A High-Resolution Study of the CO-H\textsubscript{2} Conversion Factor in the Diffuse Cloud MBM 40

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ABSTRACT

We made CO(1-0) observations of 103 lines of sight in the core and envelope of the high-latitude cloud MBM 40 to determine how the CO-H\textsubscript{2} conversion factor (X\textsubscript{CO}) varies throughout the cloud. Calibrating X\textsubscript{CO} with CH data at similar resolution (1′ for CO, 1.5′ for CH) yields values of X\textsubscript{CO} ranging from 0.6 \times 10\textsuperscript{20} to 3.3 \times 10\textsuperscript{20} cm\textsuperscript{-2} [K km s\textsuperscript{-1}]\textsuperscript{-1} with an average of 1.3 \times 10\textsuperscript{20} cm\textsuperscript{-2} [K km s\textsuperscript{-1}]\textsuperscript{-1}. Given that the cloud has a peak reddening of 0.24 mag, it should be classed as a diffuse rather than a translucent molecular cloud. The mass obtained from the CO data and our values of X\textsubscript{CO} is 9.6 M\odot for the core, 12 M\odot for the envelope, and 10 M\odot for the periphery of the cloud. A third of the molecular mass of the cloud is found in a region with E(B-V) < 0.12 mag. With these mass estimates, we determine that the cloud is not gravitationally bound.

Subject headings: ISM:molecules, ISM:clouds, ISM:abundances

1. Introduction

The empirical conversion factor between N(H\textsubscript{2}) and the velocity-integrated CO(1-0) main beam antenna temperature (∫ T\textsubscript{mb} dv ≡ W\textsubscript{CO}) is routinely used to determine the total molecular content of an interstellar cloud mapped in CO. Sometimes known as X\textsubscript{CO} (≡ N(H\textsubscript{2})/W\textsubscript{CO}), in most Galactic and extragalactic molecular studies the conversion factor is taken to be constant with a typical value of 1.8 \times 10\textsuperscript{20} cm\textsuperscript{-2} [K km s\textsuperscript{-1}]\textsuperscript{-1} (e.g., Dame et al. 2001; we will drop the units of X\textsubscript{CO} in the remainder of the paper for brevity). However, in the class of small molecular clouds with 1 mag < A\textsubscript{V} < 5 mag known as translucents, the value of X\textsubscript{CO} has been shown to vary from cloud-to-cloud and even over a given cloud (Magnani & Onello 1995; Magnani et al. 1998). In calibrating X\textsubscript{CO}, a surrogate tracer for N(H\textsubscript{2}) must be employed. Traditional techniques involve using the diffuse gamma-ray background, the assumption of virial equilibrium for the cloud in question, and the extinction produced by dust in the cloud (see review by Combes 1991). For translucent clouds these methods are not ideal given the low gas and dust column densities and the absence of virial equilibrium for many of the clouds (Magnani & Onello 1995). Thus, two more suitable methods were devised: (1) Using the infrared emission from the dust in a cloud, assuming a standard gas-to-dust ratio, and correcting for the dust associated with atomic gas along the line of sight (deVries et al. 1987); and (2) using the CH $^2\text{H}_1/2$ (F=1-1) hyperfine, ground state transition at 3335 MHz to determine N(CH), and then the linear relationship between N(CH) and N(H\textsubscript{2}) at low extinction to obtain the latter quantity (e.g., Magnani & Onello 1995).
The infrared method requires that an estimate of \( N(\text{HI}) \) along the given line of sight be made so that the emission from the dust associated with the atomic gas can be subtracted from the overall dust emission. This is somewhat problematic given that most available HI surveys are at low-resolution (21 - 45\(^\prime\)) while CO(1-0) observations are often at \( \sim 1\,\text{'} \) resolution. Another issue involves the assumption that the infrared emissivity per hydrogen nucleon is the same for dust mixed with both the atomic and molecular components (see Magnani & Onello 1995 for a discussion). Despite these issues, the infrared method has been used successfully for translucent clouds and often leads to values for \( X_{\text{CO}} \) less than \( 1 \times 10^{20} \) (deVries et al. 1987).

Observations of the CH ground state, hyperfine, main line transition at 3335 MHz and the CO(1-0) line at 115 GHz made at similar angular resolution can be used to determine \( X_{\text{CO}} \) as was done by Magnani & Onello (1995) for a sample of translucent and dark clouds. They determined that for 28 lines of sight in 18 translucent clouds \( X_{\text{CO}} \) varied from \( 0.3 \times 10^{20} \) to \( 6.8 \times 10^{20} \). Although the CH 3335 MHz line is not a good tracer of \( \text{H}_2 \) in high-extinction, high column density regions, Magnani & Onello applied the technique to 13 lines of sight in 5 dark clouds and obtained \( X_{\text{CO}} \) values ranging from \( 0.8 \times 10^{20} \) to \( 8.6 \times 10^{20} \). In a subsequent study, the CH method was applied to different regions of 2 translucent clouds and significant variation across the face of these clouds was seen: In MBM 16, \( X_{\text{CO}} \) varied from \( 1.6 \times 10^{20} \) to \( 17.3 \times 10^{20} \), and in MBM 40 from \( 0.7 \times 10^{20} \) to \( 9.7 \times 10^{20} \). These studies were made at resolutions of 8-9\('. Chastain et al. (2010) studied CH emission in two translucent clouds at significantly higher resolution (1.5\(' \) for the CH 3335 MHz line and 45\('' \) for CO(1-0)) and determined that \( W_{\text{CO}} \) and the velocity-integrated CH line strength at 3.3 GHz (\( \int T_B \, dv \equiv W_{\text{CH}} \), where \( T_B \) is the brightness temperature) did not correlate well. Unfortunately, Chastain et al. (2010) did not calculate \( X_{\text{CO}} \) for the two clouds they observed, so one of the goals of this paper is to determine \( X_{\text{CO}} \) for one of those clouds (MBM 40) that has sufficient data for statistical analysis.

The lack of correlation between \( W_{\text{CO}} \) and \( W_{\text{CH}} \) in MBM 16 and 40 implies that either CO or CH, or possibly both, do not correlate well with \( \text{H}_2 \) in lower extinction clouds. If CH is assumed to correlate fairly well with \( \text{H}_2 \) in low extinction regions - as all other studies to date have indicated (see references in §1), then the lack of correlation between \( W_{\text{CO}} \) and \( W_{\text{CH}} \) could be interpreted as a variation in \( X_{\text{CO}} \). Liszt & Pety (2012) found significant variability for \( X_{\text{CO}} \) on arcminute scales in diffuse molecular clouds and attribute this variability primarily to radiative transfer and CO chemistry effects.

Like the infrared method, the CH method also has difficulties associated with it. To derive \( N(\text{CH}) \), it is normally assumed that \( |T_{\text{ex}}(3335)| \gg T_{\text{BG}} \); however, some studies of low-extinction clouds imply otherwise (Lien 1984; Jura & Meyer 1985). Most researchers just assume (as we will - but see §3) that the excitation temperature of the 3335 MHz line is far from the value of \( T_{\text{BG}} \), but optical and UV absorption observations as described by Lien (1984) are needed to really establish the value of \( T_{\text{ex}}(3335) \) for a given line of sight. Also, while one can certainly ascribe the lack of correlation between \( W_{\text{CO}} \) and \( W_{\text{CH}} \) to variations in \( X_{\text{CO}} \), they can also be due to variations in the CH abundance (Liszt & Lucas 2002). However, a recent study by Liszt & Pety (2012) seems to show definitively that in low-extinction clouds the variation in CO excitation and abundance is significant both from cloud-to-cloud and even over different regions of a given cloud. In this paper, we will assume that, at low extinction, \( W_{\text{CH}} \) can lead to robust estimates of \( N(\text{CH}) \) and that this

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\(^1\)The GALFA HI survey from Arecibo is at significantly better resolution, but covers only those regions with \(-2^\circ \leq \delta \leq 38^\circ\).
The quantity is a linear tracer of $N(H_2)$.

The paper is organized as follows: In §2 we describe the new CO observations of MBM 40 that were made at selected regions in the core and envelope of the cloud. In §3 we will use the CH method to calibrate $X_{\text{CO}}$ at high resolution ($\sim 1.5'$) for the cloud MBM 40 (previously classified as a translucent cloud), where the CH data comes from Chastain et al. (2010). From our CO observations and the calibrated $X_{\text{CO}}$ values we will determine the mass in the core, envelope, and periphery of the cloud (§4) and discuss the gravitational stability of this object. Finally, in §5 we summarize our results.

2. Observations

Observations of the CO(1-0) rotational transition were made at the Arizona Radio Observatory (ARO) 12 m telescope at Kitt Peak National Observatory in December of 2008\textsuperscript{2}. The angular resolution of the telescope at 115 GHz was 1’ and the observations were made in position-switching mode with the off-source taken to be one degree east or west of the target in azimuth. The off positions were checked to be relatively free of dust emission using the Schlegel, Finkbeiner, & Davis (1998; hereafter SFD) dust maps. The spectrometer consisted of 100 kHz and 250 kHz filterbanks that provide velocity coverages of 62 and 167 km s$^{-1}$, respectively, with velocity resolutions of 0.26 and 0.65 km s$^{-1}$, respectively.

\textsuperscript{2}The 12 m is part of the Arizona Radio Observatory and is operated by the University of Arizona with additional funding by the Mt. Cuba Astronomical Foundation.
Fig. 1.— Positions of CO(1-0) observations for MBM 40 superimposed on an E(B-V) map from the Schlegel et al. (1998) data. Coordinates are Galactic $\ell$ and $b$ centered on $(\ell, b) = 37.4^\circ$ and $44.5^\circ$, respectively. The black squares represent the positions of our CO(1-0) observations. The coordinates and results of these observations are listed in Table 1 with averages for the detections in each region in Table 3. The dust emission from the cloud is in units of E(B-V) magnitudes on a linear scale ranging from 0.05 to 0.24 mag.
Table 1. Observations of the CO(1-0) line in MBM 40.

| RA (2000)  | Dec (2000) | ℓ   | b    | \(T_R^a\) | \(\Delta\nu\) (FWHM) | \(v_{\text{LSR}}\) | \(W_{\text{CO}}^a\) |
|------------|------------|------|------|-----------|-----------------------|-------------------|------------------|
| (h m s)    | (° ' '')   | deg | deg  | (K)       | (km s\(^{-1}\))      | (km s\(^{-1}\))   | (K km s\(^{-1}\)) |
| Periphery Region  |           |      |      |           |                       |                   |                  |
| 16 08 36.0 | 21 11 24   | 36.527 | 44.914 | 0.17 +/- 0.05 | 1.01 +/- 0.33 | 4.50 | 0.21 +/- 0.07 |
| 16 08 43.2 | 21 09 36   | 36.498 | 44.878 | 0.39 +/- 0.07 | 0.80 +/- 0.14 | 2.95 | 0.40 +/- 0.07 |
| 16 08 43.2 | 21 11 24   | 36.539 | 44.887 | 0.070 \(^b\) |                       |                   |                  |
| 16 08 43.2 | 21 13 48   | 36.585 | 44.898 |           |                       |                   | 0.070            |
| 16 08 52.8 | 21 11 24   | 36.555 | 44.852 |           |                       |                   |                  |
| 16 10 00.0 | 22 30 36   | 38.444 | 44.991 | 0.27 +/- 0.07 | 0.58 +/- 0.16 | 3.63 | 0.20 +/- 0.05 |
| 16 10 09.6 | 22 28 48   | 38.419 | 44.948 | 2.29 +/- 0.07 | 0.64 +/- 0.02 | 3.70 | 1.88 +/- 0.06 |
| 16 10 09.6 | 22 30 36   | 38.459 | 44.956 | 0.25 +/- 0.08 | 0.81 +/- 0.25 | 3.68 | 0.26 +/- 0.08 |
| 16 10 09.6 | 22 33 00   | 38.513 | 44.967 |           |                       |                   |                  |
| 16 10 14.4 | 21 08 24   | 36.624 | 44.535 |           |                       |                   | 0.070            |
| 16 10 16.8 | 22 30 36   | 38.470 | 44.929 | 0.42 +/- 0.08 | 0.66 +/- 0.12 | 4.03 | 0.35 +/- 0.06 |
| 16 10 21.6 | 21 06 00   | 36.582 | 44.496 | 0.55 +/- 0.07 | 0.52 +/- 0.07 | 2.99 | 0.36 +/- 0.05 |
| 16 10 21.6 | 21 08 24   | 36.636 | 44.508 |           |                       |                   | 0.060            |
| 16 10 21.6 | 21 10 12   | 36.676 | 44.517 |           |                       |                   | 0.060            |
| 16 10 24.0 | 22 24 36   | 38.346 | 44.874 | 1.85 +/- 0.06 | 0.76 +/- 0.03 | 3.43 | 1.80 +/- 0.06 |
| 16 10 31.2 | 21 08 36   | 36.651 | 44.472 | 0.11 +/- 0.06 | 0.92 +/- 0.50 | 4.35 | 0.13 +/- 0.07 |
| 16 10 31.2 | 22 24 36   | 38.357 | 44.848 | 1.37 +/- 0.07 | 0.68 +/- 0.04 | 3.49 | 1.19 +/- 0.06 |
| 16 10 31.2 | 22 26 24   | 38.398 | 44.856 | 0.93 +/- 0.07 | 0.63 +/- 0.05 | 3.52 | 0.74 +/- 0.05 |
| 16 10 40.8 | 22 24 36   | 38.372 | 44.812 | 0.88 +/- 0.09 | 0.71 +/- 0.07 | 3.49 | 0.80 +/- 0.08 |
| 16 12 19.2 | 22 00 00   | 37.975 | 44.330 |           |                       |                   | 0.104            |
| 16 13 36.0 | 21 41 24   | 37.685 | 43.955 | 0.61 +/- 0.05 | 1.10 +/- 0.09 | 1.89 | 0.85 +/- 0.07 |
| Envelope Region  |           |      |      |           |                       |                   |                  |
| 16 06 19.2 | 20 52 12   | 35.864 | 45.323 | 2.90 +/- 0.11 | 0.51 +/- 0.02 | 3.49 | 1.88 +/- 0.07 |
| 16 06 19.2 | 20 54 36   | 35.918 | 45.335 | 2.84 +/- 0.11 | 0.60 +/- 0.02 | 3.45 | 2.17 +/- 0.09 |
| 16 09 00.0 | 21 41 24   | 37.240 | 44.975 | 0.19 +/- 0.06 | 0.68 +/- 0.22 | 3.57 | 0.16 +/- 0.05 |
| 16 09 07.2 | 21 39 36   | 37.211 | 44.940 |           |                       |                   | 0.068            |
| 16 09 07.2 | 21 41 24   | 37.252 | 44.949 |           |                       |                   | 0.063            |
| 16 09 07.2 | 21 43 48   | 37.306 | 44.961 | 0.31 +/- 0.07 | 1.20 +/- 0.27 | 3.25 | 0.48 +/- 0.11 |
| 16 09 16.8 | 21 41 24   | 37.267 | 44.913 | 0.27 +/- 0.07 | 0.34 +/- 0.09 | 4.17 | 0.12 +/- 0.03 |
| 16 09 28.8 | 22 04 48   | 37.813 | 44.983 | 0.71 +/- 0.08 | 1.00 +/- 0.12 | 2.72 | 0.91 +/- 0.11 |
| 16 09 36.0 | 22 10 12   | 37.946 | 44.983 | 1.47 +/- 0.08 | 0.82 +/- 0.05 | 2.65 | 1.54 +/- 0.09 |
| 16 09 38.4 | 22 12 36   | 38.004 | 44.985 | 1.54 +/- 0.1 | 0.84 +/- 0.05 | 2.83 | 1.65 +/- 0.10 |
| 16 10 00.0 | 22 12 36   | 38.038 | 44.906 | 5.22 +/- 0.11 | 0.95 +/- 0.02 | 3.00 | 6.30 +/- 0.13 |
| 16 10 26.4 | 22 10 12   | 38.026 | 44.797 | 6.70 +/- 0.1 | 0.68 +/- 0.01 | 2.97 | 5.81 +/- 0.09 |
| 16 10 31.2 | 22 22 48   | 36.972 | 44.545 |           |                       |                   | 0.075            |
| 16 10 50.4 | 21 32 24   | 37.218 | 44.522 | 0.82 +/- 0.09 | 0.53 +/- 0.06 | 3.07 | 0.56 +/- 0.06 |
Table 1—Continued

| RA (2000) | Dec (2000) | $\ell$ | $b$ | $T_R$ | $\Delta v$ (FWHM) | $v_{LSR}$ | $W_{CO}^a$ |
|-----------|------------|-------|-----|-------|-----------------|-----------|------------|
| 16 10 57.6 | 21 30 00 | 37.176 | 44.484 | 0.096 |
| 16 11 04.8 | 22 10 12 | 38.086 | 44.655 | 2.49 +/- 0.09 | 0.89 +/- 0.03 | 3.37 | 2.80 +/- 0.10 |
| 16 11 16.8 | 21 30 00 | 37.207 | 44.413 | 0.106 |
| 16 11 16.8 | 21 49 48 | 37.649 | 44.511 | 1.49 +/- 0.08 | 0.72 +/- 0.04 | 3.32 | 1.37 +/- 0.07 |
| 16 11 24.0 | 21 55 12 | 37.781 | 44.511 | 2.19 +/- 0.08 | 0.85 +/- 0.03 | 3.04 | 2.36 +/- 0.08 |
| 16 11 31.2 | 21 32 24 | 37.284 | 44.372 | 1.12 +/- 0.09 | 0.99 +/- 0.08 | 3.39 | 1.41 +/- 0.11 |
| 16 11 33.6 | 21 19 48 | 37.008 | 44.299 | 0.41 +/- 0.09 | 0.38 +/- 0.08 | 3.07 | 0.20 +/- 0.04 |
| 16 11 43.2 | 21 18 00 | 36.984 | 44.255 | 0.090 |
| 16 11 43.2 | 21 19 48 | 37.024 | 44.264 | 0.68 +/- 0.09 | 0.43 +/- 0.06 | 3.00 | 0.37 +/- 0.05 |
| 16 11 43.2 | 21 22 12 | 37.077 | 44.276 | 0.088 |
| 16 11 43.2 | 21 42 36 | 37.530 | 44.378 | 0.99 +/- 0.10 | 1.02 +/- 0.10 | 3.32 | 1.28 +/- 0.13 |
| 16 11 48.0 | 21 34 48 | 37.365 | 44.321 | 1.93 +/- 0.13 | 0.81 +/- 0.05 | 3.19 | 1.99 +/- 0.13 |
| 16 11 50.4 | 21 19 48 | 37.036 | 44.237 | 0.081 |
| 16 11 57.6 | 21 49 48 | 37.714 | 44.360 | 1.35 +/- 0.08 | 0.79 +/- 0.05 | 3.16 | 1.36 +/- 0.08 |
| 16 12 02.4 | 22 00 00 | 37.949 | 44.393 | 1.09 +/- 0.11 | 0.54 +/- 0.05 | 3.32 | 0.74 +/- 0.07 |
| 16 12 09.6 | 21 58 12 | 37.920 | 44.357 | 0.72 +/- 0.10 | 0.82 +/- 0.11 | 3.00 | 0.75 +/- 0.10 |
| 16 12 09.6 | 22 00 00 | 37.960 | 44.366 | 0.64 +/- 0.09 | 0.58 +/- 0.08 | 3.06 | 0.47 +/- 0.06 |
| 16 12 09.6 | 22 01 48 | 38.000 | 44.377 | 0.50 +/- 0.10 | 0.88 +/- 0.18 | 3.08 | 0.56 +/- 0.12 |
| 16 12 31.2 | 21 37 48 | 37.501 | 44.177 | 0.43 +/- 0.07 | 0.25 +/- 0.04 | 3.13 | 0.14 +/- 0.02 |
| 16 12 40.8 | 21 36 00 | 37.476 | 44.132 | 0.33 +/- 0.11 | 0.94 +/- 0.30 | 3.18 | 0.39 +/- 0.13 |
| 16 12 40.8 | 21 37 48 | 37.516 | 44.141 | 0.37 +/- 0.10 | 0.45 +/- 0.13 | 3.22 | 0.21 +/- 0.06 |
| 16 12 40.8 | 21 40 12 | 37.570 | 44.153 | 0.46 +/- 0.11 | 0.42 +/- 0.10 | 3.21 | 0.24 +/- 0.06 |
| 16 12 48.0 | 21 37 48 | 37.528 | 44.115 | 0.104 |
| 16 14 45.6 | 22 18 00 | 38.604 | 43.877 | 0.100 |

**Core Region**

| RA (2000) | Dec (2000) | $\ell$ | $b$ | $T_R$ | $\Delta v$ (FWHM) | $v_{LSR}$ | $W_{CO}^a$ |
|-----------|------------|-------|-----|-------|-----------------|-----------|------------|
| 16 09 40.8 | 22 00 00 | 37.724 | 44.916 | 2.27 +/- 0.07 | 1.12 +/- 0.03 | 2.86 | 3.24 +/- 0.10 |
| 16 09 40.8 | 22 07 48 | 37.900 | 44.953 | 3.92 +/- 0.09 | 0.70 +/- 0.02 | 2.84 | 3.47 +/- 0.08 |
| 16 09 45.6 | 22 02 24 | 37.786 | 44.910 | 4.51 +/- 0.07 | 0.81 +/- 0.01 | 2.84 | 4.66 +/- 0.08 |
| 16 09 48.0 | 21 57 36 | 37.682 | 44.877 | 2.58 +/- 0.10 | 0.69 +/- 0.03 | 3.34 | 2.27 +/- 0.09 |
| 16 09 48.0 | 22 04 48 | 37.844 | 44.912 | 6.47 +/- 0.09 | 0.93 +/- 0.01 | 3.00 | 7.67 +/- 0.10 |
| 16 09 52.8 | 21 55 12 | 37.635 | 44.848 | 2.00 +/- 0.14 | 0.72 +/- 0.05 | 3.56 | 1.84 +/- 0.13 |
| 16 09 55.2 | 22 10 12 | 37.977 | 44.912 | 3.82 +/- 0.08 | 0.92 +/- 0.02 | 2.85 | 4.49 +/- 0.10 |
| 16 10 00.0 | 21 52 48 | 37.593 | 44.810 | 1.67 +/- 0.10 | 0.71 +/- 0.04 | 3.54 | 1.51 +/- 0.09 |
| 16 10 00.0 | 22 00 00 | 37.755 | 44.845 | 5.14 +/- 0.07 | 1.14 +/- 0.02 | 3.02 | 7.44 +/- 0.11 |
| 16 10 02.4 | 22 07 48 | 37.968 | 44.794 | 5.33 +/- 0.08 | 1.00 +/- 0.02 | 2.82 | 6.77 +/- 0.11 |
| 16 10 04.8 | 22 02 24 | 37.816 | 44.839 | 6.24 +/- 0.09 | 1.13 +/- 0.02 | 2.92 | 9.01 +/- 0.12 |
| 16 10 07.2 | 21 57 36 | 37.712 | 44.806 | 6.32 +/- 0.08 | 1.03 +/- 0.01 | 3.10 | 8.32 +/- 0.11 |
Table 1—Continued

| RA (2000) | Dec (2000) | $\ell$ | $b$ | $T_R^*$(K) | $\Delta v$(FWHM) (km s$^{-1}$) | $v_{LSR}$ (km s$^{-1}$) | $W_{CO}^a$ (K km s$^{-1}$) |
|-----------|------------|-------|-----|------------|----------------------------|----------------|----------------|
| 16 10 07.2 | 22 04 48 | 37.874 | 44.481 | 5.31 +/- 0.08 | 1.01 +/- 0.02 | 2.77 | 6.85 +/- 0.10 |
| 16 10 12.0 | 21 47 24 | 37.491 | 44.739 | 0.91 +/- 0.11 | 1.56 +/- 0.19 | 3.55 | 1.80 +/- 0.22 |
| 16 10 14.4 | 21 55 12 | 37.670 | 44.768 | 7.21 +/- 0.15 | 0.85 +/- 0.02 | 3.24 | 7.81 +/- 0.16 |
| 16 10 16.8 | 21 49 12 | 37.539 | 44.730 | 2.04 +/- 0.09 | 0.86 +/- 0.04 | 3.46 | 2.25 +/- 0.10 |
| 16 10 19.2 | 21 45 00 | 37.449 | 44.700 | 1.33 +/- 0.09 | 1.09 +/- 0.08 | 3.49 | 1.86 +/- 0.13 |
| 16 10 19.2 | 21 52 48 | 37.624 | 44.739 | 5.92 +/- 0.16 | 0.76 +/- 0.02 | 3.20 | 5.73 +/- 0.16 |
| 16 10 21.6 | 22 00 00 | 37.789 | 44.765 | 5.90 +/- 0.08 | 1.04 +/- 0.01 | 2.99 | 7.81 +/- 0.10 |
| 16 10 24.0 | 22 02 24 | 37.847 | 44.768 | 6.06 +/- 0.09 | 0.80 +/- 0.01 | 2.85 | 6.19 +/- 0.09 |
| 16 10 26.4 | 21 42 36 | 37.407 | 44.662 | 1.49 +/- 0.09 | 1.03 +/- 0.06 | 3.60 | 1.96 +/- 0.12 |
| 16 10 26.4 | 21 57 36 | 37.743 | 44.735 | 7.77 +/- 0.08 | 0.66 +/- 0.01 | 3.11 | 6.50 +/- 0.07 |
| 16 10 31.2 | 21 40 12 | 37.361 | 44.632 | 1.70 +/- 0.10 | 1.20 +/- 0.07 | 3.51 | 2.61 +/- 0.16 |
| 16 10 33.6 | 21 47 24 | 37.526 | 44.659 | 7.06 +/- 0.10 | 0.96 +/- 0.01 | 3.33 | 8.62 +/- 0.12 |
| 16 10 33.6 | 21 55 12 | 37.700 | 44.697 | 6.80 +/- 0.13 | 0.66 +/- 0.01 | 3.11 | 5.74 +/- 0.11 |
| 16 10 36.0 | 21 49 12 | 37.570 | 44.659 | 5.62 +/- 0.08 | 0.90 +/- 0.01 | 3.48 | 6.47 +/- 0.10 |
| 16 10 38.4 | 21 37 12 | 37.305 | 44.591 | 0.84 +/- 0.08 | 0.89 +/- 0.08 | 3.46 | 0.96 +/- 0.09 |
| 16 10 38.4 | 21 45 00 | 37.480 | 44.629 | 5.76 +/- 0.10 | 0.97 +/- 0.02 | 3.40 | 7.14 +/- 0.13 |
| 16 10 38.4 | 22 04 48 | 36.583 | 44.427 | 6.67 +/- 0.08 | 0.70 +/- 0.01 | 2.84 | 5.99 +/- 0.07 |
| 16 10 40.8 | 21 52 48 | 37.658 | 44.659 | 8.10 +/- 0.14 | 0.59 +/- 0.01 | 3.15 | 6.05 +/- 0.10 |
| 16 10 45.6 | 21 42 36 | 37.438 | 44.591 | 6.40 +/- 0.10 | 0.76 +/- 0.01 | 3.32 | 6.17 +/- 0.10 |
| 16 10 50.4 | 22 00 00 | 37.835 | 44.658 | 1.85 +/- 0.08 | 0.83 +/- 0.04 | 3.12 | 1.95 +/- 0.09 |
| 16 10 52.8 | 21 40 12 | 37.396 | 44.552 | 3.52 +/- 0.11 | 1.00 +/- 0.03 | 3.41 | 4.48 +/- 0.14 |
| 16 10 52.8 | 21 47 24 | 37.556 | 44.588 | 9.11 +/- 0.08 | 0.81 +/- 0.01 | 3.32 | 9.39 +/- 0.09 |
| 16 10 57.6 | 21 37 12 | 37.336 | 44.520 | 2.30 +/- 0.11 | 0.91 +/- 0.04 | 3.45 | 2.67 +/- 0.13 |
| 16 10 57.6 | 21 49 12 | 37.604 | 44.579 | 5.85 +/- 0.10 | 0.81 +/- 0.01 | 3.41 | 6.00 +/- 0.10 |
| 16 11 00.0 | 21 45 00 | 37.514 | 44.549 | 9.84 +/- 0.09 | 0.82 +/- 0.01 | 3.19 | 10.26 +/- 0.09 |
| 16 11 12.0 | 21 32 24 | 37.253 | 44.443 | 0.96 +/- 0.10 | 1.45 +/- 0.15 | 3.43 | 1.76 +/- 0.18 |
| 16 11 12.0 | 21 40 12 | 37.427 | 44.481 | 7.27 +/- 0.10 | 0.84 +/- 0.01 | 3.23 | 7.74 +/- 0.11 |
| 16 11 19.2 | 21 37 12 | 37.371 | 44.440 | 3.85 +/- 0.12 | 0.83 +/- 0.03 | 3.28 | 4.07 +/- 0.13 |
| 16 11 19.2 | 22 04 48 | 36.651 | 44.277 | 3.68 +/- 0.09 | 0.78 +/- 0.02 | 3.23 | 3.65 +/- 0.09 |
| 16 11 24.0 | 21 34 48 | 37.326 | 44.410 | 2.06 +/- 0.11 | 0.81 +/- 0.04 | 3.29 | 2.13 +/- 0.11 |
| 16 11 31.2 | 22 00 00 | 37.899 | 44.508 | 4.46 +/- 0.08 | 0.83 +/- 0.02 | 3.10 | 4.71 +/- 0.09 |
| 16 11 43.2 | 21 55 12 | 37.811 | 44.440 | 3.16 +/- 0.10 | 0.73 +/- 0.02 | 3.01 | 2.95 +/- 0.10 |

$^a W_{CO} = \int T_{mb} dv$.

$^b$If only one number is tabulated, then that is the 1-$\sigma$ rms value.
At the 12 m telescope, the CO(1-0) line antenna temperature, $T^*_A$, is corrected for the spillover and scattering efficiency of the antenna, resulting in the quantity $T^*_R$, the radiation temperature uncorrected for the antenna-beam coupling efficiency, $\eta_{mb}$. Thus, the main beam antenna temperature, $T_{mb}$, is equal to $T^*_R/\eta_{mb}$. For the 12 m telescope at 115 GHz, $\eta_{mb}$ is approximately 0.85\(^3\). Another correction factor is the beam dilution that we assume to be equal to 1 (in other words, the source fills the beam). Integration times were chosen to give rms noise values of at worst 0.1 K in the 100 kHz filterbanks.

A total of 103 lines of sight were observed in the core and envelope region of MBM 40 with 85 detections (see Figure 1 and Table 1). In columns 1 - 4 of Table 1 we list the positions of the observed lines of sight, in Right Ascension, Declination, and Galactic coordinates. The antenna temperature $T^*_R$ is listed in column 5, the line width ($\Delta v$) as the Full Width at Half Maximum (FWHM) in column 6, the LSR velocity ($v_{LSR}$) in column 7, and column 8 is the integrated CO(1-0) main beam temperature, defined as $W_{CO}$. If no line was detected for a given position we list the 1-$\sigma$ rms level in column 5. We divided MBM 40 into three regions based on E(B-V) in order to understand the effectiveness of the CO(1-0) line as a molecular tracer in different extinction regimes. The three regions are defined as: the “core” region where E(B-V) > 0.17, the “envelope” region where 0.12 ≤ E(B-V) ≤ 0.17, and the “periphery” region where E(B-V) < 0.12 mag. The core region includes the two ridges of strong CO(1-0) emission described by Shore et al. (2003) as comprising a wishbone or hairpin structure. Of the roughly 2 square degrees that comprise MBM 40 on the SFD dust maps, the periphery, envelope, and core regions cover 1.2, 0.61, and 0.20 square degrees, respectively. In the core region there were 44 CO(1-0) observations all resulting in detections. The envelope and periphery regions contained 28 out of 38 and 13 out of 21 detections, respectively. Average line values for the detections in the core, envelope, and periphery regions are shown in Table 3 along with the averages for all the detections.

### 3. Determination of $X_{CO}$ in MBM 40

Table 1 shows the positions observed in CO along with the $W_{CO}$ value for that line of sight. To calibrate $X_{CO}$, we require observations of the CH 3335 MHz line at a similar resolution. These observational data are tabulated by Chastain et al. (2010) and used to derive N(CH), the values of which are reproduced here in Table 2. In the core of the cloud, as defined in §2, there are 44 lines of sight with CO observations in Table 1 for 32 of these CO data points we have CH data. In the envelope, 4 of the 28 CO detections have corresponding CH data. Unfortunately, no CH observations were made in the periphery region.

A linear relationship between N(CH) and N(H\(_2\)) was established more than 3 decades ago and has been repeatedly confirmed by Sandell & Johansson (1982), Federman (1982), Danks et al. (1984), Mattila (1986), Magnani & Onello (1995), Liszt & Lucas (2002), Sheffer et al. (2008), Weselak et al. (2010). Based on these works, we will assume that the CH/H\(_2\) ratio in diffuse and translucent molecular clouds is 4 x 10\(^{-8}\), good to about 20%. This allows us to obtain N(H\(_2\)) once N(CH) is determined, but to derive N(CH) from obser-

\(^3\)ARO 12 Users Manual: http://aro.as.arizona.edu/12_obs_manual/12m_user_manual.html.
vations of the 3335 MHz line it is necessary to assume that $|T_{ex}| \gg T_{BG}$ for that transition, which may not necessarily be the case. On the one hand, Lien (1984) explicitly measured $T_{ex}$ for three diffuse lines of sight and obtained values between −1 and 1 K. On the other, Genzel et al. (1979) found $T_{ex} = -60 \pm 30$ in an on-source/off-source radio observation of a background quasar through the dark cloud L1500. What is the situation for MBM 40? Although direct measurements of $T_{ex}$ for the 3335 MHz transition do not exist, we can argue indirectly that if $W_{CH}$ is proportional to $N(H_2)$, then the most likely explanation is that $|T_{ex}| \gg T_{BG}$. Chastain et al. (2010) show that $W_{CH}$ is proportional to $W_{CO}$ in MBM 40, despite a small positional offset between the two tracers (likely due to some portion of the CH 3335 MHz line tracing molecular gas not detectable by the CO(1-0) line). While the CO(1-0) line may not trace all the molecular gas in a cloud, it certainly traces most of it, e.g., Dame, Hartmann, and Thaddeus (2001) in general, and Chastain (2008) in particular for MBM 40). Thus, $W_{CH}$ is proportional to $N(H_2)$ in MBM 40. Since $N(CH)$ is also proportional to $N(H_2)$, we can assume that, for MBM 40, $W_{CH} \propto N(CH)$ and so $|T_{ex}| \gg T_{BG}$.

With this assumption, $N(H_2)$ is readily derived and dividing $N(H_2)$ by $W_{CO}$ immediately yields $X_{CO}$. The resulting values are tabulated in Table 2; they range from 0.6 to $3.3 \times 10^{20}$ with an average value of $1.3 \times 10^{20}$. This compares reasonably with the values of $X_{CO}$ obtained by Magnani et al. (1998) at nearly an order of magnitude worse resolution; they obtained an average value of $2.6 \times 10^{20}$ for the core region only of MBM 40.
Table 2. Determination of $X_{\text{CO}}$ in MBM 40.

| RA (2000) (h m s) | Dec (2000) (° ′ ″) | $\ell$ deg | $b$ deg | N(CH)$_a$ x 10$^{13}$ (cm$^{-2}$) | $X_{\text{CO}}$ x 10$^{20}$ (cm$^{-2}$ K km s$^{-1}$) |
|-------------------|---------------------|------------|--------|-------------------------------|---------------------------------|
| 16 09 40.8        | 22 07 48            | 37.900     | 44.953 | 2.7 +/- 0.58                  | 1.94 +/- 0.29                  |
| 16 09 45.6        | 22 02 24            | 37.786     | 44.910 | 3.2 +/- 0.73                  | 1.72 +/- 0.30                  |
| 16 09 48.0        | 22 04 48            | 37.844     | 44.912 | 2.8 +/- 0.47                  | 0.91 +/- 0.26                  |
| 16 09 55.2        | 22 10 12            | 37.977     | 44.912 | 2.7 +/- 0.70                  | 1.50 +/- 0.33                  |
| 16 10 00.0        | 22 00 00            | 37.755     | 44.845 | 3.4 +/- 0.48                  | 1.14 +/- 0.25                  |
| 16 10 00.0        | 22 12 36            | 38.038     | 44.906 | 1.7 +/- 0.43                  | 0.67 +/- 0.32                  |
| 16 10 02.4        | 22 07 48            | 37.968     | 44.794 | 1.6 +/- 0.47                  | 0.59 +/- 0.36                  |
| 16 10 04.8        | 22 02 24            | 37.816     | 44.839 | 2.9 +/- 0.48                  | 0.80 +/- 0.26                  |
| 16 10 07.2        | 21 57 36            | 37.712     | 44.806 | 4.2 +/- 0.58                  | 1.26 +/- 0.24                  |
| 16 10 07.2        | 22 04 48            | 37.874     | 44.841 | 1.7 +/- 0.44                  | 0.62 +/- 0.33                  |
| 16 10 14.4        | 21 55 12            | 37.670     | 44.768 | 3.8 +/- 0.39                  | 1.22 +/- 0.23                  |
| 16 10 19.2        | 21 52 48            | 37.624     | 44.739 | 2.4 +/- 0.46                  | 1.05 +/- 0.28                  |
| 16 10 21.6        | 22 00 00            | 37.789     | 44.765 | 3.1 +/- 0.53                  | 0.99 +/- 0.26                  |
| 16 10 24.0        | 22 02 24            | 37.847     | 44.768 | 2.0 +/- 0.47                  | 0.81 +/- 0.31                  |
| 16 10 26.4        | 21 57 36            | 37.743     | 44.735 | 2.1 +/- 0.53                  | 0.81 +/- 0.32                  |
| 16 10 26.4        | 22 10 12            | 38.026     | 44.797 | 1.9 +/- 0.56                  | 0.82 +/- 0.36                  |
| 16 10 31.2        | 21 40 12            | 37.361     | 44.632 | 1.6 +/- 0.54                  | 1.53 +/- 0.40                  |
| 16 10 33.6        | 21 47 24            | 37.526     | 44.659 | 2.9 +/- 0.52                  | 0.84 +/- 0.27                  |
| 16 10 33.6        | 21 55 12            | 37.700     | 44.697 | 1.9 +/- 0.44                  | 0.83 +/- 0.31                  |
| 16 10 36.0        | 21 49 12            | 37.570     | 44.659 | 2.3 +/- 0.52                  | 0.89 +/- 0.30                  |
| 16 10 38.4        | 21 45 00            | 37.480     | 44.629 | 4.1 +/- 0.57                  | 1.44 +/- 0.24                  |
| 16 10 38.4        | 22 04 48            | 36.583     | 44.427 | 1.7 +/- 0.51                  | 0.71 +/- 0.36                  |
| 16 10 40.8        | 21 52 48            | 37.658     | 44.659 | 1.7 +/- 0.34                  | 0.70 +/- 0.28                  |
| 16 10 45.6        | 21 42 36            | 37.438     | 44.591 | 3.7 +/- 0.73                  | 1.50 +/- 0.28                  |
| 16 10 52.8        | 21 40 12            | 37.396     | 44.552 | 2.9 +/- 0.68                  | 1.62 +/- 0.31                  |
| 16 10 52.8        | 21 47 24            | 37.556     | 44.588 | 3.9 +/- 0.45                  | 1.04 +/- 0.23                  |
| 16 10 57.6        | 21 37 12            | 37.336     | 44.520 | 3.5 +/- 0.79                  | 3.28 +/- 0.31                  |
| 16 10 57.6        | 21 49 12            | 37.604     | 44.579 | 1.9 +/- 0.42                  | 0.79 +/- 0.30                  |
| 16 11 00.0        | 21 45 00            | 37.514     | 44.549 | 3.5 +/- 0.21                  | 0.85 +/- 0.21                  |
| 16 11 12.0        | 21 40 12            | 37.427     | 44.481 | 3.5 +/- 0.45                  | 1.13 +/- 0.24                  |
| 16 11 19.2        | 21 37 12            | 37.371     | 44.440 | 2.9 +/- 0.45                  | 1.78 +/- 0.26                  |
| 16 11 24.0        | 21 34 48            | 37.326     | 44.410 | 2.6 +/- 0.77                  | 3.05 +/- 0.36                  |
Table 2—Continued

| RA (2000) | Dec (2000) | ℓ   | b    | N(CH) \(^a\) | \(X_{\text{CO}}\) |
|-----------|------------|-----|------|-------------|------------------|
|           | (h m s)    | deg | deg  | \(\times 10^{13}\) (cm\(^{-2}\)) | \(\times 10^{20}\) (cm\(^{-2}\) K km s\(^{-1}\)) |
| 16 11 24.0| 21 55 12   | 37.781 | 44.511 | 1.2 +/- 0.37 | 1.27 +/- 0.37 |
| 16 11 31.2| 22 00 00   | 37.899 | 44.508 | 2.4 +/- 0.61 | 1.27 +/- 0.32 |
| 16 11 43.2| 21 55 12   | 37.811 | 44.440 | 2.0 +/- 0.48 | 1.69 +/- 0.31 |
| 16 11 57.6| 21 49 48   | 37.714 | 44.360 | 1.2 +/- 0.39 | 2.21 +/- 0.39 |

\(^a\) Data from Chastain et al. (2010).
Figure 2 shows how $X_{\text{CO}}$ varies with respect to $W_{\text{CO}}$. An inverse relationship seems to hold as first noted by Magnani et al. (1998). It can be seen that in areas with high $W_{\text{CO}}$ (> 8 K km s$^{-1}$), $X_{\text{CO}}$ remains fairly constant at a level of $\sim 1 \times 10^{20}$. The other extreme of the graph ($W_{\text{CO}} \leq 4$ K km s$^{-1}$) is the section with CO values that most resembles those found in the envelope and periphery of MBM 40. The curve fit to the data shows that $X_{\text{CO}}$ increases to 2-3 $\times 10^{20}$. For the core region the curve fit follows the function $X_{\text{CO}} = 4.5 \times 10^{20}[W_{\text{CO}}^{-0.78}]$ with a coefficient of determination of 0.54, and for the envelope it is $X_{\text{CO}} = 2.6 \times 10^{20}[W_{\text{CO}}^{-0.71}]$ with a coefficient of determination of 0.97. By calibrating the value of $X_{\text{CO}}$ in these low-intensity CO(1-0) regions we can determine $N(\text{H}_2)$ more confidently than by using one global value for all three cloud regions.

These trends are usually interpreted using simple models of photodissociation regions. In the core of a dark cloud, virtually all the carbon is in the form of CO and so the H$_2$ and CO are well-correlated and a standard value for $X_{\text{CO}}$ is reasonable. In the outer envelope of a molecular cloud, away from the dense core(s), the extinction is typical of the translucent regime and CO is photo-dissociated more strongly than H$_2$. There, most carbon is in the form of CI and CII while the fraction of hydrogen in molecular form is $\geq 50\%$ so that the $X_{\text{CO}}$ value should increase as $W_{\text{CO}}$ decreases (van Dishoeck & Black 1988). Unfortunately, these models, which have been used repeatedly to interpret the CO abundances and observations for molecular clouds with $A_V < 5$ mag do not encompass the full observational milieu. Recent work by Liszt & Pety (2012) establishes without any doubt that strong CO(1-0) emission (4-5 K or more in $T_{\text{mb}}$) can arise in regions with $E(\text{B-V}) \leq 0.15$ mag. This is equivalent to an $A_V < 0.5$ mag; no longer in the translucent regime according to the definition of van Dishoeck & Black (1988) but in the diffuse molecular cloud regime. Here, the CO/H$_2$ ratio and CO column densities should be too low for any detection of the CO(1-0) line, let alone a line greater than 4-5 K in $T_{\text{mb}}$. Liszt & Pety (2012) attribute these strong lines to radiative transfer (sub-thermal excitation and scattering of photons in low-density regions) and chemistry effects. Given the macroscopic turbulence in these low-density molecular clouds, it is clear the previous models of the CO photochemistry were too simplistic and must be revised to account for a more realistic radiative transfer model.

MBM 40, long identified as a translucent cloud, is instead more similar to the diffuse molecular clouds with strong CO emission discussed by Liszt & Pety (2012). The peak $E(\text{B-V})$ in the direction of MBM 40 according the SFD dust maps is 0.24 mag equivalent to an $A_V$ of 0.74 for the canonical value of $R=3.1$. However, even if the core of the cloud, defined as the wishbone-shaped region with $0.17 \leq E(\text{B-V}) \leq 0.24$ mag, could be considered “translucent” because of an anomalously high value of $R$ and/or a significantly lower than average interstellar radiation field, the envelope and periphery of the cloud are clearly diffuse molecular gas, and some of the CO(1-0) lines in these regions exceed 5 K in $T_{\text{mb}}$. MBM 40 is thus most likely a diffuse molecular cloud, even including the core region, rather than a translucent cloud as has been assumed for the last 2 decades.

We can use the $N(\text{H}_{\text{total}})$ - $E(\text{B-V})$ relation established by Bohlin et al. (1978) to check our values for $X_{\text{CO}}$ determined via the CH method. Using $N(\text{H}_{\text{total}}) = 5.8 \times 10^{21} \ [E(\text{B-V})]$ yields a value of $1.4 \times 10^{21}$ cm$^{-2}$ for the peak reddening position in MBM 40. If we take a value of $7 \times 10^{19}$ cm$^{-2}$ for $N(\text{HI})$ in the direction of the peak (Shore et al. 2003), the derived value of $N(\text{H}_2)$ based on the reddening is $\sim 7 \times 10^{20}$
Fig. 2.— $X_{\text{CO}}$ versus $W_{\text{CO}}$ for the envelope and the core of MBM 40. The envelope consists of four points and are labeled with ‘X’. The curve fit for the core is of the form $X_{\text{CO}} = 4.5 \times 10^{20}[W_{\text{CO}}^{-0.78}]$ (with a coefficient of determination of 0.54) and for the envelope it is of the form $X_{\text{CO}} = 2.6 \times 10^{20}[W_{\text{CO}}^{-0.71}]$ (with a coefficient of determination of 0.97).
cm⁻². The value of $W_{CO}$ closest to the peak reddening position yields $7.7 \times 10^{20}$ cm⁻² using a calibrated value of $X_{CO}$ for the core region of $1 \times 10^{20}$ (see below).

4. Mass of MBM 40

4.1. Determination from $X_{CO}$

To determine the mass of H₂ from our CO measurements we use the $X_{CO}$ values determined from Figure 2 in conjunction with the observed, average $W_{CO}$ values for each region. In this study all 44 observations within the core region yielded detections, with an average $W_{CO}$ value of $5.02 \pm 0.11$ K km s⁻¹. In regions of lower E(B-V), we detected CO in 28 of 38 locations in the envelope and 13 of 21 in the periphery resulting in average $W_{CO}$ values of 1.37 and 0.71 K km s⁻¹, respectively. Guided by the inverse relationship established by Figure 2, a value of $1 \times 10^{20}$ for $X_{CO}$ will be used to calculate N(H₂) in the core, while in the envelope and periphery, an $X_{CO}$ value of $2 \times 10^{20}$ is deemed more appropriate. We underscore that in MBM 40, the difference in E(B-V) between core and periphery is only a factor of 3 so that even in the core a sizable fraction of the carbon may be in the form of CI. Ingalls et al. (1997) found that in 10 high-latitude molecular clouds the ratio of C/CO averaged 1.2 implying that translucent high-latitude molecular clouds are transitional objects between clouds dominated by CO and clouds where most of the carbon is in atomic form. As a diffuse molecular cloud, MBM 40 is likely to have an even greater proportion of carbon in atomic form.

Our empirically-calibrated $X_{CO}$ values vary by a factor of 2. However, the rise in $X_{CO}$ as $W_{CO}$ decreases is driven by only 7 data points with $W_{CO} < 5$ K km s⁻¹. Thus, the uncertainty in determining the mass of the various regions of the cloud is going to be large. The basic reason for the lack of $X_{CO}$ data in the envelope is that detecting CH emission from regions of very low E(B-V) is difficult, requiring several hours of integration per point. In order to estimate the uncertainty in our $X_{CO}$ values, we can turn to the lower resolution CH data used by Magnani et al. (1998) to calibrate $X_{CO}$ in the outer regions of MBM 40. These data were at 9’ and 8’ resolution for the CH and CO transitions, respectively, but 7 of the 11 data points from that study were in the envelope and periphery of the cloud. The value of $X_{CO}$ obtained from that data is $3.15 \times 10^{20}$. Though at lower resolution, this value can be used as an independent measure of $X_{CO}$ outside the core of the cloud. Thus, we will use $2 \pm 1 \times 10^{20}$ as our estimate of the value of $X_{CO}$. This uncertainty (which drives the overall uncertainty in the mass of the cloud for the envelope and periphery) will thus be estimated at ∼50%.

To obtain the mass of MBM 40 in terms of H₂ using CO observations the regions where CO is measured must be extrapolated over the entire of the cloud. Using the average $W_{CO}$ values from Table 3 with the aforementioned $X_{CO}$ values of 2 and $1 \times 10^{20}$ for the two outermost regions and the core, respectively, the column density of molecular hydrogen can be calculated. The distance of the cloud is usually estimated to be 130 ± 10 pc (see, e.g. Chastain et al. 2010). Combining the average N(H₂) for each region, the ratio of detections/observations for each region ($β$), the angular size of each region in steradians ($Ω$), the distance to the cloud (d), and the mean molecular mass, $μ$ (taken to be 2.3 to account for helium) allows for a
determination of the mass:

\[ M_{\text{H}_2} = \beta \Omega d^2 N(\text{H}_2) \mu m_{\text{H}} \text{ (gm)} \]  

(1)

Using this method yields molecular masses of 9.6 ± 5, 12 ± 6, and 10 ± 5 M\(_{\odot}\) for the core, envelope, and periphery regions, respectively. These masses are about a factor of 2 greater than those determined from OH observations by Cotten et al. (2012) who estimated molecular masses of 3.8 ± 0.86, 7.6 ± 2.5, and 5.2 ± 6.3 M\(_{\odot}\) for the core, envelope, and periphery regions, respectively. The differences in the two estimates depend directly on the values of X\(_{\text{CO}}\) and the OH/\text{H}_2 abundance that are used in each derivation of the mass for each region. Given the uncertainties in both quantities, the agreement is satisfactory. Both the CO and OH data show that MBM 40 is a small, diffuse molecular cloud, with a mass in the 15 - 30 M\(_{\odot}\) range. More importantly, like Cotten et al. (2012), we find that as much as a third of the total cloud mass may be found in the periphery where E(B-V) < 0.12 mag. This is significant because molecular cloud mapping in CO seldom probes regions of such low extinction. If substantial molecular gas is found here, then at least some of the “dark” molecular gas found in recent studies (Grenier et al. 2005) may be spectroscopically detectable by radio means after all.

### 4.2. Virial Considerations

In addition to determining the mass of the cloud via an X\(_{\text{CO}}\) value, our CO observations allow us to determine the virial mass of the cloud and thus determine the gravitational state of MBM 40. Assuming a density distribution that scales as \(\rho^{-2}\) from the core of the cloud, a cloud in virial equilibrium should have a virial mass, \(M_{\text{vir}}\), in solar masses of 126 \(r \Delta v_{\text{tot}}^2\), where \(\Delta v_{\text{tot}}\) is the velocity width (FWHM) of the composite spectrum over the entire cloud, and \(r\) is the radius of the cloud in parsecs. We can estimate \(\Delta v_{\text{tot}}\) following Dickman & Kleiner (1985) who determine the velocity dispersion of the composite spectral profile of the cloud (\(\sigma_p\)) from the dispersion of the average velocity width for the entire cloud (\(\sigma_i\)), and the dispersion of the centroid velocities for the whole cloud (\(\sigma_c\)).

| Region      | \(T_R\) \(^{\text{a}}\) | \(\Delta v\) (FWHM) | \(v_{\text{LSR}}\) | \(\sigma_{\text{LSR}}\) | \(W_{\text{CO}}\) \(^{\text{a}}\) |
|-------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Core        | 4.57 +/- 2.40   | 0.90 +/- 0.20   | 3.20            | 0.25            | 5.02 +/- 0.11   |
| Envelope    | 1.43 +/- 1.51   | 0.71 +/- 0.24   | 3.19            | 0.29            | 1.37 +/- 0.08   |
| Periphery   | 0.78 +/- 0.68   | 0.76 +/- 0.17   | 3.51            | 0.66            | 0.71 +/- 0.06   |
| All points  | 2.96 +/- 2.57   | 0.82 +/- 0.23   | 3.25            | 0.37            | 3.16 +/- 0.09   |

\(^{\text{a}}\) \(W_{\text{CO}}\) is \(\int T_{\text{mb}} dv\).
\[ \sigma_p^2 = \sigma_i^2 + \sigma_c^2 \]

In our case, we can use the data from Table 2, where \( \sigma_c \) is equivalent to \( \sigma_{LSR} \) and \( \sigma_i \) is just the dispersion of the line widths averaged for the whole cloud. In this manner, we obtain \( \sigma_p = 0.51 \text{ km s}^{-1} \) or a \( \Delta v_{\text{tot}} = 1.2 \text{ km s}^{-1} \). Using a distance of 130 ± 10 pc, the radius of the cloud can be taken to be the \((A/\pi)^{0.5}\) assuming the cloud is spherical in shape (a reasonable assumption - see Figure 1). At 130 pc, this gives a radius of 0.8°, equivalent to 1.8 pc. With these values, \( M_{\text{vir}} = 330 \text{ M}_\odot \). Even including a contribution to the mass from the HI associated with the cloud (estimated by Chastain (2005) to be 10 \text{ M}_\odot), we see that cloud is clearly gravitationally unbound - a typical result for a high-latitude cloud and in keeping with its categorization as a diffuse molecular cloud.

5. Summary

We observed 103 lines of sight in the high-latitude cloud, MBM 40, in the CO(1-0) transition using the Arizona Radio Observatory 12 m radio telescope, detecting emission from 85 positions. The cloud was divided into 3 regions based on the reddening maps of SFD: a core region where \( 0.25 > E(B-V) > 0.17 \) mag, an envelope region where \( 0.12 \leq E(B-V) \leq 0.17 \), and an outermost periphery region where \( E(B-V) < 0.12 \) mag. The detection rates for each region were 44/44 in the core, 28/38 in the envelope, and 13/21 in the periphery.

Using previously published CH data, we calibrated the value of the CO-H\(_2\) conversion factor, \( X_{\text{CO}} \), for this cloud. The values we obtained, ranging from \( 0.6 \times 10^{20} \) to \( 3.3 \times 10^{20} \text{ cm}^{-2} [\text{K km s}^{-1}]^{-1} \) with an average of \( 1.3 \times 10^{20} \text{ cm}^{-2} [\text{K km s}^{-1}]^{-1} \), are similar to what was obtained at nearly an order of magnitude worse resolution by Magnani et al. (1998). Like those authors, we find an inverse relationship between \( X_{\text{CO}} \) and \( W_{\text{CO}} \). This has also been noted by other authors in diffuse molecular clouds (e.g. Liszt et al. 2010).

This cloud has a peak reddening of 0.24 mag which for a normal value of \( R \) places it squarely in the category of diffuse molecular clouds following the schema of van Dishoeck & Black (1986). This is in contrast to nearly all previous papers on this object, the authors of which categorized this object as a translucent molecular cloud. It is surprising that a diffuse molecular cloud should have CO(1-0) emission as intense as that seen in this object. Recently, Liszt & Pety (2012), have made a convincing case for a class of diffuse molecular cloud with strong CO(1-0) lines, similar to those from denser, more opaque molecular clouds. The intense CO emission is attributed to radiative transfer and chemistry effects. We believe this to be also the case for MBM 40.

With our calibrated values of \( X_{\text{CO}} \) for the core and outer regions of the cloud, we can determine the cloud mass in each region and overall. The values we obtain: 9.6, 12, and 10 \text{ M}_\odot for the core, envelope, and periphery, respectively, are similar to what was found by Cotten et al. (2012) using the OH 1667 MHz line as a molecular tracer. A virial analysis shows that MBM 40 is not gravitationally bound. Both studies show that as much as 1/3 of the cloud’s molecular mass may be in the outermost regions of the cloud where the
visual extinction is likely to be no more than 0.4-0.5 magnitudes.

In summary, MBM 40 is a small, nearby, diffuse molecular cloud with strong CO(1-0) emission. Like other diffuse molecular clouds, it is not gravitationally bound and destined to break up over the sound-crossing time scale (of order $10^6$ years). As such, the object is not a candidate for star formation as has been confirmed by several studies (Chol Minh et al. 2003, Shore et al. 2003, Magnani et al. 1996).

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