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THE ROLE OF PRESSURE IN GIANT MOLECULAR CLOUD FORMATION

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ABSTRACT

We examine the hypothesis that hydrostatic pressure alone determines the ratio of atomic to molecular gas averaged over a particular radius in disk galaxies. The hypothesis implies that the transition radius, the location where the ratio is unity, should always occur at the same value of *stellar* surface density in all galaxies. We examine data for 28 galaxies and find that the stellar surface density at the transition radius is indeed constant to within 40% at a value of 120 $M_\odot$ pc^{-2}. If the hypothesis can be confirmed at all radii within a large range of galaxy types and metallicities, combining it with the observed relation between the star formation rate and H_2 surface density may enable us to derive a physically motivated star formation prescription with wide applicability.

Subject headings: galaxies: ISM — galaxies: structure — ISM: clouds — ISM: molecules — molecular processes

1. INTRODUCTION

Current ideas about the formation of giant molecular clouds (GMCs) present a nagging puzzle. Some authors have suggested that GMCs form by agglomeration of preexisting molecular clouds (e.g., Scoville & Hersh 1979; Kwan & Valdes 1983). Others have argued that GMCs form primarily from atomic gas through some sort of instability or large-scale shock (e.g., Woodward 1976; Blitz & Shu 1980; Engargiola et al. 2003). In principle, both modes may occur: in galaxies that are predominantly atomic, GMCs might form by one process, and in galaxies that are primarily molecular, the GMCs might form by another. If so, two different GMC formation mechanisms could be at work in the same galaxy because many galaxies show a transition from being predominantly molecular at their centers to being predominantly atomic in their outer parts (e.g., Wong & Blitz 2002; Helfer et al. 2003). For example, in the outer parts of spiral galaxies, there is so little molecular gas (e.g., Dame et al. 1987; Dame 1993; Heyer et al. 1998) that making GMCs from atomic gas seems to be the only available formation pathway. On the other hand, the centers of many galaxies are so overwhelmingly molecular (e.g., Mauersberger et al. 1989; Young et al. 1995; Wong & Blitz 2002; Helfer et al. 2003) that it is implausible for the inner galaxy molecular clouds to form from anything other than preexisting molecular gas. The stars in these galaxies form only from molecular gas, yet there is no obvious change in the star-forming properties across the molecular/atomic transition region. How could it be that molecular clouds that form by two independent processes would show no obvious difference in their star formation properties?

One possibility is that the process of cloud formation is independent of whether the preexisting gas is atomic or molecular. That is, the ratio of atomic/molecular gas depends on some other factor, such as the ambient pressure. Because the rate of star formation depends only on the amount of molecular gas (Wong & Blitz 2002), whatever determines the molecular gas surface density determines the variation of star formation within a galaxy.

In this Letter, we consider the hypothesis that the molecular gas fraction in a galaxy disk is determined by the mean hydrostatic pressure at a particular radius. We show that if the hydrostatic pressure is the only parameter determining the molecular gas fraction, one predicts that the radius at which the atomic and molecular gas surface densities are the same, the transition radius, occurs at a constant value of the *stellar* surface density, Σ_*. Remarkably, in a sample of 28 galaxies, Σ_* is found to be constant to about 40% at the transition radius, even though the observed variation of Σ_* in these galaxies is at least 3 orders of magnitude.

2. BACKGROUND

Several authors have previously suggested that gas pressure determines the molecular fraction at a given radius in a galaxy. Spergel & Blitz (1992), for example, argued that the extraordinarily large molecular gas fraction at the center of the Milky Way is plausibly the result of the very high hydrostatic pressure in the Galactic bulge. Elmegreen (1993) suggested on theoretical grounds that the ratio of atomic to molecular gas in galactic disks results from both the ambient hydrostatic pressure as well as the mean radiation field. The dependence on the pressure is steeper than that of the radiation density ($f_{\rm mol} \propto P^{2.2} j^{-1.1}$) and ought to be the dominant factor. Observationally, Wong & Blitz (2002) showed that the radial dependence of the atomic-to-molecular gas ratio in seven molecule-rich galactic disks can be understood to be the result of the variation in interstellar hydrostatic pressure (with $f_{\rm mol} \propto P^{0.8}$).

Let us assume, therefore, that $N(H_2)/N(\text{H I})$, the ratio of H_2 column density to H I column density, is determined *only* by the midplane hydrostatic pressure, $P_{\rm ext}$. In an infinite disk with isothermal stellar and gas layers, and where the gas scale height is much less than the stellar scale height, as is typical in disk galaxies, to first order,

$$P_{\rm ext} = (2G)^{0.5} \Sigma_g v_g \left[\rho_*^{0.5} + \left(\frac{\pi}{4} \rho_g \right)^{0.5} \right], \qquad (1)$$

where Σ_g is the total surface density of the gas, v_g is the velocity dispersion of the gas, ρ_* is the midplane surface density of stars, and ρ_g is the midplane surface density of gas. The first term on the right is due to the hydrostatic pressure of the gas in the stellar potential; the second term is due to the self-gravity of the gas.

In most galaxy disks, ρ_* is much larger than ρ_g when averaged over azimuth, except in the far outer parts of a galaxy where the stars become quite rare. In the solar vicinity, for example,

$\rho_* = 0.1\ M_\odot\ \mathrm{pc}^{-3}$ (e.g., Binney & Merrifield 1998), but $\rho_g \simeq 0.02\ M_\odot\ \mathrm{pc}^{-3}$ (e.g., Dame 1993). For a self-gravitating stellar disk, $\Sigma_* = 2\sqrt{2}\rho_* h_*$, where h_* is the stellar scale height and $h_* = (v_*^2/4\pi G\rho_*)^{0.5}$. Thus, neglecting ρ_g, equation (1) becomes

$$P_{\mathrm{ext}} = 0.84(G\Sigma_*)^{0.5}\Sigma_g \frac{v_g}{(h_*)^{0.5}}, \qquad (2)$$

where Σ_g is the total surface density of the gas, v_g is the velocity dispersion of the gas, ρ_* is the midplane surface density of stars, and ρ_g is the midplane surface density of gas. A direct solution of the fluid equations by numerical integration shows that this approximation is accurate to within 10% for $\Sigma_* > 20\ M_\odot\ \mathrm{pc}^{-2}$ (where $\rho_* \rightarrow \rho_g$), which covers the range of stellar surface densities in this study.

We choose to express the midplane pressure in the form of equation (2) since there is good evidence that both h_* and v_g are constant with radius in disk galaxies. Furthermore, because of the weak dependence of P_{ext} on h_*, and because of the small variation of h_* measured among galactic disks, we expect variations of h_* to have little effect on P_{ext}. The constancy of the stellar scale height within galaxies was demonstrated by van der Kruit & Searle (1981a, 1981b) and has been confirmed in other edge-on galaxies (e.g., Fry et al. 1999). While there is some evidence that the stellar scale height flares at large radii in some galaxies (Narayan & Jog 2002), this is only found at the edges of stellar disks in regions where the stellar, gaseous, and dark matter components of the disk make comparable contributions to the potential. Adopting a constant stellar scale height is further supported by the observations of Bottema (1993), who shows that the stellar velocity dispersion follows an exponential distribution with a scale length twice that of the stellar surface density in disks. This observation suggests that the stellar disk is distributed vertically in a $\mathrm{sech}^2\, z$ profile with $\sigma_* = (\sqrt{2}\pi G\Sigma_* h_*)^{1/2}$.

While the stellar component of galactic disks can be approximated with a constant scale height, the gas component is better described by a constant velocity dispersion, σ_g, which is observed in face-on galaxies (e.g., Shostak & van der Kruit 1984; Dickey et al. 1990) and the Milky Way (Burton 1971; Malhotra 1995). The Milky Way observations show that the gas scale height decreases as the stellar surface mass density increases in a manner consistent with the gas remaining isothermal (Malhotra 1995). This ensemble of observations suggests that $\sigma_g = 8\ \mathrm{km\ s^{-1}}$ characterizes the H I velocity dispersion in the stellar-dominated regions of galactic disks.

By assumption,

$$N(\mathrm{H_2})/N(\mathrm{H\ I}) = f(P_{\mathrm{ext}}). \qquad (3)$$

Thus, since $(v_g/\sqrt{h_*})$ is approximately constant within galaxies, then

$$N(\mathrm{H_2})/N(\mathrm{H\ I}) = f[P_{\mathrm{ext}}(\Sigma_g, \Sigma_*)]. \qquad (4)$$

The mass surface density of atomic gas, $\Sigma_{\mathrm{H\,I}}$, is reasonably constant across the inner portions of galactic disk (e.g., Wevers et al. 1986; Cayatte et al. 1994; Wong & Blitz 2002). While some changes of $\Sigma_{\mathrm{H\,I}}$ with radius are observed, the variation is small compared to the changes observed in stellar surface mass density and molecular surface mass density. We may therefore adopt a single value for the surface density of atomic gas in a galaxy across the stellar disk. N(H I) saturates at a value of about $1 \times 10^{21}\ \mathrm{cm^{-2}}$ (Wong & Blitz 2002). Thus, $N(\mathrm{H_2})/N(\mathrm{H\ I})$ has a value of unity when $2N(\mathrm{H_2}) + N(\mathrm{H\ I})$ has a value of $\sim 2 \times 10^{21}\ \mathrm{cm^{-2}}$. Equation (2) therefore implies that the radius where the atomic and molecular surface densities are equal in spiral galaxies depends only on Σ_* if v_g/h_* is constant.

3. RESULTS

We use the Berkeley-Illinois-Maryland Association Survey of Nearby Galaxies (Helfer et al. 2003), an interferometric imaging survey of the CO in 44 nearby spiral galaxies, to determine the distribution of the molecular gas. To determine the H_2 surface density, we use a conversion factor of $N(\mathrm{H_2})/T_A(\mathrm{CO})\Delta v = 2 \times 10^{20}\ \mathrm{cm^{-2}}\ (\mathrm{K\ km\ s^{-1}})^{-1}$. For the H I, we adopted a single value that characterizes the column density across the galactic disk. These values were drawn from maps of galaxies reported in the literature. Adopted values and the corresponding references appear in Table 1 along with the orientation parameters and distances used in Helfer et al. (2003). If no H I observations have been reported for the galaxies, we used a value of $8\ M_\odot\ \mathrm{pc}^{-2}$, which corresponds to a surface density of $1 \times 10^{21}\ \mathrm{cm^{-2}}$, typical for the stellar disks of galaxies.

The stellar surface densities are determined using reduced K-band images from the Two Micron All Sky Survey (2MASS) Large Galaxy Atlas (Jarrett et al. 2003). We adopted a constant K-band mass-to-light ratio of $M_L/L_K = 0.5\ M_\odot/L_\odot$ (Bell & de Jong 2001). Our final sample consists of only those galaxies with both 2MASS data and CO detections. Of these, 22 galaxies have H I surface densities in the literature, and six galaxies do not. The stellar and gas surface densities are corrected to face-on values using the orientation parameters listed in Table 1.

We define the transition stellar surface density ($\Sigma_{*,t}$), where $N(\mathrm{H_2}) = N(\mathrm{H\ I})$, as the median value of the stellar surface density at all positions for which $0.9N(\mathrm{H\ I}) \leq N(\mathrm{H_2}) \leq 1.1N(\mathrm{H\ I})$. We associate this surface mass density with the transition radius R_t in the galaxy by finding the radius where the azimuthally averaged stellar surface mass density $\Sigma_*(R_{\mathrm{gal}})$ equals the transition surface density, $\Sigma_{*,t}$. In Figure 1, we plot the transition radius against the transition stellar surface density, using the adopted distances in Table 1. We also list the values of $\Sigma_{\mathrm{H\,I}}\sqrt{\Sigma_{*,t}}$ in Table 1 as a check since P_{ext} depends directly on this quantity.

Figure 1 shows a remarkable constancy of $\Sigma_{*,t}$, which is expected if $N(\mathrm{H_2})/N(\mathrm{H\ I})$ is determined by pressure only; the mean value is $120 \pm 10\ M_\odot\ \mathrm{pc}^{-2}$. Also plotted in the figure is the range of Σ_* measured for each individual galaxy. Formally, the dispersion in the mean value of $\Sigma_{*,t}$ is only 40%, yet the range of Σ_* to which 2MASS is sensitive in these galaxies varies by almost 3 orders of magnitude. The scatter in $\Sigma_{\mathrm{H\,I}}\sqrt{\Sigma_{*,t}}$ given in Table 1 is only 60%. The range of galactocentric distance where the transition radius occurs varies by more than an order of magnitude. Apparently, the constancy of $\Sigma_{*,t}$ is not due to a small range in the observed properties of the galaxies. The small scatter in $\Sigma_{*,t}$ also suggests that various assumptions, such as that of a constant value of h_* both within and among galaxies, are justified.

As a check, one can calculate the value of $\Sigma_{*,t}$ for the Milky Way, scaling the measured Σ_* at the distance of the Sun ($35\ M_\odot\ \mathrm{pc}^{-2}$; Binney & Merrifield 1998), and a radial scale length for the stars of 3 kpc (Spergel et al. 1996; Dehnen & Binney 1998). The transition radius for the Milky Way occurs at a

TABLE 1
Adopted Galactic Parameters

Galaxy Name	Distance (Mpc)	Inclination (deg)	Position Angle (deg)	$\Sigma_{\rm H\,I}$ ($M_\odot$ pc^{-2})	$\Sigma_{\rm H\,I}\sqrt{\Sigma_{*,t}}$ ($M_\odot$ pc^{-2})$^{3/2}$	Reference
NGC 628	7.3	24	25	4.9	52	1
NGC 1068	14.4	33	13	13.5	161	2
IC 342	3.9	31	37	4.0	59	3
NGC 2903	6.3	61	17	5.0	63	4
NGC 3184	8.7	21	135	8.0	81	
NGC 3351	10.1	40	13	5.0	56	5
NGC 3368	11.2	46	5	4.0	46	6
NGC 3521	7.2	58	164	8.0	75	
NGC 3627	11.1	63	176	2.2	23	7
NGC 3726	17.0	46	10	7.0	62	4
NGC 3938	17.0	24	0	7.5	67	8
NGC 4051	17.0	41	135	4.0	36	9
NGC 4258	8.1	65	176	4.5	53	4
NGC 4303	15.2	27	0	8.6	96	10
NGC 4321	16.1	32	154	5.0	49	9
NGC 4535	16.0	45	28	4.3	38	10
NGC 4569	16.8	62	23	5.4	51	10
NGC 4579	16.8	37	95	3.2	27	10
NGC 4736	4.3	35	100	8.0	123	9
NGC 4826	4.1	54	111	10.0	118	11
NGC 5005	21.3	61	65	8.0	116	
NGC 5033	18.6	62	170	8.0	62	9
NGC 5055	7.2	55	105	6.3	72	9
NGC 5248	22.7	43	110	8.0	93	
NGC 5247	22.2	29	20	8.0	73	
NGC 5457	7.4	27	40	6.3	81	9
NGC 6946	5.5	54	65	7.8	95	12
NGC 7331	15.1	62	172	8.0	87	

References.—(1) Kamphuis & Briggs 1992; (2) Brinks et al. 1997; (3) Crosthwaite et al. 2001; (4) Wevers et al. 1986; (5) Schneider 1989; (6) Warmels 1988; (7) Zhang et al. (1993); (8) van der Kruit & Shostak 1982; (9) Wong & Blitz 2002; (10) Cayatte et al. 1994; (11) Braun et al. (1994); (12) Tacconi & Young 1986.

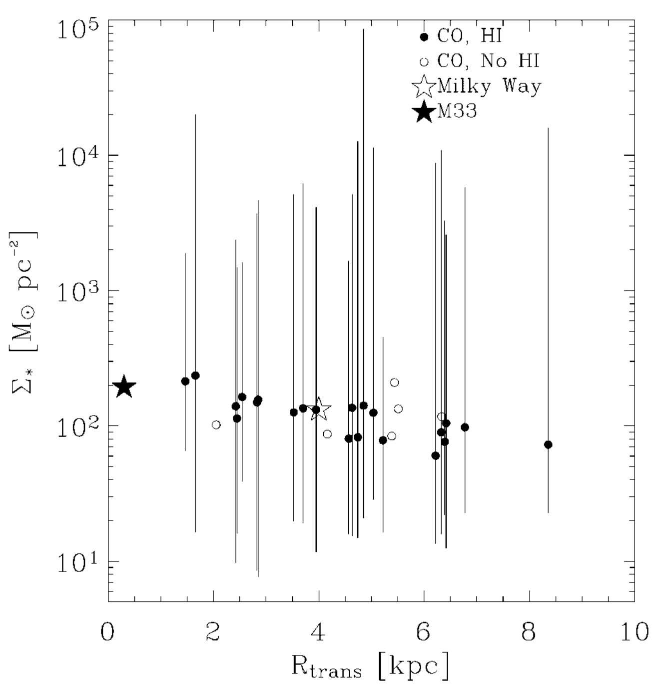

Fig. 1.—Plot of the median stellar surface mass density where $N(H_2) = N(\text{H I})$ as a function of where this surface density occurs in the galaxy. For galaxies with measured H I densities (*filled circles*, 22 galaxies), the *range* of stellar surface densities is plotted as an error bar, running between the values of the first percentile and the 99th percentile of surface density in the galaxy. Galaxies without H I measurements are plotted as open circles (six galaxies). The transition's stellar surface density is remarkably constant and has a mean value of $120 \pm 10\ M_\odot$ pc^{-2} for the 22 galaxies with both CO and H I data. Points for the Milky Way and M33 are also plotted.

galactocentric distance of about 4 kpc (Dame 1993), or about 1.3 scale lengths inward of the Sun. This converts to a stellar surface density of 132 $M_\odot$ pc^{-2}, in good agreement with the determinations in other galaxies. The trend can also be checked in M33 using the data for $f_{\rm mol}$ presented in Heyer et al. (2004), which gives $\Sigma_{*,t} = 190\ M_\odot$ pc^{-2}, where $\Sigma_{\rm H\,I} = \Sigma_{\rm H_2}$ ($R_{\rm gal}$ = 300 pc).

There appears to be a small but significant decrease in the transition surface density with radius, which may be due to a breakdown of the assumptions of a constant mass-to-light ratio, v_g and h_* with radius, or to the assumption that pressure alone determines $N(H_2)/N(\text{H I})$. A linear fit to the data in Figure 1 gives $\log \Sigma_* = (2.36 \pm 0.05) - (0.06 \pm 0.01)(R/1\ \text{kpc})\quad M_\odot\ \text{pc}^{-2}$ with errors given by the scatter in the data around the trend.

4. DISCUSSION

Figure 1 is consistent with the hypothesis that the mean hydrostatic pressure determines the ratio of atomic to molecular gas at a given radius in a disk galaxy. The small scatter in the mean value of Σ_* suggests that globally, the pressure may be the *only* important factor in determining the ratio of atomic to molecular gas. But the variation in the hydrostatic equilibrium of a disk is expected to be rather smooth. Why then do galaxies show so much azimuthal variation in the molecular gas, and by implication in the atomic-to-molecular gas ratio (Helfer et al. 2003)? Significant variations in the interstellar pressure can result from a variety of causes such as spiral shocks and explosive events (e.g., supernovae). Thus, large pressure variations can occur on all scales locally even if the mean hydrostatic pressure varies only slowly. Furthermore, even if the hydrostatic pressure drives the ratio globally, locally the radiation field can be important in determining how much of a molecular cloud can remain neutral (Hollenbach & Tielens 1999). Thus, significant deviations from the mean molecular abundance can be produced by both pressure and radiation variations.

Pressure or density? The rate of formation of molecular gas is thought to be dependent on the local gas density in the chemical reactions that produce H_2 and CO. Are we then using pressure as a surrogate for the mean gas density in determining $N(H_2)/N(\text{H I})$ as a function of galactocentric distance? Pressure, as defined in equations (1) and (2), is taken to be $\rho_g \sigma_g^2$, where σ_g includes both thermal and turbulent contributions. Because σ_g is measured to be typically 7–8 km s^{-1} and because the gas temperature of the cold gas layer where most of the gas mass resides is typically $\lesssim$100 K, the thermal pressure is only a small fraction of the turbulent pressure. Observationally, σ_g is constant with radius (see § 2); thus $P_{ext} \propto \rho_g$; variations in pressure are effectively the same as variations in density. We choose to describe the functional dependence in terms of pressure rather than density because it is directly measurable through equation (2) (assuming h_* is known), whereas the density is inferred and not directly measurable on galactic scales. But it should be kept in mind that given the measured constancy of σ_g, we cannot distinguish the effects of pressure from those of density.

What pressure is implied by $\Sigma_{*,t}$? In the Milky Way, the value of h_* is about 300 pc (Binney & Merrifield 1998), v_g is about 7 km s^{-1} (Dickey & Lockman 1990), Σ_g is 8.6 $M_\odot$ pc^{-2}, and Σ_* is 132 $M_\odot$ pc^{-2}. Using equation (2), $P_{ext}/k = 1.5 \times 10^4$ cm^{-3} K after correcting for helium. This value is still an order of magnitude below the mean internal $P_{int}/k \sim 3 \times 10^5$ cm^{-3} K for GMCs that have typical surface densities of ~100 $M_\odot$ pc^{-2} (Blitz 1993). Because $P_{int} \gg P_{ext}$, GMCs that survive for more than a crossing time, $\sim 10^7$ yr, must be self-gravitating. Using equation (2) to scale P_{ext} to the inner regions of disks suggests that GMCs are self-gravitating over nearly the entire disk.

What are the implications for understanding star formation on galactic scales? If the global atomic/molecular transition is governed by pressure across a wide range of galaxies, it will be possible to develop a prescription for star formation on global scales that is physically well motivated. The nonthermal radio continuum is tightly correlated with the far-IR emission in galaxies (e.g., Condon 1992), implying that the radio continuum is a good extinction-free indicator of the star formation rate in spiral galaxies. Murgia et al. (2002) have shown that for a sample of 180 spiral galaxies, the ratio of radio continuum to CO emission is constant to within a factor of 3, suggesting that the star formation efficiency of molecular clouds averaged over galactic scales is constant at about 3.5%. Therefore, if the relationship between pressure and $N(H_2)/N(\text{H I})$ (i.e., the function f in eqs. [1] and [2]) can be determined for all galaxies, or if the variation in f can be found for different galaxy types, then it will be possible to determine the star formation rate in galaxies by measuring the stellar and gas surface densities only. Furthermore, it will be possible to obtain the star formation rate reliably from simulations since the turbulent gas pressure can be directly calculated. In addition, if the variation in f can be measured for galaxies of low metallicity, then determining the star formation rate can be extended to high z. The measurement of f will be the subject of a future paper.

We suggest, then, that GMCs can form from either preexisting atomic or molecular gas depending on the dominant state of the diffuse interstellar medium at a particular radius in a galactic disk. That dominant state is determined by the hydrostatic pressure, modified by local perturbations such as density waves, supernova remnants, etc.

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