INFRARED EXCESS AND MOLECULAR GAS IN THE GALACTIC WORM GW 46.4+5.5

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ABSTRACT

We have carried out high-resolution (~3') H I and CO line observations along one-dimensional cuts through the Galactic worm GW 46.4+5.5. By comparing the H I data with IRAS data, we have derived the distributions of $I_{100}$ excess and $\tau_{100}$ excess, which are, respectively, the 100 $\mu$m intensity and 100 $\mu$m optical depth in excess of what would be expected from H I emission. In two observed regions, we were able to make a detailed comparison of the infrared excess and the CO emission. We have found that $I_{100}$ excess has a very good correlation with the integrated intensity of CO emission, $W_{CO}$, but $I_{100}$ excess does not. There are two reasons for the poor correlation between $I_{100}$ excess and $W_{CO}$: first, there are regions with enhanced infrared emissivity without CO, and second, dust grains associated with molecular gas have a low infrared emissivity. In one region, these two factors completely hide the presence of molecular gas in the infrared. In the second region, we could identify the area with molecular gas, but $I_{100}$ excess significantly underestimates the column density of molecular hydrogen because of the second factor mentioned above. We therefore conclude that $\tau_{100}$ excess, rather than $I_{100}$ excess, is an accurate indicator of molecular content along the line of sight. We derive $\tau_{100}/N(H) = (1.00 \pm 0.02) \times 10^{-5}$ (10$^{20}$ cm$^{-2}$)$^{-1}$, and $X = N(H_2)/W_{CO} \approx 0.7 \times 10^{15}$ cm$^{-2}$ (K km s$^{-1}$)$^{-1}$. Our results suggest that $I_{100}$ excess could still be used to estimate the molecular content if the result is multiplied by a correction factor $\xi_c = <I_{100}/N(H)>_{H_2}/<I_{100}/N(H)>_{H_2}$ ($\approx 2$ in the second region), which accounts for the different infrared emissivities of atomic and molecular gas. We also discuss some limitations of this work, which could stem from using single-temperature model and the IRAS 60 $\mu$m intensity in estimating the dust optical depth along the line of sight.

Subject headings: infrared: ISM: continuum — ISM: individual (GW 46.4+5.5) — ISM: molecules — radio lines: ISM

1. INTRODUCTION

In many studies of the interstellar medium, it is essential to determine accurately the amount of molecular gas along the line of sight. However, the most abundant molecule, H$_2$, not only has a large excitation temperature ($T_{ex} \geq 509$ K), which is not usually attainable in a cold interstellar medium, but also has very small rotational transition probabilities. In order to infer the H$_2$ column density $N$(H$_2$), therefore, we generally rely on indirect methods. The best known indirect method for estimating the H$_2$ column density is to observe other molecules such as CO, CS, or NH$_3$. However, the fractional abundance of a molecule relative to H$_2$ is unlikely to be uniform from one cloud to another, or even sometimes within a cloud. In addition, there may be some differences among the distributions of individual molecules because of their different photochemical properties. In the case of CO, which has been widely used as a tracer of H$_2$, the abundance varies from cloud to cloud by up to 3 orders of magnitude, depending on the visual extinction and astrochemical properties (Scoville & Sanders 1987; van Dishoeck & Black 1988; Magnani & Onello 1995).

The infrared all-sky maps produced by the IRAS mission presented a new opportunity to study the distribution of interstellar molecular gas. The Galactic radiation in the far-infrared (far-IR) appears to arise mostly from dust grains well-mixed with interstellar gas (Mathis, Mezger, & Panagia 1983). The IRAS 100 $\mu$m emission intensity, $I_{100}$, has been found to be tightly correlated with the total column density of interstellar gas at $|b| \geq 5\circ$, and the 100 $\mu$m emissivity per hydrogen nucleus, $I_{100}/N(H)$, seems to be fairly uniform in the solar neighborhood: $I_{100}/N(H) \approx 1$ MJy sr$^{-1}$ (10$^{20}$ cm$^{-2}$)$^{-1}$ (de Vries, Heithausen, & Thaddeus 1987; Boulanger & Pérault 1988; Heiles, Reach, & Koo 1988; Deul & Burton 1990, 1992). Therefore, $I_{100}$ excess, i.e., the IRAS 100 $\mu$m emission in excess of what is expected from the H I column density, could be used as a tracer of H$_2$ in regions where the amount of ionized gas is negligible. Based on such an idea, several groups have identified "infrared-excess" ("IR-excess") clouds in order to investigate the distribution of molecular gas. However, CO observational studies on the IR-excess clouds showed that there is a substantial difference between the distribution of IR-excess clouds and that of CO-emitting clouds (Desert, Bazell, & Boulanger 1988; Blitz, Bazell, & Désert 1990; Heithausen et al. 1993; Reach, Koo, & Heiles 1994; Meyerdierks & Heithausen 1996; Reach, Wall, & Odegard 1998). This discrepancy between the two distributions is in a sense expected, because (1) the dust abundance and radiation-field strength vary, (2) the CO abundance is low in diffuse molecular clouds, and (3) the infrared emissivity of the dust associated with molecular gas is low.

Another IRAS method for tracing molecular gas is to use 100 $\mu$m optical depth, $\tau_{100}$. This might be more accurate than using 100 $\mu$m intensity, at least in principle, because optical depth is simply proportional to the amount of dust along the line of sight if dust properties are the same. Indeed, for several high-latitude clouds, 100 $\mu$m (or 60 $\mu$m) optical depth has been found to be correlated with molecular gas column density better than the 100 $\mu$m intensity alone (Langer et al. 1989; Snell, Schloerb, & Heyer 1989; Jarrett, Dickman, & Herbstr 1989). "IRAS" clouds similar to the IR-excess clouds have been identified using this method, too (Wood, Myers, & Daugherty 1994). These pre-
We therefore have removed a smooth background emission from the continuum (100 MJy sr$^{-1}$ temperature). The regions where H I line emission are also labeled as A lines are shifted in the Galactic plane. The regions where H I 21 cm line observations were carried out using the 4 m telescope at Nagoya (HPBW = 2.5′). However, simply calculated dust optical depth after subtracting flat background emission from the 60 and 100 μm intensity maps and showed that it had a very good correlation with the integrated intensities of CO isotopes.

In this paper, we make a detailed comparison of 100 μm intensity, 100 μm optical depth, and the distribution of CO emission along several one-dimensional cuts. Our study differs from most previous studies in that we use both high-resolution (∼3′) H I and CO data in the analysis (see Reach et al. 1994). The H I data make it possible to derive accurate correlations between $\tau_{100}$ (or $I_{100}$) and N(H I), which is used to identify “τ$_{100}$-excess” (or $I_{100}$-excess) regions and to estimate the excess column densities of H nuclei. This excess H column density is compared with the distribution of CO integrated intensity, $W_{\mathrm{CO}}$, to derive the important conversion factor $X = N(\mathrm{H}_2)/W_{\mathrm{CO}}$. In comparison, most previous studies (e.g., de Vries et al. 1987; Heithausen & Thaddeus 1990) that derived the conversion factor from the IRAS data have been based on the comparison of $I_{100}$ excess and $W_{\mathrm{CO}}$, which may significantly underestimate X (Magnani & Onello 1995; Reach et al. 1998). In this paper we compare these two approaches in detail and discuss their limitations.

The object that we study in this paper is the galactic worm GW 46.4+5.5. Galactic worms are wiggly, vertical structures that look like worms crawling away from the Galactic plane in median-filtered H I maps (Heiles 1984; Koo, Heiles, & Reach 1992). GW 46.4+5.5 is an ∼8′ long, filamentary structure extending vertically from the Galactic plane in both far-IR (or H I) and radio continuum emission (Fig. 1). It is possible that GW 46.4+5.5 is the wall of a supershell similar to the North Polar Spur, but at a greater distance (Kim & Koo 1999). We describe the H I and CO line observations in § 2. In § 3 we evaluate $I_{100}$ and τ$_{100}$ excesses, using the IRAS and H I data, and compare their distributions with that of $W_{\mathrm{CO}}$. We discuss the nature of $I_{100}$ excess in GW 46.4+5.5 and some potential problems of τ$_{100}$-excess method in § 4. The main conclusions are summarized in § 5.

### 2. OBSERVATIONS

H I 21 cm line observations were carried out using the 305 m telescope at Arecibo Observatory in 1990 October. The telescope had a half-power beamwidth of 3.3′ and a beam efficiency of 0.8 at 1.4 GHz (Reach et al. 1994). We observed both circular polarizations simultaneously using two 1024 channel correlators with 5 MHz bandwidth each, so that the velocity resolution was 2.03 km s$^{-1}$ after Hanning smoothing. Each spectrum was obtained by integrating for 1 minute using frequency switching. We made a total of nine one-dimensional cuts through GW 46.4+5.5 at a set of constant Galactic latitudes. The beam separation was 3′. The positions of our one-dimensional cuts are listed in Table 1.

### CO J = 1–0 line observations were made in 1994 February using the 4 m telescope (HPBW = 2.5′) at Nagoya

| TABLE 1 |
|---|
| **Positions of One-dimensional Cuts and Off Positions** |
| **RANGE** | **OFFS** |
| Scan Number | $b$ (deg) | H I 21 cm (deg) | CO J = 1–0 Line (deg) | (l, b) (deg) |
| B1 | 1.0 | 42.5–48.0 | 43.0–45.5 | (45.0, 1.5), (43.5, 2.5) |
| B2 | 2.0 | 42.5–48.0 | 43.0–46.0 | (45.0, 1.5), (43.5, 2.5) |
| B3 | 3.0 | 42.5–48.0 | 44.0–47.0 | (43.5, 2.5), (45.5, 4.2) |
| B4 | 4.0 | 43.0–47.5 | 44.0–46.5 | (47.5, 3.5), (45.8, 4.2) |
| B5 | 5.0 | 42.5–50.0 | 45.0–48.0 | (46.5, 5.3), (49.0, 5.5) |
| B6 | 6.0 | 42.5–51.5 | 46.0–48.5 | (46.5, 5.3), (49.0, 5.5) |
| B7 | 7.0 | 42.5–51.5 | 46.5–47.5 | (45.5, 6.5) |
| B8 | 8.0 | 42.5–51.0 | 46.5–47.5 | (48.0, 8.0) |
| B9 | 9.0 | 42.5–51.5 | ... | ... |

* OFF positions for CO J = 1–0 line observations.
University in Japan. We obtained eight one-dimensional cuts in the same way as in the H I line observations. The observed positions together with their reference positions are summarized in Table 1. An SIS mixer receiver and a 1664 channel Acousto-Optical Spectrometer (AOS) with 40 MHz bandwidth were used. The velocity resolution was 0.67 km s$^{-1}$ after Gaussian smoothing. The system temperature varied in the range 480–700 K during the observing sessions, depending on weather conditions and elevation of the source. Absolute-position switching instead of frequency switching was used in order to prevent the contamination of spectra by the atmospheric CO emission. The reference positions were checked and found to be free of appreciable $(T^*_R < 0.1 \text{ K})$ CO emission. The velocity was centered at $v_{\text{LSR}} = 40 \text{ km s}^{-1}$ and the velocity coverage was from $-19$ to $+91 \text{ km s}^{-1}$. The on-source integration time was 2 minutes, and the typical rms noise level was 0.2 K per channel after Gaussian smoothing. The intensity scale was calibrated with respect to the standard source S140, which was assumed to have $T^*_R = 20 \text{ K}$ (Yang & Fukui 1992).

3. Infrared Excess and Molecular Gas

3.1. H I Gas and Infrared Excess

Figure 2 shows a sample from our H I spectrum at $(l, b) = (45^\circ10, 4^\circ00)$, where the strongest CO line emission was detected. There are three peaks at positive velocities in the H I spectrum, and the peaks in the velocity range $v_{\text{LSR}} \approx 18$–$40 \text{ km s}^{-1}$ are the components associated with GW 46.4 + 5.5 (Kim & Koo 1999). The components at negative velocities might be from the warped Galactic plane outside of the solar circle. The physical and dynamical properties of the worm will be discussed in a separate paper (Kim & Koo 1999).

We assume that the H I emission is optically thin and compute the H I column density along a given line of sight, $N(\text{H I})$, from

$$N(\text{H I}) = 1.822 \times 10^{18} \int T_b \, dv \, \text{cm}^{-2},$$  

(1)

where $T_b$ is the brightness temperature in K and $v$ is the velocity in km s$^{-1}$. Our assumption seems to be valid because the peak temperature of the H I line is much lower than the typical spin temperature of H I gas, $T_s = 125$ K, for most sight lines. The integral range is from $v_{\text{LSR}} = -100$ to $+150 \text{ km s}^{-1}$. Figure 3a is the plot of the 100 $\mu$m intensity, $I_{100}$, against $N(\text{H I})$ in the observed regions. We can see a strong correlation between the two physical parameters. Different beam sizes of the H I and IRAS observations could introduce some scattered data points in the figure. But the effect must be small because the beam sizes are roughly the same $(\sim 3')$. The figure shows only the data from the regions at $b \geq 3^\circ$ where both H I and CO line observations were made. The data at lower Galactic latitudes are not used because of the possible contribution from dust associated with ionized gas. The open circles, squares, and pentagons represent the points with detectable CO emission at $b = 3^\circ$, $4^\circ$, and $5^\circ$, respectively. The area of each symbol is proportional to the integrated CO intensity. The crosses represent the points without detectable CO. A least-squares fit excluding the points with detectable CO yields $(I_{100}/\text{MJy sr}^{-1}) = (1.32 \pm 0.02) \left[ N(\text{H I})/10^{20} \text{ cm}^{-2} \right]^{-0.76 \pm 0.007}$. Our fitting procedure involves two steps: (1) All the crosses are fitted to a straight line, and (2) the crosses within $\pm 2 \sigma$ deviation from the first fit are fitted to a new straight line. The negative zero-intercept could be from errors in the subtraction of zodiacal light. The derived $I_{100}/N(\text{H I})$ agrees with the results of previous observational studies. For example, Boulanger et al. (1996), de Vries et al. (1987), and Heiles et al. (1988) obtained $1.4 \pm 0.3, 1.0 \pm 0.4$, and $1.3 \text{ MJy sr}^{-1} (10^{20} \text{ cm}^{-2})^{-1}$, respectively.

We now compare the H I column density and 100 $\mu$m optical depth. Assuming that the far-IR emission is optically thin and that the temperature of dust grains is constant along the line of sight, the 60/100 $\mu$m color temperature, $T_d$, can be derived according to the formula

$$T_d = c_1 \left \{ \frac{1}{\lambda_{60}} - \frac{1}{\lambda_{100}} \right \} \ln \left \{ \frac{I_{100}}{I_{60}} \left( \frac{\lambda_{60}}{\lambda_{100}} \right)^{n + 3} \right \},$$  

(2)

where $c_1 = hc/k_B = 1.441$ and $n$ is the index in the emissivity law, $Q_{ab}(\lambda) \sim \lambda^{-n}$. For the graphite-silicate dust grain model of Mathis, Rumpl, & Nordsieck (1977), $n$ lies between 1 and 2 (Draine & Lee 1984). We take $n = 1.5$ in this paper. The 100 $\mu$m optical depth, $\tau_{100}$, is derived from $\tau_{100} = I_{100}/B_\nu(T_d)$, where $B_\nu(T)$ is the Planck function. Figure 3b displays the 100 $\mu$m optical depth versus the H I column density. A strong correlation also exists between these two quantities. A least-squares fit has been performed in a
similar way to yield \((\tau_{100}/10^{-5}) = (1.00 \pm 0.02) [N(H) / (10^{20} \text{ cm}^{-2})] + 0.01 \pm 0.6\). The estimated \(\tau_{100}/N(H)\) ratio is much smaller than the value \(\langle \tau_{100}/N(H) \rangle = 6.3 \times 10^{-5} (10^{20} \text{ cm}^{-2})^{-1}\), obtained by Boulanger et al. (1996) from an analysis of the Cosmic Background Explorer (COBE) mission and the Leiden-Dwingeloo H I survey data. This difference between the two values cannot be entirely due to the calibration difference between the IRAS and COBE observations. Instead, the difference may be attributed to the effects of small, transiently heated dust grains (Langer et al. 1989) and to the insensitivity of the IRAS observations to cold \((T < 15 \text{ K})\) dust grains (Snell et al. 1989; Jarrett et al. 1989; Wood et al. 1994).

If the dust-to-gas ratio and the infrared emissivity per hydrogen nucleus are uniform over the atomic and molecular regions, the infrared excess can be used to estimate the H$_2$ column density. The infrared excess may be determined either from \(I_{100}\) or \(\tau_{100}\) using the following formulae:

\[
N(\text{H}_2)_{I_{100}} = \frac{1}{2} \left[ \frac{I_{100,c}}{\langle I_{100,c}/N(H) \rangle} - N(\text{H}) \right] \text{ cm}^{-2} \tag{3}
\]

and

\[
N(\text{H}_2)_{\tau_{100}} = \frac{1}{2} \left[ \frac{\tau_{100,c}}{\langle \tau_{100,c}/N(H) \rangle} - N(\text{H}) \right] \text{ cm}^{-2}, \tag{4}
\]

where the subscript \(c\) indicates the quantity corrected for offset and the angle brackets indicate an average ratio. Since we excluded the data points with detectable CO, we may use the derived ratios as the ratios with respect to the column density of hydrogen nuclei, i.e., \(I_{100}/N(H) = 1.32 \text{ MJy sr}^{-1} (10^{20} \text{ cm}^{-2})^{-1}\) and \(\tau_{100}/N(H) = 1.00 \times 10^{-5} (10^{20} \text{ cm}^{-2})^{-1}\), respectively.

3.2. Comparison of Infrared Excess and CO Line Intensity

We have detected CO emission in five regions (Table 2). Figure 2 shows the spectrum of the strongest CO line and compares it with the corresponding H I spectrum. Note that the velocity range of our CO observations was from \(-19\) to \(+91 \text{ km s}^{-1}\), so that we could not detect the CO emission, if any, associated with the H I gas at negative velocities. It is, however, very unlikely that there is appreciable CO emission in this outer part of the Galaxy. We, in fact, made some test observations with enough velocity coverage, but could not detect any emission \((T_k < 0.2 \text{ K})\). In any case, we believe that we have detected the emission from most of the CO gas. The CO emission from regions C and D is almost certainly associated with GW 46.4 +5.5, while that from regions A and B is probably not because the velocities are very different. The CO emission from region E is also possibly related to the worm although its central velocity is somewhat lower than the velocity of the worm. The physical association of molecular gas with GW 46.4 +5.5 will be discussed in a separate paper (Kim & Koo 1999). As we have mentioned in § 3.1, the regions at \(b = 15^\circ\) (A and B) are

| Region | \(b\) (deg) | \(l\)-range (deg) | \(v_{\text{LSR}}^*\) (km s\(^{-1}\)) | \(T_k^*\) (K) | \(\Delta v_{\text{FWHM}}^*\) (km s\(^{-1}\)) |
|--------|-------------|-----------------|-----------------|-------------|-----------------|
| A ...... | 1.0 | 43.50–43.70 | +60 | 2.5 | 2.1 |
| B ...... | 1.0 | 44.50–44.75 | −10 | 2.1 | 2.9 |
| C ...... | 3.0 | 43.50–46.65 | +27 | 3.0 | 7.8 |
| D ...... | 4.0 | 44.20–45.50 | +22 | 3.3 | 5.6 |
| E ...... | 5.0 | 47.65–47.95 | +14 | 1.8 | 2.5 |

* Line parameters at peak position.
not included in our analysis because of the complication due to the presence of ionized gas. Region E is not included because it has only a few observed points. We thus limit our subsequent analysis to regions C and D.

Figures 4a and 4b compare the values of \( N(H_2) \) derived from equations (3) and (4) with the integrated CO line intensity in regions C and D, respectively. The integral ranges are from \( v_{\text{LSR}} = +20 \) to \(+40 \) km s\(^{-1}\) for region C and from \( v_{\text{LSR}} = +15 \) to \(+30 \) km s\(^{-1}\) for region D. These are velocity ranges where the CO emission is detected. In region C, the \( N(H_2)_{I_{100}} \) distribution matches very well that of \( W_{\text{CO}} \), but the \( N(H_2)_{I_{100}} \) distribution does not. The \( N(H_2)_{I_{100}} \) distribution differs from that of \( W_{\text{CO}} \) significantly at \( b \approx 46^\circ - 47^\circ \). In region D, on the other hand, both \( N(H_2)_{I_{100}} \) and \( N(H_2)_{I_{100}} \) match very well with \( W_{\text{CO}} \), although their absolute scales differ by about a factor of 2. Hence, \( I_{100} \) excess appears to trace molecular gas better than \( I_{100} \) excess, which is also obvious from Figures 3a and 3b since the points with CO are separated more clearly from those without CO in the latter. This is more clearly shown in Figure 5, where \( N(H_2)_{I_{100}} \) and \( N(H_2)_{I_{100}} \) are compared with \( W_{\text{CO}} \). \( N(H_2)_{I_{100}} \) is obviously proportional to \( W_{\text{CO}} \), whereas \( N(H_2)_{I_{100}} \) has much weaker correlation with \( W_{\text{CO}} \). We determined \( N(H_2)_{I_{100}}/W_{\text{CO}} = (0.70 \pm 0.05) \times 10^{20} \) cm\(^{-2}\) (K km s\(^{-1}\))\(^{-1}\) by a least-squares fit. The error quoted represents only a statistical error in the fit. This conversion factor is much smaller than the estimated value for molecular clouds in the Galactic plane, \( X = (1.8 - 4.8) \times 10^{20} \) cm\(^{-2}\) (K km s\(^{-1}\))\(^{-1}\) (Scoville & Sanders 1987), but comparable to that of high-latitude clouds, \( X \approx 0.5 \times 10^{20} \) cm\(^{-2}\) (K km s\(^{-1}\))\(^{-1}\) (e.g., de Vries et al. 1987; Heithausen & Thaddeus 1990; Reach et al. 1998). Since there seems to be a systematic difference between the correlations in regions C and D, we also determined the slopes of the correlations separately. They are \((0.40 \pm 0.05)\) and \((0.93 \pm 0.06) \times 10^{20} \) cm\(^{-2}\) (K km s\(^{-1}\))\(^{-1}\), respectively. This difference could be due to variations in the dust-to-gas ratio (Magnani & Onello 1995) or to variations of the gas-phase carbon abundance (Heithausen & Mebold 1989). Further study is needed to address this question.

As we will discuss in more detail in § 4.2, the correlation between \( W_{\text{CO}} \) and \( N(H_2)_{I_{100}} \) is not apparent partly because of the existence of a local heating source in region C. If we limit the analysis to region D, there is a weak correlation between the two quantities, \( N(H_2)_{I_{100}}/W_{\text{CO}} = (0.59 \pm 0.05) \times 10^{20} \) cm\(^{-2}\) (K km s\(^{-1}\))\(^{-1}\). Note that the coefficient of proportionality is about one-half that of the \( W_{\text{CO}}-N(H_2)_{I_{100}} \) relationship, the significance of which will be discussed in next section.

4. DISCUSSION

4.1. IR Excess as a Molecular Tracer

4.1.1. \( I_{100} \) Excess as a Molecular Tracer

We have found that the \( I_{100} \)-excess distribution does not correlate well with the CO distribution. The discrepancy...
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The low far-IR emissivity of molecular clouds has another important implication for using $I_{100}$ excess as a molecular tracer. The $I_{100}$ excess significantly underestimates the $H_2$ column density. In region D, the $H_2$ column density derived from $I_{100}$ excess is smaller than that derived from $\tau_{100}$ excess by about a factor of 2. This is because in equation (3) we used $\langle I_{100}/N(H) \rangle$ obtained from H I line observations. If there is a molecular cloud along the line of sight, a correct expression for the observed 100 $\mu$m emission would be

$$I_{100} = \langle I_{100}/N(H) \rangle_{H_2} N(H_2) + 2 \langle I_{100}/N(H) \rangle_{H_2} N(H_2),$$

where $\langle I_{100}/N(H) \rangle_{H_2}$ and $\langle I_{100}/N(H) \rangle_{H_1}$ are, respectively, 100 $\mu$m emissivities per hydrogen nucleus in atomic and molecular regions. Hence, we need to apply a correction factor $\xi_c$ to $N(H_2)_{100}$ in equation (3) in order to obtain an accurate $H_2$ column density:

$$\xi_c \equiv \langle I_{100}/N(H) \rangle_{H_2}/\langle I_{100}/N(H) \rangle_{H_1}.$$

Since $\langle I_{100}/N(H) \rangle_{H_1}$ is generally greater than $\langle I_{100}/N(H) \rangle_{H_2}$, $\xi_c \approx 1$ and, in GW 46.4 $+5.5$, $\xi_c \approx 2$. Our correction factor $\xi_c$ is equivalent to $\langle B_r(T_0) \rangle_{H_1}/\langle B_r(T_0) \rangle_{H_2}$ used by Magnani & Onello (1995) and Reach et al. (1998). From their study of $I_{100}$-excess clouds, Reach et al. (1998), for example, found $\xi_c = 3.8$ as an average value for the solar neighborhood. For the inner Galaxy, if we use the mean temperature of $T_{H_1} = 21.0 \pm 1.0$ K and $\langle T_0 \rangle_{H_2} = 19.0 \pm 1.0$ K derived by Sodroski et al. (1994) using the Diffuse Infrared Background Experiment (DIRBE) 140 and 240 $\mu$m observations, we obtain $\xi_c = 2.1$. Our result for $\xi_c$, however, cannot be compared directly with these results because our study is based on the $IRAS$ 60 $\mu$m brightness, which is largely affected by the emission from small grains. Since $B_r(T_0)$ is very sensitive to $T_0$, it is necessary to estimate the correction factor independently in studying specific regions (Lee, Kim, & Koo 1999).

4.1.2. $\tau_{100}$ Excess as a Molecular Tracer

According to our results, $\tau_{100}$ excess appears to be an accurate indicator of the molecular content along the line of sight; it not only traces the presence of molecular gas correctly but also increases linearly with the amount of molecular gas. There are two reasons for this. First, it separates the intensity peaks produced by enhanced infrared emissivity. Second, it corrects for the low-infrared emissivity of molecular clouds. In the present work, however, there are two limitations as discussed below.

The first limitation stems from using a mean temperature in deriving $\tau_{100}$ along the line of sight. The expression for $N(H_2)$ in equation (4) is, in fact, an exact one if dust properties and the dust-to-gas ratio remain the same in atomic and molecular regions. In practice, however, there is an error.
because, in deriving \( \tau_{100} \) on the right-hand side of equation (4), we have used an average color temperature along the line of sight (defined in eq. [2]) even if we need to use different color temperatures in deriving the optical depths of atomic and molecular regions. It is straightforward to estimate the error when there are only two dust components with different emissivities along the line of sight. If there is atomic gas of optical depth \( \tau_{100}(\text{HI}) \) at color temperature \( T_{\text{HI}} \), and molecular gas of optical depth \( \tau_{100}(\text{H}_2) \) at \( T_{\text{H}_2}(< T_{\text{HI}}) \), the ratio of the optical depth \( \tau_{100} \), derived by using a mean color temperature, to the true optical depth \( \tau_{100} \) is given by

\[
\frac{\tau_{100}}{\tau_{100}} = \left( \frac{1 + r \exp (-\Delta \tau)}{1 + r \exp \left[ -\Delta \tau / (\lambda_{60}/\lambda_{100}) \right]} \right) \frac{1 - \lambda_{60}/Z_{100}}{1 - \lambda_{60}/Z_{100}} \left( 1 + r \exp \left[ -\Delta \tau / (\lambda_{60}/\lambda_{100}) \right] \right),
\]

where \( r \equiv \tau_{100}(\text{H}_2)/\tau_{100}(\text{HI}) \), \( \Delta \tau \equiv (c_l/\lambda_{100})(1/T_{\text{HI}} - 1/T_{\text{H}_2}) \), and the other parameters have the same meanings as in § 3. The derived optical depth is always less than the true value and, as expected, the difference converges to zero as \( r \) approaches zero or infinity. Figure 6 shows, as solid lines, how \( \tau_{100}/\tau_{100} \) varies in the \((r, \Delta \tau)\) plane. The ratio \( \tau_{100}/\tau_{100} \) is affected more strongly by the warmer dust associated with atomic gas in the sense that the error in optical depth is larger at \( \tau_{100}(\text{H}_2)/\tau_{100}(\text{HI}) = r \geq 1 \) than that at \( \tau_{100}(\text{H}_2)/\tau_{100}(\text{HI}) = 1/r \) for a given value of \( \Delta \tau \). Similar figures can be found in Langer et al. (1989) and Snell et al. (1989), but Figure 6 is a generalized one. The error in optical depth would induce an error in \( N(\text{H}_2)_{100} \). The error can be determined by the following formula:

\[
N(\text{H}_2)_{100} = \frac{\tau_{100}/\tau_{100} - 1/(1 + r)}{1/(1 + r)}.
\]

The dependence of \( N(\text{H}_2)_{100}/N(\text{H}_2)_{100} \) on \((r, \Delta \tau)\) is displayed by dotted lines in Figure 6. The ratio \( N(\text{H}_2)_{100}/N(\text{H}_2)_{100} \) is in general smaller than \( \tau_{100}/\tau_{100} \) for a given \((r, \Delta \tau)\) pair. The most striking difference between the two quantities is that, as \( r \) approaches zero, the error in \( N(\text{H}_2)_{100} \) remains constant for given \( \Delta \tau \) whereas that in \( \tau_{100} \) tends to zero. Since the visual extinction is \( A_V \approx 1.5 \) mag at the CO peak in region D using \( N(\text{H})/A_V = 1.9 \times 10^{21} \text{ cm}^{-2} \text{ mag}^{-1} \) (Bohlin, Savage, & Drake 1978), \( T_{\text{HI}} \) is expected to be less than 3 K lower than \( T_{\text{HI}} \) (Mathis et al. 1983). Therefore, the error in \( N(\text{H}_2)_{100} \) may be \( \leq 20\% \) in region D, where \( \tau_{100}(\text{H}_2)/\tau_{100}(\text{HI}) \approx \frac{1}{2} \) (see Fig. 6). The error in the correction factor \( \xi \), is directly related to that in \( N(\text{H}_2)_{100} \) because it is actually derived from \( N(\text{H}_2)_{100}/N(\text{H}_2)_{100} \) : \( \xi / \xi_c = N(\text{H}_2)_{100}/N(\text{H}_2)_{100} \).

The second limitation derives from using \( I_{60} \) in estimating the dust optical depth. Interstellar dust grains are known to be composed of small, transiently heated grains and classical, large grains in thermal equilibrium (Draine & Anderson 1985; Désert, Boulanger, & Puget 1990). The emission at 60 \, \mu m comes from both small grains and large grains, while the emission at 100 \, \mu m originates mainly from large grains. Désert et al. (1990) divided dust grains into three components: polycyclic aromatic hydrocarbons (PAHs), very small grains (VSGs), and big grains (BGs). In their model, the contributions of VSGs are \( \sim 60\% \) at 60 \, \mu m and \( \sim 15\% \) at 100 \, \mu m for the solar neighborhood. Sodroski et al. (1994) found from an analysis of the DIRBE and IRAS data that the average values of the contribution of small grains at 60 \, \mu m are \( \sim 40\% \) and \( \sim 60\% \) in the inner and outer Galaxy, respectively. IRAS studies of nearby molecular clouds suggest that the small grains are present largely in the halo surrounding the clouds and that their relative abundances vary (Boulanger, Falgarone, Puget, & Helou 1990; Laureijs, Clark, & Prusti 1991; Bernard et al. 1993). Therefore, \( \tau_{100} \) that we have derived using \( I_{60} \) does not represent the usual “optical depth” of dust grains. Instead it might be largely affected by small grains with varying abundances. However, the fact that we do observe a very good correlation between \( \tau_{100} \) excess and \( W_{60} \) seems to indicate that \( \tau_{100} \) is still proportional to the amount of dust along the line of sight. Compared to \( I_{100} \), \( \tau_{100} \) can be interpreted as a quantity corrected for variation in the abundance of small grains as well as variation in the temperature of large grains. If one uses far-IR data at wavelengths longer than 100 \, \mu m, such as the DIRBE data for the 100, 140, and 240 \, \mu m wave bands, one can resolve this problem. In the present days, however, the IRAS data have the highest angular resolution among the available infrared survey data.

In the past decade, several groups have found for high-latitude clouds that \( \tau_{100} \) (or \( \tau_0 \)) is better correlated with the gas column density than \( I_{100} \) (Langer et al. 1989; Snell et al. 1989; Jarrett et al. 1989; Wood et al. 1994). At high latitudes, however, it is unlikely that the \( \tau_{100} \)-excess distribution is markedly different from the \( I_{100} \)-excess distribution, because most high-latitude clouds are diffuse and quiescent compared to the molecular clouds near the Galactic plane. In addition, the low signal-to-noise ratio of \( I_{60} \) could intro-
duce a large error in $\tau_{100}$. At low latitudes, on the contrary, the $\tau_{100}$-excess distribution is expected to represent the distribution of molecular gas much better than the $I_{100}$-excess distribution, because the number density of luminous stars increases and most molecular clouds contain high-extinction regions and/or embedded luminous stars.

4.2. Local Heating Source in GW 46.4 + 5.5

In the case of region C, the $I_{100}$-excess distribution is largely affected by the variation of dust temperature (Fig. 4a). The $I_{100}$-excess peak at $b = 46.0$ appears not to be due to dust grains associated with molecular gas but to an increase in dust temperature. We found a massive star, LS II + 12:3, near the position of interest, ($l$, $b$) = (46.0, 3.0) (Drilling 1975). The star was found to be a luminous blue giant star, O9 III (Vijapurkar & Drilling 1993). The coordinates of the star are ($\alpha$, $\beta$)$_{1950}$ = (19h03m14.3, 12°46'21") or ($l$, $b$) = (45:97, 2:75). An infrared point source (IRAS 19031 + 1247) and a radio point source with a diffuse extended envelope (Fürst et al. 1990) lie in the vicinity of the star. IRAS 19031 + 1247 seems to be an OH/IR star on the basis of its position in the (60–25) versus (25–12) $\mu$m color-color diagram (see Lewis 1994). In order to reveal the physical relationship between the two sources and the star, further studies are required. We estimate the distance of the massive star to be $d = 2.2 \pm 0.8$ kpc, using the photometric data mentioned above and the $UBV$ photometric data of Drilling (1975), $V = 10.72$, and $B - V = 1.00$ mag. Here we adopt $M_V = -5.3 \pm 0.7$ mag for O9 III (Conti et al. 1983) and $R = A_V/E_{B-V} = 3.3$ because $R$ for the region is likely to be somewhat higher than the average value for the Galactic plane (Turner 1976). The estimated value is barely in agreement with the kinematic distance of H I gas associated with GW 46.4 + 5.5, $d_{\text{kin}} = 1.4$ kpc (Kim & Koo 1999).

Figure 7 displays the large-scale distribution of the $I_{60}/I_{100}$ ratio around region C. The $I_{60}/I_{100}$ ratio is enhanced around the massive star, which is located where two arrows meet, and decreases monotonically from the star to the position of interest. Assuming that $Q_{\text{abs}}(\lambda)$ varies as $\lambda^{-n}$, the total excess infrared luminosity from the $I_{60}/I_{100}$ enhanced region can be derived from the following formula:

$$L_{\text{IR}}^\text{ex} = 4\sigma d^2 \int_{\Omega_d} [\langle \tau \rangle_{T_d} T_d^4 - \langle \tau \rangle_{T_d,B} T_d^4] d\Omega,$$

where $\sigma$ is the Stephen-Boltzmann constant, $d$ is the distance to the massive star, and the subscript $B$ indicates quantities in the absence of the star. The Planck-averaged optical depth is defined as $\langle \tau \rangle_T = \int \tau_b(T) d\lambda / B_\nu(T) d\lambda$ ($\propto T_d^{1.5}$ for $n = 1.5$). Using $d = 2.2$ kpc and $T_{d,B} = 25.2$ K ($I_{60}/I_{100} = 0.22$ with $n = 1.5$), the total excess infrared luminosity is $L_{\text{IR}}^\text{ex} = 6500 L_\odot$ over a solid angle of $\Omega_d = 2.4 \times 10^{-4}$ sr. This value is an order of magnitude smaller than the stellar luminosity, $L_\star = 2.2 \times 10^5 L_\odot$ (Panagia 1973). Hence, the star has enough luminosity to produce the observed infrared luminosity, and the $I_{100}$-excess peak at $b = 46.0$ in region C is probably due to heating by an O-type giant star.

5. CONCLUSIONS

Infrared (IR) excess, defined as the emission in excess of what would be expected from H I emission, has been used for estimating the amount of molecular gas along the line of sight. However, at the same time, there have been molecular, particularly CO, line studies showing that the method does not necessarily yield reliable results. That is, there are both IR-excess regions without detectable CO and CO-emitting regions without IR excess. Region C in our study is...
a good example. The sources that fall into the first category could be either regions with enhanced IR emissivity or diffuse molecular clouds without CO emission. In region C, it is excess heating from a nearby O star that produces an IR-excess region. On the other hand, the sources that fall into the second category could be molecular clouds with low IR emissivity. In region C, the low emissivity completely hides the presence of a molecular cloud in the infrared.

Our result shows that we can avoid the above confusion problem by using the optical-depth excess instead of IR excess, i.e., the optical depth in excess of what would be expected from H I emission. We have found a very good correlation between 100 μm optical-depth (τ_{100}) excess and integrated intensity of CO emission, W_{CO}. We derive the conversion factor between N(H_2) and W_{CO}, \( X \approx 0.7 \times 10^{20} \text{ m}^{-2} (\text{K km s}^{-1})^{-1} \) for the galactic worm GW 46.4+5.5. According to our result, however, the conversion factors in regions C and D differ by about a factor of 2, although both regions are parts of the worm. A more complete observation is necessary for the study of the variation of the conversion factor.

Another merit of using optical-depth excess, which may be more important, is that it gives an accurate value for the amount of molecular gas. IR excess would significantly underestimate N(H_2) if one uses an IR emissivity estimated from H I emission, \( \langle I_{100}/N(H)\rangle_{H_I} \). We have introduced a correction factor \( \xi_c = \langle I_{100}/N(H)\rangle_{H_I}/\langle I_{100}/N(H)\rangle_{H_2} \) which should be applied in order to account for the different IR emissivity of molecular clouds. In general \( \xi_c \approx 1 \) because dust grains in molecular clouds are usually colder than dust grains in atomic gas. In region D in our study, \( \xi_c \approx 2 \). We should therefore be rather cautious in converting IR excess to N(H_2).

Two potential problems in using optical-depth excess, however, would be the low surface brightness and the contribution of small, transiently heated grains. If the surface brightness is low, the noise and/or the systematic errors produced in the subtraction of zodiacal emission may make it impossible to derive an accurate optical depth. It would be worthwhile to check the applicability of the method at high Galactic latitudes. The second problem may be resolved by using far-IR data at wavelengths longer than 100 μm.

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