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A. Leroy

John M Cannon, *Macalester College*

F. Walter

A. Bolatto

A. Weiss



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THE LOW CO CONTENT OF THE EXTREMELY METAL-POOR GALAXY I Zw 18

ADAM LEROY,¹ JOHN CANNON,^{1,2} FABIAN WALTER,¹ ALBERTO BOLATTO,³ AND AXEL WEISS⁴

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ABSTRACT

We present sensitive molecular line observations of the metal-poor blue compact dwarf I Zw 18 obtained with the IRAM Plateau de Bure interferometer. These data constrain the CO $J = 1 \rightarrow 0$ luminosity within our 300 pc (FWHM) beam to be $L_{\text{CO}} < 1 \times 10^5 \text{ K km s}^{-1} \text{ pc}^2$ ($I_{\text{CO}} < 1 \text{ K km s}^{-1}$), an order of magnitude lower than previous limits. Although I Zw 18 is starbursting, it has a CO luminosity similar to or less than nearby low-mass irregulars (e.g., NGC 1569, the SMC, and NGC 6822). There is less CO in I Zw 18 relative to its B -band luminosity, $H\text{ I}$ mass, or star formation rate than in spiral or dwarf starburst galaxies (including the nearby dwarf starburst IC 10). Comparing the star formation rate to our CO upper limit reveals that unless molecular gas forms stars much more efficiently in I Zw 18 than in our own Galaxy, it must have a very low CO to H_2 ratio, $\sim 10^{-2}$ times the Galactic value. We detect 3 mm continuum emission, presumably due to thermal dust and free-free emission, toward the radio peak.

Subject headings: galaxies: dwarf — galaxies: individual (I Zw 18) — galaxies: ISM — radio lines: ISM

1. INTRODUCTION

With the lowest nebular metallicity in the nearby universe [$12 + \log(\text{O}/\text{H}) \approx 7.2$; Skillman & Kennicutt 1993], the blue compact dwarf I Zw 18 plays an important role in our understanding of galaxy evolution. Vigorous ongoing star formation implies the presence of molecular gas, but direct evidence has been elusive. Vidal-Madjar et al. (2000) showed that there is not significant diffuse H_2 , but Cannon et al. (2002) found $\sim 10^3 M_\odot$ of dust organized in clumps with sizes 50–100 pc. Vidal-Madjar et al. (2000) did not rule out compact, dense molecular clouds, and Cannon et al. (2002) argued that this dust may indicate the presence of molecular gas.

Observations by Arnault et al. (1988) and Gondhalekar et al. (1998) failed to detect CO $J = 1 \rightarrow 0$ emission, the most commonly used tracer of H_2 . This is not surprising. The low dust abundance and intense radiation fields found in I Zw 18 may have a dramatic impact on the formation of H_2 and structure of molecular clouds. A large fraction of the H_2 may exist in extended envelopes surrounding relatively compact cold cores. In these envelopes, H_2 self-shields while CO is dissociated (Maloney & Black 1988). The result may be that in such galaxies [C II] or far-infrared emission trace H_2 better than CO (Madden et al. 1997; Israel 1997a; Pak et al. 1998). Furthermore, H_2 may simply be underabundant, as there is a lack of grains on which to form while photodissociation is enhanced by an intense UV field. Indeed, Bell et al. (2006) found that at $Z = Z_\odot/100$, a molecular cloud may take as long as a gigayear to reach chemical equilibrium.

A low CO content in I Zw 18 is then expected, and a stringent upper limit would lend observational support to predictions for molecular cloud structure at low metallicity. However, while the existing upper limits are sensitive in an absolute sense, they do not even show I Zw 18 to have a lower *normalized* CO content than a spiral galaxy (e.g., less CO per B -band luminosity). The

low luminosity ($M_B \approx -14.7$; Gil de Paz et al. 2003) and large distance ($d = 14 \text{ Mpc}$; Izotov & Thuan 2004) of this system require very sensitive observations to set a meaningful upper limit.

In this paper we present observations, obtained with the IRAM Plateau de Bure Interferometer (PdBI),⁵ that constrain the CO luminosity, L_{CO} , to be equal to or less than that of nearby CO-poor (nonstarbursting) dwarf irregulars.

2. OBSERVATIONS

I Zw 18 was observed with the IRAM PdBI on 2004 April 17, 21, and 27, and May 13 for a total of 11 hr. The phase calibrators were 0836+710 [$F_\nu(115 \text{ GHz}) \approx 1.1 \text{ Jy}$] and 0954+556 [$F_\nu(115 \text{ GHz}) \approx 0.35 \text{ Jy}$]. One or more calibrators with known fluxes were also observed during each track. The data were reduced at the IRAM facility in Grenoble using the GILDAS software package; maps were prepared using AIPS. The final CO $J = 1 \rightarrow 0$ data cube has beam size $5.59'' \times 3.42''$ and a velocity (frequency) resolution of 6.5 km s^{-1} (2.5 MHz). The velocity coverage stretches from $v_{\text{LSR}} \approx 50$ to 1450 km s^{-1} . The data have an rms noise of $3.77 \text{ mJy beam}^{-1}$ (18 mK; $1 \text{ Jy beam}^{-1} = 4.8 \text{ K}$). The $44''$ (FWHM) primary beam completely covers the galaxy. Based on variation of the relative fluxes of the calibrators, we estimate the gain uncertainty to be $< 15\%$.

3. RESULTS

3.1. Upper Limit on CO Emission

To search for significant CO emission, we smooth the cube to 20 km s^{-1} velocity resolution, a typical line width for CO at our spatial resolution (e.g., Helfer et al. 2003). The noise per channel map in this smoothed cube is $\sigma_{20} \approx 0.25 \text{ K km s}^{-1}$. Over the $H\text{ I}$ velocity range (710–810 km s^{-1} ; van Zee et al. 1998), there are no regions with $I_{\text{CO},20} > 1 \text{ K km s}^{-1}$ (4σ) within the primary

¹ Max-Planck-Institut für Astronomie, D-69117 Heidelberg, Germany.

² Astronomy Department, Wesleyan University, Middletown, CT 06459; cannon@astro.wesleyan.edu.

³ Radio Astronomy Lab, University of California, Berkeley, CA 94720.

⁴ Max-Planck-Institut für Radioastronomie (MPIfR), 53121 Bonn, Germany.

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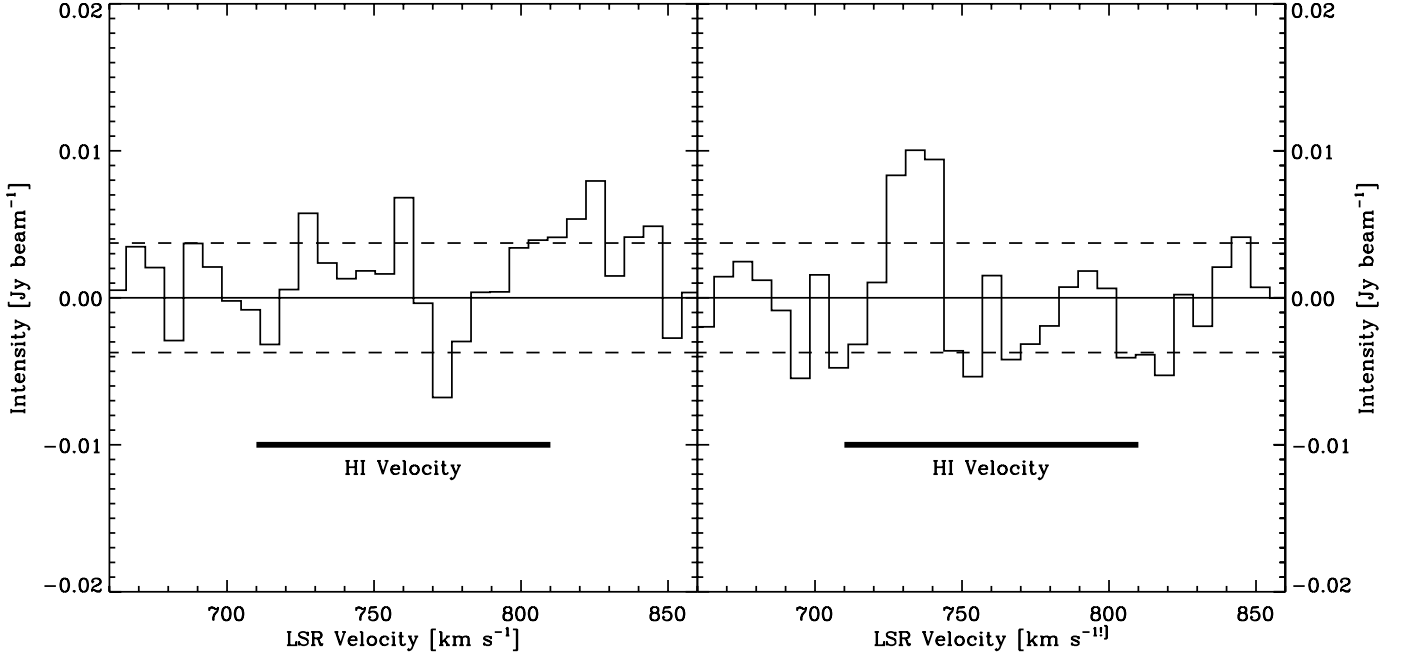


FIG. 1.—Plot of CO $1 \rightarrow 0$ spectra of I Zw 18 toward the radio continuum/ $H\alpha$ peak (*left*) and the highest significance spectra (*right*), which is still too faint to classify as more than marginal. The locations of both spectra are shown in Fig. 2. Dashed horizontal lines show the magnitude of the rms noise.

beam. We pick a slightly conservative upper limit for two reasons. First, if there were CO emission with this intensity we would be certain of detecting it. Second, the noise in the cube is slightly non-Gaussian, so that the false positive rate for $I_{\text{CO},20} > 1 \text{ K km s}^{-1}$ —estimated from the negatives and the channel maps outside the H I velocity range—is $\sim 0.2\%$, very close to that of a 3σ deviate.

For $d = 14 \text{ Mpc}$, the synthesized beam has a FWHM of 300 pc and an area of $1.0 \times 10^5 \text{ pc}^2$. Our intensity limit, $I_{\text{CO}} < 1 \text{ K km s}^{-1}$, therefore translates to a CO luminosity limit of $L_{\text{CO}} < 1 \times 10^5 \text{ K km s}^{-1} \text{ pc}^2$.

There is a marginal signal toward the southern knot of $H\alpha$ emission ($\alpha_{\text{J2000.0}} = 9^{\text{h}}34^{\text{m}}02.4^{\text{s}}$, $\delta_{\text{J2000.0}} = 55^{\circ}14'23.0''$). This emission has the largest $|I_{\text{CO},20}|$ found over the H I velocity range, corresponding to $L_{\text{CO}} \sim 8 \times 10^4 \text{ K km s}^{-1} \text{ pc}^2$, just below our limit. This same line of sight also shows $|I_{\text{CO}}| > 2 \sigma$ over three consecutive channels, a feature seen along only one other line of sight (in negative) over the H I velocity range. The marginal signal is suggestively located in the southeast of I Zw 18, where Cannon et al. (2002) identified several potential sites of molecular gas from regions of relatively high extinction. While tantalizing, the signal is not strong enough to be categorized as a detection. Figure 1 shows CO spectra toward the $H\alpha$ /radio continuum peak (Cannon et al. 2002, 2005; Hunt et al. 2005b; see our Fig. 2) and this marginal signal.

3.2. Continuum Emission

We average the data over all channels and produce a continuum map with noise $\sigma_{115 \text{ GHz}} = 0.35 \text{ mJy beam}^{-1}$. The highest value in the map is $I_{115 \text{ GHz}} = 1.06 \pm 0.35 \text{ mJy beam}^{-1}$ at $\alpha_{\text{J2000.0}} = 9^{\text{h}}34^{\text{m}}02.1^{\text{s}}$, $\delta_{\text{J2000.0}} = +55^{\circ}14'27.0''$. This is within a fraction of a beam of the 1.4 GHz peak identified by Cannon et al. (2005), $\alpha_{\text{J2000.0}} = 9^{\text{h}}34^{\text{m}}02.1^{\text{s}}$, $\delta_{\text{J2000.0}} = +55^{\circ}14'28.06''$, and Hunt et al. (2005b), $\alpha_{\text{J2000.0}} = 9^{\text{h}}34^{\text{m}}02^{\text{s}}$, $\delta_{\text{J2000.0}} = +55^{\circ}14'29.06''$. Figure 2 shows the radio continuum peak and 115 GHz continuum contours plotted over $H\alpha$ emission from I Zw 18 (Cannon et al. 2002). There is only one other region

with $|I_{115 \text{ GHz}}| > 3 \sigma_{115 \text{ GHz}}$ within the primary beam, and the star-forming extent of I Zw 18 occupies $\approx 10\%$ of the primary beam. Therefore, we estimate the chance of a false positive coincident with the galaxy to be only $\sim 10\%$.

4. DISCUSSION

Here we discuss the implications of our CO upper limit and continuum detection. We adopt the following properties for I Zw 18, all scaled to $d = 14 \text{ Mpc}$: $M_B = -14.7$ (Gil de Paz et al. 2003), $M_{\text{H I}} = 1.4 \times 10^8 M_{\odot}$ (van Zee et al. 1998), $H\alpha$ luminosity $\log_{10} H\alpha = 39.9 \text{ ergs s}^{-1}$ (Cannon et al. 2002; Gil de Paz et al. 2003), and 1.4 GHz flux $F_{1.4} = 1.79 \text{ mJy}$ (Cannon et al. 2005).

4.1. Point-Source Luminosity

Our upper limit along each line of sight, $L_{\text{CO}} < 1 \times 10^5 \text{ K km s}^{-1} \text{ pc}^2$, matches the luminosity of a fairly massive Galactic giant molecular cloud (Blitz 1993). For a Galactic CO to H_2 conversion factor, $2 \times 10^{20} \text{ cm}^{-2} (\text{K km s}^{-1})^{-1}$, the corresponding molecular gas mass is $M_{\text{mol}} \approx 4.4 \times 10^5 M_{\odot}$, similar to the mass of the Orion-Monoceros complex (e.g., Wilson et al. 2005).

4.2. Comparison with More Luminous Galaxies

In galaxies detected by CO surveys, the CO content per unit B -band luminosity is fairly constant. Figure 3 shows the CO luminosity normalized by B -band luminosity, L_{CO}/L_B , as a function of absolute B -band magnitude (L_B is extinction corrected); L_{CO}/L_B is nearly constant over 2 orders of magnitude in L_B , although with substantial scatter (much of it due to the extrapolation from a single pointing to L_{CO}).

Based on these data and assuming that L_{CO} is not a function of the metallicity of the galaxy, we may extrapolate to an expected CO luminosity for I Zw 18. For $M_{B, \text{I Zw 18}} \approx -14.7$ the CO luminosity corresponding to the median value of L_{CO}/L_B (*dashed line*) in Figure 3 is $L_{\text{CO}, \text{I Zw 18}} \approx 1.7 \times 10^6 \text{ K km s}^{-1} \text{ pc}^2$. The $H\alpha$, 1.4 GHz , and H I luminosities lead to similar predictions. Young et al. (1996) found $M_{\text{H}_2}/L_{\text{H}\alpha} \approx 10 L_{\odot}/M_{\odot}$ for

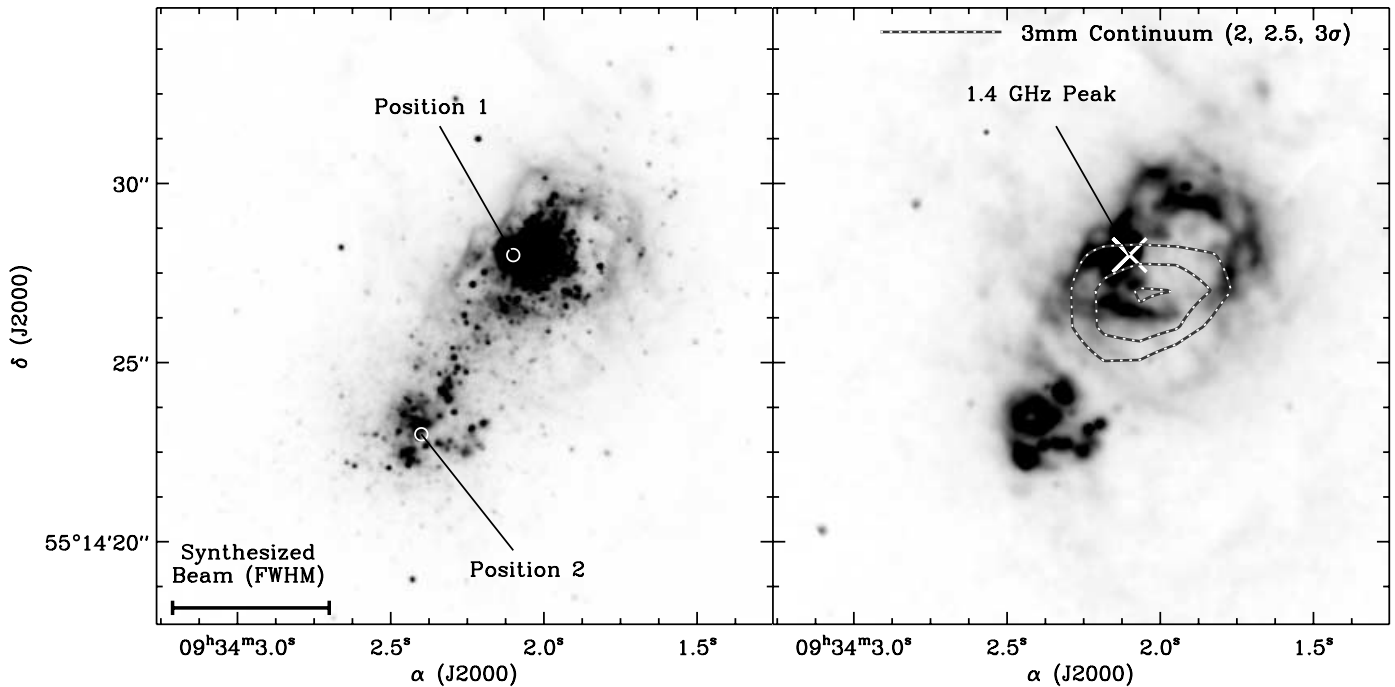


FIG. 2.—Plot of V -band (left) and $H\alpha$ (right; Cannon et al. 2002) images of I Zw 18. Overlays on the left image show the size of the synthesized beam and the locations of the spectra shown in Fig. 1. Contours on the right image show continuum emission in increments of 0.5σ significance and the location of the radio continuum peak. The primary beam is larger than the area shown. Both optical maps are on linear stretches; V -band data are obtained from MAST (Multimission Archive at STScI), originally observed for GO program 9400; PI: T. Thuan).

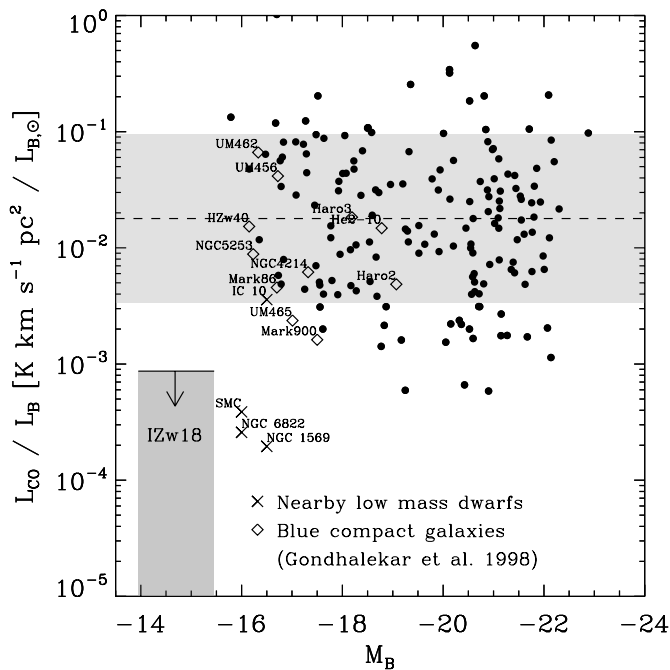


FIG. 3.—Plot of CO luminosity normalized by absolute blue magnitude for galaxies with Hubble type Sb or later (circles; Young et al. 1995; Elf Hag et al. 1996; Böker et al. 2003; Leroy et al. 2005). We also plot nearby dwarfs from Table 1 (crosses) and blue compact galaxies compiled by Gondhalekar et al. (1998; diamonds). The dark shaded region shows our upper limit for I Zw 18, with the range in M_B for distances from 10 to 20 Mpc. The dashed line and light shaded region show the median value and 1σ scatter in L_{CO}/L_B for spirals and dwarf starbursts. *Methodology:* We extrapolate from I_{CO} in central pointings to L_{CO} assuming the CO to have an exponential profile with scale length $0.1 d_{25}$ (Young et al. 1995), including only galaxies where the central pointing measures $>20\%$ of L_{CO} . We adopt B magnitudes (corrected for internal and Galactic extinction), distances (Tully-Fisher when available, otherwise Virgocentric flow corrected Hubble flow), and radii from LEDA (Lyon-Meudon Extragalactic Database; Paturel et al. 2003).

Sd-Irr galaxies, which implies $L_{CO, I Zw 18} \sim 4 \times 10^6 \text{ K km s}^{-1} \text{ pc}^2$. Murgia et al. (2005) measured $F_{CO}/F_{1.4} \approx 10 \text{ Jy km s}^{-1} (\text{mJy})^{-1}$ for spirals, which would imply $L_{CO, I Zw 18} \sim 10^7 \text{ K km s}^{-1}$. For Sd/Sm galaxies, $M_{H_2}/M_{H_1} \approx 0.2$ (Young & Scoville 1991), leading to $L_{CO, I Zw 18} \sim 5 \times 10^6 \text{ K km s}^{-1} \text{ pc}^2$. Both $M_{H_2}/L_{H\alpha}$ and M_{H_2}/M_{H_1} tend to be even higher in earlier type spirals.

Therefore, surveys would predict $L_{CO, I Zw 18} \gtrsim 2 \times 10^6 \text{ K km s}^{-1} \text{ pc}^2$, very close to the previously established upper limits of $(2-3) \times 10^6 \text{ K km s}^{-1} \text{ pc}^2$ (Arnault et al. 1988; Gondhalekar et al. 1998). With the present observations, we constrain $L_{CO} < 1 \times 10^5 \text{ K km s}^{-1} \text{ pc}^2$ and thus clearly rule out $L_{CO} \sim 10^6 \text{ K km s}^{-1} \text{ pc}^2$. This may be seen in Figure 3; even if I Zw 18 has the highest possible CO content, it will still have a lower L_{CO}/L_B than 97% of the survey galaxies.

4.3. Comparison with nearby Metal-poor Dwarfs

The subset of irregular galaxies detected by CO surveys tend to be CO-rich and actively star-forming, resembling scaled-down versions of spiral galaxies (Young et al. 1995, 1996; Leroy et al. 2005). Such galaxies may not be representative of all dwarfs. Because they are nearby, several of the closest dwarf irregulars have been detected despite very small L_{CO} . With their low masses and metallicities, they may represent good points of comparison for I Zw 18. Table 1 and Figure 3 show CO luminosities and L_{CO}/L_B for four nearby dwarfs: NGC 1569, the Small Magellanic Cloud (SMC), NGC 6822, and IC 10. The SMC, NGC 1569, and NGC 6822 have $L_{CO} \sim 10^5 \text{ K km s}^{-1} \text{ pc}^2$, close to our upper limit, and occupy a region of L_{CO}/L_B - L_B parameter space similar to I Zw 18. All four of these galaxies have active star formation but very low CO content relative to their other properties.

We test whether our observations would have detected CO in NGC 1569, the SMC, and IC 10 at the plausible lower limit of 10 Mpc (from $H_0 = 72 \text{ km s}^{-1}$) or our adopted distance of 14 Mpc. We convolve the integrated intensity maps to resolutions

TABLE 1
CO IN NEARBY LOW-MASS GALAXIES

Galaxy (1)	M_B (mag) (2)	L_{CO} (K km s ⁻¹ pc ²) (3)	$I_{CO, 210}^a$ (K km s ⁻¹) (4)	$I_{CO, 300}^a$ (K km s ⁻¹) (5)	Reference (6)
NGC 1569.....	-16.5	1.2×10^5	1.1	0.8	Greve et al. (1996)
	-16.5	0.2×10^5	0.8	0.5	Taylor et al. (1999)
SMC.....	-16	1.5×10^5	0.5	0.4	Mizuno et al. (2001); N. Mizuno et al. (2007, in preparation)
NGC 6822.....	-16	1.2×10^5	Israel (1997b)
IC 10.....	-16.5	2.2×10^6	3.8	2.2	Leroy et al. (2006)
I Zw 18.....	-14.7	$<2 \times 10^6$	Arnault et al. (1988); Gondhalekar et al. (1998)
	-14.7	$\leq 1 \times 10^5$	<1	<1	This paper

^a Peak integrated intensity at 210 and 300 pc, corresponding to our beam size at 10 and 14 Mpc, respectively.

of 210 and 300 pc and measure the peak integrated intensity. The results appear in columns (4) and (5) of Table 1. The PdBI observations of NGC 1569 resolve out most of the flux, so we also apply this test to a distribution with the size and luminosity derived by Greve et al. (1996) from single-dish observations. Our observations would detect an analog to IC 10 but not the SMC, with NGC 1569 as an intermediate case. With a factor of ~ 3 better sensitivity (requiring ~ 10 times more observing time) we would expect to detect all three nearby galaxies. However, achieving such sensitivity with present instrumentation will be quite challenging. The Atacama Large Millimeter Array (ALMA) will likely be necessary to place stronger constraints on CO in galaxies like I Zw 18.

IC 10 may be the nearest blue compact dwarf (BCD; Richer et al. 2001), so it may be telling that we would detect it at the distance of I Zw 18. The blue compact galaxies that have been detected in CO have L_{CO}/L_B similar to IC 10 (Gondhalekar et al. 1998; diamonds in Fig. 3). Most searches for CO toward BCDs have yielded nondetections, so those detected may not be representative, but I Zw 18 is clearly not among the “CO-rich” portion of the BCD population.

4.4. Interpretation of the Continuum

We measure continuum intensity of $F_{115 \text{ GHz}} = 1.06 \pm 0.35$ mJy toward the radio continuum peak. The continuum is detected along only one line of sight, so we refer to it here as a point source and compare it to integrated values for I Zw 18; $F_{115 \text{ GHz}}$ is expected to be the product of mainly two types of emission: thermal free-free emission and thermal dust emission. At long wavelengths, the integrated thermal free-free emission is $F_{1.4 \text{ GHz}}(\text{free-free}) \approx 0.52\text{--}0.75$ mJy (Cannon et al. 2005; Hunt et al. 2005b), implying $F_{115 \text{ GHz}}(\text{free-free}) = 0.36\text{--}0.51$ mJy at 115 GHz ($F_\nu \propto \nu^{-0.1}$). The H α flux predicts a similar value, $F_{115 \text{ GHz}}(\text{free-free}) = 0.34$ mJy (Cannon et al. 2005; their eq. [1]). Hunt et al. (2005a) placed an upper limit of $F_\nu(850) < 2.5$ mJy on dust continuum emission at 850 μm ; this is consistent with the $\sim 5 \times 10^3 M_\odot$ estimated by Cannon et al. (2002) given almost any reasonable dust properties. Extrapolating this to 2.6 mm assuming a pure blackbody spectrum, the shallowest plausible spectral energy distribution, constrains thermal emission from dust to be < 0.25 mJy at 115 GHz. Based on these data, we would predict $F_{115 \text{ GHz}} \lesssim 0.75$ mJy. Thus, our measured $F_{115 \text{ GHz}}$ is consistent with, but somewhat higher than, the thermal free-free plus dust emission expected based on optical, centimeter, and submillimeter data.

4.5. Relation to Star Formation

I Zw 18 has a star formation rate (SFR) $\sim 0.06\text{--}0.1 M_\odot \text{ yr}^{-1}$, based on H α and centimeter radio continuum measurements

(Cannon et al. 2002; Kennicutt 1998a; Hunt et al. 2005b). Our continuum flux suggests a slightly higher value, $\approx 0.15\text{--}0.2 M_\odot \text{ yr}^{-1}$ (following Hunt et al. 2005b; Condon 1992), with the exact value depending on the contribution from thermal dust emission. For any value in this range, the SFR per CO luminosity, SFR/L_{CO} , is much higher in I Zw 18 than in spirals. For comparison, our upper limit and the molecular “Schmidt Law” derived by Murgia et al. (2002) predict a $\text{SFR} \lesssim 2 \times 10^{-4} M_\odot \text{ yr}^{-1}$. Fits by Young et al. (1996) and Kennicutt (1998b) applied to just the molecular limit yield similar values. Again, I Zw 18 is similar to the SMC and NGC 6822, which have SFRs of 0.05 and 0.04 $M_\odot \text{ yr}^{-1}$ (Wilke et al. 2004; Israel 1997b) and $L_{CO} \sim 10^5 \text{ K km s}^{-1} \text{ pc}^2$.

4.6. Variations in X_{CO}

Several calibrations of the CO to H₂ conversion factor, X_{CO} , as a function of metallicity exist in the literature. The topic has been controversial, and these calibrations range from little or no dependence (e.g., Walter 2003; Rosolowsky et al. 2003) to very steep dependence (e.g., $X_{CO} \propto Z^{-2.7}$; Israel 1997a). Comparing the SFR to our CO upper limit, we may rule out that I Zw 18 has a Galactic X_{CO} unless molecular gas in I Zw 18 forms stars much more efficiently than in the Galaxy. Either the ratio of CO to H₂ is low in I Zw 18, or molecular gas in this galaxy forms stars with an efficiency 2 orders of magnitude higher than that in spiral galaxies.

5. CONCLUSIONS

We present new, sensitive observations of the metal-poor dwarf galaxy I Zw 18 at 3 mm using the Plateau de Bure Interferometer. These data constrain the integrated CO $J = 1 \rightarrow 0$ intensity to be $I_{CO} < 1 \text{ K km s}^{-1}$ over our 300 pc (FWHM) beam and the luminosity to be $L_{CO} < 1 \times 10^5 \text{ K km s}^{-1} \text{ pc}^2$.

I Zw 18 has less CO relative to its B -band luminosity, H I mass, or SFR than spiral galaxies or dwarf starbursts, including more metal-rich blue compact galaxies such as IC 10 ($Z_{IC 10} \sim Z_\odot/4$; Lee et al. 2003). Because of its small size and large distance, these are the first observations to impose this constraint.

We show that I Zw 18 should be grouped with several local analogs—NGC 1569, the SMC, and NGC 6822—as a galaxy with active star formation but a very low CO content relative to its other properties. In these galaxies, observations suggest that the environment affects the molecular gas, and these data suggest that the same is true in I Zw 18. A simple comparison of SFR to CO content shows that this must be true at a basic level: either the ratio of CO to H₂ is dramatically low in I Zw 18, or molecular gas in this galaxy forms stars with an efficiency 2 orders of magnitude higher than that in spiral galaxies.

We detect 3 mm continuum with $F_{115\text{ GHz}} = 1.06 \pm 0.35$ mJy coincident with the radio peak identified by Cannon et al. (2005) and Hunt et al. (2005b). This flux is consistent with, but somewhat higher than, the thermal free-free plus dust emission one would predict based on centimeter, submillimeter, and optical measurements.

Finally, we note that improving on this limit with current instrumentation will be quite challenging. The order-of-magnitude

increase in sensitivity from ALMA will be needed to place stronger constraints on CO in galaxies like I Zw 18.

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