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

TRINH X. THUAN
Astronomy Department, University of Virginia, P.O. Box 3818, University Station, Charlottesville, VA 22903-0818; txt@virginia.edu

AND

MARC SAUVAGE AND SUZANNE MADDEN
CEA/DSM/DAPNIA/Service d’Astrophysique, CE-Saclay, 91911 Gif sur Yvette Cedex, France; msauvage@cea.fr, smadden@cea.fr

Received 1998 October 1; accepted 1998 December 15

ABSTRACT

The metal-deficient \( (Z = Z_{\odot}/41) \) blue compact dwarf galaxy SBS 0335–052 was observed with ISOcAM between 5 and 17 \( \mu \text{m} \). With an \( L_{12\mu\text{m}}/L_B \) ratio of 2.15, the galaxy is unexpectedly bright in the mid-infrared for such a low-metallicity object. The mid-infrared spectrum shows no sign of the unidentified infrared bands, which we interpret as an effect of the destruction of their carriers by the very high UV energy density in SBS 0335–052. The spectral energy distribution (SED) is dominated by a very strong continuum, which makes the ionic lines of \([\text{S} IV]\) and \([\text{Ne} III]\) very weak. From 5 to 17 \( \mu \text{m} \), the SED can be fitted with a graybody spectrum, modified by an extinction law similar to that observed toward the Galactic center, with an optical depth of \( \tau_L \sim 19-21 \text{ mag} \). 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\(^3\) and 5 \( \times \) 10\(^5\) \( M_{\odot} \). Silicate grains that are present as silicate extinction bands at 9.7 and 18 \( \mu \text{m} \) can account for the unusual shape of the MIR spectrum of SBS 0335–052. It is remarkable that such a nearly primordial environment contains as much dust as galaxies that 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.

Subject headings: dust, extinction — galaxies: compact — galaxies: dwarf — galaxies: individual (SBS 0335–052) — galaxies: ISM — infrared: galaxies

1. INTRODUCTION

Galaxy formation is one of the most fundamental unsolved problems in astrophysics. Much effort has gone into the search for primeval galaxies (PGs), i.e., galaxies undergoing their first major burst of star formation, at redshifts larger than \( \sim 2 \). Several objects have been put forward as possible PGs, ranging from high-redshift radio galaxies to Ly\( \alpha \) emitters (see, e.g., Steidel et al. 1996; Yee et al. 1996). 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), which implies previous star formation and metal enrichment.

SBS 0335–052 [\( \alpha(1950) = 03\text{h}35\text{m}15\text{s}2, \delta(1950) = -05\text{d}25\text{m}9 \)] is a relatively nearby blue compact dwarf (BCD) galaxy 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\( \text{arcsec} \) = 263 pc). Thuan, Izotov, & Lipovetsky (1997) and Papaderos et al. (1998) have found that the stars in SBS 0335–052 are not older than \( \sim 100 \text{ Myr} \), which makes it a truly young galaxy. Thuan & Izotov (1997) suggest that the large \( \text{H} I \) envelope within which SBS 0335–052 is embedded may be truly primordial. Yet despite its youth and extremely low metallicity, Hubble Space Telescope (HST) images of SBS 0335–052 clearly show dust patches mixed in with the six super–star clusters (SSCs) where most of the star formation is occurring (Thuan et al. 1997). The presence of dust in combination with the intense ultraviolet radiation field from the many young stars in SBS 0335–052 suggests that there may be detectable mid-infrared (MIR) emission, as the dust will reprocess the UV starlight and re-emit it in the infrared. 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 MID Imaging instrument onboard ISO (Kessler et al. 1996). They consist of two different sets: a set of broadband filter maps, and a set obtained by imaging spectroscopy.

The broadband maps were obtained with a spatial sampling of 3\( \text{arcsec} \) pixel\(^{-1}\) and in a 3 \( \times \) 3 raster mode with a 3\( \text{pixel} \) displacement in each direction, giving a total field of view of 114\( \times \)114\( \text{arcsec} \). The raster mode increases the sensitivity and improves the flat-field correction, since in the center of the map each sky position is imaged by 9 different camera pixels. The maps were obtained with the LW9, LW10, LW8, LW6, and LW2 filters, centered respectively at 14.9, 12.0, 11.3, 7.7, and 6.7 \( \mu \text{m} \) (Table 1). Note that the LW10 filter is identical to the IRAS 12 \( \mu \text{m} \) filter. The integration time was 10.08 s per readout for all filters except LW10, for which an

\(^{1}\) Based on data obtained with ISO, an ESA project with instruments funded by the ESA member states (especially the PI countries: France, Germany, the Netherlands, and the United Kingdom) with the participation of ISAS and NASA.
integration time of 5.04 s was used. 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. This mode produces images of the full ISOCAM field of view (192’’ × 192’’) in the 2–17 μm wavelength region, with a sampling of 6’’ pixel⁻¹ and a spectral resolution λ/Δλ of ≈40. Due to the faintness of the source, we obtained observations only in the 8.78–17.34 μm wavelength range. The individual integration time was 5.04 s, and the total on-source time was 4800 s.

The various steps of ISOCAM data reduction are detailed in Starck et al. (1999), and we will only describe 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 that depend on the position of the satellite in its orbit and on the time elapsed since launch. These trends can be accurately modeled, allowing nominal dark subtraction.²

Transient corrections using the inversion algorithm of Abergel et al. (1996) were applied successfully to the broadband 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. The main effect of the correction is to add an artifact at the start of the spectrum (around 17 μm) while leaving the rest of the scan unchanged. In particular, synthesis of the LW8 and LW9 flux densities from corrected or uncorrected spectra gives flux densities 1.3 times larger than the observed broadband flux densities. That the CVF produces higher flux densities than the broadband filters is to be expected: the operational setup of ISOCAM is such that the scan starts with a short exposure through the LW2 filter with a scale of 6’’ pixel⁻¹, giving a much higher illumination on the detector than the scan itself. Since the source is very faint, the detector would need a much longer time than our adopted exposure time to stabilize down to its true level. This is not the case for the broadband maps since the broader filters allow many more photons to reach the detector, thus speeding the stabilization process. As a result, 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. The flat-fielding and photometry of 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.³ HST images (Thuan et al. 1997) reveal that most of the star formation in SBS 0335–052 occurs within a region of ~2’’ in size, so that the individual SSCs in SBS 0335–052 are not resolved by ISOCAM. Thus the flux densities given in Table 1 and plotted in Figure 1 are integrated over the whole star-forming region.

### Table 1

| Filter   | λ₀ (μm) | Δλ (10⁻¹² Hz) | Δλ (μm) | Flux Density (mJy) | 1 σ (mJy) | Luminosity* (L☉) |
|----------|---------|---------------|---------|-------------------|-----------|------------------|
| LW9      | 14.9    | 2.29          | 2.0     | 35.2              | 0.9       | 7.4 × 10⁷        |
| LW10     | 12      | 13.20         | 7.0     | 20.5              | 0.6       | 2.5 × 10⁸        |
| LW8      | 11.3    | 2.71          | 1.3     | 20.7              | 0.8       | 5.2 × 10⁷        |
| LW6      | 7.7     | 7.06          | 1.5     | 8.9               | 0.5       | 5.8 × 10⁷        |
| LW2      | 6.7     | 16.18         | 3.5     | 5.5               | 0.4       | 8.2 × 10⁷        |

* Assuming a spectral shape f ν ∝ ν⁻¹, as in the ISOCAM Cookbook.

² For more information about modeling, see A. Biviano et al. (1998), ISOCAM Dark Current Calibration Report, available on the World Wide Web at http://www.iso.vilspa.esa.es/users/expl_lib/cam_list.html.

³ The ISOCAM Cookbook is available on the World Wide Web at http://isowww.estec.esa.nl/manuals/iso_cam/.
MIR-bright objects in the TM81 catalog. In that sample the mean \( \frac{L_{\text{12}}}{L_{\text{B}}} \) ratio \( \langle \log \frac{L_{\text{12}}}{L_{\text{B}}} \rangle = -0.12 \pm 0.27 \), while already twice as high as that for spiral galaxies in the CIA 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 \( \sim 10 \) 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 \( \mu m \) luminosity to a tracer of star formation such as the Hz luminosity (Table 2), SBS 0335—052 appears to be normal. Although total Hz fluxes are scarce for BCDs, the available data give \( \langle \log L_{\text{12}}/L_{\text{Hz}} \rangle = 0.96 \pm 0.70 \) for the above samples, as compared to 0.65 \( \pm 0.03 \) 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 (Fig. 1) is compared to MIR spectra of other star-forming galaxies (see, e.g., Metcalfe et al. 1996; Vigroux 1997), two facts stand out: (1) there is no emission from the so-called unidentified infrared bands (UIBs, usually attributed to carbon-based dust; see, e.g., Papoular et al. 1996; Puget & Léger 1989). In particular, the very strong band at 11.3 \( \mu m \) is completely absent from the spectrum; and (2) there are no evident structure ionic lines, even though neon as well as sulfur lines are usually quite bright in star-forming galaxies.

In Figure 1, a hint of the [S \text{IV}] \( \lambda 10.5 \) \( \mu m \) and [Ne \text{III}] \( \lambda 15.6 \) \( \mu m \) lines can be seen. There is a feature near the position of the [Ne \text{II}] \( \lambda 12.8 \) \( \mu m \) line, but it is centered at 12.8 \( \mu m \), while the redshifted line falls at 12.98 \( \mu m \). 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 \( 5.6 \times 10^{-14} \) ergs s\(^{-1}\) \( cm^{-2} \) for the [S \text{IV}] line, \( 4.5 \times 10^{-14} \) ergs s\(^{-1}\) \( cm^{-2} \) for the [Ne \text{II}] line, and \( 5.4 \times 10^{-14} \) ergs s\(^{-1}\) \( cm^{-2} \) for the [Ne \text{III}] line.

### Table 2

| Parameter | Value |
|-----------|-------|
| \( L_{\text{H}} \) \( ^a \) | \( 5.6 \times 10^7 L_{\odot} \) |
| \( L_{\text{H}} \) \( ^b \) | \( 2.2 \times 10^7 L_{\odot} \) |
| \( L_{\text{H}} \) \( ^c \) | \( 1.2 \times 10^8 L_{\odot} \) |
| \( L_{\text{H}} \) \( ^d \) | \( 7.2 \times 10^5 L_{\odot} \) |
| \( M_{\text{H}} \) \( ^d \) | \( 9.5 \times 10^5 M_{\odot} \) |

* Flux in the 1" slit of Izotov et al. 1997, corrected for extinction using \( A_V = 0.6 \) mag and multiplied by 2 to account for aperture effects, as suggested by Thuan & Izotov 1997.
* Computed from the absolute blue magnitude in Thuan et al. 1997.
* Here \( L_{\text{B}} \) is expressed in units of the solar blue luminosity, where \( L_{\odot}/L_{\text{B}} \sim 6.25 \).
* Thuan et al. 1999.

Using the photoionization models of Stasinska (1990) with a metallicity equal to 0.02 that of the Sun, and with an integrated H\( \beta \) flux in SBS 0335—052 of \( 12.1 \times 10^{-14} \) ergs s\(^{-1}\) \( cm^{-2} \) (the flux given by Izotov et al. 1997 was multiplied by 4 to account for aperture and extinction effects, as suggested by Thuan & Izotov 1997), we predict the line intensities of [S \text{IV}], [Ne \text{III}], and [Ne \text{II}] to be \( 5.0 \times 10^{-14} \) ergs s\(^{-1}\) \( cm^{-2} \), \( 1.6 \times 10^{-14} \) ergs s\(^{-1}\) \( cm^{-2} \), and \( 7.7 \times 10^{-17} \) ergs s\(^{-1}\) \( cm^{-2} \), respectively. The predicted intensities are thus completely consistent with the upper limits. We conclude, therefore, that the weakness (or absence) of ionic fine-structure lines in SBS 0335—052 when compared to other star-forming galaxies can be explained by a very strong continuum that decreases the equivalent widths of the lines, making them difficult to detect.

None of the usual UIB features are seen, which suggests 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 \( \geq 10 \) eV cm\(^{-3} \). Puget & Léger (1989) suggest that at this radiation density the abundance of the band-emitting dust is reduced by a factor of \( \sim 10 \). Therefore, the absence of the bands can be understood as a destruction effect. This is probably enhanced by the very low metallicity of the galaxy that allows harder UV photons to travel further into the interstellar medium.

The origin of the continuum emission is more problematic. We observe what could be interpreted as either a broad emission feature at around 14 \( \mu m \), or a broad absorption feature at \( \lambda \gtrsim 16 \) \( \mu m \). We favor the second hypothesis since we know of no candidate that would show such an emission feature at \( \sim 14 \) \( \mu m \). Very small carbonaceous grains, usually thought to be responsible for the MIR continuum (Désert, Boulanger, & Puget 1990), produce featureless emission. Silicates, the other well-known component of dust, can produce emission features of various shapes, but these are centered around 10 \( \mu m \), and even in circumstellar disks they never extend beyond 12 \( \mu m \) (see, e.g., Sitko et al. 1999). On the other hand, silicate extinction bands at 9.7 and 18 \( \mu m \) can provide an explanation for the strange shape of the MIR spectrum of SBS 0335—052.

Testing this hypothesis is not straightforward since the expected shape of the dust spectrum in this wavelength range is difficult to constrain. Apart from the stochastic heating of macromolecules that produce 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., Desert 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 blackbody of variable temperature modified by an emissivity law of the form \( f_{\nu} \propto B_{\nu}(T)\nu^{-1}, (2) \) a power-law spectrum, and (3) the continuum MIR spectrum of the Galactic H II 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 derived by Draine (1989), and that observed in the direction of the Galactic center by Lutz et al. (1996). The second law differs from the first by its much higher \( A_V/A_B \) in the range 2—8 \( \mu m \). This difference is probably due to the neglect of ice coating.
on grains in the Draine (1989) model. 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 broadband data outside of the CVF range. However, a successful model will be one that also accurately predicts them.

Figure 2 shows examples of the three types of fits. Both a power law and the M17 spectrum fail to reproduce the observed SED. Power laws modified by extinction overproduce emission shortward of 8 μm (Fig. 2a), while the M17 spectrum overestimates emission longward of 14 μm (Fig. 2b). On the contrary, a blackbody spectrum modified by an emissivity law proportional to ν^{1.5} and extinguished by a screen of dust gives an excellent fit to the SED of SBS 0335−052 (Fig. 2c). The goodness of the fit depends very little on the exponent of the emissivity law, so its value cannot be used to constrain the nature of the emitting dust. Instead, the fit is 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). The predicted spectrum always overproduce the emission in these bands by factors of ~2. On the contrary, excellent fits of these bands can be obtained with the Lutz et al. (1996) extinction curve. The temperature obtained for the blackbody curve is in the range 240−260 K, but probably carries little physical meaning since the MIR-emitting grains are not likely to be in thermal equilibrium.

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. Note that since the screen model maximizes A_v for a given column density of dust, the column density derived from our fit is likely a lower limit to the true column density if emitting and absorbing dust grains are mixed.

Such a high value of extinction is in sharp contrast to the values (A_v ≤ 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, as in the case of the antennae galaxies NGC 4038/39 (Mirabel et al. 1998), most of the infrared emission is powered by invisible star clusters. Indeed, correcting the Hz flux for 20 mag of visible extinction would lead to unrealistically high star formation rates (SFRs) that would be incompatible with the non-detection of SBS 0335−052 at 1.4 GHz by the NRAO^4 VLA Sky Survey (Condon et al. 1998), or in the far-infrared by IRAS. The LW10 luminosity of 2.5 × 10^8_L_☉ is equivalent to the bolometric luminosity of 2500 O7 stars, i.e., half the equivalent number of stars in the visible SSCs. Given that in the BCD sample of TM81 <log L_{12}/L_FIR> = −0.85 ± 0.09, it is probable that in fact some 18,000 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.

^4 The National Radio Astronomy Observatory is operated by Associated Universities, Inc., under a cooperative agreement with the National Science Foundation.
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 SSCs. O’Connell, Gallagher, & Hunter (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 of ~30 pc. If we adopt the latter assumption and consider that at least three SSCs are hidden (they have the power of 2500 equivalent O7 stars needed to power the LW10 luminosity), we derive a dust mass of $\sim 3.2 \times 10^3 M_\odot$. This is very probably an underestimate of the true dust mass since there are likely many more hidden SSCs. Furthermore, dust is probably not just associated with the SSCs, but rather mixed throughout the star-forming region, especially if it has a supernova origin, as is argued later.

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 $5 \times 10^3 M_\odot$. With the H I mass given in Table 2, the gas to dust mass ratio of SBS 0335—052 is then between $\sim 2 \times 10^3$ and $\sim 3 \times 10^3$, i.e., much higher than in the Galaxy, which is not too surprising for such a low-metallicity object (Lisenfeld & Ferrara 1998). 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 that are, on average, ~10 times more metal-rich. For comparison, $\langle \log M_{\text{dust}} \rangle = 4.4 \pm 0.6 M_\odot$ in the TM81 BCD sample.

As discussed by Thuan et al. (1997), because stars in SBS 0335—052 are not older than ~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 the numerous supernova ejecta present in the BCD (see, e.g., Lucy et al. 1991 on SN 1987A; Dwek et al. 1992; Wooden et al. 1993). We can check for the plausibility of this hypothesis by adopting, for example, 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. Assuming the diameter of the dust-forming region to be 660 pc, we derive a silicate dust mass of $\sim 2 \times 10^3 M_\odot$ in the range of the above estimates.

4. CONCLUSIONS AND IMPLICATIONS

Although SBS 0335—052 is one of the most metal-deficient galaxies known ($Z_\odot/41$), it is unexpectedly bright in the MIR range, which implies a silicate dust mass in the range $10^3$—$10^5 M_\odot$. The MIR spectrum shows no sign of UIB carriers, which are probably destroyed. Despite a difference of a factor of 40 in metallicity, the Galactic center MIR extinction produces the best fit to the spectrum. This is quite different from the situation in the UV where the extinction law shows a strong dependence on metallicity (Fitzpatrick 1989). This difference is probably due to the fact that the abundance and spectral properties of the carbon-based dust responsible for the UV extinction and UIBs are more metallicity-dependent than those of the silicate grains responsible for the extinction in the MIR. A possible explanation is that the silicate grains are more resistant to photo destruction than carbon-based dust.

The derived extinction is quite high, $A_V \sim 20$ mag. Given that the total MIR luminosity already requires the bolometric luminosity of 50% more young stars than are seen in the galaxy, the total 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 is 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. This is in fact the result obtained by Flores et al. (1999) in their ISO survey of distant galaxies. They found that the cosmic SFR derived from FIR luminosities is 2–3 times higher than the SFR estimated previously from UV/ optical fluxes (Madau et al. 1996).

The ISOCAM data was analyzed using 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. T. X. T. has been partially supported by NASA grant JPL961535. We acknowledge useful conversations with Yuri Izotov.

REFERENCES

Aberl, A., et al. 1996, A&A, 315, L32
Aussel, H., Gerin, M., Boulanger, F., Desert, F. X., Casoli, F., Cutri, R. M., & Signore, M. 1998, A&A, 334, L73
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
Condon, J. J., Cotton, W. D., Greisen, E. W., Yin, Q. F., Perley, R. A., Taylor, G. B., & Broderick, J. J. 1998, AJ, 115, 1609
Desert, F. X., Boulanger, F., & Puget, J. L. 1999, A&A, 327, 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. 1998, ApJ, 501, 643
Dwek, E., Moseley, S. H., Glaccum, W., Graham, J. R., Loevenstein, R. F., Silverberg, R. F., & Smith, R. K. 1992, ApJ, 389, L21
Fitzpatrick, E. L. 1989, in Interstellar Dust, ed. L. J. Alamandola & A. G. G. M. Tielens (Dordrecht: Kluwer), 37
Flores, H., et al. 1999, ApJ, in press
Izotov, Y. I., 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
Lisenfeld, U., & Ferrara, A. 1998, ApJ, 496, 145
Lucy, L. B., Danziger, I. J., Gouilhes, C., & Bouchet, P. 1991, in Supernovae, ed. S. E. Woosley (New York: Springer), 82
Lutz, D., et al. 1996, A&A, 315, L269
Madau, P., Ferguson, H., Dickinson, M., Giavalisco, M., Steidel, C., & Fruchter, A. 1996, MNRAS, 283, 1388
Metcalfe, L., et al. 1996, A&A, 315, L105
Mirabel, F., Vigroux, L., Charmandaris, V., Sauvage, M., Gallais, P., Cesarsky, C., Madden, S., & Duc, P. A. 1998, A&A, 333, L1
O’Connell, R. W., Gallagher, J. S., & Hunter, D. A. 1994, ApJ, 433, 65
Papaderos, P., Izotov, Y. I., Fricke, K. J., Thuan, T. X., & Guseva, N. G. 1998, A&A, 338, 43
Papoular, R., Conard, J., Guilllois, O., Nenner, I., Reynaud, C., & Rouzaud, J. N. 1996, A&A, 315, 222
Puget, J. L., & Ager, 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
Sittko, M. L., Craty, C. A., Lynch, D. K., Ress, R. W., & Hannen, M. S. 1999, ApJ, 510, 408
Stark, J. L., et al. 1999, A&AS, 134, 135
Stasinska, G. 1990, A&AS, 83, 501
Steidel, C. C., Giavalisco, M., Pettini, M., Dickinson, M., & Adelberger, K. L. 1996, ApJ, 462, 17
Thuan, T. X., & Izotov, Y. I. 1997, ApJ, 489, 623
Thuan, T. X., Izotov, Y. I., & Lipovetsky, V. A. 1997, ApJ, 477, 661
Thuan, T. X., Lipovetsky, V. A., Martin, J. M., & Pustilnik, S. A. 1999, A&A, in press
Thuan, T. X., & Martin, G. E. 1981, ApJ, 247, 823
Vigroux, L. 1997, in Extragalactic Astronomy in the Infrared, ed. G. Mamon, T. X. Thuan, & J. T. T. Van (Paris: Editions Frontie`res), 63
Wooden, D. H., Rank, D. M., Bregman, J. D., Witteborn, F. C., Tielesens, A. G. G. M., Cohen, M., Pinto, P. A., & Axelrod, T. S. 1993, ApJS, 88, 477
Yee, H. K. C., Ellingson, E., Bechtold, J., Carlborg, R. G., & Cuillandre, J. C. 1996, AJ, 111, 1783