A molecular gas phase in the Cold Neutral Medium?

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Abstract. I examine the possibility that the Cold Neutral Medium of the interstellar medium in galaxies contains a molecular gas phase that may represent a significant and even the dominant amount of its mass in metal-poor regions. In spiral galaxies such regions are found at large galactocentric distances where diffuse H$_2$ gas will be untraceable through its feeble $^{12}$CO J=1–0 emission, the very lack of it being also responsible for its higher kinetic temperatures ($T_k \sim 60 - 100$ K). Sensitive sub-mm imaging of spiral galaxies has demonstrated the existence of dust well inside their HI gas distribution while recent observational work suggests a high H$_2$ formation rate from HI association onto grains. The latter is indeed a critical unknown and a high value can easily compensate for the reduction of the available grain surface in the metal-poor environments giving rise to a CO-poor, diffuse H$_2$ phase that may then contribute significantly to the mass and pressure of the interstellar medium in such environments.

1. Introduction

The use of CO rotational lines to detect the bulk of H$_2$ gas mass in galaxies and deduce its physical properties is now a well-established technique (e.g. Dickman, Snell, & Schloerb 1986; Young & Scoville 1991) employed successfully in the local Universe (e.g. Sanders, Scoville & Soifer 1991; Downes & Solomon 1998) as well as high redshifts (e.g. Brown & vanden Bout 1991; Omont et al. 1996). Nevertheless early studies have indicated serious limitations of the method in tracing metal-poor H$_2$ gas (e.g. Maloney & Black 1988; Israel 1997). These become particularly severe in metal-poor environments where the reduced dust-shielding allows UV photons to dissociate the CO molecule while leaving the largely self-shielding H$_2$ intact. This is now corroborated by firm observational evidence for the metal-poor outer parts of typical spirals (Nakai & Kuno 1995; Arimoto et al. 1996), in globally metal-poor objects like the Magellanic Clouds and Magellanic Irregulars (Israel 1997; Madden et al. 1997), and blue compact dwarf galaxies (Barone et al. 2000). Interestingly in many such environments pressure “probes” like diffuse CO-bright molecular clouds (Heyer, Carpenter, & Snell 2001) or HII regions (Rudolph et al. 1996; Elmegreen, & Hunter 2000) imply unexpectedly high pressures which then suggest the presence of a pressure agent other than HI or CO-bright H$_2$ gas.
2. H$_2$ formation rate: its role in metal-poor environments

The dominant formation mechanism of H$_2$ in interstellar environments is by HI association onto dust grains. The dust distribution according to recent sensitive maps of its sub-mm emission extends beyond the optical and well into the HI disk of a typical spiral (Nelson, Zaritsky, & Cutri 1998; Xylouris et al. 1999), and possibly out to \( \sim 2R_{25} \) (Thomas et al. 2002; Guillandre et al. 2001). Hence the two ingredients for H$_2$ formation can be found to the outermost and metal-poor parts of typical spiral disks. From Federman, Glassgold, & Kwan (1979) and an exponent of \( m=1.5 \) for their H$_2$ self-shielding function it can be shown that an HI cloud of radius \( R_{cl} \) (pc), average volume density \( n \), and temperature \( T_k \), illuminated by a FUV field strength \( G_\odot \) (\( G_\odot \) (solar) = 1) starts turning molecular when \( S > 1 \), where

\[
S = \frac{n}{n_{min}} = R_{cl}^{2/5} \left( \frac{n}{65 \text{cm}^{-3}} \right) \left( \frac{T}{100K} \right)^{3/10} \left( \frac{\mu z}{G_\odot} \right)^{3/5}.
\]  

(1)

The density \( n_{min} \) is the minimum required for the onset of the H \( \rightarrow \) H$_2$ transition and \( z = Z/Z_\odot \) is the ambient metallicity normalized to its solar value. We assumed that the H$_2$ formation rate of \( R_f = S_f T^{1/2} \) scales linearly with total grain surface and thus metallicity, and included the factor \( \mu = S_f/S_f^{(o)} \), to parametrize for a value other than the canonical \( S_f^{(o)} = 3 \times 10^{-18} \text{ cm}^3 \text{ s}^{-1} \text{ K}^{-1/2} \) (Jura 1975a). The Cold Neutral Medium (CNM) HI phase, out of which H$_2$ forms, has typically \( T_k \sim (80 - 150) \text{ K} \) with a slight increase with galactocentric distance \( R_{gal} \) (e.g. Braun 1997). Using the aforementioned H$_2$ formation criterion or equivalent expressions the steep H$_2$ \( \rightarrow \) HI transition at a particular \( R_{tr} \) in spiral disks has been modelled, and its sensitivity to variations of pressure and metallicity demonstrated (Elmegreen 1993; Honma, Sofue, & Arimoto 1995). However, all these studies have not examined the effect of a larger H$_2$ formation rate which will simply be to “push” the molecular-rich part to encompass a larger portion of a typical disk.

Molecular hydrogen formation rates that are \( \sim 4 - 8 \) times higher than the standard value are compatible with observations, since these always contain an \( n - S_f \) “degeneracy” that can yield high \( S_f \) values if the gas is less dense than assumed (e.g. Jura 1974; Jura 1975a,b). Results from ISO observations of H$_2$ rotational lines from photodissociation regions (Habart et al. 2000; Li et al. 2002) strongly favor \( \mu = S_f/S_f^{(o)} > 5 \) (see also Sternberg 1988 for early indications of such high values). If this is indeed the case \( S \) will be raised at all \( R_{gal} \). This rescaling has no effect for those regions of the disk where the old values are already \( S > 1 \) and which CO imaging shows them to be indeed H$_2$-rich, but now a larger portion of the disk will have \( S > 1 \) and thus conditions favorable for the presence of a molecular gas phase.

The dependance of the spatial extent of such a gas phase on the value of the formation rate can be easily demonstrated from Equation 1 if the FUV volume emissivity \( j_\odot \), its dust absorption coefficient \( k_d \), and the metallicity are assumed to follow a similar spatial distribution (Honma et al. 1995). Hence, neglecting the H$_2$ self-shielding contributions to the total absorption coefficient it
is \(z/G_0 = z/(j_0/k_d) \propto z\). For an exponential disk profile and defining \(S(R_{tr}) \sim 1\) it can be shown that the new \(H_2 \rightarrow H\) transition radius will be

\[
R_{tr}(\mu) = R_{tr}(1) + (\ln\mu)R_e,
\]

(2)

where \(R_e\) is the scale-length of the exponential distribution of optical light and metallicity. For \(\mu = 5\) the molecular front will now reside at least \((\ln5)R_e \sim 1.6R_e\) further, past that inferred by CO imaging. In typical disks the later is at \(R_{tr}(1) = (0.5 - 1)R_e\) (e.g. Young & Scoville 1991), thus \(R_{tr}(\mu) \sim (2 - 2.5)R_e\), which places the molecular front well inside a typical HI disk. A flattening of the abundance gradient and thus of dust grain surface per \(H\) nuclei at large \(R_{gal}\), and inclusion of \(H_2\) self-shielding strengthen the above arguments by yielding still larger values of \(S\) in the outer parts of disks.

3. \(H_2\) gas in metal-poor regions: CO-deficient, diffuse, and warm

In a metal-poor \(H_2\) gas phase with densities of \(n \sim 20\) cm\(^{-3}\) the lack of the dissociated CO molecule acting as a coolant through its numerous rotational transitions causes the gas temperature to be \(T_k \sim 100\) K, similar to that found for CNM HI over a wide range of galactocentric distances (Papadopoulos, Thi, & Viti 2002). This is not surprising since both the atomic and any molecular gas phase comprising CNM are subjected to the same dominant heating (electrons ejected from grains by FUV light) and cooling (\(C^+\) line emission) mechanisms. The additional \(H_2\) cooling through emission from its quadrupole transition \(S(0): J_u - J_l = 2 - 0\) while it does not significantly alter the heating/cooling balance away from that of the atomic CNM phase, it is still not negligible. Indeed for an \(H_2\) gas phase with volume densities and temperatures typical of the CNM, \(S(0)\) with its thermalization density of \(n_{20} \sim 54\) cm\(^{-3}\) and \(E_{20}/k \sim 510\) K, is the only \(H_2\) transition that can be significantly excited.

This line is optically thin and offers a potent observational tool for discovering whether the CNM in galaxies indeed harbors a molecular gas phase and can also yield an estimate of its mass. Tantalizing \(S(0)\) emission that may be originating from such a diffuse \(H_2\) gas phase has been detected with \(ISO\) in the edge-on spiral galaxy NGC 891 whose mass may outweighs that of HI by factors of \(\sim 5 - 15\) (Valentijn & van der Werf 1999). Sensitive observations of \(S(0)\) line emission in a variety of metal-poor environments hold the key in revealing whether such a molecular gas phase exists and with what \(H_2/\text{HI}\) mass fraction.

4. Conclusions

The Cold Neutral Medium in galaxies may contain an \(H_2\) gas phase with similar temperatures and densities that can be particularly prominent in their metal-poor regions. Its spatial extent depends sensitively on the value of the \(H_2\) formation rate on dust grains and the most promising tool for revealing its mass distribution is through the emission of its optically thin \(S(0): J_u - J_l = 2 - 0\) line.
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