DUST IN THE EXTREMELY METAL-POOR BLUE COMPACT DWARF GALAXY I Zw 18: THE SPITZER MID-INFRARED VIEW

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ABSTRACT

I Zw 18, a blue compact dwarf (BCD) galaxy with the second lowest metallicity measured in a star-forming object, has been observed with all three instruments on board the Spitzer Space Telescope. We present the deepest 5–36 μm mid-infrared (mid-IR) spectrum of this galaxy as yet obtained, as well as 3.6–70 μm imaging results. As with SBS 0335–052E, another BCD with similar metallicity, I Zw 18 shows no detectable emission from polycyclic aromatic hydrocarbons (PAHs). However, the continuum emission, from 15 to 70 μm, of I Zw 18 has a much steeper slope, more characteristic of a typical starburst galaxy of solar abundance. The neon abundance as measured from the infrared fine-structure lines is ~1/23 Z⊙, and the sulfur abundance is ~1/35 Z⊙, generally consistent with the nebular oxygen abundance of 1/30 Z⊙ derived from optical lines. This suggests that the extinction to the infrared-emitting regions of this galaxy is low, also in agreement with the optical Balmer line ratios.

Subject headings: dust, extinction — galaxies: dwarf — galaxies: individual (I Zw 18) — galaxies: starburst

1. INTRODUCTION

Low-metallicity galaxies may have been the first sites of star formation in the early universe (White & Rees 1978; Dekel & Silk 1986). Consequently, understanding their properties may provide valuable insights into the formation of the first generation of normal stars and the subsequent enrichment of the interstellar medium. However, finding truly primordial galaxies in the distant universe is beyond the reach of current technology. At high redshift, observational limitations introduce biases toward the detection of high-mass high-luminosity systems in which the short timescales of massive star formation lead to the identification of systems that are already chemically enriched (i.e., Maiolino et al. 2003). An alternative approach is to identify and study unevolved galaxies in the local universe. Such a sample is made up of the blue compact dwarf galaxies (see the review by Kunth & Östlin 2000).

Since its discovery by Zwicky (1966) and the seminal paper of Searle & Sargent (1972) I Zw 18 has been studied extensively at many wavelengths. With an oxygen abundance determined from the optical lines in H ii regions of 12 + log (O/H) = 7.17 (Skillman & Kennicutt 1993; Izotov & Thuan 1999), or ~1/30 Z⊙, it had remained the lowest metallicity BCD for over two decades, until the recent study of the western component of SBS 0335–052 (Izotov et al. 2005; Papaderos et al. 2006), which has slightly lower metallicity [12 + log (O/H) = 7.12]. Distance estimates to I Zw 18 range from ~10 Mpc (Hunter & Thronson 1995), ~12.6 Mpc (Östlin 2000), and up to ~15 Mpc (Izotov & Thuan 2004). Here we adopt a distance of 12.6 Mpc (1′′ ~ 61 pc). I Zw 18 consists of two bright knots of star formation, a northwest component and a southeast one, together they form the “main body” of the system. Both the northwest and southeast components contain numerous young star clusters, with ages ranging from 3 to 10 Myr, but the age of the underlying stellar population in I Zw 18 is still a matter of debate, with maximum ages ranging from 500 Myr to 5 Gyr (Aloisi et al. 1999; Östlin 2000; Recchi et al. 2002; Hunt et al. 2003; Izotov & Thuan 2004; Momany et al. 2005). Approximately 22′′ northwest of the main body there is a blue irregular low surface brightness star-forming region, called the “C component,” which is embedded in a common H i envelope (van Zee et al. 1998; Izotov & Thuan 2004). It is well known that some BCDs form stars at a rate that can only be maintained for ~1/3 of a Hubble time, given their store of available hydrogen. SBS 0335–052E, which has a similar metallicity [12 + log (O/H) = 7.31], is forming stars at a high rate in dense compact regions (Thuan et al. 1999; Plante & Sauvage 2002; Houck et al. 2004b). I Zw 18 is forming stars at a slower rate in complexes that are diffuse and extended (Hunt et al. 2005a). These differences have been attributed to different star formation modes. SBS 0335–052E is in an “active” mode with relatively high star formation rate (SFR) in compact dense regions, while in I Zw 18 star formation occurs in a “passive” mode in more extended regions with a relatively low SFR (Hirashta & Hunt 2004).

In this paper we present a detailed analysis of the infrared properties of the main body of I Zw 18 based on the current deepest mid-IR spectra for this galaxy, obtained using the infrared spectrograph (IRS; Houck et al. 2004a) on board the Spitzer Space Telescope (Werner et al. 2004). We also discuss the results of photometric observations with IRAC (Fazio et al. 2004) and MIPS (Rieke et al. 2004) observations. We describe the observation and data analysis in § 2. The Spitzer images and spectra are discussed in § 3, along with the observed morphologies and

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⁶ Izotov & Thuan (1999) give 1/30 Z⊙. Here we use the new oxygen solar abundance of 12 + log [O/H] = 8.69 (Allende Prieto et al. 2001), which results in a metallicity of 1/30 Z⊙.
⁷ We should note that recent results suggest that the distance to I Zw 18 may be as large as 19 ± 2 Mpc (Aloisi et al. 2007).
abundance estimates. A discussion of the SFR of I Zw 18 is given in \S 4, and we summarize our conclusions in \S 5.

2. OBSERVATIONS

2.1. Spitzer IRS Spectroscopy

I Zw 18 was observed as part of the IRS\textsuperscript{8} Guaranteed Time Observation program on 2004 March 27 using all four instrument modules. It was reobserved on 2005 April 23 with the short-low (SL) and long-low (LL) modules, with increased integration time to achieve a higher signal-to-noise ratio (S/N) over the 5–36 $\mu$m mid-IR continuum. A third even longer observation was made on 2005 December 16 with all four IRS modules. The target was acquired using the 22 $\mu$m (red) peak-up camera in high-accuracy mode, and the details of the observations are presented in Table 1.

The data were processed at the Spitzer Science Center (SSC) (pipeline vers. 14.0). The two-dimensional image data were converted to slope images after linearization correction, subtraction of darks, and cosmic-ray removal. Finally, the data were co-added.

In order to increase the S/N of the subtracted background for SL and LL, we combined the background observed in off-order and off-nod positions. A detailed explanation for this method on faint source extraction can be found in Weedman et al. (2006). After subtracting the background, the one-dimensional spectra were extracted from images with a script version of the Spectral Modeling, Analysis, and Reduction Tool (SMART, vers. 6.0.4; Higdon et al. 2004). We used tapered column extraction starting from intermediate pipeline product \texttt{dcoo} files, which only lack stray light and flat-field correction. The data from short-high (SH) and long-high (LH) \texttt{dcoo} files used the full slit extraction method from the mean of the combined images. We calibrated the flux densities by multiplying the extracted spectrum with the relative spectral response function (RSRF), which was created from the IRS standard stars, HR 6348 for SL, HD 173511 for LL and $\xi$ Dra for SH and LH, for which accurate templates are available (Cohen et al. 2003).

\footnote{The IRS was a collaborative venture between Cornell University and Ball Aerospace Corporation funded by NASA through the Jet Propulsion Laboratory and the Ames Research Center.}

| AOR Key | Date       | Instrument | On-Source Time (s) |
|---------|------------|------------|--------------------|
| 9008640 | 2004 Mar 27| IRS (SL)   | 84                 |
|         |            | IRS (LL)   | 120                |
|         |            | IRS (SH)   | 240                |
|         |            | IRS (LH)   | 120                |
| 4330759 | 2004 Apr 3 | IRAC (3.6 $\mu$m) | 120             |
|         |            | IRAC (4.5 $\mu$m) | 120             |
|         |            | IRAC (5.8 $\mu$m) | 120             |
|         |            | IRAC (8.0 $\mu$m) | 120             |
| 4349184 | 2004 Apr 7 | MIPS (24 $\mu$m) | 48              |
|         |            | MIPS (70 $\mu$m) | 231              |
|         |            | MIPS (160 $\mu$m) | 42              |
| 12622848 | 2005 Apr 23 | IRS (SL) | 480         |
|         |            | IRS (LL) | 240            |
| 16205568 | 2005 Dec 16 | IRS (SL) | 2040         |
|         |            | IRS (LL) | 840            |
|         |            | IRS (SH) | 2880           |
|         |            | IRS (LH) | 1440           |

2.2. Spitzer Imaging with IRAC and MIPS

The galaxy was imaged at 3.6, 4.5, 5.8, and 8 $\mu$m using IRAC on 2004 April 3, as well as at 24, 70, and 160 $\mu$m using MIPS on 2004 April 7 (Engelbracht et al. 2005; PID 59) (see Table 1). The IRAC high dynamic range mode was used with a four-point small cycling pattern of 30 s exposure time for each frame. This resulted in an on-source time of 120 s for each IRAC filter. The MIPS photometry mode was used in small fields with one cycle $\times$ 3 s at 24 $\mu$m and two cycles $\times$ 10 s at both 70 and 160 $\mu$m. Two offset positions ($\pm 12'$) were used to allow proper subtraction of bad pixels. The total on-source times were 48, 231, and 42 s for the MIPS 24, 70, and 160 $\mu$m bands. The imaging data were processed by the SSC pipeline version 14.0, and the final mosaics were obtained from the Spitzer archive.

3. RESULTS

3.1. Mid-IR Morphology

Many ground-based and space-borne instruments have been used to obtain optical/UV to near-IR data for I Zw 18 (Hunt & Thronson 1995; Aloisi et al. 1999; O¨ stlin 2000; Cannon et al. 2002; Hunt et al. 2003; Izotov & Thuan 2004). Hunter & Thronson (1995) first resolved the main body of I Zw 18 into stars using the Hubble Space Telescope (HST). They have also detected filaments of ionized gas up to 450 pc from the center of the galaxy. Keck II spectra revealed H$\alpha$ emission as far as $\sim$1800 pc from the main body of I Zw 18. Izotov et al. (2001) have also shown that the equivalent widths of emission lines are large in this extended envelope. This, together with the optical and near-IR colors, suggests that ionized gas dominates the emission in the outermost regions.

In Figure 1 we present images of the main body of I Zw 18 in four infrared bands (3.6, 4.5, 8, and 24 $\mu$m). At 3.6 $\mu$m, where most of the light is due to the stellar photospheric emission, the morphology of I Zw 18 is very similar to that in deep near-IR imaging (Hunt et al. 2003) and broadband optical imaging (Izotov & Thuan 2004). The northwest component is noticeably more extended and brighter than the southeast one. At 8 $\mu$m the components are still clearly resolved, while the contrast in the brightness between the two components has decreased. In normal star-forming galaxies the emission sampled by the IRAC 8 $\mu$m filter is typically dominated by dust continuum, and PAH emission when PAHs are present. Some continuum emission from the nearly Rayleigh-Jeans tail of stellar photospheric emission may also be present, even though its contribution is typically small in late-type or irregular galaxies (see Smith et al. 2007). As we discuss in the following section, no PAH features are detected in the IRS spectrum of I Zw 18 down to our 1 $\sigma \sim$ 0.2 mJy sensitivity limit. To estimate the contribution of the stellar continuum to the observed 8 $\mu$m flux, density we follow the approach of Jackson et al. (2006) and apply a scale factor of 0.4 in the 4.5 $\mu$m emission from the galaxy. This suggests that no more than $\sim$25% of the 8 $\mu$m flux can be attributed to the stars (Engelbracht et al. 2005). This was also to be expected given the observed steeply rising slope of the mid-IR spectrum. Therefore most of the main body emission seen in the 8 $\mu$m band is due to dust continuum emission. Hence we interpret this gradual shift in brightness from the northwest to the southeast component to the probable presence of more embedded star formation in the SE component, which was obscured in the optical broadband imaging. Interestingly, while optical recombination line ratios give an average extinction of only $A_V \sim$ 0.2 mag, there are also statistically significantly high H$\alpha$/H$\beta$ flux ratios ($\sim$3.4, corresponding to $A_V \sim$ 0.5 mag) in the southeast component (Cannon et al. 2002), suggesting the
existence of an appreciable amount of dust within the galaxy. Moreover, as can be seen in Figure 2, there is some extended 8 \( \mu \)m emission, although at low levels, to the west of the northwest component. This emission has similar morphology to the radio continuum emission detected in the X and L band by Cannon et al. (2005) and Hunt et al. (2005b), which has been attributed to low-frequency flux from a synchrotron halo.

In Figure 2 we show contour overlays of the 8 and 24 \( \mu \)m emission on the HST \( V \)-band image of the main body of I Zw 18. At 8 \( \mu \)m, the source is clearly resolved into two components. The centroids of the two components, especially the northwest one, are slightly displaced from their optical counterparts. Moreover, this displacement becomes even more pronounced at longer wavelengths. At 24 \( \mu \)m, the two components are blended into a single source, the centroid of which is located slightly closer to the southeast region. This displacement is real and indicates the presence of more 24 \( \mu \)m dust emission in the southeast cluster. To confirm this change in morphology we convolved the 8 \( \mu \)m image to the \( \sim 5.4'' \) size of the 24 \( \mu \)m point-spread function (PSF). Even though the resulting marginally resolved source is also elongated in the southeast to northwest direction, the peak emission was found to be slightly closer to the southeast than the northwest peak of the 24 \( \mu \)m image. This suggests an actual change in the spatial distribution of the various dust temperature components in the galaxy. In Figure 2, we also overlay the IRS SL/LL slit on the image of the galaxy. As one can see, since the SL slit is only 3.6'' wide, some of the flux from both components is not properly sampled, resulting in an underestimate of the extended emission from the galaxy. However, because the spectrograph is not sensitive to the low surface brightness emission from the areas denoted by the lowest 8 \( \mu \)m contours, this does not bias our analysis of the global spectral properties of the system or affects any of conclusions drawn.

3.2. Mid-IR Spectral Features

Figure 3 shows the 5.3–36 \( \mu \)m low-resolution spectrum of I Zw 18 as observed by the IRS. The S/N is \( \sim 3 \) times higher than that shown by Wu et al. (2006). As we discuss in § 3.4, the global shape of the mid-IR spectrum, reveals that the IRS spectrum of I Zw 18 continues to rise steeply with wavelength from 5 \( \mu \)m all the way to 36 \( \mu \)m. This is unlike the case of SBS 0335–052E (Houck et al. 2004b), the third lowest metallicity galaxy to date, which has a nearly flat continuum, peaking at \( \sim 28 \mu \)m in \( f_{\nu} \).

The improved S/N of the new spectrum enables us to detect for the first time several mid-IR forbidden lines. Fine-structure lines, such as \([\text{S} \, \text{iv}]\) at 10.51 \( \mu \)m and \([\text{Ne} \, \text{iii}]\) at 15.55 \( \mu \)m, can clearly be seen, even in the low-resolution spectrum. Several additional forbidden lines, such as \([\text{Ne} \, \text{ii}]\) at 12.81 \( \mu \)m, \([\text{S} \, \text{ii}]\) at 18.71 and 33.48 \( \mu \)m, as well as \([\text{Si} \, \text{ii}]\) at 34.82 \( \mu \)m, are identified in the high-resolution spectrum (see Fig. 4). \([\text{O} \, \text{iv}]\) at 25.89 \( \mu \)m and \([\text{Fe} \, \text{ii}]\) at 25.99 \( \mu \)m are blended in LL, but clearly resolved in LH. The line fluxes measured from the IRS high-resolution spectrum are reported in Table 2. The observed line ratio of \([\text{Ne} \, \text{ii}]\)/[\text{Ne} \, \text{ii}] is \( \sim 5 \), and the ratio of \([\text{S} \, \text{iv}]\)/[\text{S} \, \text{ii}] (18.71 \( \mu \)m) is \( \sim 2 \). This indicates that the radiation field in I Zw 18 is much harder than in a typical starburst galaxy, where \([\text{Ne} \, \text{ii}]\)/[\text{Ne} \, \text{ii}] is usually \( \lesssim 1 \) (Brandl et al. 2006), and even harder than the majority of the BCDs observed so far (Hunt et al. 2006; Wu et al. 2006).

As was the case with SBS 0335–052E, the 5–15 \( \mu \)m spectrum of I Zw 18 does not show any detectable polycyclic aromatic hydrocarbon (PAH) emission. Using the new mid-IR spectrum, we measure a 3 \( \sigma \) upper limit of 3 \( 10^{-22} \) W cm\(^{-2}\) for the 6.2 \( \mu \)m PAH feature, as well as an equivalent width (EW) of \(< 0.23 \mu \)m. The 11.2 \( \mu \)m PAH emission has an upper limit of 1.3 \( 10^{-22} \) W cm\(^{-2}\) and EW of \(< 0.12 \mu \)m. The decreasing strength of the PAH features in a low-metallicity environment is a current topic of interest (see Engelbracht et al. 2005; Wu et al. 2006; O’Halloran et al. 2006; Jackson et al. 2006; Madden et al. 2006; Beirão et al. 2006). The exact reason why PAHs tend to be absent in low-metallicity, high-excitation star-forming regions is not yet clear, although it almost certainly has to do with a combination of several effects, such as low carbon abundance, shock destruction of grains by supernovae, high ionization or excitation resulting from low metallicity, and/or extreme radiation field intensity.

3.3. Neon and Sulfur Abundances

The fine-structure lines of sulfur and neon measured in the high-resolution spectrum can be used to derive the ionic abundances relative to hydrogen. To derive these abundances one needs at least one hydrogen recombination line (usually H\( \beta \)), as well as an estimate of the electron temperature (\( T_e \)) and electron density (\( N_e \)). The H\( \beta \) fluxes for I Zw 18 reported in the literature often correspond to small regions of the galaxy or of one of the two components. The IRS SH slit from which the IR lines were measured contains part of both components. We derive the H\( \beta \) flux from the thermal component of the 3.6 cm continuum (Cannon et al. 2005), which is not affected by extinction effects and encompasses the entire main body. The SH slit includes \( \pm 52\% \) of the total H\( \beta \) emission, and this gives an H\( \beta \) flux of \( 6.1 \times 10^{-14} \) ergs cm\(^{-2}\) s\(^{-1}\). The reported electron temperatures in the literature range from 18,000 to 20,000 K for O \( \pi \) and O \( \text{iii} \) (Skillman & Kennicutt 1993; Izotov & Thuan 1999; Thuan &
of I Zw 18, the total neon abundance is \(5.3 \times 10^{-6}\), which is \(1/23\, Z_\odot\). Similarly, adding up the ionic abundance of S \(\text{iii}\) and S \(\text{iv}\), the total sulfur abundance is \(4.0 \times 10^{-7}\), which is \(1/35\, Z_\odot\). However, this might be a lower limit because sulfur abundance as derived from galactic planetary nebulae and H \(\pi\) regions is lower than the solar sulfur abundance (Pottasch \& Bernard-Salas 2006; Maciel \& Costa 2003), probably due to an overestimate of the solar value. Comparing directly with the ionic abundance from the optical (Izotov \& Thuan 1999), our Ne \(\text{iii}\) abundance is nearly twice as high, while S \(\text{iii}\) abundance agrees quite well. The difference in Ne \(\text{iii}\) could come from the electron temperature that is used to derived the ionic abundance. The optical is more affected by the change in temperature as compared to the infrared. Lowering \(T_e\) from 19,000 K to 15,000 K would double the Ne \(\text{iii}\) abundance derived from the 3869 Å line. It is known that in some PNs the temperature obtained from the Ne \(\text{iii}\) ion is lower than that from the O \(\text{iii}\) (Bernard-Salas et al. 2002). Another possible explanation is that there are some regions with dust obscuring the optical emission lines. Overall, the neon \((1/23\, Z_\odot)\) and sulfur \((1/35\, Z_\odot)\) abundances we derive using the infrared lines are consistent with the nebular oxygen abundance \((1/30\, Z_\odot)\), which supports the low extinction \((A_V = 0.2\, \text{mag})\) derived from hydrogen recombination lines by Cannon et al. (2002).

### 3.4. Comparison with SBS 0335−052E and NGC 7714

I Zw 18 and SBS 0335−052E share some properties but are very different in other aspects. Perhaps the most salient difference between their spectral energy distribution (SED) is the fraction of their luminosities emitted in the IR. Using the 15 and 30 \(\mu\)m flux densities of I Zw 18 and applying an empirical relation in starburst galaxies (Brandl et al. 2006), we derive \(L_{\text{IR}} = 1.8 \times 10^8 \, M_\odot\). While SBS 0335−052E has \(L_{\text{IR}} \sim 10^7 \, L_\odot\) and \(L_{\text{IR}}/L_{\text{B}} \sim 1.3\), I Zw 18 has \(L_{\text{IR}} \sim 10^7 \, L_\odot\) and \(L_{\text{IR}}/L_{\text{B}} \sim 0.3\); the relative infrared luminosity is a factor of 4 times greater in SBS 0335−052E. Another important difference in the infrared SEDs of I Zw 18 and SBS 0335−052E is the peak wavelength of the SED. The SED of SBS 0335−052E peaks at \(\sim 28 \, \mu\text{m}\) in \(f_{\nu}\) space (Houck et al. 2004b), indicating very little cold dust. I Zw 18 has a clear detection of \(34 \pm 2.4\, \mu\text{m}\) at \(70 \, \mu\text{m}\) (C. W. Engelbracht et al. 2007, in preparation), and the ratio of \(f_{70}/f_{35}\) is more than a factor of 5, while the same ratio in SBS 0335−052E is less than 1. This suggests that contrary to SBS 0335−052E, which is a similarly high excitation and densities in BCDs are a closer match to PN than the typical H \(\pi\) regions found in normal starburst galaxies.

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**Fig. 2.—Top:** Contour overlay of the IRAC 8 \(\mu\text{m}\) image on the HST WFPC2 F555W image taken from the HST archive. The astrometric calibration of the HST image has been derived using stars from the USNO Astrometric Catalog B1.0 and is the same image as used in Hunt et al. (2005b). The contours range from \(4 \sigma (\sigma = 0.03\, \text{Mly sr}^{-1})\) above the sky level \((1.40\, \text{Mly sr}^{-1})\) to the peak value of \(1.71\, \text{Mly sr}^{-1}\). The location of the IRS SL (3.6\' in width) and LL (10.5\') slits are also indicated with dashed and dash-dotted lines, respectively. Note that due to the extent of the galaxy and the fixed position angle of the slit, part of both the northwest and southeast components are not fully covered by the SL slit. The size of the PSF at 8 \(\mu\text{m}\) (1.8\') is also shown at the bottom right of the panel. **Bottom:** Same optical image with the contours of MIPS 24 \(\mu\text{m}\) emission (from 4 \(\sigma\) and above). The size of the PSF is 5.4\'.

**Fig. 3.—Spitzer IRS 5–36 \(\mu\text{m}\) low-resolution spectrum of I Zw 18.** No scaling factors have been applied to stitch the different orders and modules. We indicate several of the well-known mid-IR fine structure emission lines detected in the spectrum (see also Fig. 4).

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**Table 2**

| Element | Abundance |
|---------|-----------|
| Ne \(\text{iii}\) | \(5.3 \times 10^{-6}\) |
| S \(\text{iii}\) | \(4.0 \times 10^{-7}\) |
| S \(\text{iv}\) | \(1.5 \times 10^{-7}\) |
| O \(\text{iii}\) | \(1.7 \times 10^{-7}\) |
| O \(\text{iv}\) | \(2.0 \times 10^{-7}\) |

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The high excitation densities in BCDs are a closer match to PN than the typical H \(\pi\) regions found in normal starburst galaxies.

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\[ \text{Bernard-Salas et al. 2003,}\] the total neon abundance is \(5.3 \times 10^{-6}\), which is \(1/23\, Z_\odot\). Similarly, adding up the ionic abundance of S \(\text{iii}\) and S \(\text{iv}\), the total sulfur abundance is \(4.0 \times 10^{-7}\), which is \(1/35\, Z_\odot\). However, this might be a lower limit because sulfur abundance as derived from galactic planetary nebulae and H \(\pi\) regions is lower than the solar sulfur abundance (Pottasch \& Bernard-Salas 2006; Maciel \& Costa 2003), probably due to an overestimate of the solar value. Comparing directly with the ionic abundance from the optical (Izotov \& Thuan 1999), our Ne \(\text{iii}\) abundance is nearly twice as high, while S \(\text{iii}\) abundance agrees quite well. The difference in Ne \(\text{iii}\) could come from the electron temperature that is used to derived the ionic abundance. The optical is more affected by the change in temperature as compared to the infrared. Lowering \(T_e\) from 19,000 K to 15,000 K would double the Ne \(\text{iii}\) abundance derived from the 3869 Å line. It is known that in some PNs the temperature obtained from the Ne \(\text{iii}\) ion is lower than that from the O \(\text{iii}\) (Bernard-Salas et al. 2002). Another possible explanation is that there are some regions with dust obscuring the optical emission lines. Overall, the neon \((1/23\, Z_\odot)\) and sulfur \((1/35\, Z_\odot)\) abundances we derive using the infrared lines are consistent with the nebular oxygen abundance \((1/30\, Z_\odot)\), which supports the low extinction \((A_V = 0.2\, \text{mag})\) derived from hydrogen recombination lines by Cannon et al. (2002).

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\[ \text{Cutout of } 9.34'' \times 3.03'' \]

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**Fig. 2.**
low metallicity BCD, there is a significant amount of cold dust in I Zw 18.

We can further compare the properties of I Zw 18 with higher luminosity and more metal-rich starbursts. In Figure 5 we present the spectra of I Zw 18 and SBS 0335−052E, together with a typical starburst galaxy, NGC 7714 (Brandl et al. 2004), all of which have been normalized to the flux density of I Zw 18 at 22 μm. Setting aside the strong PAH emission features present in NGC 7714, there is a striking similarity between the mid-IR continuum of I Zw 18 and NGC 7714, although the latter has a metallicity of more than half solar. At short mid-IR wavelengths (λ < 10 μm), the warm dust component dominates and it does not change much even for an extended starburst galaxy (Brandl et al. 2006). At longer wavelengths, emission from larger cooler grains is dominant. After normalization at 22 μm, the 70 μm flux of I Zw 18 differs less than 20% when compared to the 70 μm flux of 9.53 Jy (C. W. Engelbracht et al. 2007, in preparation) or the IRAS 60 μm flux of 11.16 Jy for NGC 7714. Figure 5 suggests that similarly low metallicity galaxies can have both very flat or very steep spectral slope, while in the latter case the spectral slope can be as steep as that of a typical starburst. This leads us to conclude that metallicity is not the main parameter driving the difference in the shape of the mid-IR spectral slope (Wu et al. 2006) and the infrared part of the SEDs.

Based on the new Spitzer measurements of the mid- and far-infrared emission from I Zw 18 one could in principle attempt to model the global SED of the galaxy. We did explore this avenue.

Fig. 4.— Mid-IR fine structure lines of [S iv] (10.51 μm), [Ne ii] (12.81 μm), [Ne iii] (15.55 μm), [S iii] (18.71, 33.42 μm) [O iv] (25.89 μm), [Fe ii] (25.99 μm), and [Si ii] (34.82 μm) from the high-resolution spectrum of I Zw 18. Note that the sky emission has not been subtracted.
using modeling tools such as DUSTY (Ivezić et al. 1999), but with only limited success. The complex geometry of I Zw 18 and the large number of free parameters in the available models prevented us from significantly constraining the physical conditions of the dust. We thus refrain from elaborating on these results until more data are available.

4. STAR FORMATION RATE IN I Zw 18

Deriving the star formation rate in nearby galaxies from various observational indicators and understanding the possible variations in the results is extremely useful for “predicting” the properties of high-redshift galaxy populations, where only sparse data are available. Using the available data, we calculated the SFRs of I Zw 18 from different indicators and present our results in Table 3.

The SFR estimated from the Hα luminosity gives a value of 0.05 M⊙ yr⁻¹ (Kennicutt et al. 1994; Cannon et al. 2002). However, I Zw 18 has only 1/30 Z⊙ and lower metallicities may result in a reduced SFR for a given Hα luminosity (Lee et al. 2002; Rosenberg et al. 2006). Using the metallicity correction recipe of Lee et al. (2002) the SFR would be ~0.03 M⊙ yr⁻¹.

The radio continuum emission is another important diagnostic of star formation processes and it is not affected by dust extinction effects. The thermal free-free emission is a direct indicator of SFR and it is typically only ~10% of the total radio continuum at 1.4 GHz for normal galaxies (Condon 1992). However, in I Zw 18 the fraction of thermal component is 3 times the typical value (~30%; Hunt et al. 2005b; Cannon et al. 2005). Using the relation between radio free-free emission and SFR, we derive a SFR = 0.1 M⊙ yr⁻¹ (Hunt et al. 2005b). The nonthermal component of the radio continuum can also be used to calculate SFR, and we derive a SFR of 0.03 M⊙ yr⁻¹ (Condon 1992), a factor of 3 lower than the thermally derived SFR. This difference is a direct consequence of the unusual value of the “thermal/nonthermal” fraction in I Zw 18. This is an important caveat that should be considered when applying the standard correlations that have been established for normal star-forming galaxies in very young low-metallicity systems.

Finally, the SFRs estimated from the infrared are significantly lower. Using the total infrared luminosity of 1.8 x 10⁷ L⊙, we derive a SFR = 0.003 M⊙ yr⁻¹ (Kennicutt 1998), while using the 24 μm emission, we find that SFR = 0.006 M⊙ yr⁻¹ (Calzetti et al. 2005; Wu et al. 2005). This is probably because the dust content in I Zw 18 is so low while the above relations have been calibrated for sources of high optical depth, where virtually all of the UV radiation is converted to infrared luminosity. A simple calculation using the reddening curve of the Small Magellanic Cloud, assuming A_v = 0.2 magn, suggests that a significant amount of UV light has leaked out without being absorbed by the dust, and thus the lower SFRs estimated from the infrared are not unexpected. Readers should be aware of these complications when applying the canonical infrared relations for estimating the SFR in environments with low dust optical depth. If we were to assume that L_{IR} accounts for the bolometric luminosity of the obscured populations, while L_{UV} (Kinney et al. 1993) represents the contribution of the unobscured stars, and use equation (1) of Bell et al. (2005), we find a SFR of 0.02 M⊙ yr⁻¹, more consistent with the SFRs derived using the Hα or radio luminosities.

5. CONCLUSIONS

We have explored the mid-IR and far-IR properties of the archetype BCD I Zw 18 based on Spitzer data, as follows:

1. Using the low-resolution modules of the IRS, we have acquired the deepest mid-IR spectrum of this galaxy obtained so...
far. No PAH emission is found, which confirms the absence of PAHs in low-metallicity systems. However, the mid to far-IR spectral slope of I Zw 18 is surprisingly similar to that in NGC 7714, a typical starburst galaxy with high solar metallicity. This, especially the MIPS 70 μm detection, would suggest the presence of a significant amount of cold dust in I Zw 18.

2. Variations in the morphology of the galaxy from 3.6 to 24 μm imaging imply that more dust emission is present in its southeast component than in the northwest one. This agrees well with the results of Cannon et al. (2002).

3. The mid-IR fine-structure lines identified in the high-resolution spectrum of I Zw 18 imply a neon and sulfur abundance of 1/23 and 1/35 Z⊙, respectively, consistent with the optically derived oxygen abundance of 1/30 Z⊙.

4. Estimates of the star formation rates calculated from different indicators show considerable scatter. LIR and L_{24 μm} give lower SFRs when compared with results using Hα or L_{14 GHz}, probably because the low dust content in this galaxy can only convert a small fraction of the UV radiation emitted by stars into LIR. This should be considered when interpreting star formation rates derived for high-redshift low-metallicity galaxies.

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REFERENCES

Allende Prieto, C., Lambert, D. L., & Asplund, M. 2001, ApJ, 556, L63
Aloisi, A., Tosi, M., & Greggio, L. 1999, AJ, 118, 302
Aloisi, A., et al. 2007, in IAU Symp. 241, Stellar Populations as Building Blocks of Galaxies, ed. R. F. Peletier & A. Vazdekis (San Francisco: ASP), in press (astro-ph/0702216)
Beirão, P., Brandl, B. R., Devost, D., Smith, J. D., Hao, L., & Houck, J. R. 2006, ApJ, 643, L1
Bell, E. F., et al. 2005, ApJ, 625, 23
Bernard-Salas, J., Pottasch, S. R., Beintema, D. A., & Wesselius, P. R. 2001, A&A, 367, 949
Bernard-Salas, J., Pottasch, S. R., Feibelman, W. A., & Wesselius, P. R. 2002, A&A, 387, 301
Bernard-Salas, J., Pottasch, S. R., Wesselius, P. R., & Feibelman, W. A. 2003, A&A, 406, 165
Brandl, B. R., et al. 2004, ApJS, 154, 188
———. 2006, ApJ, 653, 1129
Calzetti, D., et al. 2005, ApJ, 633, 871
Cannon, J. M., Skillman, E. D., Garnett, D. R., & Dufour, R. J. 2002, ApJ, 565, 931
Cannon, J. M., Walter, F., Skillman, E. D., & van Zee, L. 2005, ApJ, 621, L21
Cohen, M., Megeath, T. G., Hammersley, P. L., Martin-Luis, F., & Stauffer, J. 2003, AJ, 125, 2645
Condon, J. J. 1992, ARA&A, 30, 575
Dekel, A., & Silk, J. 1986, ApJ, 303, 39
Engelbracht, C. W., Gordon, K. D., Rieke, G. H., Werner, M. W., Dale, D. A., & Latter, W. B. 2005, ApJ, 628, L29
Fazio, G. G., et al. 2004, ApJS, 154, 10
Higdon, S. J. U., et al. 2004, PASP, 116, 975
Hirashita, H., & Hunt, L. K. 2004, A&A, 421, 555
Houck, J. R., et al. 2004a, ApJS, 154, 18
———. 2004b, ApJS, 154, 211
Hunt, L. K., Bianchi, S., & Maiolino, R. 2005a, A&A, 434, 849
Hunt, L. K., Dyer, K. K., & Thuan, T. X. 2005b, A&A, 436, 837
Hunt, L. K., Thuan, T. X., & Izotov, Y. I. 2003, ApJ, 588, 281
Hunt, L. K., Thuan, T. X., Sauvage, M., & Izotov, Y. I. 2006, ApJ, 653, 222
Hunter, D. A., & Thronson, H. A., Jr. 1995, ApJ, 452, 238
Ivezic, Z., Nemkena, M., & Elitzur, M. 1999, preprint (astro-ph/9910475)
Izotov, Y. I., Chaffee, F. H., Foltz, C. B., Thuan, T. X., Green, R. F., Papaderos, P., Fricke, K. J., & Guseva, N. G. 2001, ApJ, 560, 222
Izotov, Y. I., & Thuan, T. X. 1999, ApJ, 511, 639
———. 2004, ApJ, 616, 768
Izotov, Y. I., Thuan, T. X., & Guseva, N. G. 2005, ApJ, 632, 210
Jackson, D. C., Cannon, J. M., Skillman, E. D., Lee, H., Gehrz, R. D., Woodward, C. E., & Polomski, E. 2006, ApJ, 646, 192
Kennicutt, R. C., Jr. 1998, ARA&A, 36, 189
Kennicutt, R. C., Jr., Tamblyn, P., & Congdon, C. E. 1994, ApJ, 435, 22
Kingey, A. L., Bohlin, R. C., Calzetti, D., Panagia, N., & Wyse, R. F. G. 1993, ApJS, 86, 5
Kunth, D., & Ostlin, G. 2000, A&A Rev., 10, 1
Lee, J. C., Salzer, J. J., Impey, C., Thuan, T. X., & Gronwall, C. 2002, AJ, 124, 3088
Maciel, W. J., & Costa, R. D. D. 2003, in IAU Symp. 209, Planetary Nebulae: Their Evolution and Role in the Universe, ed. S. Kwok, M. Dopita, & R. Sutherland (San Francisco: ASP), 551
Madden, S. C., Galliano, F., Jones, A. P., & Sauvage, M. 2006, A&A, 446, 877
Maiolino, R., Juarez, Y., Mujica, R., Nagar, N. M., & Olivera, E. 2003, ApJ, 596, L155
Momany, Y., et al. 2005, A&A, 439, 111
Ostlin, G. 2000, ApJ, 535, L99
O’Halloran, B., Satyapal, S., & Dukid, R. P. 2006, ApJ, 641, 795
Papaderos, P., Izotov, Y. I., Guseva, N. G., Thuan, T. X., & Fricke, K. J. 2006, A&A, 454, 119
Plante, S., & Sauvage, M. 2002, AJ, 124, 1995
Pottasch, S. R., & Bernard-Salas, J. 2006, A&A, 457, 189
Recchi, S., Matteucci, F., D’Ercole, A., & Tosi, M. 2002, A&A, 384, 799
Rieke, G. H., et al. 2004, ApJS, 154, 25
Rosenberg, J. L., Ashby, M. L. N., Salzer, J. J., & Huang, J.-S. 2006, ApJ, 636, 742
Searle, L., & Sargent, W. L. W. 1972, ApJ, 173, 25
Shi, F., Kong, X., Li, C., & Cheng, F. Z. 2005, A&A, 437, 849
Skillman, E. D., & Kennicutt, R. C., Jr. 1993, ApJ, 411, 655
Smith, J. D. T., et al. 2007, ApJ, 656, 770
Thuan, T. X., & Izotov, Y. I. 2005, ApJS, 161, 240
Thuan, T. X., Sauvage, M., & Madden, S. 1999, ApJ, 516, 783
van Zee, L., Westpfahl, D., Haynes, M. P., & Salzer, J. J. 1998, AJ, 115, 1000
Weedman, D. W., Le Floc’h, E., Higdon, S. J. U., Higdon, J. L., & Houck, J. R. 2006, ApJ, 638, 613
Werner, M. E., et al. 2004, ApJS, 154, 1
White, S. D. M., & Rees, M. J. 1978, MNRAS, 183, 341
Wu, H., et al. 2005, ApJ, 632, L79
Wu, Y., Charmandaris, V., Hao, L., Brandl, B. R., Bernard-Salas, J., Spoon, H. W. W., & Houck, J. R. 2006, ApJ, 639, 157
Zwicky, F. 1966, ApJ, 143, 192