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WISE DISCOVERY OF LOW-METALLICITY BLUE COMPACT DWARF GALAXIES

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ABSTRACT

We report two new low-metallicity blue compact dwarf galaxies (BCDs), WISEP J080103.93+264053.9 (hereafter W0801+26) and WISEP J170233.53+180306.4 (hereafter W1702+18), discovered using the *Wide-field Infrared Survey Explorer* (*WISE*). We identified these two BCDs from their extremely red colors at mid-infrared wavelengths and obtained follow-up optical spectroscopy using the Low Resolution Imaging Spectrometer on Keck I. The mid-infrared properties of these two sources are similar to the well-studied, extremely low metallicity galaxy SBS 0335-052E. We determine metallicities of $12+\log(\mathrm{O/H}) = 7.75$ and 7.63 for W0801+26 and W1702+18, respectively, placing them among a very small group of very metal deficient galaxies ($Z \leqslant 1/10\, Z_\odot$). Their >300 Å H$\beta$ equivalent widths, similar to SBS 0335-052E, imply the existence of young (<5 Myr) star-forming regions. We measure star formation rates of 2.6 and 10.9 $M_\odot$ yr^{-1} for W0801+26 and W1702+18, respectively. These BCDs, showing recent star formation activity in extremely low metallicity environments, provide new laboratories for studying star formation in extreme conditions and are low-redshift analogs of the first generation of galaxies to form in the universe. Using the all-sky *WISE* survey, we discuss a new method to identify similar star-forming, low-metallicity BCDs.

Key words: galaxies: abundances – galaxies: dwarf – galaxies: individual (WISEP J080103.93+264053.9, WISEP J170233.53+180306.4) – galaxies: starburst

1. INTRODUCTION

In the local universe, we observe a class of galaxies known as blue compact dwarf galaxies (BCDs) which show signatures of strong, recent, and ongoing star formation activity in low-metallicity environments. These galaxies, which appear to be experiencing their first major burst of star formation, are characterized as generally having compact sizes ($\leqslant$1 kpc), low luminosities ($M_B \geqslant -18$), strong emission line spectra, blue optical colors ($U - B \sim -0.6$), and their metal distribution peaks at one-tenth solar ($Z = 1/10\ Z_\odot$; Kunth & Östlin 2000). Typical Hβ equivalent widths range from 30 to 200 Å, implying a burst of star formation no older than a few Myr (Kunth 1999). BCDs offer pristine laboratories from which to study star formation processes, enrichment mechanisms for the interstellar medium, and the star formation history of galaxies in low metallicity and extremely dusty environments. In particular, BCDs are likely good analogs of the first generation of galaxies to form in the universe, but are at redshifts accessible to detailed study (e.g., Meier & Terlevich 1981). For a comprehensive review of BCDs and the most metal-poor galaxies, see Kunth & Östlin (2000).

Although discovered as early as the 1960s, BCDs and extremely low metallicity galaxies have remained an elusive population. The difficulty in finding low-metallicity BCDs can be viewed as stemming from several factors. First, they have low luminosities, generally much fainter than L^*. Second, at the lowest metallicities, below 0.1 solar, the major coolant species shift from [O III] to H and He (Kunth & Sargent 1986), resulting in lower [O III] λ5007/Hβ ratios. This made such sources less readily identified in the previous generation of objective prism surveys (Kunth & Sargent 1986), though recent fiber spectroscopy surveys have less significant biases. Finally, they are rare. The most abundant samples of BCDs have been acquired by the Sloan Digital Sky Survey (SDSS) which has spectroscopically identified hundreds of BCDs at redshifts of a few tenths (e.g., Izotov et al. 2006), implying a surface density of 0.1 BCD deg^{-2} to the limits of the SDSS. However, SDSS rarely finds the most extreme metal-poor systems, galaxies with $Z \lesssim 1/10\ Z_\odot$. For example, Kniazev et al. (2003) estimate 0.004 deg^{-2} for extremely metal-poor galaxies [$12 + \log(\mathrm{O/H}) \leqslant 7.65$] for $r \leqslant 17.77$ mag.

The two lowest metallicity BCDs known to date are SBS 0335-052E (Izotov et al. 1990; Melnick et al. 1992; Izotov et al. 1997; Thuan et al. 1997, 1999; Dale et al. 2001; Houck et al. 2004) and I Zw 18 (Zwicky 1966; Lauqué 1973; Thuan & Martin 1981; Davidson & Kinman 1985; Dufour & Hester 1990; Kunth et al. 1994; Hirashita & Hunt 2004; Wu et al. 2007), both of which have been extensively studied across the electromagnetic spectrum. Though the metallicities for these two systems are very similar, $12+\log(\mathrm{O/H}) < 7.3$ or $Z < 1/40\, Z_\odot$, these galaxies exhibit very different morphological and physical properties. Hirashita & Hunt (2004) investigated these differences and suggest that they are best understood if two different modes of star formation are considered, an "active mode" and a "passive mode." SBS 0335-052E is an active-mode BCD while I Zw 18 is a passive-mode BCD. In the Hirashita & Hunt (2004) framework, active BCDs host super star clusters

(SSCs) and are characterized by compact star formation regions (radius $\leqslant$50 pc), high gas densities ($\geqslant$500 cm^{-3}), rich H_2 content, large dust optical depth, and high dust temperature. Passive BCDs, in contrast, have more diffuse star-forming regions ($\geqslant$100 pc), lower gas density ($\leqslant$100 cm^{-3}), cooler dust, and lack SSCs and large amounts of H_2.

Hirashita & Hunt (2004) describe how the compactness of the star-forming regions can simultaneously explain most of the observed differences between BCDs. Compact star-forming regions will rapidly become dusty from Type II supernovae, and this dust will be effective at reprocessing photons into the infrared. In particular, the gas free-fall timescale in such systems is less than 5 Myr, which leads to run-away star formation and the efficient creation of large quantities of dust. In contrast, the dynamical time of diffuse star-forming regions, characteristic of passive BCDs, is longer than 10^7 yr. Such regions thus have lower star formation rates (SFRs) and are less infrared luminous. Hirashita & Hunt (2004) suggest that the physical state of the gas might be driven by the size and spatial distribution of dust grains.

Wu et al. (2008) show that the infrared luminosities of these prototypical BCDs differ by two orders of magnitude, with SBS 0335-052E being ∼100 times more infrared luminous than I Zw 18. The mid-infrared emission of similar low-metallicity BCDs originates mainly from hot (200–1500 K) dust, causing active BCDs to have significantly red colors at mid-infrared wavelengths. For example, Houck et al. (2004) find that the spectrum of SBS 0335-052E peaks at ∼28 μm. Dale et al. (2001) model the infrared emission of SBS 0335-052E and conclude that it can be characterized as having two dust components, a warm (∼80 K) and a hot (∼210 K) component. The prevalence of hot dust in active BCDs suggests that searching for the most extreme low metallicity, star-forming BCDs at mid-infrared wavelengths may be fruitful.

This Letter reports the discovery of two new low-metallicity BCDs discovered by the *Wide-field Infrared Survey Explorer* (*WISE*; Wright et al. 2010). Launched on 2009 December 14, *WISE* completed its first coverage of the entire sky on 2010 July 17, obtaining at least eight exposures per sky position in four passbands, 3.4, 4.6, 12, and 22 μm ($W1$, $W2$, $W3$, and $W4$, respectively). The corresponding 5σ point source sensitivities in unconfused regions are better than 0.08, 0.11, 1, and 6 mJy, respectively, and the point spread function FWHM values for the four *WISE* bands are 6''.1, 6''.4, 6''.5, and 12''.0, respectively (Wright et al. 2010). Focusing on two early examples of *WISE*-identified, low-metallicity BCDs, we discuss the physical properties of these two new BCDs and place them within the context of recent BCD literature. C.-W. Tsai et al. (2011, in preparation) present a larger sample of several dozen newly identified BCDs and discuss the selection technique in more detail. We assume a solar metallicity ($Z_\odot$) of $12 + \log(\mathrm{O/H}) = 8.96$ (Allende Prieto et al. 2001) in this Letter. Magnitudes are reported in the Vega system and, where necessary, we adopt the concordance cosmology with $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$, and $H_0 = 70$ km s^{-1} Mpc^{-1}.

2. BCD SELECTION AND KECK SPECTROSCOPY

We identified WISEP J080103.93+264053.9 (hereafter W0801+26) and WISEP J170233.53+180306.4 (hereafter W1702+18) from their extreme mid-infrared colors and relatively bright optical flux densities ($B < 19.5$, from the USNO-B1 catalog). The mid-infrared photometry was acquired from the *WISE* Preliminary Release Source Catalog (thus the “P” designation in the *WISE* nomenclature). The simultaneous multiwavelength *WISE* observations of W0801+26 and W1702+18 were carried out on UT 2010 April 12 and UT 2010 March 2, respectively, and provided total exposure times of ∼100 and 120 s, respectively. For details on the *WISE* processing in the Preliminary Release, see the *WISE* Preliminary Release Explanatory Supplement.[7] *WISE* images of the two new BCDs are presented in Figure 1. For comparison, we also show *WISE* images of the two prototypical low-metallcity BCDs, SBS 0335-052E and I Zw 18. Photometry for all four sources is presented in Table 1. The new BCDs have unique and easily identified mid-infrared colors, similar to SBS 0335-052E. In contrast, I Zw 18 is unremarkable in the *WISE* data. None of the sources are resolved by the 6'' *WISE* beam. The signal-to-noise ratios (S/N) of SBS 0335-052E and the new BCDs are >25 in all four *WISE* bands.

Noting their unusual *WISE* colors and relatively bright optical magnitudes, we obtained optical spectroscopic follow-up observations of W0801+26 and W1702+18 during twilight using the dual-beam Low Resolution Imaging Spectrometer (LRIS; Oke et al. 1995) on the Keck I telescope. We observed W1702+18 on UT 2010 March 12 and W0801+26 on UT 2010 November 8. The conditions were photometric on both nights, and both observations used the 1''.5 wide long slit, the 5600 Å dichroic, and the 400 ℓ mm^{-1} grating on the red arm of the spectrograph (blazed at 8500 Å; resolving power $R \equiv \lambda/\Delta\lambda \sim 700$ for objects filling the slit). The 2010 March observations used the 600 ℓ mm^{-1} grism on the blue arm (blazed at 4000 Å; $R \sim 1000$), while the 2010 November observations used the slightly lower resolution 400 ℓ mm^{-1} grism (blazed at 3400 Å; $R \sim 600$). A single 300 s exposure was obtained of each source during the observing runs. We processed the data using standard procedures, flux calibrated the spectra using observations of standard stars from Massey & Gronwall (1990), and corrected for Galactic extinction using the dust maps of Schlegel et al. (1998).

The final, reduced spectra show a multitude of extremely high equivalent width, narrow emission lines at low redshift and are presented in Figure 2. We have used the ratio of Hα to Hβ and Hγ to Hδ emission line strengths to derive and correct for intrinsic dust extinction assuming Case B recombination and the extinction law of Cardelli et al. (1989) with $R_V = 3.1$. For W0801+26, the Balmer line ratios are close to the extinction-free ratios of Case B, implying no significant extinction is observed. For W1702+18, we find an intrinsic extinction of $A_V = 0.18$. The derived redshifts are presented in Table 1, while Table 2 presents the extinction-corrected line flux measurements and errors obtained using the `SPECFIT` package within IRAF. Equivalent widths from Hβ are also given in Table 2.

3. RESULTS

3.1. Mid-infrared Properties

Figure 1 shows *WISE* color images of W0801+26 and W1702+18, as well as of prototypical BCDs SBS 0335-052E and I Zw 18. In the framework of Hirashita & Hunt (2004), SBS 0335-052E is an active BCD, while I Zw 18 is passive BCD. Most Galactic stars and low-redshift galaxies are dominated by a Rayleigh–Jeans spectrum at the wavelengths observed by *WISE*, providing blue colors in the color mapping shown in Figure 1. In contrast, active BCDs contain substantial quantities of dust in a dense cloud, which give them unusual and readily identified red colors at near- and mid-infrared wavelengths. BCDs like

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[7] http://wise2.ipac.caltech.edu/docs/release/prelim/index.html

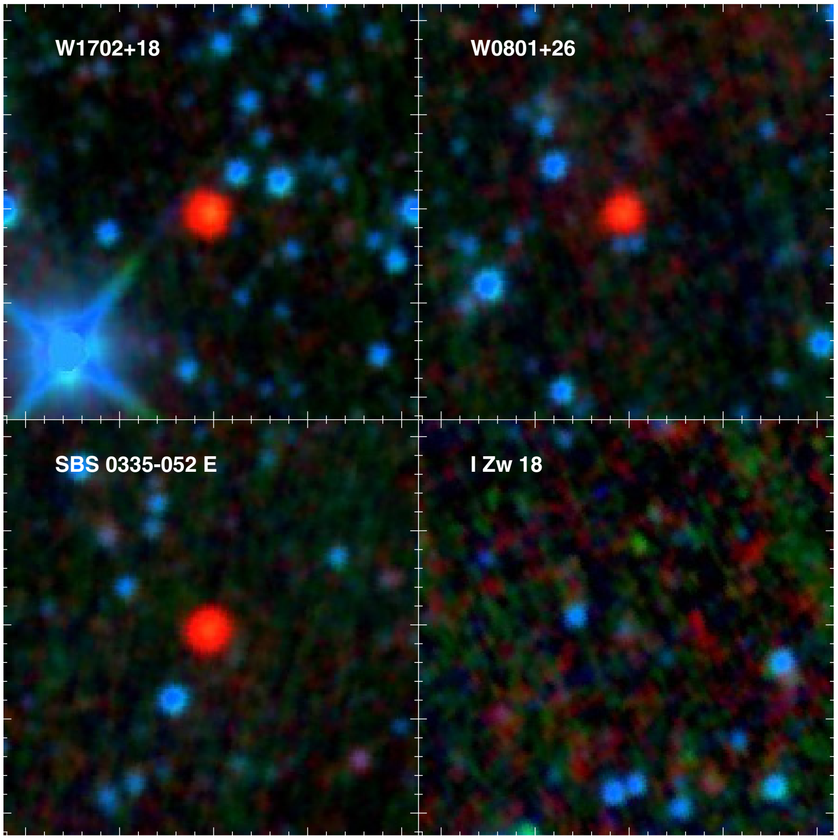

Figure 1. *WISE* color images (blue = $W1$, green = $W2$, red = $W3$) for the two newly discovered low-metallicity BCDs as well as the prototypical BCDs SBS 0335-052E and I Zw 18. Images are $5'$ on a side, with north up and east to the left. "Active" BCDs such as SBS 0335-052E and the two new BCDs have unique, extremely red *WISE* colors, making them readily identifiable from the *WISE* all-sky survey.

Table 1
Properties of Low-metallicity BCDs

BCD Property	W0801+26	W1702+18	SBS 0335-052E	I Zw 18
R.A. (J2000)	08:01:03.929	17:02:33.534	03:37:44.032	09:34:02.088
Decl. (J2000)	+26:40:53.91	+18:03:06.44	−05:02:40.26	+55:14:26.23
z	0.0260	0.0425	0.0134	0.0025
M_B (mag)	−16.8	−18.3	−17.1	−15.4
B (mag)	18.18	18.39	16.48	14.46
$W1$ (mag)	15.03 ± 0.04	14.26 ± 0.03	14.53 ± 0.03	15.39 ± 0.04
$W2$ (mag)	12.94 ± 0.03	12.03 ± 0.02	12.52 ± 0.03	14.86 ± 0.07
$W3$ (mag)	8.29 ± 0.03	7.58 ± 0.02	7.66 ± 0.02	11.88 ± 0.14
$W4$ (mag)	5.38 ± 0.03	4.96 ± 0.03	5.04 ± 0.03	7.84 ± 0.14
$12 + \log(\mathrm{O/H})$	$7.75^{+0.04}_{-0.17}$	7.63 ± 0.06	$7.11 - 7.3$	7.17

I Zw 18, on the other hand, do not contain hot dust, and thus are undistinguished in the *WISE* bands (see Table 1).

As discussed in L. Yan et al. (2011, in preparation), sources with red colors across the first two *WISE* bands, $W1 - W2 \geqslant 2$, are relatively rare. For example, the COSMOS field has only one source with such red *WISE* colors in a field slightly larger than 1 deg^2 (D. Stern et al. 2011, in preparation). The coolest brown dwarfs, with spectral types later than T5, have red $W1 - W2$ colors due to methane absorption at 3.3 μm (e.g., Burgasser et al. 2011; Kirkpatrick et al. 2011; Mainzer et al. 2011) and are quite faint at optical wavelengths. The *WISE* team has also been pursuing a population of galaxies with red $W2 - W4$ colors which appear to be dominated by heavily obscured active galactic nucleus (AGN) at $z \sim 2$ (e.g., P. R. M. Eisenhardt et al. 2011, in preparation). Such galaxies are also quite faint optically. In contrast, as shown in Table 1, low-redshift BCDs have extremely red *WISE* colors but are bright at optical wavelengths, providing for their easy identification and follow-up. C.-W. Tsai et al. (2011, in preparation) discuss the *WISE* selection of BCDs in more detail.

3.2. Spectroscopic Properties and Metallicity

The Keck spectra of W0801+26 and W1702+18, presented in Figure 2, show a multitude of strong hydrogen and oxygen emission lines as well as weak stellar continuum. These spectra are characteristic of sources whose optical emission is dominated by H II regions. Key line measurements for W0801+26 and W1702+18 are presented in Table 2. Standard diagnostic diagrams, such as comparing [O III]/Hβ to [N II]/Hα, imply that the emission lines for both new *WISE*-selected BCDs are

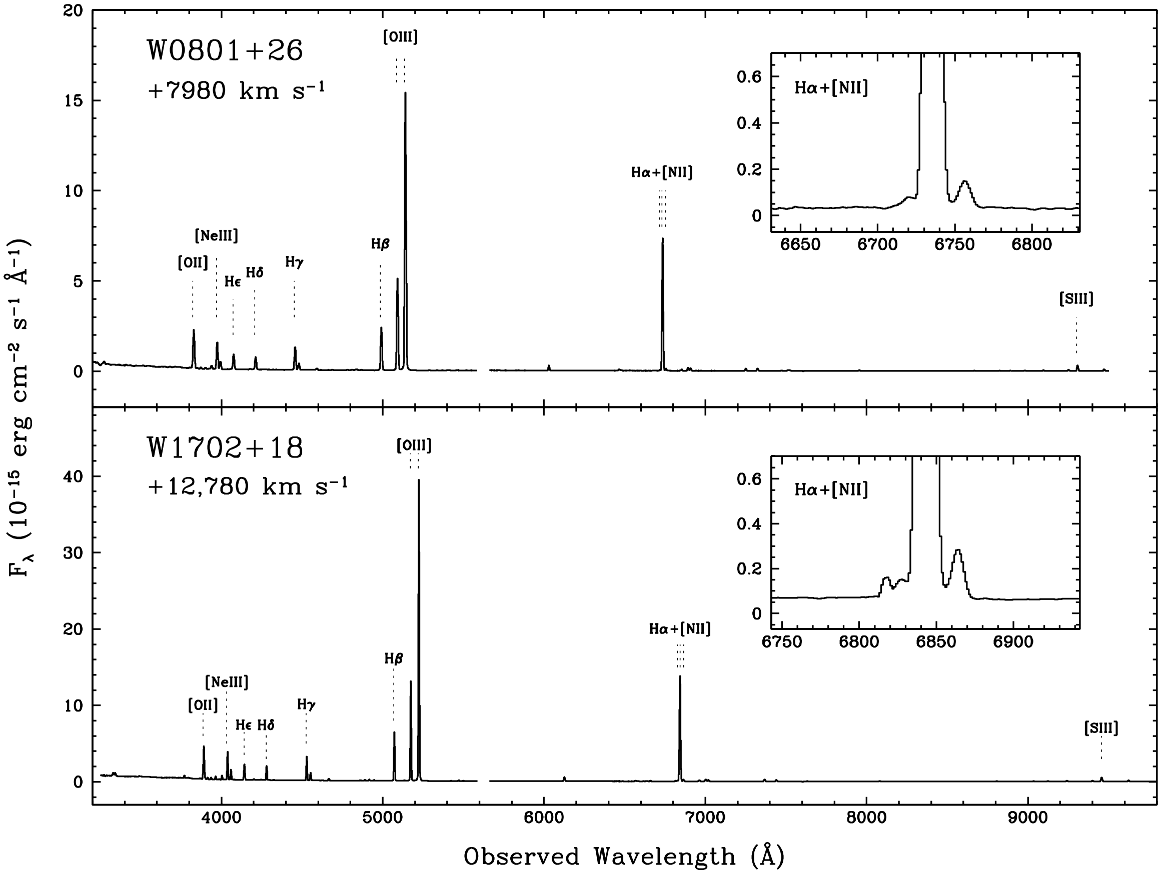

Figure 2. Spectra of W0801+26 and W1702+18, obtained with the LRIS instrument on Keck I. Both spectra show strong, narrow, high equivalent width emission lines from hydrogen and oxygen, as well as weak [N II] flanking the Hα emission line (insets). The line ratios imply that the emission is powered by star formation, not AGN activity, from very low metallicity systems.

Table 2
Spectroscopic Line Measurements

Line	W0801+26	W1702+18
[O II] 3727+3729	234.1 ± 2.6	334.2 ± 11.1
Hδ 4101	69.5 ± 1.1	127.9 ± 2.0
Hγ 4340	132.5 ± 4.1	232.1 ± 13.7
[O III] 4363	41.5 ± 3.1	84.2 ± 8.7
Hβ 4861	247.3 ± 3.0	438.5 ± 5.7
[O III] 4959	527.8 ± 11.3	921.8 ± 31.6
[O III] 5007	1596.4 ± 18.9	2679.2 ± 62.3
Hα 6563	657.4 ± 9.0	1227.2 ± 27.5
[N II] 6584	10.0 ± 0.8	21.1 ± 0.6
−EW(Hβ)	370.2 ± 6.1	324.4 ± 6.4

Notes. The top rows present the line fluxes in units of 10^{-16} erg cm^{-2} s^{-1}. The final row gives the Hβ equivalent width (EW) in units of Å.

driven by star formation processes rather than by AGN activity (e.g., Baldwin et al. 1981; Kewley et al. 2001).

One of the most striking features of the spectra presented in Figure 2 is the weakness of the [N II] lines relative to the Hα line that they flank. This immediately suggests that both galaxies have extremely low metallicities. Following the prescriptions of Izotov et al. (2006), we derive electron temperatures T_e([O III]) $\sim 1.7 \times 10^4$ K for W0801+26 and $\sim 1.9 \times 10^4$ K for W1702+18, from their [O III] line strengths at 4363, 4959, and 5007 Å. Based on the relative strengths of the Balmer lines to these oxygen lines, we then derive total heavy element abundances and metallicities of 12+log (O/H) = $7.75^{+0.04}_{-0.17}$ and 12+log (O/H) = 7.63 ± 0.06 for W0801+26 and W1702+18, respectively, where these errors were derived using a Monte Carlo method with 10,000 simulations.

Using the Hα and 22 μm flux densities we measure SFRs as prescribed in Calzetti et al. (2007). We find SFR = 2.6 and 10.9 $M_\odot$ yr^{-1} for W0801+26 and W1702+18, respectively, which imply that these two BCDs are currently undergoing very extreme bursts of star formation activity. In addition, the Hβ equivalent widths >300 Å for W0801+26 and W1702+18 imply that the ages of the stellar populations are less than 5 Myr (Schaerer & Vacca 1998).

4. DISCUSSION AND SUMMARY

The low-metallicity and mid-infrared-dominated spectral energy distributions of these newly identified, *WISE*-selected galaxies place them in a rare class of active, low-metallicity BCDs. We compare the infrared properties of these BCDs with the infrared properties of known BCDs and find that the majority of low-metallicity BCDs in the literature are several magnitudes fainter at 12 μm ($W3$) than the two new sources. The properties of the two new BCDs are strikingly similar to one of the most well-known BCD, SBS 0335-052E, suggesting that the mechanisms responsible for SBS 0335-052E might be the same mechanism at work in W0801+26 and W1702+18.

In Figure 3 we show *WISE* $W1 - W2$ color versus metallicity, 12+ log (O/H), for different samples of BCDs. After visual inspections to remove galaxies that clearly are not BCDs, we include 14 BCDs from Wu et al. (2008), 173 from Izotov et al. (2006), three from Kniazev et al. (2003), SBS 0335-052E,

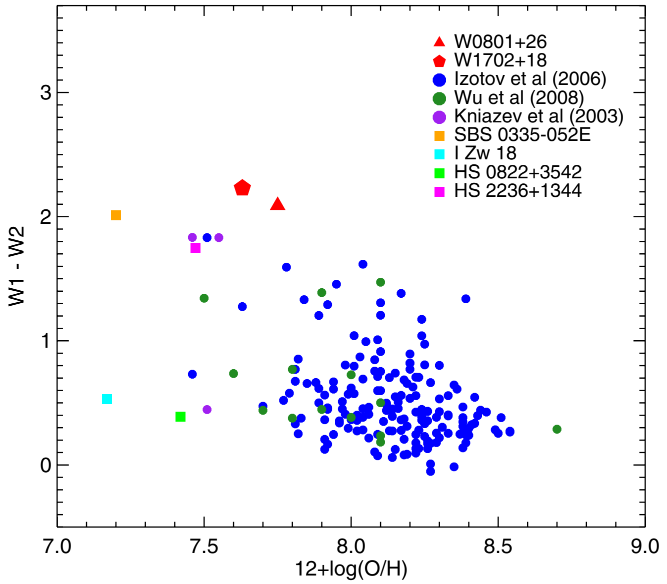

Figure 3. Mid-infrared color (Vega) vs. metallicity, 12 + log (O/H), for several samples of BCDs, as indicated. The plotted sources are required to have S/N > 5 in $W1$ and $W2$. For comparison, we also plot SBS 0335-052E, I Zw 18, HS 0822+3542, and HS 2236+1344, four of the lowest metallicity galaxies known to date. W0801+26 and W1702+18 are significantly redder in $W1 - W2$ than the majority of known BCDs.

I Zw 18, HS 0822+3542 (Izotov et al. 2006), HS 2236+1344 (Izotov & Thuan 2007), and our two newly discovered BCDs. With the exception of I Zw 18 and HS 0822+3542, we observe a slight correlation between $W1 - W2$ and metallicity for these samples, with $W1 - W2$ color becoming increasingly redder with decreasing metallicity. We apply the Spearman's rank correlation coefficient test on the Izotov et al. (2006) sample and recover a Spearman coefficient of $\rho = -0.36$. For a sample of that size, this indicates a noticeable correlation, deviating from the null-hypothesis at the 4σ level.

Since polycyclic aromatic hydrocarbon emission is largely absent in low-metallicity environments (Engelbracht et al. 2008), the mid-infrared spectra of BCDs are dominated by thermal emission with a minor contribution from nebula continuum (Smith & Hancock 2009). Thus, the 3.4 μm to 4.6 μm flux ratio is a relatively clean temperature indicator for the hot dust heated by young stars. At the lowest metallicities, $12 + \log(\mathrm{O/H}) < 7.8$, BCDs seem to group into two different color regions, $W1 - W2 \sim 2.0$ and ~ 0.5. This suggests two distinct star formation processes can be dominant, supporting the passive and active BCD modes suggested by Hirashita & Hunt (2004).

We are currently conducting follow-up observations of many more promising candidates discovered using the extreme infrared properties exhibited by these two sources and SBS 0335-052E. These results will be presented in a follow-up paper (C.-W. Tsai et al. 2011, in preparation). We expect that *WISE* will significantly increase the number of low-metallicity BCDs known, perhaps finding the most pristine example in the local universe. Such studies will allow us to construct a statistical sample from which to study and characterize the BCD population. The *WISE* BCDs will be a unique sample of mid-infrared, bright, low-metallicity galaxies for studying dust grain formation in low-metallicity environments, and will help us to understand the thermal dust emission of high-redshift, starburst galaxies.

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