PROPERTIES OF BULGELESS DISK GALAXIES. II. STAR FORMATION AS A FUNCTION OF CIRCULAR VELOCITY

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ABSTRACT

We study the relation between the surface density of gas and star formation rate in 20 moderately inclined, bulgeless disk galaxies (Sd-Sdm Hubble types) using CO(1–0) data from the IRAM 30 m telescope, H\textsc{i} emission line data from the VLA/EVLA, H\textsc{z} data from the MDM Observatory, and polycyclic aromatic hydrocarbon emission data derived from \textit{Spitzer} IRAC observations. We specifically investigate the efficiency of star formation as a function of circular velocity ($v_{\text{circ}}$). Previous work found that the vertical dust structure and disk stability of edge-on, bulgeless disk galaxies transition from diffuse dust lanes with large scale heights and gravitationally stable disks at $v_{\text{circ}} < 120 \text{ km s}^{-1}$ ($M_\odot \lesssim 10^{10} M_\odot$) to narrow dust lanes with small scale heights and gravitationally unstable disks at $v_{\text{circ}} > 120 \text{ km s}^{-1}$. We find no transition in star formation efficiency ($\Sigma_{\text{SFR}}/\Sigma_\text{H2}$) at $v_{\text{circ}} = 120 \text{ km s}^{-1}$ or at any other circular velocity probed by our sample ($v_{\text{circ}} = 46–190 \text{ km s}^{-1}$). Contrary to previous work, we find no transition in disk stability at any circular velocity in our sample. Assuming our sample has the same dust structure transition as the edge-on sample, our results demonstrate that scale height differences in the cold interstellar medium of bulgeless disk galaxies do not significantly affect the molecular fraction or star formation efficiency. This may indicate that star formation is primarily affected by physical processes that act on smaller scales than the dust scale height, which lends support to local star formation models.

Key words: galaxies: ISM – galaxies: spiral – galaxies: star formation – radio lines: galaxies

Online-only material: color figures

1. INTRODUCTION

High-resolution studies of the Milky Way and nearby galaxies show that star formation mainly occurs in giant molecular clouds (GMCs), with typical GMC masses between about $10^3$ and $10^7 M_\odot$ and radii between about ten and several hundred parsecs (e.g., Fukui & Kawamura 2010). It is challenging to study molecular gas on these scales in even the nearest galaxies ($\lesssim 4 \text{ Mpc}$; e.g., Bolatto et al. 2008) and studies of more distant galaxies can only currently investigate the average properties of gas and stars on larger scales. An advantage of more distant galaxies is that they exhibit a much wider range of physical properties, which enables investigation into the influence of environment (e.g., mid-plane pressure, metallicity, and scale height) and processes that act on larger scales (e.g., shear and large scale gravitational instabilities) on star formation.

Extragalactic studies of star formation have found that the star formation rate (SFR) surface density ($\Sigma_{\text{SFR}}$) and gas surface density ($\Sigma_\text{gas}$) are correlated in the form of the Kennicutt–Schmidt law: $\Sigma_{\text{SFR}} \propto \Sigma_\text{gas}^n$ (Kennicutt 1998). This star formation law has been studied by averaging over scales as small as about 100 pc and as large as the entire optical disk. Recent high-resolution studies have found that the SFR surface density is more strongly correlated with the molecular gas surface density ($\Sigma_\text{H2}$) than with the atomic gas surface density ($\Sigma_\text{H}$), with $\Sigma_{\text{SFR}} \propto \Sigma_\text{H2}$ and $\Sigma_\text{H}$ between 0.8 and 1.5 (Wong & Blitz 2002; Kennicutt et al. 2007; Bigiel et al. 2008; Blanc et al. 2009; Schruba et al. 2010; Liu et al. 2011; Rahman et al. 2011). This result confirms, from an extragalactic perspective, that stars form from molecular gas and has led to an expansion in the scope of many star formation studies to investigate how environment and large scale processes affect the molecular fraction in the interstellar medium (ISM).

Leroy et al. (2008) addressed environmental effects on the molecular fraction and star formation efficiency (SFE) with high-quality, 750 pc resolution observations of $\Sigma_{\text{SFR}}, \Sigma_\text{H},$ and $\Sigma_\text{H2}$ over the optical disk of 23 nearby galaxies. They compared these observations to many star formation models and thresholds and concluded that no model fit the data sufficiently well to be declared a clear favorite. This result led them to suggest that physics that acts on scales smaller than their resolution is most important for setting the molecular fraction and SFE.

While no model was an ideal fit to the data presented in Leroy et al. (2008), the best fit was arguably with a model in which the ratio of molecular to atomic surface density is related to the mid-plane pressure ($P_\text{h}$): $R_{\text{mol}} \equiv \Sigma_\text{H2}/\Sigma_\text{H} \sim P_\text{h}^{1/2}$, and the molecular SFE (SFE[H$_2$] $\equiv \Sigma_{\text{SFR}}/\Sigma_\text{H2}$) is constant, such that SFE $\equiv \Sigma_{\text{SFR}}/\Sigma_\text{H} = \text{SFE[H$_2$]} (R_{\text{mol}}/(R_{\text{mol}} + 1))$. Leroy et al. (2008) noted that a model where the molecular SFE is constant requires the population of GMCs in any region to be sampled from the same distribution of properties (e.g., size and mass), independent of environment. Furthermore, once GMCs form, the general environment cannot have a strong influence on their properties. Finally, one must compare the model to observations with a number of GMCs per resolution element so as to average over evolutionary effects. Elmegreen (1993) predicted that $R_{\text{mol}}$ should depend on the mid-plane pressure and the interstellar radiation field ($j$): $R_{\text{mol}} \propto P_\text{h}^{1/2} j^{-1}$. Assuming $\Sigma_{\text{SFR}} \propto \Sigma_\text{H2}$.
and $j \propto \Sigma_{SFE}$, the model predicts $R_{mol} \propto \rho_{H}^{\alpha}$, with $\alpha = 1.2$. Wong & Blitz (2002) studied seven molecular-dominated spiral galaxies and found $\alpha = 0.8$, while Blitz & Rosolowsky (2006) found $\alpha = 0.92$ in their study of 14 galaxies with a large range of $R_{mol}$. Values between $\alpha = 0.5$ and 1.2 encompass most of the Leroy et al. (2008) data on the SFE versus $P_{B}$ plane.

Ostriker et al. (2010) recently presented a star formation model that produces an approximately linear relationship between $R_{mol}$ and $P_{B}$. The authors divided the ISM into a diffuse component and a gravitationally bound component. The fraction of gas in each component is set by the requirement that gas pressure in the diffuse component is balanced by the gravity of stars, dark matter, and gas (both diffuse and bound), while heating (mainly by ultraviolet (UV) photons from O and B stars formed in the bound component) balances cooling. The model assumes that the SFE within the gravitationally bound component is constant. Bolatto et al. (2011) added a metallicity-dependent heating term to the Ostriker et al. (2010) model, which resulted in agreement between the large HI surface densities observed in the Small Magellanic Cloud and the surface density of diffuse gas calculated with the adjusted Ostriker et al. (2010) model.

Another leading star formation model is that of Krumholz et al. (2009), where the molecular fraction is determined by processes that act on scales no larger than $\sim 100$ pc, which is the size of atomic–molecular complexes in the model. Specifically, the molecular fraction is set by the balance between the formation of molecular hydrogen on the surfaces of dust grains and the destruction of molecular hydrogen by UV photons. Both dust shielding and $H_2$ self-shielding contribute to the survival of molecular hydrogen in the interior of the complexes. Stars form only from molecular gas and the model produces a constant molecular SFE because properties of molecular clouds, like $\Sigma_{H_2}$, are independent of general ISM conditions, at least while gas surface densities in the general ISM are less than GMC densities ($\sim 85 M_\odot$ pc$^{-2}$).

In this paper, we study star formation in a sample of 20 bulgeless disk galaxies. Bulgeless galaxies are interesting from a number of perspectives. Their existence in relatively large numbers ($\gtrsim 15\%$ of disk galaxies; Katsch et al. 2006; Kormendy et al. 2010) provides an important constraint on hierarchical galaxy formation models, in which galaxies generally have rich merger histories that lead to bulge growth. The agreement between models and observations is becoming better as feedback, high gas fractions, and satellite mergers on radial orbits are included in the models (Robertson et al. 2006; Hopkins et al. 2008; Brook et al. 2011; but see also Scannapieco et al. 2011). Under the assumption that bulges do form when significant merger events occur, bulgeless galaxies are a suitable sample to study secular evolution, where internal processes like star formation lead to changes in the galaxies, such as bulge growth (Kormendy & Kennicutt 2004).

A number of works have studied the components of star formation in late-type disk galaxies. Böker et al. (2003) found that their sample of 47 late-type spirals are similar to earlier-type spirals in that they fall on the approximately linear correlation between far-infrared (FIR) luminosity, which traces star formation, and the molecular hydrogen mass within the central few kpc. Furthermore, Matthews et al. (2005) found that low-surface brightness, late-type disks lie on this same relation. Dalcanton et al. (2004) studied the dust and cold ISM structure in a sample of 49 edge-on bulgeless disk galaxies. They inferred that there is a sharp transition in dust lane structure with circular velocity ($v_{\text{circ}}$) based on measurements of $R - K$ color versus height above the mid-plane. Galaxies with $v_{\text{circ}} < 120$ km s$^{-1}$ (we also refer to these as low-$v_{\text{circ}}$ galaxies) appear to have no dust lanes while galaxies with $v_{\text{circ}} > 120$ km s$^{-1}$ (high-$v_{\text{circ}}$ galaxies) have well-defined dust lanes (the stellar mass Tully–Fisher relation relates $v_{\text{circ}} = 120$ km s$^{-1}$ with $M_\odot \sim 10^{10} M_\odot$; Bell & de Jong 2001). The authors concluded that the transition is likely due to a transition in dust scale height rather than to a sharp transition in the quantity of dust present: Low-$v_{\text{circ}}$ galaxies have diffuse dust lanes with large scale heights while high-$v_{\text{circ}}$ galaxies have dust lanes with smaller scale heights. They came to this conclusion because the dust structure transition occurs over a relatively narrow range in circular velocity ($\sim 10$ km s$^{-1}$), and therefore over a relatively narrow range in gas and total mass, where the dust-to-gas ratio (DGR) does not vary substantially.

Dalcanton et al. (2004) also found that disk stability, parameterized by a generalized Toomre $Q$ parameter including both gas and stars (Rafikov 2001), is correlated with the dust structure, with low-$v_{\text{circ}}$ galaxies generally stable and high-$v_{\text{circ}}$ galaxies generally unstable. Furthermore, they concluded that a sharp change in the contribution of turbulence to the stability parameter is the likely cause of the stability and dust scale height transitions. The authors suggested that high-$v_{\text{circ}}$ galaxies have turbulence dominated by supernovae explosions and gravitational instabilities while low-$v_{\text{circ}}$ galaxies have turbulence dominated by only supernovae. Independent of the source of the turbulence, the turbulent velocities must be lower in the high-$v_{\text{circ}}$ galaxies to explain the stability results. An alternative interpretation for the dust structure transition is that it is due to differences in stellar surface density and dust opacity, as suggested by Hunter & Elmegreen (2006).

Dalcanton et al. (2004) noted that the cold, star-forming gas should have a similar distribution to the dust, with larger scale heights in low-$v_{\text{circ}}$ galaxies compared with high-$v_{\text{circ}}$ galaxies. They hypothesized that a transition in SFE might accompany the transition in dust scale height and stability if the volume density of gas is the relevant quantity for setting the SFR. A low-$v_{\text{circ}}$ galaxy with a larger scale height but the same $\Sigma_{\text{gas}}$ relative to a high-$v_{\text{circ}}$ galaxy will have a lower gas volume density ($\rho_{\text{gas}}$). The low-$v_{\text{circ}}$ galaxy likely also has a lower gas pressure because pressure is proportional to the gas volume density ($P \propto \rho_{\text{gas}} \sigma_{\text{gas}}^{2}$, where $\sigma_{\text{gas}}$ is the gas velocity dispersion). In the context of the star formation model where the molecular fraction is set by the mid-plane pressure, we then expect lower $R_{mol} \Sigma_{SFR}$ and SFE in the low-$v_{\text{circ}}$ galaxy.

In this paper, we address whether there is an SFE transition at $v_{\text{circ}} = 120$ km s$^{-1}$ in our sample of bulgeless disk galaxies (Section 4.2). We also investigate whether scale height differences affect the SFE and discuss implications for the scale of physical processes that are important for setting the molecular fraction and the SFE. We examine our results in light of recent star formation models such as the mid-plane pressure model and the model of Krumholz et al. (2009; Sections 4.3 and 4.4). To carry out this study, we trace molecular gas with CO(1–0) data from the Institut de Radioastronomie Millimétrique (IRAM) 30 m telescope and atomic gas with HI 21 cm data from the Very Large Array (VLA; Watson et al. 2011, hereafter Paper I). We trace the SFR with Hα data from the 2.4 m Hilmer Telescope of the MDM Observatory combined with polycyclic aromatic hydrocarbon (PAH) emission data derived from Spitzer Space Telescope Infrared Array Camera (IRAC) observations. We also estimate the stellar mass from the Spitzer IRAC data. These observations, and measurements derived from the data,
are described in Section 2. We describe the quantities that we derive from these measurements in Section 3. Our results are in Section 4 and we discuss these results in Section 5.

2. SAMPLE SUMMARY, OBSERVATIONS, DATA REDUCTIONS, AND MEASUREMENTS

Our sample is composed of 20 Sd-Sdm galaxies within 32 Mpc, with circular velocities between 46 and 190 km s\(^{-1}\). These properties are well matched to the Dalcanton et al. (2004) sample. However, in contrast to the Dalcanton et al. (2004) sample of edge-on galaxies, we selected our galaxies to be moderately inclined, with inclinations between 16° and 56°, such that we can accurately measure the SFR and gas surface densities and place the galaxies on the star formation law. Section 2 in Paper I and Table 1 provide a description of the sample selection.

Many of the measurements described in this section were carried out to derive surface densities—of gas, SFR, and stars. These surface densities must be measured over the same area. The IRAM CO(1–0) data are the limiting factor, as they are single-beam, FWHM = 21′′ measurements centered on each galaxy. Therefore, we measured the emission within a 21′′ diameter circular aperture centered on the IRAM pointing center, the coordinates of which are listed in Table 2, for the following data sets: the H1 data from the VLA, the Hα data from the MDM Observatory, and the PAH and 4.5 μm data from Spitzer IRAC.

2.1. IRAM 30 m CO(1–0)

Thirteen of our objects were observed in the CO(1–0) and CO(2–1) lines at 115 and 230 GHz in 2007 May with the IRAM 30 m telescope on Pico Veleta. Dual polarization receivers were used at both frequencies with the 512 × 1 MHz filterbanks on the CO(1–0) line and the 256 × 4 MHz filterbanks on the CO(2–1) line. The observations were carried out in wobbler switching mode with a wobbler throw of 200′′ in the azimuthal direction. At the beginning of the observations, the frequency tuning was checked by observing a bright galaxy at a similar redshift. Observations of the same calibration source on different days allowed us to check the relative calibration, which was excellent (better than 10%) for CO(1–0). The calibration in CO(2–1) was equally good, except for one day when the calibration observation was different by ~35%. Pointing was monitored on nearby quasars, Mars, or Jupiter every 60–90 minutes.
| Source        | R.A. (hh:mm:ss.s) | Decl. (dd:mm:ss) | $F_{\text{H}\alpha}$ $(10^{-16}$ erg s$^{-1}$ cm$^{-2}$) | $F_{\text{PAH}}$ (mJy) | $I_{\text{H}\alpha}$(K km s$^{-1}$) | $B_{\text{maj}}$ (arcsec) | $B_{\text{min}}$ (arcsec) | $I_{\text{CO}}$ (10$^{-4}$ K km s$^{-1}$) | $F_{21\mu}$ (mJy) | $F_{25\mu}$ (mJy) | $J$ (mag) | $K_s$ (mag) |
|--------------|------------------|-----------------|---------------------------------|-----------------|-------------------------------|-------------------|-------------------|---------------------------------|-----------------|-----------------|----------------|--------------|
| NGC 0337     | 00:59:49.9       | −07:34:44       | 10.2 ± 0.05                     | 73 ± 8          | 1.28 ± 0.17                   | 25.77 ± 0.26      | 15.06 ± 1.37     | 4.7 ± 0.3           | 11.7 ± 1.2       | 64 ± 6          | 9.876 ± 0.025 | 9.059 ± 0.045  |
| PGC 3853     | 01:05:04.9       | −06:12:45       | 0.98 ± 0.04                     | 6.9 ± 0.8       | 0.36 ± 0.05                   | 25.33 ± 0.04      | 15.47 ± 0.19     | 1.39 ± 0.18        | 3.4 ± 0.3        | 44 ± 4          | 10.031 ± 0.037 | 9.280 ± 0.080  |
| PGC 6667     | 01:49:10.3       | −10:03:40       | 2.37 ± 0.02                     | 8.5 ± 0.9       | 0.90 ± 0.12                   | 26.00 ± 0.04      | 21.00 ± 0.13     | 0.71 ± 0.13        | 2.4 ± 0.2        | 15.2 ± 1.5      | 11.678 ± 0.037 | 10.951 ± 0.080 |
| ESO 544-G030 | 02:14:56.8       | −20:12:44       | 0.85 ± 0.02                     | 5.3 ± 0.6       | 0.59 ± 0.08                   | 27.78 ± 0.04      | 12.01 ± 0.4      | <0.4               | 2.5 ± 0.3        | 12.8 ± 1.3      | ...            | ...           |
| ESO 555-G027 | 06:03:36.8       | −20:39:15       | 1.42 ± 0.05                     | 9.3 ± 1.0       | 0.44 ± 0.06                   | 29.00 ± 0.04      | 21.00 ± 0.13     | ...               | 2.4 ± 0.2        | 16.1 ± 1.6      | 11.984 ± 0.045 | 11.271 ± 0.103 |
| UGC 1862     | 02:24:24.8       | −02:09:44       | 1.97 ± 0.02                     | 4.2 ± 0.5       | 0.24 ± 0.03                   | 23.97 ± 0.04      | 15.32 ± 0.6      | 0.60 ± 0.10        | 2.2 ± 0.2        | 12.4 ± 1.2      | 11.927 ± 0.023 | 11.177 ± 0.054 |
| ESO 418-G008 | 03:31:30.7       | −30:12:48       | 1.84 ± 0.03                     | 6.7 ± 0.8       | 0.92 ± 0.12                   | 32.00 ± 0.04      | 21.00 ± 0.13     | <0.9               | 2.7 ± 0.3        | 6.7 ± 0.7       | 12.752 ± 0.049 | 12.169 ± 0.126 |
| ESO 555-G027 | 06:03:36.8       | −20:39:15       | 1.42 ± 0.05                     | 9.3 ± 1.0       | 0.44 ± 0.06                   | 29.00 ± 0.04      | 21.00 ± 0.13     | ...               | 2.4 ± 0.2        | 16.1 ± 1.6      | 11.984 ± 0.045 | 11.271 ± 0.103 |
| NGC 4713     | 12:49:58.0       | +05:18:41       | 5.35 ± 0.03                     | 7.3 ± 0.9       | 0.49 ± 0.06                   | 21.00 ± 0.04      | 21.00 ± 0.13     | 0.72 ± 0.15        | 3.5 ± 0.4        | 13.0 ± 1.3      | 11.871 ± 0.039 | 11.005 ± 0.072 |
| NGC 4942     | 13:04:19.1       | −07:38:58       | 3.55 ± 0.04                     | 10.1 ± 1.1      | 0.49 ± 0.06                   | 22.00 ± 0.04      | 21.00 ± 0.13     | 1.31 ± 0.19        | 2.6 ± 0.3        | 29 ± 3          | 11.752 ± 0.037 | 11.153 ± 0.068 |
| NGC 5906     | 15:37:36.2       | +05:58:27       | 2.11 ± 0.05                     | 9.0 ± 1.0       | 0.30 ± 0.04                   | 21.00 ± 0.04      | 21.00 ± 0.13     | 0.89 ± 0.17        | 3.4 ± 0.3        | 40 ± 4          | 12.384 ± 0.058 | 11.794 ± 0.113 |
| IC 1291      | 18:33:52.5       | +49:16:42       | 6.02 ± 0.02                     | 9.3 ± 1.0       | 0.70 ± 0.09                   | 21.00 ± 0.04      | 21.00 ± 0.13     | 0.37 ± 0.08        | 2.4 ± 0.2        | 10.2 ± 1.0      | 13.125 ± 0.052 | 12.689 ± 0.152 |

Notes. Column 1: object name. Columns 2 and 3: R.A. and decl. (J2000.0) of the pointing center of the IRAM 30 m CO(1–0) observations. All measurements within a 21'' diameter circular aperture are centered on these coordinates. Column 4: H\(\alpha\) flux within a 21'' diameter circular aperture, corrected for Galactic extinction and N\(\pi\) emission. We quote only measurement uncertainties here. Column 5: PAH flux density within a 21'' diameter circular aperture. Column 6: integrated H\(\alpha\) line intensity within a 21'' diameter circular aperture, measured from image convolved to have beam major and minor axes given in Columns 7 and 8. Columns 7 and 8: beam major and minor axes of image used for H\(\alpha\) line intensity measurement. Column 9: integrated CO(1–0) line intensity. Non-detections are quoted as 3\(\sigma\) upper limits. Column 10: 4.5 \(\mu\)m flux density within a 21'' diameter circular aperture. Column 11: total 4.5 \(\mu\)m flux density. Column 12: total J-band magnitude from 2MASS, corrected for Galactic extinction. Column 13: total \(K_s\)-band magnitude from 2MASS, corrected for Galactic extinction.
During the observation period, the weather conditions were generally good, with pointing better than 3′′. The typical system temperature was 300–500 K at 115 GHz and 500–1000 K at 230 GHz on the $T_B$ scale. At 115 GHz (230 GHz), the IRAM forward efficiency, $F_{\text{eff}}$, was 0.95 (0.91), the beam efficiency, $B_{\text{eff}}$, was 0.75 (0.54), and the half-power beam size is 21″ (11″). All CO spectra and line intensities are presented on the main beam temperature scale ($T_B$), which is defined as $T_{mb} = (F_{\text{eff}}/B_{\text{eff}}) \times T_B$. For the data reduction, we selected the observations with good quality (taken during satisfactory weather conditions and showing a flat baseline), averaged the spectra from the individual scans of the source, and subtracted a constant continuum for the CO(1–0) spectra and a linear continuum for the CO(2–1) spectra.

Figure 1 shows the CO spectra for the objects observed in 2007 May. The black spectrum shows the CO(1–0) data and the red spectrum shows the CO(2–1) data. We did not use the CO(2–1) data in this paper, but show it for completeness and to corroborate some of the weaker CO(1–0) detections. The CO(2–1) data in this paper, but show it for completeness and to corroborate some of the weaker CO(1–0) detections. The CO(1–0) line intensity within a 21″ diameter aperture (i.e., $I_{\text{H}_1}$) is given by

$$I_{\text{H}_1} = 6.07 \times 10^5 \frac{B_{\text{maj}} B_{\text{min}}}{I_{\text{H}_1}} [\text{Jy beam}^{-1} \text{ km s}^{-1}],$$

where $B_{\text{maj}}$ and $B_{\text{min}}$ are in arcseconds and now refer to the beam of the map on which we made the measurements. These values are listed in Table 2.

For the objects with $B_{\text{maj}} > 21″$, we assumed that the average line intensity within a 21″ beam is equal to the measured line intensity from our image with a larger beam. We estimated the uncertainty introduced by this assumption by convolving the integrated intensity maps of three objects with $B_{\text{maj}} < 21″$ such that the convolved beams match those of the 10 objects with $B_{\text{maj}} > 21″$. We measured the average line intensity within the 21″ diameter circular aperture and compared this to the true value measured from the map with a 21″ beam. We found that the line intensities in our test cases differ from the true values by up to 11% (in the case of the NGC 4519 beam, which has a $B_{\text{maj}} = 51″/91$) and by 4% on average. The test measurements both over and under estimate the true value depending on the emission distribution. Therefore, we included this in our uncertainty estimate, but make no correction.

The main contributors to the final uncertainty in our H I line intensities are flux calibration (5%), aliasing (up to 11% and described in Paper I), and using an image with a beam larger than 21″ to estimate the line intensity within 21″ (on average 4%). Not all objects are subject to the latter two uncertainties. Nonetheless, we conservatively assigned the quadrature sum of these uncertainties (13%) as the generic uncertainty associated with our H I line intensities within the 21″ diameter aperture.

NGC 6509 shows H I in absorption on the east side of the galaxy because it is in the foreground of the radio source 4C +06.63. The average line intensity within 21″ is unaffected because the eastern edge of the aperture and the western edge of the radio lobe are separated by about 20″.

2.2. VLA H I

2.2.1. Integrated H I Line Intensity

The H I 21 cm data for our sample were obtained from the VLA/Expanded VLA, operated by the National Radio Astronomy Observatory, for projects AZ0133 (carried out in 2001 August), AL0575 (carried out in 2002 June and November), AM0873 (carried out in 2006 October and November), and AM0942 (carried out in 2008 May and 2009 July and August). The galaxies were observed in the C or CnB configurations, which provide a nominal angular resolution of 13″. The channel width is generally 5.2 km s$^{-1}$. The observations and reductions are described further in Paper I. We measured the integrated H I line intensity from velocity-integrated intensity maps (with units of Jy beam$^{-1}$ km s$^{-1}$) created from naturally weighted data cubes. The beam major axis FWHM ($B_{\text{maj}}$) and minor axis FWHM ($B_{\text{min}}$) for each data cube are listed in Table 3 of Paper I.

Ten of our objects have $B_{\text{maj}}$ and $B_{\text{min}} < 21″$. To adjust the H I beam to match the CO(1–0) beam, we used the AIPS task CONVL to convolve the integrated intensity map so the output Gaussian beam has $B_{\text{maj}} = B_{\text{min}} = 21″$. To approximately match the H I beam to the CO(1–0) beam for the remaining 10 objects with $B_{\text{maj}} > 21″$ (on average, $B_{\text{maj}} = 29″$) and $B_{\text{min}} < 21″$, we either used the original integrated intensity map or convolved the map to have $B_{\text{min}} = 21″$ and the beam major axis approximately equal to the original $B_{\text{maj}}$.

Using the resulting maps, we measured the average H I line intensity in Jy beam$^{-1}$ km s$^{-1}$ within the 21″ diameter circular aperture ($I_{\text{H}_1}$) with the AIPS task IMEAN. These values are listed in Table 2. The integrated H I line intensity in K km s$^{-1}$ is given by

$$I_{\text{H}_1} \frac{B_{\text{maj}} B_{\text{min}}}{I_{\text{H}_1}} = 6.07 \times 10^5 [\text{Jy beam}^{-1} \text{ km s}^{-1}],$$

where $B_{\text{maj}}$ and $B_{\text{min}}$ are in arcseconds and now refer to the beam of the map on which we made the measurements. These values are listed in Table 2.

For the objects with $B_{\text{maj}} > 21″$, we assumed that the average line intensity within a 21″ beam is equal to the measured line intensity from our image with a larger beam. We estimated the uncertainty introduced by this assumption by convolving the integrated intensity maps of three objects with $B_{\text{maj}} < 21″$ such that the convolved beams match those of the 10 objects with $B_{\text{maj}} > 21″$. We measured the average line intensity within the 21″ diameter circular aperture and compared this to the true value measured from the map with a 21″ beam. We found that the line intensities in our test cases differ from the true values by up to 11% (in the case of the NGC 4519 beam, which has a $B_{\text{maj}} = 51″/91$) and by 4% on average. The test measurements both over and under estimate the true value depending on the emission distribution. Therefore, we included this in our uncertainty estimate, but make no correction.

The main contributors to the final uncertainty in our H I line intensities are flux calibration (5%), aliasing (up to 11% and described in Paper I), and using an image with a beam larger than 21″ to estimate the line intensity within 21″ (on average 4%). Not all objects are subject to the latter two uncertainties. Nonetheless, we conservatively assigned the quadrature sum of these uncertainties (13%) as the generic uncertainty associated with our H I line intensities within the 21″ diameter aperture.

NGC 6509 shows H I in absorption on the east side of the galaxy because it is in the foreground of the radio source 4C +06.63. The average line intensity within 21″ is unaffected because the eastern edge of the aperture and the western edge of the radio lobe are separated by about 20″.

2.2.2. Epicyclic Frequency

We calculated a representative epicyclic frequency ($\kappa$) for the 21″ diameter circular aperture to use in the stability analysis of Section 4.3. We used $\kappa = \sqrt{2(1 + \beta)} (v/r)$, where $\beta = d\log(v)/d\log(r)$. We determined $\beta$ and the rotation velocity, $v$, at a radius, $r$, of 5′′.25 (half the radius of the 21″ diameter aperture) from the H I rotation curves presented in Paper I, where we fit a tilted ring model to the data to derive $v$ at radii every ($B_{\text{maj}}B_{\text{min}}/2)^{0.5}$, beginning at ($B_{\text{maj}}B_{\text{min}}/2)^{0.5}$. We simply fit a line between the origin and the first point in the rotation curve, the average radius of which is 8′′.3. We used the slope of the line as an estimate of $dv/dr$ and evaluated $v$ at 5′′.25. There may be inaccuracies introduced to $\kappa$ evaluated in this manner because the origin and first point in the rotation curve are within a single beam. Therefore, we also calculated the epicyclic frequency at 10′′.5 using the same method as above.
but by fitting the line between the first and second points from the rotation curve, where the average second radius is 25\arcsec. The epicyclic frequencies calculated at 10\arcsec.5 are smaller than the values at 5\arcsec.25 by 30% on average. We used the epicyclic frequencies evaluated at 5\arcsec.25 in our stability analysis (and list these in Table 4), but include 30% uncertainties on the values. Beam smearing, where many velocity components are within the spatial beam, is likely in effect in this region. Beam smearing leads to underestimated velocities and gradients (Swaters 1999) and therefore $\kappa$ may also be underestimated. To account for this, we use $\kappa$ evaluated at 5\arcsec.25, as these values are larger.

Figure 1. CO(1–0) (black) and CO(2–1) (red) spectra for the objects observed in 2007 May. See Böker et al. (2003) for the remaining spectra. The black horizontal line designates the velocity range over which we integrated to derive the CO(1–0) line intensity. ESO 544-G03, ESO 418-G008, ESO 501-G023, and UGC 644 do not have this line because they were undetected. The dashed horizontal line is centered on the systemic velocity derived from velocity field modeling of our H\textsc{i} data, and has a width of $W_{20}$, which we derived from the integrated H\textsc{i} line profile.

(A color version of this figure is available in the online journal.)
2.3. MDM H\textalpha{}

H\textalpha{} and continuum images of the galaxies were obtained at the MDM 2.4 m Hiltner telescope over the course of observing runs in 2007 January, 2007 November, 2007 May/June, and 2008 January. Each galaxy was observed for between 30 minutes and 2.5 hr through a pair of matched, custom-made 15 nm wide narrowband filters centered at 663 nm and 693 nm, hereafter the 663bp15 and 693bp15 filters, respectively. The H\textalpha{} emission line falls within the 663bp15 bandpass for all of the galaxies in this sample. Observations were obtained with the Direct CCD camera “Echelle,” which has 2048×2048 pixels. The CCD was binned over 2×2 pixels to produce a plate scale of 0.55 pixel\(^{-1}\), which was well matched to the 1′′–1.5′′ image quality measured on most nights. The field of view was 9′. Conditions were photometric for most of the observations and a series of spectrophotometric standards were observed for flux calibration, as were a series of twilight flats. The exposure times and observation dates are listed in Table 3.

Overscan subtraction, flat fielding, cosmic-ray rejection, and bad pixel removal were performed with IRAF.\(^9\) All of the 663bp15 and 693bp15 images of each galaxy were registered to a common coordinate system with SCAMP (Bertin 2006) and a combined image for each filter was constructed with SWARP (Bertin et al. 2002).

Observations of spectrophotometric standard stars were used to determine the absolute flux calibration for the 663bp15 filter (including an airmass correction) and the relative throughput of the two filters. We calculated the expected ratio of stellar flux in these filters for late-type galaxies by using the SYNPHOT package in IRAF to convolve the filter transmission functions with a series of stellar population synthesis models (e.g., Bruzual & Charlot 2003) with both continuous and exponentially declining (\(\tau = 1\) Gyr) star formation histories. The range of flux ratios from these models and the relative throughput of the two filters were used to scale the 693bp15 image and subtract it from the 663bp15 image to create an H\textalpha{} image for each galaxy.

We measured the H\textalpha{} flux for each galaxy within the 21″ diameter circular aperture and within a circle of diameter \(D_{25}\), the \(B\)-band major isophotal diameter at 25 mag arcsec\(^{-2}\), with aperture photometry. All H\textalpha{} flux measurements were multiplied by a factor of 0.75 to account for emission from [N\textsc{ii}] \(\lambda\lambda 6548, 6584\) in the 663bp15 bandpass (Kennicutt 1983). The H\textalpha{} flux measurements were also corrected for Galactic extinction using the extinction law of O'Donnell (1994) assuming \(R_V = 3.1\) and

\(^9\) IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy (AURA) under cooperative agreement with the National Science Foundation.
reddening values from Schlegel et al. (1998) and tabulated on NED. The final values within the 21″ aperture are listed in Table 2.

A number of our galaxies show substantial variation in the Hα flux within the 21″ aperture if we vary the center of the aperture by the ~2″–3″ pointing accuracy of the IRAM 30m. Including this uncertainty, as well as uncertainty in the [N II] correction and absolute calibration uncertainties, we estimate the uncertainty in the Hα flux within the 21″ diameter aperture to be about 30%.

Figure 2 compares our Hα fluxes measured within $D_{25}$ relative to published values from Koopmann et al. (2001), James et al. (2004), Moustakas & Kennicutt (2006), and Epinat et al. (2008), where we corrected the published values for [N II] emission and Galactic extinction if necessary. Our values are on average 20% smaller than the published values. This systematic offset is comparable to our calibration uncertainty and may be due to differences in the filter profiles, the angular extent of the apertures, and the treatment of bright stars with potentially large subtraction residuals. We note that this offset corresponds to an uncertainty in the SFR surface density of less than 0.1 dex, which is smaller than the 0.2 dex uncertainty that we assign due to the variable contribution to dust heating from non-star-forming populations.

2.4. Spitzer IRAC

Fourteen of the twenty galaxies were observed as part of our Spitzer Cycle 5 Program 50102; the remaining six (NGC 337, UGC 1862, ESO 418-G008, NGC 2805, NGC 4519, and NGC 4561) were observed for various other programs. Observations for Program 50102 consisted of five, dithered observations with a frame time of 30 s in all four IRAC channels (3.6 μm, 4.5 μm, 5.8 μm, and 8 μm). Data for the other six archival data sets were comparable to our observations, with the exception that the data for UGC 1862 only include the galaxy in channels 2 and 4. In the analysis described below, we use the channel 1, 2, and 4 data.

The basic calibrated data for all 20 galaxies were processed with Sean Carey’s artifact mitigation software, which corrects for a variety of effects such as muxbleed, column pulldown/pullup, electronic banding, and first frame effect. We then created mosaics for each channel with the Spitzer Science Center’s MOPEX (MOasicker and Point source EXtractor) package. This package corrects individual images for background variations and optical distortions, and then projects them onto an output mosaic image for each channel. These mosaic images were used for five measurements for each galaxy: the inclination ($i$), position angle of the major axis (P.A.), the PAH flux density, the 4.5 μm flux density, and the exponential disk scale length.

2.4.1. Inclination and Position Angle

We estimated the inclination and P.A. for each galaxy with the IRAF e11ips task, which fits elliptical isophotes with the iterative method described by Jedrzejewski (1987). The 3.6 μm data (4.5 μm for UGC 1862) were fit because this channel has the greatest sensitivity to the old stellar population, yet is relatively insensitive to dust.

We found that the isophote fits, particularly in the outer, low-surface brightness regions, were relatively sensitive to the presence of bright stars. We therefore created masks of these stars with the SExtractor package (Bertin & Arnouts 1996) and included this mask as an input to the e11ips task. These masks also excluded regions with relatively poor coverage in the IRAC mosaic. We averaged the P.A. and ellipticity values for the largest isophotes to derive our final P.A.s and inclinations. These values were used as inputs for the rotation curve analysis described in Paper I and were reported in Table 5 of that work.

2.4.2. PAH Flux Density

We calculated the PAH flux density within the 21″ diameter circular aperture using the 8 μm images, which are dominated by the 7.7 and 8.6 μm PAH features, and the stellar emission-dominated 3.6 μm images. We measured the 8 μm and 3.6 μm flux densities using the IRAF task phot. In both measurements, we subtracted from each pixel the median sky background, which we measured within a large-radius annulus centered on the galaxy. We applied the band-specific extended source aperture correction to the 8 μm and 3.6 μm flux densities (described in the IRAC Instrument Handbook; for the 21″ diameter circular aperture, the correction is 0.985 and 0.896 for the 3.6 μm and 8 μm bands, respectively). Finally, the PAH flux density is the 8 μm flux density less the stellar emission contribution, which we estimated by scaling the 3.6 μm flux density by 0.255 (as used in Kennicutt et al. 2009). For UGC 1862, we used the 4.5 μm flux density, scaled by a factor of 0.389, to remove the stellar contribution to the 8 μm band. This scale factor is derived from values quoted in Helou et al. (2004), except we assumed that all the 4.5 μm band emission is stellar. The uncertainties on the calibrated 3.6 μm and 8 μm flux densities are about 10% (Hora et al. 2004). We quote PAH flux density uncertainties that are simple error propagated values. Our PAH flux densities are presented in Table 2.

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The NASA/IPAC Extragalactic Database (NED) is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

10 The NASA/IPAC Extragalactic Database (NED) is operated by the Jet

11 http://spider.ipac.caltech.edu/staff/carey/irac_artifacts/
2.4.3. 4.5 μm Flux Density

We calculated the total 4.5 μm flux density and the flux density within the 21′′ diameter circular aperture such that we can derive the total stellar mass and the stellar mass surface density within a 21′′ diameter aperture. Column 3: H2 mass surface density (M⊙ pc−2). The typical uncertainty is 0.06 dex. Column 4: H2 mass surface density (M⊙ pc−2), computed with XH2 = 2.8 × 1020 cm−2 (K km s−1)−1. The typical uncertainty is 0.07 dex. Column 5: SFR surface density, computed assuming the Kroupa-type IMF from Calzetti et al. (2007); M⊙ yr−1 kpc−2. We assume a typical uncertainty of 0.2 dex. Column 6: stellar mass surface density (M⊙ pc−2). We assign a typical uncertainty of 0.2 dex. Column 7: total stellar mass (M⊙). We assign typical uncertainty of 0.3 dex. Column 8: oxygen abundance derived from the total stellar mass and the mass-metallicity relation of Tremonti et al. (2004). We derive a typical statistical uncertainty of 0.11 dex, but note that strong-line metallicity methods return 12 + log(O/H) values as disparate as 0.5 dex. Column 9: stellar scale length (kpc). We estimate the uncertainty to be 20%. Column 10: epicyclic frequency (km s−1 pc−1), evaluated at 5′′25. We estimate the uncertainty to be 30%. Column 11: gas stability parameter. The typical uncertainty is 30%. Column 12: stellar stability parameter. The typical uncertainty is 60%. Column 13: combined gas and stellar stability parameter. The typical uncertainty is 40%. Column 14: mid-plane pressure (K cm−1). The typical uncertainty is 0.17 dex.

2.4.4. Exponential Disk Scale Length

We estimated the exponential scale length of each galaxy using the IRAF el11ps model task on the 4.5 μm data, allowing the center, P.A., and ellipticity to vary as a function of SMA. We fit an exponential to the mean isophotal intensity profile to derive the central surface brightness and scale length. We excluded PSF and/or bar components from the profile fit based on visual examination of the images and a provisional GALFIT (Peng et al. 2002) analysis. We created a two-dimensional image representing the el11ps model profile with bmodl1, subtracted the model from the original image, and found that the standard deviation in the region of the galaxy within the residual image is typically less than about 10 times the standard deviation in a galaxy-free region of the original image. Given the small scale structures present in most of the galaxies, we accepted these values and fits. The scale lengths are listed in Table 2 and are between 0.69 and 3.4 kpc.

We assigned an error of 20% to the scale lengths based on the comparison of the scale lengths computed as described above to scale lengths computed from ellipse runs where we held the...
P.A. and ellipticity fixed as a function of SMA at the values from Table 1. We confirmed that scale lengths derived from the 3.6 μm data are generally consistent with the values derived from the 4.5 μm data within the uncertainty (they differ by 9% on average).

3. DERIVED QUANTITIES

For all the surface density calculations below, we used the 21″ diameter aperture, to match the beam of our CO(1–0) data from IRAM. Table 4 lists the physical size of 21″ (0.7–3.2 kpc) and the parameters derived in the following sections. The surface densities are all within the deprojected area of the aperture, which we calculated with the inclinations from Table 1.

3.1. Atomic, Molecular, and Total Hydrogen Surface Density

The H\textsc{i} surface density is given by

$$\Sigma_{H\text{i}} [M_\odot \text{pc}^{-2}] = 0.015 \langle I_{H\text{i}} \rangle \cos(i),$$

(2)

where \( \langle I_{H\text{i}} \rangle \) is the integrated \( H\text{i} \) line intensity within the 21″ diameter circular aperture in K km s\(^{-1}\) from Section 2.2.1. We did not include a correction for He. The \( \Sigma_{H\text{i}} \) uncertainty is dominated by the contribution from the line intensity uncertainty and the typical uncertainty in \( \log(\Sigma_{H\text{i}}) \) is 0.06 dex. The \( H_2 \) surface density is given by

$$\Sigma_{H_2} [M_\odot \text{pc}^{-2}] = 3.2 \frac{X_{\text{CO}}}{2.0 \times 10^{20} \text{cm}^{-2} (\text{K km s}^{-1})^{-1}} I_{\text{CO}} \cos(i),$$

(3)

where \( X_{\text{CO}} \) is the CO-to-\( H_2 \) conversion factor and \( I_{\text{CO}} \) is the CO line intensity in K km s\(^{-1}\) from Section 2.1. We used a constant \( X_{\text{CO}} \) of \( 2.8 \times 10^{20} \text{cm}^{-2} (\text{K km s}^{-1})^{-1} \). We used this value rather than the Milky Way value of \( 2.0 \times 10^{20} \text{cm}^{-2} (\text{K km s}^{-1})^{-1} \) so we can plot the Kennicutt (1998) total hydrogen star formation law relative to our data. Again, we did not include a correction for He.

The typical uncertainty in \( \log(\Sigma_{H_2}) \) is 0.07 dex, due mainly to the CO line intensity uncertainty. We did not include uncertainty due to \( X_{\text{CO}} \). Leroy et al. (2011) studied five local group galaxies and concluded that \( X_{\text{CO}} \) is relatively constant at the solar value for \( 12 + \log(O/H) \gtrsim 8.4 \) and increases with decreasing oxygen abundance below \( 12 + \log(O/H) \sim 8.2–8.4 \). We have only one galaxy where we estimated that the oxygen abundance is below \( 12 + \log(O/H) = 8.4 \) (Section 3.3), so we do not expect much \( X_{\text{CO}} \) variation in our sample.

We also use the total hydrogen surface density, \( \Sigma_{H_1+H_2} = \Sigma_{H_1} + \Sigma_{H_2} \). The typical uncertainty in \( \log(\Sigma_{H_1+H_2}) \) is 0.05 dex.

3.2. Star Formation Rate Surface Density

We used \( H\alpha \) emission to trace the unobscured SFR and PAH emission to trace the obscured SFR. The \( H\alpha \) emission is due to recombination in H\text{II} regions, which are ionized by O and early B stars. PAHs are small dust grains (or large molecules) that are primarily excited by single UV photons (Sellgren 1984; Leger & Puget 1984). Because ionizing radiation is not required to heat PAHs (and in fact there is evidence that ionizing radiation destroys PAHs; Helou et al. 2004; Peeters et al. 2004), PAH emission traces lower-mass, longer-lived stars than those ultimately responsible for the \( H\alpha \) emission. PAH emission has been used to trace the total SFR (e.g., Zhu et al. 2008), but there is variation in the 8 μm luminosity at a given SFR due to environment, especially metallicity (e.g., Calzetti et al. 2007). Kennicutt et al. (2009) used 75 galaxies to calibrate SFR estimates based on \( H\alpha \) and PAH emission by comparing the combined \( H\alpha \) and PAH luminosity to the \( H\alpha \) luminosity corrected for extinction using the Balmer decrement. The authors found that SFRs calculated with \( H\alpha \) and PAH emission agreed with their reference SFRs with as little scatter as SFRs calculated with \( H\alpha \) and 24 μm emission. We used the SFR calibration of Kennicutt et al. (2009) to calculate the SFR surface density within the 21″ diameter circular aperture:

$$\Sigma_{\text{SFR}} [M_\odot \text{yr}^{-1} \text{kpc}^{-2}] = 7.30 \times 10^{10} (F_{H\alpha} + 1.1 \times 10^{-28} \nu F_{\text{PAH}}) \cos(i),$$

(4)

where \( F_{H\alpha} \) and \( F_{\text{PAH}} \) are the \( H\alpha \) flux in erg s\(^{-1}\) cm\(^{-2}\) and the PAH flux density in mJy within the 21″ diameter circular aperture, \( \nu \) is the central frequency of the 8 μm IRAC band in Hz, and the constant includes the aperture area. This assumes the initial mass function (IMF) from Calzetti et al. (2007), which is similar to that presented in Kroupa (2001). The Kennicutt et al. (2009) SFR was calibrated for galaxy-averaged data, but should be appropriate for our data because we generally probe regions that are a couple of square kpc in area and should therefore contain a number of star-forming regions. Even using both \( H\alpha \) and PAHs to trace the SFR, galaxies with low metallicity could have underestimated SFRs because the fraction of dust mass in PAHs decreases at low metallicity, particularly below \( Z/\odot = 8.3 \); Draine et al. 2007; Smith et al. 2007. In the following section, we estimate the oxygen abundance of each galaxy from the stellar mass and find that only one galaxy (ESO 501-G023) has \( 12 + \log(O/H) < 8.3 \). Therefore, we do not expect significant SFR underestimates in our sample.

Kennicutt et al. (2009) discussed that the dominant source of uncertainty in their SFRs is due to varying contributions to dust heating from older stellar populations (\( \gtrsim 100 \) Myr). Based on their suggestions, and including the fact that our sample has a limited range in morphology and therefore star formation history, we assigned a general uncertainty of 0.2 dex to our SFR surface densities. This dominates over the contribution due to \( H\alpha \) flux and PAH flux density measurement uncertainties.

In upcoming sections, we use the SFE defined as \( \Sigma_{\text{SFR}} / \Sigma_{H_1+H_2} \) in yr\(^{-1}\). The typical uncertainty in the SFE is 0.2 dex.

3.3. Stellar Mass Surface Density, Total Stellar Mass, and Oxygen Abundance

We derived the stellar mass surface density within the 21″ diameter circular aperture and the total stellar mass from the 4.5 μm flux densities. We chose to use the 4.5 μm data over the 3.6 μm data because there are no PAH emission features in the 4.5 μm band.

To estimate the stellar mass, we used a relationship between K-band mass-to-light ratio and color from Bell & de Jong (2001), derived from stellar population synthesis modeling:

$$\log(\Upsilon_*) = 1.43(J - K_s) - 1.53,$$

(5)

where \( \Upsilon_\ast \) is the mass-to-light ratio in the K band in \( M_\odot /L_{K_\odot} \), \( L_{K_\odot} \) is the solar luminosity in the K band, and the J and K\text{s} magnitudes are from the Two Micron All Sky Survey (2MASS; mainly the Extended Source Catalog, but three galaxies are in the Large Galaxy Atlas of Jarrett et al. 2003) and are listed in Table 2. The original relationship uses Johnson K magnitudes, but use of K\text{s} magnitudes does not introduce significant error to the mass. This relation is a linear combination of the...
with the rest of our analysis. We derive an average uncertainty in $12 + \log(O/H)$ of 0.11 dex.

### 3.4. Stability Parameters and Mid-plane Pressure

In Section 4.3, we study trends between SFE and stability, parameterized by a generalized Toomre $Q$ parameter (Toomre 1964; Rafikov 2001). We calculated the stability parameters within the 21' diameter circular aperture. The stability parameter for the gas and stellar components of the disk are

$$Q_{\text{gas}} = \frac{k \sigma_{\text{gas}}}{\pi G \Sigma_{\text{gas}}}$$

and

$$Q_{\text{stars}} = \frac{k \sigma_{\text{stars}}}{\pi G \Sigma_{\text{stars}}}$$

respectively, where $\kappa$ is the epicyclic frequency and $\sigma_{\text{gas}}$ and $\sigma_{\text{stars}}$ are the gas and radial stellar velocity dispersions. Rafikov (2001) calculated the stability parameter that includes both gas and stars in a thin rotating disk:

$$\frac{1}{Q_{\text{gas+stars}}} = \frac{2}{Q_{\text{stars}}} \frac{q}{1+q^2} + \frac{2}{Q_{\text{gas}}} \frac{R}{1+q^2} \frac{q}{R^2}$$

where

$$q = k \frac{\sigma_{\text{stars}}}{\kappa}, \quad R = \frac{\sigma_{\text{gas}}}{\sigma_{\text{stars}}},$$

and $k$ is a free parameter that represents the wavenumber of the perturbation. In all cases, the instability condition is when $Q < 1$ (except, strictly speaking, $Q_{\text{stars}} < 1.07$). Romeo & Wiegert (2011) included disk thickness in the stability estimation by incorporating a factor related to the ratio of the vertical to radial velocity dispersion, but we settled on the Rafikov (2001) parameter for ease of comparison with other works.

We generally made similar assumptions for the components of $Q$ as Leroy et al. (2008). We assumed $\sigma_{\text{gas}} = 11$ km s$^{-1}$ which is appropriate for the warm neutral medium, $\sigma_{\text{stars}} = 1.67 \sigma_{\text{gas}}$, and $\sigma_{\text{gas}} = (2\pi G M_{\bullet}/7.3)^{0.5}$, where $\sigma_{\text{gas}}$ is the vertical stellar velocity dispersion and $l_\bullet$ is the stellar scale length (Tamburo et al. 2009; Shapiro et al. 2003; van der Kruit & Searle 1981; van der Kruit 1988). This equation assumes that the disk is isothermal in the $z$-direction, $h_\bullet$ is constant as a function of radius, and $l_\bullet/h_\bullet = 7.3$ (as observed by Kregel et al. 2002), where $h_\bullet$ is the stellar scale height. Note that the latter two assumptions are not in conflict with a sample like Dalcanton et al. (2004) because those authors found only a transition in dust scale height with circular velocity, not in stellar scale height. We used the scale lengths and stellar mass surface densities from Sections 2.4.4 and 3.3 to derive $\sigma_{\text{stars}}$ values between 9 and 78 km s$^{-1}$.

For $\Sigma_{\text{gas}}$, we multiplied the total-hydrogen surface density ($\Sigma_{\text{H}} + \Sigma_{\text{He}}$) by a factor of 1.36 to include helium. For $\Sigma_\star$, we used the value derived in Section 3.3. For the epicyclic frequency, we used the value from Section 2.2.2, evaluated at 5'25. For the wavenumber of the perturbation, $k = 2\pi r/\lambda$, where $\lambda$ is the wavelength of the perturbation, we used the common method of varying $\lambda$ to find the minimum $Q_{\text{gas+stars}}$ ($Q_{\text{gas+stars,min}}$) for the region (e.g., Yang et al. 2007; Yim et al. 2011). This typically results in smaller, less stable $Q_{\text{gas+stars}}$ compared with $Q_{\text{gas}}$ and $Q_{\text{stars}}$. We found $\lambda = 0.5–3.8$ kpc at $Q_{\text{gas+stars,min}}$. We propagated the uncertainties in $\kappa$, $l_\bullet$, $\Sigma_{\text{gas}}$, and $\Sigma_\star$ to derive a typical uncertainty in $Q_{\text{gas}}$ of 30%, in $Q_{\text{stars}}$ of 60%, and in $Q_{\text{gas+stars}}$ of 40%.

We also calculated the mid-plane pressure ($P_h$) with the following equation from Elmegreen (1989):

$$P_h \approx \frac{\pi}{2} G \Sigma_{\text{gas}} \frac{\Sigma_{\text{gas}} + \sigma_{\text{gas}}}{\sigma_{\text{gas}}}.$$
We propagated the uncertainties in \( l_\star, \Sigma_{\text{gas}} \), and \( \Sigma_\star \) to derive a typical uncertainty in \( P_\text{H}_\text{o} \) of 40%. 

4. RESULTS

4.1. Bulgeless Disk Galaxies on the Kennicutt–Schmidt Law

In this section, we determine whether our galaxy sample follows the various versions of the Kennicutt–Schmidt law, i.e., the relation between the surface density of gas (atomic, molecular, or the sum of both) and SFR (Sections 4.1.1–4.1.3). In Section 4.2, we use these results to show that there is no transition in SFE at a circular velocity of 120 km s\(^{-1}\) or at any other circular velocity probed by our sample (\( v_{\text{circ}} = 46–190 \text{ km s}^{-1} \)). The circular velocities were derived from \( \text{H}_\text{i} \) rotation curve fits in Paper I and we include them in Table 1 for convenience.

4.1.1. Atomic Hydrogen Kennicutt–Schmidt Law

Figure 3 shows the relationship between the SFR surface density and the atomic hydrogen surface density within the 21\(^{\prime}\) diameter circular aperture, which corresponds to physical diameters of 0.7–3.2 kpc. Red squares denote galaxies with \( v_{\text{circ}} < 120 \text{ km s}^{-1} \) and blue triangles denote galaxies with \( v_{\text{circ}} > 120 \text{ km s}^{-1} \). The vertical dashed line is at 9 \( M_\odot \) pc\(^{-2}\), the typical maximum density for atomic hydrogen. For comparison, we have shown as small dots the 750 pc diameter regions from the seven spiral galaxies studied in Bigiel et al. (2008) and Leroy et al. (2008). Consistent with our assumptions, Bigiel et al. (2008) used the same Kroupa-type IMF and do not include He in their gas surface densities. An important difference between our data sets is that Bigiel et al. (2008) derived their SFR surface densities from a combination of FUV (1350–1750 Å) and 24 \( \mu \text{m} \) data while we use \( \text{H}_\alpha \) and PAH emission.

The Spearman rank correlation coefficient for our data is 0.5. For comparison, the coefficient for the Bigiel et al. (2008) data is 0.4. Our data are more correlated than the Bigiel et al. (2008) data, primarily because our sample includes several galaxies with large \( \text{H}_\text{i} \) surface densities.

4.1.2. Molecular Hydrogen Kennicutt–Schmidt Law

Figure 4 shows the relationship between the SFR surface density and the molecular hydrogen surface density. The symbols are as in Figure 3. The solid line shows the Bigiel et al. (2008) fit to the molecular hydrogen star formation law: \( \Sigma_{\text{SFR}} \propto \Sigma_{\text{H}_2} \). We discuss the offset of our data relative to this fit in Section 4.1.2.

(A color version of this figure is available in the online journal.)
We assume a slope of 1.0, calculate the intercept, and repeat this process 10⁶ times. We find that the probability of measuring a intercept greater than or equal to −3.0 is 4 × 10⁻⁶.

We can exclude two possible reasons for the offset. First, the offset is not likely due to the measurements being central values because we confirmed that the centers of the Bigiel et al. (2008) galaxies are not offset from the general trend (this can also be seen in Figure 10 of Bigiel et al. 2008). Second, our assumption of a single CO-to-H₂ conversion factor probably does not lead to underestimated molecular surface densities because our sample includes only one galaxy for which X_{CO} may be underestimated because of a low oxygen abundance, as discussed in Section 3.1. Furthermore, we do not find that galaxies with lower stellar mass, and by implication lower-oxygen abundance (down to 12 + log(O/H) = 8.25) galaxies are offset to higher molecular SFR in their study of 33 galaxies with directly measured oxygen abundances. They discussed that more observations are needed to determine whether the offset is due to X_{CO} variation or whether it represents true SFE variation.

The quoted Bigiel et al. (2008) intercept uncertainty (0.2 dex) takes into account variations in star formation tracers, uncertainty introduced by estimating the CO(1–0) line intensity from CO(2–1) data, and scatter in the data. The first of these is particularly relevant in comparing our data sets because we trace star formation with Hα and PAH data and Bigiel et al. (2008) trace star formation with FUV and 24 μm data. Our intercept is larger than the Bigiel et al. (2008) intercept by only 1.2σ, if we take their error bar as σ. In summary, our data are significantly offset from the Bigiel et al. (2008) fit to the molecular hydrogen star formation law in terms of statistical uncertainties, but are nearly consistent if systematic errors are included.

Kennicutt et al. (2007) discussed that offsets are expected between star formation laws derived from observations at different spatial resolution if the power-law index of the star formation law is not equal to one (Σ_{SFR} ∝ Σ_{gas}^N with N ≠ 1). In transitioning from high to lower resolution, the SFR and gas surface density will be decreased by approximately the same factor. If N = 1, the lower resolution data will still lie on the same relation as the higher resolution data, but at lower gas and SFR surface densities. In contrast, if N > 1 (N < 1), the lower resolution observations will be positively (negatively) offset from the higher resolution observations. This effect could contribute to our observed offset if N > 1 because our data probe up to 3.2 kpc scales and the Bigiel et al. (2008) data have 750 pc resolution. We cannot provide a firm explanation for the offset between our data and the Bigiel et al. (2008) fit, but possible reasons for the offset include the use of different star formation tracers and resolutions, X_{CO} variation, and true SFE differences.

4.1.3. Total Hydrogen Kennicutt–Schmidt Law

Figure 5 shows the relationship between the SFR surface density and the total hydrogen surface density. The vertical dashed line again shows the typical maximum H₁ density that is observed in most nearby galaxies. The Spearman rank correlation coefficient for our data and also the Bigiel et al. (2008) data is 0.8. This correlation is stronger than the correlation between SFR surface density and either atomic or molecular hydrogen surface density. In their study of star formation in the atomic-dominated regime, Schruba et al. (2011) found that the rank correlation coefficient between SFR surface density and total hydrogen surface density is similar to or somewhat larger than the value for the correlation with the molecular hydrogen surface density. However, they noted that data can be correlated with a strong rank statistic even if the parameters are related by different functions in the atomic- and molecular-dominated regimes. As in the Schruba et al. study, our stronger total hydrogen correlation is not likely related to fundamental physics.

The solid black line shows the Krumholz et al. (2009) model with 0.4 Z⊙ metallicity. The model assumes a clumping factor, c, that is the inverse of the filling factor of ~100 pc sized atomic–molecular complexes in the beam. This value is not constrained well by data, so we assume the same value as Krumholz et al. (2009): c = 5. The magenta dot-dashed line shows the Kennicutt (1998) fit to a sample of normal and starburst galaxies, where the measurements are averages over the entire optical disk. The blue dotted line shows the Kennicutt et al. (2007) fit to regions in M51 that were studied at 520 pc resolution. Kennicutt et al. (2007) attribute the offset between the blue and magenta lines to dilution effects when the power-law index of the star formation law is not 1.0 (as discussed in Section 4.1.2).

4.2. No Transition in SFE with Circular Velocity

In Section 1, we discussed that there could be an SFE transition in bulgeless disk galaxies at v_{circ} = 120 km s⁻¹, depending on the star formation model assumed. In this section, we show that there is no offset between the low- and high-v_{circ} galaxies on the star formation law. In Section 5, we interpret this result to discuss the relationship between SFE and the scale height of the cold ISM.

In Figures 3–5, there is a slight trend for low-v_{circ} galaxies to lie at lower surface densities compared with high-v_{circ} galaxies, with average low- versus high-v_{circ} surface densities...
as follows: $\log(\Sigma_{\text{H}_1}) = 0.9$ versus 1.0, $\log(\Sigma_{\text{H}_2}) < 0.6$ versus 0.9, $\log(\Sigma_{\text{H}_1+\text{H}_2}) = 1.1$ versus 1.2, and $\log(\Sigma_{\text{SFR}}) = -2.4$ versus -2.2. However, the differences are not significant; the Kolmogorov–Smirnov (K-S) test probabilities that the low-versus high-$v_{\text{circ}}$ galaxies are drawn from the same population in $\Sigma_{\text{H}_1}$, $\Sigma_{\text{H}_1+\text{H}_2}$, and $\Sigma_{\text{SFR}}$ are 0.04, 0.2, and 0.2, respectively.

Figure 6 shows the distribution of SFE in the low-$v_{\text{circ}}$ (red solid) and high-$v_{\text{circ}}$ (blue dashed) galaxies. If the slope of the star formation law is not 1.0, a sample that follows the relation would have SFE that varies as a function of $\Sigma_{\text{H}_1+\text{H}_2}$, which will tend to broaden the distributions. However, our low- and high-$v_{\text{circ}}$ objects have similar $\Sigma_{\text{H}_1+\text{H}_2}$ distributions, so this should not lead to spurious offsets between the samples. Furthermore, the $\Sigma_{\text{H}_1+\text{H}_2}$ range is not so great that it would hide any differences between the samples. We find no significant difference between the SFE distributions, with a K-S test probability of 0.8 that the low- and high-$v_{\text{circ}}$ galaxies are drawn from the same population.

We conclude that our sample of bulgeless disk galaxies does not show a strong transition in SFE at $v_{\text{circ}} = 120$ km s$^{-1}$, where Dalcanton et al. (2004) concluded that there is a strong transition in dust scale height. In Figure 7, we show that there is no circular velocity at which there is a transition in SFE. Furthermore, there is no strong trend of SFE with circular velocity within the range we probe. Finally, we find no difference in the ratio of the molecular to atomic gas surface density between the low- and high-$v_{\text{circ}}$ galaxies (the K-S test probability that the samples are drawn from the same $R_{\text{mol}}$ population is 0.4) nor do we find a transition in $R_{\text{mol}}$ at any circular velocity (Figure 8).

### 4.3. SFE Trends with Stability and Mid-plane Pressure

In this section, we address whether our sample shows a transition or trends in stability or mid-plane pressure, using the $Q_{\text{gas}}$, $Q_{\text{stars}}$, $Q_{\text{gas}+\text{stars},\min}$, and $P_h$ values calculated in Section 3.4. Figure 9 shows the SFE versus $Q_{\text{gas}}$ (left), $Q_{\text{stars}}$ (middle), and $Q_{\text{gas}+\text{stars},\min}$ (right). We find no unstable regions. The SFE generally decreases with larger, more stable $Q$ values, although the correlation is not strong. For SFE versus $Q_{\text{gas}}$, $Q_{\text{stars}}$, and $Q_{\text{gas}+\text{stars},\min}$, we find Spearman rank correlation coefficients of -0.2, -0.3, and -0.2, respectively. The sign of this correlation is as expected, but one might instead have expected a sharp decrease in SFE when $Q$ rises above 1. These results are qualitatively similar to those in Leroy et al. (2008).

Dalcanton et al. (2004) concluded that galaxies with $v_{\text{circ}} < 120$ km s$^{-1}$ are generally stable while galaxies with $v_{\text{circ}} > 120$ km s$^{-1}$ are generally unstable, especially in the central ($r < l_e$) regions. Contrary to these results, we see no evidence for a transition in stability at $v_{\text{circ}} = 120$ km s$^{-1}$; the K-S test probability that the low- and high-$v_{\text{circ}}$ galaxies are drawn from the same population of $Q_{\text{gas}}$, $Q_{\text{stars}}$, and $Q_{\text{gas}+\text{stars},\min}$ is 0.5, 0.2, and 0.8, respectively.
There are two principal differences between our assumptions for the stability inputs and those in Dalcanton et al. (2004). First, we use a constant gas velocity dispersion and they used the quadrature sum of the velocity dispersion of atomic and molecular gas (10 and 5 km s\(^{-1}\), respectively), weighted by the relative mass surface densities of the components. We use these assumptions and still find no difference in stability between the low- and high-\(v_{\text{circ}}\) galaxies. Second, Dalcanton et al. (2004) estimated the molecular hydrogen surface densities for their sample from a scaling with circular velocity (\(\Sigma_{\text{H}_2} = (v_{\text{circ}}/47.1\ \text{km s}^{-1})^{2.49}\)). This scaling relation was derived from a similar sample of galaxies with \(\Sigma_{\text{H}_2}\) values from Rownd & Young (1999) and \(v_{\text{circ}}\) estimated from single-dish \(\text{H}\text{i}\) data. Molecular hydrogen surface densities calculated using the scaling with \(v_{\text{circ}}\) are too large by a factor of six for our sample of high-\(v_{\text{circ}}\) galaxies and too large by a factor of two for our sample of low-\(v_{\text{circ}}\) galaxies. This discrepancy leads to smaller, less stable \(Q_{\text{gas}}\) and \(Q_{\text{gas+stars}}\) in the high-\(v_{\text{circ}}\) galaxies relative to the low-\(v_{\text{circ}}\) galaxies. However, even under these assumptions there is no significant difference between the low- and high-\(v_{\text{circ}}\) galaxies in their \(Q\) values. Note that the difference in our molecular hydrogen surface densities compared with the values derived from the scaling with \(v_{\text{circ}}\) may also be related to resolution differences. Our \(\Sigma_{\text{H}_2}\) measurements are within the central 21" while the Rownd & Young (1999) data have 45" resolution and a similar distance distribution.

We test whether a stability transition occurs at any circular velocity in Figure 10, where we plot \(Q_{\text{gas+stars, min}}\) versus \(v_{\text{circ}}\). There is no circular velocity below which the regions are stable.
and above which the regions are unstable. If any trend is present, it is that higher circular velocity objects are more stable.

We plot the SFE versus the mid-plane pressure in Figure 11. As seen in Leroy et al. (2008), we find an increase in SFE with increasing mid-plane pressure, but we do not probe high enough $P_h$ values or have enough data points to sample the constant-SFE region of the diagram that is clear in Leroy et al. (2008). We find no difference between the low- and high-$v_{circ}$ galaxies in their $P_h$ distributions, with a K-S test probability of 0.7 that they are drawn from the same population. Even focusing only on galaxies with the same $\Sigma_{HI+H_2}$ (within the uncertainty in the parameter), the median pressure is the same in low- and high-$v_{circ}$ galaxies.

4.4. Dependence of Star Formation on Metallicity

In this section, we use the oxygen abundance estimated from the stellar mass to study how star formation depends on metallicity and compare these results to recent theoretical work by Krumholz et al. (2009). At a given total gas surface density, the Krumholz et al. (2009) model predicts lower SFE at lower metallicity because $H_2$ survival requires a higher column density as $H_2$ self-shielding becomes more important than shielding by dust. This metallicity dependence distinguishes the model from other leading models, such as the model where mid-plane pressure determines where the ISM is molecular.

The left panel of Figure 12 shows the total hydrogen star formation law, as plotted in Figure 5, except the galaxies are divided into low-(O/H) and high-(O/H), with the division at $12 + \log(O/H) = 8.7$. The orange solid and purple dashed lines show the model of Krumholz et al. (2009) at 0.1 $Z_\odot$ and 1.4 $Z_\odot$, respectively. These metallicities correspond to the extrema of our data set, assuming $Z/Z_\odot = (O/H)/(O/H)_\odot$ and $12 + \log(O/H)_\odot = 8.86$ (Delahaye & Pinsonneault 2006). We see no evidence that the low- and high-(O/H) galaxies cluster toward the low- and high-$Z$ models, respectively.

The right panel of Figure 12 shows the offset of our data from the 0.4 $Z_\odot$ Krumholz et al. (2009) model, which provides the best fit to our data set as a whole (although note that we would expect the best fit to be the 0.7 $Z_\odot$ model, as that corresponds to the average (O/H) of our full sample). The orange solid
and purple dashed lines show the distributions of our low-\((O/H)\) and high-\((O/H)\) galaxies, as divided in the left panel. If our data clearly followed the Krumholz et al. (2009) model, high-\((O/H)\) galaxies would be positively offset from the 0.4 \(Z_\odot\) model and low-\((O/H)\) galaxies would be negatively offset. We find no significant difference between the offset of the low-versus high-\((O/H)\) galaxies (the K-S test probability that the samples are drawn from the same offset population is 0.14). A second-order effect is that the offset from the 0.4 \(Z_\odot\) model is expected to decrease with increasing \(\Sigma_{HI+H_2}\). This may be related to the narrower offset distribution for the high-\((O/H)\) galaxies, which tend to have higher \(\Sigma_{HI+H_2}\).

Figure 13 shows that there is a correlation between SFE and oxygen abundance in our data. For comparison, the line represents the Krumholz et al. (2009) model, where the SFE depends on metallicity, \(\Sigma_{gas}\), and the filling factor. We have plotted the Krumholz et al. (2009) model with \(\log (\Sigma_{HI+H_2}) = 0.8\) (no He). This is a low \(\Sigma_{HI+H_2}\) value compared to our data. Higher \(\Sigma_{HI+H_2}\) models reach constant SFE at lower metallicity. The mismatch between the average \(\Sigma_{HI+H_2}\) in the data and the best-fit \(\Sigma_{HI+H_2}\) used in the model is likely due to our assumptions for \(X_{CO}\) and the IMF in the data, our filling factor assumption in the model, and to uncertainties in the metallicity scale. For the latter, various strong-line metallicity methods return 12 + \(\log (O/H)\) values as disparate as 0.5 dex (Kewley & Ellison 2008), and it is unknown which calibration best aligns with the solar value. Therefore, the model line in Figure 13 only represents the expected trend of lower SFE at lower metallicity, at a given \(\Sigma_{gas}\). At this level, the data do show the expected trend, with a Spearman correlation coefficient of 0.6. However, upon closer inspection, this agreement is mainly due to the fact that lower-\((O/H)\) galaxies tend to have lower \(\Sigma_{HI+H_2}\) (this is most obvious in Figure 12, although also note that the K-S test probability is 0.05 that the \(\Sigma_{HI+H_2}\) distributions of the low- and high-\((O/H)\) samples are drawn from the same population, which is not strong evidence for a difference). Because of their lower \(\Sigma_{HI+H_2}\) values, the low-\((O/H)\) galaxies are closer to the atomic-dominated regime of the star formation law where SFEs are lower. This is of course consistent with the Krumholz et al. (2009) model, but is not a discriminating test of the model because many other properties correlate with gas surface density (for examples, see Leroy et al. 2008). A sample with a range of directly measured metallicities within a small range of gas surface density would provide a more discriminating test. In summary, we see no clear evidence to support the Krumholz et al. (2009) model, but our data are also not inconsistent with it.

5. DISCUSSION

In Section 4.2, we found that there is no transition in molecular fraction or SFE at any circular velocity probed by our sample. In Section 4.3, we found that all our galaxies are formally stable. While we did find a general trend of decreasing SFE with larger, more stable \(Q\) values, we found no sharp transition in stability at any circular velocity. Finally in Section 4.4, we found that SFE decreases at lower oxygen abundance, but the trend is not particularly constraining test of the Krumholz et al. (2009) model. In this section, we first address our assumption that there is a transition in dust scale height at \(v_{circ} = 120\) km s\(^{-1}\), rather than a transition in dust content. We then interpret our results to discuss the relationship between SFE and the scale height of the cold ISM. Finally, we comment on the scale of physical processes that affect star formation and discuss our results in the context of leading star formation models.

5.1. A Transition in Dust Scale Height versus Dust Content

In this section, we investigate the argument that the dust structure transition observed by Dalcanton et al. (2004) is due to a transition in dust scale height rather than a transition in the amount of dust present. Dalcanton et al. (2004) came to this conclusion because the dust structure transition occurs over a narrow range in circular velocity, where a large change in the DGR, and therefore dust content, is unexpected. All but one galaxy in our sample are detected at Infrared Astronomical Satellite (IRAS) 60 and 100 \(\mu m\), which indicates that there is at least some dust in the low-\(v_{circ}\) galaxies. We estimated a DGR proxy as the ratio of the total infrared luminosity (\(L_{TIR}\)), calculated with \(IRAS\) 25, 60, and 100 \(\mu m\) data (Moshir et al. 1990) and the Dale & Helou (2002) relation, to the combined atomic and molecular hydrogen mass. We find no transition in this DGR proxy at \(v_{circ} = 120\) km s\(^{-1}\), nor do we find any correlation between the DGR proxy and circular velocity. \(L_{TIR}\) is not necessarily proportional to the dust mass because the dust temperature may not be the same for all the galaxies; nevertheless, there is clearly a significant amount of dust in the low-\(v_{circ}\) galaxies.

Two recent studies have found convincing evidence that low-\(v_{circ}\) spirals have large dust scale heights. Seth et al. (2005) carried out a resolved stellar population study of six edge-on, late-type spirals with \(v_{circ} = 67–131\) km s\(^{-1}\) and found that the scale height of the young (\(<10^8\) yr) stellar population, which presumably formed from the cold ISM, is larger than in the Milky Way. MacLachlan et al. (2011) modeled the spectral energy distribution (SED) of three edge-on, low-surface brightness galaxies with \(v_{circ} = 88–105\) km s\(^{-1}\) and found that a significant amount of dust must be present to account for the FIR (70 and 160 \(\mu m\)) emission, but the dust must have a large scale height such that it does not significantly obscure the optical emission. The authors concluded that the galaxies have dust scale heights greater than or equal to the stellar scale heights. This is in contrast to modeling studies of high surface brightness galaxies, which concluded that the dust scale height is about half the stellar scale height (e.g., Xilouris et al. 1999).

Hunter & Elmegreen (2006) provided an alternative explanation for the dust structure transition observed by Dalcanton et al. (2004). The authors studied a large sample of irregular galaxies and found that the average \(B\)-band surface brightness is smaller than in higher-mass spiral galaxies. Based on this result, they suggested that lower stellar surface density is the cause of the transition because the gas scale height (\(h_{gas} \propto \sigma_{gas}^2 / G \rho\)), where \(\rho\) is the mass volume density of gas and stars; Blitz & Rosolowsky 2004) shares many of the same parameters with the stability parameter.

The authors discussed that dust opacity may also contribute to the observed difference in dust structure because of two effects. First, lower-\(v_{circ}\) objects should have lower metallicity, and therefore lower dust content. Second, the scale length of a lower-mass galaxy is smaller and therefore a low-\(v_{circ}\) edge-on galaxy will have less depth from the edge to the center over which to accumulate dust column density compared with a high-\(v_{circ}\) galaxy. Note that no scale height transition is needed in this interpretation. However, dust opacity is not likely the sole cause
of the dust structure transition because of the reasons listed above. Hunter & Elmegreen (2006) suggested that the observed dust structure transition is likely due to a combination of stellar surface density and dust opacity. The authors agreed that a scale height transition does occur, so if this interpretation is correct, we can still constrain the effect of scale height differences on SFE.

In Sections 5.2 and 5.3, we assume that the dust scale heights in low-\(v_{\text{circ}}\) galaxies are a factor of two larger than in high-\(v_{\text{circ}}\) galaxies. Dalcanton et al. (2004) estimated this factor by examining the dust morphology in Hubble Space Telescope images of a couple edge-on, late-type galaxies. This factor is consistent with the SED modeling results of MacLachlan et al. (2011) and Xilouris et al. (1999) if the stellar scale height distributions of low- and high-\(v_{\text{circ}}\) galaxies have significant overlap, which Dalcanton et al. (2004) found to be true (although there are low-\(v_{\text{circ}}\) galaxies where the stellar scale height is about half the value in high-\(v_{\text{circ}}\) galaxies, in which case the dust scale heights may be comparable).

5.2. The Relationship between SFE and Scale Height

In Section 4.2, we found no transition in SFE at \(v_{\text{circ}} = 120 \text{ km s}^{-1}\) or at any circular velocity probed by our sample. In this section, we interpret this result to discuss the relationship between SFE and the scale height of the cold ISM. For this discussion, we make a number of assumptions. First, we assume that our sample of bulgeless disk galaxies is similar to that of Dalcanton et al. (2004) in that galaxies with \(v_{\text{circ}} > 120 \text{ km s}^{-1}\) have narrow dust lanes while galaxies with \(v_{\text{circ}} < 120 \text{ km s}^{-1}\) have no obvious dust lanes. This is a reasonable assumption because it was our main consideration in choosing the sample, but because our galaxies are moderately inclined rather than edge-on, we are unable to directly measure the vertical dust structure. Second, as in Dalcanton et al. (2004), we assume that the dust scale heights in the low-\(v_{\text{circ}}\) galaxies are larger than in the high-\(v_{\text{circ}}\) galaxies (Section 5.1 addresses this assumption). Finally, we assume that the molecular gas and dust scale heights are comparable.

Dalcanton et al. (2004) suggested that there may be an SFE transition associated with the dust scale height transition at \(v_{\text{circ}} = 120 \text{ km s}^{-1}\). The authors gave an example that assumes the true star formation law is a correlation between the volume density of gas (\(\rho_{\text{gas}}\)) and the SFR volume density (\(\rho_{\text{SFR}}\)): \(\rho_{\text{SFR}} \propto \rho_{\text{gas}}^N\). The larger scale heights of low-\(v_{\text{circ}}\) galaxies lead to lower gas volume densities. Depending on the index, \(N\), a low-\(v_{\text{circ}}\) galaxy with the same gas surface density as a high-\(v_{\text{circ}}\) galaxy can have a lower SFR surface density and therefore a lower SFE. To consider this point, we first assume the same \(\Sigma_{\text{gas}}\) for a low- and high-\(v_{\text{circ}}\) galaxy and the following relationships between the surface and volume density of gas and SFR: \(\Sigma_{\text{gas}} \propto \rho_{\text{gas}} h\), and \(\Sigma_{\text{SFR}} \propto \rho_{\text{SFR}} h\), where \(h\) is the scale height of the star-forming gas and newly formed stars and the proportionality constant is the same for both relationships. We set \(\beta\) equal to the ratio of dust scale heights in low-\(v_{\text{circ}}\) (\(\text{Iv}\)) versus high-\(v_{\text{circ}}\) (\(\text{hV}\)) galaxies: \(\beta = h_{\text{Iv}} / h_{\text{hV}}\). Dalcanton et al. (2004) very approximately estimated this ratio to be about two. Under these assumptions, \(\Sigma_{\text{SFR, hV}} = \beta^{N-1} \Sigma_{\text{SFR, Iv}}\), where \(\Sigma_{\text{SFR, hV}}\) and \(\Sigma_{\text{SFR, Iv}}\) are the SFR surface densities of the low- and high-\(v_{\text{circ}}\) galaxy with the same \(\Sigma_{\text{gas}}\). Dalcanton et al. (2004) discussed the case where \(\beta = 2\) and \(N = 1.5\), where we expect the high-\(v_{\text{circ}}\) galaxy to have a \(\Sigma_{\text{SFR}}\) that is a factor of 1.4 larger than the low-\(v_{\text{circ}}\) galaxy. Note that if \(N = 1\) there is no expected difference in SFR surface density.

In the star formation law plots of Figures 3–5, we are sensitive to offsets in intercept between the low- and high-\(v_{\text{circ}}\) samples that are larger than the uncertainty in the intercept, which is \(\sim 0.3–0.4 \text{ dex}\), assumming an uncertainty in \(\Sigma_{\text{SFR}}\) of 0.2 dex and the number of galaxies in our low- and high-\(v_{\text{circ}}\) samples. In the case discussed by Dalcanton et al. (2004), we expect the low-\(v_{\text{circ}}\) galaxies to be offset to lower \(\Sigma_{\text{SFR}}\) by 0.15 dex. Therefore, we cannot exclude offsets at the level expected by Dalcanton et al. (2004).

The star formation law assumed above is not likely correct given that recent studies have found a strong molecular star formation law and no atomic gas star formation law. However, we can also determine the expected \(\Sigma_{\text{SFR}}\) offset if the molecular fraction is set by the mid-plane pressure and the molecular SFE is constant (see also Section 1). We assume the same \(\Sigma_{\text{H}_1+\text{H}_2}\) for a low- and high-\(v_{\text{circ}}\) galaxy, \(R_{\text{mol}} \propto \rho_{\text{h}}\), and \(P_{\text{h}} \propto \rho_{\text{H}_1+\text{H}_2} \sigma_{\text{gas}}^2\), where \(\rho_{\text{H}_1+\text{H}_2}\) is the total hydrogen volume density and the velocity dispersion of the gas is constant. In this scenario, \(P_{\text{h}}, R_{\text{mol}}\) and \(\rho_{\text{mol}}\) are lower by a factor of \(\beta\) in the low-\(v_{\text{circ}}\) galaxy compared to the high-\(v_{\text{circ}}\) galaxy. The expected offset in \(\Sigma_{\text{SFR}}\) depends on \(R_{\text{mol}}\), which varies from 0.1 to 2.7 in our sample. If \(\beta = 2\) and \(R_{\text{mol}}\) of the high-\(v_{\text{circ}}\) galaxy is 0.1 (2.7), we expect \(\Sigma_{\text{SFR}}\) to be lower by 0.3 dex (0.1 dex) in the low-\(v_{\text{circ}}\) galaxy compared with the high-\(v_{\text{circ}}\) galaxy. Given our uncertainties, this level of offset would also be difficult to detect. However, we can reject our assumption that \(P_{\text{h}}\) is lower by a factor of two in low-\(v_{\text{circ}}\) galaxies. This is evident from Section 4.3, where we found no significant difference in the mid-plane pressure distributions of the low- and high-\(v_{\text{circ}}\) galaxies, even when considering only objects with the same \(\Sigma_{\text{H}_1+\text{H}_2}\). Furthermore, we found no difference in the \(R_{\text{mol}}\) distributions of the low-versus high-\(v_{\text{circ}}\) galaxies (Section 4.2).

The two scenarios explored above predict offsets in intercept between the low- and high-\(v_{\text{circ}}\) samples that are less than the uncertainty. Therefore, we cannot clearly exclude these options. Nonetheless, our data show no evidence for a strong transition in SFE at any circular velocity. A simple interpretation that is consistent with our data is that low-\(v_{\text{circ}}\) galaxies have a lower number of molecular clouds per unit volume compared with high-\(v_{\text{circ}}\) galaxies at the same \(\Sigma_{\text{H}_1+\text{H}_2}\) but lower only by the ratio of the cold ISM scale heights in low- versus high-\(v_{\text{circ}}\) galaxies. This results in the same total number of molecular clouds within the beam for a low- and high-\(v_{\text{circ}}\) galaxy at the same \(\Sigma_{\text{H}_1+\text{H}_2}\), and thus gives the same \(\Sigma_{\text{H}}\) and \(\Sigma_{\text{SFR}}\) (assuming the molecular clouds have the same density and that we average over evolutionary effects). Note that the above applies in the molecular-dominated regime. We have few data points below \(\Sigma_{\text{H}_1+\text{H}_2} \sim 9 M_\odot \text{ pc}^{-2}\), but expect that \(\Sigma_{\text{SFR}}\) can vary substantially for galaxies with the same \(\Sigma_{\text{H}_1+\text{H}_2}\), depending on the physical processes that affect the molecular fraction (e.g., those processes discussed in Krumholz et al. 2009 and Ostriker et al. 2010).

In conclusion, we interpret our result that there is no transition in SFE at any circular velocity as evidence that scale height differences at the level of about a factor of two do not significantly affect the molecular fraction or SFE in bulgeless disk galaxies. However, offsets in SFE below our uncertainty level are still possible.

5.3. Comparison to Star Formation Models

Dalcanton et al. (2004) very approximately estimated that the dust scale heights of low-\(v_{\text{circ}}\) galaxies are about a factor of two larger than high-\(v_{\text{circ}}\) galaxies. Assuming our sample has a similar range in scale height, our results indicate that these scale
height differences, which lead to gas volume density differences also at the level of a factor of about two, do not lead to obvious differences in the SFE. Our results favor star formation models where small scale physical processes are more important than processes that act on larger scales, of order the dust and cold gas scale height (10 s to 100 pc). Based on their comparison to many star formation models without an obvious favorite, Leroy et al. (2008) discussed that physics below their resolution of 750 pc is likely most important for determining the SFE. We contribute with a further constraint that the SFE is likely affected primarily by processes that act on scales smaller than the cold gas and dust scale height.

We cannot exclude all star formation models that include large scale physics because there are processes that may affect star formation but are neither affected by nor affect the scale height. For example, our sample has no power to constrain the effects of large scale radial processes, like shear (see, e.g., Hunter et al. 1998), on star formation. In addition, star formation may be affected by environmental properties that depend on the gas volume density but also depend on other variables that counteract a variable volume density. For example, the pressure in the ISM is related to the gas volume density and velocity dispersion: \( P \propto \rho_{\text{gas}} \sigma_{\text{gas}}^2 \). While we expect the volume density to be lower in low-\( v_{\text{circ}} \) galaxies, the velocity dispersion may be larger. With the right combination of \( \rho_{\text{gas}} \) and \( \sigma_{\text{gas}} \), there could be no difference in pressure between low- and high-\( v_{\text{circ}} \) galaxies. While the latter argument illustrates our limitations, we note that there is currently no strong observational reason to assume different gas velocity dispersions between the low- and high-\( v_{\text{circ}} \) galaxies. Tamburro et al. (2009) found some variation in the central H\textsc{i} velocity dispersion in 11 galaxies ranging from early-type spirals to irregulars, but more observations are needed.

Would leading star formation models have predicted a difference in SFE in galaxies with scale heights that differ by about a factor of two? In the Krumholz et al. (2009) model, \( \Sigma_{\text{SFR}} \) is a function of metallicity, \( \Sigma_{\text{gas}} \), and the beam filling factor of \( \sim 100 \text{pc} \) sized atomic–molecular complexes. There is no direct dependence on the scale height, so we would not expect a transition in SFE unless there is a transition in the metallicity or filling factor with scale height. We find no transition in oxygen abundance at any circular velocity in our data, but there should be a correlation between these two properties given the mass–metallicity relation (e.g., Tremonti et al. 2004), which we also do not see. The filling factor of star-forming complexes is not well constrained, although there is no a priori reason to suppose that it would be different in low- versus high-\( v_{\text{circ}} \) objects. Krumholz et al. (2009) do not predict a difference in SFE in galaxies with different scale heights and the fact that we did not find a transition in SFE at \( v_{\text{circ}} = 120 \text{ km s}^{-1} \) is not a strong constraint on this model.

In the model where the mid-plane pressure sets the molecular fraction and the molecular SFE is constant, the pressure is proportional to the gas volume density, which we expect to vary between the low- and high-\( v_{\text{circ}} \) galaxies. If the gas velocity dispersion is fixed, we would expect the low-\( v_{\text{circ}} \) galaxies to have lower molecular to atomic surface density ratios and lower SFEs relative to the high-\( v_{\text{circ}} \) galaxies. However, we found no difference between the mid-plane pressure, molecular to atomic surface density ratio, or SFE distributions of the low- and high-\( v_{\text{circ}} \) galaxies. If our assumptions are correct, our result is inconsistent with this model. However, the offset in SFE expected for galaxies with cold gas scale heights that differ by about a factor of two may be less than our SFE uncertainties. Furthermore, the Ostriker et al. (2010) model relates the molecular fraction (or in their terms, the fraction of gas in gravitationally bound complexes) to the pressure of the diffuse component of the ISM. We have a constraint only on the scale height and volume density of the cold component of the ISM; therefore the Ostriker et al. (2010) model may not predict molecular fraction and SFE differences in our sample. In general, our results are somewhat more consistent with local models of star formation, like the Krumholz et al. (2009) model, but we do not find conclusive evidence for or against either the Krumholz et al. (2009) or Ostriker et al. (2010) model.

One final matter to address is whether central measurements are sufficient to determine if there is a transition in molecular fraction, SFE, and/or stability at the dust structure transition of \( v_{\text{circ}} = 120 \text{ km s}^{-1} \). One might question the use of central measurements because dust structure, SFE, and stability may be affected by the higher gas and stellar densities and shorter dynamical times characteristic of these regions. The only approach that will fully address this concern is to obtain off-center measurements of the above properties. Our single-beam CO data currently limit us from carrying out this analysis. Meanwhile, there is some evidence that our central pointings are sufficient to address these questions. First, our measurements trace a significant fraction of the disk: the 21\textsuperscript{cm} aperture probes physical scales of 0.7–3.2 kpc, which are similar to the disk scale lengths of our sample (0.7–3.4 kpc). Second, the central regions of bulgeless galaxies are more morphologically and kinematically similar to the outskirts than in a galaxy with a bulge. Finally, we expect a galaxy to be less stable against gravitational collapse in the center compared to the outer disk because the gas and stellar surface densities are larger. However, we find that both the low- and high-\( v_{\text{circ}} \) galaxies are stable. This suggests that there would also not be a stability transition at \( v_{\text{circ}} = 120 \text{ km s}^{-1} \) in off-center measurements because both the low- and high-\( v_{\text{circ}} \) galaxies would be more stable.

6. SUMMARY

We have presented a study of star formation in twenty moderately inclined, bulgeless disk galaxies. We found no transition in SFE (\( \Sigma_{\text{SFR}}/\Sigma_{\text{H}1+\text{H}2} \)) or disk stability at \( v_{\text{circ}} = 120 \text{ km s}^{-1} \). This circular velocity was previously found to be associated with a transition in the vertical dust structure of edge-on, bulgeless disk galaxies that is most likely due to a transition in the scale height of the cold ISM. We also found no transition in SFE or disk stability at any circular velocity probed by our sample. Our results demonstrate that the scale height of the cold ISM does not play a major role in setting the molecular fraction or the SFE. We also found decreasing SFE with lower oxygen abundance, which we estimated from the stellar mass. This result is consistent with the recent Krumholz et al. (2009) model, but a sample with a large range of metallicities within a small range of gas surface density would provide a more constraining test of the model. In general, our results are most consistent with local models of star formation that include physical processes that act on smaller scales than the dust and cold gas scale height (10 s to 100 pc).

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