated). The LCBGs in our sample do not appear to be dominated by velocity dispersions at large

radii. We are likely underestimating these galaxies' rotation velocities, and thus also underestimating their dynamical masses.

One way we can further infer whether LCBGs contain significant bulges is to compare their ratios of ordered to disordered motion to their ellipticity, ϵ . Using virial theorem arguments, $V_{\text{rot}}\sigma^{-1}$ can be related to ϵ by

$$\frac{V_{\text{max}}}{\sigma} = \frac{\pi}{4} \sqrt{2[(1 - \epsilon)^{-0.9} - 1]} \quad (3.4)$$

where $\epsilon = 1 - b/a$ (Sparke & Gallagher 2007). We plot this relation, which indicates the maximum ratio of ordered motions to random motions allowable for a given flatness of elliptical galaxies, in Figure 3.14. When measured within R_{25} , all of the LCBGs in our sample except one (SDSS0934+0014) lie above this relation, along with spiral galaxies and late-type dwarf galaxies from the THINGS sample (Walter et al. 2008), which shows that they rotate faster (or have smaller values of σ) than is permitted for elliptical galaxies. By contrast, all of the dwarf elliptical galaxies with a significant rotation component studied by Geha et al. (2003), and most of the dwarf ellipticals studied by van Zee et al. (2004), lie below this relation. When we measured V_{rot} at R_{eff} and the average σ within R_{eff} , the $V_{\text{rot}}\sigma^{-1}$ values of the galaxies in our sample lie near the relation, which implies that LCBGs have approximately the maximum V_{rot} possible for elliptical galaxies in their most central areas. Bershadsky et al. (2005) show that a sample of very blue ($B - V \sim 0.25$), very compact ($S\text{Be}(B) \sim 19$ mag arcsec $^{-2}$) intermediate-redshift LCBGs lie below the relation (see their Figure 2), which suggested to them that LCBGs may evolve into dwarf elliptical galaxies

once their star formation has been quenched. That study differs from ours in that it surveyed an extreme subset of intermediate-redshift LCBGs and measured ionized gas rather than H I. Pérez-Gallego et al. (2011) measured $V_{\text{rot}}\sigma^{-1}$ for ionized gas using optical emission lines for a sample of local LCBGs that has two galaxies in common with our sample (SDSS1507+5511 and Mrk 325). When compared with the ellipticities of those galaxies, the LCBGs in their sample behave in a way similar to the LCBGs in our sample measured at R_{eff} . The $V_{\text{rot}}\sigma^{-1}$ values that we have measured make the presence of large-scale classical bulges that contain gas unlikely at present in LCBGs, though the gas in the innermost regions of LCBGs may display bulge-like behavior. This suggests that if the local LCBGs in our sample are representative of the population of LCBGs that is common at $z \sim 1$, those higher-redshift LCBGs must also be dominated by ordered rotation. If this was the case, then LCBGs at higher redshifts are likely disk galaxies with extensive star formation in their disks, rather than irregular or spheroidal galaxies.

3.3.6.1 Building bulges

An alternative scenario to star formation triggered by mergers or interactions with companions is the hypothesis that LCBGs are bright, star-forming bulges (or bulge progenitors) of disk galaxies (Barton & van Zee 2001; Hammer et al. 2001). This scenario is consistent with the centrally-peaked σ values and relatively low central $V_{\text{rot}}\sigma^{-1}$ values that we find for many of the LCBGs in our sample. However, the $V_{\text{rot}}\sigma^{-1}$ values we observe across the whole radii of LCBGs are not low enough

Figure 3.14 $V_{\text{rot}}\sigma^{-1}$ plotted against ellipticity ($\epsilon = 1 - b/a$) for a variety of galaxy samples. The solid black curve is the maximum value of $V_{\text{rot}}\sigma^{-1}$ allowed for elliptical galaxies. Galaxies above this curve are too rotation-supported to be classified as elliptical galaxies. The points represent the LCBGs in our sample measured within R_{25} (filled squares) and R_{eff} (open squares), spiral galaxies from the THINGS sample (filled circles), dwarf galaxies from the THINGS sample (filled triangles), dwarf elliptical galaxies with a measured rotation component from Geha et al. (2003) (filled diamonds) and van Zee et al. (2004) (open diamonds), and for LCBGs in the Pérez-Gallego et al. (2011) sample (filled stars). ϵ values are taken from Hyperleda except for the Geha et al. (2003) sample, where ϵ is taken from Table 3 of that paper, and the van Zee et al. (2004) sample, where ϵ is taken from Table 1 of that paper. LCBG V_{rot} values are measured using a cut along the galaxies' major axes. THINGS (Tamburro et al. 2009) σ values are the average H I σ values measured within R_{HI} . THINGS V_{rot} values are taken using half of W_{20} corrected for inclination from Walter et al. (2008). Geha et al. (2003) dwarf elliptical V_{rot} and σ values are measured from optical absorption lines within 0.5-1 R_{eff} . van Zee et al. (2004) dwarf elliptical V_{rot} and σ values are measured from optical absorption lines within the last point where a rotation curve could be fit. Pérez-Gallego et al. (2011) V_{rot} values are measured from rotation curves fit to H α velocity maps, and σ values are measured from [OIII] λ 5007 maps.

for the LCBGs in our sample to be “classical” bulges which, like elliptical galaxies, are not typically rotation-supported and have $V_{\text{rot}}\sigma^{-1} < 1$ (Kormendy & Kennicutt 2004). The motion of the gas in the galaxies in our sample is dominated by rotation ($V_{\text{rot}}\sigma^{-1} > 1$) even within R_{25} , and even for the LCBGs with disturbed velocity fields, so we rule out the existence of gas-rich “classical” bulges in our sample. It is possible that the LCBGs in our sample have or are developing bars or “pseudobulges” (Kormendy & Kennicutt 2004), which are less supported by random motions than they are by rotation.

Along these lines, it is possible that LCBGs are developing “clump-origin bulges” (e.g. Noguchi 1998, 1999, 2000, 2001; Dekel et al. 2009; Elmegreen et al. 2009; Inoue & Saitoh 2012). In this scenario, gas infalling onto a galaxy’s disk develops overdensities within the disk that contract and become star-forming clumps. As the clumps orbit along with the rest of the disk, they move toward the center of the galaxy due to dynamical friction and can merge with other clumps. When these clumps merge with each other, star formation rates in the clumps increase briefly, which gives the clumps a bright, blue appearance and drives up the galaxies’ global star formation rates. Finally, the few large clumps that remain merge in the center of the galaxy, causing either a small clump-origin nuclear bulge or bar that maintains some of the the angular momentum that the clumps had in the disk. At this point, the star formation rate of the clumps rapidly declines (for a visual illustration of this process, see Figure 1 of Inoue & Saitoh 2012). The lifetimes of the clumps are governed by their size (more massive clumps are less likely to disperse due to outward pressure from their star formation), as well as their distance from the center of the galaxy (clumps

that have less distance to travel as they move toward the center are more likely to reach the center of the galaxy intact). Clumpy galaxies have been observed at a range of redshifts, including galaxies that resemble LCBGs. For example, Overzier et al. (2009) found that star-forming clumps, including large, bright central clumps, are common in a sample of Lyman Break Analog galaxies at $z \sim 0.1 - 0.3$ that have similar effective radii and dynamical masses to the LCBGs in our sample, and Garland et al. (2015) found that 40% of local LCBGs are clumpy, likely due to the buildup of accreted gas from interactions with companions or material in galaxy clusters.

To determine whether conditions in the LCBGs' disks are conducive to the formation of clumps, we can use the gas properties we measure to calculate the galaxies' Toomre parameters (Toomre 1964) for the stability of their disks' gas:

$$Q_{\text{gas}} = \frac{\sigma \kappa}{\pi G \Sigma_{\text{gas}}} \quad (3.5)$$

where $\kappa = \sqrt{2} V_{\text{rot}} R^{-1}$ for a flat rotation curve, and Σ_{gas} is the gas mass surface density. For a disk to be stable, $Q \gtrsim 1$. More accurate measures of Q incorporate the disks' stellar components as well (Dekel et al. 2009), though we limit our present analysis to the LCBGs' H I since we probe the galaxies' kinematics beyond the extent of their stellar disks, and are particularly interested in whether the kinematics of their gas are conducive to star formation. In general, incorporating a stellar component will increase a galaxy's value of Q .

Keeping in mind that a galaxy's total mass is represented by $M_{\text{dyn}} = V_{\text{rot}}^2 R/G$, we can rearrange the above inequality for $Q > 1$ so that it highlights the criterion for disk stability in terms of gas properties we can measure:

$$\frac{V_{\text{rot}}}{\sigma_{\text{gas}}} < \frac{\sqrt{2}\Sigma_{\text{total}}}{\Sigma_{\text{gas}}}. \quad (3.6)$$

where Σ_{total} is the galaxy's total surface mass density, which is calculated using its M_{dyn} within a given radius ($\Sigma_{\text{total}} = M_{\text{dyn}}/\pi R^2$). We note that for this discussion, we make the approximation that $f_{\text{gas}} = f_{\text{HI}}$. Garland et al. (2005) found that the molecular gas fraction for a sample of local LCBGs is typically $\lesssim 10\%$, so contributions to f_{gas} from molecular gas are likely to be small for the galaxies in our sample. We plot the measured values at several radii for each of the LCBGs in our sample (excluding SDSS0728+3532 and SDSS1319+5253B, which are contained within a larger H I envelope) in Figure 3.15. All of the LCBGs in our sample except Mrk 325 have stable gas disks with respect to perturbations over a range of radii (for $Q < 1$, data points would lie above the curve in Figure 3.15, and for $Q > 1$, data points lie below the curve), which means that their f_{gas} would need to be higher for their disks to be unstable given their present values of $V_{\text{rot}}\sigma^{-1}$. Two of the LCBGs in our sample (SDSS0934+0014 and SDSS1402+0955) have the potential for local instabilities to form at large radii, and other LCBGs are within error bars of having $Q \lesssim 1$, though the uncertainties on their values of $V_{\text{rot}}\sigma^{-1}$ are large. Mrk 325 has the potential for local instabilities at all radii, though we note that we find $f_{\text{gas}} > 1$ for this galaxy, which is an unrealistic value (if we instead say that $f_{\text{gas}} = M_{\text{HI}}/(M_{\text{HI}} + M_*)$, Mrk

Figure 3.15 $V_{\text{rot}}\sigma^{-1}$ within R_{eff} (red squares), R_{25} (green circles), R_{HI} (blue triangles) and outside of R_{25} (purple diamonds) for the LCBGs in our sample that do not share a common H I envelope with another galaxy. The solid line is the Toomre criterion for disk instability for a gas disk (Toomre 1964). Above the line, galaxies' disks can develop local instabilities. Below the line, turbulence prevents gas clumps from forming. Over their entire disks, LCBGs are mostly stable.

325 is mostly stable accross its disk). We note that we assume that f_{gas} is constant at all radii, which is unlikely to be the case given that the LCBGs' H I emission is centrally concentrated. In addition, our assumption that $f_{\text{gas}} = f_{\text{HI}}$ is only a first-order approximation as the contribution to the gas mass from molecular gas is likely non-negligible. These effects would result in smaller $\Sigma_{\text{total}}/\Sigma_{\text{gas}}$ at all radii than what we assume, particularly at smaller radii, which would bias Equation 3.6 toward a greater likelihood of disk instabilities at smaller radii than what we plot in Figure 3.15 (lower-radii data points will move to the left in Figure 3.15 if f_{gas} increases with decreasing radius).

In a study modeling gas infall onto galaxies, Dekel et al. (2009) found that if the cold gas streams that are feeding infall onto the disk are clumpy, the clumps more easily merge toward the center of the galaxy and form a spheroid shape, keeping the disk's average $f_{\text{gas}} < 0.3$. In this scenario, the disk is usually stable. They found that conversely, if the streams are smooth, the disk can support clumps for a longer period of time. Noguchi (2000) found that requiring the local gas density to rise above a certain threshold before star-forming clumps could form yielded simulations consistent with observations of early- and late- type disks, and that for smaller galaxies, clumps may not be able to form at all and instead the infalling gas is fed into the center of the galaxy to form a bar. To estimate the likelihood of these scenarios, we can compare the M_{HI} values that we measure for the LCBGs in our sample to the clump masses that have been observed and modeled in other studies. Elmegreen et al. (2009) found that for spiral galaxies, each clump contains an average of 0.3% of its galaxy's stellar mass, while for clump cluster galaxies (galaxies dominated by several bright clumps) each clump contains about 2% of the galaxy's stellar mass. If we make the assumption that these ratios are also approximately valid for M_{HI} , we can multiply these percentages by the average M_{HI} of the LCBGs in our sample to find the expected clump masses. On average, a clump would contain about $1 \times 10^7 M_{\odot}$ of H I in a spiral LCBG, or about $7 \times 10^7 M_{\odot}$ of H I in a clump cluster LCBG. Noguchi (2000) found that in simulations, clumps were more likely to survive migration toward the galaxies' centers in galaxies with clumps larger than $\sim 10^7 M_{\odot}$, while in galaxies with smaller clumps, the clumps were more likely to be disrupted and instead form a short bar from their gas. Though we do not have the sensitivity in our current study to measure the

masses of gas clumps, nor the resolution to measure local overdensities in the LCBGs in our sample, future studies at higher resolutions may be able to identify density variations in LCBGs' disks and determine the likely course of future evolution of the galaxies' clumps. As both low-redshift LCBGs and their high-redshift analogs are often clumpy, further understanding of this phenomenon will be useful in predicting these galaxies' evolutionary paths.

To determine whether any star-forming clumps due to gravitational instabilities in LCBGs are detectable over long timescales, we calculated the inspiral time for clumps, $t_{\text{ins}} = (V_{\text{rot}}\sigma^{-1})^2 \times t_{\text{dyn}}$, where $t_{\text{dyn}} = R_{\text{HI}}/V_{\text{rot}}$ (see, for example, Dekel et al. 2009; Genzel et al. 2014) using V_{rot} measured at R_{HI} and the average σ measured within R_{HI} for each LCBG. For the LCBGs in our sample, t_{ins} is longer than 1 Gyr (approximately the lifetime of a $\sim 2.5 M_{\odot}$, or late-B to early A-type star; Harmanec 1988; Maeder & Meynet 1989; Romano et al. 2005) for all but two LCBGs. This implies that if clumps can form in LCBGs, they can persist for several Gyr before they finally sink to LCBGs' centers if they are not disrupted. When compared with less compact and less dynamically hot disk galaxies, however, the expected t_{ins} for LCBGs is relatively short. Since disk galaxies tend to have higher values of $V_{\text{rot}}\sigma^{-1}$ at lower redshifts than at higher redshifts (Kennicutt & Evans 2012), the appearances of clumpy galaxies at $z \sim 1$ may evolve more rapidly than most disk galaxies with star-forming clumps in the local universe due to their lower t_{ins} . Thus, since local LCBGs have relatively high values of $V_{\text{rot}}\sigma^{-1}$ and compact R_{HI} , their t_{ins} are likely more comparable to those of LCBGs at higher redshifts. Future resolved observations of LCBGs will help better measure local velocity dispersions and disk inclinations,

which will better constrain inspiral times for clumps in their disks. In addition, resolving individual clumps and measuring their properties will determine whether feedback within the clumps due to radiation pressure will disperse the clumps on shorter timescales than t_{ins} .

3.3.7 Comparison with higher-redshift galaxies

Förster Schreiber et al. (2009) measured H_α velocity maps for a sample of $z \sim 2$ star-forming galaxies from the Spectroscopic Imaging survey in the Near-Infrared with SINFONI (SINS) survey. Most of the galaxies in their sample had clumpy H_α morphologies. They found that the galaxies in their sample fell into three groups based on their kinematics, with approximately a third of their sample falling into each category: rotation-dominated disks, compact dispersion-dominated galaxies, and merging systems. The H I velocity fields of the LCBGs in our sample resemble the H_α velocity fields of the rotation-supported galaxies in their sample, as shown in Figure 17 of Förster Schreiber et al. (2009). The LCBGs in our sample do not appear to be similar to star-forming galaxies supported by disordered motions; the dispersion-dominated galaxies in the Förster Schreiber et al. (2009) sample do not show a clear axis of rotation, while even the least rotationally-supported LCBGs in our sample show a clear velocity gradient.

Genzel et al. (2014) found that for a sample of 19 rotationally-supported, star-forming disk galaxies from the SINS survey with smooth velocity gradients and centrally-peaked velocity dispersions at $z \sim 2$, Q is also centrally-peaked. We can see

from Figure 3.15 that this is true for the LCBGs in our sample as well. The solid line in Figure 3.15 represents $Q = 1$, with values of Q increasing to the bottom right. We see that for the LCBGs in our sample, the measurements at the smallest radii have larger values of Q than at larger radii. As mentioned in Section 3.3.6.1, we assume in Figure 3.15 that Σ_{gas} is constant at all radii, which is unlikely to be true since the H I emission in the LCBGs in our sample is centrally-peaked. If Σ_{gas} increases with decreasing radius in the LCBGs in our sample, then Q will not be as centrally-peaked as is implied by Figure 3.15. Genzel et al. (2014) argue that increased values of Q in the centers of galaxies could lead to the formation of a central bulge and the quenching of star formation where $Q > 1$. While our measurements of rotation velocities, velocity dispersions, and gas masses suggest that a similar central bulge is possible in the LCBGs in our sample, higher-resolution measurements of H I are needed for these galaxies to more conclusively identify central bulges that could lead to the quenching of star formation in LCBGs.

3.4 Conclusions

In this study, we have measured the H I properties of nine LCBGs from resolved maps. We conclude that

- The LCBGs in our sample are rotating disk galaxies with centrally-concentrated H I intensities and velocity dispersions;

- The H I linewidths measured for these galaxies by single dishes tend to overestimate their rotation velocities, likely due to the inclusion of companions or tidal features in the beam;
- The LCBGs in our sample have values of $V_{\text{rot}}\sigma^{-1}$ that are consistent with disk galaxies rather than dwarf elliptical galaxies when measured at R_{HI} and R_{25} , though some LCBGs have $V_{\text{rot}}\sigma^{-1}$ within R_{eff} that are consistent with bulgelike behavior; and
- The disks of the LCBGs in our sample are stable on average with respect to local perturbations, though they have the potential to form local instabilities at large radii.

We have found that the LCBGs exhibit a variety of gas morphologies, from regular, symmetric rotation to asymmetric, disturbed rotation to multiple galaxies in a common H I envelope. All of the LCBGs in our sample appear to be dominated by rotation at large radii ($V_{\text{rot}}\sigma^{-1}(R_{\text{HI}}) > 1$), and have significant rotation components at smaller radii. We do not have the resolution to robustly fit the inclinations of their disks, so their inclinations, and thus their corrected V_{rot} and values of $V_{\text{rot}}\sigma^{-1}$, are highly uncertain. We do not have enough information to comment extensively on the shapes of LCBGs' rotation curves (or their mass distributions), though we have taken cuts along their major axes that display the shapes of their velocity profiles. The LCBGs in our sample tend to have asymmetric velocity profiles, which supports a scenario where LCBG star formation is the result of gas disturbance. We cannot conclusively distinguish whether this disturbance is externally or internally triggered,

but the presence of companions near most of the LCBGs in our sample are not inconsistent with external mechanisms. Even so, even the most disturbed LCBGs tend to have identifiable H I rotation axes.

When compared to previous single-dish results (Garland et al. 2004), we measure lower values of V_{rot} for all of the LCBGs in our sample except for SDSS1507+5511. Six of the nine LCBGs have smaller measured R_{HI} values than what was estimated for them using $R_{\text{HI}} \sim 2 \times R_{25}(\text{B})$ (two of the exceptions, SDSS0728+3532 and SDSS1319+5203, have H I envelopes that include other galaxies, while the other exception, SDSS0936+0106, has a measured R_{HI} that is only 6% larger than its estimated R_{HI}). These discrepancies tend to result in smaller values of M_{dyn} , and larger values of f_{gas} , for LCBGs than those calculated from single dish measurements.

Though most of them have disturbed kinematics, the LCBGs in our sample do not appear to be exclusively the result of major mergers. Seven (78%) of them have companions at comparable systemic velocities, and two (22%) of them have other galaxies within their H I envelopes. This implies that the star formation in LCBGs is not required to be solely triggered by a major merger event. Instead, some LCBGs' star formation may be the result of intrinsic bulge-building, which could be enhanced by interactions or minor mergers but does not require interactions to proceed (we note, for example, that for the two LCBGs, SDSS0728+3532 and SDSS1319+5203, that are in three-galaxy interacting systems, only one of the galaxies in each system is an LCBG).

We found that the LCBGs in our sample either already follow the Tully-Fisher relation or have the potential to evolve onto it once their starbursts, and thus B-band

luminosities, fade. While the LCBGs' $V_{\text{rot}}\sigma^{-1}$ values look like those of dwarf elliptical galaxies at the smallest radii ($R < R_{\text{eff}}$), they resemble other types of spiral galaxies more closely at $R_{25}(\text{B})$. From this, we infer that the LCBGs in our sample are likely not dispersion-dominated bulges, and that they will not likely be able to passively evolve into dwarf ellipticals once their star formation is quenched. However, some of the LCBGs in our sample may be building small central bulges, as three of the galaxies have $V_{\text{rot}}\sigma^{-1}$ values at large radii ($R > R_{25}$) that are above the threshold of disk instability necessary for infalling gas to create star-forming clumps that may later merge to form a nucleus or bar.

The variety of optical and H I morphologies, environments and kinematics of the LCBGs in our sample lends support to the picture of LCBGs being a heterogeneous class of galaxies undergoing a common, short-lived evolutionary phase in their star formation histories. Since the LCBGs in our sample do not have common H I properties, we cannot predict a single future scenario for their evolution based on their gas morphologies. This is not surprising, as the relative abundance of LCBGs at $z \sim 1$ would suggest that, if LCBGs follow a single common evolutionary path, their end products would be similarly common in the local universe.

Since LCBGs appear to have such a variety of gas morphologies, future studies of their gas properties focusing on high-resolution mapping to further probe their internal dynamics, including the presence of star-forming gas clumps, bars, or bulges related to local gravitational instabilities, will better illustrate whether they have any common intrinsic star formation triggers. Such mapping would provide data useful for modeling LCBGs' gas evolution to predict their timescales for future quenching

of their star formation. We are studying the radio continuum properties of a larger local sample of LCBGs to calculate their current star formation rates. This information, coupled with LCBGs' M_{HI} values, will help us understand whether LCBGs' gas depletion timescales given their current star formation rates are shorter than their expected timescales for star formation quenching. This will provide better understanding for the evolutionary paths of this formerly common, currently rare, class of galaxies.

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Table 3.1. Optical properties

Source ^a	Common Name	D ^b (Mpc)	R _{eff} (B) ^c (kpc)	B − V ^d	m _B ^e	M _B ^f	SBe(B) ^g B Mag'' ^{−2}	Hubble Type ^h
SDSS J011932.94+145219.0	NGC 469	54.6	1.45	0.37	14.9	-18.8	20.5	S0/a
SDSS J012539.72+011041.0 ⁱ	ARK 044	80.4	2.37	0.62	15.5	-19.0	21.3	Sb
SDSS J072849.74+353255.2	ARK 134	58.6	1.41	0.41	14.7	-19.1	20.1	Sbc
SDSS J093410.62+001431.8	UGC 05097	75.8	1.97	0.46	14.2	-20.2	19.8	Sa
SDSS J093635.36+010659.7	CGCG 007-009	76.0	2.54	0.51	14.7	-19.7	20.8	Sb
SDSS J131949.94+520341.2	SBS1317+523B	69.9	1.16	0.30	15.5	-18.7	20.1	...
SDSS J140203.52+095545.5	NGC 5414	65.3	1.75	0.45	13.9	-20.2	19.6	E?
SDSS J150748.35+551108.7	UGC 09737	49.6	1.88	0.44	14.5	-19.0	20.9	Sbc
Mrk 325 ^j	NGC 7673	44.0	1.23	0.41	13.6	-19.6	19.4	Sc

Table 3.1—Continued

Source ^a	Common Name	D ^b (Mpc)	R _{eff} (B) ^c (kpc)	B − V ^d	m _B ^e	M _B ^f	SBe(B) ^g B Mag ^{″−2}	Hubble Type ^h
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^aSDSS source names are of the form SDSS JHHMMSS.SS+DDMMSS.S and are hereafter shortened to SDSS HHMM+DDMM.

^bDistances were taken from NED’s luminosity distances using $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$.

^cHalf-light radii in the B band calculated using SDSS g and r Petrosian radii using DR7 photometry.

^dColors calculated from SDSS g and r magnitudes using DR7 photometry. Magnitudes are adjusted for extinction using SDSS DR7 Galactic reddening correction values.

^eB-band apparent magnitudes calculated from SDSS g and r magnitudes using DR7 photometry and corrected for extinction.

^fB-band absolute magnitudes calculated from m_B and luminosity distances.

^gSurface brightnesses in the B band calculated from M_B , $R_{eff}(B)$, and luminosity distances.

^hFrom Hyperleda, except SDSS0936+0106 (from NED). SDSS1319+52303 does not have a Hubble type classification in Hyperleda or NED; Galaxy Zoo (Lintott et al. 2011) classifies this galaxy as “uncertain.”

ⁱThe color and surface brightness of SDSS 0125+0110 are outside of the optical parameters that Werk et al. (2004) use to define LCBGs when we use DR7 photometry to calculate them. As these properties are within the LCBG optical parameters using DR4 photometry, we do not exclude this galaxy from our analysis.

^jMrk 325 is at the J2000 (RA, Dec) position (23:27:41.0, +23:35:21).

Table 3.2. Imaging parameters

Galaxy	High-res beam (arcsec ²)	Robustness	UV taper (k λ)	UV range (k λ)	# CLEAN iterations	Low-res beam (arcsec ²)	Robustness	UV taper (k λ)	UV range (k λ)	# CLEAN iterations
SDSS0119+1452	13×13	2	70×70	100	50	52×47	5	3×3	5	50
SDSS0125+0110	22×13	5	30×30	50	6000	54×45	5	3×3	5	35
SDSS0728+3532	13×8	5	70×70	100	180	55×53	5	3×3	5	60
SDSS0934+0014	20×20	5	30×30	40	200	75×49	5	3×3	5	25
SDSS0936+0106	12×11	3	70×70	100	100	55×46	5	3×3	5	950
SDSS1319+5203	15×12	5	30×30	50	400	63×50	5	3×3	5	50
SDSS1402+0955	23×14	2	30×30	50	6000	53×53	5	7×7	10	20
SDSS1507+5511	11×9	5	30×30	50	130	52×51	5	3×3	5	40
Mrk 325 ^a	6×6	0	...	...	50					

^aThe data cube for Mrk 325 is from a combination of B, C, and D VLA configuration observations.

Table 3.3. Companion sources visible in maps

LCBG	Companion Name	RA (J2000)	Dec (J2000)	Separation (arcminutes)	Separation ^a (R _{eff} (B))	V _{sys} ^b (km s ⁻¹)	Detected?
SDSS0119+1452	NGC 471	01:19:59.6	+14:47:10	8.2	90	4137	N
SDSS0728+3532	GALEXASCJ072841.30+353206.1 ^c	07:28:41.3	+35:32:06	2.0	24	3930	Y
	SDSS072849.02+353124.6	07:28:49.0	+35:31:24	1.5	18	4010	Y
SDSS0934+0014	UGC05097 Notes01	09:34:10.5	+00:15:29	1.0	11	4665	N
	UGC 05099	09:34:34.2	+00:05:23	11	123	4954	Y
SDSS0936+0106	SDSS093626.68+011128.8	09:36:26.7	+01:11:28	5.0	44	4900	Y
SDSS1319+5203	SBS1317+520 ^d	13:19:46.2	+51:48:06	15.6	270	...	Y
	SBS1317+523A	13:19:47.5	+52:04:13	0.6	11	4588	Y

Table 3.3—Continued

LCBG	Companion Name	RA (J2000)	Dec (J2000)	Separation (arcminutes)	Separation ^a (R _{eff} (B))	V _{sys} ^b (km s ⁻¹)	Detected?
	Mrk 251	13:20:01.0	+52:03:03	1.8	32	4581	Y
SDSS1507+5511	SDSS150804.21+551954.0	15:08:04.2	+55:19:54	9.0	69	3385	Y
Mrk 325	Mrk 326	23:28:06.1	+23:31:52	6.7	70	3519	Y

^aProjected separation from target galaxy in multiples of the target galaxy's R_{eff}(B).

^bV_{sys} is approximated from moment maps if detected, or taken from NED if not detected.

^cSDSS classifies this object as a star; NED classifies it as a UV source.

^dNED classifies this object as a QSO at z = 1.06.

Table 3.4. LCBG H I Profile Properties

Galaxy	$V_{\text{sys}}^{\text{a}}$ (km s $^{-1}$)	W_{20}^{b} (km s $^{-1}$)	$\int \text{Sdv}$ (Jy km s $^{-1}$)	M_{HI} ($10^9 M_{\odot}$)	$\frac{M_{\text{HI}}^{\text{GMRT}}}{M_{\text{HI}}^{\text{GBT}}}$ ^c	Companion in GBT beam? ^d
SDSS0119+1452	4123 ± 7	52.1 ± 13.6	1.0 ± 0.4	0.85 ± 0.29	0.4	Y
SDSS0125+0110	5875 ± 7	126.8 ± 13.8	3.3 ± 0.3	5.4 ± 0.5	...	...
SDSS0728+3532 ^e	3962 ± 7	166.1 ± 13.6	9.8 ± 1.2	7.4 ± 0.9	1.2	N
SDSS0934+0014	4903 ± 7	125.8 ± 13.7	2.2 ± 0.4	2.5 ± 0.5	0.5	Y
SDSS0936+0106	4909 ± 7	181.2 ± 13.7	2.0 ± 0.4	2.3 ± 0.5	0.6	Y
SDSS1319+5203 ^e	4607 ± 7	139.4 ± 13.7	11.2 ± 0.7	11.4 ± 0.7	1.4	Y
SDSS1402+0955	4251 ± 7	262.3 ± 13.7	4.9 ± 1.1	4.3 ± 0.9	0.7	Y
SDSS1507+5511	3358 ± 7	124.2 ± 13.6	3.8 ± 0.4	2.0 ± 0.2	1.0	N
Mrk 325 ^f	3364 ± 5	54.1 ± 10.3	3.2 ± 0.4	1.7 ± 0.2	0.3	Y

^a V_{sys} is measured halfway between the channels used to measure W_{20} . The reported uncertainty is half of a channel width.

^b W_{20} is corrected for random motions following Equation 12 of Tully & Fouque (1985), as well as corrected for inclination angle. The reported uncertainty is one channel width.

^c $M_{\text{HI}}^{\text{GBT}}$ values are taken from Garland et al. (2004).

^dTaken from Table 1 of Garland et al. (2004).

^eProperties listed are for the entire H I envelope, which contains multiple galaxies.

^fMeasurements are taken from the high-resolution cube. For data measured from a low-resolution cube, see Table 4 of Nordgren et al. (1997). Those authors found $M_{\text{HI}} = 3.6 \times 10^9 M_{\odot}$, which is 60% of the Garland et al. (2004) single-dish value.

Table 3.5. Dynamical Masses from Cuts Along Major Axes

Galaxy	$V_{\text{opt}}^{\text{a}}$ (km s $^{-1}$)	$V_{\text{sys}}^{\text{b}}$ (km s $^{-1}$)	R_{25}^{c} (kpc)	$V_{\text{rot}}(R_{25})^{\text{d}}$ (km s $^{-1}$)	R_{HI}^{e} (arcsec)	R_{HI} (kpc)	$V_{\text{rot}}(R_{\text{HI}})^{\text{f}}$ (km s $^{-1}$)	$i_{\text{opt}}^{\text{g}}$ (deg)	$M_{\text{dyn}}(R_{25})$ ($10^{10} M_{\odot}$)	$M_{\text{dyn}}(R_{\text{HI}})$ ($10^{10} M_{\odot}$)
SDSS0119+1452 ^h	4118.6 ± 13.6	4118.6 ± 13.6	7.3 ± 1.1	27.1 ± 13.6	21.2 ± 0.4	6.0 ± 0.1	27.1 ± 13.6	49.7	0.2 ± 0.14	0.18 ± 0.12
SDSS0125+0110	5877.1 ± 13.7	5877.1 ± 13.7	7.9 ± 1.4	68.6 ± 13.7	51.3 ± 0.6	20.9 ± 0.25	68.6 ± 13.7	41.5	2.0 ± 0.9	5.2 ± 2.1
SDSS0728+3532	3944.1 ± 13.5	3964.4 ± 13.5	5.3 ± 1.1	54.2 ± 13.5	51.6 ± 0.6	14.2 ± 0.2	74.5 ± 13.5	45.3	0.71 ± 0.29	1.8 ± 1.3
SDSS0934+0014	4905.8 ± 13.6	4926.3 ± 13.6	6.5 ± 1.2	$40.9 \pm 13.6^{\text{i}}$	18.0 ± 2.0	6.1 ± 0.7	47.7 ± 13.6	68.4	0.31 ± 0.21	0.38 ± 0.22
SDSS0936+0106	4883.5 ± 13.1	4909.7 ± 13.1	7.4 ± 1.2	91.7 ± 13.1	44.1 ± 0.6	15.0 ± 0.2	104.8 ± 13.1	50.6	2.4 ± 0.8	6.4 ± 1.6
SDSS1319+5203	4657.4 ± 13.6	4623.4 ± 13.6	5.4 ± 1.8	47.6 ± 13.6	49.2 ± 1.2	15.8 ± 0.4	20.4 ± 13.6	53.9	0.44 ± 0.29	0.23 ± 0.31
SDSS1402+0955	4213.0 ± 13.6	4233.4 ± 13.6	8.6 ± 1.1	115.3 ± 13.6	35.7 ± 0.6	10.5 ± 0.2	115.3 ± 13.6	54.4	4.0 ± 1.1	4.9 ± 1.1
SDSS1507+5511	3347.9 ± 13.5	3320.9 ± 13.5	7.8 ± 0.8	67.4 ± 13.5	52.5 ± 1.2	12.1 ± 0.3	80.9 ± 13.5	42.5	1.8 ± 0.7	4.0 ± 1.4
Mrk 325 ^h	3373.9 ± 10.3	3368.8 ± 10.3	7.2 ± 0.8	25.8 ± 10.3	23.0 ± 1.0	5.5 ± 0.2	25.8 ± 10.3	68.2	0.13 ± 0.10	0.10 ± 0.07

^aVelocities are measured at the position of the optical galaxy along the major axis.

^bSystemic velocities are measured at the halfway point of the major axis along the H I diameter.

^c $R_{25}(\text{B})$ taken from Hyperleda.

^dUncorrected rotation velocity at $R_{25}(\text{B})$.

^e R_{HI} is the distance between the optical center of the galaxy and the contour with a column density of $1 M_{\odot} \text{pc}^{-2}$.

^fUncorrected rotation velocity at R_{HI} .

^gInclinations taken from Hyperleda.

^hSDSS0119+1452 and Mrk 325 are less extended in H I than in the optical, so $V_{\text{rot}}(R_{25})$ is taken to be the velocity at R_{HI} .

ⁱThe H I of SDSS0934+0014 is less extended than the optical galaxy on one side. We took the velocity at the side where the H I is more extended than the optical galaxy.

Table 3.6. Comparison of H I properties to those derived from single dish data

Galaxy	$V_{\text{rot}}^{\text{G04a}}$ (km s ⁻¹)	$V_{\text{rot}}(\text{R}_{\text{HI}})^{\text{b}}$ (km s ⁻¹)	$R_{\text{HI}}^{\text{G04c}}$ (kpc)	R_{HI} (kpc)	$M_{\text{dyn}}^{\text{G04}}(\text{R}_{\text{HI}})^{\text{d}}$ (10 ¹⁰ M _⊙)	$M_{\text{dyn}}(\text{R}_{\text{HI}})^{\text{e}}$ (10 ¹⁰ M _⊙)	$M_{\star}$ (10 ¹⁰ M _⊙)	$f_{\text{gas}}^{\text{G04f}}$	$f_{\text{gas}}^{\text{g}}$
SDSS0119+1452	115	36	11.2	6.0	3.3	0.18	0.41	0.06	0.5
SDSS0125+0110	...	104	...	20.9	...	5.2	0.45	...	0.1
SDSS0728+3532 ^h	160	105	10.8	14.2	6.7	1.8	0.44	0.09	0.4
SDSS0934+0014	189	51	13.6	6.1	10.8	0.38	1.6	0.05	0.7
SDSS0936+0106	146	136	14.2	15.0	6.3	6.4	0.79	0.06	0.04
SDSS1319+5203 ^h	120	25	10.6	15.8	4.0	0.23	0.28	0.2	5.0
SDSS1402+0955	186	142	17.4	10.5	15.0	4.9	1.2	0.04	0.09
SDSS1507+5511	72	120	15.8	12.1	2.0	4.0	0.42	0.1	0.05
Mrk 325	121	28	19.2	9.1	6.3	0.1	1.1	0.1	0.4 ⁱ

^a $V_{\text{rot}}^{\text{G04}}$ is calculated using half of W_{20} , which is corrected for inclination and random motions and taken from Table 3 of Garland et al. (2004).

^b $V_{\text{rot}}(\text{R}_{\text{HI}})$ is measured using a cut along the major axis and is taken from Table 3.5 and corrected for inclination.

^c $R_{\text{HI}}^{\text{G04}}$ is esitimated to be $2 \times R_{25}$ and is taken from Garland et al. (2004).

^d $M_{\text{dyn}}^{\text{G04}}(\text{R}_{\text{HI}})$ is calculated using the M_{HI} and $M_{\text{HI}}M_{\text{dyn}}^{-1}$ values in Table 3 and Table 4 of Garland et al. (2004).

^e $M_{\text{dyn}}(\text{R}_{\text{HI}})$ is calculated using $V_{\text{rot}}(\text{R}_{\text{HI}})$ and R_{HI} and is taken from Table 3.5.

$$f_{\text{gas}}^{\text{G04}} = M_{\text{HI}}/M_{\text{dyn}}^{\text{G04}}$$

$$f_{\text{gas}}^{\text{g}} = M_{\text{HI}}/M_{\text{dyn}}$$

^hSDSS0728+3532 and SDSS1319+5203 lie within H I envelopes that include other galaxies. Their H I masses include the entire envelope, while their rotation velocities and dynamical masses calculated from a cut along their major axes include only the LCBGs.

ⁱSince $M_{\text{HI}}/M_{\text{dyn}} > 1$, likely due to an underestimation of M_{dyn} due to uncertaintiy in the inclination, we report $f_{\text{gas}} = M_{\text{HI}}/(M_{\text{HI}} + M_{\star})$.

Table 3.7. Velocity dispersions

Galaxy	$\sigma_{\text{R}_{\text{eff}}}^{\text{a}}$ (km s ⁻¹)	$V_{\text{rot}}^{\text{R}_{\text{eff}} \text{ b}}$ (km s ⁻¹)	$\frac{V_{\text{rot}}^{\text{R}_{\text{eff}}}}{\sigma_{\text{R}_{\text{eff}}}}$	$\sigma_{\text{R}_{25}}^{\text{c}}$ (km s ⁻¹)	$V_{\text{rot}}^{\text{R}_{25} \text{ d}}$ (km s ⁻¹)	$\frac{V_{\text{rot}}^{\text{R}_{25}}}{\sigma_{\text{R}_{25}}}$
	$\sigma_{\text{R}_{\text{HI}}}^{\text{e}}$ (km s ⁻¹)	$\sigma_{>\text{R}_{25}}^{\text{f}}$ (km s ⁻¹)	$V_{\text{rot}}^{\text{R}_{\text{HI}} \text{ g}}$ (km s ⁻¹)	$\frac{V_{\text{rot}}^{\text{R}_{\text{HI}}}}{\sigma_{\text{R}_{\text{HI}}}}$	$\frac{V_{\text{rot}}^{\text{R}_{\text{HI}}}}{\sigma_{>\text{R}_{25}}}$	$t_{\text{ins}}^{\text{h}}$ (Gyr)
SDSS0119+1452 ⁱ	20.7 ± 0.8	8.9 ± 17.8	0.43 ± 0.86	12.1 ± 6.7	35.5 ± 17.8	2.9 ± 2.2
	12.6 ± 6.3	29.5 ± 3.4	35.5 ± 17.8	2.8 ± 2.0	1.2 ± 0.6	1.3
SDSS0125+0110	23.0 ± 3.2	62.1 ± 20.7	2.7 ± 1.0	20.1 ± 4.3	103.5 ± 20.7	5.2 ± 1.5
	11.2 ± 6.6	8.7 ± 5.2	103.5 ± 20.7	9.2 ± 5.8	11.9 ± 7.5	17
SDSS0728+3532	40.3 ± 1.6	28.6 ± 19.0	0.71 ± 0.47	33.0 ± 5.2	76.3 ± 19.0	2.3 ± 0.7
	20.6 ± 11.1	10.0 ± 7.3	104.8 ± 19.0	5.1 ± 2.9	10.5 ± 7.9	3.4
SDSS0934+0014	41.8 ± 0.9	7.3 ± 14.6	0.18 ± 0.35	34.6 ± 8.7	44.0 ± 14.6	1.3 ± 0.5
	35.3 ± 8.2	12.3 ± 13.6	51.3 ± 14.6	1.5 ± 0.5	4.2 ± 4.8	0.2
SDSS0936+0106	45.8 ± 5.4	67.8 ± 17.0	1.5 ± 0.4	30.5 ± 10.0	118.7 ± 17.0	3.9 ± 1.4
	21.0 ± 12.7	9.4 ± 7.4	135.6 ± 17.0	6.5 ± 4.0	14.4 ± 11.5	4.5
SDSS1319+5203	37.4 ± 4.3	8.4 ± 16.8	0.23 ± 0.45	39.5 ± 7.0	58.9 ± 16.8	1.5 ± 0.5
	24.7 ± 14.3	16.8 ± 12.6	25.2 ± 16.8	1.0 ± 0.9	1.5 ± 1.5	0.6
SDSS1402+0955	47.4 ± 4.7	41.7 ± 16.7	0.88 ± 0.36	31.5 ± 14.5	141.8 ± 16.7	4.5 ± 2.1
	27.1 ± 16.1	7.3 ± 9.7	141.8 ± 16.7	5.2 ± 3.2	19.4 ± 25.9	2.0
SDSS1507+5511	22.6 ± 1.9	10.0 ± 20.0	0.44 ± 0.89	18.5 ± 7.5	99.8 ± 20.0	5.4 ± 2.3

Table 3.7—Continued

Galaxy	$\sigma_{R_{\text{eff}}}^{\text{a}}$ (km s ⁻¹)	$V_{\text{rot}}^{R_{\text{eff}}}{}^{\text{b}}$ (km s ⁻¹)	$\frac{V_{\text{rot}}^{R_{\text{eff}}}}{\sigma_{R_{\text{eff}}}}$	$\sigma_{R_{25}}^{\text{c}}$ (km s ⁻¹)	$V_{\text{rot}}^{R_{25}}{}^{\text{d}}$ (km s ⁻¹)	$\frac{V_{\text{rot}}^{R_{25}}}{\sigma_{R_{25}}}$
	$\sigma_{R_{\text{HI}}}^{\text{e}}$ (km s ⁻¹)	$\sigma_{>R_{25}}^{\text{f}}$ (km s ⁻¹)	$V_{\text{rot}}^{R_{\text{HI}}}{}^{\text{g}}$ (km s ⁻¹)	$\frac{V_{\text{rot}}^{R_{\text{HI}}}}{\sigma_{R_{\text{HI}}}}$	$\frac{V_{\text{rot}}^{R_{\text{HI}}}}{\sigma_{>R_{25}}}$	$t_{\text{ins}}^{\text{h}}$ (Gyr)
Mrk 325 ⁱ	15.2 ± 8.3	8.7 ± 8.1	119.7 ± 20.0	7.9 ± 4.5	13.8 ± 13.0	6.1
	15.7 ± 4.2	16.7 ± 11.1	1.1 ± 0.8	13.2 ± 6.0	27.8 ± 11.1	2.1 ± 1.3
	13.4 ± 5.9	13.1 ± 6.3	27.8 ± 11.1	2.1 ± 1.2	2.1 ± 1.3	1.4

^a $\sigma_{R_{\text{eff}}}$ is the average value of the Moment 2 map within R_{eff} .

^b $V_{\text{rot}}^{R_{\text{eff}}}$ is the rotation velocity measured at R_{eff} corrected for inclination.

^c $\sigma_{R_{25}}$ is the average value of the Moment 2 map within R_{25} .

^d $V_{\text{rot}}^{R_{25}}$ is the rotation velocity measured at R_{25} corrected for inclination.

^e $\sigma_{R_{\text{HI}}}$ is the average value of the Moment 2 map within R_{HI} .

^f $\sigma_{>R_{25}}$ is the average value of the Moment 2 map outside of R_{25} .

^g $V_{\text{rot}}^{R_{\text{HI}}}$ is the rotation velocity measured at R_{HI} corrected for inclination.

^h t_{ins} is the inspiral time for clumps to reach the center of a rotating disk.

ⁱ R_{25} is larger than the H I radius of SDSS0119+1452 and Mrk 325.

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Chapter 4

Global star formation properties of local luminous compact blue galaxies¹

Abstract

We have conducted a study of the global star formation properties of local ($D < 80$ Mpc) luminous compact blue galaxies (LCBGs) to characterize their current episodes of star formation. We have taken new radio continuum observations of 42 LCBGs between 26 GHz and 40 GHz with the Caltech Continuum Backend on the Green Bank Telescope (GBT), and 10 of those LCBGs at 90 GHz with the MUSTANG bolometer array on the GBT. We have combined this new data with publicly available archival radio continuum and mid- and far-infrared data to measure the contributions of emission components that trace recent star formation in these galaxies. We have found that the LCBGs in our sample all have evidence of ongoing star formation, have a range of star formation rates, and appear to be heterogeneous in their star formation properties and ages of their current star formation episodes. We have also found that the LCBGs in our sample that do not have star-forming clumps tend to have star formation indicators that predict shorter star formation timescales on average than do the LCBGs that have prominent star-forming clumps. We conclude that LCBGs are not homogeneous in their star formation properties or timescales, and that the

physical causes and outcomes of star formation in clumpy and non-clumpy LCBGs are likely to be different.

4.1 Introduction

Earlier in the Universe’s history when average levels of star formation in galaxies were much higher ($z \sim 1$), galaxies were commonly very bright, very blue, and contained high levels of star formation within a very compact radius (Koo et al. 1994). This type of galaxy is a factor of ten rarer in the local universe (Guzmán et al. 1997), which implies that these galaxies evolve rapidly toward other galaxy types once their star formation is quenched. Because of their relatively short evolutionary timescales, several groups have studied a subset of these star-forming galaxies, luminous compact blue galaxies (LCBGs), over a range of redshifts and wavelengths to better understand how galaxies have evolved since $z \sim 1$ (e.g., Guzmán et al. 1997; Pisano et al. 2001; Garland et al. 2004; Bershadsky et al. 2005; Garland et al. 2005; Noeske et al. 2006; Garland et al. 2007; Tollerud et al. 2010; Pérez-Gallego et al. 2010, 2011; Crawford et al. 2011; Garland et al. 2015). Fortunately, since they are bright (they are not dwarf galaxies, but rather $M_* \gtrsim 10^9 M_\odot$ galaxies with compact morphologies and thus high surface brightnesses), the small number of local examples of LCBGs are easily studied over a large range of wavelengths, in both line and continuum emission. Garland et al. (2015) showed that low-redshift ($D < 200$ Mpc) LCBGs, which have the optical criteria outlined in Werk et al. (2004)

¹The work in this chapter was done in collaboration with D.J. Pisano (WVU) and Catherine Garland (Castleton State College).

($B - V < 0.6$ mag, $M_B < -18.5$ mag, and $SBe < -21.0$ mag arcsec $^{-2}$) are representative of the types of galaxies that contributed approximately half of the total star formation rate density at $z \sim 1$ (Guzmán et al. 1997). To better understand these galaxies' evolutionary paths, we have performed a study of the global star formation properties of a distance-limited sample of local LCBGs to determine for how long they have undergone their current episode of star formation, for how long they can continue to form stars, what their likely morphologies will be once their star formation has been quenched, and what their quenching mechanisms are likely to be.

While LCBGs have a common set of optical properties (Werk et al. 2004) and similar appearances in the Hubble Deep Field (Noeske et al. 2006), they are neither uniform in their morphologies nor distinct from other types of galaxies in the parameter space by which they are defined. As shown in Figure 4.1, LCBGs are among the brightest, bluest, and most compact galaxies in the local universe, but they do not separate themselves from other local galaxies along those sets of properties; there are other galaxies that are as bright, as blue, or as compact as LCBGs, but LCBGs are galaxies that exhibit all three properties simultaneously (Werk et al. 2004; Garland et al. 2004). While Amram & Östlin (2001) found that intermediate-redshift LCBGs tend to have evidence of mergers, interactions, or asymmetrical distributions, and Pérez-Gallego et al. (2010) and Chapter 3 of this thesis showed that local LCBGs also have asymmetrical morphologies (with or without companions), Garland et al. (2015) have shown that a large sample of local LCBGs can have either clumpy or smooth disks (they define clumpy galaxies as having three or more visible clumps in color Sloan Digital Sky Survey images), with or without visible spiral arms, bright nu-

clei, interactions, or asymmetrical appearances, and only 20% of the LCBGs in their sample are in interacting systems. Garland et al. (2015) also showed that LCBGs can have companions, but a large percentage of them do not. Garland et al. (2015) and Crawford et al. (2011) found that LCBGs can be found in clusters, voids, and the field, though they are more likely to be found in denser environments than those with very low density. Garland et al. (2007), Pérez-Gallego et al. (2011), and Chapter 3 showed that most local LCBGs are rotating galaxies, though many show disturbed velocity fields. They are not dispersion-dominated spheroidal galaxies, as even the LCBGs with the slowest rotation velocities are still rotationally supported with respect to their velocity dispersions (Pérez-Gallego et al. 2010, Chapter 3). LCBGs should not be considered a distinct class of galaxies in the same way that blue compact dwarfs are— they span a range of metallicities, gas fractions, and masses (Garland et al. 2015)— and so we expect their star formation properties, and the causes of their most recent episodes of star formation, to be varied.

Local LCBGs have been shown to be gas-rich, with the highest column density of gas being located in their centers, so a dominant bulge with a gas-poor disk is an unlikely scenario for the majority of LCBGs (Chapter 3). That LCBGs are rotationally-supported galaxies lends support to the hypothesis that LCBGs are normal star-forming disk galaxies that are experiencing a particularly intense episode of star formation due to a recent merger, interaction with another galaxy or cluster potential, or other type of gas infall. In this scenario, while they may be building a small central bulge or bar, LCBGs will evolve into fainter, less blue rotationally-supported disk galaxies after their current star formation episodes end. In order

Figure 4.1 B-band absolute magnitude vs. B-V color (top), B-band surface brightness vs. B-V color (middle) and B-band surface brightness vs. B-band absolute magnitude (bottom) for the LCBGs in our sample (filled blue circles) and all of the galaxies within 80 Mpc for which this information was available in Hyperleda (open gray squares). LCBGs are the brightest, bluest, most compact galaxies in the nearby universe, but do not strongly separate themselves in parameter space from other types of galaxies.

to distinguish between possible evolutionary scenarios, it is necessary to construct the recent star formation histories of LCBGs and predict their future star formation timescales. While previous studies have measured star formation properties in LCBGs using $H\alpha$ observations (Pérez-Gallego et al. 2010, 2011; Garland et al. 2015), there has not been a comprehensive radio continuum study of LCBGs' global star formation properties. Since the radio continuum is an extinction-free star formation tracer that can detect deeply-embedded star formation on the shortest timescales, and LCBGs are compact enough to be unresolved with single dishes, it is an ideal tool to study the global star formation properties of these rapidly-evolving galaxies.

To characterize the global star formation properties and infer the recent star formation histories of LCBGs, we will address the following questions in this paper:

- Do LCBGs have similar star formation ages? Are they all undergoing a common star formation phase, or can different star formation ages produce similar bright, blue, compact appearances?
- Are LCBGs likely to be undergoing quenching of their star formation?
- Do the star formation properties of LCBGs correlate with optical properties such as color, luminosity, radius, or morphology?
- Can we infer what LCBGs will look like when their current episode of star formation has ended?

Since it has not yet been determined whether LCBGs are undergoing their final round of star formation before evolving to quiescent galaxy types, or just experiencing a pe-

riod of particularly elevated and centrally-concentrated star formation, it is necessary to study tracers of recent generations of star formation to better constrain LCBGs' star formation timescales. We have conducted this study by obtaining new single-dish radio continuum observations of a sample of LCBGs at 26-40 GHz and 90 GHz with the Green Bank Telescope (GBT), as well as new far-infrared ($70\mu\text{m} - 500\mu\text{m}$) observations with the Herschel observatory. We combined these observations with archival radio continuum ($\sim 1 - 100$ GHz), far-infrared (FIR; $\sim 60 \mu\text{m} - 850 \mu\text{m}$), and mid-infrared (MIR; $\sim 10 \mu\text{m} - 25 \mu\text{m}$) data to build these galaxies' spectral energy distributions (SEDs) at frequencies that are extinction-free tracers of recent star formation. Using this data, we investigate here the galaxies' spectral shapes, which can be used to indicate the presence of massive and short-lived O-type stars, recent supernovae, and dust masses and temperatures. We can use this information to model LCBGs' star formation timescales and determine whether LCBGs follow the radio-FIR correlation. We also examine evidence for the hypothesis that LCBGs are undergoing the formation of clump-origin bulges (Garland et al. 2015, Chapter 3), which are driven by disk instabilities due to gas accretion causing local overdensities of gas that can collapse to form star-forming clumps that move toward the center of the galaxies' disks due to dynamical friction (e.g. Noguchi 1998, 1999, 2000; Dekel et al. 2009; Inoue & Saitoh 2012). If this is the case in LCBGs, the merger of clumps in their disks would trigger, sustain, and ultimately quench their star formation, without requiring drastic changes in the galaxies' morphologies.

We discuss the selection of our sample of LCBGs in Section 2, describe our observations and data reduction in Section 3, discuss the SEDs that we fit to the

galaxies and the star formation rates (SFRs) we can derive from them in Section 4, discuss our results, including the radio-FIR correlation, clumpy star formation, and the outcomes of models of LCBGs' star formation properties in Section 5, and state our conclusions in Section 6. When necessary in this paper, we use $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$.

4.2 Sample Selection

We have selected 39 LCBGs within 80 Mpc from the Garland et al. (in prep) sample of ~ 2300 LCBGs within 200 Mpc. The Garland et al. (in prep) sample was originally selected from the Sloan Digital Sky Survey (SDSS) Data Release 4 (DR4, Adelman-McCarthy et al. 2006) using the optical criteria described above, and then updated Data Release 7 (DR7, Abazajian et al. 2009) photometry was applied to calculate the optical properties shown in Table 4.1. Because the galaxies we observed were originally selected using an older data release, some of the galaxies in our sample have colors, magnitudes, or surface brightnesses that fall outside of the defined range for LCBGs when these quantities are calculated using DR7 photometry. As seen in Figure 4.1, this update in photometry does not alter the characterization of LCBGs as galaxies that are bright, blue, and have high surface brightnesses compared to other galaxies. The optical constraints defined in Section 1 do not correspond to sharp boundaries in physical characteristics, but are meant to select for galaxies with similar qualities. Thus, we include in our analysis the galaxies that fall outside of the optical definitions stated in Section 1 when DR7 photometry is applied, and continue

to refer to these galaxies as “LCBGs” throughout this paper. We show the optical properties for each galaxy in Table 4.1.

All of the LCBGs in our sample have been observed in H I with single-dish observations. In addition to the SDSS LCBGs, we selected the Markarian galaxies Mrk 297, Mrk 325, and Mrk 538, which have been previously studied with single-dish and resolved H I observations, as well as CO observations (Garland et al. 2004, 2005, 2007). We chose the distance limit for our subsample of the larger sample to ensure a good chance of detecting the galaxies’ radio continuum emission at ~ 33 GHz within a relatively short on-source time. Between 26 GHz and 40 GHz, the Green Bank Telescope achieves a 1σ noise of $\sim 0.2 - 0.4$ mJy in one minute of on-source time (Mason et al. 2009). At 80 Mpc, this corresponds to an observed star formation rate (SFR) of $\sim 2.2 - 5.3$ $M_{\odot} \text{ yr}^{-1}$, depending on the relative contribution of thermal and nonthermal emission to a galaxy’s radio continuum flux at 33 GHz. Thus, we are sensitive to galaxies with relatively low star formation rates in relatively short observing times.

4.3 Observations, Data Reduction, and Flux Measurements

4.3.1 Radio continuum

We observed all of the galaxies in our sample with the Caltech Continuum Backend (CCB) on the Green Bank Telescope (GBT)², which is located in Green Bank, WV. The CCB observes with four sub-bands that are continuous in frequency between 26 GHz and 40 GHz (for more detail, see Mason et al. 2009). We observed all

of the galaxies using single pointings in the “nod” mode, where two beams alternated between on- and off-source positions so that one or the other beam was always on-source. As stated in Section 2, the CCB can achieve an RMS noise level of 0.2 – 0.4 mJy in the length of time of one nod (Mason et al. 2009). We derived the galaxies’ fluxes and uncertainties from these nods using the IDL reduction routines described in Mason et al. (2009), using observations of 3C 286, 3C 147, or 3C 48 as unresolved absolute flux calibration sources.

We also mapped five of the brightest galaxies (Mrk 297, Mrk 325, Mrk 538, SDSS1038+5330, and SDSS1153+4751) with the CCB using a centrally-weighted daisy scan pattern, with one beam mapping the source and the other beam simultaneously mapping an off-source position. We produced the maps, shown in Figure 4.2, using B. Mason’s IDL mapping routines that are optimized for CCB data. We measured the fluxes and uncertainties of these LCBGs from their maps by fitting a Gaussian function to each map using the width of the beam size for each sub-band using the AIPS task JMFIT. Since the sources appeared unresolved or marginally resolved with the GBT beam, we took the peak of the Gaussian to be the most accurate measure of the galaxies’ fluxes.

We mapped ten galaxies (SDSS0934+0014, SDSS0946+0542, SDSS1038+5330, SDSS1049+3259, SDSS1153+4751, SDSS1224+3922, SDSS1546+0224, Mrk 297, Mrk 325, and Mrk 538) with the MUSTANG Bolometer Array on the Green Bank Telescope. This is a wide-band (81 GHz - 99 GHz), mapping instrument that is de-

²The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

Figure 4.2 CCB 34.75 GHz contours overlaid on SDSS g optical images. Contours are multiples of the measured RMS of the maps. (a) SDSS1038+5330 contours are 2σ , 4σ , and 8σ , 16σ , and 32σ . (b) SDSS1153+4751 contours are 2σ , 4σ , and 6σ . (c) Mrk 297 contours are 2σ , 4σ , and 8σ . (d) Mrk 325 contours are 2σ , 4σ , and 6σ . (e) Mrk 538 contours are 2σ , 4σ , and 8σ .

scribed further in Dicker et al. (2008). MUSTANG has a typical RMS sensitivity of ~ 0.142 mJy in one hour of on-source time for a $3' \times 3'$ map (see the document available at <http://www.gb.nrao.edu/~bmason/pubs/m2mapspeed.pdf> for more information on the sensitivity of MUSTANG). The average RMS of the maps we made was 0.255 mJy, which at a distance of 69 Mpc (the distance of SDSS0934+0014, the most distant LCBG that we mapped) corresponds to a star formation rate of $5.6 M_{\odot} \text{ yr}^{-1}$ if all of the emission at 90 GHz is nonthermal, or $2.3 M_{\odot} \text{ yr}^{-1}$ if all of the emission at 90 GHz is thermal. We used a centrally-weighted daisy scan pattern to map the LCBGs in our sample, as we expect their emission at 90 GHz to be relatively compact, even with respect to the $\sim 9''$ GBT beam at 90 GHz. We reduced the MUSTANG observations using B. Mason’s MUSTANGIDL data reduction routines described in Dicker et al. (2009). During the reduction process, we employed a strict cutoff standard for each scan that excluded detectors with large variations over the scan time to mitigate adverse effects from changing atmospheric or weather conditions. We performed absolute flux calibration on the maps using observations of solar system objects (Mars, Uranus, or Ceres) taken during our observing sessions. The fluxes of the calibration sources were computed using B. Mason’s FITPLANET IDL routine that calculates a flux at 90 GHz using a known brightness temperature and angular size for the objects. We used the recommended brightness temperatures from the MUSTANG flux calibration wiki site³ for each primary flux calibrator. Table 1 at that website compiles brightness temperatures for MUSTANG primary flux calibrators calculated using several sources. Brightness temperatures for Mars were taken from Wright (2007) and multiplied by 0.941 as suggested in Weiland et al.

(2011). Brightness temperatures for Uranus were taken from Weiland et al. (2011). Brightness temperatures for Ceres were found by the MUSTANG PIs by monitoring Ceres with MUSTANG observations in 2009. Angular sizes for the flux calibrators were taken from a query of the ephemeris tool at the JPL Horizons webpage⁴ for the time of the observation. The maps that we produced are shown in Figure 4.3. We measured fluxes and uncertainties for each galaxy from their maps by fitting a Gaussian in the same way as for the CCB maps. We measured integrated fluxes for galaxies that looked significantly more extended than the 9'' beam, and measured peak fluxes for the more compact galaxies. NGC 3949 had two knots of emission, so we added the peak fluxes of these two knots together to get the galaxy's total flux at 90 GHz. When computing uncertainties on the galaxies' fluxes, we used only the central portion of the maps due to rapidly increasing uncertainties outside the centers of daisy scans. For more information on our radio continuum observations, see Table 4.2. We have listed the fluxes and uncertainties from our radio continuum observations in Table 4.3.

4.3.2 Far infrared

We used new Herschel⁵ (Pilbratt et al. 2010) observations, as well as publicly available archival Herschel maps taken from the Herschel Science Archive⁶ to measure far-infrared (FIR) fluxes for sixteen LCBGs. We used data taken by Herschel's PACS instrument (Poglitsch et al. 2010) to measure fluxes between 70 μm and 160 μm .

⁴<https://safe.nrao.edu/wiki/bin/view/GB/Pennarray/MustangFluxCalibration>

⁵<http://ssd.jpl.nasa.gov/?horizons>

Figure 4.3 MUSTANG contours overlaid on SDSS g optical images. Contours are multiples of the measured RMS of the maps. (a) Mrk 297 contours are 2σ , 4σ , and 6σ . (b) Mrk 325 contours are 2σ , 3σ , and 4σ . (c) Mrk 538 contours are 2σ , 4σ , and 8σ . (d) SDSS0946+0542 (NGC 2990) contours are 2σ , 3σ , and 4σ .

Figure 4.3 MUSTANG contours overlaid on SDSS g optical images. Contours are multiples of the measured RMS of the maps. (d) SDSS1038+5330 (NGC 3310) contours are 2σ , 4σ , and 8σ . (e) SDSS1049+3259 (NGC 3396) contours are 2σ , 4σ , and 6σ . (f) SDSS1153+4751 (NGC 3949) contours are 2σ and 3σ . (g) SDSS1224+3922 (NGC 4369) contours are 2σ , 4σ , and 8σ .

Figure 4.3 MUSTANG contours overlaid on SDSS g optical images. Contours are multiples of the measured RMS of the maps. (i) SDSS1546+0224 (NGC 5990) contours are 2σ , 4σ , and 8σ . (j) SDSS 0934+0014 (UGC 05097) contours are 2σ and 3σ .

Thirteen of the LCBGs in our sample were observed with Herschel simultaneously in both the PACS Blue ($70\ \mu\text{m}$) and Red ($160\ \mu\text{m}$) bands, and the PACS Green ($100\ \mu\text{m}$) and Red bands, and an additional three LCBGs were only observed simultaneously in the Green and Red bands (Blue and Green observations are made separately, but both shorter-wavelength observations are simultaneously conducted with observations in the Red band). We do not include LCBGs that were observed in large fields in our analysis, since the data files for large surveys were too large for us to effectively use. Four of the LCBGs in our sample appear in large archival PACS fields, and six of the LCBGs in our sample appear in large archival SPIRE fields. We observed three LCBGs (SDSS0749+3244, SDSS0812+3509, and 1507+5511) as part of proposal OT2_dpisano_1, and the remaining thirteen of the LCBGs were observed as part of proposals by other groups and have data publicly available in the Herschel Science Archive. We measured fluxes from Level 2.5 maps generated by the Herschel

automatic pipeline that have been made with version 12.1 of Herschel’s HIPE data reduction package (Ott 2010), which is the most recent version as of this writing, and the PACS calibration version 65 (also the most recent version) using imaging methods relevant for extended sources. We used an aperture photometry task in HIPE to measure the background-subtracted fluxes in fixed apertures for each wavelength for which a map was available. As we do not expect the FIR emission in LCBGs to have an extended low surface brightness component (LCBGs’ star formation is by definition enclosed in a relatively compact area), we chose the aperture sizes by eye to encompass the visible FIR emission in the maps. We chose apertures for each LCBG by measuring the extent of the galaxy’s 160 μm emission (the largest beam size of the three bands), and kept that aperture size the same for measuring fluxes at each wavelength in order to approximate beam-matched flux measurements. If two maps existed at 160 μm for a particular LCBG, we measured fluxes for both maps and averaged the fluxes together (the two flux measurements are independent). We subtracted background emission by measuring the average flux in ~ 10 small apertures around the galaxy in each map, and subtracted that average flux from the total flux in the source aperture.

We derived uncertainties on the fluxes using the procedure described in Cortese et al. (2014). This procedure takes into account the calibration uncertainty, the uncertainty in the characterization of the background, and the pixel-by-pixel variations in the map. We measured the pixel-by-pixel variation by measuring the standard

⁶Herschel is an ESA space observatory with science instruments provided by European-led Principal Investigator consortia and with important participation from NASA.

⁶<http://www.cosmos.esa.int/web/herschel/science-archive>

deviation of source-free central areas of the map. We did not include the instrumental uncertainty term that Cortese et al. (2014) includes, as this term contributed minimally to the uncertainty for the galaxies in our sample due to relatively small variations in the galaxies’ error maps within the source apertures. We measured the uncertainty of the background by calculating the standard deviation of the mean flux in the source-free apertures close to the galaxy used to measure the pixel-by-pixel variations. The flux calibration on the Herschel automatic pipeline is uncertain to within 5%, according to the Herschel PACS data reduction manual (Balog et al. 2014). We added the background uncertainties measured from the maps with the 5% calibration uncertainty in quadrature to generate the total uncertainties on the Herschel fluxes.

The average uncertainty of the PACS maps is 0.3 Jy at all three PACS subbands. This corresponds to a SFR of $0.8 \text{ M}_{\odot} \text{ yr}^{-1}$ at 78 Mpc using the relationship between $70 \text{ } \mu\text{m}$ luminosity and star formation rate derived by Calzetti et al. (2010): $\text{SFR}(\text{M}_{\odot} \text{ yr}^{-1}) = L_{70 \text{ } \mu\text{m}}(\text{erg s}^{-1})/1.7 \times 10^{43}$. We tabulate the fluxes and uncertainties measured from PACS maps in Table 4.4.

We also measured fluxes at $250 \text{ } \mu\text{m}$, $350 \text{ } \mu\text{m}$, and $500 \text{ } \mu\text{m}$ for eleven LCBGs from new and archival maps made by the SPIRE instrument on Herschel (Griffin et al. 2010), processed by the Herschel automatic pipeline in HIPE (version 12.1), and available in the Herschel Science Archive. We used the same aperture photometry procedures as for the PACS maps to measure background subtracted fluxes and uncertainties, though we increased the aperture sizes to include the galaxies’ emission, since SPIRE has a lower resolution than PACS. The flux calibration uncertainty for SPIRE data includes a factor of 1.5% from relative uncertainty, and a factor of 4%

from the absolute flux calibration uncertainty of models of Neptune, which is used as the flux calibrator for SPIRE observations (Bendo et al. 2013). We added these uncertainties in quadrature with the background uncertainties in the same way as we did for the PACS uncertainties. As with the PACS data, we chose aperture sizes by eye to encompass the visible emission in each galaxy based on the extent of emission in the lowest-wavelength SPIRE band, and kept the same aperture angular size between the three SPIRE wavelengths for each galaxy. We were not always able to match aperture sizes between PACS and SPIRE flux measurements, as SPIRE emission was frequently more extended than PACS emission. The average uncertainty in the SPIRE maps was 0.13 Jy at 250 μm , 0.07 Jy at 350 μm , and 0.03 Jy at 500 μm . We list the fluxes and uncertainties that we measure from SPIRE maps in Table 4.4.

4.4 SED Fitting

4.4.1 Radio continuum

We constructed global radio continuum spectral energy distributions (SEDs) for each of the 31 galaxies with five or more radio continuum data points using publicly available fluxes taken from the NRAO VLA Sky Survey (NVSS; Condon et al. 1998) and NRAO Faint Images of the Radio Sky at Twenty centimeters (FIRST; Becker et al. 1995) survey catalogs at ~ 1.4 GHz, our CCB and MUSTANG observations, and archival fluxes cataloged in the NASA Extragalactic Database (NED)⁷. For references to the archival data points we used, see Table 4.5.

⁷<http://ned.ipac.caltech.edu/>

We note that both the new and archival fluxes were measured using different instruments at different frequencies, which results in different beam sizes. The CCB has the advantage of observing at four frequencies simultaneously, which ensures that the four independent CCB fluxes for each source are measured using the same elevations, weather conditions, and calibrations. However, the four simultaneous observations are taken with slightly different beam sizes due to the frequency differences. These beam sizes vary from $\theta \sim 27''$ at the lowest-frequency sub-band centered on 27.75 GHz to $\theta \sim 19''$ at the highest-frequency sub-band centered on 38.25 GHz. Many of the LCBGs in our sample are unresolved at these resolutions (27 LCBGs have R_{eff} smaller than the smallest beam, another eight have R_{eff} smaller than the largest beam, and seven have R_{eff} larger than the largest beam), so this discrepancy in beam sizes should not significantly affect our flux measurements. However, if a source is resolved with respect to any of the four beams, then the flux measurements could be affected by differing amounts of emission being observed with each beam in single-pointing observations due to the differing physical sizes of each galaxy that the beam encompasses. For discussions of the effects of differing CCB beam sizes see Mason et al. (2009) and Chapter 2. To correct for the differences in beam sizes, we applied the average correction factors for each beam size that we found in Chapter 2. We calculated these factors in Chapter 2 by imaging lower-frequency archival radio continuum maps with the beam sizes of each CCB sub-band for a heterogeneous group of star-forming galaxies with a range of resolutions, from completely unresolved to heavily resolved. These average beam corrections are normalized to the 34.75 GHz beam size and are factors of 0.91 at 27.75 GHz, 0.95 at 31.25 GHz, and 1.05 at 38.25

GHz. These factors are in agreement with those found by Mason et al. (2009), and allow us to approximate beam-matched observations for galaxies that are marginally resolved.

In addition, the 1.4 GHz NVSS observations were made with a $45''$ beam, while we measured the 90 GHz MUSTANG fluxes from maps made with a $9''$ beam. For the LCBGs that are resolved by any of these beam sizes, it is necessary to take additional beam effects into consideration when comparing fluxes between NVSS, CCB, and MUSTANG observations. For a discussion of possible consequences of CCB and NVSS beam size differences, see Chapter 2. We also note that some of the archival observations, including the NVSS and FIRST data, were taken with interferometers. Thus, those observations may suffer from losses in observed emission due to missing short spacings. Since the LCBGs in our sample tend to be unresolved with respect to the VLA beam at L band in compact configurations (their half-light radii range from $3''$ to $26''$, with an average of $9.5''$), we assume that these short spacing losses are small.

When there were at least five radio continuum data points available for a galaxy (typically four flux measurements from the CCB between 26 GHz and 40 GHz, in addition to at least one lower-frequency flux measurement), we fit the radio continuum data points for each LCBG with a combination of two components: a steep-spectrum nonthermal synchrotron component and a flat-spectrum thermal free-free component, using the method described in Chapter 2.

We fit each LCBGs' SED with the function $S_\nu = A\nu^{\alpha_{NT}} + B\nu^{\alpha_T}$ using the IDL routine CURVEFIT, where A and B are scaling factors, α_{NT} is the nonthermal

spectral index, and α_T is the thermal spectral index. The spectral index is defined as

$$\alpha = \frac{\log(S_{\nu_2}/S_{\nu_1})}{\log(\nu_2/\nu_1)} \quad (4.1)$$

where ν_1 and ν_2 are the frequencies between which α is measured. We kept α_T fixed at -0.1 for all of the galaxies in our sample, as it is not expected to vary as long as the emission is optically thin (our single-dish observations are not likely to resolve significant quantities of optically thick thermal emission, which tends to occur in very compact star-forming knots; we discuss this further in the next subsection). For our first attempt at fitting radio continuum SEDs, we fixed the nonthermal spectral index at $\alpha_{NT} = -0.8$, which when combined with a thermal spectral index of $\alpha_T = -0.1$ produced a reasonable fit for 16 of the 31 LCBGs with five or more radio continuum data points (we define a “reasonable” fit to be one with the scaling factors A and B both being positive and statistically significant to the 2σ level; we do not typically have enough data points to produce fits to very high degrees of significance if we are fitting two emission components. When the LCBGs were not well-fit by this two-component function due to a steeper nonthermal spectrum than the typical $\alpha_{NT} \sim -0.8$, we fit the galaxies’ radio continuum spectra with steeper nonthermal spectral indices to probe for spectral steepening in these galaxies. We discuss these fits further in Section 4.4.2.

4.4.2 Other considerations for radio continuum SED fitting

As described in the previous subsection, we fit the LCBGs’ radio continuum emission using synchrotron and optically thin free-free components. At the frequencies over which we have radio continuum data for these galaxies ($\sim 1 - 100$ GHz), these two components are expected to be the dominant sources of emission over large spatial scales in star-forming galaxies without AGN (Condon 1992). As was the case for Chapter 2, we do not have the angular resolution in this study to detect individual star-forming regions, so it is unlikely that optically thick thermal emission characteristic of heavily-obscured star formation in small “knots” (see, for example, Beck et al. 2000; Johnson and Kobulnicky 2003; Tsai et al. 2006; Reines et al. 2008) contributes significantly to the global SEDs that we fit. Thus, we did not include this type of emission in our SED fits (if such emission contributed significantly to LCBGs’ global SEDs, we would see a positive, rather than negative, thermal spectral index). We also do not have radio observations at frequencies low enough for synchrotron self-absorption to contribute significantly to the total radio emission at the observed frequencies (such emission would be seen as a “turnover” at low frequencies, where the spectrum would rise with increasing frequency until synchrotron emission became the dominant component). In addition, anomalous microwave emission (“spinning dust”) that can contribute to the SEDs of individual star-forming regions at the observed CCB frequencies (e.g. Draine & Lazarian 1998; Murphy et al. 2010) is not expected to be detectable in our LCBGs’ global SEDs (we did not detect any such emission in the global SEDs of the local star-forming galaxies we studied in Chapter

2, even in the galaxies that were resolved by the GBT at 33 GHz). If such emission were present in detectable quantities, the galaxies' spectra would show a small bump within the CCB frequency range, which we do not see.

Even though we do not see evidence of the types of radio continuum emission discussed in the previous paragraph contributing in significant quantities to LCBGS' global radio continuum emission between 1 GHz and 100 GHz, the shapes of some of the radio SEDs that we fit appear to be influenced by processes other than the two simple components we mention above. Specifically, the synchrotron component of star-forming galaxies' SEDs can vary from the canonical $\alpha_N = -0.8$ value due to physical conditions in the galaxy. Depending on the cosmic ray injection spectrum of a particular galaxy, that galaxy's observed synchrotron spectrum can be flatter or steeper than $\alpha_N = -0.8$ (Condon 1992). Also, α_N depends on a galaxy's magnetic field, which we assume to be constant throughout each galaxy (and we assume that all of the galaxies have the same magnetic field strength), but which is likely to vary (Condon 1992). In addition, some star-forming galaxies' radio continuum SEDs appear to become steeper at frequencies of $\nu > 10$ GHz (Condon 1992) due to synchrotron aging, which happens when the electrons that produce synchrotron emission lose energy over time. The energy losses in this process are most pronounced at higher frequencies in the early stages of synchrotron aging, and become increasingly detectable at decreasing frequencies as the time since the initial supernova event increases. Since this synchrotron aging becomes more pronounced over time, the curvature of a galaxy's synchrotron spectrum is an indication of the length of time that its cosmic rays have been propagating from their original source. If we can detect

and quantify this aging, we can interpret it as a proxy for the timescale of recent star formation. We discuss the implications of this effect further in Section 4.5.2.2.

When an LCBG in our sample did not have a statistically significant, positive thermal component when fit using $\alpha_{NT} = -0.8$, we modified the synchrotron component in the galaxy’s fit. For these galaxies, we varied the value of α_{NT} by steepening it (making α_{NT} more negative) in increments of 0.05 until a positive thermal component that was stronger than 2σ was produced. We give the values of α_{NT} that produced the lowest values of χ^2 while maintaining a $> 2\sigma$ thermal component for each of these galaxies in Table 4.5. This approach accounts for steeper cosmic ray injection spectra as described in the previous paragraph, but does not fully account for steepening due to synchrotron aging since we do not have enough data points to robustly fit for curved synchrotron spectra (although it can at least indicate that such steepening is a possibility).

4.4.2.1 Galaxies with fewer than five observed fluxes

Eleven of the galaxies in our sample do not have statistically significant detections with the CCB in all four sub-bands. For these LCBGs, we averaged the fluxes in the four sub-bands and took that average flux to represent the flux across the total 26 GHz - 40 GHz range centered on 33 GHz and report that flux in Table 4.3. We do not include these galaxies in our analysis of star formation properties since we cannot quantify the relative amounts of thermal and nonthermal emission in these galaxies.

4.4.3 Star formation rates

When we were able to calculate thermal and non-thermal fluxes from fits to the LCBGs' SEDs, or when we were able to solve for thermal and non-thermal fluxes analytically, we derived total star formation rates for the LCBGs in our sample from their thermal and non-thermal fluxes at 33 GHz using equations 21 and 23 in Condon (1992) scaled to a Kroupa IMF from $0.1 M_{\odot}$ to $100 M_{\odot}$ (Kroupa 2001):

$$\left(\frac{L_N}{WHz^{-1}} \right) \sim 5.3 \times 10^{21} \left(\frac{\nu}{GHz} \right)^{-0.8} \left(\frac{SFR_N (M \geq 5 M_{\odot})}{M_{\odot} yr^{-1}} \right) \quad (4.2)$$

$$\left(\frac{L_T}{WHz^{-1}} \right) \sim 5.5 \times 10^{20} \left(\frac{\nu}{GHz} \right)^{-0.1} \left(\frac{SFR_T (M \geq 5 M_{\odot})}{M_{\odot} yr^{-1}} \right) \quad (4.3)$$

These equations infer star formation rates by assuming that a galaxy's thermal emission scales directly with the number of massive, recently-formed O-type stars present, and a galaxy's non-thermal emission is the result of the number of massive-star supernovae that have occurred in the last ~ 100 Myr (Condon 1992). We report the star formation rates for the galaxies in our sample calculated from thermal and non-thermal fluxes in Table 4.5. The star formation rates of the LCBGs in our sample range from $0.05 M_{\odot} yr^{-1}$ to $57 M_{\odot} yr^{-1}$, with an average of $1.4 M_{\odot} yr^{-1}$ with a standard deviation of $1.6 M_{\odot} yr^{-1}$ for SFRs calculated using thermal fluxes, and an average of $8.1 M_{\odot} yr^{-1}$ with a standard deviation of $12.2 M_{\odot} yr^{-1}$ for SFRs calculated using nonthermal fluxes. The thermal SFRs are not high enough for LCBGs to be considered starburst galaxies, defined as having $\log SFR \geq 0.8 \times (\log M_{*} - 8.9)$ (Luo et al. 2014), which is consistent with the results of Garland et al. (2015). Their sam-

ple, which overlaps with our sample of galaxies, reports derived SFRs from $H\alpha$ fluxes, which trace the same process as thermal free-free emission does but are measured over a smaller area of each galaxy and are more susceptible to extinction than thermal and non-thermal emission. Seven of the galaxies (SDSS0934+0014, SDSS0946+0542, SDSS1038+5330, SDSS1546+1753, Mrk 297, Mrk 325, and Mrk 538) can be considered starburst galaxies according to the Luo et al. (2014) definition when their SFRs are calculated using nonthermal fluxes. The average SFRs that we calculated from thermal and nonthermal fluxes are 1.5 ± 1.9 times and 9.2 ± 13.9 times, respectively, the average $H\alpha$ SFR calculated by Garland et al. (2015) for the LCBGs in their sample. The higher thermal SFR implies that it is likely that LCBGs have either significant obscured star formation or significant star formation in their disks that lie outside the central area sampled by the $H\alpha$ observations. The much higher nonthermal SFR could imply both of those causes, as well as a possible older episode of star formation that can contribute nonthermal emission for up to 100 Myr (Condon 1992; Kennicutt & Evans 2012).

We did not find a correlation between the SFRs that we calculated and the $B - V$ colors or surface brightnesses of the LCBGs in our sample. The LCBGs with brighter M_B tended to have higher SFRs, which implies that star formation in LCBGs is contributing to their M_B . Although we do not find a correlation between LCBGs' SFRs and their optical colors, which trace star formation on relatively long (~ 1 Gyr) timescales, we can use other properties of the LCBGs in our sample to constrain their star formation ages on much shorter ($\lesssim 100$ Myr) timescales. We will investigate these properties further in Section 4.5.

We plot the thermal and non-thermal SFRs that we calculated in Figure 4.4. If the SED fits we have derived accurately describe the two components of the galaxies' radio continuum emission, the SFRs derived from thermal and non-thermal emission should be consistent with each other. However, when we determined the emission components for the LCBGs, we assumed a fixed non-thermal spectral index as opposed to one that steepens at higher frequencies due to synchrotron energy losses over time. Since this is the case, the calculated thermal and non-thermal star formation rates, if they differ from each other substantially, could signal a more complex radio SED than the simple two-component one that we fit. As the steepness of a galaxy's synchrotron spectrum and the abundance of thermal emission both can trace the recent history of a starburst, discrepancies between the two calculated star formation rates can be used to probe the timescales of the observed star formation episode. We discuss this further in Section 5.2.2.

4.4.4 Far-infrared SEDs

In addition to the radio continuum SEDs, we also fit SEDs using archival mid- and far-infrared data taken from the IRAS Faint Source Catalog and Point Source Catalog (12 μm , 25 μm , 60 μm , 100 μm Beichman et al. 1988), AKARI Far Infrared Surveyor Bright Source Catalog (65 μm , 90 μm , 140 μm , 160 μm ; Yamamura et al. 2010), and Spitzer Enhanced Imaging Products (SEIP) catalog for the Multiband Imaging Photometer for Spitzer (MIPS, 24 μm ; Rieke et al. 2004), which are searchable on the NASA/IPAC Infrared Science Archive website⁸. We also included new

Figure 4.4 Star formation rates calculated from thermal and nonthermal radio continuum fluxes following Condon (1992) and infrared fluxes following Bell (2003) for clumpy galaxies (blue circles) and non-clumpy galaxies (green squares). The solid black line traces equal SFRs. Notice that non-clumpy LCBGs seem to have thermal SFRs that are closer to their nonthermal SFRs than clumpy galaxies do.

and archival data measured from Herschel maps as described in Section 3.2, and archival ISO (Kessler et al. 1996) and SCUBA (Holland et al. 1999) fluxes taken from NED.

To best fit the far-IR SEDs of galaxies with few far-IR data points, we fit a Casey model to the far- and mid- IR data points using the IDL procedures available at <http://herschel.uci.edu/cmcasey/sedfitting.html> and described in Casey (2012). This model fits a modified graybody to the far-IR data points that trace cold dust, and a power law to the far- and mid-IR data points that trace warmer dust components at wavelengths shorter than $\sim 60\mu\text{m}$:

$$S(\lambda) = N_{\text{bb}} \frac{\left(1 - e^{-(200 \mu\text{m}/\lambda)^\beta}\right) (c/\lambda)^3}{e^{hc/\lambda kT} - 1} + N_{\text{pl}} \lambda^{\alpha_{\text{pl}}} e^{-(\lambda/\lambda_c)^2} \quad (4.4)$$

where N_{bb} and N_{pl} are normalization constants for the graybody and power law, β is the blackbody emissivity, α_{pl} is the slope of the power law, and λ_c is the wavelength where the power law turns over. The results of this fit can be used to calculate dust temperatures, dust masses, and total infrared luminosities for each galaxy. The dust temperature that is calculated by this model is not the same quantity as T in the graybody fit, but is the temperature derived from Wien's law, $T_{\text{dust}} \propto 1/\lambda_{\text{peak}}$. These fits do a better job of addressing data sets with few far-IR data points than models that only fit a temperature and a scale factor for a graybody. For example, the Casey model interpolates the peak of the dust graybody between data points, while other models tend to force the peak to be affixed to the brightest data point. The

⁸<http://irsa.ipac.caltech.edu/applications/Gator/>

Casey (2012) model interpolates a dust temperature for each LCBG in our sample, rather than clustering around one of two temperatures (~ 30 K or 50 K), as other fits we attempted tended to do. We caution, however, that the systematic errors on the derived physical quantities from sparsely-sampled SEDs may still be large and difficult to quantify. We used a fixed value of $\beta = 1.5$ as an input for consistency (in many cases, the galaxies in our sample do not have many data points at wavelengths longer than $\sim 100 \mu m$, so leaving β as a free parameter led to large systematic uncertainties in the fits), though varying β from 1.0 to 2.0 did not change most of the calculated properties by more than a few percent. The property most affected by our choice of β was the dust mass, which is calculated using the flux measured at $850\mu m$:

$$M_{\text{dust}} = \frac{S_{850 \mu m} D_L^2}{\kappa_{850 \mu m} B_{850 \mu m}(T)(1+z)} \quad (4.5)$$

where D_L is the luminosity distance, $B(T)$ is the Planck function at the temperature resulting from the fit, and $\kappa_{850 \mu m} = 0.15 \text{ m}^2 \text{ kg}^{-1}$ (Casey 2012). The difference between calculating a dust mass using $\beta = 1.0$ and $\beta = 2.0$ is a factor of $\sim 3 - 4$ for the LCBGs in our sample. We report the derived quantities from the Casey models in Table 4.6. We plot the combined radio continuum and far- and mid-IR SEDs for each LCBG in Figure 4.5.

4.4.5 Infrared star formation rates

We calculated star formation rates derived from total IR luminosities using Equation 5 of Bell (2003). We used the version of the equation for galaxies with total

Figure 4.5 Radio continuum ($\sim 1 - 100$ GHz) and far- and mid-infrared ($\sim 12 \mu\text{m} - 500 \mu\text{m}$) data points for each galaxy that was detected with all four CCB sub-bands. These data points include new observations at 26-40 GHz, 90 GHz, and $70 \mu\text{m} - 500 \mu\text{m}$, as well as archival radio continuum data referenced in Table 4.5 and archival infrared data from IRAS, AKARI, Herschel, Spitzer, ISO, and SCUBA. In some cases, the error bars are smaller than the point sizes. The best-fit spectral energy distribution for each galaxy is also plotted. The purple dashed line is the nonthermal ($\alpha_N \leq -0.8$) component, the blue dotted line is the thermal ($\alpha_T = -0.1$) component fit to the radio continuum data. The solid black line is the sum of the two components. The nonthermal spectral index that we fit to each galaxy is listed in Table 4.5. We also fit a modified graybody combined with a powerlaw using a Casey (2012) fit (see Equation 4) to the infrared data points (black dot-dashed line).

Figure 4.5 Continued.

Figure 4.5 Continued.

Figure 4.5 Continued.

infrared luminosities ($8 - 1000 \mu\text{m}$) of $L_{\text{TIR}} < 10^{11} L_{\odot}$, and scaled the equation to use a Kroupa (2001) IMF:

$$\text{SFR}(M_{\odot} \text{ yr}^{-1}) = 0.77 \times 10^{-10} L_{\text{TIR}} \left(1 + \sqrt{\frac{10^9 L_{\odot}}{L_{\text{TIR}}}} \right). \quad (4.6)$$

All of the LCBGs in our sample have $L_{\text{TIR}} < 10^{11} L_{\odot}$, so we do not need to take into account different scaling coefficients appropriate for higher-luminosity galaxies. These SFRs include a correction that takes into account older stellar populations, since unlike thermal and nonthermal radio continuum emission, there is a significant contribution to a galaxy's total IR emission from less-massive, longer-lived stars (Bell 2003). The SFRs that we calculated are tabulated in Table 4.5. We also plot the SFRs derived from total IR luminosities against those derived from thermal and nonthermal luminosities in Figure 4.4. We find that the SFRs we calculate using total IR luminosities are lower on average than those calculated using nonthermal radio continuum fluxes derived from SED fits, and consistent with thermal radio continuum SFRs. Since the SFRs we calculated from IR emission are corrected for contributions from older stellar populations, it makes sense that they are consistent with the SFRs calculated from thermal emission, which do not need such a correction as they are calculated from emission that directly measures the shortest-lived stars (Bell 2003). The nonthermal SFRs, however, are not corrected for contributions from older cosmic rays (and are calibrated assuming a correlation between nonthermal emission and FIR emission that has not been corrected for contributions due to old stars), so the fact that we see much higher nonthermal SFRs than thermal or IR SFRs

in some LCBGs suggests that those LCBGs may have had higher SFRs in the past ~ 100 Myr than they have had more recently.

4.5 Discussion: Star formation properties of LCBGs

4.5.1 Radio-FIR correlation

It is well-established that star-forming galaxies exhibit a correlation between their radio continuum synchrotron emission and total FIR emission (Helou et al. 1985). Since the processes that create synchrotron emission and FIR emission both trace recent star formation, this result is not surprising, though it is not certain what the root physical cause of this close relationship is. It has been recently argued (Bressan et al. 2002; Bell 2003; Lacki et al. 2010) that the radio-FIR correlation is not necessarily due to linked physical processes that produce both types of emission, but instead is a fortunate coincidence due to both radio continuum and FIR emission being produced by recently-formed stars over similar timescales, and that the correlation may not be as tight under certain conditions (such as in galaxies with very low masses). If LCBGs do not follow the radio-FIR correlation, there may be a physical process occurring in these galaxies other than star formation that would distinguish LCBGs from other star-forming galaxies of similar masses.

To test whether LCBGs look like other star-forming galaxies (such as the heterogeneous sample of galaxies in Chapter 2) with respect to the radio-FIR correlation, we plotted their radio continuum fluxes at 1.4 GHz (which mostly contains synchrotron emission) taken from our fit to the LCBGs' radio continuum data against FIR fluxes

calculated from fits to the LCBGs' FIR data points. The total FIR flux density from $\sim 40 - 120\mu m$ can be estimated by $S_{FIR} = 2.58S_{60\mu m} + S_{100\mu m}$ (Helou et al. 1985). As seen in Figure 4.6, the 1.4 GHz data correlates relatively tightly with the FIR fluxes for the LCBGs in our sample, which is consistent with LCBGs behaving like star-forming galaxies without active galactic nuclei (AGN).

To further investigate this behavior, we calculated $q_{1.4}$, which is a measure of the ratio of S_{FIR} to $S_{1.4GHz}$. q_ν is defined in Helou et al. (1985) as

$$q_\nu = \log \left(\frac{S_{FIR} \cdot 1.26 \times 10^{-14} \text{Wm}^{-2}}{3.75 \times 10^{12} \text{Hz}} \right) - \log \left(\frac{S_\nu}{\text{Wm}^{-2} \text{Hz}^{-1}} \right). \quad (4.7)$$

Condon (1992) found that the average $q_{1.4}$ for several non-AGN samples of galaxies is 2.3, with a 1σ scatter of 0.2. The average value of $q_{1.4}$ for the LCBGs in our sample is also $q_{1.4} = 2.3$ with a 1σ scatter of 0.2, which is consistent with both the Condon (1992) result and the result we found in Chapter 2 for a heterogeneous sample of star-forming galaxies, as well as models by Bressan et al. (2002). To determine whether the radio-FIR correlation in LCBGs is affected by the presence of thermal emission or synchrotron aging in these galaxies (traced by the spectral index of their radio continuum emission), we plotted $q_{1.4}$ against the spectral index between 1.4 GHz and 33 GHz, $\alpha_{1.4-33}$ of each LCBG. If the radio-FIR correlation is uncorrelated with radio spectral index (and thus unaffected by the presence of thermal emission or steepening of nonthermal spectra due to synchrotron aging), then $q_{1.4}$ should be the same regardless of the value of $\alpha_{1.4-33}$ (we plot $q_{1.4}^{-1}$ rather than $q_{1.4}$ to emphasize our radio continuum observations; larger relative amounts of radio continuum emission are

Figure 4.6 Radio continuum fluxes and FIR fluxes for clumpy (blue circles) and non-clumpy (green squares) LCBGs in our sample. The radio continuum fluxes are calculated using fits to our data at 1.4 GHz (top) and 33 GHz (bottom). LCBGs appear to follow the radio-FIR correlation, though the increased scatter in the correlation at higher frequencies is likely due to higher contributions from thermal emission at those frequencies.

higher on the plot). As seen in Figure 4.7, galaxies with flatter spectral indices tend to have a higher proportion of FIR emission to radio continuum emission than average, while galaxies with steeper spectral indices tend to have a larger contribution of radio continuum emission than FIR emission. We discuss the implications this relationship may have for star formation timescales in Section 4.5.2.2.

At 33 GHz, a star-forming galaxy’s emission will typically contain approximately equal amounts of synchrotron and free-free emission (see Equation 5 of Condon 1992). Thus, if the “radio” component of the radio-FIR correlation is actually understood to be synchrotron emission, the increased proportion of thermal emission at 33 GHz relative to what is typically found at 1.4 GHz may induce increased scatter in the radio-FIR correlation at 33 GHz. We find that the radio-FIR correlation continues to hold for LCBGs at 33 GHz (similar to what was found for the group of star-forming galaxies studied in Chapter 2). As predicted, we find that the radio-FIR correlation for the LCBGs in our sample has more scatter at 33 GHz than at 1.4 GHz. This scatter is likely due to both the larger fraction of thermal emission at 33 GHz and the steepening of synchrotron spectra at higher frequencies in some galaxies (Lacki et al. 2010). We plot this relationship in Figure 4.6. As we did for the LCBGs’ 1.4 GHz fluxes, we also plotted the radio-FIR correlation at 33 GHz (q_{33}^{-1}) as a function of spectral index between 1.4 GHz and 33 GHz ($\alpha_{1.4-33}$). We found that the LCBGs that have higher thermal fractions implied by flatter spectral indices tend to have a higher ratio of emission at 33 GHz to FIR emission, as was found in Chapter 2. We discuss the implications that this result has for the ages of LCBGs’ most recent episodes of star formation in Section 4.5.2.2.

Some of the LCBGs at spectral indices of $\alpha_{1.4-33} \lesssim -0.8$, however, had noticeably lower ratios of radio continuum emission to FIR emission than the other LCBGs at similar spectral indices. This is visible both at 1.4 GHz and 33 GHz. Though these galaxies have spectral indices that indicate relatively high thermal fractions, their ratios of 33 GHz emission to FIR emission resemble LCBGs with much lower thermal fractions. This means that these galaxies either have a relative deficit of radio continuum emission or a relative excess of FIR emission with respect to what would be anticipated from the radio-FIR correlation. We discuss the galaxies that deviate from the radio-FIR correlation in the next subsection.

4.5.1.1 Galaxies off the radio-FIR correlation

When we found $q_{1.4}$ and q_{33} using archival NVSS 1.4 GHz, new 33 GHz, and archival IRAS 60 and 100 μm fluxes, six LCBGs (SDSS0826+4558, SDSS1049+3259, SDSS1224+3922, SDSS1248+1058, SDSS1319+3015, and SDSS1423+3400) had values of q^{-1} that were significantly lower than other LCBGs with similar spectral indices (see Table 4.5). To investigate the LCBGs that are brighter in the infrared than would be expected from the radio-FIR correlation, we first attempted to correct for observational effects that could depress the observed radio continuum emission or inflate the observed FIR emission relative to expected quantities. First, we tested whether this discrepancy was the result of scatter in the radio-FIR correlation at higher frequencies. To do this, we compared our results at 1.4 GHz and 33 GHz to see if this discrepancy is seen at only one radio frequency. The galaxies that have an apparent

excess of FIR emission with respect to their radio continuum emission (high values of q_ν) show this excess at both 1.4 GHz and 33 GHz. Since these two radio continuum fluxes were measured with different beam sizes, using different telescopes, as part of different surveys, it is not likely to be the case that the deficit of radio continuum emission is solely due to increased scatter in the radio-FIR correlation at high frequencies, calibration issues with our 33 GHz observations, or smaller physical areas of emission being observed with the smaller beam size at 33 GHz relative to the 1.4 GHz or FIR beam sizes.

Since the galaxies that deviate from the radio-FIR correlation show this behavior at both 1.4 GHz and 33 GHz, the next step to test whether this is an observational effect is to look at the FIR emission. If the beam sizes at 60 μm and 100 μm are much larger than at radio continuum frequencies, then galaxies with larger angular sizes could have more of their emission observed by instruments at FIR wavelengths than at 1.4 GHz or 33 GHz. In addition, if a galaxy has a close companion, a larger beam may introduce confusion from the companion that is not seen in a smaller beam. The 60 μm and 100 μm beam sizes of IRAS observations ($1' - 2'$) are larger than either the 1.4 GHz VLA beam in D configuration used to measure NVSS data points ($45''$) or the 33 GHz GBT beam ($23''$), so it is possible that the six LCBGs with low values of q_ν^{-1} are resolved with both radio beams. This would result in the larger IRAS beam containing a larger physical emission region than the smaller radio beams. If resolved galaxies are observed using a larger beam at FIR wavelengths than at radio wavelengths, the resulting effect on their fluxes will be that their FIR emission will appear enhanced with respect to their radio continuum emission (especially if strong

emission regions like star-forming knots are left out of the radio continuum beam but included in the FIR beam, or if confusion with a companion galaxy is an issue). We do not suspect that this concern is relevant in this case for three reasons. First, not all of the six galaxies are resolved by both the GBT and NVSS beams. The effective half-light radii of these six LCBGs, which contain most of their blue light and thus the majority of their star formation, range from $\sim 6''$ to $\sim 12''$. Second, the LCBGs showing excess FIR emission all have spectral indices between 1.4 GHz and 33 GHz, $\alpha_{1.4-33}$, that are flatter than the typical nonthermal spectral index of $\alpha = -0.8$. As was shown in Chapter 2, when spectral indices are measured using resolved observations of different beam sizes, it is often the case that those spectral indices appear steeper than would be expected for global measurements of galaxies with ongoing star formation due to the higher frequency fluxes being measured with a smaller beam. Since we do not see this effect in the six IR-bright LCBGs, we infer that any flux correction for beam size is likely to be small in these galaxies.

Third, in order to control for possible problems with the IRAS data for these six galaxies, we recalculated q_ν using archival FIR data from the AKARI Bright Source Catalog. Using AKARI 70 μm and 140 μm fluxes, the equation to find q_ν is:

$$q_{\text{AKARI},\nu} = \log \left(\frac{1.47 \times 10^{12} \text{ Hz } (L_{90\mu\text{m}}) + 0.831 \times 10^{12} \text{ Hz } (L_{140\mu\text{m}})}{\text{W m}^{-2} \text{ Hz}^{-1}} \right) - \log \left(\frac{L_\nu}{\text{W/m}^2} \right) \quad (4.8)$$

(Takeuchi et al. 2010). We found that the LCBGs follow the same trend with $q_{\text{AKARI},\nu}^{-1}$ vs. $\alpha_{1.4-33}$ as they do with $q_{\text{IRfit},\nu}^{-1}$ vs. $\alpha_{1.4-33}$. In addition, the six galaxies that lie below the $q_{\text{IRAS},\nu}^{-1}$ vs $\alpha_{1.4-33}$ relation also lie below the $q_{\text{AKARI},\nu}$ vs. $\alpha_{1.4-33}$ relation

at both 1.4 GHz and 33 GHz. Since the AKARI beam size is close to the NVSS 1.4 GHz beam size ($\sim 45''$), this discrepancy is unlikely to be related to differing beam sizes between FIR and radio continuum observations.

After fitting the radio continuum and FIR SEDs of the LCBGs in our sample, we calculated $q_{1.4}$ and q_{33} using fluxes derived from our fits to the radio continuum and FIR data, shown in Table 4.6 and plotted in Figure 4.7. The six discrepant LCBGs continue to have low values of $q_{1.4}^{-1}$ and q_{33}^{-1} with respect to other LCBGs with similar spectral indices when we use fluxes from SED fits, though using fluxes calculated from the SED fits appears to moderate this effect. In addition, three more LCBGs (SDSS0823+2120A, SDSS0823+2120B, and SDSS1157+3217) also appear to have values of $q_{1.4}$ and q_{33} that imply enhanced FIR emission with respect to radio continuum emission when we include fluxes from Herschel data in their SEDs. These three LCBGs have close companions (SDSS0823+2120A and SDSS0823+2120B are separated from each other by $\sim 0.7'$, and SDSS1157+3217 is separated from its companion by $1.8'$), do not have IRAS observations (SDSS0823+2120A and SDSS0823+2120B also do not have AKARI observations), and in Herschel observations appear to be partially blended with their companions. Thus, we interpret the FIR enhancement in these three additional LCBGs to likely be due to confusion with emission from their companions.

Since we see the enhanced FIR emission with respect to radio continuum emission for the same six LCBGs in four independent data sets (IRAS, AKARI, NVSS, and our 33 GHz GBT data), and it persists, though to a lesser extent, when we cal-

Figure 4.7 q_{ν}^{-1} vs. $\alpha_{1.4-33}$ calculated from fluxes derived from SED fits to radio continuum and far-infrared data. q_{-1} is calculated using a ratio of total far-infrared ($40 - 120 \mu\text{m}$) flux and 1.4 GHz (top) and 33 GHz (bottom) radio continuum fluxes. Points closer to the top of each plot have relatively more radio continuum emission, and points close to the bottom of each plot have relatively more far-infrared emission. At 1.4 GHz, galaxies with flatter values of $\alpha_{1.4-33}$ tend to have more far-infrared emission, while at 33 GHz, galaxies with flatter $\alpha_{1.4-33}$ have more radio continuum emission. We interpret both of these results as being due to increased quantities of emission that trace the most recent star formation at flatter $\alpha_{1.4-33}$.

culate radio continuum and FIR fluxes from fits to their SEDs, we interpret that this effect is most likely to be intrinsic to the galaxies.

We do not believe that the six IR-bright galaxies' discrepancy from the radio-FIR correlation is due to the presence of active galactic nuclei (AGN) in these LCBGs. Vardoulaki et al. (2015) found that galaxies with AGN tend to have $q_{1.4}$ values that are more than 2σ lower than the mean, which in the case of the LCBGs in our sample would be $q_{1.4} < 1.9$. None of the LCBGs in our sample have values of $q_{1.4}$ that are that low, although SDSS0946+0542 comes close. In contrast, the discrepant LCBGs in our sample have values of q that are larger than would be expected if the LCBGs followed the radio-FIR correlation. Instead of having elevated values of radio continuum emission relative to FIR emission, which would be expected for AGN, the discrepant LCBGs in our sample have higher amounts of FIR emission relative to their radio continuum emission. In addition, when we classified the LCBGs in our sample according to the BPT classification scheme that distinguishes AGN and star-forming galaxies (Baldwin et al. 1981) following Brinchmann et al. (2004), none of the fifteen LCBGs in our sample that we were able to classify had line ratios that would indicate the presence of an AGN (one LCBG, SDSS0123+0016, had a composite classification, but we have not calculated q_ν values for this galaxy because we did not detect it in all four CCB sub-bands).

Since we have established that beam size discrepancies, observational effects, calibration issues, or AGN are not likely to be the cause of enhanced FIR fluxes, we explore other possible physical causes of FIR enhancement. One possible physical cause of galaxies being brighter in the FIR than would be expected from the radio-FIR

correlation is that the radio-FIR correlation may not trace galaxies' star formation activity as closely as the tightness of the correlation across multiple galaxy types would suggest. Bell (2003) asserts that the radio-FIR correlation is not as accurate of a predictor of star formation rates as may be expected, especially for galaxies with very low and very high luminosities. Low-mass star-forming galaxies can have weaker magnetic fields that cannot constrain synchrotron emission from recent supernovae as efficiently as higher-mass galaxies. This would have the effect of depressing the observed synchrotron emission relative to what is produced given a galaxy's supernova rate (Bell 2003), which would result in an underestimation of that galaxy's star formation rate. These low-mass galaxies also typically are more optically thin to the far ultraviolet (FUV) emission that is absorbed by dust and re-radiated as FIR emission, which leads to a depression of their observed FIR fluxes as well (Bell 2003). If the six LCBGs in our sample with higher ratios of FIR to radio continuum emission have low magnetic fields such that their observed synchrotron emission is lower than expected, but are not correspondingly optically thin to FUV emission, that could explain their higher than expected values of $q_{1.4}$ and q_{33} . However, the low-luminosity, low-mass galaxies for which the radio-FIR correlation appears coincidental rather than a true reflection of the galaxies' star formation rates tend to be dwarfs. The FIR-enhanced LCBGs in our sample are, like all LCBGs, not dwarfs ($M \sim 10^9 M_{\odot}$), though their IR luminosities are lower than the average IR luminosity of our sample.

Another scenario that could be common to the FIR-bright LCBGs is that they host a star formation episode that is in its earliest stages. If this is the case, then these galaxies' star-forming regions are deeply obscured by dust and have not been

present for long enough to produce several generations of supernovae. In this scenario, both the relatively low fraction of radio continuum emission relative to FIR emission and the similar, relatively flat radio spectral indices that the FIR-bright galaxies exhibit are explained by a single burst recent enough for few supernovae to have occurred, and synchrotron-producing cosmic rays from the few supernovae that have occurred to not have lost a significant amount of energy. Since synchrotron emission is typically stronger than free-free emission in global measurements of star-forming galaxies, a deficit of synchrotron emission due to a very recent burst would be expected to significantly alter the ratio of radio continuum to FIR emission with respect to what would be expected given the radio-FIR correlation. In addition, a denser, clumpier ISM will be more optically thick to FUV emission from young, massive stars (Bell 2003). This could enhance the FIR emission relative to what would be expected for a less dense ISM, as optically thick dust will re-radiate FUV photons as FIR emission more efficiently than if the dust was optically thin (Bell 2003). Most of the LCBGs in our sample have clumpy appearances as classified in Garland et al. (2015). With the current data we have, we cannot conclusively determine why some LCBGs deviate from the radio-FIR correlation, though future resolved observations may better identify physical properties that would explain this discrepancy.

4.5.2 Clumpy star formation in the disk

4.5.2.1 Background

The physical processes that trigger and sustain star formation in LCBGs are not well constrained. Some authors (Amram & Östlin 2001) have argued that LCBGs are likely the result of mergers due to their relatively low ratios of rotational motion to random motions and their disturbed appearances. However, LCBGs do not appear to have a high rate of mergers or close companions relative to other types of galaxies (Werk et al. 2004; Garland et al. 2015), so their star formation is not necessarily required to be triggered by interactions. Other authors (Barton & van Zee 2001; Bershadsky et al. 2005) have argued that LCBGs are undergoing a final, galaxy-wide burst of star formation as they form their bulges due to internal processes, and will subsequently fade to become compact red galaxies like dwarf ellipticals once their current burst is finished. However, it is likely that winds from supernovae produced in the current starburst are not strong enough to blow out all of the LCBGs' gas, which would be required to completely suppress their star formation as is needed for LCBGs to rapidly evolve into early-type galaxies (Werk et al. 2004), since such winds are only effective in expelling large quantities of gas for galaxies with $M_{\text{gas}} \lesssim 10^6 M_{\odot}$ (Mac Low & Ferrara 1999).

One hypothesis for the cause of star formation in LCBGs that does not require interactions or a high-SFR, rapidly gas-depleting starburst results from a buildup of infalling cold gas onto the galaxies' disks (Garland et al. 2015). The gas can be from cold streams, which are more likely to cause a galaxy-wide star formation

episode, or from mergers or interactions, which can fuel short episodes of localized star formation (Kannappan et al. 2013). This gas collects in local overdensities in the disk to form star-forming clumps (Noguchi 1999, 2000, 2001; Dekel et al. 2009). These clumps can then merge with each other as they move toward the centers of the galaxies due to dynamical friction. When the clumps merge, the star formation rates increase within the clumps, which elevates the average star formation rate of the disk. If the clumps are long-lived enough to reach the centers of their host galaxies (a scenario that is more likely for galaxies of larger masses or smaller radii), they will merge together in the galaxies' centers, creating a compact nuclear region with a bright, blue appearance, high surface brightness, and high star formation rate. Once the clumps either disperse or use up all of their gas, their elevated star formation is quenched and the galaxies' global SFRs return to the background rate of the star formation in their disks. Depending on the total gas supply and the speed with which it can accrete, the clump formation and migration can happen in one burst or over several waves, taking anywhere from <1 Gyr to 5 Gyr (Noguchi 2000). This process does not necessarily result in a spheroidal or elliptical “red and dead” galaxy, but more likely a post-starburst disk galaxy with a central nucleus, bar, or pseudobulge that contains the remnants of the star-forming clumps (Noguchi 1999). The clumps do not necessarily affect the kinematics of the galaxies' disks, but rather follow the disks' rotation as they migrate, and maintain a sense of the disks' rotation even after they merge in the nucleus (Noguchi 1998). Thus, clump-hosting galaxies do not need to be the progenitors of spherically-shaped galaxies, though they can produce a spherical central component. Since a population of compact red galaxies that mirrors

the number density of LCBGs at higher redshifts has not been found at low redshifts, it is unlikely that LCBGs all evolve into a type of galaxy like dwarf ellipticals once their star formation has been quenched (Garland et al. 2004). In contrast, a scenario where LCBGs are a transient phase of disk galaxies that have experienced recent gas accretion allows LCBGs' future evolutionary paths to be diverse once their gas supply is no longer large enough to sustain clumpy star formation. For further discussion of this process in LCBGs, see Garland et al. (2015). For a discussion of how clumpy star formation would affect the H I properties of LCBGs, see Chapter 3.

Clumpy star-forming galaxies have been observed, classified, and modeled over a large range of redshifts (e.g. Conselice 2003; Elmegreen et al. 2004; Elmegreen & Elmegreen 2005; Overzier et al. 2009; Elmegreen et al. 2009; Wuyts et al. 2012; Guo et al. 2015). These galaxies appear to comprise a significant fraction of star-forming galaxies at $z > 1$, but are less common in the local Universe. Wuyts et al. (2012) found that such clumps are likely short-lived phenomena, with lifetimes of 100-200 Myr. Since our observations of star formation tracers can probe LCBGs' star formation properties on even shorter timescales ($\sim 10 \text{ Myr} - 100 \text{ Myr}$), quantifying these properties in LCBGs will allow constraints on the expected lifetimes of their current star formation episodes. Recently, Guo et al. (2015) found that for galaxies with $\log(M_*/M_\odot) < 9.8$, the fraction of star-forming galaxies that have UV-detected clumps outside the galaxies' centers is relatively constant at 60% between $z \sim 0.5$ and $z \sim 3$, and for galaxies with $9.8 < \log(M_*/M_\odot) < 10.6$, this fraction is 55% between $z \sim 3$ and $z \sim 1.5$ and $\sim 40\%$ at $z \sim 0.5$ (the median stellar mass of the LCBGs in our sample is $\log(M_*/M_\odot) = 9.77$). While the prevalence of star-forming galaxies

with relatively high masses and clumpy morphologies has decreased since LCBGs were most common at $z \sim 1$, the fraction of $z \sim 0$ LCBGs that are clumpy is relatively high ($\sim 40\%$, Garland et al. 2015). Thus, local LCBGs may be an important population in determining how such galaxies have evolved. If we can understand how the star formation properties and timescales of the clumpy and non-clumpy LCBGs in our sample compare, we may be able to better understand how LCBGs evolve once their episodes of clumpy star formation end.

While we do not have the spatial resolution in our study to investigate the star formation properties of individual clumps, we can compare the global star formation rates and star-forming properties of clumpy LCBGs to those of non-clumpy LCBGs, as well as compare the star formation timescales we have modeled to the timescales of gas infall and clump merger that we can calculate using gas properties measured in Chapter 3 to determine the likelihood that this scenario explains the current episode of star formation in LCBGs.

4.5.2.2 Modeling the SF properties of clumpy and non-clumpy LCBGs

One of the major goals of this study is to characterize the physical properties and timescales of star formation in LCBGs to better understand whether LCBGs' star formation is emerging, ongoing, or quenching. Previous studies have measured SFRs of LCBGs using FIR emission (Garland et al. 2005) and $H\alpha$ emission (Pérez-Gallego et al. 2010; Garland et al. 2015), and measured their atomic (Garland et al. 2004, 2015, Chapter 3) and molecular (Garland et al. 2005) gas content, and

found that LCBGs have both the fuel necessary to form stars and have evidence of active star formation. Since we have made extinction-free global measurements of star formation indicators that trace star formation on the shortest timescales, we are in the position to constrain the ages of LCBGs' current episodes of star formation and determine whether clumpy and non-clumpy LCBGs are exhibiting similar star formation properties.

In modeling the SEDs of LCBGs between 1.4 GHz and the mid-IR, we have derived an abundance of quantities that trace recent star formation in these galaxies. We calculated SFRs using thermal, nonthermal, and IR fluxes. We have also quantified the fraction of thermal emission at a particular frequency, the radio continuum spectral index of each source, and the dust temperature and dust mass of each galaxy.

In addition to these properties calculated from LCBGs' SEDs, we have also calculated stellar masses for each LCBG using B-V colors from SDSS and K-band near-IR magnitudes from the 2MASS survey following Bell & de Jong (2001). This enables us to use the dust masses and SFRs we have derived to calculate dust mass fractions and timescales to build up the current stellar mass for each LCBG. We have explored correlations between these properties for the galaxies in our sample, and report them in this section. We have also modeled a star-forming clump using Starburst99 galaxy evolution models (Leitherer et al. 1999) using a single instantaneous burst of the average clump mass ($10^7 M_{\odot}$) that we estimated in Chapter 3 for a typical LCBG using the average measured H I content of nine LCBGs. We apply a low initial metallicity to this modeled clump to be consistent with a clump formed from gas accreted onto a galaxy. We compare the star formation properties we find

for the LCBGs in our sample to the timescales for this “clump” when appropriate to constrain the timescales of LCBGs’ current episode of star formation.

We plot the star formation rates of each galaxy calculated from thermal, non-thermal, and IR fluxes (Equations 4.2, 4.3, and 4.6) in Figure 4.4, as well as the instantaneous thermal and nonthermal SFRs evolved with time for the model star-forming clump. The LCBGs in our sample tend to have higher nonthermal SFRs than thermal or IR SFRs, which when compared to model SFRs derived from each emission component implies that their current episode of star formation has lasted for longer than $\sim 10\text{Myr}$. When we compare the SFRs of clumpy LCBGs to non-clumpy LCBGs, the non-clumpy LCBGs are more likely to have higher thermal SFRs when compared to nonthermal and IR SFRs, and more likely to have higher IR SFRs when compared to nonthermal SFRs than clumpy galaxies are. Since thermal emission probes the most recent star formation, we interpret non-clumpy LCBGs’ elevated thermal SFRs as an indication that their current star-forming episode is more recent than for clumpy LCBGs. Figure 4.8 demonstrates the timescales of thermal and non-thermal star formation rates for our modeled clump. Since thermal SFRs probe star formation on the shortest timescales, we will use thermal SFRs to approximate the current instantaneous SFR in the LCBGs in our sample. Nonthermal SFRs probe star formation on longer ($< 100\text{ Myr}$) timescales (Condon 1992), so can be used as a comparison to approximate past SFRs.

Since Starburst99 models do not account for steep radio continuum spectra due to synchrotron aging, it is difficult to model star formation timescales for galaxies with $\alpha_{1.4-33} < -0.8$. To better constrain these timescales, we wanted to find a proxy for

Figure 4.8 Star formation rates as a function of time calculated from modeled thermal and nonthermal radio continuum fluxes following Condon (1992) using a Starburst99 model of a $10^7 M_{\odot}$ star-forming clump. Thermal emission dominates until ~ 3 Myr after the beginning of the star formation episode, when nonthermal emission becomes the dominant emission component.

star formation timescales that we could measure for all of the LCBGs in our sample. Bressan et al. (2002) found, using models of radio continuum and FIR data for star-forming galaxies, that the steepening of α , as well as the ratio of a galaxy's SFR to its 1.4 GHz luminosity, correlate well with the age of a starburst. Since it has not been established whether LCBGs are a common phase of star formation that happens at a particular time in most star-forming galaxies' history, it was important to use our observations that trace very recent star formation to establish star formation ages for the LCBGs in our sample. To test whether LCBGs have similar star formation ages according to this model, we plotted both $\log(\text{SFR}_T/L_{1.4\text{GHz}})$ and $\log(\text{SFR}_{\text{IR}}/L_{1.4\text{GHz}})$ against $\alpha_{1.4-33}$ for the clumpy and non-clumpy LCBGs in our sample in Figure 4.9. To compare to what would be expected for a star formation episode at different ages, we also found these values for our model clump.

As shown in Figure 4.9, both $\log(\text{SFR}_T/L_{1.4\text{GHz}})$ and $\alpha_{1.4-33}$ change predictably with time for a modeled star-forming clump. The ratio of a galaxy's instantaneous thermal SFR to its 1.4 GHz luminosity is high at the beginning of a star formation episode (as would be expected at times before many SNe have occurred), and becomes lower as time progresses and the SNe whose resulting synchrotron emission increases a galaxy's 1.4 GHz luminosity increase in number. Since spectral steepening due to synchrotron energy losses is most prominent at higher frequencies, and thermal emission typically contributes $\sim 10\%$ of a galaxy's total luminosity at 1.4 GHz (Condon 1992), a star-forming galaxy's 1.4 GHz luminosity should stay relatively stable for a much longer time period after the beginning of a star formation episode than luminosities at higher frequencies. Thus, we can interpret the decreasing $\log(\text{SFR}_T/L_{1.4\text{GHz}})$ over

Figure 4.9 Top left: Evolution with time of the ratio of the instantaneous SFR calculated using Equation 23 of Condon (1992) from the number of ionizing photons produced in a Starburst99 simulation of a $10^7 M_{\odot}$ star-forming clump and the luminosity of the clump at 1.4 GHz. Top right: Evolution with time of $\alpha_{1.4-33}$ for the same clump. Bottom left: Combination of the top two plots to show how the $\text{SFR}/L_{1.4}$ correlates with $\alpha_{1.4-33}$. We can interpret higher values of $\text{SFR}/L_{1.4}$ and flatter values of $\alpha_{1.4-33}$ as corresponding to earlier times. Bottom right: $\text{SFR}/L_{1.4}$ vs $\alpha_{1.4-33}$ for the LCBGs in our sample. SFRs calculated using thermal fluxes are plotted as circles, and SFRs calculated using IR fluxes are plotted as triangles. Clumpy LCBGs are in blue and non-clumpy LCBGs are in green.

time as being primarily due to an increasing supernova rate at early times (between ~ 3 Myr and ~ 40 Myr in the model). Since the model is an instantaneous burst that does not account for synchrotron aging, $\log(\text{SFR}_T/L_{1.4\text{GHz}})$ appears to rapidly rise to its original, pre-supernova value when all of the stars large enough to become supernovae have evolved. In a physical star-forming clump, $\log(\text{SFR}_T/L_{1.4\text{GHz}})$ is likely to continue to decrease as the 1.4 GHz luminosity increases over 50 Myr or more and the thermal emission component decreases once high-mass stars have evolved, but then reaches a stable value after ~ 100 Myr once the supernovae have stopped occurring (see Figure 5 of Bressan et al. 2002).

As expected, $\alpha_{1.4-33}$ also becomes steeper with time in the modeled clump (like the modeled $\log(\text{SFR}_T/L_{1.4\text{GHz}})$, it abruptly and unphysically returns to a pre-supernova value once the supernova-producing high-mass stars have evolved, but in a physical star-forming clump $\alpha_{1.4-33}$ would be expected to continue to steepen with time as electrons lose energy). When $\log(\text{SFR}_T/L_{1.4\text{GHz}})$ and $\alpha_{1.4-33}$ are plotted together, we see that we can interpret higher values of $\log(\text{SFR}_T/L_{1.4\text{GHz}})$ and flatter values of $\alpha_{1.4-33}$ as corresponding to earlier times in the star formation episode, while low values of $\log(\text{SFR}_T/L_{1.4\text{GHz}})$ combine with steep values of $\alpha_{1.4-33}$ to signify late times.

We compare this relationship to data for the LCBGs in our sample in Figure 4.9. We used both thermal and IR SFRs in our comparison, since thermal SFRs give the best measure of current unobscured star formation, and IR SFRs are calculated independently of our radio continuum fits. We see that LCBGs with $\alpha_{1.4-33} > -0.8$ follow the modeled relationship closely using both types of SFRs, though the scatter

is larger when we use IR SFRs. These LCBGs have values of $\log(\text{SFR}/L_{1.4\text{GHz}})$ and $\alpha_{1.4-33}$ that correspond to modeled ages of $\sim 4-30$ Myr, indicating that their current episodes of star formation are very young. On the other hand, the LCBGs with $\alpha_{1.4-33} < -0.8$ show a large scatter in their values of $\log(\text{SFR}/L_{1.4\text{GHz}})$, especially when the two SFRs are compared. Bressan et al. (2002) show that $\log(\text{SFR}/L_{1.4\text{GHz}})$ rises to an asymptotic value (zero in their models) after ~ 100 Myr once their model starbursts reach a quiescent phase. Combined with the very steep values of $\alpha_{1.4-33}$, we can interpret that the LCBGs with $\alpha_{1.4-33} < -0.8$ have star formation ages greater than ~ 40 Myr, and possibly greater than ~ 100 Myr for their current star formation episodes. Since all of the LCBGs have nonzero values of SFR_T , it is not likely that LCBGs are completely quenched, but it seems that some of them have been actively forming stars for a significant period of time, and may be showing signs of declining star formation.

As we have classified LCBGs as clumpy or non-clumpy, and as Garland et al. (2015) have hypothesized that clumpy and non-clumpy LCBGs may be experiencing different modes of star formation, we have distinguished the clumpy and non-clumpy LCBGs in Figure 4.9 to investigate whether the two types of LCBGs have different star formation timescales. We find that non-clumpy LCBGs tend to have the high values of $\log(\text{SFR}/L_{1.4\text{GHz}})$ and flat values of $\alpha_{1.4-33}$ that imply young ages, while clumpy LCBGs show a range of values, and thus a range of ages. It is possible that some clumpy LCBGs are experiencing a similar evolutionary phase to the non-clumpy LCBGs that would explain their young ages, while other clumpy LCBGs are galaxies whose current episode of star formation either began long ago and is currently

decreasing, or is relatively young but exists within a more quiescent galaxy, as may be the case in a minor merger or interaction.

To continue investigating the star formation ages of clumpy and non-clumpy LCBGs, we return to the q^{-1} vs. $\alpha_{1.4-33}$ plots in Figure 4.7. We have shown that flatter values of $\alpha_{1.4-33}$ correspond to younger star formation ages, and we can infer that the increased amount of thermal emission that leads to higher values of q_{33}^{-1} also correspond to younger ages (Bressan et al. 2002, Chapter 2). The q^{-1} vs. $\alpha_{1.4-33}$ plots at 1.4 GHz and 33 GHz appear to support the picture that non-clumpy LCBGs have young star formation ages, while clumpy LCBGs show a range of ages. At 33 GHz, non-clumpy LCBGs have the higher contributions of thermal emission characteristic of recent episodes of star formation (the increased thermal emission in non-clumpy LCBGs is confirmed in Figure 4.4). At 1.4 GHz, non-clumpy LCBGs are more likely to have enhanced FIR emission (or a deficit of radio continuum emission). Since FIR emission traces more recent star formation than nonthermal radio continuum emission does when the FIR SFRs are corrected for contributions from old stars (Bell 2003), the relative enhancement of FIR emission in the non-clumpy LCBGs supports a picture of non-clumpy LCBGs having younger star formation ages. We can also see that LCBGs have ranges of values of q_{33}^{-1} and $\alpha_{1.4-33}$ that are similar to the ranges of the heterogeneous sample of star-forming galaxies that we studied in Chapter 2. This supports LCBGs being a heterogeneous class of galaxies with a range of star formation ages.

In addition to the star formation properties that we have derived from radio continuum observations, we have also calculated dust masses and dust temperatures

for the LCBGs in our sample. We have plotted the dust temperatures and dust mass fractions ($f_{\text{dust}} = M_{\text{dust}}/(M_{\text{dust}} + M_*)$) of the LCBGs in our sample with respect to their $\alpha_{1.4-33}$ in Figure 4.10. Since the LCBGs' dust masses and dust temperatures were found independently of their radio continuum properties, we can compare these properties to the galaxies' $\alpha_{1.4-33}$ (and thus their star formation timescales) without encountering systematic biases from the fits to our data.

The LCBGs in our sample exhibit trends in their dust properties with respect to their $\alpha_{1.4-33}$. At flatter values of $\alpha_{1.4-33}$, LCBGs have lower dust mass fractions, while at steeper values of $\alpha_{1.4-33}$, higher dust mass fractions predominate. In addition, non-clumpy LCBGs are likely to have relatively low dust mass fractions ($f_{\text{dust}} \lesssim 0.03\%$) while clumpy LCBGs have dust mass fractions that range from $\sim 0.005\%$ to $\sim 0.3\%$. There is also a trend of higher dust temperatures in LCBGs with flatter values of $\alpha_{1.4-33}$. Since higher dust temperatures tend to occur in regions of active star formation due to heating from FUV emission from young stars, it is not surprising that these two properties are correlated in LCBGs. As with other star formation properties, we find that the non-clumpy LCBGs tend to have higher dust temperatures, while the clumpy LCBGs have a range of dust temperatures, though the scatter is large. Using these three combined properties, we can hypothesize that the non-clumpy LCBGs (and some clumpy LCBGs) are experiencing a young, galaxy-wide episode of star formation that temporarily depletes the dust in their host galaxies while the stars are forming, and will eventually build up their dust masses once the newly-formed stars have evolved. Some clumpy LCBGs' steeper values of $\alpha_{1.4-33}$, higher dust mass

Figure 4.10 Top: $\alpha_{1.4-33}$ vs. dust mass fraction for clumpy (blue circles) and non-clumpy (green squares) LCBGs. LCBGs with flatter spectral indices tend to have lower dust mass fractions, indicating that LCBGs with more recent episodes of star formation have less cold dust than LCBGs with older episodes of star formation. Bottom: $\alpha_{1.4-33}$ vs. dust temperature for the same LCBGs. Symbols are as in the top plot. Non-clumpy galaxies tend to have higher dust temperatures, which are correlated with ongoing star formation.

fractions, and lower dust temperatures are consistent with either an old burst that is declining, or a small young burst that coexists with older generations of stars.

Finally, we plotted the gas depletion timescales and ratios of each LCBG's stellar mass to its SFR calculated using thermal emission against their $\alpha_{1.4-33}$ in Figure 4.11. We calculated the LCBGs' gas depletion timescales given their current SFRs using $\tau_{\text{gas}} = (G/D) \times M_{\text{dust}}/\text{SFR}_T$ where G/D is the total hydrogen gas mass ($M_{\text{HI}} + M_{\text{H}_2}$) to dust mass ratio. Here we use the value of $G/D \sim 143$ modeled using solar metallicities (Draine et al. 2007), though this ratio is highly dependent on a galaxy's metallicity and star formation history (e.g. Draine et al. 2007; Dwek & Cherchneff 2011). We find that the LCBGs with flatter values of $\alpha_{1.4-33}$ have shorter τ_{gas} ($\sim 10 \text{ Myr} - 200 \text{ Myr}$), while galaxies with steeper values of $\alpha_{1.4-33}$ have τ_{gas} of 100 Myr or longer. Thus, it is likely that the LCBGs that appear to have younger star formation ages will use up their gas quickly if their SFRs remain relatively constant in the future, while the LCBGs with older average star formation ages can in theory sustain their current SFRs for a relatively long time as long as their star formation is not actively being quenched.

To further investigate LCBGs' star formation histories, we have plotted the ratio of the LCBGs' stellar mass to their thermal SFRs in Figure 4.11. This ratio gives a timescale for the galaxies to build their current stellar mass, if their current SFRs have always remained constant in the past. If LCBGs with flatter $\alpha_{1.4-33}$, which we have established correlates with younger ages, have short timescales to build up their stellar masses, we can infer that these LCBGs have either built up their stellar masses relatively quickly, or that they have temporarily elevated SFRs.

Figure 4.11 Top: The gas depletion timescale for each LCBG given the current thermal SFR vs. $\alpha_{1.4-33}$. The LCBGs with flatter spectra tend to have shorter gas depletion timescales, implying that they will exhaust their gas supplies in $\lesssim 200$ Myr if their current SFRs remain constant in the future. Bottom: The timescale for building up each LCBG's current stellar mass given the current thermal SFR vs. $\alpha_{1.4-33}$. The LCBGs with steeper spectra tend to have longer stellar mass timescales, many of which are longer than the Hubble time, which implies that they had higher SFRs in the past. Similarly, the flatter-spectrum LCBGs have stellar mass timescales on the order of a few Gyr, which suggests that they currently have elevated SFRs. Clumpy galaxies are represented as blue circles, and non-clumpy galaxies are represented as green squares.

Using the LCBGs’ thermal SFRs as a tracer of the best estimate of their current SFRs, we find that the non-clumpy LCBGs tend to have lower timescales to build up their stellar masses given their current SFRs than some of the clumpy LCBGs do (and none of the non-clumpy LCBGs have a stellar mass buildup timescale longer than the age of the Universe). Since the clumpy LCBGs with steep values of $\alpha_{1.4-33}$ are more likely to have unphysically high stellar mass buildup timescales, we can infer that their SFRs were likely higher in the past than they are now. Though we cannot distinguish through this relationship between scenarios where steep- $\alpha_{1.4-33}$ LCBGs are experiencing a declining large star formation episode, or a small current star formation episode, possibly confined to a few bright clumps, that coexists with an older disk, we find that the star formation properties of LCBGs support LCBGs having a range of star formation ages (and non-clumpy LCBGs having very recent star formation).

4.6 Conclusions

We have obtained new single-dish radio continuum observations of 42 LCBGs from 26 GHz to 40 GHz and ten of those LCBGs at 90 GHz to measure extinction-free tracers of recent star formation. We have also compiled archival radio continuum and new and archival far- and mid-IR fluxes for the galaxies that we detected in all four sub-bands between 26 GHz and 40 GHz and fit their SEDs from ~ 1 GHz to $\sim 12 \mu\text{m}$ to characterize the star formation properties of these galaxies. We have found that for the local LCBGs in our sample:

- Star formation properties such as SFRs, $\alpha_{1.4-33}$, q^{-1} , $\log(\text{SFR}/L_{\text{FIR}})$, dust mass fractions, dust temperatures, and stellar mass buildup timescales correlate with ages of recent star formation episodes.
- All of the LCBGs for which we fit SEDs have evidence of ongoing star formation (traced by the presence of thermal emission), so are not likely to have recently been quenched.
- The LCBGs in our sample are heterogeneous in their star formation properties, and do not appear to be experiencing a uniform phase of their star formation histories.
- On average, non-clumpy LCBGs have evidence of very recent star formation (some as recent as $\lesssim 10$ Myr).
- Clumpy LCBGs have evidence of having a range of star formation ages, from $\lesssim 10$ Myr to ~ 100 Myr. Some have properties consistent with very recent star formation, while others appear to have older star formation ages traced by their steep spectral indices.
- For clumpy LCBGs with star formation properties that correlate with older ages, we cannot distinguish between an episode of star formation similar to the current star formation episodes in younger galaxies that happened in the past and an ongoing but small current episode of star formation coexisting with an older disk.

Our global measurements of star formation properties provide the first extinction-free systematic study of star formation indicators in LCBGs. Combined with our resolved H I observations of ten LCBGs in Chapter 3 that suggested that gas conditions in LCBGs could be conducive to the formation of clump-origin bulges (or short bars, in the case of non-clumpy LCBGs), and the results of Garland et al. (2015) that show that local LCBGs have similar properties to the most compact LCBGs at $z \sim 1$, and clumpy and non-clumpy galaxies have different optical and H I properties and environments, we can begin to develop a picture of the physical conditions of star formation in LCBGs.

What is still not clear is why some clumpy LCBGs appear to have longer timescales of their most recent star formation episodes as suggested by their star formation properties than other clumpy and non-clumpy LCBGs. Future studies of LCBGs that can resolve individual star-forming clumps will be able to probe star formation in the clumps to see whether the physical properties of clumpy LCBGs' clumps are similar to the physical properties throughout non-clumpy LCBGs' nuclei or disks. In addition, obtaining the ages of individual star-forming clumps and distinguishing them from the disk ages of clumpy LCBGs, as well as conducting a resolved study of clumpy LCBGs' gas, may be able to distinguish causes of clumpy star formation in LCBGs and determine whether clumpy LCBGs are mostly quiescent with a few star-forming clumps or are in the process of quenching. We have collected beam-matched VLA data at four frequency ranges from 1 GHz to 45 GHz for the LCBGs for which we have MUSTANG observations to identify star-forming clumps and probe their physical properties. If we can identify the different modes

of star formation in clumpy and non-clumpy LCBGs, we will better understand how star-forming galaxies have evolved since $z \sim 1$.

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Table 4.1. Optical properties

Source	Common Name	RA (J2000)	Dec (J2000)	D ^a (Mpc)	R _{eff} (B) ^b (kpc)	B − V ^c	M _B ^e	SBe(B) ^f	M _* (10 ⁹ M _⊙)	Hubble ^g Type	Clumpy? ^h
SDSS0025+1406	AGC102024	00:25:36.5	+14:06:55	75.0	1.8	0.37	-18.6	21.2	1.5 ± 0.3	Sd*	y
SDSS0041+1513	CGCG434-030	00:41:16.2	+15:13:02	75.0	1.7	0.55	-18.5	21.3	2.8 ± 0.3	Sc*	n
SDSS0123+0016	MGC+00-04-113	01:23:54.7	+00:16:57	78.0	1.7	0.57	-18.7	21.0	3.9 ± 0.4	S0*	n
SDSS0124+0050	CGCG385-104	01:24:30.7	+00:50:04	72.7	1.6	0.43	-18.4	21.2	2.3 ± 0.4	E*	n
SDSS0349+0109	KUG0346+010	03:49:08.9	+01:09:47	59.1	2.2	0.37	-19.3	21.0	7.1 ± 0.5	I	y
SDSS0749+3244	KUG0746+328	07:49:37.3	+32:44:19	63.1	1.2	0.58	-18.3	20.7	2.6 ± 0.2	Sc	n
SDSS0812+3509	KUG0809+353	08:12:14.8	+35:09:25	74.7	1.5	0.53	-18.4	21.0	2.6 ± 0.3	Sc*	n
SDSS0823+2120A	IC2338	08:23:32.7	+21:20:17	77.1	1.8	0.47	-19.4	20.3	8.4 ± 0.5	SBc	n
SDSS0823+2120B	IC2339	08:23:34.2	+21:20:52	77.6	3.1	0.54	-19.9	21.1	12.4 ± 0.5	Sc	n
SDSS0826+4558	UGC04393	08:26:04.4	+45:58:04	30.7	1.5	0.44	-18.2	21.2	2.6 ± 0.2	Sbc	y
SDSS0934+0014	UGC05097	09:34:10.6	+00:14:32	69.0	2.1	0.49	-19.8	20.3	12.5 ± 0.7	Sa	y

Table 4.1—Continued

Source	Common Name	RA (J2000)	Dec (J2000)	D ^a (Mpc)	R _{eff} (B) ^b (kpc)	B − V ^c	M _B ^e	SBe(B) ^f	M* (10 ⁹ M _⊙)	Hubble ^g Type	Clumpy? ^h
SDSS0944+6558	UGC05188	09:44:09.6	+65:58:39	47.6	1.0	0.51	-19.2	19.2	6.1 ± 0.2	E	n
SDSS0946+0542	NGC2990	09:46:17.1	+05:42:32	44.6	2.4	0.58	-19.9	20.6	12.4 ± 0.5	Sc	y
SDSS1038+5330	NGC3310	10:38:45.8	+53:30:12	14.1	0.6	0.47	-18.9	18.6	5.7 ± 0.1	SABb	y
SDSS1049+3259	NGC3396	10:49:55.1	+32:59:27	23.1	1.3	0.42	-18.6	20.5	5.7 ± 0.3	SBm	y
SDSS1053+3354	NGC3442	10:53:08.1	+33:54:37	24.9	0.7	0.47	-18.1	19.5	2.2 ± 0.1	Sab	y
SDSS1109+1043	NGC3547	11:09:55.9	+10:43:15	22.6	1.4	0.52	-18.2	21.0	2.5 ± 0.1	Sb	y
SDSS1122+3745	NGC3652	11:22:39.0	+37:45:54	28.7	2.1	0.54	-18.8	21.4	3.9 ± 0.2	Sc	y
SDSS1145+0909	NGC3876	11:45:26.7	+09:09:39	41.1	1.6	0.43	-19.2	20.4	4.9 ± 0.4	Sab	y
SDSS1153+4751	NGC3949	11:53:41.7	+47:51:31	11.6	1.2	0.55	-18.4	20.5	3.5 ± 0.1	Sbc	y
SDSS1157+3217	NGC3995	11:57:44.1	+32:17:39	46.7	3.5	0.44	-20.1	21.1	11.3 ± 0.5	SABm	y
SDSS1203+6031	MRK45	12:03:34.9	+60:31:53	59.8	1.2	0.57	-18.0	20.9	2.0 ± 0.2	Sbc	n

Table 4.1—Continued

Source	Common Name	RA (J2000)	Dec (J2000)	D ^a (Mpc)	R _{eff} (B) ^b (kpc)	B − V ^c	M _B ^e	SBe(B) ^f	M* (10 ⁹ M _⊙)	Hubble ^g Type	Clumpy? ^h
SDSS1217+1247	KUG1214+130	12:17:16.5	+12:47:43	71.5	1.5	0.48	-18.6	20.8	2.6 ± 0.3	Sab	n
SDSS1224+3922	NGC4369	12:24:36.2	+39:22:59	15.0	0.6	0.54	-18.2	19.2	4.4 ± 0.1	Sa	y
SDSS1225+5430	NGC4384	12:25:12.0	+54:30:22	36.2	1.5	0.56	-19.0	20.5	6.5 ± 0.4	Sa	y
SDSS1229+0749	NGC4470	12:29:37.8	+07:49:27	33.4	2.1	0.56	-19.4	20.8	7.0 ± 0.3	Sa	y
SDSS1241-0007	UM512	12:41:36.1	-00:07:06	68.1	1.0	0.49	-18.2	20.4	1.9 ± 0.3	S0	n
SDSS1242-0004	NGC4632	12:42:32.0	-00:04:57	24.0	2.8	0.42	-19.6	21.2	9.8 ± 0.3	Sc	y
SDSS1248+1058	NGC4694	12:48:15.1	+10:59:01	16.7	0.8	0.58	-18.3	19.7	5.0 ± 0.1	S0	n
SDSS1300+0230	NGC4900	13:00:39.1	+02:30:05	13.7	1.7	0.60	-18.2	21.5	4.3 ± 0.2	SBc	y
SDSS1319+3015	NGC5089	13:19:39.3	+30:15:24	30.4	1.3	0.55	-18.1	21.0	3.0 ± 0.2	SBb	y
SDSS1423+3400	UGC09221	14:23:42.4	+34:00:33	55.3	1.6	0.55	-19.1	20.5	6.5 ± 0.3	SBab	n
SDSS1430+0716	NGC5645	14:30:39.3	+07:16:30	19.7	1.7	0.54	-18.4	21.2	3.8 ± 0.3	SBcd	y

Table 4.1—Continued

Source	Common Name	RA (J2000)	Dec (J2000)	D ^a (Mpc)	R _{eff} (B) ^b (kpc)	B − V ^c	M _B ^e	SBe(B) ^f	M* (10 ⁹ M _⊙)	Hubble ^g Type	Clumpy? ^h
SDSS1533-0137	UGC09888	15:33:05.6	-01:37:42	39.9	2.3	0.60	-19.0	21.4	5.9 ± 0.4	SBcd	y
SDSS1546+0224	NGC5990	15:46:16.3	+02:24:56	52.5	2.3	0.26	-19.4	21.0	79.4 ± 3.4	SABa	n
SDSS1546+1753	NGC5996	15:46:58.9	+17:53:03	47.1	2.5	0.56	-19.7	20.9	10.6 ± 0.4	SBbc	y
SDSS1602+3208	CGCG167-018	16:02:50.9	+32:08:41	61.0	1.8	0.53	-18.6	21.3	2.9 ± 0.2	Sab	n
SDSS1605+4120	UGC10200	16:05:45.9	+41:20:41	28.5	0.7	0.30	-18.5	19.2	2.0 ± 0.1	Sc	n
SDSS2239+1352	KUG2236+136	22:39:21.9	+13:52:56	74.7	1.5	0.31	-19.0	20.3	2.3 ± 0.5	S0*	n
Mrk 297 ⁱ	NGC 6052	16:05:13.0	+20:32:32	67	2.0	0.4	-21.0	20.6	4.2 ± 0.2	Sc	y
Mrk 325 ⁱ	NGC 7673	23:27:41.0	+23:35:21	49	2.4	0.4	-20.0	20.0	10.9 ± 0.3	Sc	y
Mrk 538 ⁱ	NGC 7714	23:36:14.1	+02:09:19	40	2.8	0.4	-20.1	20.2	17.8 ± 0.4	Sb	y

^aDistances were calculated from SDSS redshifts using $H_0 = 70 \text{Mpc/km s}^{-1}$.

^bHalf-light radii in the B band calculated using SDSS g and r Petrosian radii.

^cColors calculated from SDSS g and r magnitudes.

^dB-band apparent magnitudes calculated from SDSS g and r magnitudes.

^eB-band absolute magnitudes calculated from m_B and luminosity distances.

^fSurface brightnesses in the B band calculated from M_B and $R_{eff}(B)$.

^gHubble type taken from Hyperleda except where noted (Hubble types marked with a * are taken from NED).

^hClumpiness classifications were made by K.R. and C.G. by eye as described in Garland et al. (2015).

ⁱOptical properties are taken from Garland et al. (2004).

Table 4.2. Radio continuum observation details

Source	Observing session ^a	Number of scans ^b	Flux calibrator	Notes
CCB observations				
SDSS0025+1406	11A-1	3	3C48	
SDSS0041+1513	11A-1	3	3C48	
SDSS0123+0016	11A-1	3	3C48	
SDSS0124+0050	11A-1	3	3C48	
SDSS0349+0109	11B-3	7	3C48	
SDSS0749+3244	11B-3	7	3C48	
SDSS0812+3509	11B-1	10	3C147	
SDSS0823+2120A	11A-2	5	3C286	
SDSS0823+2120B	11A-2	5	3C286	
SDSS0826+4558	11A-2	5	3C286	
SDSS0934+0014	11A-2	5	3C286	
SDSS0944+6558	11A-2	6	3C286	
SDSS0946+0542	11A-2	5	3C286	
SDSS1038+5330	11B-3	2.6	3C48	Map
SDSS1049+3259	11A-2	2	3C286	

Table 4.2—Continued

Source	Observing session ^a	Number of scans ^b	Flux calibrator	Notes
SDSS1053+3354	11A-2	2	3C286	
SDSS1109+1043	11A-2	4	3C286	
SDSS1122+3745	11A-2	2	3C286	
SDSS1145+0909	11A-2	4	3C286	
SDSS1153+4751	11B-4	4	3C147	Map
SDSS1157+3217	11A-2	2	3C286	
SDSS1203+6031	11B-3	7	3C48	
SDSS1217+1247	11A-2	4	3C286	
SDSS1224+3922	11A-2	2	3C286	
SDSS1225+5430	11A-2	6	3C286	
SDSS1229+0749	11A-2	4	3C286	
SDSS1241-0007	11A-2	4	3C286	
SDSS1242-0004	11A-2	4	3C286	
SDSS1248+1058	11A-2	4	3C286	
SDSS1300+0230	11A-3	7	3C286	
SDSS1319+3015	11A-3	4	3C286	

Table 4.2—Continued

Source	Observing session ^a	Number of scans ^b	Flux calibrator	Notes
SDSS1423+3400	11A-3	4	3C286	
SDSS1430+0716	11A-3	4	3C286	
SDSS1533-0137	11A-3	4	3C286	
SDSS1546+0224	11A-3	4	3C286	
SDSS1546+1753	11A-3	4	3C286	
SDSS1602+3208	11A-3	4	3C286	
SDSS1605+4120	11A-3	4	3C286	
SDSS2239+1352	11A-1	3	3C48	
Mrk 297	10A-6	2	3C286	Map
Mrk 325	10A-7	3	3C48	Map
Mrk 538	10A-7	4	3C48	Map
MUSTANG observations				
SDSS0934+0014	11B-8	6	Mars	Map
SDSS0946+0542	11B-8	6	Mars	Map
SDSS1038+5330	11B-5	3	Mars	Map
SDSS1049+3259	11B-8	6	Mars	Map

Table 4.2—Continued

Source	Observing session ^a	Number of scans ^b	Flux calibrator	Notes
SDSS1153+4751	11B-5	2	Mars	Map
SDSS1224+3922	11B-7	4.6	Mars	Map
SDSS1546+0224	11B-8	3.4	Mars	Map
Mrk 297	10A-1	3	Ceres	Map
Mrk 325	10A-8	5	Uranus	Map
Mrk 538	10A-8	3	Uranus	Map

^aThe dates of each observing session were: 2010 March 9 (10A-1), 2010 March 31 (10A-6), 2010 April 1 (10A-7), 2010 October 18 (10A-8), 2011 April 14 (11A-3), 2011 October 24 (11B-1), 2012 January 1 (11B-3), 2012 January 6 (11B-4), 2012 January 20 (11B-5), 2012 February 7 (11B-7), and 2012 February 8 (11B-8).

^bFor the galaxies that were not mapped, the number of scans is the number of 70 second nods on each galaxy. For galaxies that were mapped, the number of scans is the number of full nine minute daisy-pattern cycles.

Table 4.3. Observed Fluxes

Source	27.75 GHz (mJy)	31.25 GHz (mJy)	34.75 GHz (mJy)	38.25 GHz (mJy)	33 GHz ^a (mJy)	Notes ^b 90 GHz
SDSS0025+1406	...	...	...	...	0.099 ± 0.029	A _v
SDSS0041+1513	...	...	...	...	0.078 ± 0.029	A _v
SDSS0123+0016	...	...	...	...	0.32 ± 0.03	A _v
SDSS0124+0050	...	...	...	...	0.33 ± 0.12	A _v
SDSS0349+0109	0.72 ± 0.25	0.70 ± 0.11	0.63 ± 0.06	0.47 ± 0.20	0.63 ± 0.09	
SDSS0749+3244	...	...	...	...	0.18 ± 0.05	A _v
SDSS0812+3509	...	...	...	...	0.46 ± 0.21	A _v
SDSS0823+2120A	0.86 ± 0.12	0.83 ± 0.06	0.65 ± 0.06	0.71 ± 0.09	0.76 ± 0.04	
SDSS0823+2120B	0.79 ± 0.11	0.58 ± 0.06	0.67 ± 0.06	0.76 ± 0.09	0.70 ± 0.04	

Table 4.3—Continued

Source	27.75 GHz (mJy)	31.25 GHz (mJy)	34.75 GHz (mJy)	38.25 GHz (mJy)	33 GHz ^a (mJy)	Notes ^b	90 GHz
SDSS0826+4558	0.45 ± 0.10	0.48 ± 0.06	0.46 ± 0.05	0.47 ± 0.09	0.47 ± 0.04		
SDSS0934+0014	2.21 ± 0.11	2.04 ± 0.06	1.89 ± 0.07	1.41 ± 0.09	1.89 ± 0.04		1.88 ± 0.58
SDSS0944+6558	1.49 ± 0.07	1.16 ± 0.06	1.04 ± 0.06	0.84 ± 0.10	1.13 ± 0.04		
SDSS0946+0542	3.30 ± 0.09	2.86 ± 0.06	2.47 ± 0.07	2.01 ± 0.09	2.66 ± 0.04		0.78 ± 0.19
SDSS1038+5330	24.17 ± 1.08	21.92 ± 0.79	20.32 ± 0.96	18.78 ± 1.41	21.6 ± 0.02	Map	7.69 ± 1.05
SDSS1049+3259	3.28 ± 0.12	2.84 ± 0.07	2.48 ± 0.11	2.07 ± 0.13	2.67 ± 0.05		1.13 ± 0.16
SDSS1053+3354	1.34 ± 0.13	1.14 ± 0.07	1.02 ± 0.11	1.06 ± 0.14	1.14 ± 0.06		
SDSS1109+1043	1.09 ± 0.06	0.89 ± 0.04	0.89 ± 0.06	0.68 ± 0.08	0.89 ± 0.03		
SDSS1122+3745	1.30 ± 0.13	1.06 ± 0.08	0.95 ± 0.11	0.97 ± 0.13	1.07 ± 0.06		

Table 4.3—Continued

Source	27.75 GHz (mJy)	31.25 GHz (mJy)	34.75 GHz (mJy)	38.25 GHz (mJy)	33 GHz ^a (mJy)	Notes ^b	90 GHz
SDSS1145+0909	0.87 ± 0.06	0.82 ± 0.04	0.62 ± 0.05	0.64 ± 0.09	0.74 ± 0.03		
SDSS1153+4751	4.26 ± 1.07	3.89 ± 1.03	4.46 ± 1.38	3.81 ± 1.82	4.10 ± 0.68	Map	2.74 ± 0.76
SDSS1157+3217	1.89 ± 0.13	1.68 ± 0.09	1.24 ± 0.12	1.17 ± 0.14	1.50 ± 0.06		
SDSS1203+6031	...	...	...	...	0.084 ± 0.043	Av	
SDSS1217+1247	0.16 ± 0.06	0.15 ± 0.04	0.20 ± 0.05	0.16 ± 0.09	0.17 ± 0.03		
SDSS1224+3922	4.37 ± 0.13	4.00 ± 0.08	3.60 ± 0.12	3.57 ± 0.14	3.89 ± 0.06		1.34 ± 0.17
SDSS1225+5430	1.86 ± 0.07	1.67 ± 0.06	1.50 ± 0.07	1.49 ± 0.10	1.63 ± 0.04		
SDSS1229+0749	1.08 ± 0.06	0.83 ± 0.04	0.70 ± 0.05	0.55 ± 0.09	0.79 ± 0.03		
SDSS1241-0007	...	...	...	...	0.076 ± 0.031	Av	

Table 4.3—Continued

Source	27.75 GHz (mJy)	31.25 GHz (mJy)	34.75 GHz (mJy)	38.25 GHz (mJy)	33 GHz ^a (mJy)	Notes ^b	90 GHz
SDSS1242-0004	1.52 ± 0.06	1.36 ± 0.05	1.11 ± 0.06	0.87 ± 0.09	1.22 ± 0.03		
SDSS1248+1058	0.57 ± 0.06	0.60 ± 0.04	0.51 ± 0.05	0.50 ± 0.09	0.55 ± 0.03		
SDSS1300+0230	1.21 ± 0.08	0.99 ± 0.08	0.67 ± 0.06	0.63 ± 0.08	0.88 ± 0.04		
SDSS1319+3015	0.75 ± 0.11	0.64 ± 0.07	0.63 ± 0.09	0.59 ± 0.10	0.65 ± 0.05		
SDSS1423+3400	0.62 ± 0.11	0.70 ± 0.07	0.68 ± 0.08	0.67 ± 0.09	0.67 ± 0.04		
SDSS1430+0716	0.90 ± 0.09	0.74 ± 0.08	0.70 ± 0.08	0.64 ± 0.09	0.75 ± 0.04		
SDSS1533-0137	0.63 ± 0.10	0.44 ± 0.08	0.35 ± 0.07	0.41 ± 0.09	0.46 ± 0.04		
SDSS1546+0224	5.05 ± 0.09	4.39 ± 0.08	3.89 ± 0.08	3.50 ± 0.09	4.21 ± 0.04		2.11 ± 0.18
SDSS1546+1753	2.11 ± 0.09	1.85 ± 0.08	1.63 ± 0.07	1.33 ± 0.09	1.73 ± 0.04		

Table 4.3—Continued

Source	27.75 GHz (mJy)	31.25 GHz (mJy)	34.75 GHz (mJy)	38.25 GHz (mJy)	33 GHz ^a (mJy)	Notes ^b	90 GHz
SDSS1602+3208	...	...	...	...	0.12 ± 0.04	Av	
SDSS1605+4120	1.30 ± 0.10	1.30 ± 0.07	1.23 ± 0.08	1.26 ± 0.09	1.27 ± 0.04		
SDSS2239+1352	...	...	...	...	0.14 ± 0.03	Av	
Mrk 297	7.22 ± 0.01	6.62 ± 0.01	5.34 ± 1.05	6.08 ± 1.74	6.32 ± 0.50	IM	4.6 ± 1.0
Mrk 325	4.33 ± 0.77	3.83 ± 0.01	3.71 ± 0.70	2.88 ± 0.93	3.69 ± 0.35	IM	1.15 ± 0.43
Mrk 538	10.27 ± 0.44	9.10 ± 0.02	8.82 ± 0.02	7.94 ± 0.01	9.03 ± 0.11	IM	2.81 ± 0.39

^aThe 33 GHz data is the average of the four CCB fluxes.

^bMap: Flux integrated from maps. Av: Source was not detected in all four sub-bands; only the average flux is reported.

Table 4.4. Herschel Fluxes

Source	70 μm (Jy)	100 μm (Jy)	160 μm (Jy)	250 μm (Jy)	350 μm (Jy)	500 μm (Jy)	Notes
SDSS0749+3244	< 0.72	< 0.72	0.41 ± 0.23	0.62 ± 0.04	0.27 ± 0.03	0.12 ± 0.01	3σ upper limit
SDSS0812+3509	< 0.21	< 0.21	< 0.37	...	...	...	3σ upper limit
SDSS0823+2120A	0.94 ± 0.08	1.23 ± 0.09	1.08 ± 0.08	0.50 ± 0.03	0.18 ± 0.02	0.018 ± 0.004	
SDSS0823+2120B	1.17 ± 0.08	1.33 ± 0.09	1.22 ± 0.07	0.58 ± 0.03	0.20 ± 0.02	0.021 ± 0.004	
SDSS1049+3259	5.42 ± 0.29	6.76 ± 0.35	4.95 ± 0.19	2.13 ± 0.10	0.84 ± 0.05	0.27 ± 0.02	
SDSS1053+3354	...	3.19 ± 0.16	3.02 ± 0.32	1.53 ± 0.08	0.66 ± 0.04	0.23 ± 0.02	
SDSS1109+1043	...	4.29 ± 0.22	4.15 ± 0.46	3.22 ± 0.17	1.63 ± 0.10	0.67 ± 0.06	
SDSS1157+3217	6.94 ± 0.56	9.02 ± 0.63	7.01 ± 0.41	...	...	...	
SDSS1423+3400	1.36 ± 0.15	1.88 ± 0.16	1.73 ± 0.10	0.85 ± 0.05	0.35 ± 0.03	0.11 ± 0.01	

Table 4.4—Continued

Source	70 μm (Jy)	100 μm (Jy)	160 μm (Jy)	250 μm (Jy)	350 μm (Jy)	500 μm (Jy)	Notes
SDSS1430+0716	...	4.95 ± 0.25	6.10 ± 0.94	4.13 ± 0.29	2.23 ± 0.12	0.94 ± 0.06	
SDSS1507+5511 ^a	0.38 ± 0.08	0.35 ± 0.08	1.15 ± 0.25	...	...	...	
SDSS1546+0224	12.51 ± 0.76	16.44 ± 0.93	14.29 ± 0.53	7.72 ± 0.37	3.36 ± 0.20	1.13 ± 0.07	
SDSS1546+1753	6.78 ± 0.43	9.26 ± 0.53	7.74 ± 0.44	...	...	...	
SDSS1605+4120	1.73 ± 0.10	1.83 ± 0.11	1.19 ± 0.07	0.62 ± 0.06	0.29 ± 0.04	0.11 ± 0.02	
Mrk297	8.23 ± 0.56	10.50 ± 0.64	8.27 ± 0.37	4.58 ± 0.22	2.06 ± 0.13	0.73 ± 0.05	
Mrk538	12.00 ± 0.66	12.52 ± 0.69	8.00 ± 0.30	...	...	...	

^aSDSS1507+5511 is not part of the sample that we observed with the GBT, but was part of the sample of LCBGs that we observed using Herschel.

Table 4.5. Radio Continuum Properties of LCBGs detected by all four CCB sub-bands

Source	α_N^{fit}	$\alpha_{1.4-33}$	Thermal Fraction at 33 GHz	Log Max # ^a O7.5V Stars	SNe Rate ^b (yr ⁻¹)	Thermal SFR (M _⊙ yr ⁻¹)	Nonthermal SFR (M _⊙ yr ⁻¹)	References ^c
SDSS0349+0109	-0.8	-0.79 ± 0.05	0.02 ± 0.11	2.74	0.033	0.089 ± 0.43	4.52 ± 0.32	N
SDSS0823+2120A	-0.8	-0.61 ± 0.02	0.50 ± 0.07	4.36	0.033	3.70 ± 0.44	4.44 ± 0.18	F
SDSS0823+2120B	-0.8	-0.45 ± 0.03	0.75 ± 0.08	4.50	0.015	5.04 ± 0.44	1.99 ± 0.18	F
SDSS0826+4558	-0.8	-0.69 ± 0.08	0.32 ± 0.15	3.17	0.0044	0.24 ± 0.11	0.61 ± 0.10	N
SDSS0934+0014	-0.9	-0.86 ± 0.02	0.14 ± 0.05	4.14	0.17	2.21 ± 0.69	22.6 ± 1.0	N, D78
SDSS0944+6558	-0.8	-0.76 ± 0.03	0.14 ± 0.06	3.58	0.032	0.62 ± 0.24	4.38 ± 0.21	N
SDSS0946+0542	-1.10	-1.04 ± 0.02	0.18 ± 0.03	4.01	0.18	1.63 ± 0.28	25.2 ± 0.8	N, D78
SDSS1038+5330	-0.95	-0.90 ± 0.01	0.16 ± 0.03	3.86	0.088	1.16 ± 0.20	12.0 ± 0.2	N, C83, H85, G91, S75, M73
SDSS1049+3259	-0.8	-0.76 ± 0.02	0.14 ± 0.04	3.32	0.018	0.33 ± 0.10	2.41 ± 0.11	N
SDSS1053+3354	-0.85	-0.76 ± 0.03	0.27 ± 0.07	3.30	0.0091	0.32 ± 0.08	1.24 ± 0.07	N
SDSS1109+1043	-0.9	-0.81 ± 0.04	0.26 ± 0.08	3.09	0.0072	0.20 ± 0.06	0.98 ± 0.08	N
SDSS1122+3745	-1.05	-0.98 ± 0.04	0.21 ± 0.08	3.29	0.024	0.31 ± 0.11	3.33 ± 0.23	N
SDSS1145+0909	-0.95	-0.85 ± 0.04	0.28 ± 0.08	3.58	0.023	0.61 ± 0.17	3.11 ± 0.28	N, D78
SDSS1153+4751	-1.10	-0.99 ± 0.04	0.32 ± 0.12	3.30	0.017	0.32 ± 0.12	2.36 ± 0.07	N, C83, H85, G91, S75
SDSS1157+3217	-0.8	-0.60 ± 0.02	0.52 ± 0.05	4.25	0.023	2.86 ± 0.24	3.13 ± 0.07	N, F, S75

Table 4.5—Continued

Source	α_N^{fit}	$\alpha_{1.4-33}$	Thermal Fraction at 33 GHz	Log Max # ^a O7.5V Stars	SNe Rate ^b (yr ⁻¹)	Thermal SFR (M _⊙ yr ⁻¹)	Nonthermal SFR (M _⊙ yr ⁻¹)	References ^c
SDSS1224+3922	-0.8	-0.61 ± 0.02	0.50 ± 0.04	3.64	0.0061	0.70 ± 0.04	0.84 ± 0.04	N
SDSS1225+5430	-0.8	-0.67 ± 0.01	0.38 ± 0.03	3.92	0.019	1.32 ± 0.09	2.62 ± 0.04	N, F
SDSS1229+0749	-1.05	-0.97 ± 0.05	0.23 ± 0.09	3.33	0.025	0.35 ± 0.13	3.40 ± 0.31	N, D78, V04
SDSS1242-0004	-1.15	-1.10 ± 0.03	0.14 ± 0.06	3.04	0.031	0.17 ± 0.07	4.23 ± 0.26	N, D78
SDSS1248+1058	-0.8	-0.60 ± 0.07	0.52 ± 0.13	2.92	0.0011	0.13 ± 0.03	0.15 ± 0.03	N, V04
SDSS1300+0230	-1.35	-1.29 ± 0.03	0.17 ± 0.06	2.46	0.014	0.046 ± 0.016	1.86 ± 0.09	N, D78
SDSS1319+3015	-0.8	-0.60 ± 0.06	0.52 ± 0.13	3.51	0.0042	0.52 ± 0.11	0.58 ± 0.09	N
SDSS1423+3400	-0.8	-0.61 ± 0.05	0.51 ± 0.12	4.04	0.015	1.76 ± 0.34	2.05 ± 0.28	N
SDSS1430+0716	-1.05	-0.95 ± 0.06	0.29 ± 0.12	2.94	0.0073	0.14 ± 0.06	1.00 ± 0.14	N
SDSS1533-0137	-1.15	-1.03 ± 0.07	0.34 ± 0.15	3.40	0.024	0.40 ± 0.17	3.23 ± 0.49	N
SDSS1546+0224	-0.95	-0.89 ± 0.02	0.19 ± 0.03	4.37	0.24	3.75 ± 0.62	32.2 ± 1.2	N
SDSS1546+1753	-1.0	-0.92 ± 0.03	0.23 ± 0.05	3.96	0.090	1.46 ± 0.31	12.2 ± 0.6	N, D78, B95
SDSS1605+4120	-0.8	-0.69 ± 0.04	0.34 ± 0.08	3.56	0.010	0.58 ± 0.13	1.37 ± 0.13	N
Mrk 297	-0.8	-0.79 ± 0.01	0.049 ± 0.019	4.18	0.41	2.42 ± 0.96	56.5 ± 1.1	N, D78, S76, B95, B91, S75
Mrk 325	-0.8	-0.77 ± 0.01	0.11 ± 0.03	4.00	0.11	1.62 ± 0.38	15.6 ± 0.4	N, D78, B95, S06

Table 4.5—Continued

Source	α_N^{fit}	$\alpha_{1.4-33}$	Thermal Fraction at 33 GHz	Log Max # ^a O7.5V Stars	SNe Rate ^b (yr ⁻¹)	Thermal SFR (M _⊙ yr ⁻¹)	Nonthermal SFR (M _⊙ yr ⁻¹)	References ^c
Mrk 538	-0.8	-0.71 ± 0.01	0.29 ± 0.01	4.64	0.15	6.99 ± 0.28	20.6 ± 0.3	N, D78, G91, S06, B95
Average ^d	-0.91 ± 0.15	-0.81 ± 0.18	0.29 ± 0.16	3.63 ± 0.55	0.059 ± 0.090	1.35 ± 1.64	8.09 ± 12.22	
Clumpy	-0.94 ± 0.16	-0.85 ± 0.17	0.25 ± 0.13	3.54 ± 0.53	0.062 ± 0.093	1.10 ± 1.49	8.51 ± 12.65	
Non-clumpy	-0.82 ± 0.06	-0.66 ± 0.14	0.42 ± 0.21	3.90 ± 0.58	0.049 ± 0.083	2.23 ± 1.93	6.66 ± 11.38	

^aThe maximum number of O7.5V-type stars that could output the thermal emission we observe. This is calculated using Equation 2 in Condon (1992) and the estimate that one O7.5V-type star outputs 10⁴⁹ Lyman continuum photons per second (Vacca et al. 1996).

^bThe supernova rate that we can infer from the nonthermal emission we observe. This is calculated using Equation 18 in Condon (1992).

^cReferences for archival data points used to fit SEDs. N: NVSS (Condon et al. 1998), F: FIRST (Becker et al. 1995), D78: Dressel & Condon (1978), C83: Condon (1983), H85: Hummel et al. (1985), G91: Gregory & Condon (1991), S75: Sramek (1975), M73: McCutcheon (1973), V04: Vollmer et al. (2004), B95: Bica et al. (1995), S76: Sramek & Tovmassian (1976), B91: Becker et al. (1991), S06: Schmitt et al. (2006).

^dUncertainties on the averages are 1 σ standard deviations.

Table 4.6. Far-infrared star formation properties

Source	$S_{\text{FIR}}^{\text{a}}$ (Jy)	T_{dust} (K)	$\log(M_{\text{dust}})$ ($M_{\odot}$)	SFR_{IR} ($M_{\odot} \text{ yr}^{-1}$)	$Q_{\text{NVSS,IRAS}}$	$Q_{\text{CCB,IRAS}}$	$Q_{1.4,\text{fit}}$	$Q_{33,\text{fit}}$
SDSS0349+0109	2.771 ± 0.004	29.0 ± 2.6	5.77 ± 0.07	0.83 ± 0.39	1.93	3.03	2.07	3.16
SDSS0823+2120A	3.287 ± 0.004	28.3 ± 1.5	6.10 ± 0.06	1.24 ± 0.41	...	...	2.34	3.18
SDSS0823+2120B	3.936 ± 0.003	28.8 ± 1.3	6.15 ± 0.06	1.58 ± 0.47	...	...	2.69	3.31
SDSS0826+4558	2.742 ± 0.004	28.6 ± 1.9	5.20 ± 0.07	0.24 ± 0.14	2.53	3.49	2.35	3.30
SDSS0934+0014	10.173 ± 0.004	29.5 ± 2.1	6.38 ± 0.06	2.71 ± 0.86	2.15	3.32	2.08	3.26
SDSS0944+6558	6.938 ± 0.005	34.6 ± 4.0	5.58 ± 0.07	1.15 ± 0.52	2.20	3.22	2.29	3.33
SDSS0946+0542	17.526 ± 0.003	27.4 ± 1.2	6.44 ± 0.06	2.30 ± 0.66	2.08	3.47	1.92	3.35
SDSS1038+5330	112.591 ± 0.003	32.9 ± 1.4	5.84 ± 0.06	1.57 ± 0.48	2.04	3.27	2.03	3.26

Table 4.6—Continued

Source	S _{FIR} ^a (Jy)	T _{dust} (K)	log(M _{dust}) (M _⊙)	SFR _{IR} (M _⊙ yr ^{−1})	Q _{NVSS,IRAS}	Q _{CCB,IRAS}	Q _{1.4,fit}	Q _{33,fit}
SDSS1049+3259	19.289 ± 0.003	30.7 ± 1.1	5.64 ± 0.06	0.78 ± 0.27	2.50	3.51	2.36	3.40
SDSS1053+3354	5.146 ± 0.003	23.1 ± 0.6	5.86 ± 0.06	0.35 ± 0.17	2.29	3.32	2.17	3.21
SDSS1109+1043	7.504 ± 0.003	20.8 ± 0.6	6.21 ± 0.06	0.38 ± 0.18	...	...	2.34	3.46
SDSS1122+3745	8.997 ± 0.004	28.2 ± 1.6	5.67 ± 0.06	0.54 ± 0.25	2.24	3.57	2.12	3.46
SDSS1145+0909	4.805 ± 0.003	30.2 ± 1.3	5.56 ± 0.06	0.59 ± 0.25	2.25	3.42	2.17	3.34
SDSS1153+4751	48.528 ± 0.003	26.7 ± 1.0	5.76 ± 0.06	0.50 ± 0.23	2.17	3.63	2.22	3.57
SDSS1157+3217	22.730 ± 0.004	27.6 ± 1.7	6.56 ± 0.06	2.97 ± 0.86	...	...	2.90	3.72
SDSS1224+3922	25.381 ± 0.003	26.4 ± 1.0	5.74 ± 0.06	0.47 ± 0.21	2.58	3.36	2.53	3.37

Table 4.6—Continued

Source	S _{FIR} ^a (Jy)	T _{dust} (K)	log(M _{dust}) (M _⊙)	SFR _{IR} (M _⊙ yr ⁻¹)	Q _{NVSS,IRAS}	Q _{CCB,IRAS}	Q _{1.4,fit}	Q _{33,fit}
SDSS1225+5430	5.849 ± 0.004	22.6 ± 1.5	6.28 ± 0.06	0.63 ± 0.32	2.22	3.29	2.18	3.10
SDSS1229+0749	6.644 ± 0.004	23.8 ± 1.7	6.13 ± 0.06	0.70 ± 0.34	2.30	3.59	2.11	3.45
SDSS1242-0004	15.586 ± 0.004	18.9 ± 1.2	6.83 ± 0.06	0.93 ± 0.45	2.28	3.77	2.12	3.63
SDSS1248+1058	4.433 ± 0.004	24.5 ± 1.4	5.26 ± 0.06	0.13 ± 0.09	2.74	3.55	2.62	3.45
SDSS1300+0230	17.692 ± 0.003	20.6 ± 0.7	6.16 ± 0.06	0.38 ± 0.19	2.31	4.04	2.07	3.85
SDSS1319+3015	3.466 ± 0.005	25.9 ± 2.7	5.53 ± 0.08	0.28 ± 0.19	2.43	3.24	2.44	3.27
SDSS1423+3400	3.475 ± 0.003	24.9 ± 0.6	6.16 ± 0.06	0.78 ± 0.28	2.55	3.38	2.41	3.25
SDSS1430+0716	5.965 ± 0.003	18.4 ± 0.26	6.34 ± 0.06	0.29 ± 0.14	2.35	3.65	2.14	3.44

Table 4.6—Continued

Source	S _{FIR} ^a (Jy)	T _{dust} (K)	log(M _{dust}) (M _⊙)	SFR _{IR} (M _⊙ yr ⁻¹)	Q _{NVSS,IRAS}	Q _{CCB,IRAS}	Q _{1.4,fit}	Q _{33,fit}
SDSS1533-0137	3.630 ± 0.004	21.3 ± 1.4	6.32 ± 0.06	0.53 ± 0.28	2.14	3.54	2.04	3.45
SDSS1546+0224	38.335 ± 0.003	26.1 ± 0.5	7.05 ± 0.06	7.04 ± 1.10	2.31	3.50	2.27	3.49
SDSS1546+1753	15.340 ± 0.003	26.2 ± 1.0	6.55 ± 0.06	2.31 ± 0.65	2.31	3.54	2.21	3.48
SDSS1605+4120	5.180 ± 0.003	31.7 ± 1.1	5.21 ± 0.06	0.40 ± 0.18	2.20	3.15	2.21	3.15
Mrk 297	23.018 ± 0.003	26.0 ± 0.4	7.05 ± 0.06	6.59 ± 1.04	1.94	3.15	2.01	3.09
Mrk 325	16.566 ± 0.004	30.3 ± 1.8	6.23 ± 0.06	2.27 ± 0.70	2.18	3.25	2.13	3.18
Mrk 538	45.703 ± 0.003	40.3 ± 0.9	5.97 ± 0.06	4.92 ± 0.85	2.29	3.19	2.27	3.24
Average (all) ^b	16.6 ± 21.7	26.9 ± 4.7	6.0 ± 0.5	1.5 ± 1.8	2.3 ± 0.2	3.4 ± 0.2		

Table 4.6—Continued

Source	$S_{\text{FIR}}^{\text{a}}$ (Jy)	T_{dust} (K)	$\log(M_{\text{dust}})$ ($M_{\odot}$)	SFR_{IR} ($M_{\odot} \text{ yr}^{-1}$)	$q_{\text{NVSS,IRAS}}$	$q_{\text{CCB,IRAS}}$	$q_{1.4,\text{fit}}$	$q_{33,\text{fit}}$
Average (clumpy)	18.7 ± 23.4	26.5 ± 4.9	6.1 ± 0.4	1.4 ± 1.6	2.2 ± 0.2	3.4 ± 0.2		
Average (non-clumpy)	9.4 ± 12.8	28.4 ± 3.7	5.9 ± 0.6	1.8 ± 2.4	2.4 ± 0.2	3.3 ± 0.1		

^a S_{FIR} is the total far-IR ($40 - 1000\mu\text{m}$) flux, and is calculated by $S_{\text{FIR}} = 2.58 \times S_{60\mu\text{m}} + S_{100\mu\text{m}}$ using the derived $60\mu\text{m}$ and $100\mu\text{m}$ fluxes from a Casey (2012) fit to the far-IR data.

^bAverages are reported as average $\pm 1\sigma$ where σ is the standard deviation.

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Chapter 5

Conclusions

5.1 Summary of results in this thesis

In the three studies presented in this thesis, I have applied analysis of observations of resolved H I and star formation tracers of $z \sim 0$ luminous compact blue galaxies (LCBGs) to better understand these rapidly-evolving analogs to the star-forming galaxies common at $z \sim 1$. While we do not yet have an unambiguous picture of the physical causes that trigger, sustain, and quench star formation over such a rapid period of time in these galaxies, we have better constrained likely scenarios for such activity. In summary, we have learned the following about $z \sim 0$ LCBGs:

- We have confirmed that LCBGs are a heterogeneous class of galaxies. They have varied H I kinematics, star formation properties, and timescales of their most recent episodes of star formation.
- LCBGs are H I-rich galaxies that are rotationally-supported at all radii. They are not dispersion-dominated, compact bulgelike galaxies like dwarf ellipticals.
- LCBGs have ongoing star formation, with a range of ages since their most recent star formation episode began, from ~ 10 Myr to ~ 100 Myr or more.

- Some LCBGs appear to have a young stellar population distributed throughout their disks, while others either have a declining disk-wide burst, or localized ongoing star formation on top of a more quiescent disk.
- LCBGs' H I and global star formation properties are consistent with gravitational instabilities that trigger and sustain star formation due to a combination of local overdensities of gas and favorable internal kinematic conditions in the galaxies.

When we combine H I data and radio continuum and far-infrared star formation tracers, we can begin to develop a picture of the evolution of LCBGs. As LCBGs were ten times more common at $z \sim 1$ than they are in the local Universe, it is clear that these galaxies must evolve quickly. Until recently, possibilities for LCBGs' star formation triggers and evolutionary paths have not been well-constrained. With the recent discovery that LCBGs can be clumpy (Garland et al. 2015), and evidence that clumpy and non-clumpy LCBGs have different properties (Garland et al. 2015, Chapter 4), we can begin to construct a model of LCBG evolution.

5.2 A model for LCBGs' past, present, and future

Since there does not seem to be a population of galaxies in the local Universe that is an obvious descendant of $z \sim 1$ LCBGs (Guzmán et al. 1997), and $z \sim 0$ LCBGs do not appear to have a high rate of major mergers that would dramatically change their morphology (Garland et al. 2015), it is likely that the $z \sim 0$ galaxies that were formerly LCBGs at $z \sim 1$ are hiding in plain sight, as was suggested by Noeske

et al. (2006). Rather than forming a class of galaxies with a distinct morphology such as dwarf elliptical galaxies, LCBGs are likely disk galaxies in a particular phase of their evolution where they experience a short-lived phase of enhanced and centrally-concentrated star formation due to an increased gas fraction. As a result of this star formation, LCBGs will likely build a nuclear bulge or short bar (dynamically similar to the “pseudobulges” described in Kormendy & Kennicutt (2004) and modeled for clumpy galaxies in Inoue & Saitoh (2012), rather than a large, S0/Sa-type bulge) before running out of gas. Once their current star formation episode declines, their star formation rates will likely return to the background levels characteristic of disk galaxies with similar masses.

We can see that this scenario explains LCBGs’ H I properties that we described in Chapter 3, and star formation properties that we described in Chapter 4. In Chapter 3, we found that LCBGs have values of $V_{\text{rot}}\sigma^{-1}$ in their centers that are similar to those of pseudobulges or bars in the centers of some disk galaxies. In addition, their $V_{\text{rot}}\sigma^{-1}$ values at the edges of LCBGs are sufficient for gravitational instabilities that can form star-forming clumps. When these clumps merge and migrate throughout the disk, they can make a galaxy’s disk appear bright and blue due to the enhanced star formation within the clumps. If they are long-lived enough to reach the galaxy’s center while still forming stars, they can form a bright, compact nuclear bulge that can continue to form stars for as long as they have gas. In a less massive galaxy, these instabilities will not form long-lived clumps, but can instead funnel gas to the galaxy’s center to form a short bar, or form short-lived clumps that form stars for a short period of time before dispersing, which can replenish the surrounding area with

gas that can later form new clumps. These bulges and bars have values of $V_{\text{rot}}\sigma^{-1}$ in simulations that are consistent with what we find in the centers of LCBGs.

For this gravitational instability scenario to result in a galaxy with an appearance similar to LCBGs, a “sweet spot” of galaxy mass and radius may be necessary. A galaxy is more likely to support long-lived clumps if it is massive (more massive galaxies form more massive clumps, and more massive clumps have longer lifetimes), and if it is compact (clumps reach the centers of compact galaxies faster than galaxies with large radii due to shorter dynamical times Dekel et al. 2009). In addition, a particular ratio of gas mass fraction to $V_{\text{rot}}\sigma^{-1}$ is necessary in order for gravitational instabilities to develop (e.g. Toomre 1964; Noguchi 2000; Dekel et al. 2009). Garland et al. (2015) found that $z \sim 0$ LCBGs have effective radii characteristic of the lower end of the range of radii of LCBGs at $z \sim 1$. It is possible that LCBGs were more common at higher redshifts, and less common in the local Universe, because conditions at $z \sim 1$ made it more likely for galaxies to inhabit this “sweet spot” of centrally-concentrated clumpy star formation, and due to cosmic downsizing and galaxy interactions since $z \sim 1$ it is difficult to find galaxies with the mass, radius, gas mass fraction, and kinematics necessary to have sustained, centrally-concentrated star formation at $z \sim 0$. Local LCBGs could be the few galaxies that inhabit this intersection of phase space, whether they have recently become massive and gas-rich enough to undergo enhanced star formation due to the accretion of primordial gas from a cosmic filament or satellite galaxies through minor mergers, or whether they are massive galaxies that have undergone past generations of star formation but have been recently “recycled” due to gas from a minor merger or interaction with a cluster

potential (Kennicutt & Evans 2012). Tollerud et al. (2010) hypothesized that the relative rarity of LCBGs at low redshifts could be due to cosmic downsizing, and that conditions at $z \sim 0$ are less hospitable to the types of star formation that were common at $z \sim 1$. Our observations support that hypothesis, as well as suggest that the necessary conditions are met in LCBGs in more than one way.

Our findings in Chapter 4 support LCBGs being a heterogeneous class of galaxies undergoing a common star formation phase. The non-clumpy LCBGs in our sample all have star formation properties that are consistent with a relatively young ($\lesssim 30$ Myr) episode of star formation. The clumpy LCBGs, meanwhile, appear to have a range of star formation ages. Some of the clumpy LCBGs have properties similar to the non-clumpy LCBGs, while others appear to have star formation that is either declining from a previous phase with properties similar to the non-clumpy LCBGs, or existing primarily in only a few star-forming clumps but not distributed throughout the rest of the disk, which has older star formation properties on average. We cannot distinguish between these two scenarios for the clumpy galaxies with the current data that we have, but future resolved studies of clumpy LCBGs' disks may be able to determine whether one of these scenarios is dominant. Even so, it is clear that there are multiple avenues available for galaxies to undergo an LCBG-like phase of star formation.

Since we have measured LCBGs' star formation properties using extinction-free star formation tracers, we have been able to distinguish a range of star formation ages for LCBGs even though these galaxies appear similar in optical studies. LCBGs are clearly not all the same age, so we can expect that they have different star formation

triggers and quenching mechanisms, and will end up with different appearances once their star formation has been quenched. It seems that $z \sim 0$ LCBGs are likely to divide into two groups: those that are undergoing a major episode of star formation that their entire disks are participating in, and those undergoing localized star formation due to a recent influx of gas.

While we cannot definitively characterize LCBGs as participating in either of these two scenarios with our global observations, future resolved observations of star formation tracers in LCBGs will be able to identify star-forming clumps, estimate their ages and their gas depletion timescales, and compare their ages to that of the star formation in LCBGs' disks. Similarly, future resolved CO observations will be able to better identify areas in LCBGs' disks where molecular gas fractions and kinematics indicate the potential for local instabilities. Also, future detailed studies of LCBGs' environments will be able to constrain whether LCBGs with younger star formation spread throughout their disks are more likely to be the isolated galaxies that may be undergoing a version of primordial accretion-enhanced star formation that was common for the $z \sim 1$ LCBGs. If it is found that isolated LCBGs are more likely to have younger bursts that involve their entire disks, then these $z \sim 0$ LCBGs may serve as a “missing link” between star formation at $z \sim 1$ and the star formation that is currently occurring in smaller galaxies such as Blue Compact Dwarfs. In addition, such a discovery may not only help explain the evolution of star-forming galaxies in the latter half of the Universe's history, but may also make these LCBGs useful as laboratories to study the growth of nuclei in star-forming galaxies.

If this two-path model of star formation in LCBGs is accurate, it is likely that these galaxies evolve into more passive disk galaxies with nuclear bulges or bars once their stores of cold gas are used up and their current phase of star formation ends. In this way, though the end products of LCBGs do not suggest that they undergo wild transformations, we can better understand how galaxies have evolved from being bright, blue, and compact to fainter, redder, and smoother.

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Appendix A

Individual galaxies discussed in Chapter 3

A.1 SDSS0119+1452

SDSS0119+1452 (NGC 469) is a galaxy that shows rotation in its Moment 1 map (though it has a narrow linewidth), but also has an excess clump of H I off of its southwest corner (no similar feature appears in the SDSS optical images). Its axis of rotation in the Moment 1 map coincides with what appears to be the optical minor axis. Its optical morphology looks asymmetric, with a blue, clumpy center and no discernable spiral arms. Hyperleda classifies it as S0-Sa. NED identifies a companion (NGC 471) about $8'$ ($90 \times R_{\text{eff}}(\text{B})$) away that is visible in SDSS images but is not detected in our H I observations. At low resolutions, the gas clump is merged with the galaxy's gas, but at higher resolutions it appears separate. It is possible that it is connected at a low column density level, but at high resolutions it does not overlap with the galaxy at even the 2σ level (~ 0.5 mJy/beam in the high-resolution data cube).

A.2 SDSS0125+0110

SDSS0125+0110 (ARK 044) is a rotating galaxy in the NGC 533 group. It has no nearby companions. It has the least-disturbed morphology of all of the galaxies in

our sample, and a redder center than most of the other LCBGs discussed here. This galaxy was not in the original Garland et al. (2004) sample, and following the SDSS DR7 photometry, it does not fall within the LCBG criteria defined by Werk et al. (2004); it is slightly redder and less compact. Hyperleda classifies this galaxy as Sb.

A.3 SDSS0728+3532

SDSS0728+3532 (ARK 134) is a rotating galaxy with a large, low column density H I tidal tail extending to the south. The tail appears to be caused by an interaction with at least one other blue galaxy (SDSS0728+3531), which optically coincides with the location of the H I emission of the tail (though it does not have an obvious velocity component in the Moment 1 map distinct from the tidal tail, so we cannot confirm that it is the cause of the tidal tail). More H I emission is detected to the west of SDSS0728+3532 in our observations, which coincides with another blue galaxy in SDSS images. There is no optical emission corresponding to the the tidal tail visible in SDSS images. Hyperleda classifies SDSS0728+3532 as an Sbc.

A.4 SDSS0934+0014

SDSS0934+0014 (UGC 05097) has a disturbed morphology and may be face-on, as its rotation curve is difficult to fit (though Hyperleda gives its optical inclination as 68°). It has a companion about $11'$ ($123 \times R_{\text{eff}}(\text{B})$) to the southeast, and also has a blue companion $1'$ ($11 \times R_{\text{eff}}(\text{B})$) to the north (UGC 05099) that is not detected in either the low-resolution or high-resolution maps. SDSS0934+0014 and its northern companion

are not obviously interacting in the SDSS optical image, but SDSS0934+0014 shows much more disturbed rotation than its H I profile indicates, so interaction is possible. There is a steeper gradient in both velocity contours and velocity dispersion contours near the border of the two galaxies, which could also indicate that some interaction is taking place. The H I profile at the location of the interaction does appear to have multiple components. NED classifies SDSS0934+0014 as a pair of galaxies, with a faint elliptical galaxy also interacting with SDSS0934+0014 to the north. Hyperleda classifies SDSS0934+0014 as an Sa galaxy.

A.5 SDSS0936+0106

SDSS0936+0106 (CGCG 007-009), like SDSS0125+0110, is a non-disturbed, non-interacting rotating galaxy. Unlike SDSS0125+0110, SDSS0936+0106 does have a blue companion galaxy about $5'$ ($44 \times R_{\text{eff}}(\text{B})$) to the northwest. There does not seem to be any evidence of the two galaxies interacting from the H I moment maps. Its H I emission is centrally peaked, its rotation is ordered, and its velocity dispersion is higher at the center and lower at the edges. Hyperleda does not have a classification for SDSS0936+0106, though NED classifies it as Sb.

A.6 SDSS1319+5203

SDSS1319+5203 (SBS 1317+523B) is one of a trio of blue galaxies sharing a common H I envelope as seen at low resolution. The other two galaxies are not LCBGs. One, Mrk 251, is blue and compact, though it is too faint to be classified as

an LCBG. The other, SBS 1317+523A, is blue and bright, but its surface brightness is too low to qualify for LCBG status. SBS 1317+523B is included in the Garland et al. (2004) sample, but all three galaxies are well within the 9' GBT beam, so contamination from both galaxies likely affects their measurements. Hyperleda classifies SBS 1317+523B as Sb-Sbc, and Mrk 251 as Sab. The galaxy group is dominated by SBS 1317+523A and the velocity field for the system shows interaction between it and SBS 1317+523B.

A.7 SDSS1402+0955

SDSS1402+0955 (NGC 5414) is a bright, blue galaxy that does not appear to have any companions detected in H I, though in an SDSS image there appear to be several nearby galaxies in the plane of the sky. Its velocity field shows that it appears to be regularly rotating. Hyperleda classifies it as an elliptical galaxy in a multiple-galaxy system, though NED does not have a galaxy with velocity information at a similar velocity to SDSS1402+0955 within 5' of the LCBG. The SDSS optical image does appear asymmetrical, with a diffuse stellar halo that may show signatures of past interaction. The H I image shows a bit of asymmetry on the receding edge, so it is possible that a past interaction or merger could have upset the galaxy's rotation enough to make rotation curve fitting difficult, even if position-velocity plots look relatively undisturbed.

A.8 SDSS1507+5511

SDSS1507+5511 (UGC 09737) is a rotating galaxy with an excess of gas above its plane of rotation. It has a faint blue companion about $9'$ ($69 \times R_{\text{eff}}(\text{B})$) to the northeast (in the direction of the excess gas) that is detected in our H I observations. Hyperleda classifies UGC 09737 as a compact Sbc galaxy. Its H I emission is centrally peaked, with its peak coinciding with the optical emission of the galaxy. While its velocity field shows rotation, it is difficult to fit a rotation curve to this galaxy without large errors given the spatial resolution of our observations.

A.9 Mrk 325

Mrk 325 (NGC 7673) is a disturbed galaxy that has a companion, Mrk 326, that was observed in H I by Nordgren et al. (1997) and that we also detect in our H I observations. Pérez-Gallego et al. (2010) observed Mrk 325 in $\text{H}\alpha$ and found that, while it has an asymmetric, complex velocity field likely resulting from a minor merger, it is a rotating galaxy with a position angle of 168° and $V_{\text{rot}} = 30 \text{ km s}^{-1}$ before correcting for inclination. The minor merger may be with an infalling dwarf galaxy, which Pérez-Gallego et al. (2010) find has a separate kinematic component from the rest of Mrk 325. Garland et al. (2007) observed Mrk 325 in H I with the VLA in C configuration with a beam size of $\sim 20''$ and found that its emission is disturbed and shows a small velocity gradient. Our H I map, which combines the Garland et al. (2007) map with new B configuration data and archival D configuration maps from Nordgren et al. (1997), shows similar morphology and velocity information, and does

not feature an obvious major axis of rotation. Nordgren et al. (1997) described Mrk 325 as a face-on galaxy with a possible warp. Hyperleda classifies Mrk 325 as an Sc.