DUST-TO-GAS RATIO IN THE EXTREMELY METAL-POOR GALAXY I Zw 18

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ABSTRACT

The blue compact dwarf galaxy I Zw 18 is one of the most metal-poor systems known in the local universe (12+log(O/H) = 7.17). In this work we study I Zw 18 using data from Spitzer, Herschel Space Telescope, and IRAM Plateau de Bure Interferometer. Our data set includes the most sensitive maps of I Zw 18, to date, in both the far-infrared and the CO J = 1 → 0 transition. We use dust emission models to derive a dust mass upper limit of only M_{dust} < 1.1 \times 10^4 M_\odot (3\sigma limit). This upper limit is driven by the non-detection at 160 \mu m, and it is a factor of 4–10 times smaller than previous estimates (depending on the model used). We also estimate an upper limit to the total dust-to-gas mass ratio of M_{dust}/M_{gas} < 5.0 \times 10^{-5}. If a linear correlation between the dust-to-gas mass ratio and metallicity (measured as O/H) were to hold, we would expect a ratio of 3.9 \times 10^{-4}. We also show that the infrared spectral energy distribution is similar to that of starbursting systems.

Key words: galaxies: dwarf – galaxies: individual (I Zw 18) – galaxies: ISM

Online-only material: color figure

1. INTRODUCTION

The link between dust-to-gas mass ratio (DGR) and heavy-element abundance (metallicity) in galaxies remains an open issue (e.g., Lisesen & Ferrara 1998; Edmunds 2001; Hunt et al. 2005). Specifically, in very low metallicity systems (12+log(O/H) ≲ 8) it is unclear how the DGR scales with metallicity. Models considering dust destruction by supernovae (Hirashita et al. 2002) or mass outflows from the galaxy (Lisenfeld & Ferrara 1998) predict a nonlinear relation. On the other hand, if the fraction of metals incorporated in the dust is constant (James et al. 2002), we expect a linear relation between DGR and metallicity, in a sense that the ratio decreases as metallicity decreases. Measurements of DGRs over a range of metallicity are necessary to better constrain this relationship.

The blue compact dwarf galaxy I Zw 18 has one of the lowest nebular metallicities measured to date. Skillman & Kennicutt (1993) measure an oxygen abundance of 12+log(O/H) = 7.17. This is 3.2% of the solar abundance (using the scale of Asplund et al. 2009). Most local universe galaxies have 12+log(O/H) ∼ 8.5 (e.g., Moustakas et al. 2010, for SINGS), and the Milky Way has 12+log(O/H) ∼ 8.7 (Baumgartner & Mushotzky 2006). I Zw 18 therefore represents the extreme low end of the metallicity range in the local universe and is thus a key datum for understanding the relationship between DGR and metallicity.

The dust mass of I Zw 18 is poorly known. Typical galaxies of similar morphology (blue compact dwarfs) have dust masses that range between 10^6 and 10^7 M_\odot, with DGR ranging between 10^{-3} and 10^{-5} (Lisenfeld & Ferrara 1998). Using Ha/H\beta flux ratios as a dust tracer, Cannon et al. (2002) find a total dust mass for I Zw 18 of (7–10) \times 10^5 M_\odot by assuming a linear scaling between DGR and metallicity (as measured by O/H).

Engelbracht et al. (2008), using Spitzer data limited by a non-detection at 160 \mu m, measure an upper limit for the dust mass of 4.2 \times 10^5 M_\odot. A more recent study of a large sample by Galametz et al. (2011) uses previously published Spitzer and SCUBA data to constrain the dust mass of I Zw 18 to be ≲ 1.1 \times 10^5 M_\odot and the DGR to ≲ 4.5 \times 10^{-4}.

I Zw 18 contains intense radiation fields stemming from active star formation. It therefore provides a nearby testing ground to probe the physics of distant primeval sources. Previous studies using Spitzer (Engelbracht et al. 2008; Wu et al. 2007) show that its continuum emission from 15 to 70 \mu m has a slope characteristic of a starburst galaxy of solar abundance. Moreover, its mid-infrared spectrum from 5 to 36 \mu m shows no detectable emission from polycyclic aromatic hydrocarbons (PAHs). Such low abundance of PAHs is likely the consequence of a high radiation field in combination with the low metallicity of the source.

In this paper we estimate the DGR for I Zw 18. We use previously unpublished Spitzer Space Telescope and archival Herschel Space Observatory9 continuum observations, combined with dust emission models and a gas mass (van Zee et al. 1998) to constrain the radiation field intensity, temperature, dust mass, and DGR in I Zw 18. Throughout this paper we assume a distance of 18.2 Mpc (Alonso et al. 2007). Revisions to this distance will affect our dust and gas masses, but not the DGR.

2. METHODS

2.1. Observations

We use a variety of data from several different facilities to map the far-infrared, sub millimeter, millimeter, and radio wave

9 Herschel is an ESA space observatory with science instruments provided by European-led Principal Investigator consortia and with important participation from NASA.
emission of I Zw 18. Therefore, our data set uses the following observatories and instruments: Spitzer Multiband Imaging Spectrometer (MIPS; Rieke et al. 2004), Herschel Photodetector Array Camera and Spectrometer (PACS; Poglitsch et al. 2010), Herschel Spectral and Photometric Imaging Receiver (SPIRE; Griffin et al. 2010), IRAM Plateau de Bure Interferometer (PdBI), and Very Large Array (VLA). In this section we will briefly describe new observations.

Spitzer: We observed I Zw 18 at 70 and 160 μm using MIPS in photometry mode as part of a cycle 5 proposal (PI: A. Bolatto; AOR: 22369536). The total observation time was 8 hours. The reduction of these images very closely follows the procedure described in Gordon et al. (2007) and Stansberry et al. (2007) for the 70 and 160 μm maps, respectively.

Herschel/PACS: We use archival 70 and 160 μm observations from Herschel. The observations were taken with PACS using the Large Scan Map mode as part of the Herschel Guaranteed Time Key Program, Dwarf Galaxy Survey (PI: S. Madden; ObsID: 1342187135/36). The scan maps were taken at 90° angles from one another at the medium scan speed (200 s−1) and then combined together in order to reduce the noise caused by streaking along the scan direction. The scan leg length is 40′, and the total on-source time for the combined images was 192 s.

Unlike Spitzer data, the methods to reduce PACS data are still evolving significantly. Therefore, we reduce the data in two separate ways. We first use Herschel Interactive Processing Environment (HIPE) v4.2 with the standard pipeline scripts. We also process the data up to level 1 in HIPE v7. We use the standard pipeline, which includes pixel flagging, flux density conversion, and sky coordinate association for each pixel of the detector. At this stage, the PACS timelines are still affected by 1/f noise and baseline drifts. In order to subtract the baseline, remove glitches, and project the timelines on the final map, we applied the scanamorphos algorithm (H. Roussel 2012, in preparation) to the level-1 PACS timelines.

Herschel/SPIRE: We use archival Herschel Spectral and Photometric Imaging Receiver (SPIRE; Griffin et al. 2010) photometric observations at 250, 350, and 500 μm. Observations were made in the large map mode with the nominal scan speed of 30 arcsec s−1 and the cross-scanning method as part of Herschel Science Demonstration Phase (PI: S. Madden; ObsID: 1342188663). Data reprocesing was carried out in HIPE using the standard large map pipeline with the latest SPIRE calibration tree available, which includes deglitching. We also applied the scanamorphos algorithm (H. Roussel 2012, in preparation) to the level-1 SPIRE timelines.

SPIRE/PdBI: We present new observations of the CO J = 1 → 0 transition in I Zw 18 using the IRAM Plateau de Bure Interferometer as project t027 (PI: A. Leroy). The data were observed on 2009 September 24, 27, and 28 using the “5Dq” configuration, meaning that five telescopes were operational and that the array was in a compact configuration. These data are calibrated in the standard way in 2009 December using the PdBI pipeline implemented in the CLIC and MAPPING packages of GILDAS. The effective time on-source was 12.5 hr after flagging during the pipeline run. The effective bandwidth was ~850 MHz, or about 2200 km s−1 with native resolution ~2.5 MHz (6.5 km s−1). We do not detect CO emission. At 26 km s−1 velocity resolution we achieved an rms noise of 1.26 mJy beam−1, implying a 4σ flux upper limit for a point source of 0.131 Jy km s−1.

VLA: The observations used to construct the H1 map are described in van Zee et al. (1998). We obtained two hours of Rapid Response 21 cm VLA observations (project 08B-246; PI: A. Bolatto) to evaluate the Galactic foreground contribution. This contribution can be estimated by measuring the H1 column density toward I Zw 18 and converting it to dust emission using typical high-latitude Galactic ratios (e.g., Boulanger et al. 1996). The observations were obtained during the move between CN2 and D configuration with a synthesized beam size of 67″ × 41″ and a native resolution of 6.1 kHz (1.3 km s−1). The data were reduced in AIPS using the standard procedure and calibrations, and care was taken to remove the baselines affected by the frequency aliasing problems due to the VLA–JVL transition. At 10.3 km s−1 velocity resolution we achieved an rms noise of 0.1 mJy beam−1, implying an H1 column density of NH1 = 2.4 × 1018 cm−2. Galactic neutral hydrogen emission was observed in the central 30 km s−1 of the passband. Nonetheless, even after spatially filtering the 160 μm MIPS map to approximately match the uv coverage of the VLA, the correlation between the high-resolution H1 column density and the 160 μm surface brightness remained extremely low (Figure 2), showing that most of the emission present in the 160 and 250 μm images is not due to the high-latitude Galactic foreground.

2.2. Photometry

In Figure 1 we present the Spitzer MIPS 70 and 160 μm maps and the Herschel PACS 160 μm image for I Zw 18. Overlaid on each image is the H1 column density distribution observed by van Zee et al. (1998). The H1 contours correspond to 0.7, 1.4, and 5 × 1020 cm−2 enclosing 98%, 96%, and 78% of the total flux at 70 μm. We use the MIPS 70 μm map over the PACS 70 μm because it has a much better surface brightness sensitivity (0.17 versus 2.87 mJy sr−1), yielding a better signal-to-noise ratio. The bulk of the 70 μm emission coincides with the H1 column density maximum. This peak also coincides with the location of active star-forming regions observed by Cannon et al. (2002) using the Hubble Space Telescope (HST). The diffuse component at 70 μm extends preferentially ~3 kpc northwest from the peak. We subtract the background emission measured in a region free of sources. We integrate the flux using a circular aperture with radius of 45″ centered at the peak of the 70 μm emission and applying an aperture correction factor of 1.13 (determined by integrating over the point-spread function and compatible with those in the MIPS Instrument Handbook). The calibration error on Spitzer is about 5% at 70 μm. We estimate a photometry error of 1.7 mJy by adding in quadrature the calibration uncertainty and the background noise. We measure a total flux density of 33.6 ± 1.7 mJy at 70 μm. Our flux value is consistent with the 70 μm flux measured by Engelbracht et al. (2008) of 34.9 ± 4.79 mJy.

The Spitzer 160 μm map is confusion limited. The bulk of the emission is associated with sources outside the H1 emitting region of I Zw 18. Although the Galactic latitude of I Zw 18 is ~44°, it is possible that Galactic cirrus could be a significant source of confusion. We use the VLA H1 observations to explore this possibility. Figure 2 shows the MIPS 160 μm and the SPIRE 250 μm map of a ~5 × 5 arcmin field around I Zw 18. The thick lines represent the H1 foreground emission from VLA.
Figure 1. Left two panels show the Spitzer images of I Zw 18 at 70 and 160 μm. The right panel shows the Herschel PACS image at 160 μm. Overlaid as black contours is the H1 column density distribution from van Zee et al. (1998) using the VLA. The contours are 0.7, 1.4, and 5 × 10^20 cm^-2. The black circle in the bottom right corner of each panel corresponds to the respective beam size of the FIR observations. The smaller circle in the first panel corresponds to the beam size of the H1 observations. At 70 μm, the bulk of the emission coincides with the H1 contours and the diffuse emission extends preferentially toward the NW. I Zw 18 is undetected in both 160 μm maps.

(A color version of this figure is available in the online journal.)

Figure 2. Spitzer 160 μm (left) and Herschel 250 μm (right) maps of a ~5 × 5 arcmin field around I Zw 18. The thick black contours show the VLA observations of the Galactic H1 foreground emission at 2σ, 4σ, and 6σ significance level. The thin black contours are the same as shown in Figure 1. The VLA beam size is θ = 67′′ × 41′′ and is shown in the corner of the left panel. The SPIRE 250 μm beam is shown in the right panel. The bulk of the 160 μm emission, located southeast of our object, fragments into at least three point sources in the 250 μm map, which has finer spatial resolution. There is no correlation between the far-infrared and the Galactic H1 foreground emission, suggesting that the confusion is dominated by background galaxies.

The thin lines represent the H1 emission of I Zw 18. It is clear from visual inspection that the maxima of the H1 foreground and the 160 and 250 μm emission are not coincident. We find a Pearson correlation coefficient close to zero. In most of the Spitzer confusion-limited images at 160 μm the confusion is mainly due to faint unresolved background sources (Dole et al. 2004). The bulk of the 160 μm emission, located southeast of our object, fragments into at least three point sources in the 250 μm map, which has finer spatial resolution. The 160 μm peak also coincides with several background galaxies in deep B- and R-band images (S. Janowiecki 2009, private communication). The difference between the 160 and 250 μm maps is consistent with what one would observe if the peak of the emission at 160 μm is associated with background galaxies.
The background contamination and the absence of correlation between the 160/250 μm emission and the H1 foreground emission make it impossible to recover the flux associated with I Zw 18. Thus, we use an annular sector around the galaxy to measure a 1σ surface brightness sensitivity of 0.18 mJy sr⁻¹ that includes the effects of confusion. We estimate the flux upper limit multiplying this value by the area associated with the \( 1.4 \times 10^{20} \text{atom cm}^{-2} \) H1 contour that encloses 96% of the 70 μm flux and 62% of the H1 mass. To find the aperture correction factor associated with this area, we can approximate the contour using a circular aperture of 48″ radius. This corresponds to an aperture correction factor of 1.6 at 160 μm. After applying the aperture correction factor, we obtain a corresponding 3σ flux upper limit of 40.5 mJy. This new upper limit is a factor of ~2 lower than the previous upper limit published by Engelbracht et al. (2008).

The Herschel PACS image at 160 μm also fails to detect I Zw 18. In this case, however, the image is not confusion limited. The 1σ surface brightness sensitivity is 1.8 mJy sr⁻¹. If we assume that the emission from I Zw 18 is compact on 12″ scales, the corresponding 3σ flux upper limit integrating over the 12″ beam and applying an aperture correction factor of 1.32 is 27.2 mJy.

We will work with the PACS 160 μm flux upper limit of 27.2 mJy for the rest of the paper. However, the upper limit measured from the PACS data relies on the assumption that the source is compact. If the 160 μm emission is significantly extended over scales larger than 12″ (~1 kpc), it may be more appropriate to use the MIPS 160 μm upper limit of 40.5 mJy.

Finally, the SPIRE maps at 250, 350 and 500 μm show no detection of I Zw 18. From these images we measure a surface brightness sensitivity using an annular sector around the source. We then apply aperture corrections and point-source color corrections assuming \( \beta = 1.5 \) (\( \beta \) in \( f_\lambda \propto \nu^{\beta} \)) described in the SPIRE Photometry Cookbook.\(^{11}\) We measure 3σ flux upper limits of 22.2, 23.9, and 25.4 mJy at 250, 350, and 500 μm, respectively.

3. RESULTS

3.1. Dust Mass

We use two methods to estimate the dust mass of I Zw 18. In the first, we follow the procedure outlined by Hildebrand (1983), assuming an idealized graybody source with a single temperature. In the second, we use the Draine & Li (2007, hereafter DL07) model. The main difference between the DL07 model and the idealized graybody is that DL07 assume a grain size distribution that reproduces the observed wavelength-dependence extinction in the Milky Way and consequently a distribution of temperatures. Given the extreme nature of I Zw 18, it is not clear that either model is exactly applicable. Nonetheless, we used them so we can make a consistent comparison to larger samples of galaxies.

3.1.1. Modified Blackbody Model

For an idealized cloud, the dust mass is estimated by fitting its far-infrared spectrum as the product of a blackbody spectrum \((B_{\lambda,T})\) and a mass absorption coefficient \((\kappa_\lambda)\). The absorption coefficient varies with wavelength as the negative power of the grain emissivity index \((\kappa_\lambda \propto \lambda^{-\beta})\), where \(\beta\) represents the emissivity index. Then, for a cloud that is optically thick to starlight and optically thin to far-infrared emission, the dust mass \(M_{\text{Dust}}\) is given by the following expression:

\[
M_{\text{Dust}} = \frac{F_\lambda D^2}{\kappa_\lambda B_{\lambda,T}}
\]

where \(D\) is the distance to the galaxy, \(F_\lambda\) is the observed flux, and \(B_{\lambda,T}\) is the blackbody intensity. The flux at any point on a graybody spectrum is \(F_\lambda \propto B_{\lambda,T} \lambda^{-\beta}\), with \(\beta\) independent of wavelength. Therefore, we can solve for the color temperature \((T_{70/160})\) using the ratio \(F_{70}/F_{160}\).

Measured values for \(\kappa_\lambda\) at 250 μm (\(\kappa_{250}\)) span the range \(\approx 5–15 \text{ cm}^2 \text{ g}^{-1}\) (Alton et al. 2004), and commonly used values for \(\beta\) are 1–2 depending on the environment. For this work we adopt \(\kappa_{250} = 9.5 \text{ cm}^2 \text{ g}^{-1}\) and \(\beta = 1.5\); these are commonly used values for low-metallicity galaxies (e.g., Leroy et al. 2007a). Using \(\beta = 1\) or 2 changes our dust mass limits by ~10%.

Figure 3 shows the spectral energy distribution (SED) of I Zw 18. The source is only detected at 70 μm. At longer wavelengths each point corresponds to a 3σ flux upper limit. Among these limits, the 160 μm upper limit represents the strongest constraint on the I Zw 18 SED. Thus, based on the 70 and 160 μm emission, the modified blackbody spectrum model constrains the dust temperature to be \(T_{70/160} > 33.7 \text{ K}\). This translates into a predicted 850 μm flux of 0.28 mJy, compatible with the observed upper limit of 1.25 mJy (Galametz et al. 2011).

Combining our temperature lower limit with the 70 μm flux, Equation (1) yields a dust mass of \(M_{\text{Dust}} \approx 3.2 \times 10^3 M_{\odot}\). If we use the MIPS 160 μm upper limit instead of the PACS upper limit, we measure a temperature limit \(T_{70/160} > 29.8 \text{ K}\) and a dust mass a factor of ~2 higher, i.e., \(M_{\text{Dust}} < 6.9 \times 10^3 M_{\odot}\).

3.1.2. Draine and Li Model

For a detailed description we refer to DL07 and Draine et al. (2007). Essentially, DL07 models characterize the dust as a mixture of carbonaceous and amorphous silicate grains with size distributions chosen to match the observed extinction in the Milky Way. To characterize the intensity of the radiation that is heating the dust, the model adopts the spectrum of

\[^{11}\text{Bendo & The SPIRE-ICC (2011), http://herschel.esac.esa.int/twiki/pub/Public/SpireCalibrationWeb/SPIREPhotometryCookbook_jul2011_2.pdf.}\]
the local interstellar radiation field (this may not be a good approximation for I Zw 18, a starburst system characterized by high-intensity radiation fields and low metallicity). In DL07, most dust is heated by the interstellar radiation field, and a small fraction is heated by stronger radiation fields associated with star formation.

We caution the reader that estimating dust masses based on broadband infrared fluxes, as we do here, is a poorly constrained technique; there are very few data points compared to the number of parameters in the model. The DL07 model uses five parameters to characterize the emission from dust in galaxies: \( M_{\text{Dust}}, U_{\text{min}}, U_{\text{max}}, \gamma, \) and \( \alpha \). The dust mass is represented by \( M_{\text{Dust}} \), and \( U_{\text{min}} \) represents the interstellar radiation field heating the diffuse interstellar medium (ISM), and \( U_{\text{max}} \) represents the upper limit on the interstellar radiation field. The starlight heating the dust is described using the dimensionless parameter \( U \), which by definition is always between \( U_{\text{min}} \) and \( U_{\text{max}} \). The value \( U = 1 \) is the local interstellar radiation in the Milky Way. The parameter \( \gamma \) represents the fraction of gas that is exposed to strong radiation fields with intensities in the range \( U_{\text{min}} < U < U_{\text{max}} \). Finally, \( \alpha \) characterizes the distribution of starlight intensities. In practice, we fix two of these parameters, \( \alpha \) and \( U_{\text{max}} \). We adopt the values set by Draine & Li (2007) of \( U_{\text{max}} = 10^6 \) and \( \alpha = 2 \). Therefore, three parameters are free in the model (\( M_{\text{Dust}}, U_{\text{min}}, \) and \( \gamma \)). We remind the reader that we constrain this model with only four broadband fluxes, at 8, 24, 70, and 160 \( \mu \)m. We can also use the returned values of these parameters to calculate a temperature for the majority of the dust grains \( (T_{\text{min}}) \), the fraction of dust luminosity that originates in photon-dominated regions \( (f_{\text{PDR}}) \), and the dust-weighted mean starlight intensity \( \langle U \rangle \).

Muñoz-Mateos et al. (2009) derived empirical fits relating a grid of DL07 emission model outputs to the Spitzer fluxes. In particular, the DL07 parameters \( M_{\text{Dust}}, \gamma, \) and \( f_{\text{PDR}} \) can all be derived using measurements at 8, 24, 70, and 160 \( \mu \)m. We can calculate \( U_{\text{min}} \) using \( \langle U \rangle \) and \( \gamma \) according to Equation (33) in DL07. For the I Zw 18 fluxes at 8 and 24 \( \mu \)m, we used the values measured by Engelbracht et al. (2008) of 0.47 and 6.28 mJy, respectively. The agreement between the dust mass derived using the empirical fits and DL07 models is very good, with a scatter of about 9% and an offset of +5%. The DL07 dust masses are strongly dependent on \( R_{70} \equiv \langle \nu F_{\nu} \rangle_{70}/\langle \nu F_{\nu} \rangle_{160} \), with \( M_{\text{Dust}} \propto R_{70}^{1.8} \). \( R_{70} \) is sensitive to the temperature of the largest grains dominating the FIR emission, and any new constraint or detection at 160 \( \mu \)m will strongly affect the resulting dust mass. Essentially, the smaller the 160 \( \mu \)m flux, the hotter the temperature and thus the less dust is needed to produce the observed 70 \( \mu \)m emission.

The derived dust properties for I Zw 18 are summarized in Table 1. Median values for 48 SINGS galaxies analyzed by Draine et al. (2007) and three starburst systems out of the same sample are included for comparison. The lower limits obtained for \( U_{\text{min}}, \langle U \rangle, \) and \( f_{\text{PDR}} \) in I Zw 18 are high compared to the mean values in the SINGS sample (Draine et al. 2007). The high radiation intensity environment of I Zw 18 is comparable to starbursting systems like Mrk 33, Tol 89, and NGC 3049, as also found by Wu et al. (2007). We find that the DL07 model yields a mass upper limit of \( M_{\text{Dust}} < 1.1 \times 10^4 M_\odot \). Just like the modified blackbody case, if we use the MIPS 160 \( \mu \)m upper limit instead of the PACS upper limit, we measure a dust mass a factor of \( \sim 2 \) higher, i.e., \( M_{\text{Dust}} < 2.6 \times 10^4 M_\odot \).

3.2. Comparison of Dust Masses

The DL07 dust mass upper limit is a factor of \( \sim 3.5 \) larger than the dust mass estimated using the modified blackbody model. The DL07 model treats dust emission as an ensemble of dust grains at different temperatures that includes larger masses of dust at colder temperatures than what is predicted by the single-temperature fit. Therefore, it is not surprising that this model generates a higher dust mass than the modified blackbody model. However, the fact that these two measurements are not extremely different increases our confidence in the dust mass limit, which we conservatively take to be that resulting from the DL07 model.

It is interesting to compare this result to other modeling efforts for I Zw 18 and low-metallicity galaxies. In particular, Galametz et al. (2011) determine dust masses in a large sample of galaxies with literature data, using full SED modeling based on the Zubko et al. (2004) grain model. They find that the inclusion of submillimeter-wave data tends to drive dusty galaxies toward lower dust masses, while for low-metallicity galaxies the inclusion of submillimeter-wave constraints yields higher dust mass predictions than those from far-infrared alone. By contrast, Draine et al. (2007) found their masses to be robust to the inclusion of submillimeter-wave data. This is in part driven by modeling choices, in particular the use of dust temperatures and the interpretation of submillimeter-wave data. This is in part driven by modeling choices, in particular the use of a minimum dust temperature and the interpretation of submillimeter-wave data.

3.3. Gas Mass

The total H\textsc{i} mass of I Zw 18 is \( M_{\text{H}_1} = 2.3 \times 10^8 M_\odot \) (van Zee et al. 1998). The molecular content of I Zw 18, however,
remains unknown since no CO emission has been detected. Our new upper limit on the CO J = 1 → 0 luminosity of I Zw 18 is \( L_{\text{CO}} \lesssim 10^5 \text{ K km s}^{-1} \text{ pc}^2 \) (4\( \sigma \)), which corresponds to \( M_{\text{H}_2} \lesssim 450,000 M_\odot \) for a standard conversion factor \( \alpha_{\text{CO}} = 4.5 M_\odot (\text{K km s}^{-1} \text{ pc}^2)^{-1} \). Note that our luminosity is similar to that quoted by Leroy et al. (2007b) because we adopt here a larger distance (for matched smoothing and assumptions we improve the sensitivity of that study by a factor of two). Using this Milky-Way-based conversion factor, \( M_{\text{H}_2} \) is at most 0.2\% of the total gas mass.

There is no reason to expect that the Milky-Way-based conversion factor between CO luminosity and \( \text{H}_2 \) mass applies to low-metallicity galaxies like I Zw 18. In the Local Group, \( \alpha_{\text{CO}} \) is a strong function of metallicity (Leroy et al. 2011). Genzel et al. (2012) derive a correlation between oxygen abundance and conversion factor, \( \alpha_{\text{CO}} \). Applying their formula to a galaxy with the metallicity of I Zw 18, we find a conversion factor \( \alpha_{\text{CO}} \approx 477.5 M_\odot (\text{K km s}^{-1} \text{ pc}^2)^{-1} \). This factor is \( \sim 100 \) times larger than \( \alpha_{\text{CO}} \) in a typical spiral galaxy. Using this conversion factor, we calculate a molecular gas mass upper limit of \( M_{\text{H}_2} \lesssim 4.8 \times 10^5 M_\odot \). This \( M_{\text{H}_2} \) is \( \sim 20\% \) of the total gas mass.

There is some evidence that, at low metallicities, the star formation activity may be a better indicator of the molecular mass than the CO emission (Krumholz et al. 2011; Bolatto et al. 2011; Schruba et al. 2011). The \( H\alpha \) flux of I Zw 18 suggests a recent star formation rate (SFR) of \( \sim 0.1 M_\odot \) yr\(^{-1}\). In large star-forming galaxies, a typical \( \text{H}_2\)-to-SFR ratio (\( \text{H}_2 \) depletion time) is \( \sim 1–2 \) Gyr (Bigiel et al. 2011). The \( \text{H}_2 \) mass corresponding to this amount of star formation in such a galaxy would thus be \( \sim 10^8 M_\odot \). Given the level at which star formation obviously dominates the morphology and ISM conditions in I Zw 18, we strongly suspect that this kind of equilibrium assumption very much overestimates the \( \text{H}_2 \), which will have been dissociated or otherwise destroyed by the recent burst. Nonetheless, even in this limit the \( \text{H}_2 \) only makes up \( \sim 30\% \) of the integrated gas mass. The similarity with the results obtained from applying the Genzel et al. (2012) correlation is not surprising, since the underlying assumption is the same. Because of its uncertainty, we do not include the \( \text{H}_2 \) correction in the following calculations.

### 3.4. Dust-to-Gas Mass Ratio and Metallicity

Draine et al. (2007) find that the DGR changes significantly depending on whether the dust mass is compared to the total gas mass or only the gas mass enclosed in the aperture where the infrared emission is measured. For example, for IC 2574 (a dwarf galaxy in the SINGS sample), only 19\% of the \( \text{H}_1 \) gas mass is enclosed in the area where the infrared emission is detected (Walter et al. 2007). We take the point of view that these are two valid definitions of the DGR: global, or local where the dust emission is detected. Using the total \( \text{H}_1 \) mass from van Zee et al. (1998), we measure an upper limit for the global DGR \( \lesssim 5 \times 10^{-5} \). Using instead the \( \text{H}_1 \) mass enclosed in the area were we measure the 160\( \mu \)m flux upper limit (62\% of the total \( \text{H}_1 \) mass) yields a local DGR \( \lesssim 8.1 \times 10^{-5} \).

Figure 4 shows the DGR as a function of oxygen abundance for I Zw 18 and a subsample of SINGS galaxies. Open symbols indicate 3\( \sigma \) upper limits. The solid line represents a linear scaling of the DGR with metallicity. This linear relation assumes that the abundances of all heavy elements are proportional to the oxygen abundance and that the same fraction of all heavy elements are in solid form as in the Milky Way (Draine et al. 2007). The I Zw 18 DGR upper limit is primarily driven by the upper limit in the dust mass, while in the SINGS galaxies the upper limits are due to lower limits in the gas mass (due to the non-inclusion of \( \text{H}_2 \)). As we discussed in Section 3.1, we obtain different dust masses for I Zw 18 depending on the assumption we make about the distribution of the 160\( \mu \)m emission (point-like with PACS and extended with MIPS). The
open star shows the DGR of I Zw 18 when we assume pointlike emission, while the upper limit of the bar shows the DGR when we assume extended emission. For the SINGS galaxies, the dust and gas masses are from Draine et al. (2007) and the metallicities are from Moustakas et al. (2010). Note that Draine et al. (2007) compute molecular gas masses assuming a fixed $X_{\text{CO}}$ factor of $4 \times 10^{20} \text{cm}^{-2} (\text{K km s}^{-1})^{-1}$ following Blitz et al. (2007). We show SINGS galaxies with and without measured SCUBA fluxes as triangles and circles, respectively, as Draine et al. (2007) find that the dust mass estimates with and without SCUBA data can differ by a factor of $\sim 2$.

The left panel of Figure 4 shows the global DGR, estimated using the total gas masses. The right panel shows how the DGR changes when estimating it locally in low-metallicity systems, including I Zw 18, by using the gas mass enclosed in the region where the infrared emission is detected. For SINGS galaxies with metallicities $12 + \log(O/H) \lesssim 8.1$, the total DGR seems to agree within a factor of $\sim 2$ with a linear relationship between DGR and metallicity. Low-metallicity galaxies do not seem to follow the same linear correlation that includes the Milky Way DGR. The I Zw 18 global DGR falls below the linear scaling by a factor of $\sim 8$. The right panel of Figure 4 shows the local DGR. The DGRs of the SINGS low-metallicity systems scale up and appear consistent with the linear relationship within a factor of $\sim 2$, although most of the low-metallicity points are only upper limits. For I Zw 18, however, the local DGR falls below the linear scaling by a factor of $\sim 5$. Therefore, our dust mass limits for I Zw 18 suggest a breakdown of the linear relationship between DGR and metallicity at very low metallicities. Note further that, at least in terms of the global DGR, I Zw 18 seems to continue the trend found for other low-metallicity galaxies.

We show in Figure 4 that only one of the seven SINGS galaxies with $12 + \log(O/H) \lesssim 8.1$ has a DGR that is not an upper limit. It may be possible that the local DGR of this system is higher than other low-metallicity galaxies and the trend is really steeper than linear, as our result for I Zw 18 and other studies suggest (Lisenfeld & Ferrara 1998; Muñoz-Mateos et al. 2009). Clearly more work is needed to determine, robustly, whether low-metallicity galaxies do or do not follow the linear scaling shown in Figure 4.

Note that the abundance of oxygen may not be the correct abundance to refer to. Indeed, the abundances of refractory elements that constitute the bulk of the dust such as carbon or silicon are likely more relevant to establishing the DGR. Garnett et al. (1999), for example, find a trend of increasing C/O with $O/H$ for a sample of irregular and spiral galaxies observed with HST. This could suggest that the nonlinear trend of DGR with metallicity is really an artifact of using O/H as a proxy for metallicity, and the relation could become more nearly linear when plotted against C/H. Garnett et al. (1999) find a gas-phase abundance of C in I Zw 18 that is significantly higher than that predicted by the extrapolation of the observed C/O versus $O/H$ trend in low-metallicity irregular galaxies. In fact, C/O in I Zw 18 is only 0.3 dex lower than solar. This is barely enough to reconcile our limits on the local DGR with a linear trend with C/H, and probably not enough to explain our low global DGR, but it certainly goes in the right direction.

4. CONCLUSIONS

In this work we study I Zw 18 using data from Spitzer, Herschel Space Telescope, and IRAM Plateau de Bure Interferometer. We reduce the flux upper limit at 160 $\mu$m by a factor of $\sim 3$ and the CO $J = 1 \rightarrow 0$ flux upper limit by a factor of $\sim 2$ compared to previous measurements. Combining these observations with the dust emission model from Draine & Li (2007), we constrain the dust mass to be $M_{\text{dust}} < 1.1 \times 10^4 M_\odot$. We note that any dust mass measurement relies on assumptions about the mass emissivity of dust grains in the ISM, with the important associated systematic uncertainties. We find a global dust-to-gas mass ratio of $M_{\text{dust}}/M_{\text{gas}} < 5.0 \times 10^{-5}$, while the ratio measured in regions where the 70 $\mu$m emission peaks is $M_{\text{dust}}/M_{\text{gas}} < 8.1 \times 10^{-5}$.

These measurements suggest that low-metallicity galaxies do not follow the same linear relationship between metallicity and DGR as typical local spirals. At face value our DGR upper limit is inconsistent with the hypothesis that the fraction of heavy elements incorporated into dust is the same in high-metallicity galaxies (such as the Milky Way) and in extremely low metallicity galaxies (such as I Zw 18). There are other scenarios, however, that can produce a break or nonlinear power-law relationship between DGR and metallicity. For instance, models that include more detailed physical processes such as the production and destruction of dust by supernovae, removal of dust through outflows from galaxies, and dust production in the envelopes of stars (e.g., Lisenfeld & Ferrara 1998; Edmunds 2001; Hirashita et al. 2002) may yield nonlinear relations. Much more work is needed with sensitive maps of low-metallicity galaxies, like I Zw 18, to better understand the relationship between DGR and metallicity.

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Facilities: Spitzer, Herschel, VLA, IRAM:Interferometer

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