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MOLECULAR GAS IN SPIRAL GALAXIES: A NEW WARM PHASE AT LARGE GALACTOCENTRIC DISTANCES?

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ABSTRACT

There is now strong evidence suggesting that the ^{12}CO $J = 1–0$ transition, widely used to trace H_2 gas, significantly underestimates its mass in metal-poor regions. In spiral disks such regions are found at large galactocentric distances, where we show that any unaccounted H_2 gas phase is likely to be diffuse ($n \sim 5–20$ cm^{-3}) and warmer ($T_{kin} \sim 50–100$ K) than the cool ($T_{kin} \sim 15–20$ K) CO-luminous one. Moreover, we find that a high value of the H_2 formation rate on grains, suggested by recent observational work, can compensate for the reduction of the available grain surface in the metal-poor part of typical galactic disks and thus enhance this CO-poor H_2 component, which may be contributing significantly to the mass and pressure of spiral disks beyond their optical radius.

Subject headings: dark matter — galaxies: individual (NGC 891) — galaxies: ISM — ISM: molecules

1. INTRODUCTION

The use of ^{12}CO, the most abundant molecule after H_2 itself, to trace H_2 gas has been a widely used practice since the discovery of bright ^{12}CO $J = 1–0$ emission in Orion (Wilson, Jefferts, & Penzias 1970). The most easily excited H_2 transition, the quadrupole $S(0)$: $J_u - J_l = 2–0$, corresponds to $\Delta E_{20}/k \sim 510$ K, much too high to be significantly populated in the cool interstellar medium (ISM; $T_{kin} \sim 10–50$ K) revealed by the ^{12}CO $J = 1–0$ transition ($\Delta E_{10}/k \sim 5.5$ K). Furthermore, the large optical depths of the latter ($\tau_{10} \sim 5–10$) reduce its critical density of $n_{cr}^{(10)} \sim 380$ cm^{-3} (for $T_{kin} = 50$ K; Kamp & Zadelhoff 2001) to $\sim n_{cr}^{(10)}(1 - e^{-\tau_{10}})\tau_{10}^{-1} \sim 40–80$ cm^{-3}, similar to the lowest average densities observed in giant molecular clouds (GMCs). Hence the ^{12}CO $J = 1–0$ transition is expected to be excited even in the coldest and most diffuse regions of the molecular ISM.

However, its large optical depths (e.g., Martin, Sanders, & Hills 1984; Sage & Isbell 1991; Falgarone 1997) do not allow a straightforward use of its luminosity together with a [$^{12}CO/H_2$] abundance ratio for H_2 mass estimates. The widely used $X_{CO} = M(H_2)/L_{CO}$ factor (where L_{CO} is the velocity/area-integrated brightness temperature of ^{12}CO $J = 1–0$) is based on the notion of an effectively optically thin medium, where the ^{12}CO line emission arises from an ensemble of small, radiatively decoupled cells not overlapping in space or velocity. Then the high optical depths arise locally within the individual cells and the observed wide line profiles result from their macroscopic motions rather than their intrinsic, much narrower line widths (e.g., Martin et al. 1984; Young & Scoville 1991 and references therein). This picture, along with the observed virialization of molecular clouds (see, e.g., Larson 1981) over a wide range of scales ($\sim$0.1–100 pc), allows a statistical derivation of X_{CO} as an ensemble average that is relatively insensitive to local molecular cloud conditions (e.g., Dickman, Snell, & Schloerb 1986; Young & Scoville 1991; Bryant & Scoville 1996) and, for scales $\gtrsim 10$ pc, is expected to yield the correct H_2 mass to within a factor of 2.

The existence of such cells is supported by high angular and velocity resolution studies of galactic clouds (e.g., Falgarone et al. 1998; Tauber 1996), while the statistical robustness of X_{CO} for a variety of conditions has been verified using both observational (e.g., Young & Scoville 1991 and references therein) and theoretical (e.g., Kutner & Leung 1985; Dickman, Snell, & Schloerb 1986; Maloney & Black 1988; Wolfire, Hollenbach, & Tielens 1993; Sakamoto 1996; Bryant & Scoville 1996) methods. However, these studies also suggest a likely failure of this method in two particular environments, namely, (1) galactic and/or starburst nuclei, where nonvirial motions cause the luminous ^{12}CO emission to overestimate the H_2 mass (e.g., Dahmen et al. 1998; Downes & Solomon 1998), and (2) metal-poor regions, where it seriously underestimates the H_2 mass (e.g., Maloney & Black 1988; Arimoto, Sofue, & Tsujimoto 1996; Israel 1988, 1997, 1999). The last case is the most serious one since then ^{12}CO emission is usually faint and thus precludes the observation of more optically thin isotopes such as ^{13}CO and $C^{18}O$ that could yield the H_2 mass without using the X_{CO} factor.

In this paper we show that the decreasing metallicity with galactocentric radius in disks and a larger H_2 formation rate open up the possibility of large amounts of H_2 gas being there, hitherto undetected by the conventional method. This phase will be warm, diffuse, and devoid of CO and may contribute significantly to the pressure and total mass of the disk.

2. SPIRAL DISKS: H_2 FORMATION IN THE METAL-POOR PARTS

Molecular hydrogen in interstellar conditions forms from H I association onto dust grains (e.g., Gould & Salpeter 1963) and deep submillimeter imaging shows the grain distribution extending beyond the optical and well into the H I disk (Nelson, Zaritsky, & Cutri 1998; Xylouris et al. 1999) and possibly out to $\sim 2R_{25}$ (Thomas et al. 2001, 2002; Cuillandre et al. 2001). *Thus the basic "ingredients" for* H_2 *formation can be found to the outermost parts of the disk as defined by the* H I *distribution itself.* Using the results of Federman, Glassgold, & Kwan (1979), with an exponent of $m = 1.5$ for the H_2 self-shielding function, we find that an H I cloud of radius $R_{\rm cl}$ (pc), average volume density n, and temperature T, illuminated by a FUV field strength G_0 [$G_0(\rm solar) = 1$], starts turning molecular when $s > 1$, where

$$s = \frac{n}{n_{\rm min}} = R_{\rm cl}^{2/5}\left(\frac{n}{65\ \rm cm^{-3}}\right)\left(\frac{T}{100\ \rm K}\right)^{3/10}\left(\frac{\mu z}{\rm G_0}\right)^{3/5} . \quad (1)$$

The density $n_{\rm min}$ is the minimum required for the onset of an H I–to-H_2 transition, and $z = Z/Z_\odot$ is the normalized metallicity. We kept the explicit temperature dependence of the H_2 formation rate $R_f = S_f T^{1/2}$, assumed that it scales linearly with total grain surface and thus metallicity, and included the factor $\mu = S_f/S_f^{(o)}$, to parametrize for a value different than the currently adopted $S_f^{(o)} = 3 \times 10^{-18}$ cm^3 s^{-1} K$^{-1/2}$ (Jura 1975a).

Over an H I disk it is $T(\rm H\ I) \sim 80$–150 K, with a slight increase with galactocentric distance $R_{\rm gal}$ (e.g., Braun 1997), a temperature range typical of the warm neutral halos around molecular clouds (e.g., Andersson & Wannier 1993) where the H I–H_2 transition zone lies. Thus no significant variation of s is expected because of a strongly varying $T(R_{\rm gal})$. The influence of the z/G_0 ratio is less straightforward since significant metallicity gradients exist in spiral disks (e.g., Henry 1998; Garnett 1998 and references therein) along with the well-known exponential optical (and hence FUV) light profiles. Their effects have been thoroughly modeled by Elmegreen (1989, 1993) and applied to spiral galaxies by Honma, Sofue, & Arimoto (1995). The latter find the metallicity gradient to be the main cause of the so-called molecular front, the steep H_2–to-H I transition at a particular $R_{\rm tr}$ deduced for most spirals from CO imaging. Evidently a larger H_2 formation rate will alter this picture by "pushing" this front to encompass a larger portion of a typical disk. Rates that are ~4–8 times higher than the standard value are compatible with observationally deduced upper limits (Jura 1974), since they always contain an n-S_f "degeneracy" that can bias S_f estimates toward lower values (e.g., Jura 1975a, 1975b; van Dishoeck & Black 1986). Recent results from *Infrared Space Observatory* (*ISO*) observations of H_2 rotational lines from photodissociation regions (Habart et al. 2000; Li et al. 2002) strongly favor $\mu = S_f/S_f^{(o)} \gtrsim 5$ (see also Sternberg 1988 for early indications of such high values), which will raise the value of s at all $R_{\rm gal}$.

This rescaling has no effect for those regions of the disk where the old values are already $s > 1$ and which CO imaging shows to be indeed H_2-rich, but now a larger portion of the disk is expected to have $s > 1$ and thus conditions favorable for an H I–to-H_2 transition. A rough estimate of this new radius can be obtained from the results of Honma et al. (1995) that show this transition to occur very sharply at a particular $R_{\rm tr}$. The expected FUV volume emissivity j_0, its dust-absorption coefficient k_d, and the metallicity follow a similar spatial distribution (Honma et al. 1995); hence, neglecting the H_2 self-shielding contributions to the total absorption coefficient corresponds to $z/G_0 = z/(j_0/k_d) \propto z$. For an exponential disk profile and $s(R_{\rm tr}) \sim 1$, it is

$$R_{\rm tr}(\mu) = R_{\rm tr}(1) + (\ln \mu) R_e , \quad (2)$$

where R_e is the scale-length of the exponential distribution of optical light and metallicity. Thus the molecular front will now reside at least $(\ln 5)R_e \sim 1.6R_e$ farther, past that inferred by CO imaging. In typical disks the later is at $R_{\rm tr}(1) = (0.5$–$1)R_e$ (e.g., Young & Scoville 1991; Regan et al. 2001), and thus $R_{\rm tr}(\mu) \sim (2$–$2.5)R_e$ places the molecular front well inside a typical H I disk. A flattening of the abundance gradient, and thus of dust grain surface per H nuclei, at large $R_{\rm gal}$ (Henry 1998) and H_2 self-shielding will only strengthen the above arguments by yielding still larger values of s in the outer parts of the disk.

Therefore, it now seems that the molecular front in spirals, deduced from CO imaging, is in reality a (low) metallicity-induced ^{12}CO detection threshold, and *the necessary conditions for H_2 formation exist over a much larger part of a typical spiral disk.* This is not surprising since it is known that $X_{\rm CO} \propto z^{-1}$ to z^{-2} (e.g., Arnault et al. 1988; Israel 1997), which alone implies a $R_{\rm tr}$ larger than that found by using ^{12}CO imaging and a constant value of $X_{\rm CO}$.

2.1. *The Role of Pressure in the* H I–H_2 *Transition*

In obtaining the previous result we assumed no significant changes of (n, $R_{\rm cl}$) of the various clouds with $R_{\rm gal}$, which leaves only the z/G_0 variable to define $R_{\rm tr}$. In a forthcoming paper we will present a more detailed analysis of the H I–H_2 transition without such simplifications, yet a reformulation of s in terms of cloud mass M and boundary pressure P_e suggests that the aforementioned assumptions do not subtract from the generality of our result. Using the results of Elmegreen (1989) (his S function and s are related simply as $s = S^{3/5}$), we obtain

$$s \sim 1.1\left(\frac{P_e}{10^4\ \rm cm^{-3}\ K}\right)^{13/20}\left(\frac{M}{10^5\ M_\odot}\right)^{-3/10} \times \left(\frac{T}{100\ \rm K}\right)^{3/10}\left(\frac{\mu z}{\rm G_0}\right)^{3/5} . \quad (3)$$

It is clear that unless M is a strong function of $R_{\rm gal}$, a radially declining P_e is the only other important factor besides $\mu z/G_0$ in determining $R_{\rm tr}$. The increase of s with decreasing M seems counterintuitive, but it is due to the fact that small clouds have higher average densities than big ones with the same boundary pressure. This stems from the widespread virialization of most of the clouds, which in combination with the observed velocity dispersion versus cloud size relation (e.g., Larson 1981) yields $n \propto R_{\rm cl}^{-\alpha}$ ($\alpha \sim 1$). In the metal-rich part of a typical spiral, where CO can be relied upon as an H_2 gas-mass tracer, the bulk of the H_2 mass is distributed in a cloud hierarchy, with $M \sim 10^5\ M_\odot$ being typically the upper limit. The value of the latter is not observed to change with galactocentric distance (e.g., Elmegreen & Elmegreen 1987) except in galactic centers where tidal effects may truncate such a cloud hierarchy at higher minimum densities and cloud masses (e.g., Maloney & Black 1988).

The measurement of P_e, especially as a function of $R_{\rm gal}$, is not easy, and deducing it by assuming equipartition with the random cloud motions (e.g., Honma et al. 1995) relies on a known total gas surface density, which is what needs to be determined. This task is easier for the Galaxy, whose disk we consider typical in that respect. In this case a pressure probe sampling its outer parts, namely, diffuse CO-luminous molecular clouds, suggests pressures of $P_e(12\ \mathrm{kpc}) \sim (1\text{–}2) \times 10^4\ \mathrm{cm}^{-3}$ K (Heyer, Carpenter, & Snell 2001), which are higher than expected and similar to the solar neighborhood value. Farther out, pressures of $P_e(17\ \mathrm{kpc}) \sim 5 \times 10^3\ \mathrm{cm}^{-3}$ K are typical, with few clouds reaching up to $\sim 10^5\ \mathrm{cm}^{-3}$ K (Brand & Wouterloot 1995). It is straightforward to show that since $0.25 \lesssim z/G_0 \lesssim 1$ (at $R_{\rm gal} \lesssim 17$ kpc), for $\mu = 5$, such P_e values yield $s \gtrsim 1$. Thus the H_2 formation conditions are fulfilled out to $\sim 2.5 R_e (\sim 17$ kpc). This radius is well past the location of the ^{12}CO $J = 1\text{–}0$ brightness peak at ~ 5 kpc or any significant ^{12}CO emission (e.g., Blitz 1997) and well into the H I disk. Interestingly, H II regions, another potential pressure probe, may also hint at larger than expected pressures in the outer Galaxy (Rudolph et al. 1996) and dwarf irregular galaxies (Elmegreen & Hunter 2000). In both of these cases, low metallicities make ^{12}CO a poor indicator of H_2 gas, which may thus be responsible for the high pressures.

3. MOLECULAR GAS AT LARGE GALACTOCENTRIC RADII: CO-DEFICIENT AND WARM

The arguments for favorable conditions for an H I–to-H_2 phase transition presented here do not and could not yield a mass estimate for the associated H_2 gas. Nevertheless, the simple fact that this gas resides in the metal-poor parts of the disk, untraceable, by CO can offer significant insights regarding its state. An obvious consequence of the low metallicities is reduced dust shielding, which allows even the weaker FUV radiation field at large values of $R_{\rm gal}$ to dissociate the mainly dust-shielded CO and confine it to much smaller volumes while leaving the largely self-shielding H_2 intact. A typical range of $G_0 \sim 0.3\text{–}0.6$ and an $\mu \sim 5$ yields a minimum H_2 formation density of $n_f \sim 5\text{–}7\ \mathrm{cm}^{-3}$ for cloud sizes of $\sim 10\text{–}50$ pc. Observations of CO-luminous molecular clouds yield average densities of $\sim 50\text{–}500\ \mathrm{cm}^{-3}$ irrespective of galactocentric distance; hence $n \sim 5\text{–}500\ \mathrm{cm}^{-3}$ and $z \sim 0.15$ are appropriate inputs for photodissociation region (PDR) models of the molecular gas at large $R_{\rm gal}$. Similar modeling of metal-poor gas has been performed before, but at much higher UV fields and gas densities than here (e.g., Pak et al. 1998).

We investigate the gas abundance of warm H_2 using a PDR code that models the chemistry of a diffuse cloud represented as a semi-infinite slab with a pseudo–time-dependent multipoint chemical simulation (Viti, Williams, & O'Neill 2000). The UMIST chemical database (Millar et al. 1997) was used with some changes (see Viti et al. 2000). The heating, the cooling, and CO emission is as described by Taylor, Harquist, & Williams (1993); we have, however, made the following changes: (1) the thermal balance is achieved using Ridder's method, a fast nonlinear convergence algorithm; (2) the heating mechanisms have been revised and now include also large grains and polycyclic aromatic hydrocarbons (Weingartner & Draine 2001), as well as UV pumping (not important for low values of G_0 and densities) and chemical heating; and (3) the collisional rates have been updated to include all the dominant collisional partners for such an ISM phase (H, H_2, He). All our runs were performed assuming a microturbulent line formation with a typical width of $\sim 3\ \mathrm{km\ s}^{-1}$, and, following Tielens & Hollenbach 1985, the level populations are updated from the outside in. The heating caused by the decay of the turbulent gas is negligible.

The results are summarized in Figure 1, where it becomes apparent that in diffuse gas of subsolar metallicity the CO-deficient H_2 gas dominates the cloud. This radiation-driven spatial segregation also maintains a temperature difference in which the pure H_2 phase stays always warmer than the CO-luminous one. This simply reflects the different dominant coolants present, namely, ^{12}CO and its isotopes for the CO-luminous phase and C II and H_2 for the CO-deficient one. Average temperatures of $T_k \sim 15\text{–}20$ K are observed for most quiescent CO-luminous molecular clouds in the disk (with $T_k \sim 30\text{–}60$ K found only in star-forming warm "spots") and remain almost constant with $R_{\rm gal}$. In the Galaxy this is beautifully demonstrated by *COBE* observations of CO $J+1 \rightarrow J$ ($J = 0\text{–}7$) lines that show invariant *relative* strengths, suggesting that $T_k \sim 20$ K over the entire disk except the Galactic center (Fixsen, Bennett, & Mather 1999). This temperature is similar to those of several individual molecular clouds, some as far as $R_{\rm gal} \sim 30$ kpc (Digel, de Geus, & Thaddeus 1994), and also similar to that measured by *COBE* for the bulk of the dust in the Galaxy (Sodroski et al. 1994; Lagache et al. 1998) and by submillimeter imaging in other spirals (e.g., Alton et al. 1998). Such gas temperatures are indeed expected for the dust-shielded ($A_v \gtrsim 4$) CO-rich H_2 clouds, where CO cooling (Goldsmith, & Langer 1978; Neufeld, Lepp, & Melnick 1995) lowers T_k to that of the concomitant dust, whose temperature is weakly dependent on the ambient interstellar radiation field and thus on $R_{\rm gal}$.

For the unshielded regions of the molecular ISM, now expected to contain the bulk of the H_2 gas mass in the metal-poor parts of spiral disks, lack of the CO coolant will keep $T_k > T_{\rm dust}$ (e.g., Tielens & Hollenbach 1985). Its temperature range can be found from

$$\Lambda_{\rm C\,II} + \Lambda_{\rm H_2} = \Gamma_{\rm ph} + \Gamma_{\rm CR}\ , \tag{4}$$

where the cooling (Λ) due to the C II and H_2 lines is balanced by the photoelectric heating from dust grains $\Gamma_{\rm ph}$ (e.g., Tielens & Hollenbach 1985) and cosmic rays. Unlike solar metallicity environments, the cooling due to H_2 lines may now be important and is included.

The C II emission emanates from a two-level system, hence following Hollenbach, Takahashi, & Tielens (1991), and for optically thin emission it is

$$\Lambda_{\rm C\,II} = 1.82 \times 10^{-23} zn \left[1 + \frac{1}{2} e^{92/T} \left(1 + \frac{n_{\rm cr}}{n}\right)\right]^{-1}\ \mathrm{ergs\ s}^{-1}\ , \tag{5}$$

where $n_{\rm cr} \sim 3 \times 10^3\ \mathrm{cm}^{-3}$ is the transition's critical density, and all carbon is assumed in the form of C II, mixed with a fully molecular gas phase at an abundance of $[\mathrm{C/H}] = 3 \times 10^{-4} z$.

For the expected range of densities and $T_k \lesssim 200$ K (a typical upper limit for the cold neutral medium (CNM) in spiral disks), only the $S(0)$ and $S(1)$ lines rotational lines of H_2 can

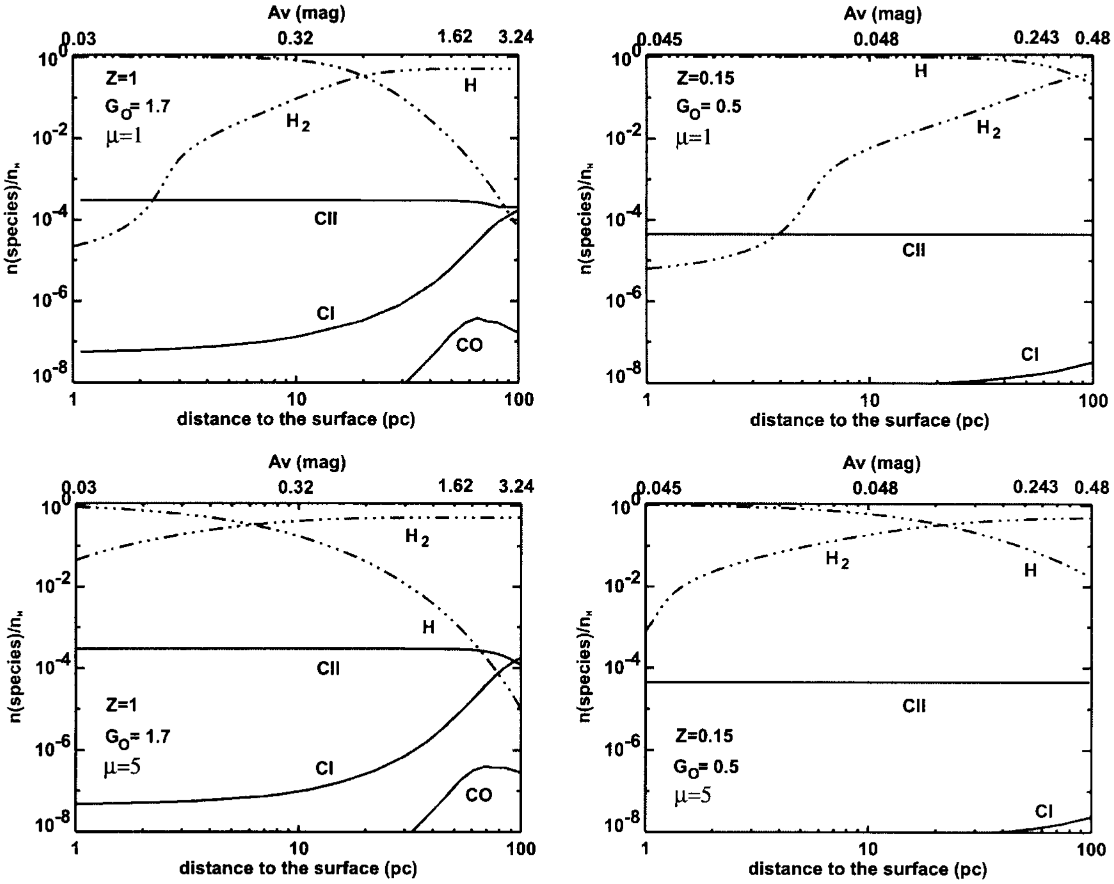

FIG. 1.—Relative abundance profiles of H_2, H, C II, C I, and CO for a one-side illuminated cloud with total H nuclei density of $n = 20$ cm^{-3} (see text). The values of metallicity, FUV field and formation rate used are denoted in the upper or bottom left. The effect of an enhanced formation rate in making the cloud H_2-dominated within much smaller spatial scales is apparent.

be appreciably excited and thus contribute to the cooling. Moreover, since no radiative or collisional processes " mix " ortho-H_2 (J = odd) and para-H_2 (J = even) states, we can consider $S(0)$ and $S(1)$ as practically arising from two different molecules, each approximated by a two-level system; therefore

$$\Lambda_{H_2} = 2.06 \times 10^{-24} \frac{n}{1+r_{op}} \left\{1 + \frac{1}{5} e^{510/T} \left[1 + \frac{n_{cr}(0)}{n}\right]\right\}^{-1} \times (1 + R_{10}) \text{ergs s}^{-1} , \quad (6)$$

where $r_{op} = (n_3 + n_1)/(n_2 + n_0)$ is the ortho-to-para H_2 ratio, $n_{cr}(0) \sim 54$ cm^{-3} is the critical density of the $S(0)$ transition, and $R_{10} = \Lambda_{S(1)}/\Lambda_{S(0)}$, namely,

$$R_{10} = 26.8 r_{op} \left(\frac{1 + 1/5e^{510/T}\{1 + [n_{cr}(0)/n]\}}{1 + 3/7e^{845/T}\{1 + [n_{cr}(1)/n]\}}\right)_{op} . \quad (7)$$

The critical density of the $S(1)$ transition is $n_{cr}(1) \sim 10^3$ cm^{-3}, and this term dominates for the warmest and densest gas in the chosen parameter space.

We adopt the latest photoelectric heating model of Weingartner & Draine (2001), with Γ_{ph} proportionally scaled by the normalized metallicity factor z and parameters corresponding to carbonaceous grains (the last two models in their Table 2). The assumed electron abundance is the average for the CNM, under a similar set of (z, G_0), i.e., $n_e/2n \sim 5 \times 10^{-4}$ (Wolfire et al. 1995). Finally, we include a heating factor from cosmic rays, $\Gamma_{CR} = 6.4 \times 10^{-28}$ n ergs s^{-1} (Goldsmith & Langer 1978), which is $\lesssim 10\%$ of the photelectric term.

For $G_0 = 0.3$–0.6, $z = 0.15$, and $r_{op} = 1$–3, both a diffuse ($\sim$5–20 cm^{-3}) and a dense ($\sim$100–500 cm^{-3}) H_2 gas phase satisfy equation (4), with the former being warmer ($\sim$50–100 K) than the latter ($\sim$20–30 K). At least for the Galaxy, these solutions can be further constrained by the values of the total pressure $P_e \lesssim (5$–$20) \times 10^3$ cm^{-3} K, at $R_{gal} \gtrsim 8$ kpc, where

$$P_e = nk_BT + 56.8n\sigma_z^2 \quad (8)$$

(e.g., van Dishoeck & Black 1986). The second term expresses the nonthermal part of the pressure due to the macroscopic motions of the gas, which are assumed to be of turbulent origin, with σ_z being the one-dimensional FWHM of a Gaussian distribution. The velocity dispersions of CO-bright molecular clouds or H I in face-on spirals yield $\sigma_z \sim 5$ km s^{-1} (Combes 1999 and references therein); hence the aforementioned constraints on the total disk pressure correspond to $n \sim 5$–15 cm^{-3} (for $T \lesssim 100$ K). *Thus a metal-poor, warm, and diffuse* H_2 *gas in the outer parts of spiral disks is likely to exist*, and it may indeed be the type of gas detected through its $S(0)$ line with *ISO* in the edge-on spiral NGC 891 (Valentijn & van der Werf 1999), with a reported temperature of $T \sim 90$ K and a mass that outweighs that of H I by factors of $\sim$5–15.

Several issues regarding such a gas phase remain open, namely, its thermal stability, its low star formation rates, its exact relation to the H I gas distribution, and the dynamical evolution of such potentially massive gaseous disks. Moreover, an enhanced H_2 formation rate, if indeed at work, may alter relevant aspects of the "standard" ISM picture (e.g., gas heating) that must be taken into account in a detailed analysis. These and other issues will be the subject of a future paper.

4. CONCLUSIONS

In the light of mounting evidence that the standard method of using rotational line emission of the ^{12}CO molecule to trace H_2 underestimates its mass at low metallicities, we examined the state of such gas in the disks of spiral galaxies at large galactocentric distances. Our results can be summarized as follows:

A high H_2 formation rate along with the presence of dust throughout a typical H I disk, both suggested by recent observations, raise the possibility of an extended H_2 gas phase, well past the one inferred by the ^{12}CO brightness distribution.

This phase is likely to be warm and diffuse, and it may be responsible for the observed high total pressures at large Galactocentric distances in the Galaxy. In the case of NGC 891 such a massive gaseous reservoir may have already been detected through its $S(0)$ line emission.

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