STAR FORMATION MODELS FOR THE DWARF GALAXIES NGC 2915 AND NGC 1705

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ABSTRACT

Crucial to a quantitative understanding of galaxy evolution are the properties of the interstellar medium that regulate galactic-scale star formation activity. We present here the results of a suite of star formation models applied to the nearby blue compact dwarf galaxies NGC 2915 and NGC 1705. Each of these galaxies has a stellar disk embedded in a much larger, essentially starless H i disk. These atypical stellar morphologies allow for rigorous tests of star formation models that examine the effects on star formation of the H i, stellar, and dark matter mass components, as well as the kinematics of the gaseous and stellar disks. We use far-ultraviolet and 24 μm images from the Galaxy Evolution Explorer and the Spitzer Infrared Nearby Galaxies Survey, respectively, to map the spatial distribution of the total star formation rate surface density within each galaxy. New high-resolution H i line observations obtained with the Australia Telescope Compact Array are used to study the distribution and dynamics of each galaxy’s neutral interstellar medium. The standard Toomre Q parameter is unable to distinguish between active and non-active star-forming regions, predicting the H i disks of the dwarfs to be sub-critical. Two-fluid instability models incorporating the stellar and dark matter components of each galaxy, in addition to the gaseous component, yield unstable portions of the inner disk. Finally, a formalization in which the H i kinematics are characterized by the rotational shear of the gas produces models that very accurately match the observations. This suggests the time available for perturbations to collapse in the presence of rotational shear to be an important factor governing galactic-scale star formation.

Key words: galaxies: ISM – galaxies: star formation

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1. INTRODUCTION

Galaxies are gravitationally bound systems of stars, gas, and dark matter (DM). The interaction and evolution of these mass components results in a change of the observable properties of the galaxy as a whole. An understanding of the processes governing galaxy formation and evolution is still a major challenge to astronomers. The goal is to quantitatively define the relationships between galactic-scale star formation activity and the properties of the interstellar medium (ISM; e.g., Wyder et al. 2009). Current observing facilities allow for high-quality multi-wavelength observations of comparable resolution and sensitivity to be carried out for nearby galaxies (e.g., Leroy et al. 2008). These observations are used to test current theories of galactic-scale star formation.

The cold gas component of a galaxy is its fuel for star formation. On global as well as localized length scales the distribution of these mass components is known to correlate with the star formation activity (Kennicutt 1983, 1989, 1998; Bigiel et al. 2008; Leroy et al. 2008). In addition to the distribution of the gas, it is also the kinematics that play a role in regulating the star formation activity. For example, while self-gravity drives gas perturbations to collapse under mutual gravity, the centrifugal forces associated with their rotational motions will impede the structure growth by counteracting the inward gravitational force (Toomre 1964; Kennicutt 1989).

Similarly, rotational shear will tear adjacent gas clouds apart before they have the chance to coalesce to form a single denser body of gas (Wyder et al. 2009). The self-gravity of a galaxy’s ISM is determined by the gravitational potential of its mass components. The stellar potential, for example, contributes to the self-gravity of the gas, thereby making it more susceptible to gravitational collapse and hence star formation (e.g., Rafikov 2001; Leroy et al. 2008). Star formation models are used to understand how all of these processes work together to control the star formation in galaxies. Both the ability and inability of these models to accurately describe the star formation contribute to a further understanding of the complex interplay between the various ISM properties that regulate the star formation activity.

In order to compare modeling results to observations, a quantitative measure of a galaxy’s star formation activity is required. One of the most widely used tracers of high-mass star formation is the Hα emission line arising from the recombination of ionized hydrogen. This traces a galaxy’s star formation over the relatively short lifetimes (a few million years) of the most massive stars. In recent years, Galaxy Evolution Explorer (GALEX) observations of nearby galaxies have allowed the ultraviolet (UV) flux originating from the photospheres of high-mass O- and B-type stars to be used as a diagnostic of the directly observable star formation rate (SFR). As Lee et al. (2009) point out, a galaxy’s UV flux probes a fuller mass spectrum of massive stars, and thus measures star formation averaged over a longer $\sim 10^8$ yr timescale. The UV emission alone is, however, an insufficient tracer of the SFR. Several authors (e.g., Salim et al. 2007 and references therein) have compared Hα and UV SFRs for nearby galaxies. The general consensus is that UV SFRs tend to be slightly lower than Hα SFRs. The discrepancy is attributed to the effects of internal dust extinction which lowers the observed UV flux. When UV emission from high-mass stars is absorbed by dust, it is re-emitted at infrared wavelengths. As Kennicutt (1998) points out, internal dust extinction serves as one of the largest sources of systematic error in SFR measurements. Combining a measure of a star-forming galaxy’s infrared emission with a measure of its UV emission yields a measure of the total SFR that is consistent with the rate inferred from Hα spectroscopic imaging.

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Calzetti et al. (2007), for a sample of 33 nearby galaxies observed with the Multiband Imaging Photometer for Spitzer at 24 μm, showed that using the 24 μm emission to account for the dust extinction allows for an accurate determination of the total number of ionizing photons in an H_\text{II} region.

Dwarf galaxies are particularly useful laboratories in which to study star formation. Being morphologically and dynamically simpler systems than larger spiral galaxies, they allow us to stringently test star formation theories in the domains of low gas surface densities, extreme DM content, and lower rotational shear rates. This paper presents the results of a detailed study of the star formation activity in two nearby dwarfs, NGC 2915 and NGC 1705. Each galaxy has a small stellar disk embedded in a much larger H_\text{I} disk. Using the Australia Telescope Compact Array (ATCA) we have obtained new deep, high-resolution H_\text{I} line observations of these galaxies in order to study their extended H_\text{I} disks in unprecedented detail. We aim to link the H_\text{I} characteristics of each galaxy to its observed star formation activity. Far-ultraviolet (FUV) and 24 μm imaging from the GALEX and Spitzer satellites, respectively, is used to quantify the star formation activity. We combine all of these data to produce a suite of detailed star formation models that are used to understand the observed star formation in the context of the distribution and kinematics of the neutral ISM. The results of our analyses are compared to those of Leroy et al. (2008) who carried out similar analyses for their sample of 23 nearby late-type galaxies from The H_\text{I} Nearby Galaxy Survey (THINGS; Walter et al. 2008). This is done so that the results can be interpreted in the context of other more typical star-forming galaxies.

The structure of this paper is as follows. Section 2 introduces NGC 2915 and NGC 1705. The new H_\text{I}, ultraviolet, and 24 μm data sets that are utilized in this work are presented in Section 3. The method of estimating the total SFRs is presented in Section 4 together with total SFR maps of the galaxies. Each of the star formation models is introduced and described in detail in Section 5. The modeling results for each galaxy are also shown in Section 5, with comparisons to the results of Leroy et al. (2008) included. The total star formation activity of each galaxy is used to estimate the possible unseen H_\text{2} content of each system in Section 6. The results of this paper are summarized in Section 7.

2. NGC 2915 AND NGC 1705

At a distance of 4.1 ± 0.3 Mpc (Meurer et al. 2003) NGC 2915 is a nearby galaxy with the optical properties of a blue compact dwarf and the H_\text{I} characteristics of a late-type spiral. The optical disk has a B-band absolute magnitude of M_B = −15.90 and 25th magnitude isophotal radii of 1.2 kpc and 1.9 kpc in the B and R bands, respectively (Meurer et al. 1994), for the here adopted distance of 4.1 Mpc. The stellar disk is contained within a very small region at the center of a large H_\text{I} disk which extends out to \geq 22 B-band scale lengths (Meurer et al. 1996; Elson et al. 2010). The H_\text{I} disk has a well-defined spiral structure as well as a bar-like feature co-located with the stellar disk. No significant star formation is observed in the outer H_\text{I} disk, only a few faint H_\text{II} regions have been detected from deep H_α imaging (Meurer et al. 1999; Werk et al. 2010).

Both Meurer et al. (1996) and Elson et al. (2010) have used the extended H_\text{I} disk of NGC 2915 to trace its gravitational potential out to large galactocentric radii. Both investigations find the galaxy to be extremely DM-dominated, with a total mass-to-blue-light ratio as high as M_{\text{tot}}/L_B \sim 140 M_\odot/L_{\odot, B} (Elson et al. 2010). The H_\text{I} velocity field of NGC 2915 was analyzed in further detail by Elson et al. (2011) who find dynamical evidence for elliptical streaming and radial flow patterns within the H_\text{I} disk, as well as a possibly aspherical DM halo. Bureau et al. (1999) showed that the H_\text{I} spiral structure can be caused by gravitational torques associated with a slow-rotating tri-axial DM halo.

NGC 1705, another blue compact dwarf, is well known for hosting one of the most intense starbursts (relative to its mass) in the local universe. Tosi et al. (2001) used the Hubble Space Telescope (HST) to resolve the brightest red giant stars in the galaxy, thereby estimating a distance of 5.1 ± 0.6 Mpc. The system has a B-band absolute magnitude of M_B = −15.6 ± 0.2 (Marlowe et al. 1999). Meurer et al. (1992) identified two stellar populations in NGC 1705 which they refer to as the high and low surface brightness populations. The young stellar disk has a B-band 25th magnitude isophotal radius of 1.2 kpc for the here adopted distance of 5.1 Mpc. The galaxy’s intense star formation activity is concentrated in its central high surface brightness stellar population and is driven mainly by a powerful super star cluster, NGC 1705-1 (Sandage 1978; Melnick et al. 1985), which contributes almost half of the total ultraviolet luminosity of the galaxy (Meurer et al. 1998). Annibali et al. (2003) found evidence for star formation activity that commenced at least 5 Gyr ago. The authors also showed the star formation history of NGC 1705 to be very complex, confirming the existence of a recent burst of star formation between 10 and 15 Myr ago. Consistent with the HST observations of NGC 1705-1, Annibali et al. (2003) found the young and intermediate-aged stars to be concentrated near the very center of the galaxy.

Like NGC 2915, the stellar disk of NGC 1705 is embedded in a large, extended H_\text{I} disk. The first H_\text{I} synthesis observations of the galaxy were carried out by Meurer et al. (1998) who provided dynamical evidence for a galactic blowout that is powered by the central super star cluster. No distinct spiral structure is visible in the H_\text{I} distribution. The general H_\text{I} kinematics of NGC 1705 are those of a rotating disk. The DM properties of the galaxy were first modeled by Meurer et al. (1998), who showed the system to be DM-dominated at nearly all radii.

3. DATA

Both galaxies have been observed at 21 cm, infrared, optical, and ultraviolet wavelengths. This section presents and describes the multi-wavelength data sets utilized in this paper.

3.1. H_\text{I} Line Observations

Meurer et al. (1996, 1998) used the ATCA to carry out the first H_\text{I} synthesis observations of NGC 2915 and NGC 1705, respectively. Meurer et al. (1996) used their data to produce the first mass models of a blue compact dwarf. In this work we utilize new H_\text{I} synthesis observations from the ATCA with significantly improved sensitivity and spatial resolution.

The H_\text{I} line data for NGC 2915 are those of Elson et al. (2010). These data have a spatial resolution of 17.0′× 18.2′, a factor of ~2 improvement on the Meurer et al. (1996) observations. The rms of the noise in a channel is \sim 0.6 mJy beam^{-1}, the channel width is 3.2 km s^{-1}. The reader is referred to Elson et al. (2010) for a full description of the observation setups, the data reduction procedures, and a presentation of the various H_\text{I} data products including the channel maps. An H_\text{I} surface density map of NGC 2915 produced using the data from Elson et al. (2010) is shown in the top panel of Figure 1. For reference, a 3.6 μm IRAC
approach and approximate the 86 hr worth of on-source data that will be discussed in detail in our upcoming publication. This is the focus of this work.

The H$_i$ observations are able to resolve the central region of the H$_i$ disk into two overdensities. Also visible is the clear spiral structure as well as a plume-like feature extending from the center of the galaxy toward the northwest. It is this H$_i$ surface density map that is used to investigate the star formation laws in this paper.

The new NGC 1705 ATCA H$_i$ synthesis observations used in this work will be discussed in detail in our upcoming publication (E. C. Elson et al. 2012, in preparation). For this work it suffices to say that approximately 86 hr worth of on-source observations were obtained for the galaxy using baselines up to 6 km in length to produce an H$_i$ data cube with a spatial resolution of 16.7' x 14'.5 and a channel width of 3.48 km s$^{-1}$. The rms flux of the noise in a line-free channel of the cube is $\sim 0.7$ mJy beam$^{-1}$. An H$_i$ surface density map produced from these data is shown in the top panel of Figure 2. A 3.6 $\mu$m IRAC Spitzer image of the stellar disk is again shown in the bottom panel of the figure for comparison. The new H$_i$ data clearly resolve the central H$_i$ concentration of the galaxy into two overdensities with a combined mass of $\sim 3 \times 10^7 M_\odot$. These central H$_i$ overdensities have their peaks separated by $\sim 0.8$ kpc and straddle the extremely luminous super star cluster.

### 3.2. Ultraviolet and Infrared Imaging

Both NGC 2915 and NGC 1705 have been observed with the GALEX satellite (Martin et al. 2005) as part of the GALEX Nearby Galaxy Survey (Gil de Paz et al. 2007), and with the Spitzer satellite as part of the Spitzer Nearby Galaxies Survey (Kennicutt et al. 2003). For each galaxy, the GALEX FUV imaging and the Spitzer 24 $\mu$m imaging is used to trace the directly observable and dust-obscured SFRs, respectively. These two tracers are combined to yield an estimate for the total SFR (Section 4.1).

The GALEX FUV band, centered at 1450 Å, covers the wavelength range 1350–1750 Å. The angular resolution for this band is $\sim 4.5$. The FUV data were photometrically calibrated and corrected for attenuation due to dust in the Galaxy. The Schlegel et al. (1998) dust extinction maps were used to estimate $E(B-V) \sim 0.275$ mag and $E(B-V) \sim 0.008$ mag for NGC 2915 and NGC 1705, respectively. These $B-V$ extinction measures were converted to FUV extinction magnitudes of $A_{\text{FUV}} = 8.24 \times E(B-V) = 2.26$ mag and $A_{\text{FUV}} = 8.24 \times E(B-V) = 0.06$ mag (Wyder et al. 2007). Neither the FUV nor 24 $\mu$m images of either galaxy suffer from significant star crowding effects. No foreground star subtraction was performed.

The MIPS instrument on board the Spitzer satellite has a field of view of $5^\prime \times 5^\prime$ in the 24 $\mu$m band with a resolution of $\sim 6^\prime$ and high signal-to-noise ratios. Bigiel et al. (2008) allude to the fact that the MIPS point-spread function at 24 $\mu$m is severely non-Gaussian, yet presents no significant problems when the data are smoothed to resolutions of $\sim 20^\prime$. Again, no foreground star subtraction was performed for either galaxy.

To facilitate a direct comparison of the FUV, 24 $\mu$m, and H$_i$ data of each galaxy, all images were placed on the same astrometric grid with the same spatial resolution. The FUV and 24 $\mu$m images of each galaxy were smoothed, using a Gaussian convolution function, to a resolution equal to the full width at half-maximum of the synthesized beam of the corresponding H$_i$ data. Next, these images were re-gridded to the same pixel size and astrometric grid as the H$_i$ line data. These smoothed, re-gridded FUV and 24 $\mu$m images of NGC 2915 and NGC 1705 are shown in Figures 3 and 4, respectively.

### 4. DERIVED DATA

The aim of this work is to understand which properties of the neutral ISM regulate the star formation activity within each galaxy. In order to do so we require quantitative measures of the star formation activity as well as parameterizations of the ISM kinematics. This section describes our preferred method of deriving total SFR surface density estimates for each galaxy, and also the rotation curve and ISM velocity dispersion parameterizations required for the star formation models.
4.1. The Total Star Formation Rate

The prescription of Leroy et al. (2008) is used to linearly combine the FUV and 24-μm imaging of each galaxy to yield an estimate of the total SFR surface density, $\Sigma_{\text{SFR}}$, in units of $M_\odot$ yr$^{-1}$ kpc$^{-2}$:

$$\frac{\Sigma_{\text{SFR}}}{M_\odot \text{yr}^{-1} \text{kpc}^{-2}} = \frac{\Sigma_{24\mu m}}{M_\odot \text{yr}^{-1} \text{kpc}^{-2}} + \frac{\Sigma_{\text{FUV}}}{M_\odot \text{yr}^{-1} \text{kpc}^{-2}}$$

$$= 3.2 \times 10^{-3} \frac{I_{24}}{\text{MJy sr}^{-1}} + 8.1 \times 10^{-2} \frac{I_{\text{FUV}}}{\text{MJy sr}^{-1}},$$

where $I_{24}$ and $I_{\text{FUV}}$ are the 24-μm and FUV surface brightnesses, respectively. Very importantly, Leroy et al. (2008) show that this choice of coefficients yields $\Sigma_{\text{SFR}}$ values that are consistent with the Hα–24-μm calibration of Calzetti et al. (2007) and that when the 24-μm emission is ignored the FUV $\Sigma_{\text{SFR}}$ estimates reduce to those of Salim et al. (2007). The calibration of $\Sigma_{\text{SFR}}$ uses the initial mass function (IMF) from Calzetti et al. (2007) which is a Kroupa-type two-component IMF that extends to $120M_\odot$. Some authors (e.g., Meurer et al. 2009) argue that the IMF is not universal and that the slope of the upper end varies systematically. A non-universal IMF implies that the SFR measured in a galaxy is highly sensitive to the tracer used in the measurement. However, in this work we assume a standard two-component Kroupa IMF. The $\Sigma_{\text{SFR}}$ maps for NGC 2915 and NGC 1705 are shown in Figures 3 and 4, respectively.

4.2. Rotation Curve Parameterizations

The star formation models investigated in this work require a measure of the galaxy’s rotation curve as input. To this end the rotation curves are parameterized using the function

$$V(r) = V_{\text{flat}}[1 - \exp(-r/l_{\text{flat}})],$$

where $V_{\text{flat}}$ and $l_{\text{flat}}$ approximate the asymptotic velocity of the outer rotation curve and the length scale over which it approaches this constant velocity, respectively. This parameterization is easily analytically differentiable. For NGC 2915, the rotation curve derived by Elson et al. (2010) is used. This rotation curve was derived by fitting a tilted ring model to the H I velocity field. The best-fitting parameters are $V_{\text{flat}} = 83.9$ km s$^{-1}$ and $l_{\text{flat}} = 74'8$ (1.5 kpc). The rotation curve for NGC 1705 was generated by parameterizing the H I line profiles of an integrated position–velocity slice extracted from the new H I data cube (the full details of the derivation of this rotation curve will be presented in our forthcoming publication E. C. Elson et al. 2012, in preparation). This rotation curve is very similar to that derived previously by Meurer et al. (1998) and is best parameterized by $V_{\text{flat}} = 72.8$ km s$^{-1}$ and $l_{\text{flat}} = 52'9$ (1.3 kpc). The rotation curves together with their respective parameterizations are shown in Figure 5.

4.3. H I Velocity Dispersions

The star formation models also require an estimate of the gas velocity dispersion. For some of the models considered in this work, Kennicutt (1983, 1989) and Martin & Kennicutt (2001) used a constant gas velocity dispersion of $\sigma_{\text{gas}} = 6$ km s$^{-1}$, without distinguishing between the various thermal phases of the ISM. Several authors have investigated and emphasized the importance of a cold phase of the ISM for the stability

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**Figure 2.** Top panel: NGC 1705 H I surface density map extracted from the new ATCA H I synthesis data. The color scale is described in units of $M_\odot$ pc$^{-2}$ by the color bar. The black ellipse represents the B-band $R_25$ radius of 1.2 kpc. The filled star marks the central position of the super star cluster, NGC 1705. The hatched circle in the lower left corner of the panel represents the half-power beam width of the synthesized beam. Bottom panel: 3.6-μm IRAC Spitzer image of the old stellar disk of NGC 1705. The black ellipse is the same as that in the panel above. The cross marks the position of the photometric center; $\delta_{J2000} = 04^h54^m13^s50$, $\delta_{J2000} = -53^\circ21'30''00$ (Skrutskie et al. 2006). The color scale is described in units of MJy sr$^{-1}$ by the color bar.

(A color version of this figure is available in the online journal.)
Figure 3. FUV, 24 μm, and total star formation rate surface density maps for NGC 2915. Top left panel: GALEX FUV image of the stellar disk. Top middle panel: Spitzer 24 μm image of the stellar disk. The FUV and 24 μm images have been smoothed and re-gridded. Top right panel: star formation rate surface density map for the stellar disk, constructed by combining the FUV and 24 μm images according to Equation (2). Bottom panel: the full star formation rate surface density map. The single black contour marks the edge of the H I disk. The white contour within the stellar disk is at a level of 0.0018 M⊙ yr⁻¹ kpc⁻².

(A color version of this figure is available in the online journal.)

Figure 4. FUV, 24 μm, and total star formation rate surface density maps for NGC 1705. Left panel: GALEX FUV image of the stellar disk. Middle panel: Spitzer 24 μm image of the stellar disk. The FUV and 24 μm images have been smoothed and re-gridded. Right panel: star formation rate surface density map constructed by combining the FUV and 24 μm images according to Equation (2). The outer black contour marks the edge of the H I disk. The inner black contour within the stellar disk is at a level of 0.1 M⊙ yr⁻¹ kpc⁻².

(A color version of this figure is available in the online journal.)
of disk galaxies. As an example, de Blok & Walter (2006) studied the H\textsc{i} line profiles of NGC 6822 to identify separate warm and cold phases with velocity dispersions of $\sim$8.2 km s$^{-1}$ and $\sim$ 4.4 km s$^{-1}$, respectively. They showed that the velocity dispersion of the cold component, when used with a Toomre $Q$ criterion, gives an optimal description of ongoing star formation in NGC 6822, superior to that using the more conventional criterion, Equation (4) becomes:

$$Q = \frac{\sigma_{\text{gas}} \kappa}{\pi G \Sigma_{\text{gas}}}$$

(4)

is less than unity. The self-gravity, pressure, and kinematics of the gas disk are represented by $\Sigma_{\text{gas}}$, $\sigma_{\text{gas}}$, and $\kappa$, respectively. $G$ is the gravitational constant. The epicyclic frequency, $\kappa$, is a measure of the Coriolis or centrifugal forces stemming from the rotation of the perturbations. Following Kennicutt (1989), $\kappa$ is estimated as

$$\kappa(R) = 1.41 \frac{V}{R} \sqrt{\frac{1}{1 + \frac{R dV}{V dR}}}$$

(5)

where $V$ is the rotation velocity at a radius $R$. It is the combination of random motions and centrifugal accelerations from epicyclic eddies that support the ISM against collapse due to self-gravity. The Toomre criterion therefore describes the abilities of perturbations to rotate around their center of gravity and thus their stability against gravitational collapse.

Kennicutt (1989) used a sample of 15 spiral galaxies to observationally test the Toomre criterion on galactic length scales. More recently, Martin & Kennicutt (2001) applied the prescription of Toomre (1964) to a sample of 32 star-forming spiral galaxies and compared the radial distributions of $Q_{\text{gas}}$ to H\textsc{i} radial surface brightness profiles. For a sub-sample of 26 galaxies with well-defined thresholds they found a median value of $\alpha_Q = 0.69 \pm 0.2$ for the ratio of the gas surface density to critical surface density defined by Equation (4), $\Sigma_{\text{crit}} = \frac{\sigma_{\text{gas}} \kappa}{\pi G \Sigma_{\text{gas}}}$. Using this ratio as an empirical calibration for the Toomre criterion, Equation (4) becomes

$$Q_{\text{gas}} = \frac{\alpha Q \sigma_{\text{gas}} \kappa}{\pi G \Sigma_{\text{gas}}}$$

(6)

This empirical version of the Toomre stability criterion is used throughout this work. Gravitational instability of the gas is predicted by $Q_{\text{gas}} < 1$.

5. STAR FORMATION MODELS

This section deals with the various star formation models generated for NGC 2915 and NGC 1705. Each model is introduced and its method of implementation discussed. The results are presented together with a comparison to those of Leroy et al. (2008), who carried out similar analyses for their sample of 23 nearby star-forming galaxies from THINGS. This is done so that the results can be interpreted in the context of other typical star-forming dwarf galaxies.

5.1. Single-fluid Toomre Criterion

5.1.1. Introduction

Safronov (1960) was the first to show that perturbations in a thin, rotating gaseous disk can become unstable to gravitational collapse due to the effects of the self-gravity of the disk.
5.1.3. Results and Discussion

The results for NGC 2915 and NGC 1705 are shown in Figures 6 and 7, respectively. Most striking is the fact that, using the above-mentioned inputs, the Toomre criterion predicts the H\textsubscript{i} disk of both galaxies to be sub-critical, that is $Q_{\text{gas}} > 1$ for every resolution element in the H\textsubscript{i} total intensity map. This result is inconsistent with the star formation activity observed at the center of each galaxy. The lower panel of Figure 6 shows the logarithmic $Q_{\text{gas}}$ distribution for NGC 2915 which is approximately Gaussian, peaking at $\log Q_{\text{gas}} \approx 0.55$, far-removed from $Q_{\text{gas}} = 1$ required for gravitational instability.

Despite there being no $Q_{\text{gas}} \leq 1$ in the presence of clear star formation activity at the center of NGC 2915, the $Q_{\text{gas}}$ map does still exhibit the general structure that one might expect if it were to correctly predict the star formation activity. The $Q_{\text{gas}}$ radial profile (Figure 6, middle panel) shows the lowest $Q_{\text{gas}}$ values to occur at the center of the galaxy, as well as a clear drop in the $Q_{\text{gas}}$ values at the edge of the stellar disk ($R = R_{\text{25}}$).

The situation is similar for NGC 1705 whose logarithmic $Q_{\text{gas}}$ distribution is double-peaked with $Q_{\text{gas}} > 1$ throughout the H\textsubscript{i} disk. This galaxy’s intense star formation activity is not well-described by the $Q_{\text{gas}}$ criterion. The very large estimates of $Q_{\text{gas}} \sim 10^{1.5}$ for the outer H\textsubscript{i} disk are consistent with the
results of Meurer et al. (1998). As described above, the lowest $Q_{\text{gas}}$ values again occur near the galaxy’s central stellar disk despite the model predicting the H I disk to be sub-critical.

5.1.4. Comparison to Other Star-forming Dwarfs

How do the results of NGC 2915 and NGC 1705 compare to those of other star-forming dwarfs? Leroy et al. (2008) found almost no area of the inner disks of their THINGS galaxies to be formally unstable to gravitational collapse. Rather, they found that $Q_{\text{gas}} \sim 4$ is typical for the region $R \lesssim 0.8 R_{25}$ and that $Q_{\text{gas}} \gtrsim 10$ is common for larger radii. In this sense, the results for NGC 2915 and NGC 1705 are consistent with the sample of Leroy et al. (2008). The authors find no clear evidence of a $Q_{\text{gas}}$ threshold that can unambiguously distinguish between star-forming regions of high and low efficiency. Leroy et al. (2008) did, however, use $\sigma_{\text{gas}} = 11 \, \text{km s}^{-1}$ as their preferred measure of the kinetic support of the ISM. They go on to point out that under various assumptions regarding the H$_2$ content and the thermal pressure of the galaxies, the median value of $Q_{\text{gas}}$ in the outer disks of dwarfs agrees quite well with the threshold value of $Q_{\text{gas}}$ determined by Kennicutt (1989) and Martin & Kennicutt (2001). Our results for NGC 2915 and NGC 1705, as well as those of Leroy et al. (2008), are also similar to those of Hunter et al. (1998) who, for their sample of dwarf galaxies, found $Q_{\text{gas}}$ to be systematically higher by a factor of $\sim 2$ than the value of determined by Kennicutt (1998).

5.2. Stars+Gas Two-fluid Toomre Criterion

5.2.1. Introduction

The Toomre criterion discussed in the previous section incorporates only the gravitational potential of the gaseous disk. In addition to its gaseous potential, the stellar potential of a galaxy plays an important role in regulating the gravitational stability of the ISM by contributing to its self-gravity. For this reason, two-fluid instability models incorporating the gaseous and stellar potentials are particularly relevant to systems in which the stellar and gas masses are comparable. NGC 2915 and NGC 1705 have stellar masses of $\sim 3.2$ and $8.8 \times 10^8 M_\odot$, respectively. Each galaxy also contains at least $10^8 M_\odot$ of H I. This section therefore deals with two-fluid instability models that incorporate the stellar and gaseous potentials of NGC 2915 and NGC 1705.

Rafikov (2001) determined the instability condition for a thin, rotating disk composed of gaseous and stellar components to be

$$\frac{1}{Q_{\text{gas},*}} = \frac{2}{Q_*} \frac{q}{1 + q^2} + \frac{2}{Q_{\text{gas}}} \frac{q}{1 + q^2 R_\sigma^2} > 1. \quad (7)$$

In this equation $Q_* \equiv \kappa \sigma_{*,r}/\pi G \Sigma_*$, $q \equiv \kappa \sigma_{*,r}/\kappa_*$, with $k$ being the wave number of the instability. The radial velocity dispersion of the stars in the plane of the stellar disk is represented by $\sigma_{*,r}$, and $R_\sigma \equiv \sigma_{\text{gas}}/\sigma_{*,r}$.

5.2.2. Methodology

The gravitational effects of the stellar mass component of each galaxy were determined using Spitzer IRAC 3.6 $\mu$m imaging. Ellipses fitted to 3.6 $\mu$m surface brightness isophotes of NGC 2915 suggest a constant inclination of $\sim 55^\circ$ and a position angle of $\sim 306^\circ$ for the old stellar population. A radial profile (Figure 8, top panel) was derived by azimuthally averaging the stellar surface densities in thin annuli. The parameterization of this profile is

$$\log_{10} \left( \frac{\Sigma_*}{M_\odot \, \text{pc}^{-2}} \right) = -0.012 - \frac{R}{\text{arcsec}} + 2.21. \quad (8)$$

An identical procedure was carried out to generate a stellar surface density radial profile for NGC 1705 (Figure 8, bottom panel). A constant inclination and position angle of $45^\circ$ was assumed. The parameterization of the resulting profile is

$$\log_{10} \left( \frac{\Sigma_*}{M_\odot \, \text{pc}^{-2}} \right) = -0.015 - \frac{R}{\text{arcsec}} + 2.37. \quad (9)$$

All stellar surface densities were inclination corrected so that Equations (8) and (9) parameterize the face-on values. The two-fluid stability criterion of Rafikov (2001) requires an estimate of the radial component of the stellar velocity dispersion of each galaxy, $\sigma_{*,r}$. The prescription of Leroy et al. (2008) was followed to determine $\sigma_{*,r}$ as a function of galactocentric radius. Leroy et al. (2008) made four assumptions in order to determine the radial stellar velocity dispersion.

1. The scale height of an exponential stellar disk is constant with galactocentric radius. This is a typical observation for edge-on galaxies (Kregel et al. 2002).
2. A flattening ratio of $l_s/h_s = 7.3 \pm 2.2$, where $l_s$ and $h_s$ are the disk scale length and scale height, respectively. This is the average volume-corrected flattening of the disk light for the sample of 34 edge-on spiral galaxies of de Grijs (1998) as determined by Kregel et al. (2002). From the IRAC 3.6 $\mu$m imaging, the stellar disk scale lengths of NGC 2915 and NGC 1705 were determined to be $l_s \sim 0.6$ kpc and $l_s \sim 0.14$ kpc, respectively, leading to $h_s \sim 0.08$ kpc and $h_s \sim 0.02$ kpc.
3. The stellar disk is isothermal in the $z$-direction. Under the assumption of hydrostatic equilibrium, this leads to...
The radial profiles of these maps are shown in Figure 12 while the distribution of $1/Q_{\text{gas,s}}$ is shown in Figure 13.

The NGC 2915 results are considered first. Even with the gravitational potential of the stellar disk included, the galaxy is sub-critical with $1/Q_{\text{gas,s}} < 1$ throughout its H$\text{I}$ disk for all implemented wave numbers. This two-fluid instability criterion, like the single-fluid instability criterion considered in the previous section, formally fails to predict the observed star formation activity at the center of NGC 2915. The extra self-gravity of the ISM induced by the stellar potential is still not enough to counteract the large epicyclic frequencies at inner radii. Despite this formal failure for the central part of the galaxy, the instability maps again produce the sort of structure that one might expect for a late-type galaxy. Beyond the radial extent of the stellar core, the two-fluid $1/Q_{\text{gas},s}$ maps resemble the single-fluid $Q_{\text{gas}}$ maps. This result is expected since the stellar potential is negligible in the outer gaseous disk of the galaxy. Including the gravitational influence of the stellar disk of NGC 2915 leaves the inner portion of its H$\text{I}$ disk only marginally stable against gravitational collapse for the smallest wave numbers, corresponding to perturbation length scales of $\sim0.5$ kpc. This result is fairly consistent with that of Leroy et al. (2008). The authors found no clear evidence of a single-fluid Toomre $Q_{\text{gas}}$ criterion that could unambiguously distinguish between high and low star formation efficiency regions. However, when using Equation (7) to include the effects of stellar gravity they found that some regions became gravitationally unstable. Including the stellar gravity led to large portions of the gaseous disks in their sample being only marginally stable against large-scale gravitational collapse, similar to our NGC 2915 result.

The situation is only slightly better for the NGC 1705 instability maps, which for some of the implemented wave numbers have $1/Q_{\text{gas,s}} > 1$. The $Q_{\text{gas,s}} = 1$ level is marked with a single black contour in the instability maps shown in Figure 11. The best instability model is that for a wave number of $k = 10\pi$, which corresponds to a perturbation length scale of $\lambda = 200$ pc. This model predicts the very central regions of the H$\text{I}$ disk to be unstable. In the context of a two-fluid Toomre criterion, the gravitational potential of the stellar disk seems to contribute enough self-gravity to the ISM to yield the central disk unstable. Large perturbation length scales of $\lambda \sim 0.8$ kpc make the entire H$\text{I}$ disk of the galaxy unstable against gravitational collapse. This demonstrates the inappropriateness of the perturbation size. Perturbations with wave number $k \sim 10\pi$ yield only the inner disk unstable while the degree of instability is roughly constant over the outer H$\text{I}$ disk. The $1/Q_{\text{gas},s}$ parameters for NGC 1705 generally span a small range of values. As Leroy et al. (2008) point out, a small spread in $1/Q_{\text{gas},s}$ values is consistent with a self-regulating star formation scenario in which the gravitational potential associated with newly formed stars will seed further gravitational collapse of the ISM.

Finally, it should be mentioned that several sources of uncertainty affect the results of these two-fluid instability analyses. The main source is the lack of direct measurements of the stellar velocity dispersions. The observed stellar surface density radial profile of each galaxy has been used to infer a stellar velocity dispersion profile. This approach assumes that $\sigma_{s} \propto \Sigma_{s}^{0.5}$ (Leroy et al. 2008). This assumption may well affect the results of the star/gas two-fluid stability analyses.

5.2.4. Comparison to Other Dwarfs

A main finding of Leroy et al. (2008) was that considering the contribution of the stellar potential to the self-gravity of...
Figure 10. NGC 2915 stars+gas two-fluid instability maps for various perturbation length scales. The common color scale is specified by the color bar at the top of the figure and represents the two-fluid instability parameter, $1/Q_{\text{gas}}$. The perturbation wave number, $k = 2\pi/\lambda$, for each instability map is shown in the top left corner of the panel. Wave numbers of $k = 40, 20, 10, 6, 4, \text{and} 2.5 \pi$ correspond to wave lengths of $\lambda = 0.005, 0.1, 0.2, 0.3, 0.5, \text{and} 0.8 \text{kpc}$, respectively. The gaseous disk is expected to be unstable to large-scale gravitational collapse in regions where $1/Q_{\text{gas}} > 1$. For all of the above-presented maps, the instability criterion predicts a sub-critical gaseous disk for NGC 2915. (A color version of this figure is available in the online journal.)

5.3. Dark Matter+Gas Two-fluid Toomre Criterion

5.3.1. Introduction

The results of the previous section demonstrate the important role that the stellar gravitational potential of a galaxy can play in regulating the star formation activity. This section attempts to answer the question of whether the DM can play a similar role.

NGC 2915 and NGC 1705 are both DM-dominated galaxies. NGC 2915 contains about $1.4 \times 10^{10} M_\odot$ of dark mass within $\sim 10 \text{kpc}$ of its center and has its DM strongly concentrated with a core density of $0.17 M_\odot \text{pc}^{-3}$ and a core radius of $r_c \sim 0.9 \text{kpc}$ (Elson et al. 2010). This is for the case in which the halo is modeled as a pseudo-isothermal sphere. The situation is similar for NGC 1705, which contains $\sim 3.1 \times 10^{9} M_\odot$ of DM within $\sim 6 \text{kpc}$ of its center, and which has a core density of $0.01 M_\odot \text{pc}^{-3}$ and a core radius of $1.2 \text{kpc}$ (E. C. Elson et al. 2012, in preparation). Since these galaxies contain dense concentrations of DM where the active star formation is observed, it is feasible that the portion of the DM halo of each galaxy that is co-located with its H\textsc{i} disk plays a role in regulating the star formation activity.

For NGC 2915, Bureau et al. (1999) proposed the self-gravitational effects of a large DM component co-located with the system’s H\textsc{i} disk as a possible explanation for its observed H\textsc{i} spiral structure. Masset & Bureau (2003) used hydrodynamical simulations to further explore this proposed mechanism, comparing the results to the observations using customized column density constraints. They found that when the observed H\textsc{i} density is scaled up by a factor of 10, the disk develops a spiral structure that closely resembles the observed
Figure 11. NGC 1705 stars+gas two-fluid instability maps for various perturbation length scales. The intensity scale of each map is specified by the color bar at the top of the panel and represents the two-fluid instability parameter, $1/Q_{\text{gas,*}}$. The perturbation wave number, $k = 2\pi/\lambda$, for each instability map is shown in the top left corner of the panel. Wave numbers of $k = 40, 20, 10, 6, 4, \text{and} 2.5$ times $\pi$ correspond to wave lengths of $\lambda = 0.005, 0.1, 0.2, 0.3, 0.5, \text{and} 0.8$ kpc, respectively.

The gaseous disk is expected to be unstable to large-scale gravitational collapse in regions where $1/Q_{\text{gas,*}} > 1$. The single black contour shown in some of the panels is at a level of $1/Q_{\text{gas,*}} = 1$, enclosing the region of the galaxy in which gravitational instability is formally expected.

(A color version of this figure is available in the online journal.)

one. They suggest that the disk of NGC 2915 contains a large dark mass component that is closely linked to the observable neutral ISM. They show further that the proposed scaling does not result in widespread star formation in the outer H\textsc{i} disk, consistent with observations.

Hunter et al. (1998) state that disk DM “effectively acts like stars in a two-fluid instability, giving extra self-gravity to small perturbations in the gas.” In this section we therefore test an analogous version of the stars+gas instability criterion from Section 5.2 by replacing the stellar quantities with corresponding DM quantities. The two-fluid DM+gas instability criterion is

$$\frac{1}{Q_{\text{gas,DM}}} \equiv \frac{2}{Q_{\text{DM}}} \frac{q}{1 + q^2} + \frac{2}{Q_{\text{gas}}} \frac{R_{\sigma}}{1 + q^2 R_{\sigma}^2} > 1, \quad (11)$$

where $Q_{\text{DM}} \equiv \kappa \sigma_{\text{DM}}/\pi G \Sigma_{\text{DM}}$, $q \equiv k \sigma_{\text{DM}}/\kappa$, with $k$ being the wave number of the instability. The velocity dispersion of the DM is expected to be much larger than that of the H\textsc{i}, meaning that equal masses of gaseous and DM will have different effects on the gravitational instability of the gas.

5.3.2. Methodology

$\Sigma_{\text{DM}}$ radial profiles for the galaxies are required by Equation (11). Each galaxy has its dynamics best explained by a pseudo-isothermal sphere parameterization of its DM halo:

$$\rho_{\text{DM}}(r) = \frac{\rho_0}{1 + \left(\frac{r}{r_c}\right)^2}, \quad (12)$$

where $\rho_0$ is the DM core density and $r_c$ is the core radius. The DM surface density (in units of $M_\odot$ pc$^{-2}$) along a particular line of sight is modeled as the DM volume density at the corresponding galactocentric radius integrated over the thickness of the H\textsc{i} disk:

$$\Sigma_{\text{DM}}(r) = \int_{-h_{\text{gas}}}^{h_{\text{gas}}} \rho_{\text{DM}}(r) dh \quad (13)$$
Figure 12. Radial profiles of the NGC 2915 and NGC 1705 stars+gas two-fluid instability maps shown in Figures 10 and 11, respectively. From top to bottom the profiles correspond to wave numbers of $k = 40, 20, 10, 6, 4,$ and $2.5$ times $\pi$. (A color version of this figure is available in the online journal.)

$$\frac{1}{Q_{\text{gas},*}} = \int_{-h_{\text{gas}}}^{h_{\text{gas}}} \frac{\rho_0}{1 + (r/r_c)^2} dh$$  \hspace{1cm} (14)

$$\frac{1}{Q_{\text{gas},*}} = \frac{2h_{\text{gas}}\rho_0}{1 + (r/r_c)^2}.$$ \hspace{1cm} (15)

$H_\text{i}$ scale heights of $h_{\text{gas}} = 0.41$ and $0.24$ kpc are adopted for NGC 2915 and NGC 1705, respectively. These estimates were generated using the prescription of Walter & Brinks (1999). Adopting the $\rho_0$ and $r_c$ pseudo-isothermal sphere parameters mentioned in Section 5.3, the $\Sigma_{\text{DM}}$ radial profiles shown in Figure 14 are obtained.

Also required by Equation (11) is an estimate of the DM velocity dispersion. In lieu of any such determination for either galaxy, we use the three-dimensional velocity dispersion of an isotropic isothermal sphere:

$$\sigma_{\text{DM}} = \sqrt{\frac{3}{2}} V_{\text{flat}},$$  \hspace{1cm} (16)

where $V_{\text{flat}}$ is the asymptotic velocity of the outer rotation curve. Adopting the best-fitting $V_{\text{flat}}$ parameters from Section 4.2, $\sigma_{\text{DM}}$ estimates of 102.7 and 89.2 km s$^{-1}$ are obtained for NGC 2915 and NGC 1705, respectively. Finally, whereas a range of wave numbers were tested in Section 5.2, here we test single wave numbers of $k = 2.5\pi$ and $4\pi$ for NGC 2915 and NGC 1705, respectively.

5.3.3. Results and Discussion

The results for NGC 2915 and NGC 1705 are presented in Figures 15 and 16, respectively. The results suggest that part of the inner $H_\text{i}$ disk of each galaxy can become unstable to gravitational collapse when additional self-gravity of the gas caused by the disk DM is incorporated. Disk DM could therefore

Figure 13. Distributions of the NGC 2915 and NGC 1705 stars+gas two-fluid instability maps shown in Figures 10 and 11, respectively. (A color version of this figure is available in the online journal.)

Figure 14. NGC 2915 and NGC 1705 dark matter surface density profiles (solid and dashed curves, respectively), as specified by Equation (15), used to construct the gas+DM two-fluid instability maps.

Figure 15. Gas+DM two-fluid instability map for NGC 2915. The color bar describes the $1/Q_{\text{gas,DM}}$ values. The pseudo-isothermal parameters used to generate the map are specified in the lower left corner. $\rho_0$ and $r_c$ are in units of $M_\odot$ pc$^{-3}$ and kpc, respectively. The edge of the stellar disk is delimited by the solid white $\Sigma_{\text{gas}} = 0.0018 M_\odot$ pc$^{-2}$ contour while the gravitationally unstable portion of the gas disk is outlined by a solid black $1/Q_{\text{gas,DM}} = 1$ contour. (A color version of this figure is available in the online journal.)
contribute toward regulating the star formation activity near the centers of NGC 2915 and NGC 1705.

Using each galaxy’s pseudo-isothermal sphere parameterization to estimate the amount of DM co-located with its H\textsc{i} disk ensures that the inner H\textsc{i} disk (where \(\rho_{\text{DM}}(r)\) is high) contains more dark mass than the outer H\textsc{i} disk (where \(\rho_{\text{DM}}(r)\) is relatively lower). The resulting distribution of \(\Sigma_{\text{DM}}\) values is different to the one obtained by simply boosting each line-of-sight \(\Sigma_{\text{HI}}\) measurement by a constant factor.

In their review of cold gas accretion in galaxies, Sancisi et al. (2008, p. 211) allude to the fact that “it is remarkable that there is such a pronounced spiral structure in the outer regions of spirals where DM dominates and even in dwarfs where the dark halo is believed to be predominant everywhere.” The question, they therefore say, is “whether these systems have light disks surrounded by massive dark halos or, rather, have heavy and dark disks.” The modeling results from this section allow this question to be partly addressed for the cases of NGC 2915 and NGC 1705. It has been shown that only a heavy disk scenario can account for the observed star formation in both NGC 2915 and NGC 1705. This result, together with the result of Masset & Bureau (2003) that a heavy disk allows for the natural formation of NGC 2915’s observed H\textsc{i} spiral structure, suggests that certainly NGC 2915 may have a heavy H\textsc{i} disk, and very likely NGC 1705 too, with significant amounts of dark mass distributed within each of them.

5.4. Shear-based Instability Criterion

A common feature of all the models presented so far is their characterization of the global kinematics of a galaxy—they all incorporate the epicyclic frequency. This section investigates a star formation model for which the kinematics are quantified not in terms of the Coriolis force (i.e., \(\kappa\)), but rather the rotational shear.

5.4.1. Introduction

Hunter et al. (1998) suggest the Coriolis force incorporated in the Toomre \(Q\) instability criterion to become less important in the presence of rotational shear. It is the time available for clouds to collapse in the presence of rotational shear, they argue, that regulates a galaxy’s star formation activity. Hunter et al. (1998) use Oort’s \(A\) constant,

\[
A = 0.5 \left( \frac{V}{r} - \frac{dV}{dr} \right),
\]

(17)

to quantify the rotational shear of the gas. Their so-called shear-based parameter for gravitational instability is then

\[
S_{\text{gas}} = \frac{\alpha_A \sigma_{\text{gas}} A}{\pi G \Sigma_{\text{gas}}},
\]

(18)

Based upon the idea that a perturbation must grow by a factor of \(\sim 100\) in the presence of shear for the instability to be significant, Hunter et al. (1998) estimate \(\alpha_A \sim 2.5\). This value of \(A\) matches the contrast between the surface densities of neutral and molecular interstellar media in the presence of rotational shear. It also allows the condition \(Q_{\text{gas}} \lesssim 1\) to be met over the \(V \propto R \) portion of the rotation curve. Regions within the galaxy that have \(S_{\text{gas}} < 1\) should be forming stars while regions with \(S_{\text{gas}} > 1\) should be stable against large-scale gravitational collapse.

Hunter et al. (1998) point out that using \(A\) to quantify the gas kinematics instead of \(\kappa\) makes very little difference for a flat rotation curve. They estimate the two thresholds to be the same to within 12% for a flat rotation curve. The difference between the two thresholds is most apparent for rising rotation curves where the rotational shear is low. Under such circumstances \(S_{\text{gas}}\) can be significantly lower than \(Q_{\text{gas}}\). Figure 17 shows radial profiles of the epicyclic frequency and rotational shear for the
Figure 18. Top panel: $S_{\text{gas}}$ instability map for the H\textsc{i} disk of NGC 2915. Middle panel: radial profile of the $S_{\text{gas}}$ instability map. Bottom panel: distribution of $\log_{10}(S_{\text{gas}})$ values. The color bar above the upper panel describes the $S_{\text{gas}}$ values. The single yellow contour in the map is at a level of $S_{\text{gas}} = 1$ and encloses the unstable region of the H\textsc{i} disk. The single white contour in the upper panel, at a level of $\Sigma_{\text{SFR}} = 0.0018 \, M_\odot \, yr^{-1} \, kpc^{-2}$, approximates the edge of the stellar disk of NGC 2915.

(A color version of this figure is available in the online journal.)

parameterization of the rotation curve of NGC 2915 (Figure 5). Most noticeable is the fact that the rotational shear is a factor $\sim 5$–$30$ smaller in magnitude than the epicyclic frequency within $R \lesssim 150''$. The situation for NGC 1705 is very similar, and it is therefore within the spatial extent of the stellar disks of the galaxies that a shear-based characterization of the kinematics is expected to be most influential when incorporated into a star formation model.

5.4.2. Methodology

$S_{\text{gas}}$ maps were produced for NGC 2915 and NGC 1705 according to Equation (18). As for $\kappa$ in the Toomre $Q_{\text{gas}}$ criterion, the shear parameter, $A$, for each line of sight was approximated as the azimuthally averaged shear corresponding to the galactocentric radius of the resolution element. The shear radial profile was determined for each galaxy using Equation (17) together with the parameterization of the galaxy’s rotation curve.

5.4.3. Results and Discussion

The $S_{\text{gas}}$ maps for NGC 2915 and NGC 1705 are shown in Figures 18 and 19, respectively. The $S_{\text{gas}}$ criterion correctly describes the star formation activity at the center of each galaxy’s gaseous disk. The $S_{\text{gas}} = 1$ contours of the shear maps are able...
to accurately trace the edges of the stellar disks of the galaxies. By simply using a shear-based characterization of the global dynamics, the $S_{\text{gas}}$ criterion can correctly locate the unstable portions of the disks without the need for extra stellar or DM self-gravity. There appears to be no tight correlation between $S_{\text{gas}}$ and the observed star formation activity. Within the central star-forming region of each galaxy, the $S_{\text{gas}}$ parameters vary significantly (e.g., a factor of $\sim 10$ for the case of NGC 1705’s stellar disk).

5.4.4. Comparison to Other Dwarfs

The NGC 2915 and NGC 1705 findings are consistent with the results of Leroy et al. (2008), who found the inner disks of their galaxies to be more nearly super-critical in the context of a shear-based star formation threshold than in the context of a $Q_{\text{gas}}$ criterion. Consistent with our results for NGC 2915 and NGC 1705 is the fact that Leroy et al. (2008) find a simple shear criterion to perform better than the star+gas two-fluid criterion for their sample of THINGS galaxies. Leroy et al. (2008) found that, according to this shear-based instability criterion, there are regions of high star formation activity within the disk that are formally unstable against the tendency to gravitationally collapse, instead of being formally stable.

6. MOLECULAR HYDROGEN CONTENT

Nowhere in this work have we made provisions in the star formation models for a possible molecular component of each galaxy’s ISM. Stars are known to form from molecular clouds, and so the presence of molecular gas is expected for each galaxy. Despite this expectation, however, no published CO detections exist for NGC 2915 or NGC 1705. In this work we therefore could not directly study the possible links between the star-forming properties of the galaxies and their molecular interstellar media.

Bigiel et al. (2008) showed that a Schmidt-type power law with index $N = 1.0 \pm 2$ relates $\Sigma_{\text{H}_2}$ to the molecular gas surface density ($\Sigma_{\text{H}_2}$) across a sample of THINGS spiral galaxies, implying that $\text{H}_2$ forms stars at a constant efficiency. This relation allows an estimate of the molecular content of a system to be obtained from its observed star formation activity. Using the total SFR surface density maps of NGC 2915 and NGC 1705, respective total molecular gas masses of $M_{\text{H}_2} = 5.7 \pm 3.4 \times 10^7 M_{\odot}$ and $M_{\text{H}_2} = 7.4 \pm 3.0 \times 10^7 M_{\odot}$ are inferred to be contained within each galaxy’s $R_{25}$ isophotal radius. The $\text{H}_1$ masses of NGC 2915 and NGC 1705 are known to be $\sim 5.5 \times 10^8 M_{\odot}$ (Elson et al. 2010) and $\sim 1.1 \times 10^8 M_{\odot}$ (Meurer et al. 1998), respectively, suggesting molecular-to-atomic-$\text{H}_1$ mass ratios of $M_{\text{H}_2}/M_{\text{H}_1} = 0.08$ and $M_{\text{H}_2}/M_{\text{H}_1} = 0.48$. These mass ratios are lower than the average ratio of $M_{\text{H}_2}/M_{\text{H}_1} = 0.89$ for the 23 gas-rich late-type galaxies from the THINGS sample of Leroy et al. (2008). This is not surprising given the small sizes of the stellar disks of NGC 2915 and NGC 1705 relative to the sizes of their extended $\text{H}_1$ disks.

Radial profiles of the SFR surface density maps were used together with the above-mentioned Schmidt-type power law from Bigiel et al. (2008) to generate the $\text{H}_2$ surface density radial profiles shown in Figure 20. For comparative purposes each galaxy’s $\text{H}_1$ profile is also shown. The inferred $\text{H}_2$ surface densities within the $R_{25}$ radius of NGC 2915’s stellar disk are much lower ($\lesssim 2 M_{\odot} \text{pc}^{-2}$) than the corresponding $\text{H}_1$ surface densities. Incorporating them into the star formation laws would result in an increase of the gas surface density by a factor of 1.2 at most. Such an increase will not significantly affect the results presented in this work. From the $Q_{\text{gas}}$ radial profiles of NGC 2915 and NGC 1705 presented in Figures 6 and 7, it is clear that a boost factor of at least $\sim 2$ is required to yield the innermost portions of each galaxy’s gaseous disk gravitationally unstable.

Because of the intense star burst activity near the center of NGC 1705, some of the system’s inferred $\text{H}_2$ surface densities are much higher than the corresponding $\text{H}_1$ surface densities. Caution has to be exercised in the case of NGC 1705, however. Although the THINGS sample of late-type galaxies of Bigiel et al. (2008) does include 11 late-type dwarfs, none of those systems exhibit star formation activity as extreme as that of NGC 1705. It is highly likely that extreme systems such as NGC 1705 do not obey the same star formation law as do more typical star-forming systems. In this sense we cannot quantitatively comment on the extent to which an incorporation of NGC 1705’s $\text{H}_2$ content into the star formation models will affect the results presented in this work.

7. SUMMARY

This paper deals with the investigations of various star formation models for the blue compact dwarf galaxies NGC 2915 and NGC 1705. Both galaxies contain small stellar disks embedded in much larger $\text{H}_1$ disks. We have used GALEX FUV and Spitzer 24 $\mu$m imaging of each galaxy to estimate its total SFR. New deep, high-resolution $\text{H}_1$ synthesis observations of each system have been used to quantify the distribution and kinematics of its neutral ISM.

The star formation models incorporate various properties of each galaxy’s ISM to determine which regions within the galaxy should be unstable against the tendency to gravitationally collapse and hence form high-mass stars on varying galactic length scales. The success or failure of these models sheds...
light on the interplay between the key properties of the ISM that regulate the star formation activity. The star formation thresholds in NGC 2915 and NGC 1705 are not purely local phenomena. The Toomre single-fluid $Q_{\text{gas}}$ criterion as well as the stars+gas and DM+gas two-fluid criteria ($Q_{\text{gas},a}$ and $Q_{\text{gas},DM}$, respectively) all use the epicyclic frequency at a given galactocentric radius within the galaxy as a measure of its kinematics. The $Q_{\text{gas}}$ criterion incorrectly predicts the entire H\textsc{i} disks of both NGC 2915 and NGC 1705 to be sub-critical. This result is consistent with that of Leroy et al. (2008), who found almost no area of the inner disk for their sample of 23 THINGS galaxies to be formally unstable to gravitational collapse in a Toomre $Q_{\text{gas}}$ context. These results suggest the Toomre $Q_{\text{gas}}$ criterion to be of limited utility in terms of distinguishing star-forming regions of high and low efficiency.

The stellar potential of each galaxy is expected to play a crucial role in regulating the star formation activity. Despite this expectation, however, the $Q_{\text{gas},a}$ criterion also fails for NGC 2915, whose entire H\textsc{i} disk is predicted to be sub-critical. The model cannot describe NGC 2915’s central star formation activity. The situation improves for NGC 1705 for which perturbation length scales of $\lambda \sim 200$ pc lead to predictions of its inner H\textsc{i} disk being formally gravitationally unstable.

Disk DM can account for the observed star formation activity in NGC 2915 and NGC 1705. Both galaxies are known to be extremely DM-dominated. The fraction of their DM that is co-located within the H\textsc{i} disk is treated as contributing to the self-gravity of the ISM. Assuming a pseudo-isothermal sphere parameterization of each galaxy’s DM halo, both NGC 2915 and NGC 1705 have formally unstable inner H\textsc{i} disks. This result does not hold for the case in which the distribution of the assumed disk DM exactly traces the H\textsc{i} distribution.

The final star formation model investigated in this paper is a shear-based model built on the premise that it is the time available for clouds to collapse in the presence of rotational shear that regulates a galaxy’s star formation. Indeed, adopting the rotational shear as a characterization of the global kinematics allows the $S_{\text{gas}}$ criterion to accurately locate the unstable parts of both NGC 2915’s and NGC 1705’s H\textsc{i} disks without the need for stellar or DM self-gravity. The same general result was obtained by Leroy et al. (2008), who found the inner disks of their galaxies to be more nearly super-critical in the context of a shear-based $S_{\text{gas}}$ criterion than in the context of a $Q_{\text{gas}}$ criterion.

In conclusion, despite NGC 2915 and NGC 1705 both being unusual star-forming galaxies, their star formation activity can be partly understood in terms of the self-gravity of the ISM which, in turn, is controlled by the combined effects of the gravitational potentials of their various mass components. Alternatively, the star formation activity in each system can be accounted for by correctly characterizing its global kinematics. Throughout this work, in lieu of published CO data, we have ignored any possible H$_2$ components. Molecular hydrogen must be present, it is unlikely that the observed star formation could be taking place without it. Based on our measured SFRs, we have estimated the amount of H$_2$ within each galaxy to be of the order of $\sim 10^7 M_\odot$ ($\sim 2$--3 orders of magnitude less than the dynamical mass of each galaxy). Although we cannot reliably incorporate the effects of this mass component into our star formation models, they are not expected to significantly affect the results.

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