CO EMISSION IN LOW-LUMINOSITY, H I–RICH GALAXIES

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ABSTRACT

We present $^{12}\text{CO}$ 1 → 0 observations of 11 low-luminosity ($M_b > -18$), H I–rich dwarf galaxies. Only the three most metal-rich galaxies, with $12 + \log (\text{O}/\text{H}) \approx 8.2$, are detected. Very deep CO spectra of six extremely metal-poor systems [$12 + \log (\text{O}/\text{H}) \leq 7.5$] yield only low upper limits on the CO surface brightness, $I_{\text{CO}} < 0.1 \text{ K km s}^{-1}$. Three of these six have never before been observed in a CO line, while the others now have much more stringent upper limits. For the very low metallicity galaxy Leo A, we do not confirm a previously reported detection in CO, and the limits are consistent with another recent nondetection.

We combine these new observations with data from the literature to form a sample of dwarf galaxies that all have CO observations and measured oxygen abundances. No known galaxies with $12 + \log (\text{O}/\text{H}) < 7.9$ ($Z < 0.1 Z_\odot$) have been detected in CO. Most of the star-forming galaxies with higher [$12 + \log (\text{O}/\text{H}) > 8.1$] metallicities are detected at similar or higher $I_{\text{CO}}$ surface brightnesses. The data are consistent with a strong dependence of the $I_{\text{CO}}/M_{\text{H}_2} \equiv X_{\text{CO}}$ conversion factor on ambient metallicity. The strikingly low upper limits on some metal-poor galaxies lead us to predict that the conversion factor is nonlinear, increasing sharply below $\sim 1/10$ of the solar metallicity [$12 + \log (\text{O}/\text{H}) \leq 7.9$].

Key words: galaxies: dwarf — galaxies: ISM

1. INTRODUCTION

Carbon monoxide (CO) is commonly used as a tracer of cool molecular gas, because molecular hydrogen (H$_2$), the dominant species in the molecular phase, has no strong emission lines from which the column density of H$_2$ may easily be determined. Since the rotational transitions of CO in the millimeter and submillimeter regime are relatively easy to excite, it is possible to use the luminosity in one of these lines to estimate the column density and mass of molecular gas, provided one knows the correct conversion. The conversion factor, $X_{\text{CO}}$, from $I_{\text{CO}}$ to $N_{\text{H}_2}$ has been determined for the Milky Way galaxy to be $\sim 3 \times 10^{20} \text{ cm}^{-2} (\text{K km s}^{-1})^{-1}$ for the $^{12}\text{CO}$ 1 → 0 transition (Strong et al. 1988; Scoville & Sanders 1987). The application of this Milky Way value to external galaxies has been controversial, as the value may depend on the physical conditions in those galaxies which are difficult to determine observationally and may differ greatly from those in our own galaxy (Dickman, Snell, & Schloerb 1986; Israel et al. 1986; Maloney & Black 1988, hereafter MB88).

One of the characteristics of a galaxy that may affect the relation between CO luminosity and H$_2$ gas mass is its metal abundance. If the abundance of the CO molecule is low, the column density of CO may not be great enough to allow self shielding from dissociating radiation. In this case, the size of the CO emitting region within a given molecular cloud will shrink, while the H$_2$ is unaffected. Thus, the filling factor will decrease, reducing the CO luminosity for a given molecular gas mass (MB88). Rubio, Lequeux, & Boulanger (1993) have found observational evidence of this effect in the SMC. Their data for a number of molecular clouds show a correlation between cloud size and the CO-to-H$_2$ conversion factor. They suggest that the smaller clouds are the dense cores of larger clouds in which the diffuse CO outside the cores has been dissociated (cf. MB88).

Observational studies have led to conflicting conclusions concerning the presence of molecular clouds in actively star-forming dwarf galaxies. Since the pioneering work of Elmegreen, Elmegreen, & Morris (1980), it has been clear that the CO molecule is difficult to detect in dIs and therefore, that the CO surface brightnesses are much lower in dIs than in spiral galaxies. Under the assumption that the CO/H$_2$ ratio is constant everywhere, this implied that the molecular gas content of dwarf galaxies must be very low (Young, Gallagher, & Hunter 1984; Tacconi & Young 1987).

On the other hand, studies by Wilson (1995, hereafter W95) and Verter & Hodge (1995) have provided strong evidence that the conversion factor depends on the metal abundance of the galaxy. By measuring molecular cloud virial masses and comparing them to their CO luminosities, W95 showed that the CO-to-H$_2$ conversion increases as the metallicity of the host galaxy decreases over the range of $8 \leq 12 + \log (\text{O}/\text{H}) \leq 9$. This supported the conclusions made by Cohen et al. (1988) and Rubio et al. (1991) based on observations of the Magellanic Clouds. Verter & Hodge (1995) added very deep CO 2 → 1 observations of the extreme dwarf galaxy GR 8 and were unable to detect any
The proximity of GR 8 (2.2 Mpc; Tolstoy et al. 1995) allows very low upper limits on \(L(\text{CO})\). Combined with an inference of the minimal molecular mass present to support the current star formation in GR 8, this was also interpreted as an indication of a metallicity dependence of the CO-to-\(H_2\) conversion factor.

Studies of this type have been limited primarily to galaxies of relatively high metallicities in order to detect CO emission. Indeed, the nondetection of GR 8 by Verter & Hodge (1995), with an oxygen abundance of 12 + log (O/H) = 7.47 (Skillman, Kennicutt, & Hodge 1989) illustrates this difficulty. In fact, the only low-metallicity dwarf irregular galaxy to have been detected in CO is Leo A, observed by Tacconi & Young (1987), at 12 + log (O/H) = 7.3. A recent observation of Leo A by L. Young (1997, private communication) failed to confirm the detection of CO in Leo A. We decided to try to confirm this important result ourselves and to supplement the understanding of CO emission in low-metallicity environments by observing additional metal poor dwarf galaxies.

Here we present \(^{12}\text{CO} \, 1 \to 0\) observations of 11 galaxies covering a range of oxygen abundances from 7.3 \(\geq 12 + \log (O/H) \geq 8.2\). Some of these galaxies have been previously observed in CO. We confirm previous detections for several galaxies, and we obtain very deep upper limits for others. We present the first published CO data on three galaxies, UGC 4483, DDO 187, and UM 422. Section 2 contains a description of the observations and data reduction, while § 3 describes the results. In § 4 we combine the new observations with a thorough search of the literature to examine
the relationship between CO surface brightness and metal abundance in these low-mass systems.

2. $^{12}$CO OBSERVATIONS AND DATA REDUCTION

2.1. Observations

We observed five galaxies with the NRAO $^{2}$ 12 m telescope at Kitt Peak, in the $1 \rightarrow 0$ (115 GHz) transition of $^{12}$CO on 1998 January 5–11: Leo A, Sextans A, DDO 210, DDO 187, and Pegasus. Three galaxies (UM 422, Mrk 178, and UGC 4483) were observed on 1994 March 10–13 and three more (NGC 1569, NGC 4214, and NGC 5253) on 1995 June 18–21. The 3 mm SIS receiver was used with the filterbank spectrometer and a 1 MHz filter, yielding 256 channels per spectrum, and a channel width of 2.6 km s$^{-1}$.

The receiver was tuned to the central velocity of the H I distribution in each galaxy. Operating at 115 GHz, the half-power beam width is 55$''$. System temperatures varied from between ~300 and 500 K during the course of the observations, infrequently rising higher during the 1998 January run due to weather conditions. The pointing was checked about every 2 hours by observing Venus or Mars. The observations were conducted in beam switching mode, with a beam throw of 2$'$ at 1.25 Hz, except for Leo A and Sextans A, which have too large an angular extent. For these galaxies, the absolute position switching mode was used to ensure a reference beam uncontaminated by emission from the galaxy. For comparison, one position in Leo A was also observed in beam switching mode.

2.2. Observing Strategy

Part of the motivation for our observations was to reobserve Leo A to confirm the detection of Tacconi & Young.

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3. RESULTS: CO DETECTIONS AND UPPER LIMITS

3.1. Individual Galaxies

Table 1 gives the positions, optical diameters, H I heliocentric central velocities, and velocity widths from the literature for each of the newly observed galaxies, as well as the central velocities, velocity widths (full widths at 50% max), the rms noise, and the integrated intensities ($I_{CO} = \int T_K dv$) of the CO line or the upper limits. Reported errors on $I_{CO}$ are computed from $N^{1/2} \times \sigma_{rms} \times \delta v_{chan}$, where $N$ is the number of channels in which CO was detected, $\sigma_{rms}$ is the noise in the spectrum, and $\delta v_{chan}$ is the channel width in km s$^{-1}$.

**Leo A.—**Leo A is a dwarf irregular galaxy for which Tacconi & Young (1987) claim a CO detection. We observed three positions in this galaxy, two corresponding to the locations of the cold H I component discovered by Young & Lo (1996) and the third at the same position observed by Tacconi & Young (1987). Comparing this position with the H I map of Young & Lo (1996) shows that the claimed CO detection arises in a large depression in the H I column density. We detected CO at none of the three positions, including that observed by Tacconi & Young. The nondetection of CO is in accord with the low metallicity of Leo A and the nondetection of other systems with similarly low metallicities. The rms noise for the spectra we have obtained in Leo A range from 2.7 to 5.5 mK when smoothed to 5.2 km s$^{-1}$ velocity resolution. For a resolution of 20.8 km s$^{-1}$ the range is 1.3–2.6 mK. In comparison, the detection from Tacconi & Young is 19 mK with a velocity width of 25 km s$^{-1}$.

**Sextans A.—**The dwarf irregular galaxy Sextans A was most recently observed in CO (prior to our own observations) by Ohta et al. (1993). They observed a single

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**TABLE 1**

**VELOCITIES AND LINE WIDTHS**

| Galaxy Name   | $\alpha$(1950) | $\delta$(1950) | $D_{LS}$ (arcmin) | $v_0$(H I) (km s$^{-1}$) | $\Delta v_{LS}$(H I) (km s$^{-1}$) | $I_{CO}$ (K km s$^{-1}$) | $\sigma(T_K)$ (K) |
|---------------|----------------|----------------|-------------------|--------------------------|-------------------------------|------------------------|------------------|
| NGC 1569      | 04 26 05       | +64 44 23      | 3.1               | -89                      | 74                            | 0.685 ± 0.104           |
| UGC 4483      | 08 32 07       | +69 57 16      | 1.1               | 156                      | 49                            | 0.007                  | <0.195          |
| Leo A         | ...            | ...            | 5.0               | 20                       | 33                            | 0.002                  | ...              |
| Leo A-1(ABS)  | 09 56 38       | +30 58 50      | ...               | ...                      | ...                           | 0.004                  | <0.101          |
| Leo A-2       | 09 56 21       | +30 59 29      | ...               | ...                      | ...                           | 0.006                  | <0.143          |
| Leo A-3       | 09 56 32       | +30 59 12      | ...               | ...                      | ...                           | 0.004                  | <0.075          |
| Leo A-1(BPS)  | 09 56 38       | +30 58 50      | ...               | ...                      | ...                           | 0.003                  | <0.070          |
| Sextans       | 10 08 36       | -04 27 34      | ...               | ...                      | ...                           | 0.004                  | <0.088          |
| Sextans A-1   | 10 08 32       | -04 27 34      | ...               | ...                      | ...                           | 0.006                  | <0.143          |
| Sextans A-2   | 10 08 21       | -04 26 40      | ...               | ...                      | ...                           | 0.006                  | <0.143          |
| Sextans A-3   | ...            | ...            | ...               | ...                      | ...                           | 0.006                  | <0.225          |
| UM 422        | 11 17 40       | +02 47 58      | 2.3               | 1600                     | 90                            | 0.002                  | <0.120          |
| Mrk 178       | 11 30 45       | +49 30 46      | 1.4               | 250                      | 30                            | 0.002                  | <0.225          |
| NGC 4214      | ...            | ...            | 9.6               | 290                      | 62                            | 0.005                  | 0.542 ± 0.078   |
| NGC 4214a     | 12 13 09       | +36 36 16      | ...               | ...                      | 294                           | 0.005                  | <0.069          |
| NGC 4214b     | 12 13 11       | +36 35 44      | ...               | ...                      | ...                           | 0.013                  | <0.044          |
| NGC 4214d     | 12 13 11       | +36 36 48      | ...               | ...                      | ...                           | 0.005                  | <0.225          |
| NGC 5253      | 13 37 05       | -31 23 30      | 4.5               | 408                      | 60                            | 0.009                  | 0.725 ± 0.148   |
| DDO 187       | 14 13 38       | +23 17 10      | 1.9               | 154                      | 33                            | 0.003                  | <0.070          |
| DDO 210       | 20 44 06       | -13 01 55      | 2.3               | -137                     | 21                            | 0.005                  | <0.125          |
| Pegasus       | 23 26 04       | +14 27 15      | 4.6               | -183                     | 23                            | 0.005                  | <0.132          |

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**Note:**—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

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**References:**—(H82) Hunter et al. 1982; (MI) Melisse & Israel 1994; (Se88) Skillman et al. 1988; (TBGS) Taylor et al. 1995; (TM81) Thuan & Martin 1981; (KS95) Kobulnicky & Skillman 1995.
position coinciding with the peak H\textsc{\i} column density determined from the map of Skillman et al. (1988), attaining an rms noise in their spectrum of 48 mK for a velocity resolution of 2.6 km s\textsuperscript{-1}. We have observed two positions in Sextans A, the main peak in the H\textsc{\i} column density, as well as a secondary peak. These two peaks are positioned on either side of a depression in the H\textsc{\i} column density that coincides with the center of the optical galaxy. In our observations of the secondary H\textsc{\i} peak (labeled as position 3 in Table 1) we used the H\textsc{\i} hole as the position for the reference beam. Thus, emission at that location would appear as an absorption feature in the spectrum of Figure 1. The velocity difference between the gas at these two locations due to the rotation of the galaxy is large enough (~10 km s\textsuperscript{-1}) that an apparent absorption feature would not cancel out emission at position 3. The rms noise in our spectra span the range 3.4–5.5 mK at 5.2 km s\textsuperscript{-1} velocity resolution, and 1.3–24 mK for 20.8 km s\textsuperscript{-1} resolution.

**DDO 210.**—DDO 210, another gas-rich dwarf irregular galaxy, is among those observed in CO by Tacconi & Young (1987), who did not detect it. They give a 2 \sigma upper limit on the integrated CO intensity, $I_{\text{CO}}$ of 0.41 K km s\textsuperscript{-1}, compared to our 5 \sigma upper limit of 0.12 K km s\textsuperscript{-1}. We used the H\textsc{\i} maps by Lo, Sargent, & Young (1993) to direct our single pointing observation at the peak of the H\textsc{\i} column density. The Tacconi & Young (1987) position falls approximately one beam width to the east of ours, although still on an area of high H\textsc{\i} column density. We note that the oxygen abundance we use for DDO 210 is derived from its absolute density. The & Young position falls approximately 20 km s\textsuperscript{-1} to the east of ours, although still on an area of high H\textsc{\i} column density.

**DDO 187.**—DDO 187 is also a dwarf irregular, but it has not been previously observed in CO. We obtained a spectrum from a single position in the galaxy, centered on the peak of the H\textsc{\i} column density as determined from the data of Lo, Sargent, & Young (1993). Smoothing the spectrum to 5.2 km s\textsuperscript{-1}, we reach an rms noise of 2.7 mK, while for 20.8 km s\textsuperscript{-1} the noise is 1.6 mK.

**Pegasus.**—The Pegasus dwarf irregular galaxy has also been observed in CO by Tacconi & Young (1987), who do not detect it, giving a 2 \sigma upper limit on the integrated CO intensity of 0.38 K km s\textsuperscript{-1}. This compares to our 5 \sigma upper limit of 0.08 K km s\textsuperscript{-1}. The position observed by Tacconi & Young (1987) is ~1’ north of the position we have observed and is on the edge of the dense region of H\textsc{\i} for which our observed position is the H\textsc{\i} peak.

**NGC 5253.**—The amorphous galaxy NGC 5253 is a 4 \sigma detection in the smooth spectrum, with a peak intensity at roughly 400 km s\textsuperscript{-1}, the systemic velocity of the H\textsc{\i} distribution. Turner, Beck, & Hurt (1997) also obtained a detection (14 Jy km s\textsuperscript{-1} = 6–8 \sigma) of NGC 5253 at the velocity of the H\textsc{\i} using the Owens Valley Radio Observatory millimeter array. Using the SEST telescope, Wiklind & Henkel (1989) find an integrated CO intensity of 1.3 K km s\textsuperscript{-1}, which corresponds to 27.3 Jy km s\textsuperscript{-1} assuming a gain of 21 Jy K\textsuperscript{-1} at 115 GHz. For the 12 m telescope, we adopt a gain of 34 Jy K\textsuperscript{-1} (NRAO 12 m user’s guide), which yields 24.6 ± 5.0 Jy km s\textsuperscript{-1}, consistent with the SEST value, and roughly twice the OVRO interferometer value. The discrepancy between single dish and interferometer measurements is to be expected if the interferometer resolves out CO emission on large angular scales. NGC 5253 was also observed by Jackson et al. (1989), who did not detect it with the NRAO 12 m telescope, with an rms noise of 0.10 K in their spectrum, a value slightly higher than in our own spectrum.

**NGC 1569.**—NGC 1569 has been classified as a Magellanic irregular. Israel & de Bruyn (1988) have found evidence that it is in a poststarburst phase, in which the massive star formation has recently ceased. For this galaxy we find an integrated CO intensity of 0.685 ± 0.104 K km s\textsuperscript{-1}. The CO spectrum shows an absorption signature near 0 km s\textsuperscript{-1} due to Galactic foreground CO emission in the reference beam. Rogstad, Rogoor, & Whiteoak (1967) obtained an H\textsc{\i} spectrum toward NGC 1569 that shows H\textsc{\i} emission at ~ −90 km s\textsuperscript{-1}, and also detected a narrow emission feature at ~0 km s\textsuperscript{-1} from the Galaxy. The two features are well separated, so there should not be any contamination from the off-beam reference position affecting the line profile.

**NGC 4214.**—NGC 4214 is classified as SBm III and is one of the most luminous of the observed galaxies. Four positions separated by 45", were observed. These are designated a, b, d, and e. CO is detected at two of the four positions, with an integrated CO intensity of 0.900 ± 0.105 K km s\textsuperscript{-1}. A direct comparison of these results to other CO observations of NGC 4214 is problematic because of different beam sizes (IRAM; Becker et al. 1995) or overlapping beams (Thronson et al. 1988). Our results are at least consistent with the center position 3 \sigma detections reported by Thronson et al. ($I_{\text{CO}} = 1.0 ± 0.35$ K km s\textsuperscript{-1}) and Tacconi & Young (1985; $I_{\text{CO}} = 0.94 ± 0.22$ K km s\textsuperscript{-1}). Becker et al. (1995) have mapped this galaxy in the $^{12}$CO 2 → 1 transition, finding the emission to be confined to a region roughly thirty arcseconds in diameter. Our observations cover this area and should detect all the $^{12}$CO 1 → 0 emission.

**Mrk 178.**—Mrk 178 is a low-luminosity dwarf with an abundance of 12 + log (O/H) = 8.0 (Kobulnicky & Skillman, in preparation) Mrk 178 has been observed in CO previously but has only a high upper limit (rms noise = 20 mK; Morris & Lo 1978). Our spectrum shows no emission down to a limit of $I_{\text{CO}} < 0.2$ K km s\textsuperscript{-1}. The rms noise in the final averaged spectra is 2 mK, a factor of 10 lower than that obtained by Morris & Lo (1978).

**UGC 4483.**—UGC 4483 is a very low abundance dwarf galaxy [12 + log (O/H) = 7.5] in the nearby M81 group (Skillman et al. 1994). Its appearance is dominated by a single giant star-forming complex. It has no previous CO observations in the literature, and no CO emission was detected in our spectrum, which has an rms noise of 2 mK. The upper limit on $I_{\text{CO}}$ is less than 0.195 K km s\textsuperscript{-1}.

**UM 422.**—The H\textsc{\i} galaxy UM 422 (UGC 6345) is an emission line galaxy from the sample of Salzer, MacAlpine, & Boroson (1989) and was included in the VLA H\textsc{\i} survey of H\textsc{\i} galaxies of Taylor et al. (1995). It is the most distant galaxy in this paper and was included in our sample because
of its low metal abundance. This galaxy has not been previously observed in CO. The rms noise in our spectrum is 2 mK, with an upper limit on $I_{CO}$ of 0.120 K km s$^{-1}$.

Table 2 gives distances, optical luminosities, oxygen abundances, integrated CO intensities and CO "luminosities" for galaxies we have observed. $L_{CO}$ is determined using the relation: $L_{CO} = I_{CO}A_S$, where $A_S$ is the source area (see, e.g., Sanders, Scoville, & Soifer 1991).

In the case of UM 422, the most distant galaxy we observed, the star-forming region traced by H$\alpha$ emission is approximately the size of the telescope beam. Thus, our assumption of extended emission is adequate, as long as spatially extended star formation can be taken as indicating the presence of spatially extended molecular gas. Without knowledge of the true CO spatial distribution, our assumption will at least provide reasonable relative estimates for the CO luminosities and H$_2$ masses among galaxies in our sample.

4. DISCUSSION

4.1. The Dependence of CO Emission on Metal Abundance

We have carried out these observations with the goal of better understanding the relationship of CO emission to metal abundance in dwarf galaxies. Because all of these galaxies (with the exception of DDO 210) are currently experiencing at least some massive star formation, we can infer the presence of molecular gas. Even dwarf irregular galaxies with relatively low rates of massive star formation can be detected in CO, especially if they are nearby. To supplement our 11 galaxies we have searched the literature for low-luminosity dwarfs, which have been observed in the $^{12}$CO 1 $\rightarrow$ 0 line. These previous works include Morris & Lo (1978), Rowan-Robinson, Phillips, & White (1980), Elmegreen et al. (1980), Israel & Burton (1986), Tacconi & Young (1987), Thronson & Bally (1987), Arnault et al. (1988), Sage et al. (1992), Wilson (1992), Hunter & Sage (1993), Brinks & Taylor (1997), Israel et al. (1995), Young et al. (1995), and Gondhalekar et al. (1998). In an effort to keep the galaxy sample as homogeneous as possible, we selected only those galaxies with $M_B \geq -18$. For CO data, we are careful to convert $I_{CO}$ from the published temperature units (usually $T_{d*}$ or $T_{mb}$) into the units used here, $T_{mb}$. Since most galaxies have not been mapped in CO with an interferometer, we use the telescope beam size at the distance of the galaxy as a consistent first order estimate the source diameter. The data we have collected from the literature are presented in Table 3. Unfortunately, only a small fraction of these galaxies have published chemical abundances from optical spectroscopy.

Our primary objective is to study the dependence of CO emission on ambient metal abundance, independent of variations in galaxy size, distance, and optical luminosity. Verter & Hodge (1995) and Wilson (1995) use observations of individual molecular clouds in nearby galaxies to characterize the variation of $X_{CO}$ with metallicity. Our data do not allow us to determine this conversion factor. Instead, our approach is to study a larger sample of extremely metal-poor galaxies using very sensitive CO observations obtained with a telescope beam that is comparable to the size of the target galaxies. Since the galaxies lie at different distances up to 20 Mpc, the telescope beam samples an ensemble average of many molecular clouds in the target galaxies. In most cases, the size of the CO emitting region is not known. Thus, the spectra for each pointing represent a mean CO surface brightness for the nearby resolved galaxies, and a lower limit on the CO surface brightness for the most distant objects, where the emitting region may be much smaller than the beam. It is not immediately apparent which physical properties (e.g., $I_{CO}$, $X_{CO}$, $M_H$) derived from the spectra make for the best analysis.

We first examined the CO luminosity, $L_{CO}$, as a function of metal abundance as indicated by $12 + \log O/H$. However, because metallicity correlates strongly with optical luminosity in galaxies of all types (see, e.g., Lequeux et al. 1979; Skillman et al. 1989) we find that more metal-rich, and thus the most luminous, galaxies have larger $L_{CO}$. This result is not especially informative. Larger galaxies contain more matter, and not surprisingly, they should have more CO as well, even if the $I_{CO}/N_H$ conversion factor is identical to smaller, more metal-poor galaxies. Next, we considered normalizing the CO luminosity of each galaxy by some fiducial indicator of its mass, such as optical luminosity or H I mass. This has the advantage of producing distance-independent quantities like $L_{CO}/M_{H_I}$ or $L_{CO}/L_B$. However, we find that for a given metal abundance, the scatter in each of these exceeds an order of magnitude. This scatter results, in part, because the CO, H I and optical data

**TABLE 2**

**PROPERTIES OF OBSERVED DWARF GALAXIES**

| Galaxy Name | Distance (Mpc) | $M_B$ | Reference | Abundance 12 + log O/H | Reference | $I_{CO}$ (K km s$^{-1}$) | $L_{CO}$ (10$^6$ K km s$^{-1}$ pc$^2$) |
|-------------|----------------|-------|------------|----------------------|----------|------------------------|---------------------------------|
| NGC 1569    | V Zw 16        | 2.2   | IvD        | -16.9                | T88      | 8.19 $\pm$ 0.02         | KS97 0.685 $\pm$ 0.104          |
| NGC 4214    | UGC 7278       | 4.1   | MI         | -17.9                | T88      | 8.20 $\pm$ 0.05         | KS96 0.900 $\pm$ 0.105          |
| NGC 5253    | UGC A369       | 4.1   | KS95      | -17.2                | T88      | 8.20 $\pm$ 0.06         | Ke97 0.725 $\pm$ 0.148          |
| UM 422      | UGC 6345B      | 21.3  | TBGS      | -13.7                | SMB      | 8.0 $\pm$ 0.2           | Te95 $<$0.120 $<$3.0            |
| Mer 178     | UGC 6541B      | 4.2   | TMB1      | -14.4                | T88      | 8.0 $\pm$ 0.02          | KS96 $<$0.225 $<$0.22           |
| Pegasus     | DDO 216        | 0.76  | Ge98      | -12.3                | T88      | 7.93 $\pm$ 0.11         | Se97 $<$0.0044 $<$0.132         |
| UGC 4883    |                | 4.0   | MI         | -13.4                | T88      | 7.50 $\pm$ 0.03         | Se94 $<$0.195 $<$0.18           |
| Sextans A   | DDO 75         | 1.4   | De97      | -14.1                | T88      | 7.5 $\pm$ 0.2           | SKH $<$0.017 $<$0.143           |
| DDO 210     |                | 4     | Ge93      | -13.4                | MI        | 7.4 $\pm$ 1.3          | ... $<$0.11 $<$0.125            |
| DDO 187     | UGC 9128       | 4.4   | AGM       | -13.9                | T88      | 7.75 $\pm$ 0.05         | vZ97 $<$0.076 $<$0.070          |
| Leo A       | DDO 69         | 0.69  | Te98      | -11.7                | T88      | 7.3 $\pm$ 0.2           | SKH $<$0.0357 $<$0.143          |

* Estimated from the magnitude/abundance relation from Skillman et al. 1989.

REFERENCES.—(IvD) Israel & van Driel 1990; (MI) Melli & Israel 1994; (KS95) Kobulnicky & Skillman 1995; (TBGS) Taylor et al. 1995; (TMB1) Thuan & Martin 1981; (Ge98) Gallagher et al. 1998; (De97) Dohn-Palmer et al. 1997; (Ge93) Greggio et al. 1993; (AGM) Aparicio et al. 1988; (Te98) Tolstoy et al. 1998; (T88) Tully 1988; (SMB) Salzer et al. 1989; (K97) Kobulnicky & Skillman 1997; (KS96) Kobulnicky & Skillman 1996; (Ke97) Kobulnicky et al. 1997; (Te97) Terlevich et al. 1991; (Se97) Skillman et al. 1997; (Se94) Skillman et al. 1994; (SKH) Skillman et al. 1989; (vZ97) van Zee et al. 1997.
| Galaxy Name | Galaxy Name | Distance (Mpc) | Reference | $M_n$ | Reference | $12 + \log O/H$ | Reference | $I_{\text{CO}}$ (K km s$^{-1}$) | Reference | $I_{\text{CO}}$ (10$^4$ K km s$^{-1}$ pc$^2$) |
|-------------|-------------|----------------|-----------|-------|-----------|----------------|-----------|-------------------------------|-----------|----------------------------------|
| NGC 1156    | VV 531      | 6.4            | T88       | −17.5 | T88       | 8.29(0.20)     | T80       | <1.2                          | HS93      | <2.7                             |
| UGC A372    | Mrk 67      | 22.4           | T88       | −16.0 | TMB1      | 8.21(0.08)     | KS96      | <0.62                         | S92       | <2.8                             |
| NGC 6822    | DDO 209     | 0.7            | T88       | −15.6 | T88       | 8.19(0.07)     | KS96      | >1.81(0.25)                   | W92       | 0.05 (0.01)                      |
| II Zw 40    | UGC A116    | 10.3           | T88       | −17.2 | T88       | 8.06(0.02)     | KeUP      | 0.46(0.10)                    | Ye95      | 1.82 (0.40)                      |
| II Zw 70    | Mrk 829     | 23.1           | T88       | −17.1 | T88       | 8.06(0.08)     | KS96      | <0.38                         | Ye95      | <7.6                             |
| UM 439      | UGC 06578   | 14.7           | vZ95      | −15.8 | SMB       | 8.05(0.02)     | KS96      | <0.48                         | S92       | 5.79                             |
| I Zw 123    | Mrk 487     | 15.0           | T88       | −16.1 | T88       | 8.02(0.09)     | KS96      | <1.06                         | Aae88     | <2.13                            |
| SMC          | ...         | 0.06           | BW97      | −16.3 | BT        | 7.98(0.02)     | Pe78      | <1.00(0.5)                     | Ie93      | <5200(2600)                      |
| UM 462      | Mrk 1307    | 13.9           | TBGS      | −15.7 | S92       | 7.96(0.02)     | KS96      | <0.28                         | BT        | <3.02                            |
| I Zw 36     | UGC A281    | 4.7            | T88       | −13.9 | T88       | 7.93(0.07)     | VT83      | 0.45(0.10)                    | Ye95      | 0.37 (0.08)                      |
| NGC 2366    | DDO 42      | 2.9            | T88       | −16.7 | T88       | 7.89(0.02)     | GDe94     | <0.60                         | HS93      | <0.28                            |
| UGC 3974    | DDO 47      | 2.1            | T88       | −13.2 | T88       | 7.85(0.01)     | SKH       | <0.46                         | Ye95      | <0.076                           |
| UM 461      | ...         | 11.7           | S92       | −14.1 | S92       | 7.76(0.02)     | KS96      | <0.78                         | S92       | 5.96                             |
| NGC 4789A   | DDO 154     | 4.0            | T88       | −14.1 | T88       | 7.67(0.06)     | vZ97      | <2.6                          | ML78      | <2.32                            |
| GR8          | DDO 155     | 1.7            | T88       | −11.6 | T88       | 7.47(0.02)     | SKH       | <0.09                         | VH95      | <0.015                           |
| I Zw 18     | Mrk 116     | 14.3           | T88       | −14.8 | TM81      | 7.21(0.05)     | SK93      | <0.27                         | Ge98      | 1.26                             |
| Arp 4        | DDO 14      | 19.8           | T88       | −17.9 | T88       | ...            | ...       | <1.38                         | IB86      | <30.1                            |
| NGC 3353    | Haro 3      | 16.8           | T88       | −17.9 | T88       | ...            | ...       | 1.46(0.21)                    | S92       | 3.68 (0.53)                      |
| UM 549      | ...         | 78.7           | SMB       | −17.9 | SMB       | ...            | ...       | <0.27                         | Ge98      | <37.8                            |
| UGC 12632   | DDO 217     | 9.2            | T88       | −17.7 | T88       | ...            | ...       | <0.99                         | IB86      | <4.68                            |
| NGC 2537    | Mrk 86      | 9.0            | T88       | −17.6 | T88       | ...            | ...       | 0.83(0.12)                    | S92       | 0.60(0.09)                       |
| UGC 10310   | DDO 204     | 15.8           | T88       | −17.5 | T88       | ...            | ...       | 3.2                           | ML78      | <44.6                            |
| UM 471      | ...         | 146.6          | SMB       | −17.5 | SMB       | ...            | ...       | <0.46                         | Ge98      | <220                             |
| NGC 4605    | UGC 07831   | 4.0            | T88       | −17.4 | T88       | ...            | ...       | 1.30(0.3)                     | TB87      | 3.39 (0.78)                      |
| HoII        | DDO 50      | 4.5            | T88       | −17.3 | T88       | ...            | ...       | <0.46                         | Ye95      | 0.35                             |
| UM 465      | UGC 6877    | 15.4           | T88       | −17.3 | T88       | ...            | ...       | 0.63(0.18)                    | S92       | 8.3(2.3)                         |
| UGC 05478   | DDO 73      | 23.4           | T88       | −17.2 | T88       | ...            | ...       | 0.30                          | Ie95      | <9.17                            |
| NGC 4670    | Haro 9      | 11.0           | T88       | −17.2 | T88       | ...            | ...       | 2.62                          | Aae88     | <2.83                            |
| UM 286      | ...         | 21.6           | T88       | −17.0 | T88       | ...            | ...       | 0.73                          | Ge98      | <7.70                            |
| UM 334      | ...         | 69.5           | SMB       | −17.0 | SMB       | ...            | ...       | 0.36                          | Ge98      | <39.3                            |
| UM 454      | ...         | 50.1           | SMB       | −17.0 | SMB       | ...            | ...       | 0.73                          | Ge98      | <41.4                            |
| NGC 4144    | UGC 7151    | 4.1            | T88       | −16.9 | T88       | ...            | ...       | <4.0                          | RR80      | <3.75                            |
| UM 351      | ...         | 104.2          | SMB       | −16.9 | SMB       | ...            | ...       | <0.27                         | Ge98      | <66.3                            |
| NGC 4523    | DDO 135     | 16.8           | T88       | −16.8 | T88       | ...            | ...       | <0.57                         | Ye95      | <6.01                            |
| UM 374      | ...         | 79.1           | SMB       | −16.8 | SMB       | ...            | ...       | <0.46                         | Ge98      | <65.1                            |
| NGC 7077    | Mrk 900     | 13.3           | T88       | −16.7 | T88       | ...            | ...       | 0.50(0.09)                    | S92       | 0.79(0.14)                       |
| UGC A441    | Mrk 328     | 19.6           | T88       | −16.6 | T88       | ...            | ...       | <1.04                         | S92       | <3.57                            |
| UM 483      | Mrk 1313    | 30.8           | TBGS      | −16.5 | SMB       | ...            | ...       | <0.73                         | Ge98      | <15.7                            |
| IC 2574     | DDO 81      | 2.7            | T88       | −16.4 | T88       | ...            | ...       | <1.8                          | Es80      | <0.73                            |
| Galaxy Name | Galaxy Name | Distance (Mpc) | Reference | $M_B$ | Reference | Abundance | Reference | $I_{CO}$ (K km s$^{-1}$) | Reference | $L_{CO}$ (10$^6$ K km s$^{-1}$ pc$^2$) |
|-------------|-------------|----------------|-----------|-------|-----------|-----------|-----------|-------------------------|-----------|----------------------------------|
| NGC 1560    | UGC 03060   | 3.0            | T88       | -16.4 | T88       | ...       | ...       | <4.0                    | RR80      | <2.01                           |
| UM 491      |             | 26.3           | TBGS      | -16.3 | SMB       | ...       | ...       | <0.73                   | Ge98      | 11.4                            |
| UM 456      |             | 23.3           | TBGS      | -16.1 | S92       | ...       | ...       | <0.64                   | Ge98      | 7.86                            |
| NGC 4707    | DDO 150     | 8.0            | T88       | -16.1 | T88       | ...       | ...       | 1.59(0.26)              | Ye95      | 0.26(0.04)                      |
| NGC 3738    | UGC 06565   | 4.3            | T88       | -16.1 | T88       | ...       | ...       | 0.37(0.10)              | Ye95      | 0.26(0.07)                      |
| NGC 2976    | UGC 05221   | 2.1            | T88       | -16.1 | T88       | ...       | ...       | 1.0(0.2)                | TB87      | 0.86(0.14)                      |
| NGC 3274    | UGC 05721   | 5.9            | T88       | -16.0 | T88       | ...       | ...       | <0.1                    | TB87      | 0.6                             |
| UM 323      |             | 25.5           | TBGS      | -15.9 | SMB       | ...       | ...       | <0.55                   | Ge98      | 8.09                            |
| UM 452      |             | 19.2           | TBGS      | -15.9 | SMB       | ...       | ...       | <0.64                   | Ge98      | 5.34                            |
| UGC 09366   | DDO 168     | 7.4            | T88       | -15.5 | T88       | ...       | ...       | <4.0                    | RR80      | 12.2                            |
| UGC 08320   | DDO 168     | 3.6            | T88       | -15.5 | T88       | ...       | ...       | <4.0                    | RR80      | 2.89                            |
| UGC 0333    | UGC 08105   | 10.4           | S92       | -15.3 | S92       | ...       | ...       | <0.87                   | S92       | 5.25                            |
| UGC 09405   | DDO 194     | 5.7            | T88       | -15.2 | M1        | ...       | ...       | <4.0                    | RR80      | 7.26                            |
| Hol         | DDO 63      | 4.4            | T88       | -15.2 | T88       | ...       | ...       | <4.0                    | RR80      | 4.32                            |
| UGC 05272   | DDO 64      | 6.5            | T88       | -15.1 | T88       | ...       | ...       | <0.75                   | i95       | 1.77                            |
| UGC 02014   | DDO 22      | 9.4            | T88       | -14.9 | M1        | ...       | ...       | <0.95                   | IB86      | 5.20                            |
| UGC 05764   | DDO 83      | 6.9            | T88       | -14.9 | T88       | ...       | ...       | 0.57(0.20)              | i95       | 1.52(0.53)                      |
| UGC 07698   | DDO 133     | 3.8            | T88       | -14.9 | T88       | ...       | ...       | <4.0                    | RR80      | 3.23                            |
| UGC 03860   | DDO 43      | 7.2            | T88       | -14.6 | T88       | ...       | ...       | <0.32                   | i95       | 0.93                            |
| UGC 07577   | DDO 125     | 3.0            | T88       | -14.6 | T88       | ...       | ...       | <4.0                    | RR80      | 2.01                            |
| VII Zw 499  | DDO 165     | 2.8            | T88       | -14.6 | T88       | ...       | ...       | <4.0                    | RR80      | 1.75                            |
| I Zw 87     | DDO 190     | 3.7            | T88       | -14.5 | T88       | ...       | ...       | <0.46                   | i95       | 0.35                            |
| UGC 05340   | DDO 68      | 5.9            | T88       | -14.4 | T88       | ...       | ...       | 0.30(0.15)              | i95       | 0.58(0.29)                      |
| UGC 06817   | DDO 99      | 3.1            | T88       | -14.3 | T88       | ...       | ...       | <4.0                    | RR80      | 2.15                            |
| IC 1574     | DDO 226     | 4.5            | T88       | -14.3 | T88       | ...       | ...       | <4.0                    | RR80      | 4.52                            |
| UGC 06900   | DDO 101     | 5.9            | T88       | -14.3 | T88       | ...       | ...       | <0.75                   | i95       | 1.46                            |
| UGC 04426   | DDO 52      | 6.3            | T88       | -14.2 | T88       | ...       | ...       | <0.63                   | i95       | 1.40                            |
| UGC 08760   | DDO 183     | 3.3            | T88       | -13.9 | T88       | ...       | ...       | <0.30                   | i95       | 0.18                            |
| UGC 07559   | DDO 126     | 2.8            | T88       | -13.2 | T88       | ...       | ...       | <4.0                    | RR80      | 1.75                            |
| UGC 07599   | DDO 127     | 3.5            | T88       | -13.0 | T88       | ...       | ...       | <4.0                    | RR80      | 2.74                            |
| M81 DwA      |             | 4.3            | T88       | -12.3 | PT        | ...       | ...       | <0.27                   | Ye95      | 0.19                            |

References.—(T88) Tully 1988; (vZ95) van Zee et al. 1995; (TBGS) Taylor et al. 1995; (SMB) Salzer et al. 1989; (TM81) Thuan & Martin 1981; (BT88) Bothun & Thompson 1988; (K96) Kobulnicky & Skillman 1996; (KeUP) Kobulnicky et al. 1998; (KS95) Kobulnicky & Skillman 1995; (Pe78) Pagel et al. 1978; (VT83) Viallefon & Thuan 1983; (GDe94) Gonzalez-Delgado et al. 1994; (SKH) Skillman et al. 1989; (vZ97) van Zee et al. 1997; (SK93) Skillman & Kennicutt 1993; (HS93) Hunter & Sage 1993; (W92) Wilson 1992; (Ye95) Young et al. 1995; (Ae88) Arnault et al. 1988; (BT) Brinks & Taylor 1997; (ML78) Morris & Lo 1978; (VH95) Verter & Hodge 1995; (Ge98) Gallagher et al. 1998; (IB86) Israel & Burton 1986; (TB87) Thronson & Bally 1987; (Ie95) Israel et al. 1995; (RR80) Rowan-Robinson et al. 1980; (Ee80) Elmegreen et al. 1980; (FT) Patterson & Thuan 1996.
sample different regions of the galaxy. The H I and optical measurements refer to the global properties of a galaxy, including material at large radii, while, in all but the most distant targets, the CO data represent relatively localized measurements that cover only the central star-forming regions. Furthermore, extinction and the recent star formation history strongly influences the measured optical luminosity. Ideally, such a normalization by optical luminosity or H I mass should be made using optical imaging or aperture synthesis H I mapping, which is spatially matched to the single-dish CO beam.

We finally decided to use the integrated CO intensity, \( I_{\text{CO}} \), as the unit of comparison between galaxies of different metallicity. \( I_{\text{CO}} \) is a measure of the mean CO surface brightness (K km s\(^{-1}\) beam\(^{-1}\)) and is roughly independent of distance as long as the CO beam is not much larger than the emitting region. Since \( I_{\text{CO}} \) measures the amount of CO emission per unit beam area, the major problem with this quantity is that the CO beam subtends larger areas with increasing galaxy distance. For more distant galaxies, which are smaller than the beam area, the measured quantity represents only a lower limit on the CO surface brightness. In an effort to make a robust comparison between galaxies, we exclude from further analysis all objects more distant than 10 Mpc. At 10 Mpc, the 55° FWHM beam of the NRAO 12 m telescope used in most of these observations subtends 2.7 kpc. This is approximately the size of CO emitting central regions of Magellanic irregular galaxies such as NGC 4214 (Becker et al. 1995). CO detections with 55° resolution in dwarf galaxies significantly more distant than 10 Mpc will yield probable lower limits on the CO surface brightness, \( I_{\text{CO}} \). The opposite problem exists for very nearby galaxies, where the telescope beam resolves individual giant molecular clouds. The CO data of Israel et al. (1993) in the LMC and SMC show a larger scatter in \( I_{\text{CO}} \), which probably reflects the real brightness variations between molecular clouds centers and intercloud regions. We include the LMC in the plot for comparison purposes, although it violates our absolute magnitude limit. For the LMC and SMC we adopt the mean \( I_{\text{CO}} \) values. Since Israel et al. (1993) chose locations in the LMC and SMC to contain molecular clouds and star-forming regions, this mean represents an upper limit on the true mean \( I_{\text{CO}} \) that would be observed from a distance of 2–5 Mpc, which is typical of the dwarf galaxies under consideration. The rest of the galaxies in the sample (except NGC 6822) are more distant than 1 Mpc, so that these smaller scale brightness variations are smoothed out by the relatively larger beam area.

In Figure 2 we plot \( \log I_{\text{CO}} \) versus the oxygen abundance \([ 12 + \log (\text{O/H}) ]\) for dwarf galaxies less than 10 Mpc away. Galaxies with CO detections appear as filled circles, while undetected objects appear as upper limits. We plot I Zw 36 with an open circle since it represents a less secure (4 \( \sigma \)) detection (Tacconi & Young 1987; Young et al. 1995) and it has not been subsequently reobserved. We show only the brightest position for NGC 6822 reported by Wilson (1992). We plot the mean \( I_{\text{CO}} \) for the LMC and SMC reported by Israel et al. (1993).

Figure 2 reveals a clear dichotomy between systems with \( 12 + \log (\text{O/H}) > 8.0 \) and the very metal-poor systems. All of the galaxies with CO detections have higher metallicities; the only one detected below \( 12 + \log (\text{O/H}) = 8.0 \) is I Zw 36 (Tacconi & Young 1987). All galaxies with lower metallicities are nondetections with very low limits. The nondetections at low metallicities are consistent with a strong dependence of the CO surface brightness on metallicity. To test this visual impression of the data quantitatively, we randomly redistributed the \( x \) - and \( y \) -values of the 19 objects in Figure 2 \([ I_{\text{CO}} ]\) and \([ 12 + \log (\text{O/H}) ]\) 100,000 times. In only 97 of these 100,000 tests did all eight detected objects in Figure 2 fall above an oxygen abundance of 7.9. The chance of obtaining the result randomly is only 0.1%, strongly suggesting that metal-poor dwarfs have markedly lower CO surface brightnesses.

In previous works there has also been a clear trend for high-metallicity galaxies to have a high CO emission, while most of the low-abundance galaxies were undetected. Tacconi & Young (1985) noted a dependence of \( L_{\text{CO}} \) on metal abundance, although their sample of galaxies contained relatively massive, metal-rich objects and only one object with \( 12 + \log (\text{O/H}) < 8.5 \). They presented a plot similar to our Figure 2, showing a clear correlation of \( L_{\text{CO}} \) with O/H for irregular and spiral galaxies, albeit with considerable scatter. Gondhalekar et al. (1998) also find a similar result. Part of this correlation was undoubtedly due to the underlying luminosity—metal abundance correlation among galaxies (see, e.g., Lequeux et al. 1979; Skillman et al. 1989). Arnault et al. (1988) made a similar plot using \( L_{\text{CO}}/M_{\text{HI}} \), which shows a correlation between \( L_{\text{CO}}/M_{\text{HI}} \) and oxygen abundance. They include spiral galaxies, while we specifically excluded spiral galaxies from our plot, both because the physical conditions of the molecular gas are likely to be different from dwarf galaxies, and because the concept of a global metal abundance is ill defined. Spiral galaxies often show large abundance gradients (see, e.g., Zaritsky, Kennicutt, & Huchra 1994), whereas dwarf and irregular galaxies have very uniform abundances (Pagel, Edmunds, & Smith 1980; Kobulnicky & Skillman 1996,
1997; Devost, Roy, & Drissen 1997). Sage et al. (1992) present much the same plot (their Fig. 4a) from which they concluded that there is no correlation between $L_{\text{CO}}/M_{H_2}$ and metal abundance. Our restricted sample includes none of the Sage et al. galaxies, which are all more distant than 10 Mpc or more luminous than dwarf galaxies.

Figure 2 should be free from all of these biases due to differing distances, galaxy sizes, metallicities, and luminosities. We plot CO surface brightness rather than luminosity, and we include only dwarf galaxies that are chemically homogeneous. We also extend the metallicity baseline to much lower values of O/H in order to place stronger constraints on the role of metallicity in determining the CO surface brightness. Unfortunately, Figure 2 is relatively sparse because so few dwarf galaxies have sensitive CO observations, and few of those have accurate metallicity determinations.

To increase the sample size using more of the galaxies from Table 3, we plot $I_{\text{CO}}$ versus $L_B$ in Figure 3. Given the metallicity-luminosity relationship for dwarf irregular galaxies, the luminosity can serve as a metallicity and size indicator. Mindful of the historical problems with false CO detections at low signal-to-noise (e.g., Leo A) we further impose the restriction that the CO detection must be at the 4 $\sigma$ level or better. This excludes three objects, NGC 3738, DDO 83, and DDO 68, from Table 3. Labels and filled circles or large arrows denote galaxies with measured metallicities that appear in Figure 2. Filled triangles denote additional CO detections in objects without measured metallicities. Small arrows mark additional upper limits for galaxies that have been observed in CO. The addition of these 34 galaxies reinforces the striking trend seen in Figure 2. Galaxies detected in CO cluster near log $I_{\text{CO}} = 0$ and have $M_B$ brighter than $-15.5$. No galaxies fainter than $M_B = -15$ are detected, with the exception of the 4 $\sigma$ I Zw 36. Because I Zw 36 stands out in this way in Figures 2 and 3, it would be worthwhile to reobserve it for confirmation of the detection. The CO upper limits of the additional data from the literature do not constrain the behavior of $I_{\text{CO}}$ at low metallicities as strongly as the new observations presented here.

Since CO emission is considered a tracer of the molecular gas, it might be expected from the above result that low-abundance galaxies would also be deficient in molecular gas compared to the amount of atomic gas. However, the conversion rate from CO to $H_2$ depends on abundance, in the sense that the lower the abundance, the higher the conversion rate. Therefore, the low-abundance galaxies will have the highest conversion rates (e.g., MB88), and thus may not necessarily have lower $H_2$ masses. The best evidence for a metallicity-dependent conversion factor dependent comes from CO observations of giant molecular clouds in metal poor systems in nearby galaxies (Verter & Hodge 1995; W95). The new, very sensitive data we present here further strengthen their conclusions, and even suggest a rapid (nonlinear) increase in $X_{\text{CO}}$ below $12 + \log (O/H) = 8.0$. Spaans et al. (1998) find such a sharp change in $X_{\text{CO}}$ approximately this same metallicity in their models of the multiphase galactic medium. Even more sensitive observations with the next generation of millimeter-wave telescopes may be able to confirm this prediction of a steep decline in CO surface brightness, and a steep increase in the $I_{\text{CO}}/H_2$ conversion factor in very metal-deficient environments.

5. SUMMARY

$^{12}$CO 1 $\rightarrow$ 0 observations of 11 galaxies with oxygen abundances $12 + \log (O/H)$ in the range 8.4–7.3 yield the most sensitive data yet on very metal-deficient galaxies. The six objects that have low abundances $[12 + \log (O/H) < 8.0]$ are not detected to upper limits of 0.1 K km s$^{-1}$. Three of these six have never before been observed in a CO line, while the others now have much more stringent upper limits. For the very low-metallicity galaxy Leo A, we do not confirm a previously reported detection in CO, but the upper limit is consistent with an unpublished nondetection by L. Young (1997, private communication).

We combine these new observations with data from the literature to form a sample of dwarf galaxies that all have CO observations and measured oxygen abundances. None of the galaxies with $12 + \log (O/H) < 7.9$ are detected. Most of the galaxies with higher metallicities are detected at a similar CO surface brightness, $log I_{\text{CO}} \approx -0.1$ K km s$^{-1}$. These data are consistent with a strong dependence of the $I_{\text{CO}}/M_{H_2} = X_{\text{CO}}$ conversion factor on ambient metallicity. The low upper limits on some galaxies, together with the molecular gas implied by the presence of star formation, are consistent with hypothesis that the conversion factor is nonlinear, increasing sharply around 1/10 of the solar metallicity $[12 + \log (O/H) \approx 8.0]$.

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