

Transition between atomic and molecular hydrogen in the Galaxy: vertical variation of the molecular fraction

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Received 28 December 1995 / Accepted 22 June 1996

Abstract. We derive radial and vertical distributions of H I and H₂ gas densities in our Galaxy by using the terminal velocity method. We calculate the molecular fraction (f_{mol}) defined as the ratio of the molecular hydrogen to total hydrogen gas density at galactic longitude $l = 33^\circ \sim 64^\circ$ and galactic latitude $b = -2^\circ \sim +2^\circ$. The thickness of the molecular dominant region ($f_{\text{mol}} \geq 0.8$) is approximately constant (109 ± 12 pc) at galactocentric distance $R \simeq 4.7\text{--}7.2$ kpc. The molecular fraction decreases suddenly at a critical height from the galactic plane, below which the gas disk is almost totally molecular, while it is almost atomic beyond this height. We show that the vertical f_{mol} variation can be reproduced by a model which takes into account the phase transition between H I and H₂ gases in the interstellar matter.

Key words: ISM: general; atoms; molecules – galaxy: structure

1. Introduction

The major constituents of the interstellar matter (ISM) in the Galaxy are the neutral atomic (H I) and molecular (H₂) hydrogen gases. The distributions of the H I and H₂ gases have been obtained through observations of the 21-cm and CO-line emissions, respectively. It is known that the H I gas is distributed in the outer region of the Galaxy, while H₂ gas is more concentrated toward the galactic center (e.g., Burton 1988; Combes 1991). However, the mutual relation of the distributions of H I and H₂ gases in the Galaxy, which will be deeply coupled with the transition between these two phases of the ISM, has been not yet investigated in detail.

Elmegreen (1993) has proposed a phase-transition theory of the H I and H₂ gases, in which the molecular fraction (f_{mol}), as defined by the ratio of the H₂ gas mass density to the total hydrogen gas density, is determined by the interstellar pressure, UV radiation intensity and the metal abundance. Sofue et al. (1995) and Honma et al. (1995) have studied the radial variation of f_{mol} in several galaxies, and found that the molecular

fraction decreases suddenly at a certain galactocentric distance, which they called the molecular front. They further modeled the molecular front phenomenon based on the phase-transition theory of the H I and H₂ gases in the ISM.

Since the Milky Way Galaxy has been observed extensively both in the H I and CO lines at much higher linear resolution than external galaxies, we may be able to study the molecular front phenomenon in the Galaxy not only in the radial direction but also in the perpendicular direction to the galactic plane. In this paper we analyze latitude-velocity ($b-v$) diagrams of the H I- and CO-line emissions of the Galaxy by applying the terminal velocity method, and derive the H I and H₂ gas distributions in the (R, z) plane, where R is the galactocentric distance and z is the height from the galactic plane. We further derive the distribution of the molecular fraction in the (R, z) plane, and investigate the hydrogen phase transition in the z direction. We also model the result based on the phase-transition theory of ISM.

2. Data and procedure

2.1. Data

We use the H I survey of Bania & Lockman (1984) observed with the Arecibo 304-m radio telescope. The H I data are in the forming $b-v$ diagrams, and maps are sampled at intervals of $\Delta b = 2'$ with a half-power beamwidth of $4'$, and the latitude coverage is $\pm 3^\circ$. We also use the CO survey of Knapp et al. (1985) observed with the 7-m telescope at the Bell-Telephone Laboratories. The CO maps are sampled at intervals of $\Delta b = 2'$ with a half-power beamwidth of $100''$, and the latitude coverage is $\simeq \pm 2^\circ$. The longitude coverage of the H I and CO data are $l = 33^\circ \sim 64^\circ$ and $l = 10^\circ \sim 77^\circ$, respectively. Both maps are spaced at equal intervals in longitude: $\Delta \sin l = 0.025$. We used the Arecibo H I data, which have the highest resolution for H I observations, in order to compare with the CO data of a resolution $100''$ and to examine the vertical (latitude) variation of gas density. Table 1 shows the observational parameters of the data, and Fig. 1 shows examples of the H I and CO $b-v$ diagrams superposed on each other.

Table 1. Observational parameters

	H I	CO ($J = 1 \rightarrow 0$)
	Bania & Lockman	Knapp et al. (1985)
Telescope	Arecibo	Bell Laboratories
Aperture	304 m	7 m
Wavelength	21 cm	2.6 mm
HPBW	4'	1'40''
Longitude extent	33° ~ 64°	10° ~ 77°
Latitude extent	±3°	≈ ±2°
Δv	1.03 km s ⁻¹	0.65 km s ⁻¹
Δb	2'	2'
R (kpc) ^a	4.68 ~ 7.65	1.49 ~ 8.29
Longitude interval	$\Delta \sin l = 0.025$, or $\Delta l = 1^\circ 43' / \cos l$	
Radius interval	$\Delta R = R_0 \Delta \sin l = 212.5$ pc	

^a The distance to the Galactic Center is taken to be $R_0 = 8.5$ kpc.

2.2. Molecular fraction

We adopt the following relations between the column density N of the atomic and molecular hydrogen and the intensity I of the H I and CO line emissions:

$$N_{\text{H}}[\text{cm}^{-2}] = C_1 I_{\text{H I}} \quad (1)$$

and

$$N_{\text{H}_2}[\text{cm}^{-2}] = C_2 I_{\text{CO}}, \quad (2)$$

where C_1 and C_2 are the conversion factors. In this paper we regard C as a constant and adopt

$$C_1 = 1.8 \times 10^{18} \text{ cm}^{-2}/(\text{K km s}^{-1}) \quad (3)$$

and

$$C_2 = 2.8 \times 10^{20} \text{ cm}^{-2}/(\text{K km s}^{-1}) \quad (4)$$

(Burton 1988; Bloemen et al. 1985). However, Arimoto et al. (1996) point out that the CO-to-H₂ conversion factor in spiral galaxies is dependent on the radial distance from the Galactic Center as

$$C_2 = C_2^0 10^{0.39R/R_e}, \quad (5)$$

where the coefficients have been given as $C_2^0 = 0.9 \times 10^{20} \text{ cm}^{-2}/(\text{K km s}^{-1})$ and $R_e = 6.6$ kpc. Although our study will be based on an assumption of a constant C_2 factor as Eq. (4), we examine the effect of the radial variation of C_2 on our result, and discuss it in the last section.

The number density n is given by

$$n = N/\Delta r, \quad (6)$$

where Δr is the depth along the line of sight.

We define the molecular fraction f_{mol} as the ratio of the molecular hydrogen gas density to the total hydrogen gas density, which is expressed by mass density ρ or number density n by

$$f_{\text{mol}} = \frac{\rho_{\text{H}_2}}{\rho_{\text{H}} + \rho_{\text{H}_2}} = \frac{2n_{\text{H}_2}}{n_{\text{H}} + 2n_{\text{H}_2}}. \quad (7)$$

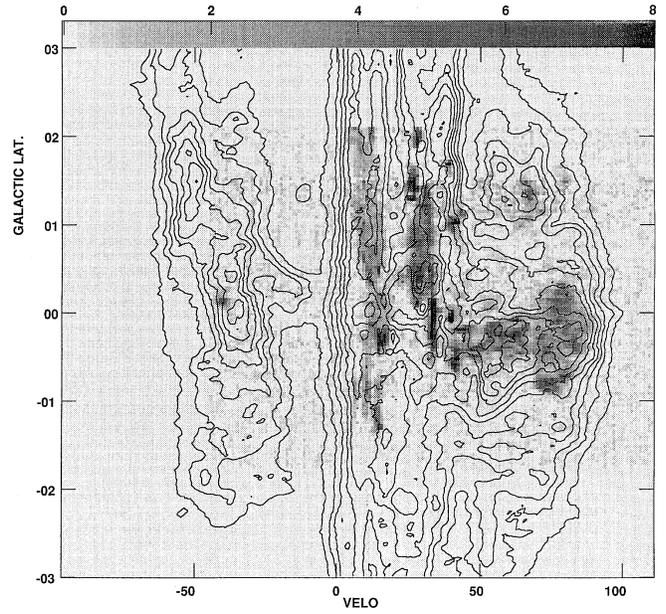


Fig. 1. A latitude-velocity ($b - v$) contour map of the H I brightness temperature at $l = 39^\circ$. The ordinate is galactic latitude in degrees, and the abscissa is velocity relative to the LSR in km s⁻¹. Contours are drawn at 10% interval of the peak brightness (114 K). A $b - v$ map of the CO emission at $l = 39^\circ$ is superposed in gray scale

2.3. Tangent points and terminal-velocity method

Assuming a circularly symmetric model of the Galaxy, we can obtain distances to the emission at terminal velocities in the first and fourth quadrants ($0^\circ < l < 90^\circ$ and $270^\circ < l < 360^\circ$). The radial velocity at each galactic longitude l in the first quadrant is given by

$$v_r = \left[\frac{R_0}{R} V(R) - V_0 \right] \sin l, \quad (8)$$

where $V(R)$ is the rotation velocity at galactocentric distance R , $R_0 (= 8.5$ kpc) is the distance of the sun from the galactic center, and $V_0 (= 220$ km s⁻¹) is the rotation velocity at $R = R_0$.

Terminal-velocity emission comes from the tangent point at a galactocentric radius

$$R = R_0 |\sin l|, \quad (9)$$

and the galactic latitude b corresponds to the height from the galactic plane as

$$z = R_0 \cos l \tan b. \quad (10)$$

The actual velocity profiles do not have a sharp cutoff due to the velocity dispersion of the gas. So, we regard the integrated emission within a certain velocity range of width Δv around the terminal velocity as a contribution of the gas at the tangent point. We adopt a velocity width $\Delta v = 6.5$ km s⁻¹ at any longitude, which we found to be a typical width of the CO velocity profile corresponding to a terminal-velocity emission component at $b \approx 0$. In fact, this value is consistent with the velocity dispersion

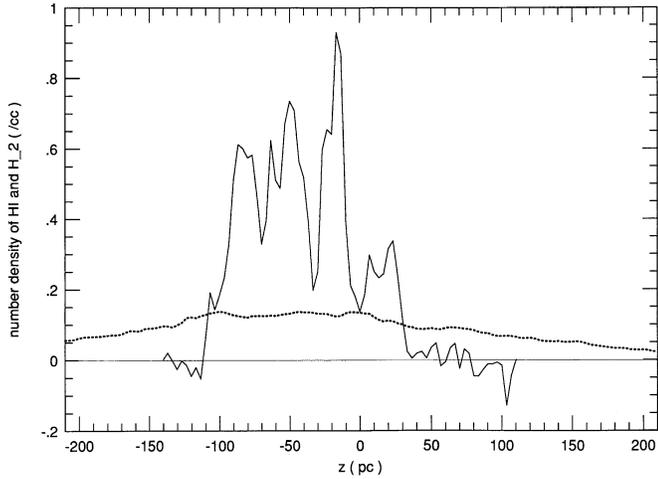


Fig. 2. Vertical distributions of the atomic hydrogen gas (dotted line) and the molecular hydrogen gas (solid line) at $l = 53^\circ$. The ordinate is the number density in H I cm^{-3} and $\text{H}_2 \text{ cm}^{-3}$. (Note that the ordinate scaling for H_2 should be doubled when comparing the two curves in mass.) The abscissa is the height from the galactic plane

obtained by Malhotra (1994), who finds that the value of the velocity dispersion varies 3.8 km s^{-1} at 2.5 kpc to 7.1 km s^{-1} at 7.5 kpc. The depth along the line of sight corresponding to this velocity width is given by

$$\Delta r = 2R_0 \sin l \left[\left(\frac{V_0}{V_0 - \Delta v} \right)^2 - 1 \right]^{1/2} \approx 0.50 R_0 \sin l. \quad (11)$$

Based on these relations we calculated number densities of H and H_2 at each longitude and latitude using latitude-velocity ($b-v$) diagrams, and obtained vertical density distributions as a function of height z from the galactic plane. Then, we arranged the thus obtained z distributions at various longitudes in the order of the distance from the galactic center, and obtained two dimensional maps of the distributions of H and H_2 gases in the (R, z) plane.

3. Results

3.1. H I and H_2 distributions

As seen from the $b-v$ diagram (Fig. 1), the H I gas is distributed smoothly in the velocity direction at any longitude, and therefore, at any point along the line of sight. On the other hand, the H_2 gas distribution is clumpy. The H I and H_2 distributions in the z direction are also clearly different (Fig. 2): the H I distribution has a flat plateau near the galactic plane and gentle skirts, while most of H_2 profiles have multiple peaks, and the maximum density is much higher than that of H I . The CO distribution is not centered on the Galactic plane, which is consistent with previous studies (Malhotra 1994; Dame et al. 1987).

Figures 3a and b show the (R, z) distributions of H I and H_2 , respectively. These figures, therefore, represent cross sections of our Galaxy along the tangent velocity circle. The density

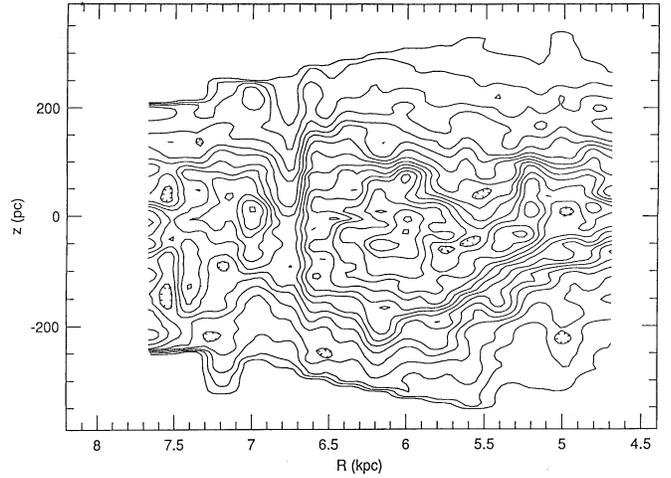


Fig. 3a. The (R, z) distribution of the H I gas density. Contours are drawn at intervals of 0.01 H cm^{-3}

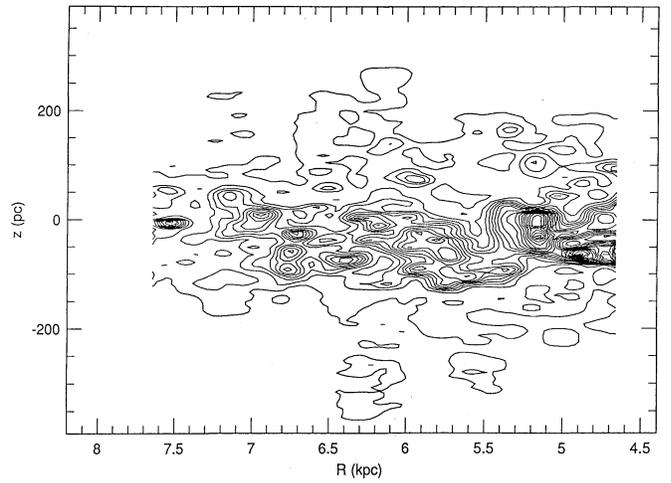


Fig. 3b. The (R, z) distribution of the H_2 gas density. Contours are drawn at intervals of $0.1 \text{ H}_2 \text{ cm}^{-3}$

distribution of H I gas in the z direction extends for a few hundred parsecs, while the extent of H_2 is not more than 100 pc: there is little CO emission at high latitudes. Note, however, that these two cross sections are not fully sampled in the longitude direction, because the observations have been obtained every $\Delta \sin l = 1/40$ ($\Delta l = 1.^\circ 4 \cos l \Delta R = 212.5 \text{ pc}$) with a beam width $4'$ for H I and $100''$ for CO.

In Fig. 4, we show an (R, z) distribution of H_2 gas for the whole range covered by the present CO data from the galactic center region ($l = 10^\circ$, $R = 1.49 \text{ kpc}$) to the solar neighborhood ($l = 77^\circ$, $R = 8.29 \text{ kpc}$). This figure includes the region shown in Fig. 3b. Figure 5a shows radial distributions of H I and H_2 gases averaged at $|z| < 100 \text{ pc}$. A radial distribution of CO emissivity in our Galaxy has been obtained by Robinson et al. (1988) and Sanders et al. (1984). Our result is approximately agree with theirs. The variation of the H_2 number density is much larger than that of H I . Note that the highest density region for H_2 in Fig. 4 and 5 corresponds to the ‘4-kpc molecular ring’,

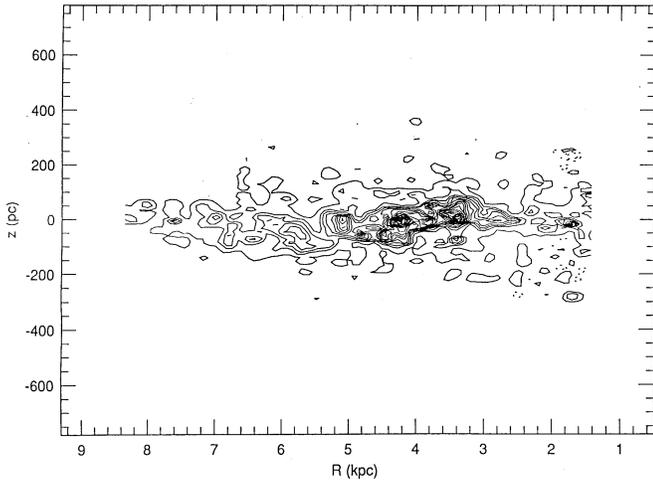


Fig. 4. The (R, z) distribution of the H_2 gas density for the whole range of the CO data. Contours are drawn at intervals of $0.2 \text{ H}_2 \text{ cm}^{-3}$

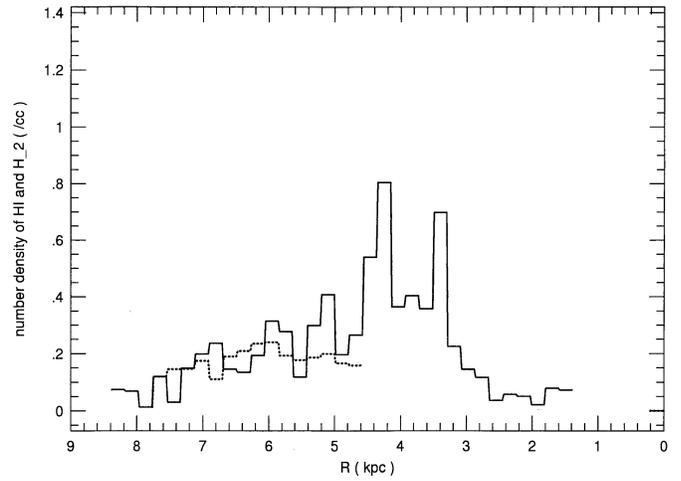


Fig. 5b. The same as Fig. 5a, but including the radial variation of the CO-to- H_2 conversion factor C_2 as given by Eq. (5)

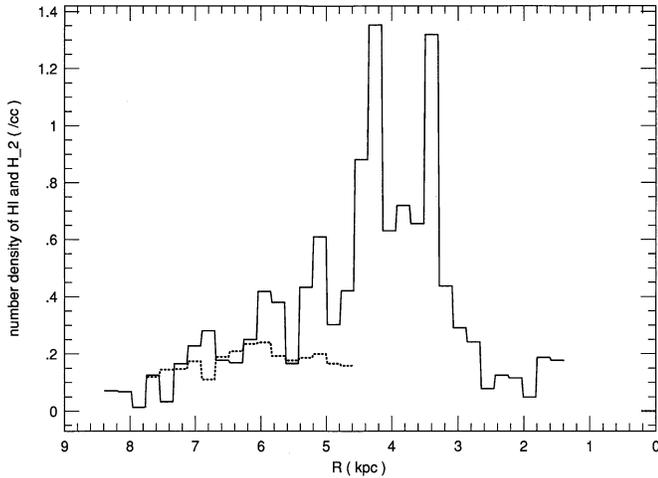


Fig. 5a. Radial distributions of H I gas density (dotted line) and H_2 gas density (solid line) averaged in $|z| < 100 \text{ pc}$

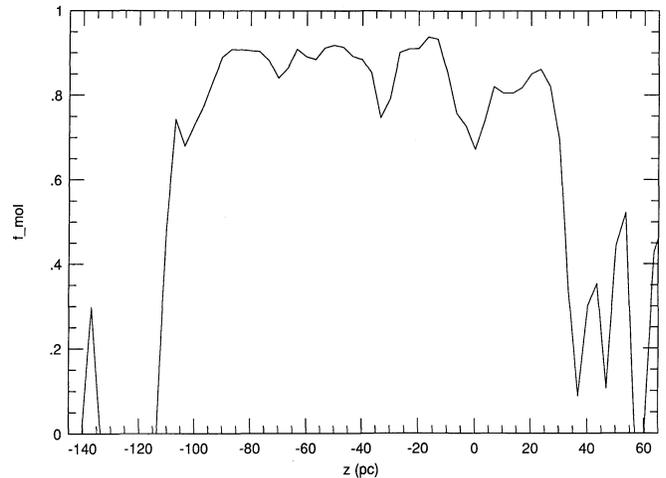


Fig. 6. The molecular fraction at $l = 53^\circ$ as a function of z . The ordinate is f_{mol}

and that the H_2 gas density in the inner region within 3 kpc and outside of 7 kpc is an order of magnitude smaller than that in the 4-kpc ring. Figure 5b shows the same as Fig. 5a but using the C_2 factor as given by Eq. (5), which takes into account the radial variation of the CO-to- H_2 conversion factor. The H_2 density distribution changes drastically in the inner region of the Galaxy, indicating much less molecular gas within $R \sim 4$ kpc.

3.2. Variation of f_{mol}

We calculated f_{mol} for a region shown in Fig. 3, where both the H I and H_2 densities are obtained. Negative values in the observed CO intensity (H_2 density) have been replaced with zero. Figure 6 shows an example of the z -variation of f_{mol} at $l = 53^\circ$. It is evident that the value of f_{mol} is almost unity near the galactic plane, and decreases rapidly to zero in a narrow range of z as z increases.

This phenomenon is commonly seen at all longitudes except at $l = 61^\circ$ and 64° ($R \leq 7.5$ kpc) where the amount of H_2 is small. This fact indicates the existence of a z -directional boundary of a region with a high H_2 fraction, which we call the molecular front in the z -direction. Most of hydrogen gas is in the molecular phase in the region near the galactic plane, sandwiched between the two molecular fronts, whereas in the outer (higher) region it is in the atomic phase.

Figure 7 shows the two dimensional distribution of f_{mol} as a contour map in the (R, z) plane. The centroid of the molecular dominant disk, where $f_{\text{mol}} \geq 0.8$, is waving, corresponding to the fact that the molecular gas disk is corrugating (e.g. Malhotra 1994). It is remarkable that the thickness of the molecular dominant disk is almost constant at $109 \pm 12 \text{ pc}$. On the other hand, it is known that the scale height of the H I layer is larger than it. A thickness of H I layer between half-density points has approximately constant value: 220 kpc over $4 \leq R \leq 8$ kpc (Dickey & Lockman 1990). When we compare the thickness of

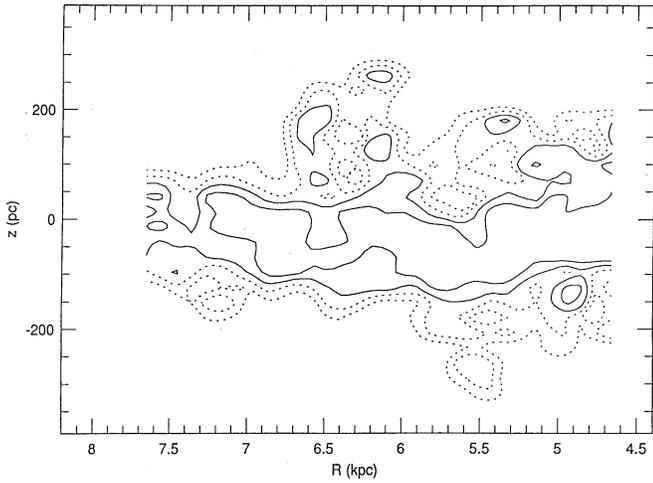


Fig. 7. The (R, z) distribution of the molecular fraction. Contours are drawn at an interval of 0.2. Dashed lines show $f_{\text{mol}}=0.2, 0.4$, and solid lines $f_{\text{mol}}=0.6, 0.8$

molecular dominant disk with the scale height of H I gas, we can express that the atomic hydrogen layer wraps the molecular disk.

Figure 8a shows radial variations of the molecular fraction calculated for number densities of H I and H₂ averaged within $|z| < 50$ and 200 pc of the galactic plane. In both cases the molecular fraction decreases from 0.8 to 0.6 with increasing R . Though we can not clearly see the phase transition in this region, curves are consistent with the fact that the molecular fraction is almost unity in the the central few kpc region (Sofue et al. 1994). Particularly, the curve for $|z| < 200$ pc indicates a decrease of f_{mol} beyond $R \simeq 7.5$ kpc. This may be consistent with the existence of the radial molecular front indicated from an analysis of longitude-velocity diagrams of the Galaxy (Sofue et al. 1994). Since the H₂ gas density over $R \geq 8$ kpc is much smaller than that of inner region (Dame et al. 1987), it is expected that the molecular fraction will decrease suddenly beyond this radius. Figure 8b shows the same variation but considering the radial dependency of CO-to-H₂ conversion factor. The radial molecular front slightly change. However, no significant effect is found.

3.3. Model analysis

The three crucial parameters which determine f_{mol} are the interstellar pressure (P), the intensity of dissociative UV radiation field (U), and the metal abundance (Z) which is related to the amount of interstellar dust and shields UV photon (Elmegreen 1993). Based on the phase-transition theory (Elmegreen 1993), Honma et al. (1995) has developed a computing code to model the molecular front in galactic scale. By applying this code, we calculate the variation of molecular fraction in the z -direction.

Since it is reasonable to assume that the pressure is proportional to the gas density, we consider the following two cases: first, $P(z)$ is traced by the observed total gas density distribution in the z -direction (n_{tot}), and second, $P(z)$ is expressed by a

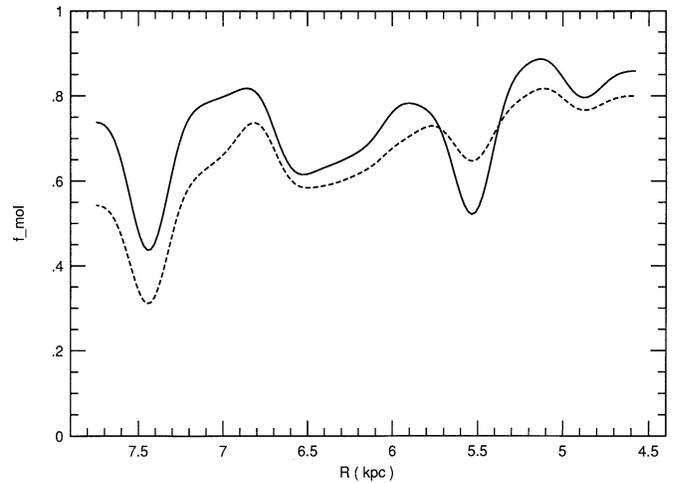


Fig. 8a. Radial variations of the molecular fraction averaged within $|z| < 50$ pc (solid line) and 200 pc (dashed line)

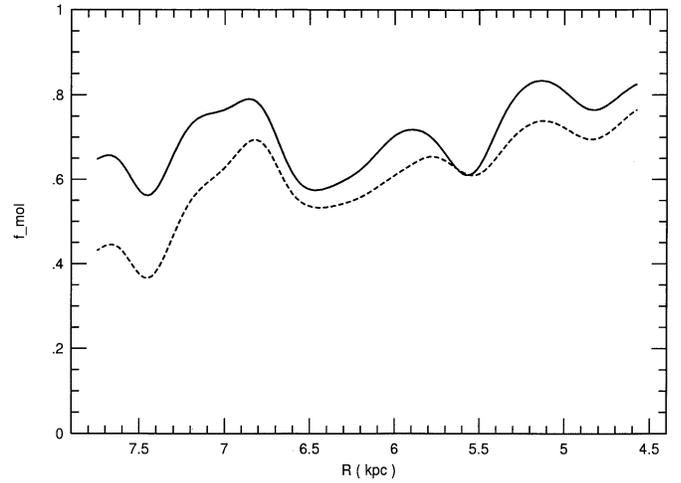


Fig. 8b. The same as Fig. 8a but including the effect of radial dependency of CO-to-H₂ conversion factor

Gaussian function of z , considering the hydrostatic balance of the gas pressure with the gravity in the z -direction. According to van der Kruit & Searle (1982) we assume that the intensity of the radiation field is expressed as

$$U(R, z) = U_0 e^{(-R/R_U)} \text{sech}^2(z/z_0), \quad (12)$$

where $R_U = 5.0$ kpc is a scale distance from the galactic center, and $z_0 = 0.7$ kpc is the scale height in the z -direction. For the metallicity, we do not have any information about the gradient in the z -direction. So, we assume that the value of Z is constant against z , while it varies with R as $Z = Z_0 e^{-(R-R_0)/R_Z}$.

Figure 9 shows a thus calculated variation of the molecular fraction for $l = 53^\circ$. The solid line corresponds to the observed $n_{\text{tot}}(z)$, and the dashed line to the Gaussian distribution of $P(z)$ in which the parameter of the Gaussian function was taken so that it fits the observed $n_{\text{tot}}(z)$. Even for such a round pressure distribution as a Gaussian, f_{mol} shows a shoulder-like variation, indicating the phase transition clearly. The curve of f_{mol} cal-

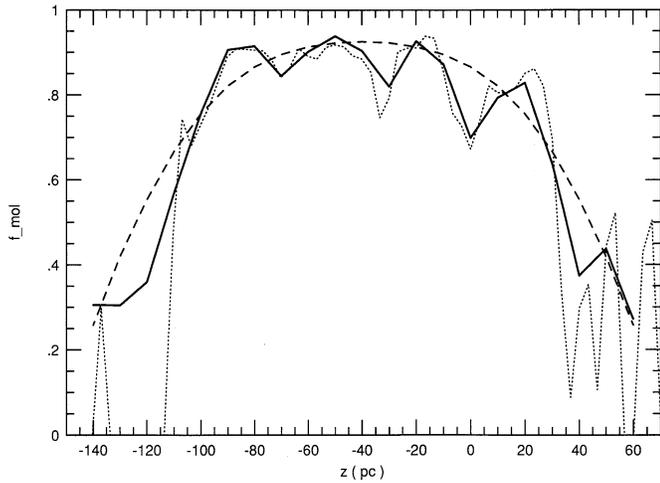


Fig. 9. The molecular fraction calculated theoretically for $l = 53^\circ$. The solid line is for the case where the observed $n_{\text{tot}}(z)$ was used to calculate $P(z)$. The dashed line corresponds to a Gaussian distribution of $P(z)$. The dotted line shows the observed f_{mol} (Fig. 6)

culated for the observed $n_{\text{tot}}(z)$ shows a sharper variation at a critical height, and agrees well with the observed f_{mol} variation (Fig. 6) and reproduces the molecular front in the z -direction. Though it has been considered that the most important parameter for the molecular front is the metal gradient (Honma et al. 1995), our results shows that the molecular front is reproduced without a metal gradient.

4. Discussion

The radial molecular front has been observed in our Galaxy as well as in many external galaxies (Sofue et al. 1994; Honma et al. 1995), in which the front is found at $R \sim 5\text{--}10\text{kpc}$. In our result for our Galaxy, although f_{mol} is almost unity in $4.8 \leq R \leq 7.2\text{ kpc}$, the radial decrease of f_{mol} may occur at $R \geq 7.5\text{ kpc}$, where the value of f_{mol} drops from ~ 0.8 to less than 0.6. Since the H I gas density varies more gradually than the H₂ gas at $R \geq 7\text{ kpc}$, we may expect that the molecular gas is not any more dominant in the outer region of $R = 7.5\text{ kpc}$. This indicates that the molecular front in our Galaxy is located at $R \simeq 7.5\text{ kpc}$ and the transition region from H₂ to H I and vice versa is as narrow as $\Delta R \sim 2\text{ kpc}$ in the radial direction.

From the z -directional variation of f_{mol} , we found the molecular fronts in the direction perpendicular to the galactic plane. The molecular hydrogen disk is sandwiched by a thicker H I envelope. In the molecular region near the galactic plane, between

the two fronts, the ISM is almost totally in the molecular phase with $f_{\text{mol}} \geq 0.8$, while in the outer region, the gas is almost totally H I. We stress that the transition between H I and H₂ is taking place within the narrow range at a height of $z \simeq \pm 50\text{ pc}$ at $R \leq 7\text{ kpc}$.

In this paper, we have not taken to account a metallicity gradient in the z -direction, since the existence of the z -gradient of the metallicity has not been reported. Even if it exists, the scale height of the variation would be a few hundred pc, because it will reflect the scale height of old population stars. Therefore, it will be reasonable to assume that the metallicity gradient in z -direction is small or not present in our region of $|z| < 100\text{ pc}$.

It has been found that the CO-to-H₂ conversion factor (C_2 factor) increases exponentially with the radius due to the metallicity gradient (Arimoto *et al.* 1996). This implies that the C_2 value in the region considered here (from $R=4$ to 7 kpc) varies by a factor of 1.5. We have examined the radial variations of the H₂ density and f_{mol} by taking into account this effect. We found that the radial molecular front slightly moves outwards, but not significant change of the property of the f_{mol} distribution in the z -direction was found.

Acknowledgements. We thank M. Honma for his valuable comments and for providing us with the code to model the molecular front. We are also indebted to Drs. T. M. Bania, G.R. Knapp, and S. Malhotra for providing us with the H I and CO data in a machine readable formats.

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