Modeling the Dust Spectral Energy Distributions of Dwarf Galaxies

Suzanne C. Madden

Service d’Astrophysique, CEA Saclay, Orme des Merisiers 91191 Gif-sur-Yvette France
(smadden@cea.fr)

Abstract. Recent efforts on the modeling of the infrared spectral energy distributions (SEDs) of dwarf galaxies are summarised here. The characterisation of the dust properties in these low metallicity environments is just unfolding, as a result of recently available mid-infrared to millimetre observations. From the limited cases we know to date, it appears that the hard radiation fields that are present in these star-bursting dwarf galaxies, as well as the rampant energetics of supernovae shocks and winds have modified the dust properties, in comparison with those in the Galaxy, or other gas and dust rich galaxies. The sophistication of the SED models is limited by the availability of detailed data in the mid infrared and particularly in the submillimetre to millimetre regime, which will open up in the near future with space-based missions, such as Herschel.

INTRODUCTION

Dwarf-like galaxies are thought to be the most popular actors playing the role of building blocks in the hierarchical galaxy formation theater. We have in our local universe a vast cast of dwarf galaxies which purport to be analogs of these cosmologically important characters. They generously provide convenient laboratories to peer into the details of the interplay between star formation and the interstellar medium (ISM) under conditions of low metallicity, as low as 1/50 solar metallicity. The effects of low metallicity on the ongoing processes in galactic environments, while poorly understood, can be far reaching in terms of star formation, supernova feedback, dust composition and evolution, molecule formation, galaxy morphology and in general, all heating and cooling processes. Starbursting dwarf galaxies typically harbour super starclusters (SSCs), which are compact, dense sites of starburst activity, and alert us to the fact that while they are low mass galaxies, over the years, they have gained the reputation for impressive star formation activity, often concentrated in very young clusters. Yet how much of this activity is hidden from us due to dust in these systems? These are important issues to address for the sake of characterising star formation in the early universe.

The metallicity of the ISM of a galaxy evolves as a function of the enrichment of the metals, in part, from the donation of stellar winds from evolved stars, and more prolifically, due to supernovae events. Dust is also subsequently altered and destroyed due to the harsh effects from stellar radiation and winds and shocks due to supernovae. The observed SEDs of galaxies are their fossil footprints, which, if deciphered accurately, should unveil important characteristics of the history of the events of the galaxy.

As recent as five years ago, a review on the modeling of the SEDs of dwarf galaxies
would not have been a concept. Efforts in this direction have been hampered by the intrinsically faint infrared (IR) luminosities of these sources, in spite of the fact that many of them are currently undergoing significant local starburst activity. Compounding this effect, there has been the preconceived notion that metal-poor galaxies do not contain much dust to be concerned about and that optical photons arrive to us unobscured, thus revealing all. Therefore, historically, their physical properties have been well-studied at optical wavelengths. The folly of ignoring dust effects is becoming more and more apparent as studies of the dust and gas properties of dwarf galaxies have advanced.

Here, I summarise some of the efforts that have been directed specifically toward the modeling of the SEDs of dwarf galaxies. While many other sophisticated SED models that exist today explain the observations of a variety of galaxies, and can also be applied to dwarf galaxies, I will focus on the direct efforts made toward the interpretation of dwarf galaxies and which go beyond the single or multiple grey-body only assumptions.

**THE “DUSTY” MODEL APPLIED TO DWARF GALAXIES**

The DUSTY model of Ivezić and Elitzur [2] takes into account absorption, emission and scattering by dust using self-similarities. All output is dimensionless and must be scaled back to the observed SED. This method makes for a clever mathematical convenience in solving the radiative transfer problem with many parameters. With DUSTY, the central star cluster is specified as well as dust composition and dust radial distribution. DUSTY then calculates the radial distribution of the dust temperature. Caution must be taken when using this model, since no stochastic heating processes are invoked for the dust. All of the dust is assumed to be in thermal equilibrium with the radiation field.

![Figure 1](image.png)

**FIGURE 1.** Results of the SED modeling of SBS0335-052 [3] using the DUSTY model [2].

The SEDs of SBS0335-052, (1/40 solar metallicity), and NGC 5253 (1/6 solar metallicity) have been modeled using DUSTY [3], [4]. SBS0335-052 was shown by ISOCAM to harbor a significant amount of dust, due to absorption of the 9.7 μm silicate feature,
accounting for $A_V = 30$ to 40 [5]. These mid infrared (MIR) results alone point to a deeply-embedded SSC. Applying the DUSTY model to these two galaxies (Figure 1 Figure 2), the authors note that the observations require dust with a flatter size distribution, favoring larger grain sizes than those in our Galaxy. The predominance of larger grains, and decrease of smaller grains was explained as an effect of local, very young star clusters. One possibility would be the fact that the high energy densities in close proximity to massive young clusters may preclude the survival of very small grains and PAHs, which also appear to be absent. While silicate dust is obviously present in SBS0335-052, model results point to the absence of silicate grains in NGC 5253, where only carbon-based grains are used. The non-negligible dust masses that are determined from the observed SEDs, attributed to a single cluster in each case, are of the order of $10^5 \text{M}_\odot$. If stochastic heating does prove to be an important process in these environments, then the mass of dust will necessarily decrease. In both of these cases, the dust that is modeled using DUSTY is perhaps characteristic of local environments around star clusters, rather than dust that appears to be globally distributed throughout the galaxy.

FIGURE 2. Results of the SED modeling of NGC5253 [4], using the DUSTY model [2]. The inset contains a zoom into the MIR regime from 7 to 30$\mu$m.

A DUST EVOLUTION SED MODEL FOR DWARF GALAXIES

Prompted by the possibility of dwarf galaxies being templates for primeval galaxies, Takeuchi et al. [6] have created a dust SED model which incorporates the dust evolution

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1 Note that the dust mass in SBS0335-052 was overestimated in Plante and Sauvage [3] because the 60$\mu$m ISOPHOT point was too high
hypotheses of Hirashita and Ferrara [7]. The assumption for the SED model is that the galaxies are very young \((10^6 \text{ to } 10^8 \text{ yr})\) primeval galaxies. Thus dust production is predominantly due to Type II supernovae. The dust that is destroyed by supernova shocks is negligible, due to the youth of the galaxy, compared to the dust formation rate. The far infrared luminosity, \(L_{FIR}\), and the dust temperature, \(T_{dust}\), evolves as a function of enrichment based on the supernova Type II grain formation model of Todini and Ferrara [8] and includes small stochastically-heated silicate grains \((a < 10 \text{ Å})\) and bigger carbon grains \((a \sim 300 \text{ Å})\) in thermal equilibrium with the radiation field.

**FIGURE 3.** Results of the SED model of Takeuchi et al. [6] recently applied to SBS+0335-052 [9]. The squares are the observations cited in the original model of Takeuchi et al. [6] and the triangles are the new Spitzer data [10]. The solid line is the revised model fit to the observations.

Takeuchi et al. [6] applied this model to the extremely low metallicity galaxies SBS0335-052 (1/41 solar metallicity) and IZw18 (1/50 solar metallicity). The IR data for IZw18 is almost non-existent, but the model appeared to explain the available observations for SBS0335-052 well, concluding the presence of very hot dust (peak of 30 to 50 \(\mu m\)), in the first several Myr of its life. However, the original Takeuchi et al. [6] model (fitted to ISOPHOT data) deviates from recent Spitzer data longward of 20 \(\mu m\). Now, the observed SED is flatter in the FIR, peaking toward shorter wavelengths \((\sim 30 \mu m)\) [10]. In order to account for the new Spitzer data, this model has since been improved by decreasing the radius of the effective star forming region, which correspondingly reduced the age of the starburst to \(3 \times 10^6\) years [9] (Figure 3). In the framework of Takeuchi et al. [6], further improvements to the model have been made [11], by modifying the size distribution according to the more sophisticated supernovae recipe of Nozawa et al. [12], who take into account the radial density profile and temperature evolution of the dust mass in the supernovae ejecta. The model can be applied successfully to primeval...
USING THE DÉSERT ET AL DUST MODEL FOR DWARF GALaxy SEDs

The Désert et al. [13] dust model, originally used for the Milky Way galaxy, assumes the dust emission and extinction is due to 3 different dust components: the aromatic band carriers (PAHs), the very small (1.2 to 13 nm) carbon grains (VSGs), and the classical big (15 to 110 nm) grains (BGs). Each component has a unique size distribution and the model includes the process of stochastic heating. Madden [14] first applied this model to explain the dust SED of dwarf galaxies, allowing the grain size distributions to vary, depending on the physical properties within the galaxies. This dust model was used, in conjunction with a stellar evolution model (PEGASE: [15]) and a photoionisation model (CLOUDY: [16]) to develop a self-consistent model to simultaneously explain the galactic extinction and emission for the dwarf galaxies NGC 1569, NGC 1140, IIZw40 and He 2-10 ([17]; [18]), with metallicity values ranging from 1/6 to near solar metallicity.

The resulting dust properties of the modeled Galliano et al. [18] sample of dwarf galaxies are strikingly different from those of the Galaxy and are dominated by small grains, (∼ 3nm) stochastically heated even at wavelengths as long as 100 µm in some cases (Figure 4). This is in contrast to results modeling local regions using the DUSTY code [3] [4], where the dust size distributions favored larger grains sizes, and a deficit of smaller grains. Additionally, a cold dust component (T ∼ 7 to 10 K), carrying at least 50% of the mass of the galaxy, has been invoked to explain the submm/mm excess observed in all of the galaxies modeled in such detail [17] [18]. The presence of a cold dust component (< 10K) has also been observed in dwarf galaxies of the Virgo Cluster, from ISOPHOT observations [19].

FIGURE 4. Examples of the MIR to mm observed data and modeled SED (left: [18]) and the MIR spectra for IIZw40 (right: [20]). Note the dearth of PAHs in the MIR spectra and the prominent [SIV]λ 10.5µm and the [NeIII]λ 15.5µm lines.

Lisenfeld et al. [21] also applied the Désert et al. [13] dust model to interpret the
observed SED of NGC 1569. Their approach differs from that of the Galliano et al. \[17\] model, in that the dust size distributions for each component of NGC 1569 are fixed to those of the Galaxy. Additionally the submm data sets are different and not completely consistent, due to different calibration procedures. The model of Lisenfeld et al. \[21\] assumes the spectral shape of the Galactic radiation field, which is softer than the global intrinsic radiation field as solved for by Galliano et al. \[17\]. While their final fit shows an enhancement of the Galactic very small grain component, relative to that of the big grain component, the differences in the modeling approaches are sufficient to make it difficult to properly compare the two models and results.

**SED Model Constraints: MIR gas and dust and dearth of PAHs**

One of the unique, important aspects of the detailed modeling procedure by Galliano et al. \[17\] is pointing out the necessity of the detailed MIR spectra in constraining the full dust SED as well as offering the very important gas and dust spectral information in a wavelength regime suffering little extinction. Diagnostic fine structure nebular lines (e.g. [ArIII] 9\(\mu\)m, [SIV] 10.5 \(\mu\)m, [NeII] 12.7 \(\mu\)m, [NeIII] 15.6 \(\mu\)m) as well as the 9.7 and 18 \(\mu\)m silicate bands and the PAH bands lie in the MIR regime.

![FIGURE 5. Examples of the variations of the modeled ISRFs for 4 of the dwarf galaxies, compared to the softer ISRF of the Galaxy.](image)

As was initially shown in Madden \[14\], PAHs are not a very abundant dust component, globally, in dwarf galaxies (Figure 4), in contrast to the global ISM of dust-rich starburst galaxies and spiral galaxies. Recent Spitzer data also confirm this \[10\]. To investigate the absence of PAHs in dwarf galaxies, the hardness of the intrinsic modeled interstellar radiation fields (ISRFs) of the sample from Galliano et al. \[18\] were compared (Figure 5). As the ISRFs become harder, the absence of PAHs becomes more evident in the MIR spectra. Likewise, as the ratio of the [NeIII]/[NeII] MIR lines becomes larger, due to increasingly harder radiation fields (e.g.\[22\]), the PAH intensity drops remark-
The correlation between the hardness of the global ISRFs indicated by the [NeIII]/[NeII] MIR line ratios and the PAH/15µm small dust continuum for a sample of HII regions [23], metal rich starburst galaxies, and metal poor galaxies [20]. As the ratio of the [NeIII]/[NeII] MIR lines becomes larger (e.g. > 7 for dwarf galaxies), the PAH intensity drops remarkably, relative to the MIR continuum (Figure 6 [20]). For the dwarf galaxies, the values of [NeIII]/[NeII] > 7, as compared to an order of magnitude less for Galactic HII regions. The hardness of the global radiation field seems to be a factor that plays an important role in the destruction of the PAHs [20]. There is no obvious correlation with metallicity and the absence of PAHs for the few moderate metallicity cases here. However, the decrease of metals does result in a larger mean free path length for photons. Thus on a global scale, the hard photons could traverse larger areas, impacting larger scales in these galaxies, subsequently destroying a larger volume of PAHs in the galaxies [14].

**SUMMARY OF SED MODEL RESULTS**

From the limited number of dwarf galaxy SED models that have been constructed to date, each has its different origin, philosophy and limitations. All of the results point to the presence of non-negligible amounts of dust in low metallicity systems. The DUSTY models applied to localised starforming regions in SBS0335-052 and NGC 5253 ([3]; [4]), while not incorporating the process of stochastic heating, conclude the tendency for larger grains to survive, rather than smaller grains. In contrast, from global scale modelling of a small sample of dwarf galaxies, using the dust model of Désert et al. [13], most of the grain populations are characterised by small grain sizes (∼3 -4 nm) and are
stochastically heated ([21]; [17]; [18]). Additionally, a large, massive cold (T ∼ 5 to 10 K) dust component is an explanation for the excess submm/mm emission observed the dwarf galaxy sample of [17] and observed in other dwarf galaxies of the Virgo Cluster [19]. The physical details of the dust as well as the quantity of dust present in these galaxies are important to understand in order to determine their extinction properties. Limitations in the sophistication of the SED modeling efforts are related to the difficulty in sampling the submm to mm wavelength regime with sufficient detail. This will be remedied soon, with the launch of Herschel in 2007. Thus much further progress in modeling the SEDs of intrinsically faint sources, such as dwarf galaxies, can be made.

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