THE EXTRAORDINARY MID-INFRARED SPECTRUM OF THE BLUE COMPACT DWARF GALAXY SBS 0335-052

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ApJS sup accepted (Spitzer Special Issue)

ABSTRACT

SBS0335-052 is a blue compact dwarf galaxy (BCD) with one of the lowest known metallicities, \(Z = Z_\odot/41\), making it a local example of how primordial starburst galaxies and their precursors might appear. A spectrum obtained with the Infrared Spectrograph (IRS1) on the Spitzer Space Telescope clearly shows silicate absorption features, emission lines of [SIV] and [NeIII], and puts strong upper limits on the PAH emission features. The observed low resolution spectrum \((\text{R} \sim 90)\) extends from 5.3 to 35 \(\mu\text{m}\) and peaks at \(\sim 28\mu\text{m}\). The spectrum is compared to IRS observations of the prototypical starburst nucleus NGC 7714. SBS0335-052 is quite unlike normal starburst galaxies, which show strong PAH bands, low ionization emission lines, and a continuum peak near 80 \(\mu\text{m}\). The continuum difference for \(\lambda > 30\mu\text{m}\) implies a substantial reduction in the mass of cold dust. If the spectrum of this very low metallicity galaxy is representative of star forming galaxies at higher redshifts, it may be difficult to distinguish them from AGNs which also show relatively featureless flat spectra in the mid-IR.

Subject headings: dust, extinction — galaxies: individual (SBS0335-052) — galaxies: starburst

1. INTRODUCTION

By virtue of their low metallicities, small size and low optical luminosity \((M_B \geq -18)\), Blue Compact Dwarf galaxies (BCDs) may be local examples of the building-blocks for the earliest galaxies \((\text{Rees} 1998)\). A large number of BCDs have been identified based on their blue colors and very low metallicities as determined by optical spectroscopy, which implies that star formation has begun only recently \((\text{see Kunth \\& Ostriker} 2004)\) for a review). Their blue color arises from one or more intense regions of active star formation that often appear nearly devoid of dust. The first identified member of this class was I Zw 18 \((\text{Searle \\& Sargent} 1972)\), which still remains the most metal poor member of the class with \(Z = Z_\odot/50\). Another object with similarly low metallicity \(Z = Z_\odot/41\), is SBS0335-052 \((\text{Izotov et al.} 1995)\) at a distance \(d = 57.6\text{ Mpc}\). In the case of SBS0335-052 six regions of massive star formation, five visible and one obscured, have been identified, with ages less than 25Myr and a total luminosity of \(\sim 10^9L_\odot\). All six are within a region of \(\sim 2\)″ or \(\sim 500\)pc in size \((\text{Thuan et al.} 1997)\), but roughly 75% of the total luminosity comes as mid-infrared (mid-IR) radiation \((\text{Plante \\& Sauvage} 2003)\). A few similar cases of obscured super star clusters which contribute a considerable fraction of the total luminosity of the host galaxy in the mid-IR have been observed so far. These include the Antennae interacting galaxies \((\text{Mirabel et al.} 1998)\) and the Wolf-Rayet galaxy He 2-10 \((\text{Vacca et al.} 2002)\). The frequency and implications of this phenomenon at higher redshifts \((z > 0.1)\) will require higher sensitivity observations of the mid-IR emission than have been available to date. SBS0335-052 was known to have an infrared-emitting dust continuum \((\text{Thuan et al.} 1994)\), and its dust properties have already been studied quite extensively with both the Infrared Space Observatory (ISO) and from ground based telescopes \((\text{Dale et al.} 2001)\) \((\text{Plante \\& Sauvage} 2002)\). However, there is still disagreement regarding whether the emitting dust is optically thick \((\text{Thuan et al.} 1995)\) or optically thin \((\text{Dale et al.} 2001)\). This impacts the question of how enshrouded the first generations of stars can be and whether or not there may exist a population of “optically-quiet” objects which are visible in the infrared but not in the optical.

We chose SBS0335-052, along with approximately 20 other well studied BCDs, to investigate the characteristics of star formation at very low metallicities using the IRS \((\text{Houck et al.} 2004)\) on Spitzer \((\text{Werner et al.} 2004)\). Similar low metallicity objects may be detected at much higher luminosity and much greater redshifts in Spitzer discovery surveys.

2. OBSERVATIONS

SBS0335-052 was observed using both IRS low resolution modules. The spectrum extends from 5.3 to 35 \(\mu\text{m}\) and was obtained on 6 February 2004. The red peak-up camera in medium-accuracy mode was used to locate the mid-IR centroid of the source and move it to the center of the spectrograph slits. The total integration time was 42 minutes with 28 minutes for the Short-Low module and 14 minutes for the Long-Low module. The total elapsed time including the telescope slew, target acquisition, settling, array conditioning, and integration was 61.3 minutes.

The basic processing of the data, such as ramp fit-
ting, dark sky subtraction, removal of cosmic rays, droop and linearity correction, wavelength calibration, etc, was performed using the IRS pipeline at the Spitzer Science Center (version S9.1). The resulting spectral images were sky-subtracted and a one-dimensional spectrum then extracted. The peak-up images were also used to derive a photometric point at 22µm (filter bandwidth 18.5–26.0µm). As described in detail in chapter 7 of the Spitzer Observer’s Manual, during IRS peak up we obtain 6 images of the science target. The on source time for the 22µm peak-up images of our target was 6×8=48 seconds and each image was created by reading the array in double-correlated sample mode. We processed the data on the ground to remove cosmic rays and the residual noise of the electronics. The resulting image had a prominent diffraction ring and was indistinguishable from the image of a point source. The conversion to flux density was based on a number of calibration stars for which peak-up images, IRS spectra, and reliable templates are available (Cohen et al. 2003). We find that the 22µm flux density of SBS 0335-052 is 70±11mJy.

3. RESULTS

3.1. Mid-IR Spectral Properties

Figure 1 shows the 5.3–35µm spectrum of SBS 0335-052 as observed by the IRS. Our data are in good agreement with the overall shape and intensity of the 5–15µm ISO spectrum of Thuan et al. (1999), but our signal to noise is at least a factor of 10 higher. This enables us for the first time to directly detect a few mid-IR ionic lines, while placing strong upper limits on others. The 9.7µm silicate absorption feature is clearly evident in our spectrum, and the 18µm feature is probably present. Using the silicate absorption profile measured towards the Galactic center Chiar & Tielens (2004), we find that for a screen model A9.7µm = 0.49mag, assuming a blackbody background source. More importantly, our spectrum indicates that the emission from the galaxy peaks at ~28µm which, as we discuss in the following section, has important consequences in estimating the dust mass and grain size distribution. In Figure 1 we also present a scaled version of the IRS low-resolution spectrum for the prototype starburst nucleus of NGC 7714 Brandl et al. (2004). Normalizing its flux to the corresponding flux of SBS 0335-052 at 14µm (the actual flux for NGC 7714 is ~9.5 times larger than shown). As also noted by Thuan et al. (1999), a striking difference between the spectrum of SBS 0335-052 and that of a more typical starburst is the absence of strong polycyclic aromatic hydrocarbon (PAH) features and low excitation ionic lines. In starburst galaxies, emission from PAHs is thought to originate from the photodissociation envelopes bordering the H II regions produced by the ionizing starburst. How these features can be absent in a low-metallicity starburst is an important astrophysical question. One possibility is that the absence of PAHs is due to low abundance of carbon and/or nucleating grains; another possibility is that PAHs are quickly destroyed. Table 1 shows that the observed line ratios of log([SIV]/[SIII])≥0.48, and log([NeII]/[NeIII])≥0.69 are similar to the most extreme example of ultra-compact H II regions in our Galaxy. The ratios indicate that the radiation field is extremely hard and corresponds to an effective stellar temperature of $T_{eff}$ ≥ 4×104K, assuming solar abundance (see Martin-Hernández et al. 2002). This would suggest that the absence of PAHs results from their destruction by the hard UV photons and strong winds produced by the massive stars (i.e. Allain et al. 1989). Such a scenario is quite likely since in low metallicity systems the attainment of UV photons is small and consequently their mean free path in the interstellar medium can be larger and photodissociation of PAH may occur over considerably larger scales than those seen in typical Galactic H II regions. Whatever the PAH life-cycle is in SBS 0335-052, the primary result is the well-defined absence of these features in the mid-IR.

Our spectrum displays strong [SIV]λ10.51µm, and [NeIII]λ15.55µm lines, while [SIII], [NeII], and H2 0-0 S(3) may also be present (see Table 1). The observed (not corrected for extinction) [NeIII] and [SIV] fluxes in conjunction with the free-free radio emission have been used to derive the ionic abundances Osterbrock 1989). This method is a priori more robust than using hydrogen recombination lines because it is relatively free of complicating factors: extinction, uncertainties about electron temperatures and densities as well as underlying stellar absorption and wind associated emission features. Using the results of Hunt et al. (2004), which suggest a free-free emission of $S_{f RF} = 0.27$ mJy at 5GHz and electron density of ~2000cm−3, as well as the helium abundance as given by Izotov et al. (1997) we find that Ne++/H++=1.05×10−5 which is ~9% of the solar value and S++/H++=4.3×10−7 or ~2% of solar Anders & Grevesse 1993; Grevesse & Noels 1994). These estimates are lower bounds on the total Ne and S abundances because only a single ionic state has been measured and extinction corrections have not been made. Had we corrected for extinction based on the observed

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6 http://ssc.spitzer.caltech.edu/documents/som/
mid-IR line fluxes of SBS0335-052

| Ion    | λ(μm) | Flux (×10^{-17} W m^{-2}) |
|--------|-------|-----------------------------|
| SIV    | 10.51 | 1.62±0.09                   |
| SIII   | 18.71 | <0.54                       |
| NeII   | 12.81 | <0.28                       |
| NeIII  | 15.55 | 1.40±0.08                   |
| H2 0-0 S(3) | 9.67 | <0.37                       |

The upper limits are 3-σ.

9.7 μm silicate absorption, the corresponding A_{10.51μm} = 0.33 mag and A_{15.56μm} = 0.072 mag would imply that the abundances could be higher by a factor of 1.36 and 1.07 respectively. These abundances are higher than the Z_⊙/41 metallicity that is derived for oxygen from the optical observations and imply that the region probed by our spectrum has polluted its environment by mass loss from supernovae (SNe) and Wolf-Rayet stars.

However, there are a number of issues associated with the above mentioned abundances which must be considered. There is an inconsistency between the radio measurements and the fluxes of the hydrogen recombination lines quoted in the literature. If we use the 5 GHz free-free emission of Hunt et al. (2004) to predict the corresponding extinction corrected Hβ flux we find a value of 6.1×10^{-14} erg cm^{-2} s^{-1} which is lower than the observed (not corrected for extinction) value of 8.5×10^{-14} erg cm^{-2} s^{-1} by Izotov & Thuan (1998). The predicted Bro flux is also a factor of ~2–5 less than the one observed and Hunt et al. (2004) advocate that winds could account for some of the Bro flux. It remains unclear why these winds would not affect the other recombination lines. Even if we were to consider possible errors in the estimate of the thermal radio emission the puzzle remains. Clearly a fraction of the observed IR line fluxes originates from the dust-free “optical” region of the galaxy. To estimate this we can use the optical [NeIII]λ3868Å measurements and derived physical conditions of the interstellar gas by Izotov et al. (1997) to predict the corresponding [NeIII]λ15.55μm flux. For a T_e = 20,000 K Izotov et al. (1997) derives 19,200 K for O III) we find that the [NeIII]λ15.55μm flux predicted by the optical measurements is 0.75×10^{-14} erg cm^{-2} s^{-1}, ~2 times lower than what is observed. This would suggest that indeed there is a star forming region of the galaxy which is not accessible in the optical. The result though depends strongly on the electron temperature. If T_e = 15,000 K then the predicted mid-IR flux is similar to the one observed. However, this would place the Ne^{++} region at the same temperature as the O^{+} region; an unlikely situation. The 9.7 μm silicate feature clearly indicates that there is a powerful source of luminosity hidden behind a screen of at least A_{α_9.7 μm} ~ 0.5 mag or A_{V} ~ 15 mag. Clearly all of these uncertainties can strongly affect any abundance calculations.

Another major difference between the two spectra shown in Figure 1 is that in SBS0335-052 the continuum shortward of ~15 μm appears similar to that which underlies the emission features in NGC 7714. However, these continua depart dramatically at longer wavelengths. The continuum of NGC 7714 increases rapidly at longer wavelengths because of a relatively more massive cool dust component which characterizes many luminous infrared galaxies. Conversely, the spectrum of SBS0335-052 peaks at 28 μm. In Figure 2 we have drawn an offset power-law, f_ν ∼ ν^{1.3}, to the IRS spectrum to extrapolate to longer wavelengths. Using the non thermal 1.46GHz flux density of the galaxy measured by Hunt et al. (2004) and the radio to far-infrared correlation, we predict that the far-infrared luminosity is F_{f_ν} (43–123 μm) = 2×10^{-15} W m^{-2}. The corresponding average flux density over this wavelength range is ~44 mJy. Even if the entire far-infrared luminosity originates from the 60 μm band, the corresponding flux density would be 58 mJy, well below the 112 mJy measurement at 65 μm. However, the 58 mJy estimate is consistent with the IRS spectrum which clearly decreases at wavelengths longer than 30 μm.

These two major differences, no PAH features and relatively flat continuum, provide an initial indication that the PAH criterion for identifying starbursts may not apply to systems of low metallicity. Mid-IR spectra of Active Galactic Nuclei (AGN) often display ionic lines and also lack PAH emission features, but the continua are typically even flatter between 5–20 μm than SBS0335-052 (see ISO observations of Seyfert 1s by Clavel et al. 2000, or the nuclear spectrum of NGC 1068 by Sturm et al. 2000 and Le Floc’h et al. 2001 as well as Peeters et al. 2004). If metal poor galaxies such as SBS0335-052 can be present at z ~ 0, it is likely that similar systems may exist not only as high-z primordial galaxies, but also at intermediate redshifts 0.5 < z < 1.5 where moderate luminosity galaxies (L_{IR} < 10^{11} L_⊙) are accessible with the deep infrared surveys performed by Spitzer. Far-infrared and submillimeter photometric methods for estimating redshifts based on spectral energy distributions (SEDs)
of nearby metal rich systems, with continuum peaking at $\sim 100 \, \mu m$, would fail to identify metal poor systems with SEDs similar to that of SBS 0335-052, which peaks at $\sim 28 \, \mu m$.

3.2. IR luminosity and Dust Mass

The luminosity of a dust obscured source is the integrated infrared flux corrected for the object’s distance. However, determining the total dust mass depends crucially on the dust’s temperature, distribution, and the optical properties. Takeuchi et al. (2003) concluded from their 5–15 $\mu m$ ISO spectrum that the starburst responsible for heating the dust which produces the mid-IR continuum in SBS 0335-052 is heavily obscured, with an optical extinction $A_V \sim 20$ mag. They also modeled the dust continuum as being represented by a single temperature of about 260K and an emissivity, $\epsilon$, $\sim \nu^{1.5}$. On this basis they suggested that the young star clusters visible optically were independent of the obscured clusters. These general conclusions have been supported by Hunt et al. (2001; 2004), Plante & Sauvage (2002), and Takeuchi et al. (2003). If correct, this interpretation implies that primordial starbursts of very low metallicity can nevertheless surround themselves with sufficient dust to be completely hidden optically. A very different conclusion was reached by Dale et al. (2001), using ground-based mid-IR imagery; they conclude that the optical extinction to the starburst which heats the dust is less than one magnitude and that a two component dust model is needed, with temperatures of about 80K and 210K. Both components are optically thin, and the bolometric luminosity is dominated by the cooler component.

All previously published models extending beyond 20 $\mu m$ had their assumed spectral anchored to the IRAS and ISO limits at 60 and 100 $\mu m$, as well as to the ISO detection at 65 $\mu m$ (Dale et al. 2001; Plante & Sauvage 2002). The shape and intensity of the IRS spectrum clearly demonstrates that those far-infrared values do not accurately reflect the true shape of the spectrum, which is inconsistent with a flux density above $\sim 70$ mJy anywhere in the 30–100 $\mu m$ range (see Figure 2). We have fit both the new IRS spectrum and the old ISO spectrum with a simple two-temperature model with emissivity of $\epsilon \sim \nu^{1.5}$. In both cases good fits are obtained with dust temperatures of $\sim 65$ and $\sim 150$K. While the $\sim 150$K component is the same for both models, the required dust mass for the cool component is 4 times less for the Spitzer spectrum. Scaling to the predicted 100 $\mu m$ flux, we estimate the mass of the cool dust to be $6 \times 10^5$ M$_\odot$ for the spectrum based on the ISO data and $1.5 \times 10^5$ M$_\odot$ for the IRS spectrum (Hildebrand 1983; Cox 2000). These masses are considerably below the masses reported previously ($\sim 10^5$ M$_\odot$, see Takeuchi et al. 1999; Hunt et al. 2001; Plante & Sauvage 2002). Qualitatively this is because the cool component in the Spitzer model is warmer and produces less flux than the cold component in the ISO models. Dramatic changes in the dust properties could increase the dust mass, but the materials used in the cited models do not differ greatly from the standard. Several models, including the one developed by Takeuchi et al. (2003), derive a large fraction of the dust components from the SNe ejecta produced in the enshrouded super star clusters. However, the amount of dust produced by SNe in low metallicity systems is predicted to be rather low (i.e. Todini & Ferrara 2001). Furthermore, in SNe remnants of our Galaxy most of the dust appears to be very cold (T$\sim$18K, Dunne et al. 2003). The fact that the Spitzer data suggest that much less cool dust is required eases the problem of accounting for the in situ dust generation.

4. CONCLUSIONS

The very low metallicity Blue Compact Dwarf galaxy SBS 0335-052 is shown to have a very unusual spectrum which is quite different from the spectrum of typical starburst galaxies — the flux density, $f_\nu$, peaks at $\sim 28 \, \mu m$ while the luminosity, $L_\nu$, peaks at $\sim 20 \, \mu m$. There are no detectable PAH emission features. The spectrum is characterized by a warm ($\sim 150$K) dust component with a more massive cool ($\sim 65$K) dusty envelope. However, the mass of the cool region is far less than what had been previously estimated. Silicate absorption features are clearly present ($A_{\text{sil}} \gtrsim 0.49$ mag). Preliminary analysis of the infrared ionic lines suggests that the young central cluster may have already polluted the cocoon enshrouding it, and its metallicity could be higher than that determined from optical observations alone. Upcoming mid-IR spectroscopy using the high resolution modules of IRS will provide higher sensitivity and more accurate line fluxes. Theoretical models have indicated that the dust responsible for the mid-IR emission can be explained by ejecta from type 2 SNe and Wolf-Rayet stars in the buried super star cluster. However, there are no complete models to date that fit the mid-IR spectrum and include dynamics of the dust generation and entrapment mechanisms.

We would like to thank an anonymous referee whose comments greatly improved the paper. The IRS was designed and built by Ball Aerospace Corporation under contract from Cornell University. Many dedicated individuals at Ball made the IRS a success. The IRS pipeline data reduction tools were developed at the Spitzer Science Center. This work is based in part on observations made with the Spitzer Space Telescope, which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under NASA contract 1407. Support for this work was provided by NASA through Contract Number 1257184 issued by JPL/Caltech.

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