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Low Density Molecular Gas in the Galaxy

K. S. Usuda[1,2] *, T. Hasegawa[2], T. Handa[2], J. -I. Morino[2], T. Sawada[2], S. Sakamoto[2], T. Oka[2], M. Seta[2], K. Sorai[2], M. Hayashi[1], R. Booth[3], L. -Å. Nyman[3,4], L. Bronfman[5], J. May[5], A. Luna[5], P. Shaver[6], and G. J. White[7,8]

[1] Subaru Telescope, National Astronomical Observatory of Japan, 650 North A'ohoku Place, Hilo, HI 96720, USA
[2] Institute of Astronomy, University of Tokyo, Osawa, Mitaka, Tokyo, 181-8588, Japan
[3] Onsala Space Observatory, S-439 92 Onsala, Sweden
[4] European Southern Observatory, Casilla 19001, Santiago 19, Chile
[5] Departmento de Astronomía, Universidad de Chile, Casilla 36-D, Santiago, Chile
[6] European Southern Observatory, D-85748 Garching, Germany
[7] Department of Physics, Queen Mary and Westfield College, University of London, Mile End Road, London E1 3NS, U.K.
[8] Stockholm Observatory, S-133 36 Saltsjobaden, Sweden

1. Introduction

The distributions and physical conditions in molecular gas in the interstellar medium have been investigated in both the Galaxy and towards external galaxies. For example, Galactic plane surveys in the CO J=1-0 line with the Columbia 1.2-m telescope and with the Five College Radio Astronomy Observatory (FCRAO) 14-m telescopes have been able to trace spiral arms more clearly than HI surveys have been able to reveal, and indicate that most of molecular mass is contained in Giant Molecular Clouds (GMCs). Extensive maps of the whole Milky Way showed two prominent features, the 4-kpc molecular ring and the Galactic center. The physical conditions in the Galaxy have been studied by comparing the intensity of CO J=1-0 line with those of other lines, e.g., ^{13}CO J=1-0, higher J transitions of CO, and dense gas tracers such as HCO$^+$, CS, and HCN.

Previous studies were however strongly biased towards regions where CO emission was known to be intense. The radial distribution of molecular hydrogen shows that most of the H_2 gas which is indirectly traced by observations of its associated CO emission, originates from the inner Galaxy (Dame 1993). Extending outwards from a galacto-centric distance of $\sim$ 7 kpc. the H_2 mass surface density decreases dramatically, and HI dominates over H_2 in the outer Galaxy. What are physical conditions of molecular gas where the CO emission is relatively weak, and can we *really* trace *all* of the molecular gas through observations of CO ? These kinds of problems have not been solved yet, but are addressed in our study.

2. CO J=2-1 Survey in the Outer Galaxy

In order to investigate the physical conditions in molecular gas which shows only weak CO emission, we have made two molecular line studies. One is an extensive outer Galaxy CO survey in the CO J=2-1 emission line, which is able to trace excited gas, and the other is an absorption line study towards bright continuum sources, which is sensitive to gas insufficiently excited to radiate emission line radiation.

For the emission line study, we used the twin 60-cm radio telescopes located in both hemispheres. The Tokyo - Nobeyama Radio Observatory (NRO) telescope is at Nobeyama, Japan and the Tokyo - Onsala - European Southern Observatory (ESO) - Calán telescope is at La Silla,

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* *e-mail:* <`kumiko@naoj.org`>

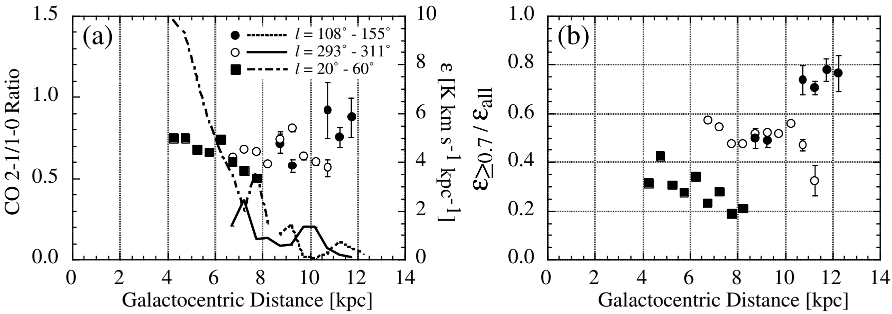

Fig. 1: Radial distributions of CO volume emissivity ε in lines, the CO 2-1/1-0 ratio in symbols (a), and fraction of high ratio (≥ 0.7) gas (b). The first quadrant data was taken by Sakamoto et al. (1997).

Chile. These telescopes were designed so that their half-power beam widths (HPBW) at 230 GHz matched those of the 1.2-m telescopes (9 arcminutes) used in the Columbia CO J=1-0 survey. The northern survey towards the Perseus arm covers the area $l = 108^\circ.0 - 155^\circ.25$, $b = -2^\circ.75 - +2^\circ.75$ on a $0^\circ.125$ grid, with a total area ≈ 236 deg^2. The data were smoothed to $0^\circ.5$ angular resolution to allow direct comparison with the $0^\circ.5$ 'superbeam' of the Columbia survey (Dame et al. 1987). The southern survey of the Carina arm covers the area $l = 293^\circ.0 - 310^\circ.875$, $b = -1^\circ.125 - +1^\circ.125$ on a $0^\circ.125$ grid, with a total area of ≈ 40 deg^2. Our data was compared with the Columbia southern survey (Grabelsky et al. 1987; Bronfman et al. 1988).

The distribution of the CO emission reveals a number of discrete features in both the Perseus, and the far-side Carina arms. Most of the CO emission originates from molecular clouds - but notably, emission in the intercloud regions is barely detectable. We define molecular clouds as regions surrounded by a continuous surface in (l, b, v) space at the 3σ level in the CO J=1-0 line. A total of 13 clouds in the Perseus arm and 19 clouds in the Carina arm were identified. Assuming virial equilibrium, we estimate that the $N(\mathrm{H_2})/W(\mathrm{CO})$ conversion factor, X, in the outer Galaxy is $(5.4 \pm 0.5) \times 10^{20}\mathrm{cm}^{-2}(\mathrm{K\,km\,s^{-1}})^{-1}$, some three times larger than that inferred towards the inner Galaxy, $(1.9 \pm 0.5) \times 10^{20}\mathrm{cm}^{-2}(\mathrm{K\,km\,s^{-1}})^{-1}$. Using this X factor, we derive the luminosity mass of molecular clouds. Since all of identified molecular clouds are likely to be GMC's, we will assume that mean mass is comparable with similar clouds in the inner Galaxy (Dame et al. 1986). The mean CO 2-1/1-0 intensity ratio is 0.6 ± 0.2 for the Perseus arm and 0.68 ± 0.10 for the Carina arm. These values are comparable with those towards the Orion B (0.62 ± 0.01) and Orion A GMCs (0.75 ± 0.01; Sakamoto et al. 1994), but differ from that seen towards the Taurus dark cloud (0.53 ± 0.01; Hayashi et al. in preparation).

We show radial distributions of the CO J=1-0 volume emissivity, ε, and the 2-1/1-0 ratio in Figure 1(a). In the outer Galaxy, the volume emissivity is extremely low and the arm/interarm contrast is high. The 2-1/1-0 ratio is higher than that in the inner Galaxy especially in the Perseus arm, and widely scattered over a range of $\approx 0.6 - 1.0$. The ratio averaged over galactocentric annuli reflects the fraction of high ratio (≥ 0.7) gas. Figure 1(b) shows that in the outer Galaxy, the fraction of high ratio gas dominates the contribution from low ratio (< 0.7) gas.

In summary, the properties of the molecular gas in the outer Galaxy are as follows: (1) The intensity of CO emission per unit mass is low. (2) The contrast between spatially compact components such as molecular clouds and the diffuse component due intercloud gas is high. (3) The fraction of high ratio gas, as inferred from the 2-1/1-0 ratios dominates that of of low ratio gas. In the inner Galaxy, we can see both compact components with high ratio gas and diffuse components surrounding compact components which are characterized by showing low ratios.

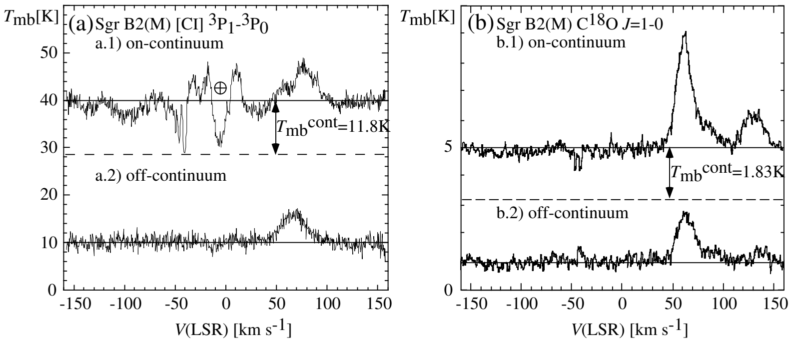

Fig. 2: On-(top) and off-(bottom) continuum profiles toward Sgr B2(M) in [CI] $^3P_1$-$^3P_0$ (a) and $C^{18}O$ J=1-0 (b). The intensity is given in units of the main-beam brightness temperature. $T_{\rm mb}^{\rm cont}$ is the level of the continuum emission.

By contrast, we only detect compact components in CO emission in the outer Galaxy. There are two possibilities: molecular gas does not exist in the intercloud region, or that conditions in the molecular gas are insufficient to excite the CO lines. In the latter case, the density of this putative unexcited gas is estimated to be $n(H_2) \lesssim 300{\rm cm}^{-3}$ from Large Velocity Gradient (LVG) line formation model calculations (e.g., Sakamoto et al. 1994).

3. Absorption Line Study in [CI] and $C^{18}O$

Although we cannot see emission lines from unexcited gas, its presence can still be inferred if absorption lines can be detected against a bright continuum source. We have made observations toward Sgr B2(M), the brightest continuum source at millimeter and submillimeter wavelength. Using the James Clark Maxwell Telescope (JCMT) at Mauna Kea, Hawaii, we observed the [CI] $^3P_1 -^3 P_0$ at 492 GHz, $C^{18}O$ J=3-2 at 329 GHz, and J=2-1 at 220 GHz lines. For the $C^{18}O$ J=1-0 observations at 110 GHz we used the NRO 45-m telescope located at Nobeyama, Japan. For both the [CI] and $C^{18}O$ J=1-0 lines, observations were made towards the continuum source as well as at an adjacent position lying just off the continuum peak. This allowed us to simultaneously determine the optical depths (τ) and excitation temperatures ($T_{\rm ex}$). In Figure 2 spectra are shown towards the on- and off- continuum positions in the [CI] (a) and $C^{18}O$ J=1-0 lines (b). At the on-continuum position in [CI], we see emission of Sgr B2(M) itself at $V_{\rm LSR}$ = +76 km s^{-1}, and several absorption lines which probably arise in foreground clouds. In $C^{18}O$, we see two sharp absorption lines at -42 and -46 km s^{-1} at the on-continuum position and emission at -42 km s^{-1} at the off source position, which originates from the 3-kpc arm.

After determining τ and $T_{\rm ex}$ independently, we estimated the physical parameters of the absorption features with an aid of LVG calculations. The calculations were made for gas kinetic temperatures $T_{\rm k}$ = 15, 20, and 30 K, since the excitation temperatures of most of [CI] absorption features appear to be higher than 10 K. For the 3-kpc arm, the molecular hydrogen density is $n(H_2) \lesssim 500$ cm^{-3}, as derived from [CI] and $\lesssim 160$ cm^{-3} from $C^{18}O$. These results are consistent with the density of $\lesssim 600$ cm^{-3} estimated from the CS J=2-1 and 3-2 absorption by Greaves (1995). The absorption lines appear to originate from less dense molecular gas.

From our data, the column densities of CI and $C^{18}O$ in the 3-kpc arm are (1-7) $\times 10^{17}$ cm^{-2} and (3-5) $\times 10^{17}$ cm^{-2}, respectively. Assuming a terrestrial abundance value [CO]/[$C^{18}O$] = 500, and adopting a relative CO abundance [CO]/[H_2] = 8 $\times 10^{-5}$ appropriate to the solar neighborhood (Irvine et al. 1987), the H_2 column density is $N(H_2) = (4.0 \pm 1.8) \times 10^{22}$ cm^{-2}. Adopting a 'normal' X factor in the inner Galaxy, the intensity of CO emission should be 100 K km s^{-1}. However, the observed CO intensity of the 3-kpc arm is less than 7 K km s^{-1}. This suggests that we underestimate the molecular gas abundance by a factor of $\sim$ 30.

4. Conclusions

In the CO emission line study towards the outer Galactic plane, we find that evidence of any diffuse component in emission is barely detectable. In the absorption line study, we have by contrast detected a large amount of low density molecular gas by observing [CI] and $C^{18}O$ absorption lines towards Sgr B2(M). These results suggest that there may be a substantial amount of unexcited molecular gas which remains undetected, because its associated CO *emission* is weak, since the density is insufficiently high to excite CO into emission. The existence of this unexcited molecular gas is confirmed by several other observational studies. CO absorption lines in the outer arm toward 2013+370 and 0727-115 have been detected by Lequeux et al. (1993), for which the derived column densities are higher than those estimated from CO emission in the outer arm. Additionally, Hasegawa et al. (1983) examined cold HI clouds near the W3/4 cloud in self-absorption in the HI 21-cm line. According to their analysis, most of mass traced by HI self-absorption is in the molecular form, and the estimated virial masses are comparable with those estimated from ^{13}CO emission lines. On the other hand, Dame (1993) found a tight anti-correlation between CO emission and 2.4 μm emission in the first quadrant. The 2.4 μm continuum is thought to be absorbed by GMCs in the inner Galaxy, and such a tight anti-correlation implies that unexcited molecular gas can be neglected in a global scale in the inner Galaxy. Further absorption line studies toward several lines of sight are needed to estimate the contribution of low density molecular gas in the outer Galaxy.

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