H₂, CO, and Dust Absorption through Cold Molecular Clouds

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Abstract

The abundance of H₂ in molecular clouds, relative to the commonly used tracer CO, has only been measured toward a few embedded stars, which may be surrounded by atypical gas. We present observations of near-infrared absorption by H₂, CO, and dust toward stars behind molecular clouds, providing a representative sample of these molecules in cold molecular gas, primarily in the Taurus Molecular Cloud. We find N_H₂/AV ≈ 1.0 × 10²⁴ cm⁻², N_CO/AV ≈ 1.5 × 10¹⁷ cm⁻² (1.8 × 10¹⁷ including solid CO), and N_H₂/N_CO ≈ 6000. The measured N_H₂/N_CO ratio is consistent with that toward embedded stars in various molecular clouds, but both are less than that derived from millimeter-wave observations of CO and star counts. The difference apparently results from the higher directly measured N_CO/AV ratio.

Key words: ISM: molecules – ISM: abundances – dust, extinction

1. Introduction

Molecular hydrogen, H₂, is undoubtedly the most abundant species in molecular clouds. It and atomic helium must constitute ~98% of the mass in molecular clouds. However, both of these species are very difficult to observe. Cold helium gas has no detectable transitions at wavelengths that are observable through molecular clouds. H₂ has electric quadrupolar vibrational and rotational transitions in the infrared, but the weakness of these lines makes them very difficult to observe in absorption, and the wide spacing between the H₂ energy levels causes their emission lines to be observable only from unusually hot or radiatively excited gas.

Due to the difficulty of observing H₂, CO is most often used to measure the column density of gas in molecular clouds, with an assumed H₂/CO abundance or line flux ratio. A number of authors have attempted to determine these ratios in order to calibrate cloud masses determined from CO observations. Dickman (1978) made millimeter-wavelength J = 1 − 0 observations of 12CO, which he compared to determinations of AV based on star counts. Assuming N_H₂/AV = 1.25 × 10²¹ cm⁻², he derived N_H₂ = 5 × 10⁵ N_CO. Assuming 12CO/13CO = 60, this corresponds to N_H₂/N_CO = 8300. Frerking et al. (1982) extended Dickman’s work to larger column densities and rarer CO isotopomers, which are less affected by line saturation. They found somewhat different relations for the Taurus and Ophiuchus molecular clouds and for different CO isotopomers. Their results are generally consistent with N_H₂/AV = 1.7 × 10¹⁴ cm⁻², or N_H₂/N_CO = 1.2 × 10⁴ for the interiors of clouds, at AV > 4. They also give the ratio known as X_CO = N_H₂/NICO = 1.8 × 10²⁰ cm⁻² (K km s⁻¹)⁻¹, which is used to derive H₂ column densities from CO observations. More recently, Pineda et al. (2010) measured N_CO and AV at higher angular resolution in the Taurus Molecular Cloud (TMC). They found a nonlinear relation between N_CO and AV consistent with freeze-out of CO at AV > 10, and a variation in the N_CO/AV ratio with location in the cloud. On average they found N_CO/AV = 1.0 × 10¹⁷ cm⁻² at AV < 10, and assuming N_H₂/AV = 9.4 × 10²⁰ cm⁻², N_H₂/N_CO = 9000. Other recent studies include Pineda et al. (2008) and Lee et al. (2014), who measured X_CO in the Perseus molecular cloud. Lee et al. (2014) found substantial variations in X_CO among regions in Perseus and large variations in X_CO on small scales. These and other determinations of N_H₂/N_CO and X_CO are reviewed by Bolatto et al. (2013). However, most determinations of the relation between the H₂ column density and the CO column density or emission depend on the assumed X_CO/AV ratio, which might not be valid in dense molecular clouds.

Although infrared lines of H₂ are quite weak, it is possible to observe them in absorption through sufficiently large columns of molecular gas. The 2–2.4 μm ν = 1 − 0 lines are the most favorable, as they are the strongest infrared lines of H₂. They also have the advantages that they lie close in wavelength to the ν = 2 − 0 band of CO, allowing simultaneous or nearly simultaneous measurements of column densities of these two molecules, and that they lie in a relatively transparent region of the telluric spectrum, in the near-infrared K band. There have been three direct determinations of N_H₂/N_CO in molecular clouds using the K-band absorption lines of these molecules. Lacy et al. (1994) detected absorption in the ν = 1 − 0, J = 2 − 0 (or S(0)) line of H₂ and low-J lines of the ν = 2 − 0 band of CO toward the embedded star NGC 2024 IRS 2. They derived an N_H₂/N_CO ratio of 4000 ± 3000. Kulesa (2002) observed these lines toward five additional high-mass stars embedded in molecular clouds. His observations are consistent with N_H₂/N_CO = 3500–7000, with all measured ratios being less than the ratios determined by Dickman (1978) and Frerking et al. (1982). Goto et al. (2015) added one additional source, NGC 7538 IRS 1, and measured N_H₂/N_CO = 3600.

However, all of the sources in which H₂ and CO infrared absorption has been observed are embedded stars, and from the relatively high temperatures derived from the CO lines most of the absorption must occur in gas close to the stars, which may have unusual chemistry. It is also possible that UV radiation from the stars excites H₂ emission, which could contaminate the absorption lines. In this paper we present observations of
stars lying behind molecular clouds. The lines of sight to these stars should probe more typical molecular cloud gas and should be uncontaminated by H$_2$ emission; even if there is diffuse emission along the lines of sight to these stars, it would be removed by the sky subtraction during data reduction.

### 2. Observations

Observations were made with the Immersion Grating Infrared Spectrograph (IGRINS; Park et al. 2014; Mac et al. 2016) on the 2.7 m Harlan J. Smith telescope at McDonald Observatory. IGRINS is a high-resolution ($R = 45,000$) near-infrared cross-dispersed spectrograph, which simultaneously covers the $H$ and $K$ spectral bands (1.45–2.45 μm). For this project only the $K$ band, which includes the $v = 1 - 0$ S(0), S(1), and Q-branch lines of H$_2$ and the $v = 2 - 0$ P and R branches of CO, was used. The telescope was nodded to move object images between two positions along the $10' \times 15''$ entrance slit in an ABBA pattern. The exposure time per nod position was 300 s, and typically six ABBA sequences, or 2 hr of on-source time, were acquired for each target, with a goal of a statistical signal-to-noise ratio (S/N) of 1000. Nearby A0V stars were used for telluric comparison, with similar exposure times and somewhat better S/Ns.

Three categories of targets were observed: young stars in molecular clouds still surrounded by their natal gas and dust, which we refer to as embedded stars; stars lying behind molecular clouds, which we refer to as background stars; and relatively unextincted stars that were observed to test our photospheric spectrum models, which we refer to as foreground stars. Four embedded stars in the Taurus and Monoceros clouds were observed. Eight background stars were observed, five lying behind the Taurus cloud and three lying behind clouds in Ophiuchus and Serpens. All but one of these were late-type giants, with complicated photospheric spectra, necessitating modeling to extract interstellar lines, as is described below. And five foreground stars, with similar spectral types to the background giants, were observed. Observations of several other stars were attempted, which either had too little extinction to show interstellar absorption or too low S/N to provide useful results. A list of targets and observing parameters is given in Table 1.

The data were reduced with a custom Fortran pipeline, which performed standard procedures of spike removal, flat-fielding with a lamp spectrum, distortion correction, and point-source spectrum extraction. Telluric absorption lines in comparison star spectra were used for wavelength calibration. After spectrum extraction, the target spectra were divided by comparison star spectra and telluric residuals. In addition, residuals due to changes in the telluric water vapor between the target and comparison star observations were corrected by adding or subtracting a small fraction of a model for the telluric water absorption.

Spectra of the Taurus background sources are shown in Figure 1 (low-J CO band region) and Figure 2 (H$_2$ S(0) line region). The spectra are shifted to the stellar rest frames, with shifted positions of the interstellar lines marked. Wavelengths are in vacuum. In Figure 2 observations from different nights are shown separately to allow an estimate of the noise level. All other figures show time-weighted averages of data from multiple nights. All plotted spectra are corrected for telluric absorption. Although photospheric features are generally much stronger than the interstellar lines, comparison of the spectra makes it apparent that H$_2$ absorption was detected toward Elias 3–16 and Tamura 8. H$_2$ absorption is probably present in Elias 3–13 and Kim 1–59, but it is blended with a photospheric emission.

| Name               | Sp Type | Location          | $K$ mag | Dates$^b$ | Int Time |
|--------------------|---------|-------------------|---------|-----------|----------|
| Embedded stars     |         |                   |         |           |          |
| Elias 3–1          | YSO     | Taurus            | 5.8     | 2015 Dec 03 | 40 m     |
| Elias 3–18         | YSO     | Taurus            | 6.3     | 2015 Dec 03 | 60 m     |
| IRAS 04278+2253    | YSO     | Taurus            | 5.8     | 2015 Dec 03 | 40 m     |
| AFGL 989$^c$       | Cl II YSO | Monoceros     | 4.9     | 2015 Dec 03 | 40 m     |
| Background stars   |         |                   |         |           |          |
| Elias 3–13         | K2III   | Taurus            | 5.5     | 2015 Dec 02.04 | 40 + 80 m |
| Elias 3–16         | K2III   | Taurus            | 5.2     | 2015 Dec 02.04 | 40 + 80 m |
| Tamura 8           | K3III   | Taurus            | 7.5     | 2015 Dec 02.04 | 80 + 40 m |
| HD 283809          | F8?     | Taurus            | 6.2     | 2016 Jan 23, 24, 25 | 40 + 40 + 40 m |
| Kim 1–59           | K2III   | Taurus            | 7.9     | 2015 Dec 03 | 40 m     |
| Elias 2–15         | M6III   | Ophiuchus         | 5.3     | 2015 Jun 18  | 40 m     |
| Elias 2–35         | K6III   | Ophiuchus         | 7.3     | 2015 Jul 24  | 60 m     |
| SVS76 Ser 9        | G0III?  | Serpens           | 8.5     | 2015 Jul 24  | 80 m     |
| Foreground stars   |         |                   |         |           |          |
| HR 5899            | K4III   | Serpens           | 2.3     | 2016 Jul 17 | 8 m      |
| HR 7800            | K7III   | Cygnus            | 2.0     | 2016 Jul 15 | 12 m     |
| HR 7919            | K2III   | Cygnus            | 3.3     | 2016 Jul 15 | 12 m     |
| HR 7956            | K3III   | Cygnus            | 1.8     | 2016 Jul 17 | 8 m      |
| HR 7969            | K5III   | Cygnus            | 2.3     | 2016 Jul 17 | 12 m     |

Notes.

$^a$ Spectral types taken from SIMBAD; generally uncertain.

$^b$ Precipitable water vapor was ~30 mm for 2015 June–July, ~2 mm for 2015 December, ~3 mm for 2016 January, and ~30 mm for 2016 July observations.

$^c$ AFGL 989 = NGC 2264 IRS 1 = Allen’s Star.
HD 283809 is a hot star, lacking strong photospheric features, but with less foreground absorption, making the detection of H$_2$ absorption less certain, although a feature is present at the expected wavelength. The interstellar CO lines are more difficult to recognize in the observed spectra, due to the strong photospheric CO lines, but are apparent after division by models, as discussed below. No sources show evidence of H$_2 S(1)$ absorption.

Spectra of the CO R-branch region toward the Taurus and Monoceros embedded sources are shown in Figure 3. Only the $R(0)$–$R(3)$ lines and corresponding $P$-branch lines are seen toward Elias 3–1 and Elias 3–18. The $R(0)$–$R(3)$ lines are seen toward AFGL 989. IRAS 04278+2253 shows a complicated spectrum, with narrow lines at $R(0)$–$R(3)$ and two sets of broader lines at higher $J$. It is difficult to identify the lines falling between the stronger high-$J$ lines toward IRAS 04278+2253, with the low-$J$ lines appearing to be missing. These lines may be highly blueshifted, with the $R(0)$ line possibly lying between the narrower $R(3)$ and $R(2)$ lines, near 2.34 $\mu$m. Broad absorption or emission lines may also be present toward Elias 3–1 and Elias 3–18. Spectra of the H$_2$ $S(0)$ line region toward the Ophiuchus and Serpens sources are shown in Figure 4, none of which show clear evidence of H$_2$ absorption. Elias 2–15 and Elias 2–35 are cooler than the background stars in Taurus, resulting in complicated photospheric spectra.

### 3. Spectrum Modeling

#### 3.1. Smooth Spectrum Sources

The hot star HD 283809 and the dust-enshrouded embedded sources Elias 3–1, Elias 3–18, IRAS 04278, and AFGL 989
have relatively flat, smooth spectra, simplifying their modeling. The modeling procedure started with flats spectra on which the interstellar lines were superimposed. The CO level populations were assumed to be described by a single-temperature Boltzmann distribution. Because the lines are spectrally unresolved and may be somewhat optically thick, a curve of growth was used to calculate the line equivalent widths, and narrow lines with these equivalent widths were used in the models. The line shapes in the curve-of-growth calculation were assumed to be Gaussian. CO line strengths were taken from HITRAN (Rothman et al. 2013). Next, the source spectra with the interstellar lines superimposed were multiplied by a model for the telluric atmosphere transmission, and those spectra were convolved with the instrumental resolution and CO column densities, temperatures differs from the observed telluric absorption because the CO on the line is not fully resolved at our 45,000 resolution. The instrumental resolution and CO column densities, temperatures, and line widths were considered free parameters, which were adjusted to give the best fit to the observed spectra. The fit parameters are given in Table 2.

The effect of line saturation is very similar to that of non-LTE populations or a mixture of different temperatures along the line of sight if only $R$-branch lines are included in the modeling. However, inclusion of the $P$-branch breaks this degeneracy as the optical depths of the $R$-branch lines, especially $R(1)$, are greater than those of the corresponding $P$-branch lines. Using line widths that fit the observed $P$-branch to $R$-branch equivalent width ratios, the CO spectra of HD 283809, Elias 3–1, and Elias 3–18 are well fitted by single-temperature models; all with temperatures of $\sim$10 K. The fitted line widths for these sources are in the range of $0.4$–$0.5$ km s$^{-1}$. The gas toward AFGL 989 is considerably warmer, $T \approx 35$ K, and more turbulent; the $P/R$ line ratios are consistent with optically thin lines. Some background sources, discussed below, also show broader lines. Emission in the CO lines should be negligible, as gas temperatures are far too low to excite $v = 2$ states, and radiatively excited states decay quickly via $v = 2 \rightarrow 1$ transitions.

The column densities of the different rotational states of CO toward AFGL 989 and HD 283809 are shown in a Boltzmann diagram in Figure 5. For AFGL 989 the lines are broad enough that the correction for optical depth is small, and only the column densities assuming the lines to be optically thin are shown. The derived column densities both with and without correction for saturation are shown for HD 283809. The correction is substantial for the $J = 0$ and $J = 1$ lines and significantly improves the fit to a single-temperature population distribution. The other two sources in this figure are discussed below.

A similar procedure was used to derive the H$_2$ $J = 0$ column density from the S(0) line, except that saturation of this weak line is negligible. The line strength was calculated from Turner et al. (1977). The low temperature of the CO gas toward HD 283809, Elias 3–1, and Elias 3–18 indicates that only the $J = 0$ state of H$_2$ should be populated if the H$_2$ ortho:para ratio is thermalized at the gas temperature. Only the S(0) line was detected toward HD 283809, consistent with this expectation. S(0) was not detected toward Elias 3–1 or Elias 3–18, but S(1) was detected in emission, and both lines were seen in emission from IRAS 04278, presumably from hot or fluorescent gas near these sources. Because of the dominance of H$_2$ emission toward these sources, we did not attempt to derive the H$_2$ column densities along these lines of sight.

H$_2$ S(0) was seen in absorption toward AFGL 989, whereas S(1) and Q(1–4) were seen in emission. The presence of both emission and absorption toward this source complicates its modeling, but the observation of Q-branch lines allows us to correct for emission in the S(0) line, albeit with substantial uncertainty. We calculated the emission contribution to S(0) by multiplying the flux in the Q(2) emission line, which originates in the same $v = 1$, $J = 2$ upper state as S(0), by the branching ratio and a reddening factor. Q(2) absorption should be negligible as the $J = 0$ state should not be populated in the cold absorbing gas. The reddening between Q(2) and S(0) was calculated based on the assumption that $A_V$/N$_{CO} = 5.5 \times 10^{-18}$, the average of the ratio for the sources toward which we measured both. We note that this corrected equivalent width is consistent with that observed by Kulesa (2002) with a smaller aperture, which was probably less affected by emission. We attempted to use the S(1) and Q(3) lines to measure the extinction to the source, assuming that both are dominated by emission, but the large uncertainty in the Q(3) flux and the small wavelength difference between these lines resulted in too large an uncertainty to be useful.

### 3.2. Late-type Stellar Spectrum Modeling

Except for HD 283809, the background stars (Elias 3–13, Elias 3–16, Kim 1–59, Tamura 8, Elias 2–15, Elias 2–35, and SVS Ser 9) are all late-type giants, which have complicated photospheric spectra. Consequently, it was necessary to remove photospheric features from the observed spectra to measure the interstellar lines.

To generate synthetic spectra to model the background stars, we used the current version of the LTE line analysis code MOOG (Sneden 1973). Line lists for these calculations were generated from current molecular laboratory data (CO, Goorvitch 1994; CN, Sneden et al. 2014; OH, Brooke et al. 2016; with band 4 Available at http://www.as.utexas.edu/~chris/moog.html.
Table 2
Measured Interstellar Gas and Dust Absorption Properties

| Name          | \( N_{\text{CO thin}} \) (10^{18} \text{ cm}^{-2}) | \( N_{\text{CO avg}} \) (10^{18} \text{ cm}^{-2}) | \( T_{\text{CO}} \) (K) | \( v_{\text{LSR}} \) (km s\(^{-1}\)) | \( b_{\text{CO}} \) (km s\(^{-1}\)) | \( N_{\text{H2}} \) (10^{22} \text{ cm}^{-2}) | \( J-K \) (mag) | \( E_{b} \) (mag) | \( A_{J} \) (mag) | \( A_{K} \) (mag) |
|---------------|---------------------------------|---------------------------------|----------------|----------------|----------------|----------------|---------------|---------------|---------------|---------------|
| Embedded stars|                                 |                                 |                 |                |                |                |               |               |               |               |
| Elias 3–1     | 0.96                            | 2.1                             | 10.9            | 7.9            | 0.40           | undet          | ...           | ...           | 10.5\(^{a}\) |               |
| Elias 3–18    | 0.55                            | 0.86                            | 10.0            | 6.4            | 0.33           | undet          | ...           | ...           | 19.0\(^{a}\) |               |
| IRAS 04278\(^{b}\) | 0.73\(^{c}\)   | 1.0\(^{d}\)   | 12.0\(^{e}\)  | 9.3\(^{e}\)  | 0.57\(^{e}\)  | emiss          | ...           | ...           | ...           |               |
| AFGL 989      | 4.1                             | 4.4                             | 35.0            | 50.5           | 3.1\(^{f}\)   | 1.4\(^{f}\)   | ...           | ...           | ...           |               |
| Background stars|                                 |                                 |                 |                |                |                |               |               |               |               |
| Elias 3–13    | 0.90                            | 1.9                             | 9.1             | 6.4            | 0.32           | 1.5            | 3.05          | 2.30          | 3.7           | 12.4          |
| Elias 3–16    | 1.4                             | 2.6                             | 9.8             | 6.8            | 0.49           | 1.5            | 5.45          | 4.50          | 7.2           | 24.3          |
| Tamura 8      | 1.3                             | 2.5                             | 9.5             | 6.4            | 0.61           | 1.7            | 5.07          | 4.49          | 7.2           | 24.2          |
| HD 283809     | 0.84                            | 1.3                             | 8.4             | 6.0            | 0.41           | 0.75           | 0.83          | 0.83          | 1.33          | 4.5           |
| Kim 1–59      | 0.8                             | 1.1                             | 10.0            | 6.4            | 1.5            | 0.9\(^{f}\)   | 2.87          | 2.12          | 3.4           | 11.4          |
| SVS76 Ser 9   | 2.7                             | 2.9                             | 12.9            | 0.0            | 1.1            | 0.9\(^{f}\)   | 4.33          | 3.48          | 5.6           | 18.8          |

Notes.

\(^{a}\) Doppler b parameter = \(e^{-1}\) HW. FWHM = 1.66b.
\(^{b}\) Intrinsic J–K colors of K giants based on fitted \( T_{\text{eff}} \). Intrinsic colors of HD 283809 assumed equal to 0.0 mag.
\(^{c}\) Using \( R_{V} = 5.5 \) extinction curve of Weingartner & Draine (2001), \( A_{J}/E_{J,K} = 1.60 \), and \( A_{K}/E_{J,K} = 5.4 \).
\(^{d}\) Teixeira & Emerson (1999).
\(^{e}\) Multiple velocity and temperature components are seen toward IRAS 04278+2253. A fit to the \( J = 0–3 \) CO lines, which are dominated by the coldest component, is given here.
\(^{f}\) Based on \( S(0) \) equivalent width corrected for emission based on \( Q(2) \) emission.

Figure 5. Boltzmann diagram for CO toward AFGL 989, HD 283809, Tamura 8, and Elias 3–16. Data for HD 283809, Tamura 8, and Elias 3–16 are offset horizontally by 50, 100, and 150 K, respectively. Crosses and plus signs are for \( P \)- and \( R \)-branch lines, respectively, assuming the lines to be optically thin. Diamonds and squares are for these lines after correction for saturation, assuming Gaussian line curves of growth, with line widths derived from the \( P(1)/R(1) \) and \( P(2)/R(2) \) equivalent width ratios. Column densities are derived from measured equivalent widths. Lines are from single-temperature fits to the spectra as described in the text.

The five foreground red giants serve two purposes: as standards for our stellar computations and for determination of residuals to the model spectra, which we use to correct the models of the background stars. Their \textit{Hipparcos}-based parallaxes (van Leeuwen 2007) and spectral types were taken from the SIMBAD database (Wenger et al. 2000); these are listed in Table 3. The mean distance of these stars is \( \sim 165 \) pc, and thus they are close enough to be essentially unreddened. Stellar parameters for the foreground red giants have been reported in the recent literature. All have \( T_{\text{eff}} \) estimates in the very large sample spectral energy distribution study of McDonald et al. (2012). Four of the five stars are included in the PASTEL stellar parameter catalog (Soubiran et al. 2010, 2016). Their \( T_{\text{eff}}, \log g \), and \([\text{Fe/H}] \) values\(^{7}\) are adopted here and listed in Table 3. We use these parameters as fundamental anchors for all of the program stars.

HR 7800 is not in the PASTEL catalog. McDonald et al. (2012) derived \( T_{\text{eff}} = 3832 \) K for this star. For our stars with \( T_{\text{eff}} \) estimates by both PASTEL and McDonald, Zijlstra, & Boyer, the mean difference is \( (T_{\text{eff}} \text{PASTEL} - T_{\text{eff}} \text{McDonald}) \approx -175 \) K. We therefore adjusted the HR 7800 temperature to \( T_{\text{eff}} = 3760 \) K. We lack independent knowledge of this star’s other atmospheric parameters. We extrapolated downward in temperature from the other foreground giants and adopted a rough gravity estimate of \( \log g = 1.40 \). In Table 3 we see that all stars with PASTEL parameters are slightly metal-poor, \([\text{Fe/H}] \approx -0.15 \). We adopted this value also for HR 7800. Finally, we adopted a

\(^{7}\) We adopt the standard stellar spectroscopic notation (Wallstein & Helfer 1999) that for elements A and B, \([A/B] \equiv \log_{10}(N_{A}/N_{B})_{\odot} - \log_{10}(N_{A}/N_{B})_{\odot} \). We use the definition \( \log g(A) \equiv \log_{10}(N_{A}/N_{B}) + 12.0 \) and equate metallicity with the stellar \([\text{Fe/H}] \) value.
uniform microturbulent velocity of \(2.5 \text{ km s}^{-1}\) for all of these cool red giants.

The CNO group elements are coupled via molecule formation, and their abundances ideally should be derived iteratively. Our goal for both the foreground and the background stars is simpler, to match synthetic and observed stellar spectra to effect a cancellation of these spectra. Therefore, we first simplified the process by assuming \([\text{O}/\text{Fe}]\) for each star. This is justified for metal-rich red giants; see many surveys, e.g., Lambert & Ries (1981), Kjaergaard et al. (1982), Afşar et al. (2012), and Holtzman et al. (2015). Then we synthesized the CO-dominated wavelength region 2.326–2.355 \(\mu\text{m}\), where the CO interstellar medium (ISM) lines are also located. Over most of this region the main stellar features are individual lines of the \(^{12}\text{CO}\) \(v = 3 – 1\) band, with additional contributions from 2–0 lines. The \(R\)-branch headband of the \(^{13}\text{CO}\) 2–0 band begins at about 2.334 \(\mu\text{m}\), and the \(^{12}\text{CO}\) 4–2 bandhead begins at about 2.353 \(\mu\text{m}\). Carbon isotopic ratios vary widely over the range \(5 \lesssim \frac{^{12}\text{C}}{^{13}\text{C}} \lesssim 30\) in high-metallicity red giants. In principle we could derive carbon isotopic ratios for all of the stars. However, almost all \(^{12}\text{CO}\) lines are very strong (saturated) in our stars, while the \(^{13}\text{CO}\) features are much weaker. Therefore, there is an interplay between adopted microturbulent velocities and derived \(^{12}\text{C}/^{13}\text{C}\) values. Proper resolution of this issue would involve synthesizing a much larger wavelength range and careful attention to excitation potential strength dependences of the \(^{12}\text{CO}\) lines. This exercise is beyond the scope of our work. We do see significant \(^{13}\text{CO}\) absorption in all stars, and after some numerical experiments we adopted uniformly \(^{12}\text{C}/^{13}\text{C} = 15\) for our syntheses.

We varied the carbon abundances until best synthetic/observed matches were achieved. After determining the carbon, we then used similar observed spectrum matching to derive stellar nitrogen abundances from CN lines located in the 2.21–2.24 \(\mu\text{m}\) region, which also includes the ISM H\(_2\) \(v = 1 \rightarrow 0 S(0)\).

In Table 3 we list the derived \([\text{C}/\text{Fe}]\) and \([\text{N}/\text{Fe}]\) abundances for the five foreground red giants, adopting the Asplund et al. (2009) solar abundances for computations of these abundance ratios. We have grouped the four stars with PASTEL parameters and have listed their mean values before presenting the quantities separately for HR 7800. \([\text{O}/\text{Fe}]\) is also entered in the table to emphasize its defined value of 0.00. It is apparent that the PASTEL red giants have nearly identical abundances, with \([\text{C}/\text{Fe}] = -0.34\) and \([\text{N}/\text{Fe}] = +0.61\), with small star-to-star scatter. HR 7800, with parameters based on shifting its literature \(T_{\text{eff}}\) to be consistent with the PASTEL stars, has \([\text{C}/\text{Fe}]\) and \([\text{N}/\text{Fe}]\) values in good agreement with the means of the other four stars within uncertainties. These abundances are also in accord with previous studies that have found deficiencies of carbon and overabundances of nitrogen in high-metallicity thin-disk red giants, e.g., Lambert & Ries (1981), Kjaergaard et al. (1982), Tautvaišienė et al. (2010), and Afşar et al. (2012).

The residuals of our fits to the foreground star spectra are highly correlated. We attribute this to systematic errors in the models, due to missing lines and erroneous line strengths or

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**Table 3**

**Parameters of Foreground Red Giants**

| Name     | \(d\) (pc) | Sp Type | \(T_{\text{eff}}\) (K) | \(\log g\) (cm s\(^{-2}\)) | \([\text{Fe}/\text{H}]\) | \(\xi\) (km s\(^{-1}\)) | \([\text{C}/\text{Fe}]\) | \([\text{N}/\text{Fe}]\) | \([\text{O}/\text{Fe}]\) |
|----------|-----------|---------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| HR 5899  | 115       | KIII    | 4100           | 3920           | 1.68           | -0.17          | 2.5            | -0.30          | +0.65          | 0.00          |
| HR 7919  | 138       | KIII    | 4557           | 4485           | 2.40           | -0.08          | 2.5            | -0.45          | +0.55          | 0.00          |
| HR 7956  | 136       | KIII    | 4388           | 4190           | 2.12           | -0.12          | 2.5            | -0.30          | +0.60          | 0.00          |
| HR 7969  | 180       | KIII    | 4256           | 4010           | 1.78           | -0.23          | 2.5            | -0.30          | +0.65          | 0.00          |
| Mean     | ...       | ...     | 4325           | 4151           | 2.00           | -0.15          | 2.5            | -0.34          | +0.61          | 0.00          |
| \(\sigma\) | ...       | ...     | 194            | 249            | 0.33           | ...            | 0.06           | ...            | 0.07           | 0.05          |
| HR 7800  | 259       | KIII    | 3932           | 3760           | 1.40           | -0.15          | ...            | -0.30          | +0.50          | ...           |

**Notes.**

\(^{a}\) McDonald et al. (2012).

\(^{b}\) Soubiran et al. (2016).

\(^{c}\) The log ratio to solar abundances from Asplund et al. (2009): \(\log \epsilon(\text{C}) = 8.43\), \(\log \epsilon(\text{N}) = 7.83\), \(\log \epsilon(\text{O}) = 8.69\).

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**Table 4**

**Parameters of Background Stars**

| Name     | Sp Type\(^{a}\) | \(T_{\text{eff}}\) (K) | \(\log g\) (cm s\(^{-2}\)) | \([\text{Fe}/\text{H}]\) | \(\xi\) (km s\(^{-1}\)) | \([\text{C}/\text{Fe}]\) | \([\text{N}/\text{Fe}]\) | \([\text{O}/\text{Fe}]\) |
|----------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| Elias 3–13 | KIIII        | 4400           | 2.20           | -0.15          | 2.5            | -0.35          | +0.55          | 0.00          |
| Elias 3–16 | KIIII        | 3950           | 1.70           | -0.15          | 2.5            | -0.30          | +0.60          | 0.00          |
| Tamura 8   | GIII         | 4900           | 2.80           | -0.15          | 2.0            | -0.30          | +0.70          | 0.00          |
| Kim 1–59   | KIIII        | 4400           | 2.20           | -0.15          | 2.5            | -0.25          | +0.30          | 0.00          |
| SVS76 Ser 9 | KIII         | 4150           | 2.00           | -0.15          | 2.5            | -0.30          | +0.70          | 0.00          |
| Elias 2–35 | KIII         | 3800           | 0.50           | -0.15          | 2.5            | -0.25          | +0.40          | 0.00          |
| Mean      | ...          | ...            | ...            | ...            | ...            | -0.29          | +0.54          | ...           |

**Notes.**

\(^{a}\) Based on fitted \(T_{\text{eff}}\) values.

\(^{b}\) The log ratio to solar abundances from Asplund et al. (2009): \(\log \epsilon(\text{C}) = 8.43\), \(\log \epsilon(\text{N}) = 7.83\), \(\log \epsilon(\text{O}) = 8.69\).
positions, and we expect the same errors to occur in our models for the background stars. Consequently, we averaged the residuals of the foreground star models and added a multiple of this average residual spectrum to the background star models to minimize their residuals, as is discussed below.

3.4. Analyses of Background Red Giants

The background stars lie in heavily extincted sight lines. Therefore, they are faint in the optical spectral region; thus, they lack Hipparcos parallaxes and have not been treated to high-resolution spectroscopic analysis. All of the background stars lie close to the Galactic plane \( b \lesssim 16^\circ \). Therefore, they are almost surely the same kinds of thin-disk giants that make up our foreground sample. We made this assumption and extended it to assert that, for the purposes of this ISM study, the regularities of the foreground red giants apply to the background stars.

In particular, we assumed that the background stars have \([\text{Fe}/\text{H}] = -0.15\) and \(^{12}\text{C}/^{13}\text{C} = 15\). we again used micro-turbulent velocities of \(2.5 \text{ km s}^{-1}\), except for the warmer star Tamura 8, for which we took \(2.0 \text{ km s}^{-1}\) as a reasonable estimate. Further, we desired to end up with approximately the same \([\text{C}/\text{Fe}]\) and \([\text{N}/\text{Fe}]\) values as the means in the foreground sample. CO formation is very sensitive to temperature, due to its large dissociation energy \((D_0 = 11.1 \text{ eV})\), and to a lesser extent so is CN \((D_0 = 7.8 \text{ eV})\). Therefore, we computed trial synthetic/observed spectrum matches, altering the \(T_{\text{eff}}\) (with \( \log g \) changes to match) until \([\text{C}/\text{Fe}] \approx -0.3\) was achieved. Then these models were applied to the CN spectra, and the best-fit \([\text{N}/\text{Fe}]\) was adopted. The results of these exercises are listed in Table 4. Although the carbon abundances were forced to agree with the mean value of the foreground sample, the nitrogen abundances were assessed independently (within the constraints of the steps leading to derivation of the carbon), and their mean is in reasonable agreement with that of the foreground stars.

3.5. Background Star and ISM Parameters

To derive interstellar gas properties, the observed background star spectra were first modeled with a procedure like that used for the flat-spectrum sources, but starting with the best-fitting model photospheric spectra. The spectra of the Taurus background sources, after division by the model photospheric spectra, including a fraction of the foreground star residual spectrum, are shown in Figures 6 and 7. Rotational level populations derived from the spectra of Tamura 8 and Elias 3–16 after the modeling described above, and both before and after correction for optical depths of the CO lines, are shown in Figure 5.

Since at most four CO rotational states \((J = 0–3)\) had detectable absorption lines toward these stars, two-temperature fits could not be justified, and the single-temperature models provided good fits to the observations. CO absorption was detected toward all sources in Table 1, but the quality of the fits to the photospheric spectra of Elias 2–15 and Elias 2–35 was too poor to allow measurement of the CO parameters, probably as a result of the low temperatures of these stars. \( \text{H}_2 \text{S} (0) \) absorption was reliably detected toward Elias 3–16 and Tamura 8, probably detected toward Elias 3–13 and HD 283809, and possibly present toward Kim 1–59. None of the background sources showed evidence of \( \text{H}_2 \text{S} (1) \) absorption (or emission), as is expected given the low gas temperatures \((\sim 10 \text{ K})\) derived from the CO spectra.

4. Interstellar Gas Properties

Derived interstellar absorption parameters are given in Table 2. In addition to the fit parameters, estimates of the dust extinction to the sources are given. Extinctions for the background K giant stars are based on colors from the Two Micron All Sky Survey (Cutri et al. 2003) with intrinsic colors based on our fitted effective temperatures with the \( T_{\text{eff}}\)-color relationship of Alonso et al. (1999). The intrinsic \( J-K \) color of the hot star HD 283809 is assumed to be zero. SIMBAD quotes a spectral type of F8. This spectral type corresponds to \( J-K \approx 0.3 \) (Alonso et al. 1999). However, Straižys (1982) used medium-resolution spectroscopy to demonstrate that HD 283809 is a B-type star, for which \( J-K \sim 0 \). The Weingartner & Draine (2001) \( R_V = 5.5 \) extinction curve, which gives \( A_V/E_{B-V} = 5.4 \), was used to calculate \( A_V \).

No uncertainties are given for the quantities in Table 2, as the statistical uncertainties in the fits are generally small compared to systematic uncertainties, which are difficult to quantify. The CO column densities, \( N_{\text{CO, cog}} \), depend strongly on the value of the CO line width, \( b_{\text{CO}} \), through its effect on the curve of growth. The need for a curve-of-growth correction to the column densities derived assuming the lines to be optically
thin can be seen in Figure 6. If the CO lines were optically thin, the R(1) line would be twice as strong as the P(1) line, whereas the observed ratio is closer to unity. The value of b_{CO} is constrained primarily by this ratio (and to a lesser extent by the observed R(2)/P(2) ratio, which in optically thin gas would be 1.5). Unfortunately, these lines are in a spectral region with substantial photospheric (and telluric) absorption, so the derived p_{CO} value depends on the quality of the stellar models. The similar values of b_{CO} for the high-S/N Taurus cloud sources (including HD 283809, which did not require stellar modeling) encourage us that these values are reasonably reliable, but we would guess that they could easily be in error by ±0.1 km s^{-1}, resulting in errors in N_{CO} ~20%. Errors in T_{CO} due to the uncertainty in b_{CO} are typically ±2 K.

Statistical uncertainties and stellar modeling uncertainties make comparable contributions to the possible errors in N_{HI} for the background K giants. We estimate that N_{HI} for Elias 3–16 and Tamura 8 is uncertain by ~25%. N_{HI} is uncertain by ~50% for Elias 3–13 and HD 283809. We consider H_{2} to be only marginally detected for Kim 1–59 and SVS Ser 9. The H_{2} S(0) line is clearly detected toward GL 989 (and was previously detected by Kulesa 2002), but the correction for S(0) emission adds considerable uncertainty to our N_{HI} determination. We estimate the uncertainty in N_{HI} to be ±50% (based on our measurements; the fact that Kulesa [2002] measured a very similar number with a smaller beam that would be less affected by emission indicates that the actual error is probably smaller than this).

The primary sources of uncertainty in the extinction values for the background stars are the intrinsic colors of the K giants and the assumption of the Weingartner & Draine (2001) R_{V} = 5.5 extinction curve. We use the colors of Alonso et al. (1999) with our fitted T_{eff} values to determine the intrinsic colors. The Weingartner & Draine (2001) R_{V} = 5.5 extinction curve is fitted to molecular cloud observations, so it should be appropriate for our lines of sight. Their R_{V} = 3.1 curve gives an only slightly larger A_{V}/E_{F-K} of 5.5.

5. Discussion and Conclusions

The measured column densities of H_{2} and CO, the extinctions, and the ratios of these quantities are given in Table 5. All three quantities were measured toward Elias 3–13, Elias 3–16, Tamura 8, and HD 283809. N_{HI} and N_{CO} were measured toward AFGL 989, but the extinction is unknown. N_{CO} and A_{V} were measured toward Kim 1–59 and SVS Ser 9, but N_{HI} is quite uncertain.

5.1. N_{HI}, N_{CO}, and A_{V}

For the four sources where N_{CO} and A_{V} were most reliably measured, all of which lie behind the TMC, N_{COISM}/A_{V} = (1.0–2.9) × 10^{17} cm^{-2}, with an average of 1.5 × 10^{17} cm^{-2}, and N_{COISM}/A_{V} = (1.3–2.9) × 10^{17} cm^{-2}, with an average of 1.8 × 10^{17} cm^{-2}, where N_{COISM} includes solid CO. Frerking et al. (1982) measured N_{COISM}/A_{V} = 1.7 × 10^{14} cm^{-2}, which corresponds to N_{COISM}/A_{V} = 0.85 × 10^{17} cm^{-2}, lower than any of our values and a factor of ~1.8 below our average. Pineda et al. (2010) measured N_{COISM}/A_{V} = 1.0 × 10^{17} cm^{-2}, a factor of 1.5 below our average, and N_{COISM}/A_{V} = 1.4 × 10^{17} cm^{-2}, a factor of 1.3 below our average.

For the four sources where N_{HI} and A_{V} were most reliably measured, N_{HI}/A_{V} = (0.7–1.7) × 10^{17} cm^{-2} and the average is 1.07 × 10^{17} cm^{-2}. These sources lie behind the TMC, including the sources with more uncertain values of N_{HI} would increase the range and lower the average to 0.92. Our average value of N_{HI}/A_{V} is consistent with the assumption that the diffuse ISM value of N_{HI}/A_{V} of 1.9 × 10^{17} cm^{-2} (Bohlin 1978) is valid in molecular clouds and that essentially all H atoms reside in H_{2} molecules.

For the four Taurus background sources where N_{CO} and N_{HI} were most reliably measured, N_{HI}/N_{CO} ranges from 5800 to 7900, with an average of 6600, and N_{HI}/N_{CO} ranges from 4500 to 7500, with an average of 5800. AFGL 989, in Monoceros, has a lower N_{HI}/N_{CO} value, but because it is an embedded star, which required a correction for H_{2} emission, we do not conclude that the difference necessarily indicates a difference between the two clouds. Kim 1–59 (behind the TMC) appears to have a higher ratio, and SVS Ser 9 (in Serpens) appears to have a lower ratio, but the detection of H_{2} absorption in these sources is quite uncertain. Our N_{HI}/N_{CO} value is consistent with the value measured toward high-mass embedded young stars by Lacy et al. (1994), Kulesa (2002), and Goto et al. (2015). As was concluded by those authors, the N_{HI}/N_{CO} ratio is a factor of ~2 lower than derived from millimeter-wave CO emission and star counts (Frerking et al. 1982). Goto et al. (2015) suggest that there is a trend in this ratio, with N_{HI}/N_{CO} increasing with Galactocentric distance. All of our sources lie within 1 kpc of the Sun, so we cannot test this conclusion. Our average measured value of N_{HI}/N_{CO} (5800) corresponds to ~30% of the total interstellar...
carbon being in CO, assuming the solar C/H ratio, and 60% of
gas-phase carbon being in CO, assuming that 50% of carbon
resides in grains. This is more than has been assumed in the
past, but it still leaves some of the interstellar carbon
unaccounted for.

5.2. Variations in Ratios and Uncertainties

Are the variations in \( \frac{N_{\text{CO}}}{A_{\nu}} \), \( \frac{N_{\text{H}_2}}{A_{\nu}} \), and \( \frac{N_{\text{H}_2}}{N_{\text{CO}}} \) either
among the TMC sources or between different molecular
clouds, significant? The values of \( \frac{N_{\text{CO}}}{A_{\nu}} \) and \( \frac{N_{\text{H}_2}}{A_{\nu}} \) toward HD 283809 appear to be significantly higher than toward the
other sources, although the \( \frac{N_{\text{H}_2}}{N_{\text{CO}}} \) ratio is in the middle of
the range observed. This difference is probably real. It could
result from an underestimate of \( A_{\nu} \), but this would require a
negative intrinsic J–K color, which seems unlikely. Among the
Taurus sources other than HD 283809, variations in the ratios
are probably not significant. The observations of sources
toward Monoceros, Ophiuchus, and Serpens are not sufficiently
reliable to make a strong statement about any variations
between molecular clouds.

Our conclusion that \( \frac{N_{\text{H}_2}}{N_{\text{CO}}} \) is lower than generally
assumed is consistent with the conclusion based on observations
of high-mass embedded stars. But our conclusion that
\( \frac{N_{\text{CO}}}{A_{\nu}} \) has been underestimated, rather than \( \frac{N_{\text{H}_2}}{A_{\nu}} \) being
overestimated, is more surprising. The largest uncertainty in
our determination of \( N_{\text{CO}} \) is in the curve-of-growth correction
for optical depth in the CO lines. This correction is based on
the ratios of equivalent widths of \( P \)- and \( R \)-branch lines, especially \( P(1) \) and \( R(1) \), and the assumption of Gaussian line
shapes. However, it is apparent from inspection of the data that
a saturation correction is required, and a line shape with
stronger wings, such as a Lorentzian, would require a greater
CO column density and hence an even lower \( \frac{N_{\text{H}_2}}{N_{\text{CO}}} \) ratio.
The determination of \( A_{\nu} \) depends on the intrinsic colors of the
background stars and the assumed extinction law. However,
J–K colors of K2III–K5III stars vary by only \( \pm 0.12 \) mag, and the
value of \( A_{\nu}/E_{j-K} \) does not vary significantly with \( R_v \). For the
\( \frac{N_{\text{CO}}}{A_{\nu}} \) ratios measured by Dickman (1978), Freking et al.
(1982), and Pineda et al. (2010) to be erroneously low would
require that rotational line emission underestimates \( N_{\text{CO}} \) or that
star counts overestimate \( A_{\nu} \). Pineda et al. (2010) find variations
in \( \frac{N_{\text{CO}}}{A_{\nu}} \) with location in the TMC. To test whether our
observations were made at atypical locations, we compared our
values of \( N_{\text{CO}} \) and \( A_{\nu} \) with theirs in the same directions
(although at spatial resolution of 40" for \( N_{\text{CO}} \) and 200" for \( A_{\nu} \)), using data provided by J. L. Pineda (2017, private
communication). The values of \( A_{\nu} \) toward our stars were
0.8–1.8 times theirs, a difference consistent with likely spatial
variations. However, our values of \( N_{\text{CO}} \) were consistently
larger than theirs, with a ratio of 1.5–4.5, and our average
\( \frac{N_{\text{CO}}}{A_{\nu}} \) ratio was 2.1 times theirs. Since our measurements
of \( N_{\text{CO}} \) and \( A_{\nu} \) were necessarily along the same lines of sight, we
do not think that observational bias or selection effects should
have affected our value of \( \frac{N_{\text{CO}}}{A_{\nu}} \).

5.3. Comparison with Chemical Models

There are many studies of molecular abundances in
interstellar clouds. Near the cloud surfaces, in photodissociation
regions, the models predict that hydrogen is predominantly
molecular beyond \( A_v \sim 1 \) and that carbon becomes first
neutral and then molecular (predominantly CO) at \( A_v \sim 3 \)
(Hollenbach & Tielens 1999). If all H is in \( \text{H}_2 \) and all C is in
CO, \( \frac{N_{\text{H}_2}}{A_{\nu}} \sim 10^{22} \text{ cm}^{-2} \) and \( \frac{N_{\text{H}_2}}{N_{\text{CO}}} \sim 3500 \), assuming that
50% of carbon is in grains. Beyond \( A_v \sim 10 \) an increasingly
large fraction of CO is observed to freeze out onto grains
(Whittet et al. 2007). But this simple layered structure is
somewhat contradicted by the observation of \([\text{C} I]\) emission
from deep within molecular clouds (Plume et al. 1994). Glover
et al. (2010) have made a model of \( \text{H}_2 \) and CO abundances in
turbulent molecular clouds, in which the nonuniform density
structure allows UV photons to penetrate into the clouds, where
they can dissociate CO. They do not include CO freeze-out, but
their model should be a better approximation to molecular
cloud structure than uniform density models, and since the
observed solid CO abundance along our lines of sight is small
compared to the gas-phase CO, the neglect of freeze-out should
not be a serious problem for our sources. They find highly
spatially variable column densities and \( \frac{N_{\text{H}_2}}{N_{\text{CO}}} \) ratios in their
models, but their mass-weighted mean \( \frac{N_{\text{H}_2}}{N_{\text{CO}}} \) ratios are
similar to our observed ratios, and their spatially resolved
\( \frac{N_{\text{H}_2}}{N_{\text{CO}}} \) ratios are similar to ours where their \( \text{H}_2 \) column
densities are similar to ours. They assume a much larger

\[
\text{Table 5}
\text{Column Density and Extinction Ratios}
\begin{array}{cccccccc}
\text{Name} & N_{\text{CO}}/A_{\nu} & N_{\text{H}_2}/A_{\nu} & N_{\text{H}_2}/N_{\text{CO}} & A_{\nu} & \frac{N_{\text{CO}}/A_{\nu}}{N_{\text{CO}}/A_{\nu}} & \frac{N_{\text{H}_2}/A_{\nu}}{N_{\text{CO}}/A_{\nu}} & \frac{N_{\text{H}_2}/A_{\nu}}{N_{\text{CO}}/A_{\nu}} & \frac{N_{\text{H}_2}/A_{\nu}}{N_{\text{CO}}/A_{\nu}} \\
\text{Elias 3–13} & 1.9 & 0.11 & 0.5 & 12.4 & 1.53 & 1.2 & 7900 & 7500 \\
\text{Elias 3–16} & 2.6 & 0.74 & 1.5 & 24.3 & 1.07 & 1.4 & 6800 & 4500 \\
\text{Tamura 8} & 2.5 & 0.65 & 1.7 & 24.2 & 1.03 & 1.3 & 5800 & 5800 \\
\text{HD 283809} & 1.3 & 0.0 & 0.75 & 4.5 & 2.9 & 2.9 & 1.7 & 5800 & 5800 \\
\text{Kim 1–59} & 1.1 & 0.4 & 1.6 & 10.3 & 1.07 & 1.5 & 1.7 & 14,500 & 10,700 \\
\text{AFGL 989} & 4.0 & - & - & - & - & - & - & 5800 & 5800 \\
\text{SVS Ser 9} & 2.9 & 0.8 & 0.9 & 18.8 & 1.54 & 2.0 & 3100 & 2400 \\
\text{Average} & - & - & - & - & 1.52 & 1.8 & 1.07 & 6600 & 5800 \\
\end{array}
\]

Notes

\(^{a}\) Teixeira & Emerson (1999). Chiar et al. (1995) give slightly lower numbers, but Whittet et al. (2007) point out that solid CO should be included, as CO on grains may be converted to CO\(_2\).
\(^{b}\) Extinction derived from J–K colors, based on fitted \( T_{\text{eff}} \) and \( A_v/E_{j-K} = 5.4 \).
\(^{c}\) Estimated from \( A_v \) based on formula from Whittet et al. (2007).
\(^{d}\) Intrinsic J–K assumed = 0.
\(^{e}\) Uncertain. Consistent with 0.

\(^{f}\) Average of more reliably determined ratios. Anomalous value of gas/dust toward HD 283809 increases the ratios to \( A_v \).
turbulent velocity than we observe through the TMC (5 vs. 
\sim 0.5 \text{ km s}^{-1} \text{ rms}), but otherwise their model appears to fit our 
observations reasonably well. Their conclusion that \( \text{N}_{\text{H}_2}/\text{N}_{\text{CO}} \)
and \( \text{N}_{\text{H}_2}/A_{\text{V}} \) vary across a cloud tends to support the reality of
the variations we observe, although we might expect smaller
variations in the more quiescent TMC. It would be desirable to
run a model with parameters appropriate to the TMC. It would
also be desirable to observe more sources behind the TMC and
other molecular clouds.

5.4. \( \text{H}_2 \) Ortho:Para, Gas T and b, and \( \chi_{\text{CO}} \)

A determination of the \( \text{H}_2 \) ortho:para ratio in cold molecular
clouds would be of interest. We did not detect \( S(1) \) (ortho-\( \text{H}_2 \))
asorption. Our limit is not strong, but toward the two sources
with the strongest \( S(0) \) absorption, Elias 3–16 and Tamura 8,
we can rule out \( S(1) \) absorption stronger than about one-half of
the \( S(0) \) absorption. The \( S(1) \) absorption per molecule in the
\( J = 1 \) state is 0.58 times the \( S(0) \) absorption per molecule in the
\( J = 0 \) state. Consequently, the ortho:para ratio must be less
than 1, consistent with the low-temperature value of 0, and
clearly less than the high-temperature value of 3.

The interstellar gas temperature and line width may also be
of interest. Toward the sources both behind and embedded in
the TMC, the CO temperature lies between 8.4 and 12.0 K,
with an average value of 10.0 K. Toward these sources, the CO
Doppler \( b \), or \( e^{-1} \), line width lies between 0.33 and 1.5 \text{ km s}^{-1},
with an average value of 0.58 \text{ km s}^{-1}. The variation among
these sources of \( T \) is probably not signifi
cant, but the variation
of \( b \) probably is. It may be due to multiple velocity components
along the lines of sight or turbulence.

Finally, we note that the value of \( \chi_{\text{CO}} = \text{N}_{\text{H}_2}/\text{A}_{\text{CO}} \), which is
often used to interpret molecular abundances and cloud masses,
is not necessarily affected by a change in \( \text{N}_{\text{H}_2}/\text{N}_{\text{CO}} \). Most
determinations of \( \chi_{\text{CO}} \) are made by comparing the integrated
intensity of the \( ^{12}\text{CO} \) \( J = 1 \) – 0 line to \( \text{H}_2 \) column densities
determined from extinction measurements, with an assumed
\( \text{N}_{\text{H}_2}/A_{\text{V}} \) ratio. Thus, they do not depend directly on \( \text{N}_{\text{H}_2}/\text{N}_{\text{CO}} \),
and our measured \( \text{N}_{\text{H}_2}/A_{\text{V}} \) ratio is consistent with that typically
assumed. Lee et al. (2014) discuss the cause of the variation in
\( \chi_{\text{CO}} \) in the Perseus molecular cloud and conclude that the
variations are primarily caused by variations in density, turbulence,
and the interstellar radiation field.

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