DUST IN AN EXTREMELY METAL-POOR GALAXY: MID-INFRARED OBSERVATIONS OF SBS 0335−052

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ABSTRACT

The metal deficient ($Z = Z_\odot/41$) Blue Compact Dwarf Galaxy (BCD) SBS 0335−052 was observed with ISOCAM between 5 and 17 μm. With a $L_{12\mu m}/L_B$ ratio of 2.15, the galaxy is unexpectedly bright in the mid-infrared. The spectral energy distribution (SED) is dominated by a very strong continuum which makes the ionic lines of [SIV] and [NeIII] very weak. From 5 to 17 μm the SED can be fitted with a grey-body spectrum, modified by an extinction law similar to that observed toward the Galactic Center, with an optical depth of A_V $\sim$19-21 mag. Such a large optical depth implies that a large fraction (as much as $\sim 75\%$) of the current star-formation activity in SBS 0335−052 is hidden by dust with a mass between $3{\times}10^3\,M_\odot$ and $5{\times}10^5\,M_\odot$. It is remarkable that such a nearly primordial environment contains as much dust as galaxies which are 10 times more metal-rich. If the hidden star formation in SBS 0335−052 is typical of young galaxies at high redshifts, then the cosmic star formation rate derived from UV/optical fluxes would be underestimated.

1. INTRODUCTION

Galaxy formation is one of the most fundamental unsolved problems in astrophysics. Much effort has gone into the search for primeval galaxies (hereafter PGs), i.e. galaxies undergoing their first major burst of star formation, at redshifts larger than ∼2. Several objects have been put forward as possible PGs, ranging from high-redshift radio-galaxies to Lyα emitters. However, most of these candidate PGs appear to already contain a substantial amount of heavy elements (as indicated for example by the presence of P Cygni profiles), implying previous star formation and metal enrichment.

SBS 0335−052 is a relatively nearby Blue Compact Dwarf Galaxy (hereafter BCD) with an absolute magnitude M_B= -16.7 and which appears to be undergoing its first burst of star formation. With a metallicity of only $Z_\odot/41$ (Izotov et al. 1997), it is the second most metal-deficient galaxy known, after I Zw 18 ($Z_\odot/50$). With a redshift of 0.0136 and a Hubble constant of 75 km s^{-1} Mpc^{-1}, it is at a distance of 54.3 Mpc ($1''=263$ pc). Thuan et al. (1997) have found that the stars in SBS 0335−052 are not older than $\sim$ 100 Myr, making it a truly young galaxy. Yet, despite its youth and extremely low metallicity, HST images of SBS 0335−052 clearly show dust patches mixed in with the six super-star clusters where most of the star formation is occurring (Thuan et al. 1997). We have therefore obtained MIR observations of SBS 0335−052 with the Infrared Space Observatory (ISO) to study the properties of dust and star formation in a truly metal-deficient environment, similar to those prevailing at the epoch of galaxy formation.

2. OBSERVATIONS AND DATA REDUCTION

The observations were obtained with ISOCAM (Cesarsky et al. 1996a), the MIR imaging instrument aboard ISO (Kessler et al. 1996). They consist of two different sets: a set of broad-band filter maps, and a set obtained by imaging spectroscopy.

The broad-band maps were obtained with a spatial sampling of 3″ per pixel and in a 3×3 raster mode with a 3-pixel displacement in each direction. We used the LW9, LW10, LW8, LW6 and LW2 filters, centered respectively at 14.9, 12.0, 11.3, 7.7 and 6.7 μm. Note that the LW10 filter is identical to the IRAS 12 μm filter. Total on-source times were 860 s for LW10 and 1540 s for the other filters. Imaging spectroscopy was performed using the Circular Variable Filter (CVF) facility of ISOCAM with a sampling of 6″ per pixel and a spectral resolution $\lambda/\Delta\lambda$ of $\simeq 40$. Due to the faintness of the source we obtained observations only in the 8.78- 17.34 μm wavelength range. The total on-source time was 4800 s.

The various steps of ISOCAM data reduction[1] are detailed in Stark et al. (1998) and we will only describe

[1]We used the software package "CIA", a joint development by the ESA Astrophysics Division and the ISOCAM consortium. The ISOCAM consortium is led by the ISOCAM PI, C. Cesarsky, Direction des Sciences de la Matière, C.E.A, France.

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here aspects that depart from the methods discussed in that paper: dark current subtraction and transient correction.

The dark current is known to show secular trends which depend on the position of the satellite in its orbit and on the time elapsed since launch. These trends can be accurately modelled (see Biviano et al. 1998), allowing nominal dark subtraction.

Transient corrections using the inversion algorithm of Abergel et al. (1996) were applied successfully to the broad-band observations. For the CVF observations, the known oversimplification of the method combined with the intrinsic faintness of the source results in errors of similar magnitude for both corrected and uncorrected CVF data. Synthesis of the LW8 and LW9 flux densities from corrected or uncorrected spectra gives flux densities 1.3 times larger than the observed ones. Thus we have adopted for the remaining discussion the CVF spectrum uncorrected for transient effects and scaled down by a factor of 1.3. Figure 1 displays the spectral energy distribution of SBS 0335−052. Flat-fielding and photometry for the CVF scan were made following Aussel et al. (1998). Conversion from camera units to mJy was performed using the calibration factors given in the *ISOCAM Cookbook*[2]. Most of the star formation in SBS 0335−052 occurs within a region of ∼2.5" in size, so that the individual super-star clusters in SBS 0335−052 are not resolved by ISOCAM.

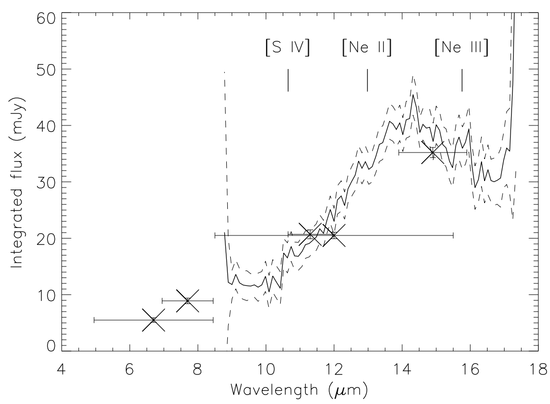

Figure 1. The spectral energy distribution of SBS 0335−052. Crosses represent broad-band observations with horizontal bars showing the width of the filters. 1σ errors bars are smaller than the symbols. Broad-band flux densities have been integrated over the point spread function. The thick line is the CVF spectrum with the effects of varying point spread function with wavelength taken into account. The dashed lines show ±1σ errors. Expected positions of the [SIV]λ10.5μm, [NeII]λ12.8μm, and [NeIII]λ15.6μm emission lines are indicated.

[2] *http://www.iso.vilspa.esa.es/manuals/iso_cam/.*

3. DISCUSSION

3.1. Global properties

Since the ISOCAM LW10 filter is equivalent to the IRAS 12 μm filter, it is interesting to see how the integrated properties of SBS 0335−052 compare with those of other BCDs and irregular galaxies. We have thus compiled IRAS and Hα data for the Thuan & Martin (1981) catalog of BCDs, hereafter TM81, as well as for the sample of BCDs and irregular galaxies in Sauvage et al. (1990) to perform the comparison.

With a 12 μm to blue luminosity ratio L_{12}/L_B of 2.15±0.06, SBS 0335−052 is comparable to the most MIR-bright objects in the TM81 catalog. In that sample the mean L_{12}/L_B ratio ($<\log L_{12}/L_B> = -0.12\pm0.27$), while already twice as high as that for spiral galaxies in the CfA catalog (Sauvage & Thuan 1994), is a factor of 3 smaller than the ratio for SBS 0335−052. This shows that even though the BCD is ∼ 10 times more metal-poor than the galaxies in TM81, it nevertheless contains a significant amount of dust heated by an intense UV radiation field.

If we compare the 12 μm luminosity to a tracer of star formation such as the Hα luminosity, SBS 0335−052 appears to be normal. Although total Hα fluxes are scarce for BCDs, the available data give $<\log L_{12}/L_{H\alpha}> = 0.96\pm0.70$ for the above samples, as compared to 0.65±0.03 for SBS 0335−052. Thus, even though the metallicity of the BCD is exceptionally low, and the galaxy unusually MIR-bright, its star-forming properties appear to be normal when compared to other BCDs.

3.2. The Mid-infrared spectrum

When the MIR spectral energy distribution of SBS 0335−052 (Figure 1) is compared to MIR spectra of other star-forming galaxies (see e.g. Vigroux 1997), two facts stand out : (1) there is no emission from the so-called Unidentified Infrared Bands (hereafter UIBs, usually attributed to carbon-based dust, see e.g. Puget & Léger 1989; Papoular et al. 1996); and (2) there are no evident fine structure ionic lines, even though neon as well as sulfur lines are usually quite bright in starburst galaxies.

In Figure 1, a hint of the [SIV]λ10.5μm and [NeIII]λ15.6μm lines can be seen. The quality of our spectrum prevents us from actually measuring line fluxes. Instead we compute upper limits as twice the local rms noise times the instrumental profile width at 20% of peak intensity at the line location. We obtain upper limits of $5.6\times10^{-14}\,\mathrm{erg\,s^{-1}\,cm^{-2}}$ for [SIV], $4.5\times10^{-14}\,\mathrm{erg\,s^{-1}\,cm^{-2}}$ for [NeII], and $5.4\times10^{-14}\,\mathrm{erg\,s^{-1}\,cm^{-2}}$ for [NeIII]. These upper limits are completely consistent with the prediction of the photoionization model of Stasinska (1990). We conclude, therefore, that the weakness (or absence) of ionic fine-structure lines in SBS 0335−052 can be explained by a very strong continuum which decreases the equivalent widths of the lines, making them difficult to detect.

None of the usual UIB features are seen, suggesting that their carbonaceous carriers are absent or have been destroyed. As the star-forming region, 660 pc in diameter, contains 5000 equivalent O7 stars (Izotov et al. 1997), the average energy density is $\gtrsim 10\,\mathrm{eV\,cm^{-3}}$. Puget & Léger (1989) suggest that at this stage, the abundance of the band-emitting dust is reduced by a factor of ∼10. Therefore the absence of the bands can be understood as a destruction effect. The origin of the continuum emission is more problematic. We observe what could be interpreted as either a broad emission feature at around 14 μm, or a broad absorption feature at $\lambda \gtrsim 16\,\mu$m. As we know of no candidate which would show such an emission feature we favor the second interpretation. Indeed silicate absorption bands at 9.7 and 18 μm could provide an explanation for the strange shape of the MIR spectrum of SBS 0335−052.

Testing this is not straightforward as the expected shape of the dust emission spectrum in this wavelength range is difficult to constrain. Apart from the stochastic heating of macromolecules giving rise to the UIBs, MIR emission is thought to be produced by very small grains in a thermal regime intermediate between equilibrium and stochastic heating (see e.g. Désert et al. 1990). We have therefore attempted to fit the spectral energy distribution (SED) of SBS 0335−052 with different screen models where the emission spectrum was successively: (1) a black-body modified by an emissivity law of the form $f_\nu \propto B_\nu(T)\,\nu^{1-2}$; (2) a power-law spectrum; and (3) the continuum MIR spectrum of the Galactic HII region M17 with UIBs and ionic lines removed (Cesarsky et al. 1996b). The free parameters of the underlying spectra include in all cases a scaling factor, in addition to the temperature in case (1) and the power-law slope in case (2). A further uncertainty comes from the extinction curve to be used. We have tried two different laws, the standard MIR extinction law of Draine (1989), and that observed in the direction of the Galactic Center by Lutz et al. (1996). The latter differs from the previous one by its much higher A_λ/A_V in the range 2-8 μm. This difference is ascribed to ice coating on grains. The free parameter associated with the extinction curve is simply the absolute extinction at a reference wavelength. Our fitting procedure searches for best fits to the CVF scan data only. There is no attempt to fit the broad-band data outside of the CVF range. However, a successful model will be one that also accurately predicts them.

Both a power law and the M17 spectrum fail to reproduce the observed SED. Power laws overproduce emission shortward of 8 μm while the M17 spectrum overestimates emission longward of 14 μm. On the contrary, a black-body spectrum modified by an emissivity law proportional to $\nu^{1.5}$ and extinguished by a screen of dust, gives an excellent fit to the SED of SBS 0335−052 (Figure 2). The fit is very sensitive to the shape of the extinction law. It is impossible to obtain a good fit for the LW2 and LW6 bands with the standard extinction curve of Draine (1989). On the contrary, excellent fits of these bands can be obtained with the Lutz et al. (1996) extinction curve. The temperature obtained for the black-body curve probably carries little physical meaning since the MIR-emitting grains are not likely to be in thermal equilibrium.

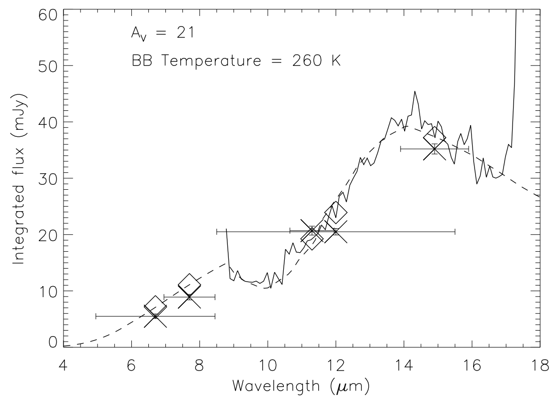

Figure 2. The best-fit model (dashed line) for the spectral energy distribution of SBS 0335−052. It consists of a black-body of temperature 260 K, with an exponent of 1.5 for the emissivity law, and A_V = 21 mag. The extinction curve of Lutz et al. (1996) gives the best results. Open diamonds show the prediction of the best-fit spectrum for broad-band measurements. The agreement with the observations is satisfactory for all filters.

The information we derive concerning the dust extinction is more physical. Given the uncertainties in our data, we obtain an equivalent A_V of 19-21 mag. Such a high value of extinction is in sharp contrast to the values ($A_V \leq 0.6$ mag) derived by Izotov et al. (1997) from optical spectrophotometric observations. The large difference between the optical and infrared extinctions implies that the heating sources responsible for the infrared emission detected by ISO are probably too deeply embedded in dust to be detected in the visible and that most of the infrared emission is powered by invisible star clusters. Indeed, correcting the Hα flux for 20 mag of visible extinction would lead to unrealistically high star formation rates which would be incompatible with the non-detection of SBS 0335−052 in the far-infrared by IRAS.

The LW10 luminosity of $2.5 \times 10^8\ L_\odot$ is equivalent to the bolometric luminosity of 2500 O7 stars, i.e. half the equivalent number of stars in the visible super-star clusters. Given that in the BCD sample of TM81, $<\log L_{12}/L_{FIR}> = -0.85 \pm 0.09$, it is probable that in fact some 18000 equivalent O7 stars are required to power the total infrared emission. This implies that even in very low-metallicity environments such as those characterizing PGs, a significant fraction, i.e. ∼ 3/4, of the total star formation activity of a galaxy can be effectively hidden from UV/optical observations.

From the extinction derived in the MIR, we can estimate the dust mass. As MIR extinction is essentially due to silicates (Draine & Lee 1984), this result will likely be a lower limit as some carbon-based dust can also be present. Using the dust model of Draine & Lee (1984), we obtain a dust surface density of 1.5 $M_\odot\,pc^{-2}$. To derive a dust mass, we need to estimate lower and upper bounds to the dust spatial extent. For a lower bound, we assume that the dust is only associated with hidden super-star clusters (SSCs). O'Connell et al. (1994) found that SSCs typically have a very compact core with a half-light radius of ~ 3 pc, embedded in considerably more extended halos with diameters ~ 30 pc. If we adopt the latter value, and consider that at least 3 SSCs are hidden (they have the power of 2500 equivalent O7 stars needed to power the LW10 luminosity), we derive a dust mass of $\sim 3.2 \times 10^3\, M_\odot$. A likely upper limit to the spatial extent of the dust is the size of the region where reddening is observed by HST (Thuan et al. 1997), i.e. 660 pc. This gives a dust mass of $5\times10^5\, M_\odot$.

With the HI mass given in Thuan et al. (1997), the gas-to-dust mass ratio of SBS 0335−052 is then between $\sim 2 \times 10^3$ and $\sim 3 \times 10^5$, i.e. much higher than in the Galaxy, which is not too surprising for such a low metallicity object. More extraordinary is the fact that the dust mass in SBS 0335−052 can be of the same order of magnitude as that in BCDs which are on average ~ 10 times more metal-rich ($<\log M_{dust}> = 4.4\pm0.6\, M_\odot$ in the TM81 BCD sample).

Because stars in SBS 0335−052 are not older than $\sim$100 Myr, there is not enough time for the silicate dust to be made in the envelopes of red giant stars. Rather silicate grains probably condensed out of supernova ejecta (see e.g. Dwek et al. 1992). Adopting the supernova silicate dust mass input rate of $0.5\, M_\odot\, pc^{-2}\, Gyr^{-1}$ obtained by Dwek (1998) for the Galactic Center at 0.1 Gyr, the age of SBS 0335−052, and assuming the diameter of the dust-forming region to be 660 pc, we derive a silicate dust mass of $\sim 2\times10^4\, M_\odot$, i.e. in the range of the above estimates.

4. CONCLUSIONS AND IMPLICATIONS

Although SBS 0335−052 is one of the most metal-deficient galaxies known, it is unexpectedly bright in the MIR range, implying a silicate dust mass in the range 10^3–$10^5\, M_\odot$. The SED shows pronounced extinction, $A_V \sim 20$ mag. Given that the total MIR luminosity already requires the bolometric luminosity of 50% more young stars than are seen in the galaxy, the star formation rate (SFR) as derived from the optical or UV luminosities must underestimate the true star formation rate by at least 50%, and more likely by a factor of 4 as argued above. Thus if SBS 0335−052 is a representative example of PGs, the cosmic star formation rate will be systematically underestimated if based only on UV and optical fluxes.

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REFERENCES

Abergel, A., et al. 1996, A&A, 315, L329

Aussel, H., Gerin, M., Boulanger, F., Désert, F. X., Casoli, F., Cutri, R. M., & Signore, M. 1998, A&A, 334, L73

Biviano, A., Sauvage, M., Roman, P., Boulade, O., Gallais, P., & Okumura, K. 1998, "The ISOCAM dark current calibration report", ESA Technical report

Cesarsky, C., et al. 1996a, A&A, 315, L32

Cesarsky, D., Lequeux, J., Abergel, A., Perault, M., Palazzi, E., Madden, S., & Tran, D. 1996b, A&A, 315, L309

Desert, F. X., Boulanger, F., & Puget, J. L. 1990, A&A, 237, 215

Draine, B. T. 1989, in Infrared spectroscopy in astronomy, ed. B. H. Kaldeich, (Noordwijk:ESA), 93

Draine, B. T., & Lee, H. M. 1984, ApJ, 285, 89

Dwek, E., Moseley, S. H., Glaccum, W., Graham, J. R., Loewenstein, R. F., Silverberg, R. F., & Smith, R. K. 1992, ApJ, 389, L21

Dwek, E. 1998, ApJ, 501, 643

Izotov, Y., Lipovetsky, V. A., Chaffee, F. H., Foltz, C. B., Guseva, N. G., & Kniazev, A. Y. 1997, ApJ, 476, 698

Kessler, M. F., et al. 1996, A&A, 315, L27

Lutz, D., et al. 1996, A&A, 315, L269

O'Connell, R. W., Gallagher, J. S., & Hunter, D. A. 1994, ApJ, 433, 65

Papoular, R., Conard, J., Guillois, O., Nenner, I., Reynaud, C., & Rouzaud, J. N. 1996, A&A, 315, 222

Puget, J. L., & Leger, A. 1989, ARA&A, 27, 161

Sauvage, M., & Thuan, T. X. 1994, ApJ, 429, 153

Sauvage, M., Thuan, T. X., & Vigroux, L. 1990, A&A, 237, 296

Starck, J. L., et al. 1998, A&A, in press

Stasinska, G. 1990, A&AS, 83, 501

Thuan, T. X., & Martin, G. E. 1981, ApJ, 247, 823

Thuan, T. X., Izotov, Y. I., & Lipovetsky, V. A. 1997, ApJ, 477, 661

Vigroux, L. 1997, in Extragalactic astronomy in the infrared, ed. G. Mamon, T. X. Thuan, & J. T. T. Van, (Paris: Editions Frontières), 63