

THE MOLECULAR ISM IN LOW SURFACE BRIGHTNESS DISK GALAXIES

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ABSTRACT

We present models for the interstellar medium in disk galaxies. In particular, we investigate whether the ISM in low surface brightness galaxies can support a significant fraction of molecular gas given their low metallicity and surface density. It is found that the abundance and line brightness of CO in LSB galaxies is small and typically below current observational limits. Still, depending on physical details of the ISM, the fraction of gas in the form of molecular hydrogen can be significant in the inner few kiloparsecs of a low surface brightness galaxy. This molecular gas would be at temperatures of ~ 30 – 50 K, rather higher than in high surface brightness galaxies. These results may help explain the star-forming properties and inferred evolutionary history of LSB galaxies.

Subject headings: galaxies: evolution — galaxies: ISM — galaxies: spiral — galaxies: structure — ISM: molecules — ISM: structure

1. INTRODUCTION

Low surface brightness (LSB) disk galaxies represent a class of galactic systems that have experienced very slow evolution since their formation epoch. Their low surface brightnesses ($\gtrsim 1$ mag arcsec⁻² below the canonical Freeman (1970) value of $\mu_0^b = 21.65 \pm 0.3$ mag arcsec⁻²) indicate that, over the age of the universe, their mean stellar birthrate per unit area has been significantly lower than that of typical high surface brightness (HSB) disks. Their current rate of star formation is similarly low—while some H II regions do exist in LSBs, the global star formation rate in LSBs is lower by an order of magnitude than comparably sized HSBs (McGaugh 1992; Knezek 1993; McGaugh & Bothun 1994; Rönnback & Bergvall 1994; de Blok, van der Hulst, & Bothun 1995; de Blok 1997). The lack of significant star formation is reflected in the low metallicities of LSBs, which are typically $\lesssim 1/3$ solar (McGaugh 1994; Rönnback & Bergvall 1995; de Blok & van der Hulst 1998a). Not coincidentally, LSBs are also very gas-rich systems. McGaugh & de Blok (1997) found that the gas mass fraction of galaxy disks correlates strongly with surface brightness. In LSBs, as much as 50% of the disk mass is in the form of gas, compared to $\sim 10\%$ at high surface brightnesses. Their low surface brightnesses, low star formation rates, low metallicities, and large gas fractions all argue that LSBs are systems that are forming stars much more slowly than their HSB counterparts.

The suppressed rate of star formation in LSB disks must ultimately be connected to the differing physical conditions of the interstellar medium (ISM) between LSB and HSB disk galaxies. As star formation is presumed to take place in molecular clouds, the molecular content of LSBs is of particular interest. In typical HSB spirals, the mass of molecular gas is comparable to that in neutral H I (e.g., Young & Knezek 1989). The situation in LSBs may be quite different—while several CO surveys of LSBs have been made (e.g., Schombert et al. 1990, hereafter S90; Knezek

1993; de Blok & van der Hulst 1998b, hereafter dBvdH), CO emission has not been detected in any LSB disk galaxy. If CO emission traces molecular gas content in the same way as in normal HSB galaxies, then the upper limits on molecular gas in LSBs are typically $M_{\text{H}_2}/M_{\text{H I}} \lesssim 0.1$ and are more severe in a few cases. These upper limits have led to the speculation that the low disk surface densities in LSBs preclude molecular cloud formation and, in turn, inhibit star formation (e.g., S90; van der Hulst et al. 1993; Bothun, Impey, & McGaugh 1997). Alternatively, the lack of CO detection may simply reflect the fact that the CO/H₂ conversion factor is not a universal constant, so that perhaps large quantities of molecular H₂ exist despite the lack of detected CO emission.

Unfortunately, an observational answer to the question of the molecular content of LSBs is inexorably tied to the CO/H₂ conversion factor and its dependency on environment. For example, Wilson (1995) and Israel (1997) recently showed that the CO/H₂ conversion factor was a strong function of metallicity; this dependency raises the upper limits on the derived molecular content of LSBs. Nonetheless, even accounting for metallicity effects, previous CO surveys should have detected CO in LSBs if they had $M_{\text{H}_2}/M_{\text{H I}}$ ratios similar to HSBs. Other dependencies should also play a role. For example, the local gas density and temperature can affect CO/H₂ (e.g., Maloney & Black 1988; Scoville & Sanders 1987). These are in turn affected by the ionizing radiation field and the density structure (“clumpiness”) of the ISM. In LSBs all these factors may well be significantly different than expected for HSBs, such that the true molecular-to-atomic gas mass ratio ($M_{\text{H}_2}/M_{\text{H I}}$) is only weakly constrained by direct CO measurements.

To explore the ISM properties of LSB galaxies in a manner independent of the CO/H₂ conversion factor, we take a complementary, theoretical route toward understanding the molecular content of LSB galaxies. We construct models of an inhomogeneous ISM under varying physical conditions, spanning a range of disk galaxy types. The models employ a Monte Carlo approach to radiative transfer (see Spaans 1996) and explicitly solve for the CO emissivity and $M_{\text{H}_2}/M_{\text{H I}}$ ratio in galactic disks. We investigate models on a grid of metallicity, surface brightness, and ISM density structure, tracking the changing physical conditions between LSB and HSB disk galaxies. In particular,

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we address the questions of how much molecular H_2 is expected in LSB disks, and whether the lack of observed CO in LSBs in fact indicates a lack of molecular gas.

2. ISM MODELING

2.1. Modeling Technique

The code developed by Spaans (1996) and its extensions as discussed in Spaans & van Dishoeck (1997), Spaans & Norman (1997), and Spaans & Carollo (1998) is used to derive the physical and chemical structure of the ambient ISM in LSBs. The interested reader is referred to these papers for a detailed description of the code's structure. The main features can be summarized as follows:

1. For a given metallicity, geometry, global pressure structure and distribution of illuminating (ultraviolet) sources, the thermal and chemical balance of the medium is computed in three dimensions. The continuum (dust attenuation) and line transfer is modeled through a Monte Carlo method. The self-shielding of H_2 and CO and the shielding of CO by H_2 absorption lines is explicitly included. The heating processes include photoelectric emission by large molecules like polycyclic aromatic hydrocarbons (PAHs) and dust grains (Bakes & Tielens 1994), cosmic-ray heating, collisional de-excitation of ultraviolet pumped H_2 , and H_2 dissociation heating. It is assumed that 10% of the gas phase carbon is incorporated into PAHs. This yields roughly equal photoelectric heating contributions from carbonaceous particles larger and smaller than 10^{-6} cm. Generally, photoelectric emission dominates the heating rate unless the visual extinction exceeds 3 mag. The cooling processes include fine-structure emission of C^+ , C, and O, rotational line emission of CO, and vibrational ($v = 1-0$) H_2 emission. All level populations are computed in statistical equilibrium and the line emission is again modeled through a Monte Carlo technique.

2. The solutions to the thermal balance equations allow, for a given hydrodynamic pressure, multiple solutions. These constitute the possible multiphase structure of the ISM as first suggested by Field, Goldsmith, & Habing (1969). If multiple solutions exist, then one finds from a stability analysis that there is a $\sim 10^4$ K diffuse medium and a ~ 50 K dense component. It is the density structure derived from these solutions which couples strongly with the chemical balance of interstellar gas, and therefore with the amount of molecular gas which is supported by the stellar radiation field and the ambient pressure of the galaxy. This thermal stability approach does not incorporate the effects of hydrodynamic phenomena such as shocks or gravity. The cold component has a typical density of $\sim 50-300 \text{ cm}^{-3}$ and is representative of diffuse and translucent clouds in the Milky Way. To allow the inclusion of shocks and gravity in a phenomenological way, the dense phase is allowed to exhibit inhomogeneities. That is, the ambient pressure determines the *mean* density of this phase, while gravity as well as shocks drive perturbations in it.

2.2. Model Parameters and Their Implementation

To investigate the molecular content of the ISM the following model parameters are considered: average gas density, the average UV interstellar radiation field (ISRF), metallicity, surface density, and ISM density structure. These parameters are not all independent. To capture the essential dependencies of the ISM structure on ambient

physical conditions, the following scaling relations are adopted.

The H I volume density $n_{H I}$ correlates with H I surface density $\Sigma_{H I}$ according to

$$n_{H I} = \Sigma_{H I} / H, \quad (1)$$

where $H = 300$ pc is the scale height of the galaxy model. Using data from de Blok, McGaugh, & van der Hulst (1996), one can derive a rough correlation between local surface brightness μ^B and local H I density:

$$\log \Sigma_{H I} \approx -0.12 * \mu^B + 3.6. \quad (2)$$

With this relationship, the H I surface density and stellar surface brightness do not drop off in lockstep; instead, the H I surface density falls off more slowly. While this is generally true, it should be emphasized that this relation is admittedly crude with a lot of real scatter. The aim is more to characterize the general behavior of disks to search for physically meaningful trends rather than to attempt to model specific individual galaxies. In global terms, the gas mass fraction of the disk increases as surface brightness decreases such that very low surface brightness disks ($\mu_0^B \gtrsim 23$) can have half their baryonic mass in the form of gas (McGaugh & de Blok 1997), even assuming a trivial amount of molecular gas mass.

The luminosity profiles of disk galaxies (especially LSBs) are generally exponential,

$$\mu^B(r) = \mu_0^B + 1.086 * (r/h), \quad (3)$$

with scale length h and central surface brightness in B magnitudes per square arcsecond μ_0^B . Combining equations (2) and (3), one finds

$$\log \Sigma_{H I} \approx -0.12 * \mu_0^B - 0.13 * (r/h) + 3.6. \quad (4)$$

Again, the relationship implies that, as a function of radius, the H I surface density drops off more slowly than the stellar surface brightness, reproducing the extended gaseous disks observed in disk galaxies. In this parameterization, the gas surface density is exponential, but with a scale length 3.3 times larger than that for the stars. While real gas disks are not as well described by exponentials as the stellar component, we again stress this is merely a convenient approximation for modeling purposes. Deviations from this approximation will alter only details and not the general trends of interest and are probably small compared to the uncertainty in the modeling process. Because equation (4) describes the H I surface density, while the model inputs are in terms of total ($H I + H_2$) gas surface density, we use an iterative scheme to arrive at the final model. First we calculate the model assuming a total surface density given by equation (4). From this initial model, we derive the H_2 mass profile, then add this profile to the original H I profile to produce a total gas mass profile. This total profile is then used as input to calculate a new, consistent ISM model.

To parameterize the strength of the ISRF in our models, we assume that the ISRF is dominated by the contribution from the stellar populations in galaxies. Under this assumption, the ISRF scales with surface brightness:

$$I_{UV} = I_{UV}(MW) * 10^{0.4 * [\mu_0^B(MW) - \mu_0^B]}, \quad (5)$$

where $I_{UV}(MW)$ is the strength of the ISRF in the Milky Way given by Draine (1978), and $\mu_0^B(MW)$ is the central surface brightness of the Milky Way disk (assumed to be 21 mag arcsec $^{-2}$). The wavelengths in the UV relevant to our

results are between 912 and 1110 Å, where lie all the H₂ and CO absorption lines which lead to photodissociation of the molecules. By scaling the UV ISRF with *B*-band surface brightness, we are assuming that the spectral shape is *independent* of surface brightness. That is, we assume that the stellar populations that give rise to the ISRF do not drastically change as a function of surface brightness. This assumption is perhaps suspect. Since there is generally less star formation in LSB than in HSB galaxies, one might suspect the UV ISRF to be relatively weaker in LSBs than implied by the difference in *B*-band surface brightness. On the other hand, LSBs do tend to be blue, late-type galaxies, which have harder spectral shapes in the optical. So one might equally well expect this trend to continue into the UV, resulting in the opposite effect: the difference in *B*-band surface brightness might overstate that in the UV. Without strong constraints on the UV properties of LSBs we choose simply to hold the shape of the ISRF fixed with optical surface brightness. If the UV ISRF is relatively greater (less) than we assume, more (fewer) molecules will be destroyed, and so on balance there will be less (more) gas mass in molecular form.

With the gas density and UV ISRF defined in terms of the disk surface brightness, we can similarly define a parameter closely akin to the ionization parameter:

$$\log U = \log (I_{\text{UV}}/\Sigma_{\text{H I}}) = -0.28\mu_0^B + \text{constant}, \quad (6)$$

which essentially measures the number of ionizing photons per atom. Because of our assumption that the ISRF scales linearly with surface brightness, while the gas density drops more slowly, LSB galaxies should have lower values of *U* than HSBs. If, however, LSBs have a harder spectral shape than HSBs (due perhaps to a younger, hotter mean stellar population), this assumption may underestimate *U* in LSBs. While we use surface brightness as a fundamental input parameter for the models, we note that with the pseudoionization parameter *U* defined this way, models with central surface brightnesses 0, 1, 2, and 3 mag arcsec⁻² below that of the Milky Way correspond to values of *U*/*U*_{MW} = 1.0, 0.5, 0.28, and 0.15, respectively.

Finally, we need to characterize the inhomogeneity of the dense phase, if it is supported, in the models. This inhomogeneity can be parameterized by *choosing* a certain volume fraction *F* of the gas in high-density clumps with a fixed density contrast *C*. The size of the clumps is not varied and assumed equal to 2 pc, typical for translucent clouds in the Milky Way. By investigating a range of density contrasts, and therefore clump extinction, this somewhat arbitrary length does not strongly influence the results. We calculate one model (“H,” see Table 1) that is completely homogeneous and lacks any density structure, representing a limiting extreme. Two more models are explored that have modest amounts of structure (“I1, I2,” with small *C* and large *F*). Finally, the clumpy ISM models (“C1, C2,” large *C* and small *F*; see Table 1) are chosen to represent our own Galaxy at high ISM pressure.

With these parameterizations, we are left with three variables describing the model galaxies: metallicity, ionization parameter, and ISM clumpiness. We create a grid of models spanning a range of plausible values: central surface brightness $\mu_0^B = 21 \rightarrow 24$, metallicity $Z/Z_\odot = 1 \rightarrow 0.1$, and ISM types H (homogeneous, $P \sim 10^3$ K cm⁻³), I1 and I2 (intermediate, $P \sim 2 \times 10^3$ K cm⁻³), and C1 and C2 (clumpy, $P \sim 10^4$ K cm⁻³). These models thus capture the

TABLE 1
ISM MODELS

Model	C ^a	F ^b
H.....	1	1.0
I1	2	0.5
I2	4	0.25
C1.....	20	0.25
C2.....	60	0.1

^a Density contrast between high-density and low-density gas.

^b Volume-filling factor of high-density gas.

properties of both high surface brightness spirals as well as low surface brightness disks. For each model we calculate the H₂ gas mass fraction as a function of radius, as well as the CO emissivity and mass-averaged gas temperature. From these models, we can analyze ISM trends with surface brightness and address the question of molecular gas content in low surface brightness disks.

3. RESULTS

3.1. Molecular Gas Fractions

Figure 1 shows $\Sigma_{\text{H}_2}/\Sigma_{\text{H I}}$ as a function of radius for several characteristic models. Several trends are immediately obvious:

1. At fixed metallicity and ISM structure, lower surface brightness models have *higher* molecular fractions (Fig. 1a). Because the number of ionizing photons per hydrogen atom decreases with decreasing surface brightness, the molecules in the low surface brightness models are less apt to be dissociated by the background ISRF.
2. At fixed surface brightness and ISM density structure, models with lower metallicity have lower molecular hydrogen gas content (Fig. 1b). This result is due to the fact that dust grains act as formation sites for molecules; lower metallicities mean fewer dust grains to drive molecule formation.
3. At fixed surface brightness and metallicity, clumpier ISM models have higher molecular gas fractions (Fig. 1c). In clumpy models, a larger mass fraction of the gas is found in denser cores and shielded from the background ISRF. Molecules in diffuse ISM models lack this shielding and are more easily dissociated by the UV background.

How well do these models describe actual disk galaxies? One point of constraint is provided by the Milky Way ISM. The high surface brightness, solar metallicity, and clumpy ISM model shows a mean H₂/H I mass ratio ~ 1 averaged across the inner scale length of the disk, similar to that inferred for Milky Way–like Sb galaxies (Young & Knezek 1989). This result is not surprising, since the ISM models were scaled to the ISRF and structure of the Milky Way’s ISM, but nonetheless it is reassuring that we recover the correct physical description for the given model inputs.

Assigning a model to LSB galaxies is not as straightforward. Certainly, LSB disks are lower in metallicity (Webster et al. 1983; McGaugh 1994; de Blok & van der Hulst 1998a) than HSB galaxies such as the Milky Way. Their reduced surface brightnesses also probably results in lower ionization parameters, although stellar population differ-

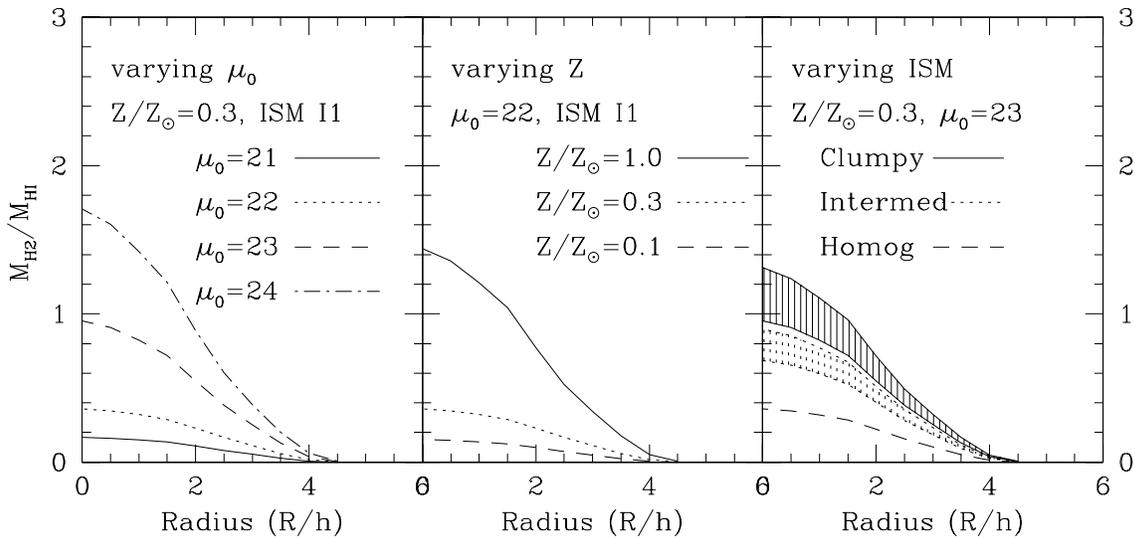


FIG. 1.—Radial $H_2/H\text{ I}$ mass ratio for representative model galaxies. Radii are measured in units of the disk scale length (i.e., R/h). (Left) With metallicity and ISM structure held fixed, lowered surface brightnesses lead to high molecular mass ratios. (Center) With surface brightness and ISM structure held fixed, the molecular mass ratio drops quickly with decreasing metallicity. (Right) At fixed metallicity and surface brightness, models with greater degrees of ISM density structure have greater molecular mass ratios. In this panel, vertical lines connect the two ISM choices for each of the “clumpy” and “intermediate” ISM models (see text).

ences may modify this somewhat. The density structure of the ISM in LSBs is not well determined, precisely due to the fact that CO measurements have not yielded any detections. Because of the lowered mass surface density of LSB disks (de Blok & McGaugh 1996, 1997), it is likely that the ISM pressures are too low to support the amount of multiphase structure found in the Milky Way. Such was the case in hydrodynamical models of LSB galaxies by Gerritsen & de Blok (1998), where a multiphase ISM was virtually absent. Models H (homogeneous) and I1 and I2 (intermediate) are therefore likely candidates to describe the density structure of LSB galaxies.

Figure 2 shows the $H_2/H\text{ I}$ mass ratio averaged over the inner disk scale length as a function of central surface brightness for the entire grid of models. For metallicities

typical of LSBs ($Z/Z_\odot = 0.1\text{--}0.3$), the models are lower in molecular content than the Milky Way, as expected. Interestingly, though, the models are far from being void of molecular gas; mass fractions of 0.25–0.5 are typical. Again, the lowered ionization parameter as a function of surface brightness results in *higher* molecular fractions (at fixed metallicity and ISM structure) for lower surface brightness galaxies. In fact, for very low surface brightnesses, the molecular content can rival that of HSBs if they have any significant degree of clumpiness in their ISM. However, at such low surface brightnesses, the ISM pressures are probably too low to support this level of structure.

Nonetheless, our models suggest that typical LSB galaxies have molecular contents that are only factors of 2–3 below that of normal HSB spirals. The CO mass-averaged

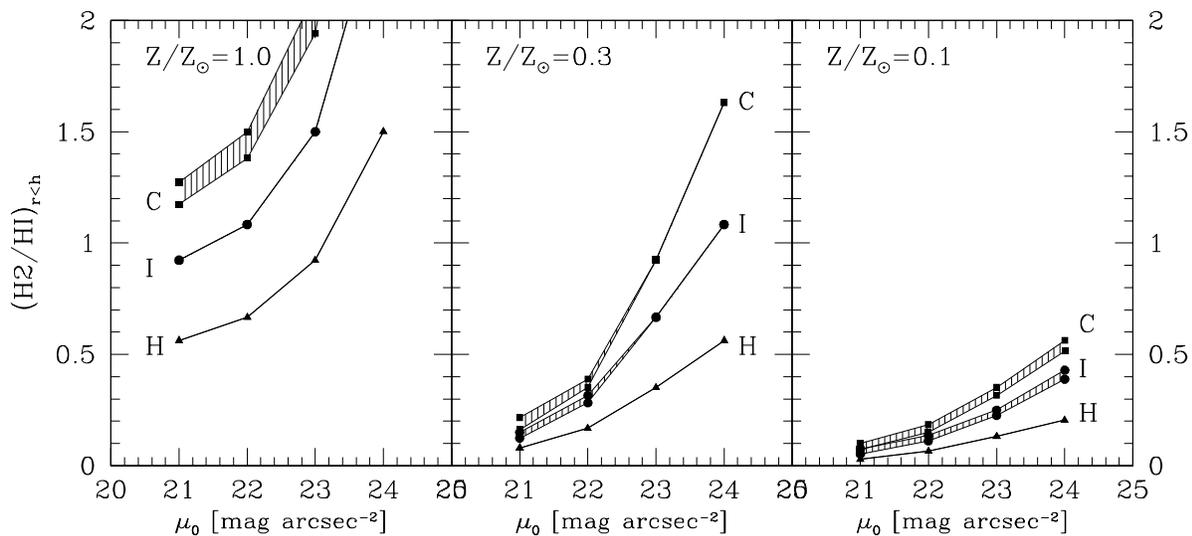


FIG. 2.— $H_2/H\text{ I}$ mass ratio, averaged over the inner scale length of the models, as a function of model surface brightness. Curves labeled “C,” “I,” and “H” refer to ISM models with clumpy, intermediate, and homogeneous density structure, respectively. (Left) $Z = Z_\odot$; (center) $Z = 0.3 Z_\odot$; (right) $Z = 0.1 Z_\odot$.

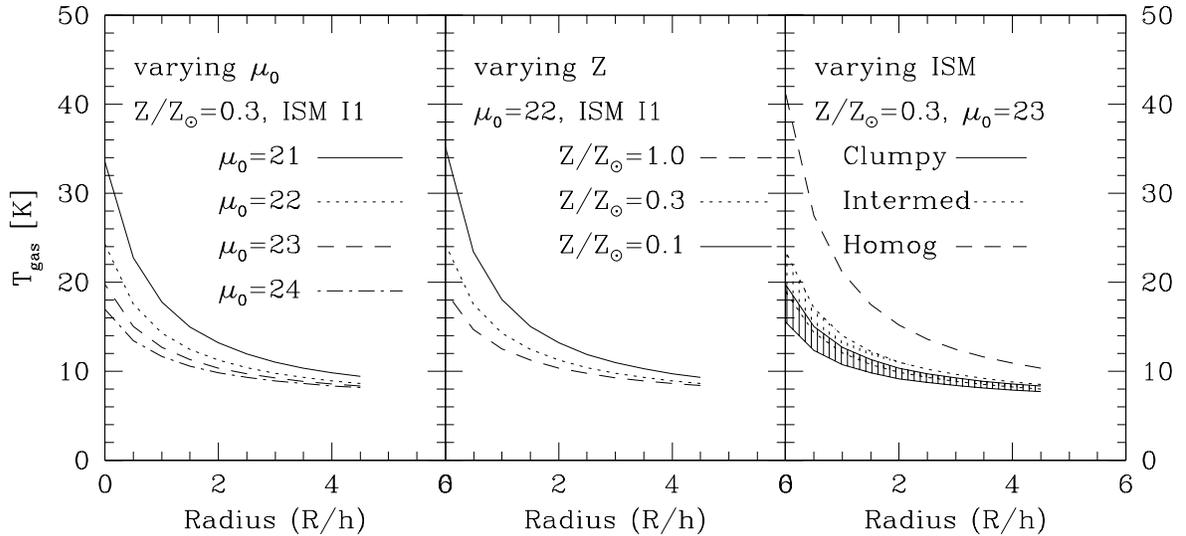


FIG. 3.—Mean molecular gas temperature, as a function of radius, for representative galaxy models. Radii are measured in units of the disk scale length (i.e., R/h). (Left) With metallicity and ISM structure held fixed, lowered surface brightnesses lead to colder molecular gas. (Center) With surface brightness and ISM structure held fixed, the molecular gas temperature rises with decreasing metallicity. (Right) At fixed metallicity and surface brightness, models with less density structure in their ISM have higher molecular gas temperatures. In this panel, vertical lines connect the two ISM choices for each of the “clumpy” and “intermediate” ISM models (see text).

gas temperatures in the molecular phase are presented in Figure 3 as a function of radius. It is immediately obvious that the molecular gas in LSBs is by no means very cold, in contrast with their multiphase counterparts. Typical temperatures are around 30–50 K, similar to Spitzer-type H I clouds in our own Milky Way. In Figure 4 we show the cumulative H_2 gas mass fraction averaged over the inner

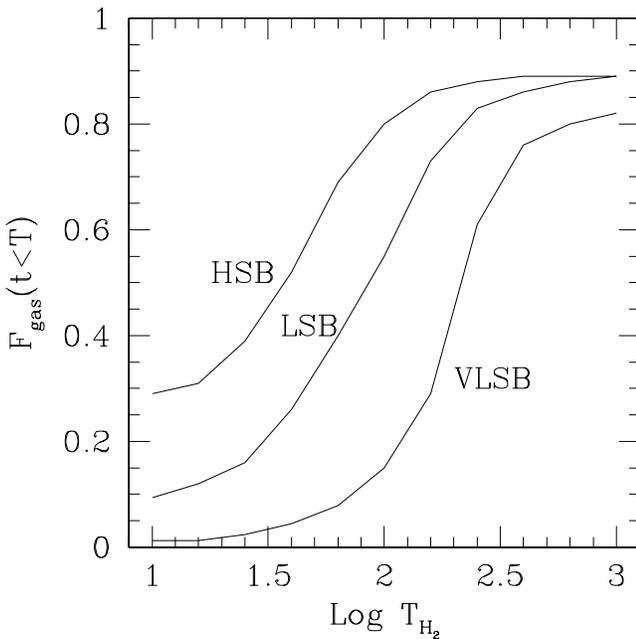


FIG. 4.—Cumulative histogram of molecular gas fraction as a function of temperature. The high surface brightness (HSB) model has $Z = Z_\odot$, $\mu_0^B = 21$, and the clumpy “C2” ISM structure. The low surface brightness (LSB) model has $Z = 0.3 Z_\odot$, $\mu_0^B = 23$, and the intermediate “I1” ISM structure. The very low surface brightness (VLSB) model has $Z = 0.1 Z_\odot$, $\mu_0^B = 24$, and the homogeneous “H” ISM structure. For the HSB model, nearly half the molecular gas is colder than 30K; for the LSB and VLSB models only 20% and $\lesssim 5\%$ of the molecular gas, respectively, is that cold.

scale length as a function of temperature for a Milky Way–like model ($\mu_0^B = 21$, $Z/Z_\odot = 1$, ISM C2), a typical LSB model ($\mu_0^B = 23$, $Z/Z_\odot = 0.3$, ISM I1), and a very low surface brightness model ($\mu_0^B = 24$, $Z/Z_\odot = 0.1$, ISM H). For the Milky Way model, nearly 50% of the molecular gas is at or below 30 K, compared to 20% and only a few percent for the typical and extreme LSB models. Coupled with the decrease in total molecular content in the LSB models, our calculations suggest that LSBs should have very small total amounts of cold molecular gas.

Such high temperatures argue against efficient star formation in LSBs, but self-consistent rates of the order of $\sim 0.05 M_\odot \text{ yr}^{-1}$ appear feasible in these low-metallicity environments (Norman & Spaans 1997; Gerritsen & de Blok 1998). This star formation rate is similar to observed star formation rates in LSBs (McGaugh & Bothun 1994; Rönnback & Bergvall 1994; de Blok et al. 1995). In conclusion, the lack of detected CO emission in LSBs does not preclude the presence of modest amounts of molecular H_2 gas. The CO detectability of an LSB depends on both the CO abundance and excitation in the galaxy; we turn now to predictions of the CO intensity of LSBs in order to directly compare to searches for CO emission from LSBs.

3.2. CO Intensity and the CO/ H_2 Conversion Factor

To calculate the CO intensity of the models, the root mean square velocity of the interstellar clouds, the vertical velocity dispersion, is taken equal to 10 km s^{-1} , a typical value in the Milky Way and other galaxies. The turbulent velocity width of individual clouds is assumed equal to 3 km s^{-1} , consistent with the observed correlation between cloud size and line width for the Milky Way (Maloney & Black 1988). We calculate the face-on CO intensities for our different ISM models, integrated over the inner scale length.

Figure 5 shows the variation in $I(\text{CO})$, the CO intensity in K km s^{-1} , as a function of metallicity, surface brightness, and ISM structure. As with the $H_2/H \text{ I}$ mass ratio, several trends are immediately apparent: lower metallicity, higher surface brightnesses, and a more diffuse ISM all act to lower

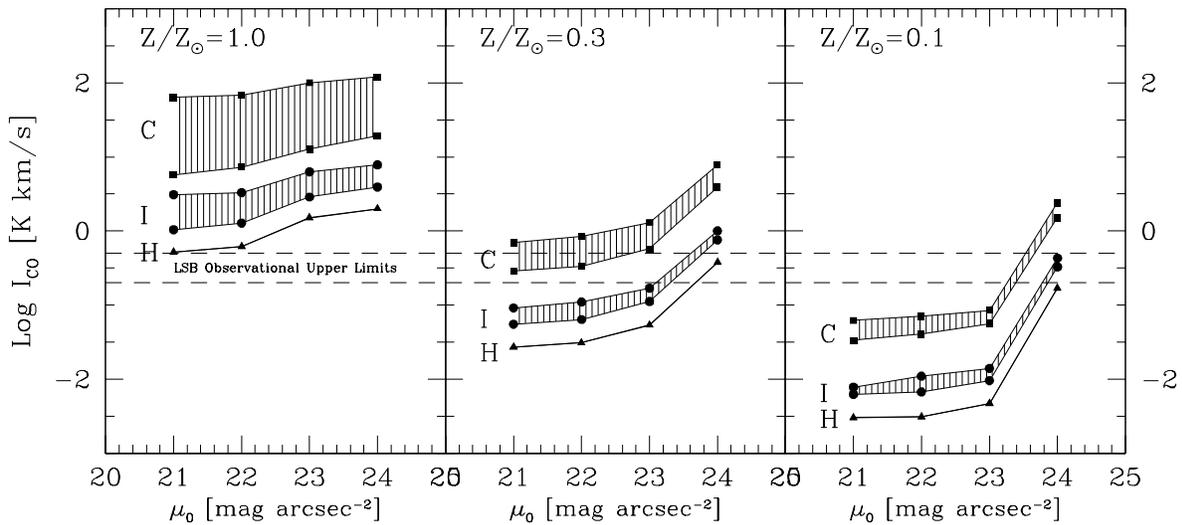


FIG. 5.—CO intensity as a function of surface brightness for the different model galaxies. Curves labeled “C,” “I,” and “H” refer to ISM models with clumpy, intermediate, and homogeneous density structure, respectively. Left: $Z = Z_{\odot}$; center: $Z = 0.3 Z_{\odot}$; right: $Z = 0.1 Z_{\odot}$. The dashed horizontal lines show the range of observational *upper limits* for LSB systems from S90 and dBvdH. Clumpy, high-metallicity systems (such as normal spiral galaxies) are easy to detect. Low-metallicity LSB galaxies have much lower CO intensities but may not be impossible to detect in CO, depending on details of their metallicity and ISM density structure.

the CO intensity in the models. All these trends are as expected. Lower metallicities mean fewer carbon and oxygen atoms are available to form the CO molecule; higher surface brightnesses result in a stronger ISRF, which destroys the CO molecule; and a diffuse ISM is less effective at shielding the CO molecules against radiative dissociation.

Also plotted on Figure 5 are the observational upper limits to the CO intensity of LSB galaxies determined by S90 and dBvdH. If LSBs have solar metallicity, these observations should have detected CO emission. But the subsolar metallicities of LSBs (McGaugh 1994) result in lowered CO intensities, making detection difficult. At $Z/Z_{\odot} \sim 0.3$, the CO emission is only a factor of ~ 2 – 5 below the obser-

vational limits, suggesting that deeper CO mapping may in fact reveal the molecular ISM of moderately metal poor LSBs. However, reducing the metallicity by another factor of 3 reduces the CO emission to levels 30 times fainter than the current observational limits; detecting these LSBs in CO will be very hard indeed. This drop in CO emission occurs in spite of the presence of a fair amount of H_2 in the models.

Perhaps most germane to the observational status of molecular gas in LSB disk galaxies is the conversion factor $X = n(H_2)/I(CO)$ in units of $10^{21} \text{ cm}^{-2} (\text{K km s}^{-1})^{-1}$. Figure 6 shows this value calculated for the grid of ISM models. As expected, X shows significant and systematic variation between the different models. At solar metalli-

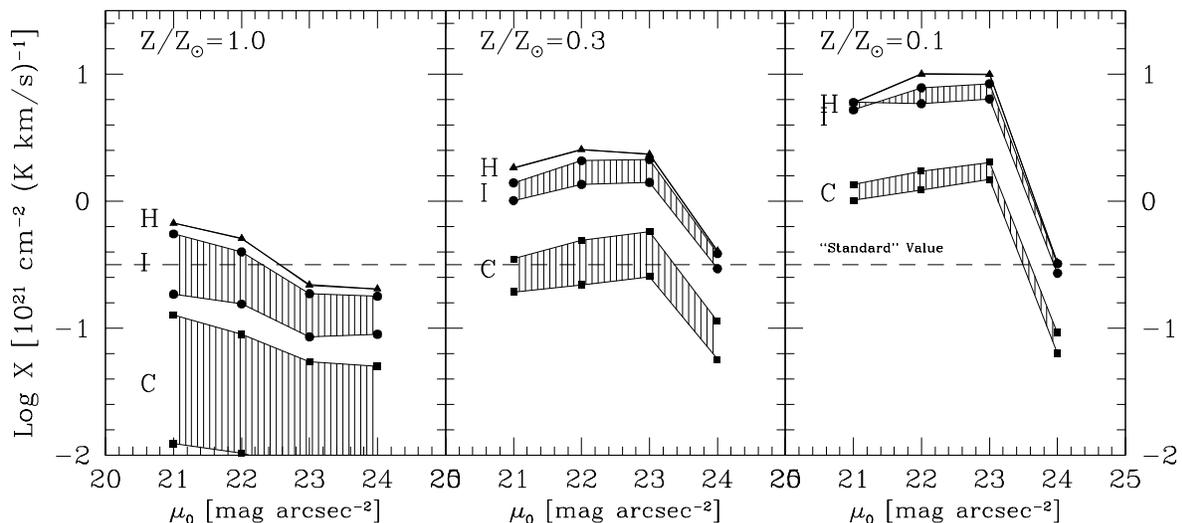


FIG. 6.—CO-to- H_2 conversion factor, X , as a function of surface brightness for the different model galaxies. Curves labeled “C,” “I,” and “H” refer to ISM models with clumpy, intermediate, and homogeneous density structure, respectively. Left: $Z = Z_{\odot}$; center: $Z = 0.3 Z_{\odot}$; right: $Z = 0.1 Z_{\odot}$. The dashed horizontal line shows the “standard” value typically used in CO studies (e.g., Scoville & Sanders 1987). Our models show that the value of X has a strong environmental dependence, varying by as much as 2 orders of magnitude over the range of parameters studied.

cities, $X \sim 0.1$ – 1 , spanning the “standard” value of X derived from Milky Way observations (~ 0.2 – 0.5 ; see, e.g., Scoville & Sanders 1987). Because the CO intensity scales nonlinearly with density, and in a different manner from the H_2 mass, X has a strong dependence on the density structure of the ISM. Our models calculate the properties of the ISM over the inner disk scale length, averaging over both cloud and intercloud regions. As the ISM becomes more clumpy, X decreases as the CO intensity rises faster than the H_2 mass fraction. The value of X determined in the Milky Way may therefore be quite different from that applicable to galaxies with a more homogeneous ISM.

Aside from the dependence on ISM density structure, there is also a clear correlation between X and metallicity: as metallicity drops, the value of X increases. Such a trend has also been seen in observational data (e.g., Wilson 1995; Israel 1997), and in models of low-metallicity clouds (Maloney & Black 1988). The strength of this trend is still quite uncertain. Israel (1997) finds a strong dependence on metallicity ($\partial \log X / \partial \log Z = -2.7 \pm 0.3$), whereas Wilson (1995) derives a weaker relationship, $\partial \log X / \partial \log Z = -0.67 \pm 0.1$. In our models, the relationship is dependent on the ISM phase structure but falls in the range $\partial \log X / \partial \log Z = -1$ to -2 . Again, however, it is difficult to directly compare our theoretical values with those determined observationally due to the different physical scales involved.

Given the strong dependence on metallicity and ISM density structure, it is clear that use of the standard Milky Way value of X is suspect in LSB galaxies. We can instead turn the problem around and ask, given our theoretical calculation of X , what are the inferred constraints on the molecular gas fraction of LSBs from the CO studies of S90 and dBvdH. If our models are correct, X in LSBs may be greater than the “standard value” by as much as a factor of 10, significantly raising the upper limits on LSB molecular gas content. A similar conclusion was reached by dBvdH, who explored the consequences of a nonstandard value of X . In that study, a value of X of 4 times the galactic value was favored, resulting in upper limits for LSB molecular contents of $M_{H_2}/M_{H_1} < 0.25$. Our models favor the use of a high value of X for LSBs, and indicate that the correct value may be even a factor of 2 higher than that favored by dBvdH. If so, the current nondetections of CO in LSBs still allow for significant molecular component of the ISM. More stringent limits on the molecular content of LSBs must await deeper CO observations.

4. DISCUSSION

Our models indicate that even very low surface brightness galaxies may not be completely void of molecular gas—instead, the ISM may contain 10%–20% of molecular gas (and perhaps more, depending on the detailed physical structure of the ISM). The physical conditions in this gas may be very different from the conditions in the molecular ISM of the Milky Way. If the ISM pressure is extremely low, as might be expected due to the low surface mass density of LSB disks, the molecular phase of the ISM will be diffuse and generally warmer than found in Galactic giant molecular clouds. The warm temperature is due largely to the lack of shielding from the ISRF in a diffuse ISM; even a modest multiphase ISM can self-shield the molecular gas and lower the gas temperature. However, the low surface densities and star formation rates of LSB galaxies make it

hard to generate and/or sustain such a multiphase ISM (e.g., Gerritsen & de Blok 1998).

Aside from the explicit dependencies of the models on ISM structure, ionization parameter, and metallicity, other more implicit model dependencies should also be reiterated. Our models assume that the UV ISRF scales with optical surface brightness. Stellar population differences between LSB and HSB galaxies are not well-determined, but the blue colors of LSBs argue that their stellar populations may be hotter than those of HSBs. If so, we may underestimate the ISRF in LSBs, thereby overestimating their molecular content. Similarly, we have modeled an ISM where the neutral gas density increases continually into the center of the model, whereas many LSBs show central depressions of gas density. Again, this effect may push us toward artificially high molecular contents (by underestimating the ionization parameter). However, the H I mass profiles of LSBs are varied, so rather than acting as a systematic effect in our models, the dependency on gas profile is perhaps better viewed as a caution against overinterpreting our results as they apply to *individual* LSBs. A third model dependency worth noting is the assumption that the dust-to-gas ratio of the galaxies scales linearly with metallicity. One expects something very close to this from simple considerations of chemical evolution (Edmunds & Eales 1998), and such a relationship is supported by observational data (e.g., Issa, MacLaren, & Wolfendale 1990). These dependencies are all tied to the systematic properties of LSBs, which remain ill constrained. Rather than attempting any further iteration on the models, we leave these effects as a caveat to the ensuing discussion.

These uncertainties notwithstanding, our models may also shed light on the lowered efficiency of star formation in LSB disks. Compared to HSBs, LSB galaxies have a lower fraction of molecular material from which they can produce stars. In addition, whatever molecular gas exists, it is in a more diffuse, warmer state than is typical for molecular material in HSBs. These warm temperatures and low densities act to help stabilize any existing molecular clouds against gravitational collapse. Indeed, since the Jeans length scales as $(T/\rho)^{1/2}$, the size scale for the collapse of ISM substructure is quite large in LSBs. The larger size of any unstable patches makes them very susceptible to differential shear in the rotating disks, so that gravitational collapse and subsequent star formation in the ISM of LSBs will be quite difficult. Even in the solid body portion of the rotation curve, where rotational shear is not a factor, the star formation rates remain low due to the increased collapse time of low-density structure.

This stability has been parameterized (e.g., Quirk 1972; Kennicutt 1989) in a form very similar to the Toomre Q parameter for the growth of axisymmetric modes (Toomre 1964). Under such prescriptions, star formation occurs when the gas surface density exceeds some critical value: $\Sigma_{\text{gas}} > \alpha \kappa \sigma / 3.36G$, where κ is the epicyclic frequency of the disk, σ the velocity dispersion of the gas, and α is a constant ~ 1 . Studies of LSB galaxies have shown that the H I surface density is generally below this critical threshold for star formation (van der Hulst et al. 1993). In fact, the innermost regions of LSB disks are often suppressed in H I; adding diffuse, undetected H_2 increases the gas surface density and may make LSB galaxies somewhat more susceptible to induced star formation (e.g., Mihos et al. 1997; O’Neil, Bothun, & Schombert 1998). However, the required

amount is not very reasonable. There are some LSBs with star formation at small radii where the H I gas is subcritical by a factor of 4 or more (W. J. G. de Blok 1998, private communication), quite a bit more than can be made up by molecular gas for reasonable model parameters. Whether this is a failure of our models or of the Quirk-Kennicutt criterion (or both) is unclear.

Similar to the local stability criteria, parameters exist to describe the stability of disks to growing global bar modes. One such parameterization is the Toomre X_2 parameter: $X_2 = \kappa^2 R / 4\pi G \Sigma_d$, where Σ_d is the total disk mass surface density. If $X_2 \gg 1$, disks are stable against $m = 2$ perturbations (Toomre 1981). Mihos et al. (1997) showed that because of their lowered disk surface density and increased dark matter content (relative to HSB disks), LSB galaxies are quite stable against such induced bar modes. The inclusion of additional disk mass in the form of molecular ISM reduces this disk stability, but sufficient dark matter exists in LSB galaxies to make them stable against all but the strongest perturbations.

We note in passing that the quantity of mass in this (as yet undetected) molecular ISM is not nearly sufficient to account for all the dark matter in LSB disks. Even under the dubious assumption of a maximum (stellar) disk, de Blok & McGaugh (1997) showed that the mass deficit in the inner regions of LSB galaxies is quite severe—significant amounts of dark matter must exist all the way into the centers of LSB disks. Under reasonable assumptions for the physical conditions in LSBs, our models suggest that the molecular ISM can increase the disk surface density *at most* by $\lesssim 50\%$. To account for all the mass deficit implied by the rotation curve fitting of de Blok & McGaugh (1997), the molecular ISM would need to be very cold and very clumpy, raising questions of why LSBs remain stable and how disk star formation is quenched.

The different evolutionary histories of HSB and LSB galaxies can be traced to differences in their disk surface densities and in the conditions of their ISMs. A plausible evolutionary scenario for HSB galaxies has been outlined

by Spaans & Norman (1997). In this scenario, once the proto-HSB gas disk forms, star formation begins at a retarded rate in the primordial molecular hydrogen ISM. This star formation generates supernovae and enriches the ISM, leading to a multiphase ISM that is able to cool and form stars efficiently—an HSB disk galaxy is born. In contrast, when a proto-LSB forms, it, too, forms a molecular ISM, but with a smaller molecular mass fraction and at lower surface density. At these low surface densities, it is difficult to trigger star formation or form/maintain a multiphase ISM. As a result, the LSB evolves little from its primordial conditions, maintaining its low surface brightness and metallicity, and high gas fraction.

Under “critical density” conditions for star formation, one might expect some bimodal surface brightness distribution for disk galaxies, as galaxies will naturally follow one of two alternative paths depending on their surface density. There is a claim of a bimodal surface brightness distribution in one cluster (Tully & Verheijen 1997), but this does not appear to be a general property of field galaxies (de Jong 1996). Instead, it is more likely that there is a continuum of physical conditions in disk galaxies driven ultimately by surface density. Low-density environments result in lowered star formation activity (as $t_{\text{dyn}} \sim \rho^{-1/2}$ even the absence of any critical density models) and suppress the formation of a multiphase ISM; as surface density increases along a galactic sequence, star formation and surface brightness increase, accompanied by a rise in the amount of complex phase structure (and higher molecular fractions) in the ISM. It is through this interplay that galaxy evolution and ISM processes shape the (cosmological) star formation rate.

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