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THE RATIO OF H_2 COLUMN DENSITY TO ^{12}CO INTENSITY IN THE VICINITY OF THE GALACTIC CENTER

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ABSTRACT

Observations from the *COBE*[7] Diffuse Infrared Background Experiment (DIRBE) at wavelengths of 140 and 240 μm are combined with the Goddard-Columbia ^{12}CO ($J = 1 \rightarrow 0$) surveys to derive an estimate for X, the ratio of H_2 column density to ^{12}CO intensity, within approximately 400 pc of the Galactic center. The H_2 column density is inferred from the infrared observations by assuming a proportionality between dust-to-gas mass ratio and gas metallicity. It is found that the value of X in the Galactic center region is a factor of 3–10 lower than the corresponding ratio for molecular cloud complexes in the inner Galactic disk. Therefore, the use of the inner disk value of X to derive the mass of molecular hydrogen in the vicinity of the Galactic center and the 300 MeV–5 GeV gamma ray flux from that region will result in overestimates of both quantities. We attribute the so-called gamma-ray deficit from the Galactic center region to the erroneous use of a constant value of X throughout the Galaxy.

Combining our results with several virial analyses of giant molecular cloud complexes in the Galactic disk, we find that the value of X increases by more than an order of magnitude from the Galactic center to a Galactocentric distance of 13 kpc. This implies that studies of the large-scale ^{12}CO emission from our own Galaxy and external spiral galaxies, in which a constant ratio of H_2 column density to ^{12}CO intensity was adopted, have significantly overestimated the relative amount of molecular hydrogen at small Galactocentric distances and significantly underestimated the relative amount of molecular hydrogen at large Galactocentric distances.

Subject headings: Galaxy: center — ISM: abundances — ISM: molecules

1. INTRODUCTION

Because molecular hydrogen has no permitted transitions at radio frequencies, indirect methods are used to deduce information on this gas-phase component of the interstellar medium. The most useful diagnostic tool for studying the large-scale distribution of molecular hydrogen within the Galaxy has been the 2.6 mm ($J = 1 \rightarrow 0$) line of ^{12}CO, which is a less abundant trace molecule. Large-scale surveys in this line are essential to studies of the highly complex structure, dynamics, and physical conditions of the region within a few hundred parsecs of the Galactic center, where most of the gaseous material is in molecular form (Sanders, Solomon, & Scoville 1984; Burton & Liszt 1992). Comparisons of ^{12}CO observations with *COS B* high-energy (300 MeV – 5 GeV) gamma-ray observations (Blitz et al. 1985; Stacy, Dame, & Thaddeus 1987), *IRAS* 60 and 100 μm observations (Osborne et al. 1987), and interstellar extinction data (Issa, MacLaren, & Wolfendale 1990) imply that the value of X_c, the factor that converts the intensity of the ^{12}CO ($J = 1 \rightarrow 0$) line to an H_2 column density in the vicinity of the Galactic center, may be significantly lower than the value of X for molecular cloud complexes in the Galactic disk, and therefore, a more reliable determination of X_c is critical to molecular gas studies of the Galactic center region.

Derivation of X_c will also have important implications for studies of the large-scale distribution of molecular hydrogen in the Milky Way and other spiral galaxies. The approach of many of these studies (see, for example, Solomon et al. 1987; Young 1990; and references therein) has been to assume that the value of X does not vary with galactic location. It has been argued (Solomon, Scoville, & Sanders 1979) that this assumption is justified empirically by the fact that in large-scale CO surveys of the inner Galaxy the ^{12}CO ($J = 1 \rightarrow 0$) line intensity varies proportionally to the intensities of the lines of less abundant species, such as ^{13}CO, which are believed to trace the molecular mass adequately. The generally accepted interpretation of this observed proportionality, and current conceptual basis for the use of the ^{12}CO ($J = 1 \rightarrow 0$) line as a molecular mass tracer, is that molecular cloud complexes consist of a large number of statistically similar optically thick clumps (i.e., cloudlets) that do not overshadow each other in position-velocity space, and therefore, the ^{12}CO ($J = 1 \rightarrow 0$) line intensity is simply proportional to the number of molecular cloudlets in the beam of the telescope (Morris & Rickard 1982).

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It is possible, however, that X varies significantly on a large-scale due to large-scale variations in the physical conditions (e.g., density, temperature) of the cloudlets (Maloney & Black 1988; Combes 1991). Recent virial analyses (Mead & Kutner 1988; Digel, Bally, & Thaddeus 1990; Sodroski 1991) of giant molecular cloud complexes in the outer Galaxy suggest that the value of X in the outer Galaxy is a factor of 2–3 greater than the value of X for inner Galaxy complexes, which may result from a radial decrease with increasing Galactocentric distance in the heating rate and therefore the gas kinetic temperature of the cloudlets comprising the complexes. A determination of the value of X in the vicinity of the Galactic center will refine our estimates of this possible radial gradient in X.

The DIRBE instrument on board NASA's *Cosmic Background Explorer* (*COBE*) satellite has provided an unprecedented opportunity to study the large-scale infrared emission from the Galactic Plane region over a large range of wavelengths from 1 to 240 μm (Hauser et al. 1991; Boggess et al. 1992; Silverberg et al. 1993). The DIRBE 140 and 240 μm observations are an efficient tracer of the interstellar medium's dust grain component that attains an equilibrium temperature in the ambient radiation field and constitutes most ($>70\%$) of the dust mass (Sodroski et al. 1994; § 2). Therefore, if the large-scale variation in the gas-to-dust mass ratio from one region of the Galaxy to another is independently inferred (e.g., from heavy-element abundance estimates), the DIRBE observations can be combined with ^{12}CO observations to derive an estimate of the large-scale variation in X. In this paper, we apply this method and show that the value of X is a factor of 3–10 lower in the Galactic center region than in the inner Galactic disk. Our results are expected to be more reliable than previous estimates of X_c using *IRAS* 60 and 100 μm observations (e.g., Osborne et al. 1987), since contamination of the *IRAS* bands by emission from small, transiently heated dust grains results in overestimates of dust temperature and gross underestimates of dust column density (Sodroski et al. 1987, 1994; Draine 1990; Mathis 1990). Possible limitations of our analysis owing to the low ($\sim 0^{\circ}.7$) angular resolution of the DIRBE instrument (e.g., uncertainty in opacity estimates due to possible beam dilution effects) are addressed in § 2. Evidence in the DIRBE data for a low value of X_c has been reported by Sodroski et al. (1994).

In § 2, we present the infrared and radio data used in our analysis and derive an estimate for X_c. In § 3, we discuss the implications of our results for high-energy gamma-ray studies of the Galactic center region and large-scale molecular studies of the Galaxy and external spiral galaxies. Our results are summarized in § 4.

2. DATA AND ANALYSIS

2.1. *Longitude Profiles of the Far-Infrared and ^{12}CO Emission*

Longitude profiles of the 140 μm, 240 μm, and velocity-integrated ^{12}CO emission averaged over the $-0^{\circ}.75$ to $0^{\circ}.75$ latitude interval have been derived by Sodroski et al. (1994) using a preliminary version of the DIRBE data (angular resolution $\sim 0^{\circ}.7$) averaged over the entire 10 months of cryogenic operation (Annual Average Maps: see *COBE* DIRBE Explanatory Supplement 1994), and ^{12}CO data (angular resolution $\sim 0^{\circ}.5$) from Dame et al. (1987). For each of these profiles, we have derived an analytical expression of the form $Al + B$ for the emission from the Galactic disk over the Galactic longitude range $-20^{\circ} < l < 20^{\circ}$ from a linear least-squares fit to the intensities within the regions $-20^{\circ} < l < -4^{\circ}$ and $4^{\circ} < l < 20^{\circ}$. The best-fit estimates of the coefficients A and B are listed in Table 1. We then subtracted the corresponding analytical expression for the Galactic disk component from each profile to obtain the Galactic center region emission profiles, shown in Figure 1. Throughout the remainder of this paper the term "Galactic center region" refers to the longitude region $358^{\circ}.5 < l < 3^{\circ}.5$ (see Fig. 1), which corresponds to the region of the Galactic disk within approximately 400 pc of the Galactic center. Based on the deviations of the Galactic emission profiles from the corresponding analytical approximations in the fitted regions, the uncertainties in the Galactic center region emission profiles over the range $359^{\circ} < l < 1^{\circ}.5$ due to inaccuracies in the removal of the Galactic disk component (i.e., neglect of small-scale structure) are estimated to be less than 15%. Absolute calibration uncertainties of 10% in the DIRBE 140 and 240 μm observations do not significantly affect this analysis since it is based on a relative comparison of different regions in the Galactic plane (see § 2.3). The DIRBE photometric scale at each of these wavelengths is stable over the sky to better than 2% (*COBE* DIRBE Explanatory Supplement 1994). This analysis is restricted to the region $300^{\circ} < l < 40^{\circ}$, $|b| < 1^{\circ}.25$, where the zodiacal light component is everywhere estimated to be less than 1% of the observed emission at 140 and 240 μm. For the remainder of this analysis, we neglect the contribution of neutral atomic hydrogen to the gas column density in the Galactic center region. Since it is believed that more than 90% of the mass of gas in the Galactic center region (Galactocentric distance less than 400 pc) is in molecular form (Sanders et al. 1984; Güsten 1989), this assumption should not lead to large errors in our derived results.

2.2. *Dust Temperature and 240 Micron Optical Depth Profiles*

Longitude profiles of the dust temperature and the 240 μm optical depth for the Galactic center region were derived from the longitude profiles of the disk-subtracted 140 and 240 μm Galactic center region intensities, I_{140} and I_{240}, respectively, by assuming that the dust distribution along each line of sight is isothermal and has a λ^{-2} emissivity law (see Hauser et al. 1984 and Sodroski et al. 1987 for details of this type of analysis). Over the longitude range $358^{\circ}.5 < l < 3^{\circ}.5$, the derived dust temperature varies from 20 to 27 K and has a mean value of 23 K. The derived 240 μm optical depth profile is shown in Figure 2. The peak value at $l = 1^{\circ}$ is 0.013, showing that, averaged over the $0^{\circ}.7$ DIRBE beam, the Galactic center region is optically thin at wavelengths > 140 μm. However, this conclusion is based upon the assumption that there is not a

TABLE 1

ANALYTICAL EXPRESSIONS FOR EMISSION FROM GALACTIC DISK COMPONENT

PROFILE	FIT: $I = Al(\mathrm{deg}) + B$ $(-20^{\circ} < l < -4^{\circ}, 4^{\circ} < l < 20^{\circ}; \lvert b \rvert < 0^{\circ}.75)$	
	A	B
I_{140}(MJy sr^{-1})......	9 ± 6	2080 ± 70
I_{240}(MJy sr^{-1})......	4 ± 3	1330 ± 40
I_{CO}(K km s^{-1})	0.08 ± 0.07	86 ± 4

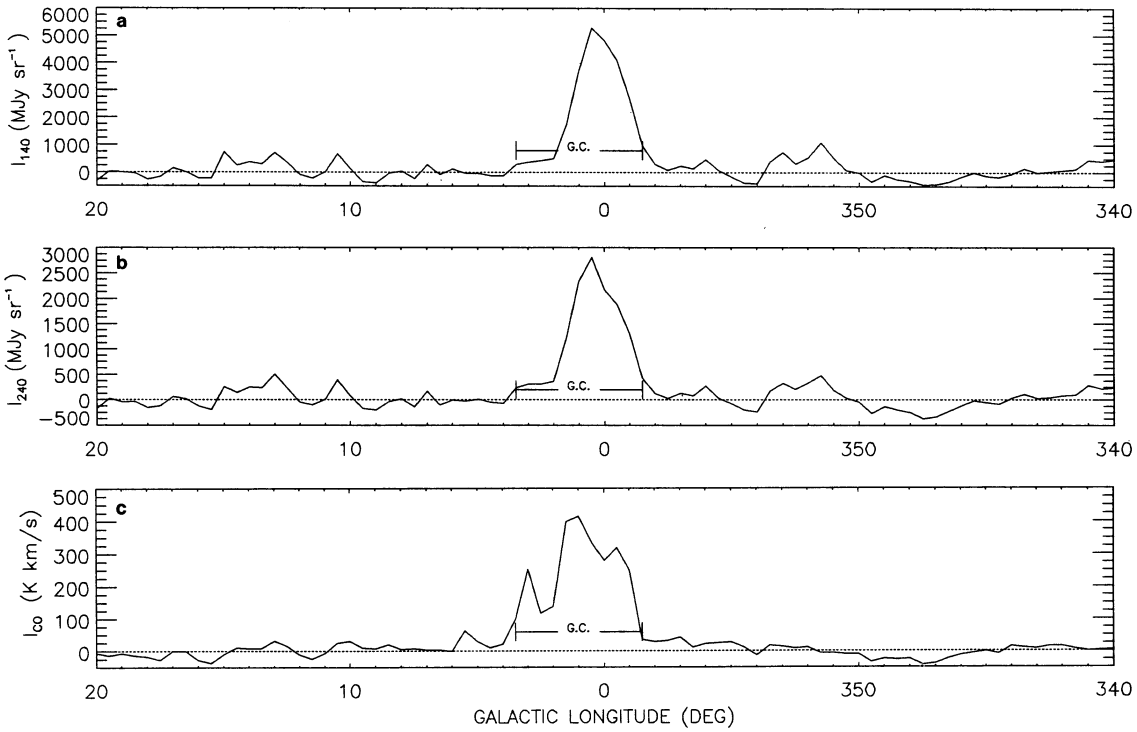

FIG. 1.—Longitude profiles of the (*a*) 140 μm, (*b*) 240 μm, and (*c*) velocity-integrated ^{12}CO emission from the Galactic center region ($358\overset{\circ}{.}5 < l < 3\overset{\circ}{.}5$), after subtraction of analytical approximations (see text) for the Galactic disk emission. In all of the profiles the intensity at each longitude represents the mean intensity within the latitude region $|b| < 0\overset{\circ}{.}75$, and the angular resolution and sampling in longitude are $\sim 0\overset{\circ}{.}7$ and $0\overset{\circ}{.}5$, respectively. The ^{12}CO data at a given longitude were integrated over the velocity interval where emission was detected in a velocity-longitude map of the Galactic plane region.

large amount of clumpiness in the dust distribution along each line of sight. We discuss this point further in § 2.3.

2.3. *Derivation of X in the Galactic Center Region*

We assume that the dust within 400 pc of the Galactic center does not have unusual properties and, therefore, the dust mass absorption coefficient in the Galactic center region is not significantly different from that in the inner Galactic disk. Throughout this paper the term "inner Galactic disk" refers to the region 2 kpc < Galactocentric distance < 7 kpc, where most of the molecular gas inside the solar circle (i.e., the "molecular ring") lies (see, for example, Bronfman et al. 1988). Defining R_X to be the ratio of the X values in the inner Galactic disk and Galactic center region, we find that R_X can be written as (see, for example, Sodroski et al. 1994)

$$R_X \equiv \frac{X_i}{X_c} = \frac{W_c}{\tau_c}\,\frac{\tau_i}{W_i}\,\frac{G_i}{G_c}\,, \qquad (1)$$

where W is the mean velocity-integrated ^{12}CO intensity, τ the mean 240 μm optical depth of the dust associated with molecular gas, and G the mean gas-to-dust mass ratio for molecular clouds, and where the subscripts i and c denote the inner Galactic disk and Galactic center region, respectively. From the longitude profiles of the velocity-integrated ^{12}CO emission (Fig. 1) and 240 μm optical depth (Fig. 2), we find $\tau_c/W_c = (2.2 \pm 0.1) \times 10^{-5}$ K^{-1} km^{-1} s. From the results of a decomposition of the Galactic 140 and 240 μm emission within the regions $300° < l < 350°$, $|b| < 1\overset{\circ}{.}25$ and $10° < l < 40°$, $|b| < 1\overset{\circ}{.}25$ into components associated with molecular ($T_{\rm dust} \sim 19$ K), neutral atomic hydrogen ($T_{\rm dust} \sim 17$–22 K), and extended low-density ionized ($T_{\rm dust} \sim 29$ K) gas (Sodroski et al. 1994), we obtain $\tau_i/W_i = (5.8 \pm 1.0) \times 10^{-5}$ K^{-1} km^{-1} s. The error estimates take into account uncertainties in the removal of the Galactic disk component and the noise levels of the far-infrared and ^{12}CO surveys. They do not, however, include the DIRBE absolute calibration uncertainties, which affect the values of τ_c and τ_i equally and are therefore not propagated

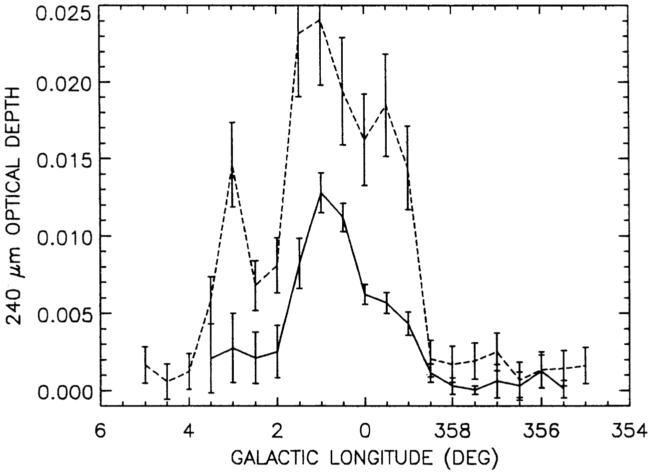

FIG. 2.—The 240 μm optical depth profile derived with our single-temperature analysis (*solid line*) and the expected 240 μm optical depth profile (*dashed line*) using the velocity-integrated ^{12}CO profile and assuming values for the ratio of H_2 column density to ^{12}CO intensity and gas-to-dust mass ratio equal to the corresponding values for inner Galaxy molecular complexes. Error estimates take into account uncertainties in removal of the Galactic disk component and derivation of τ_i/W_i (see text), and the noise levels of the far-infrared and ^{12}CO surveys.

into the estimate of R_X. We also note that adopting a different emissivity index within the range $1.5 < n < 2$ would change the derived value of R_X by less than 5%. Assuming that G_c is equal to G_i, we obtain $R_X = 2.7 \pm 0.5$, i.e., the value of X is a factor of approximately 3 higher in the Galactic center region than in the inner Galactic disk. Put another way, the derived 240 μm dust optical depth in the Galactic center region from this single-temperature analysis is a factor of approximately 3 lower than that expected from the velocity-integrated ^{12}CO emission, assuming that the values of the ratio of H_2 column density to ^{12}CO intensity and the gas-to-dust mass ratio for Galactic center region molecular gas are equal to the corresponding values for inner Galaxy complexes (Fig. 2).

It is probable, however, that the gas-to-dust mass ratio in the Galactic center region is significantly lower than the value for the inner Galactic disk. Dust formation in the interstellar medium is believed to occur primarily through (1) condensation in the winds of evolved stars and ejecta from novae and supernovae, and (2) accretion in dark clouds (Gehrz 1989). Recent heavy-element abundance estimates using radio, infrared, and optical observations (Wannier 1989; Wilson & Rood 1994) imply that the metallicity of the Galactic center region is greater than that in the inner Galactic disk. This suggests that the Galactic center region has produced more dust-forming material per unit mass of gas, and has had a higher mean star formation rate per unit mass of gas, than the inner Galactic disk. Therefore, if stars in the Galactic center region had been at least equally efficient in forming dust as stars in the inner Galactic disk, the mean rate of dust formation per unit mass of gas via mechanism (1) was higher for the Galactic center region than in the inner Galactic disk. Observations of lines of symmetric top molecules (Güsten et al. 1985), density-tracing molecules such as CS (Bally et al. 1987), and of ^{12}CO ($J = 1 \rightarrow 0$, $J = 2 \rightarrow 1$ through $J = 5 \rightarrow 4$; see Sanders et al. 1984; Bennett et al. 1994), ^{13}CO (Bally et al. 1987), and neutral atomic hydrogen (Burton & Liszt 1992) imply that molecular clouds in the Galactic center region have a significantly higher gas kinetic temperature, have an order of magnitude higher density (both conducive to accretion processes Seab 1987), and contain a much greater fraction of the total gas mass than do their inner Galactic disk counterparts (see also Güsten 1989). Therefore, the mean rate of dust formation per unit gas mass through mechanism (2) is also likely to have been higher for the Galactic center region than in the inner Galactic disk. Dust destruction is not expected to have had a major effect on dust abundances in the Galactic center region, since interstellar shocks will not penetrate into the high-density clouds typical of this region (Seab 1987). Observational evidence for an inverse relation between gas-to-dust mass ratio and heavy element abundance, Z, in the Galactic disk is presented by Issa et al. (1990) and Sodroski et al. (1994). Assuming this relation we obtain $G_i/G_c = Z_c/Z_i = 1.5$–3 (Wannier 1989; Cox & Laureijs 1989; Wilson & Rood 1994) and $R_X \equiv X_i/X_c = 3$–10. Adopting a value of $X_i \sim 2.2 \times 10^{20}$ molecules cm^{-2} K^{-1} km^{-1} s (Lebrun et al. 1983; Bloemen 1985; Dame et al. 1986; Solomon et al. 1987; Strong et al. 1988; § 3.2), this implies that $X_c \sim (2\text{–}7) \times 10^{19}$ molecules cm^{-2} K^{-1} km^{-1} s.

It is important to determine whether the conclusion that X_c is a factor of 3–10 lower than X_i could result from a breakdown of the assumption that the dust distribution along each line of sight within the Galactic center region is isothermal. If there exist warm and cold dust components along the line of sight, the derived value of dust temperature will be biased toward the higher temperature component, resulting in an inferred value of τ_c that is lower than the actual value (We note that this is not a serious concern for our derived value of τ_i since an underestimate of τ_i would result in an underestimate of R_X). To test for the possible presence of a massive cold dust component in the Galactic center region that is undetected by DIRBE, we fit a two-temperature dust model with λ^{-2} emissivities to the *COBE* Far-Infrared Absolute Spectrophotometer (FIRAS) Galactic center spectrum (100 μm $< \lambda <$ 1000 μm), from which the contribution of the Galactic disk was removed by subtracting the average of the FIRAS spectra at $l = 350°$ and $l = 10°$. Fixing the temperature of the cold dust component, the temperature of the warm dust component and the column density of each component were varied until the best fit to the disk-subtracted spectrum was found. This procedure was repeated many times, varying the assumed temperature of the cold dust component within the range 6–15 K (Mathis, Mezger, & Panagia 1983), in steps of 1 K, and the assumed emissivity index within the range 1.5 to 2.5, in steps of 0.5. In all cases the derived column density of the cold dust component was less than 1% (1 σ upper limit) of that of the warm dust component, implying that there is no evidence for a significant amount of cold dust near the Galactic center within the above range of temperatures. Although FIRAS has a 7° beam, this result should apply to the region analyzed in this paper because the Galactic center region is bright enough and its latitude extent is small enough such that the disk-subtracted FIRAS Galactic center spectrum is dominated by emission from $|b| < 0\overset{\circ}{.}75$. Based on the range of dust temperatures (i.e., 20 to 27 K) derived from the 140 and 240 μm data, the estimated uncertainty in τ_c due to neglect of a dust temperature distribution along each line of sight is about 30%. This uncertainty estimate is consistent with the results of the analysis of the Galactic emission from 3.3 to 900 μm by Pajot et al. (1989), who conclude that Galactic emission at wavelengths larger than 150 μm is a very good tracer of the total column density of the dust. A similar conclusion was drawn by Reach et al. (1995), who decomposed the FIRAS Galactic spectra between 100 μm and 1000 μm into warm ($T_{\rm dust} \sim$ 16–23 K), intermediate-temperature ($T_{\rm dust} \sim$ 10–14 K), and very cold ($T_{\rm dust} \sim$ 4–7 K) dust components.

Another assumption inherent in our analysis is that the Galactic center region and inner Galactic disk are optically thin at wavelengths greater than 140 μm, so that the derived 240 μm optical depth along each line of sight is a reliable tracer of dust (and hence gas) column density. The low values of the derived 240 μm optical depth (Fig. 2, and Fig. 2*d* of Sodroski et al. 1994) indicate that most of the area sampled by the DIRBE beam contains optically thin regions, but optically thick compact regions that do not contribute a large fraction of the observed flux could also be present. This is more of a concern for the Galactic center region than for the inner Galactic disk, because mean gas densities of giant molecular clouds are more than a factor of 10 greater in the Galactic center region than in the inner disk, and masses of giant molecular clouds in the two regions are comparable (Gusten 1989). For a given gas-to-dust mass ratio, dust column density is proportional to (mass)$^{1/3}$ (density)$^{2/3}$.

The importance of optical depth effects for the Galactic center region can be estimated using the 800 μm map of Lis & Carlstrom (1994), which covers a $1\overset{\circ}{.}5 \times 0\overset{\circ}{.}2$ region around the Galactic center with an angular resolution of 30″. The peak intensity in their map occurs toward Sgr B2 and corresponds to a 140 μm optical depth of approximately 8, assuming a dust emissivity spectral index of 2.0 and a dust temperature of 23 K. However, most of the flux in their map arises from regions with intensities less than 18 Jy per beam, which corresponds to a 140 μm optical depth of 0.4 under the same assumptions. For a uniform dust slab with a 140 μm optical depth of 0.4, emissivity index of 2.0, and dust temperature of 23 K, our analysis would underestimate the dust temperature by 7% and overestimate the 240 μm optical depth by 15%. Therefore, based on the 800 μm map, it is unlikely that the presence of high optical depth regions could have resulted in significant errors in the derived value of the 240 μm optical depth averaged over the Galactic center region. We also emphasize that unless clumping is much more extreme for inner disk molecular clouds than in the Galactic center region, high optical depth structure on angular scales smaller than 30″ (corresponding to a linear scale of 1.2 pc at a distance of 8.5 kpc) would have caused our derived value of R_X to be lower than its actual value, i.e., the actual discrepancy between X_c and X_i would be even greater than our derived factor of 3–10.

A reduced value of X in the Galactic center region may occur for one or both of the following reasons: (1) The macroturbulent cloud model of giant molecular cloud complexes (Maloney & Black 1988; Wolfire, Hollenbach, & Tielens 1993) implies that the value of X varies approximately inversely with molecular gas kinetic temperature, which is known to be significantly higher (factor of $\sim$5–10) in the Galactic center region than in the inner Galactic disk (Güsten et al. 1985). Possible molecular gas heating mechanisms in the Galactic center region include heating by low-energy (1–10 MeV) cosmic rays, magnetic viscous heating, shock heating (i.e., turbulent dissipation), and grain photoelectric heating (see, for example, Güsten 1989). The derived values of 20 to 27 K for the dust temperature in the Galactic center region (see § 2.2) are much lower than the molecular gas kinetic temperatures of 50–100 K derived by Morris et al. (1983) and Güsten et al. (1985) using radio observations of symmetric top molecules within the region $358° < l < 2°$, $|b| < 10'$. This result supports the conclusion of Odenwald & Fazio (1984) that radiative heating of the dust by stellar sources, and the subsequent transfer of energy to the gas via gas-grain collisions, is not the primary heating process for the molecular gas in the Galactic center region. (2) The presence of large velocity dispersions within the molecular gas in the Galactic center region may lower the effective optical depth of the ^{12}CO ($J = 1 \rightarrow 0$) line, resulting in more ^{12}CO ($J = 1 \rightarrow 0$) line emission per unit mass of molecular gas and therefore a significantly lower value of X. This possibility has been suggested by Stacy et al. (1987) and Stark et al. (1989), who found evidence for the existence in the Galactic center region of giant molecular cloud complexes with very large line widths ($\langle v_{\rm rms} \rangle = 20$–$60$ km s^{-1}) relative to their inner Galaxy counterparts. Stark et al. (1989) also found evidence for the existence of a diffuse, low optical depth, molecular intercloud medium, which may give rise to a large fraction of the ^{12}CO emission from within 300 pc of the Galactic center.

3. ASTROPHYSICAL IMPLICATIONS

3.1. *Comparison with Gamma-Ray Studies*

Our conclusion that X is a factor of 3–10 lower in the Galactic center region than in the inner Galactic disk is directly relevant to studies of the high-energy (300 MeV–5 GeV) gamma-ray emission from the Galactic center region (Blitz et al. 1985; Stacy et al. 1987). From *COS B* observations, Blitz et al. (1985) derived an upper limit of 4×10^{-7} photons cm^{-2} s^{-1} to the high-energy (300 MeV–5 GeV) gamma-ray flux from the region within 400 pc of the Galactic center. If the density of cosmic rays in the central region of the Galaxy is greater than or equal to the mean cosmic-ray density in the Galactic disk (Bloemen 1985), this implies that the mass of molecular hydrogen gas in the Galactic center region is $<6 \times 10^7$ $M_\odot$ (3 σ upper limit), which is more than a factor of 5 lower than the molecular hydrogen gas mass estimate of $\sim 3 \times 10^8$ $M_\odot$ (Sanders et al. 1984) from ^{12}CO observations assuming $X_c = 3.6 \times 10^{20}$ molecules cm^{-2} K^{-1} km^{-1} s. For an assumed value of $X_c = X_i = 2.2 \times 10^{20}$ molecules cm^{-2} K^{-1} km^{-1} s (see § 3.2), there is still a factor of 3 discrepancy.

In order to account for this discrepancy, Blitz et al. (1985) suggest that the value of X, and/or the density of cosmic-ray nuclei that produce the high-energy gamma rays, is significantly lower in the Galactic center region than in the Galactic disk. The results of our analysis of the DIRBE 140 and 240 μm data imply that this discrepancy is largely due to a low X_c/X_i ratio and that the mass of molecular hydrogen gas in the Galactic center region is approximately (2–6) $\times 10^7$ $M_\odot$, which is 85%–90% of the total gas mass in this region (Burton & Liszt 1978; Güsten 1989). Additional support for this interpretation comes from ^{13}CO ($J = 1 \rightarrow 0$) observations of the Galactic center region (Heiligman 1987; Bally et al. 1988), which imply (Güsten 1989) a total molecular hydrogen mass within 500 pc of the Galactic center of approximately 8×10^7 $M_\odot$, and from CO observations of several external galaxies by Wall et al. (1993), who derived values of the ratio of H_2 column density to ^{12}CO intensity within the central 20″ (170–530 pc) diameter regions of the sample galaxies that are 5 to 20 times smaller than X_i in the Milky Way.

3.2. *Radial Variation of X*

The results of this analysis, when combined with several virial analyses (Dame et al. 1986; Digel et al. 1990; Sodroski 1991) of giant molecular cloud complexes in the Galactic disk, suggest that there exists a general trend of increasing X with increasing Galactocentric distance D_G. The value of X increases by more than an order of magnitude from the Galactic center to $D_G = 13$ kpc (Fig. 3). A least-squares fit of a line to the data in Figure 3 gives an intercept of (-0.34 ± 0.08) and a slope of (0.12 ± 0.01), showing that the trend in X is highly significant. In these virial studies, the authors used the Goddard-Columbia ^{12}CO surveys of the Galactic plane region to estimate the value of X in various Galactocentric distance ranges by comparing the virial masses of giant molecular cloud complexes with their ^{12}CO luminosities. Since all of the Goddard-Columbia ^{12}CO surveys were undertaken with either the Columbia Millimeter-Wave Telescope in New York, or the nearly identical Columbia Southern Millimeter-Wave Telescope in Cerro Tololo, Chile, calibration differences between the various surveys are small and do not have a significant effect on the results of Figure 3.

It should be noted that the results of Figure 3 are consistent with previous large-scale determinations of X. The value of $X = 2.2 \times 10^{20}$ molecules cm^{-2} K^{-1} km^{-1} s for the Galactocentric distance range 4.5 to 7 kpc, derived by Sodroski (1991) using data from Dame et al. (1986) corrected for a Sun-to-Galactic center distance of 8.5 kpc, is in very good agreement with earlier estimates (Lebrun et al. 1983; Bloemen 1985; Solomon et al. 1987, and references therein). Correlation

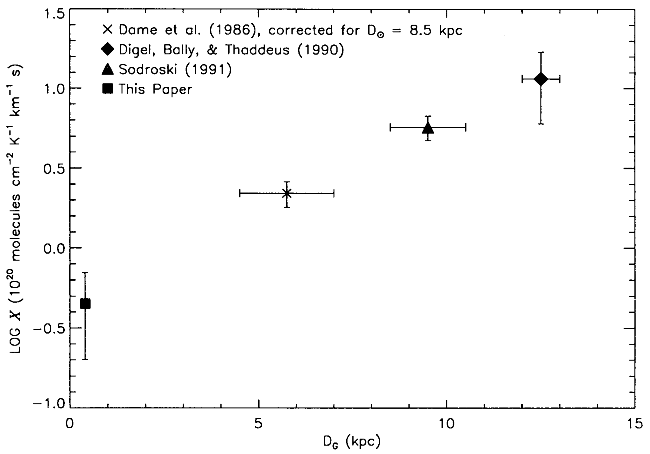

FIG. 3.—Distribution with Galactocentric distance of the logarithm of X, the ratio of H_2 column density to ^{12}CO intensity. Shown in the figure are the results derived in this paper ($D_G < 400$ pc) and the results of several virial analyses of giant molecular cloud complexes in the Galactocentric distance ranges 4.5 to 7 kpc (Sodroski 1991 using data from Dame et al. 1986), 8.5 to 10.5 kpc (Sodroski 1991), and 12 to 13 kpc (Digel, Bally, & Thaddeus 1990). For the virial analyses the vertical error bar shows the statistical uncertainty in X (Digel et al. 1990; Sodroski 1991). The value of X increases by more than an order of magnitude from $D_G \sim 0$ kpc to $D_G = 13$ kpc.

analyses of high-energy gamma-ray data with CO and H I data have provided independent information on the large-scale variation of X with Galactocentric distance. Results are reviewed by Bloemen (1989). An analysis using *COS B* data above 150 MeV by Strong et al. (1988) did not find a significant difference between the apparent X value for 2 kpc $< D_G <$ 7 kpc and the value for $D_G >$ 7 kpc. However, the uncertainties were large enough that a factor of 2 variation in X could not be ruled out, so the result of Strong et al. (1988) is consistent with the variation in X shown in Figure 3.

Almost all of the large-scale studies of the Galactic disk that have used the ^{12}CO ($J = 1 \rightarrow 0$) line as a tracer of molecular hydrogen (Solomon et al. 1987, and references therein) are based on the assumption that the value of X does not vary significantly (i.e., on a large-scale) with Galactic location. The results of Figure 3 suggest that these studies have significantly overestimated the relative amount of molecular hydrogen at small Galactocentric distances, and significantly underestimated the relative amount of molecular hydrogen at large Galactocentric distances. The large-scale variation in X implied by Figure 3 may result from a decrease in the heating rate, and therefore the gas kinetic temperature, of giant molecular cloud complexes with increasing Galactocentric distance (Maloney & Black 1988; Sodroski 1991), and possibly in part from large-scale variations in cloud optical depth (Stacy et al. 1987).

Since X increases rapidly with increasing Galactocentric distance within the Galactic disk, it is probable that X varies significantly with Galactocentric distance in many other spiral galaxies as well. One of the results of studies of the ^{12}CO emission from external spiral galaxies, in which a constant value of X was assumed, is that the surface density of molecular hydrogen in many of these galaxies increases exponentially toward the galactic center (Young & Scoville 1982; Young 1990; and references therein). In light of our current findings, this result must be called into question. It is important to note that an exponentially increasing molecular hydrogen surface density with decreasing Galactocentric distance is inconsistent with density wave models of disk galaxies. As first pointed out by Oort (1974), for a disk galaxy with a grand-design spiral pattern and typical rotation curve there will exist an increase in the star formation rate per unit gas mass with decreasing Galactocentric distance owing to the increase in the angular velocity of the gas toward the center of the disk and the resulting greater frequency with which the gas encounters the density wave. Therefore, the gas depletion rate will be greater at smaller Galactocentric distances. The galactic models of Maloney (1987) have shown the following: (1) gas distributions that were exponential 10^{10} yr ago should now be very flat, and (2) the gas distributions inferred from ^{12}CO observations of disk galaxies assuming a constant X require initial gas distributions that exceed the dynamical masses derived from the rotation curves of the galaxies.

4. SUMMARY

In summary, comparison of the DIRBE 140 and 240 μm observations of the Galactic plane region with the Goddard-Columbia ^{12}CO surveys yields an estimate for X_c, the ratio of H_2 column density to ^{12}CO intensity in the vicinity of the Galactic center. We have found a value of X_c that is a factor of 3–10 lower than the value of X for inner Galaxy complexes and attribute the so-called gamma-ray deficit from the Galactic center region to the incorrect use of a constant value of X throughout the Galaxy. Combining this result with several virial analyses of giant molecular cloud complexes in the Galactic disk implies that the value of X increases by more than an order of magnitude from the Galactic center to a Galactocentric distance of 13 kpc. It is concluded that studies of the large-scale ^{12}CO emission from our own Galaxy and external spiral galaxies, in which a constant value of X with Galactocentric distance was assumed, have derived molecular hydrogen surface density distributions that may be significantly in error.

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