Low-Metallicity effects on the Gas and Dust Properties in Dwarf Galaxies

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Abstract

We are beginning to obtain observations of dwarf galaxies covering infrared wavelengths extending out to the submillimetre domain, thus providing us with information that enables us to determine self-consistent gas and dust properties. The effects of the low metallicity properties of dwarf galaxies are studied through dust observations in conjunction with the FIR fine-structure cooling lines. For example, there is a striking enhancement of the I[C II]/I(CO) in dwarf galaxies that is explained by the decreased attenuation of the UV light in molecular clouds, hence a larger [C II] filling factor. One of the consequences of this is that the observed CO intensity may not be measuring the entire molecular gas mass, due to the presence of self-shielded H_2 in the [C II]-emitting zones, which are not traced by the CO. Mid-infrared observations show a striking dearth of aromatic band carriers, which are believed to be responsible for gas heating through the photoelectric effect. In spite of the defficiency of these small grains, cooling in the photodissociation regions via [C II] seems to be an efficient process. Modeling the full infrared spectral energy distribution in dwarf galaxies reveals the presence of very cold (7 to 10 K) dust, which accounts for a large fraction of the dust mass, until now missed by models using IRAS observations alone.

1 Introduction

To construct a comprehensive picture of a galaxy's history, understanding the distribution of its energy budget in terms of gas and dust is a necessary step. Observations covering numerous characteristic wavelength regimes must be considered, thus, sampling the various components of the interstellar medium (ISM). While the UV to NIR wavelength continua give us relatively direct information of the stellar populations, this radiation is subject to varying amounts of absorption before we view it. Some of this energy is absorbed by the gas directly in H II regions or transferred to the gas in photodissociation regions (PDRs) and reemitted as molecular bands and atomic ionic and recombination lines, from wavelengths covering the UV to submm wavelengths and beyond. Some of the stellar energy is absorbed by the dust, revealed through extinction measurements, and reradiated in MIR to submillimetre wavelengths as thermal emission. Therefore, models of the ISM in galaxies must consider these interdependent processes and be self-consistent. Until recently, our knowledge of the wavelength window from the MIR to the FIR has been limited by the low spatial and spectral resolution provided by IRAS, and has been rather sketchy when it comes to detailed studies of the ISM of individual galaxies. The Infrared Space Observatory (ISO) (Kessler et al. 1996) has been a recent turning point in this effort, providing high spectral and spatial resolution and unprecedented sensitivity in the MIR to FIR wavelengths, providing us with more detailed observations of dwarf galaxies.

In spite of the fact that dwarf galaxies are the most numerous type of galaxies in the local universe, many aspects of their ISM properties have been difficult to ascertain owing to their low

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mass, hence, low metallicity. While the atomic gas is relatively abundant, accurate determination of the molecular gas reservoir has been difficult since CO detections have been challenging, if possible at all, in many dwarf galaxies (e.g. Taylor et al. 1998). We approach the study of the ISM in dwarf galaxies through the observations of the dust and the photodissociation regions (PDR) gas properties. Knowledge of the detailed properties of galactic ISM traced by the wavelength windows covering the mid-infrared (MIR) and far-infrared (FIR) has been limited by the low spatial and spectral resolution provided primarily by IRAS. We are incorporating our MIR, FIR and submillimetre (submm) observations in a study of the energy redistribution in starburst galaxies in order to understand the effects of the star formation on the surrounding gas and dust. We have complementary information of the gas cooling through fine-structure emission lines in the FIR. Here I summarize our progress to date in our study of star forming low-metallicity dwarf galaxies. These are thought to be dynamically simpler systems compared to spiral galaxies, for example, and the absence of major dynamical complications allows us to 'simplify' model assumptions and the interpretation of observations.

2 Far-infrared observations: the [C II] emission from PDRs

The 158 μm $^2P_{3/2} - ^2P_{1/2}$ far infrared [C II] fine structure line has proven to be a valuable measure of the global star formation activity in galaxies in a variety of luminosity regimes, at least in the luminosity regime up to 10^{10} $L_\odot$ (Stacey et al. 1991). In the case of higher luminosities, the interpretation of the [C II] line observations may not be as straightforward (e.g. Malhotra et al. 1997; Luhman et al. 1998). We have obtained KAO (Kuiper Airborne Observatory) and ISO observations of the [C II] fine structure line emission in a sample of 15 dwarf galaxies (Jones et al. 1997) with metallicities ranging from 0.1 to 0.5 solar. As the ionization potential of carbon is 11.3 eV, less than that of H I, photons can escape the H II regions, dissociate molecules, and ionize atoms in the PDRs on the surfaces of nearby molecular clouds exposed to the stellar UV radiation. Carbon is one of the most abundant species in these regions and the observed [C II] line intensity can be traced back to the radiation source due to the fact that the UV photons heat the dust which emits thermal radiation in the MIR to submillimetre wavelengths. Subsequently, energetic electrons, ejected from the dust through the photoelectric effect, heat the gas. The gas subsequently cools via emission from molecules and atomic fine structure lines, predominantly the 158 μm [C II] and the 63 μm [O I] transitions in PDRs. It is therefore the photoelectric effect which couples the radiation field with the dust heating and gas cooling. There are a variety of PDR models which provide tools to differentiate physical properties, such as density, radiation field strength and filling-factors in galaxies (see review and references in Hollenbach & Tielens 1997).

In the context of a typical PDR, the C^+-emitting shell and CO core of a molecular cloud have similar beam filling factors. Therefore, the I[C II]/I(CO) line ratio can be a measure of the PDR emission relative to the molecular core emission and an indicator of the degree of star formation activity in galaxies. Active galaxies have a ratio of I[C II]/I(CO) $\sim$ 6300, which is 3 times greater than that observed in more quiescent galaxies (Stacey et al. 1991). Our [C II] survey shows that for dwarf galaxies, this ratio ranges from 6000 to 70,000, which is up to 10 times greater than values for normal metallicity starburst galaxies (Figure 1). We also observe an overall enhancement in the I[C II]/I(FIR) in these regions compared to those in normal metallicity galaxies, which was also observed in the LMC (Mochizuki et al. 1994; Poglitsch et al. 1995; Pak et al. 1998). The I[C II]/FIR ratio is a direct measure of the fraction of the UV energy reemerging in the [C II] cooling line, and is usually between 0.1% and 1% for normal metallicity galaxies (Stacey et al. 1991), while we find up to 2% for dwarf galaxies. The glaring underabundance of observed CO in dwarf galaxies and relatively high FIR/CO luminosities have often been interpreted as unusually high star formation efficiency. Although how to convert the observed CO to H_2 mass in low metallicity environments

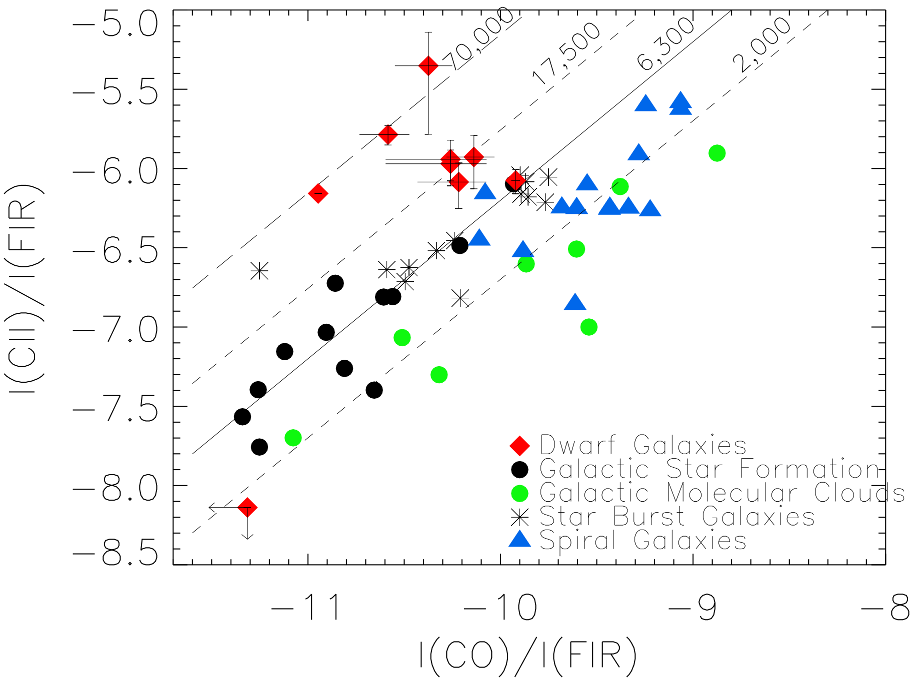

Figure 1: Comparison of [C II] emission in normal metallicity regions with low-metallicity galaxies. Lines of constant I[C II]/I(CO) ratios run diagonally across the plot and range from ~ 2000 for quiescent galaxies and Galactic molecular cloud regions (Stacey et al. 1991) up to ~ 70,000 for some dwarf galaxies. The ratios of both axes are normalized to the local interstellar radiation field (1.3×10^{-4} erg s^{-1} cm^{-2} sr^{-1}).

is not always clear (Israel et al. 1986; Wilson 1995). While all these observational effects are a consequence of the lower metal abundance and the decreased dust to gas ratio, we do not find an unambiguous direct correlation of the I[C II]/I(CO) and I[C II]/FIR ratios with metallicity in our surveys.

The reduced dust abundance in these environments allows the UV radiation to penetrate deeper, leaving a smaller CO core surrounded by a larger C^+-emitting region, thus enhancing the I[C II]/I(CO) ratios (Maloney & Black 1988). Consequently, as the FUV flux travels further, the intensity suffers greater geometrical dilution, resulting in a lower beam-averaged FIR flux, which can account for the increased I[C II]/FIR ratios. However, due to the shelf-shielding properties of H_2 (e.g. Abgrall et al 1992), the presence of molecular gas in the C^+-emitting region, outside the CO core, can be non-negligible. Based on [C II] observations in IC 10, for example, we speculate that up to 100 times more H_2 may be 'hidden' in C^+-emitting regions compared to that deduced only from CO observations and using the Galactic CO-to-H_2 conversion factor (Madden et al. 1997).

3 The Dust Properties: The MIR ISOCAM Observations

We are following up some sources from our [C II] survey with MIR observations. In Figure 2 we show ISOCAM spectra covering 5 to 17 μm for 3 galaxies from our [C II] survey, II Zw 40, NGC 1140 and NGC 1569 along with NGC 5253 (Crowther et al. 1999) and the notoriously metal-poor SBS 0335-052 (Thuan et al. 1999). As often seen in starburst galaxies, the MIR spectra are dominated by steeply rising continua longward of ~ 10 μm (e.g. Dudley 1999; Laurent et al. 2000; Sturm et al. 2000), as evident in NGC 1569, II Zw 40, SBS 0335-052 and NGC 5253. Thermal emission from hot small grains with mean temperatures of the order of 100's of K are responsible for the MIR continuum emission. The unidentified infrared bands (UIBs) at 6.2, 7.7, 8.6, 11.3 and 12.6 μm, are proposed to be due to aromatic hydrocarbon particles undergoing stochastic temperature fluctuations (i.e. PAHs: Léger & Puget 1984; Allamandola et al. 1989; coal grains: Papoular et al 1991) and are observed to peak in the PDR zones around the H II regions. The UIBs are not very conspicuous in the spectra of II Zw 40, SBS 0335-052 and NGC 5253 and are only very barely present NGC 1569, while they can be distinguished in the spectrum of NGC 1140. Several ground state fine-structure nebular lines are present also in the MIR spectra, the most prominent being 15.6 μm [Ne III] (energy potential $\sim$ 41 eV) and 10.5 μm [S IV] (energy potential $\sim$ 35 eV). Weaker, lower energy lines may also present, such as the 8.9 μm [Ar III] line and the [Ne II] 12.8 μm line, which can be blended with the 12.6 μm UIB. Compare these dwarf galaxy spectra, for example, to a normal metallicity starburst galaxy, M82, (Figure 2).

Spectra of normal starburst galaxies, as well as spiral galaxies (e.g. Helou et al. 2000; Vogler et al. 2001) show prominent UIBs, in contrast to environments around AGNs, which are devoid of UIBs (e.g. Roche et al. 1991; Dudley 1999; Laurent et al. 2000) as well as the central regions of starbursts (e.g. Normand et al. 1995) and inside H II regions. When compared to spectra characteristic of PDRs and H II regions (i.e. M17: Cesarsky et al. 1996; Vertraete et al. 1996), the global MIR spectrum of II Zw 40 is remarkably similar to that of an H II region. In contrast, NGC 1140, which has a very flat continuum, yet very strong [Ne III] line, does have a more obvious contribution from PDR regions, globally, as shown in its MIR spectrum. Likewise, the MIR spectra of N 66, the most prominent H II region in the SMC, shows a scarcity of UIBs in the vicinity of the most massive central cluster (Contursi et al. 1999).

We have also obtained 450 and 850 μm observations of these galaxies from SCUBA on the JCMT (Galliano et al 2001; Madden et al. 2001) to sample the more extreme range of the dust IR spectra. With these data, along with the ISOCAM and IRAS data, we construct a dust SED, and interpret this with the help of a dust model.

4 The Dust Modeling

We have adopted the Désert et al. (1990) dust model to explain the dust emission spectra. The dust emission is divided into three components, each with a defined power-law size distribution, minimum and maximum grain sizes, and dust mass, namely: polycyclic aromatic hydrocarbons (PAHs, radii of a few to 10 Å) with emission bands corresponding to the MIR UIB carriers, carbonaceous very small grains (VSGs, radii $\sim$ 10 to a few 100 Å) which are the primary source of the MIR continuum, and big grains, peaking in the FIR wavelength regime, and composed of carbon-coated amorphous silicates (BG, radii $\sim$ 100 to 1000 Å). The PAHs, and generally most of the VSGs, undergo large temperature fluctuations due to the stochastic absorption of energetic photons from the ISRF, while the BGs are in thermal equilibrium with the local ISRF. In the Désert et al. model, the dust temperature distribution for a given input ISRF is calculated as a function of the input grain size distributions (PAH, VSG and BG), the dust composition, and the nature of the heating process (stochastic *vs.* equilibrium). We have used a stellar population synthesis model, PEGASE (Fioc & Rocca-Volmerange 1997), in conjunction with a photoionization model, CLOUDY (Ferland 1996), to constrain the input global ISRF for each galaxy. With constraints provided by the important diagnostic lines of neon, sulphur, and argon, found in the ISOCAM MIR spectra, and the optical and NIR data from the literature, we constructed a composite SED which traces stellar populations ranging from about 4 to 20 Myr.

The Désert et al. model with 3 components alone does not match the SCUBA data points at 450 μm and 850 μm and misses a cooler dust component that must be taken into account. We have

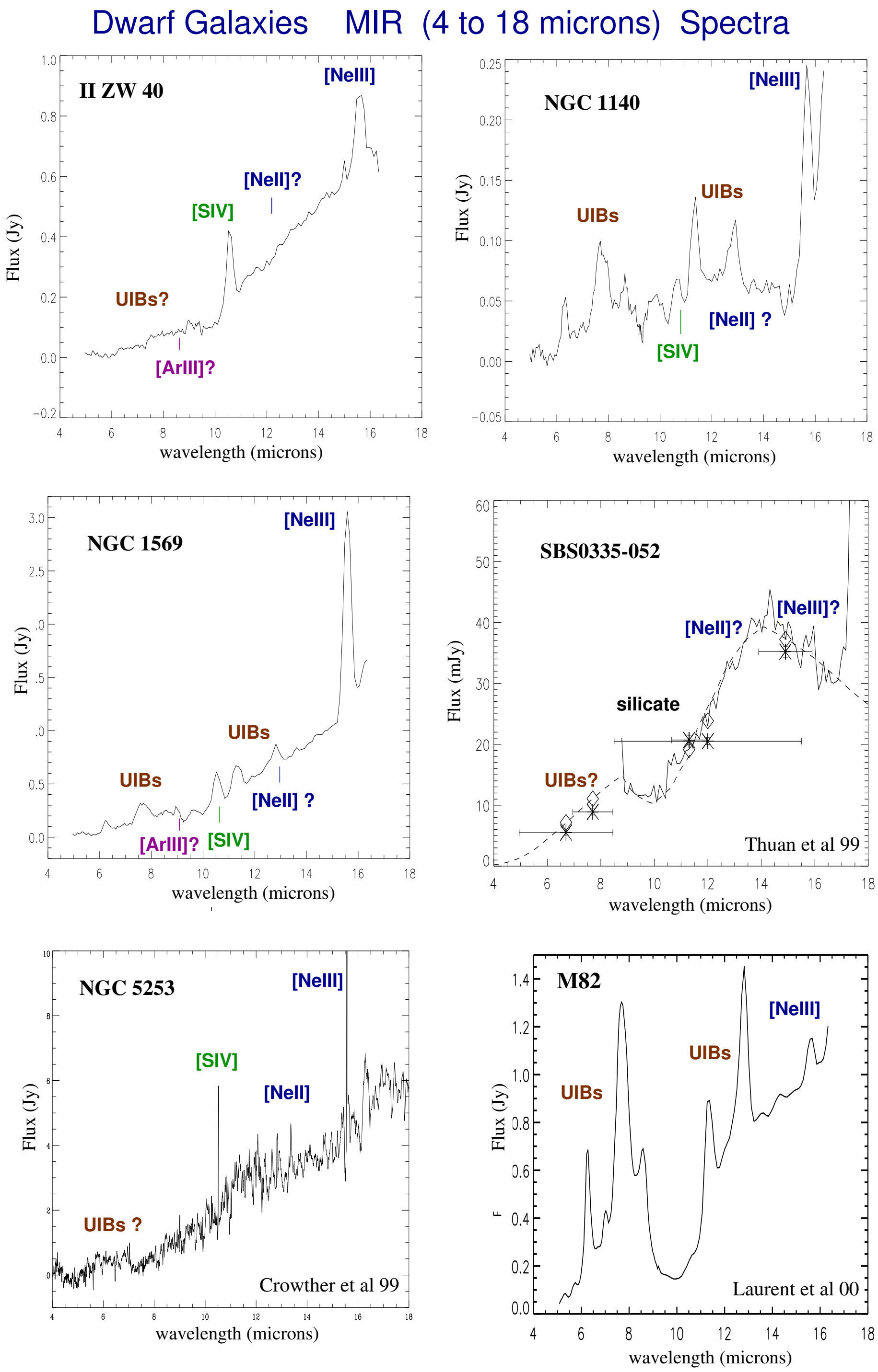

Figure 2: ISOCAM MIR spectra of dwarf starburst galaxies: II Zw 40, NGC 1569, NGC 1140, SBS 0335-052 and NGC 5253 (Crowther et al 1999). Also shown for contrast, is the MIR spectrum of a normal metallicity starburst galaxy, M82 (Laurent et al. 2000). The horizontal lines in SBS 0335-052 are broad band measurements; the dashed line is a blackbody with $A_V \sim 20$. (Note the absorption attributed to amorphous silicates at ~ 9 and 18 μm).

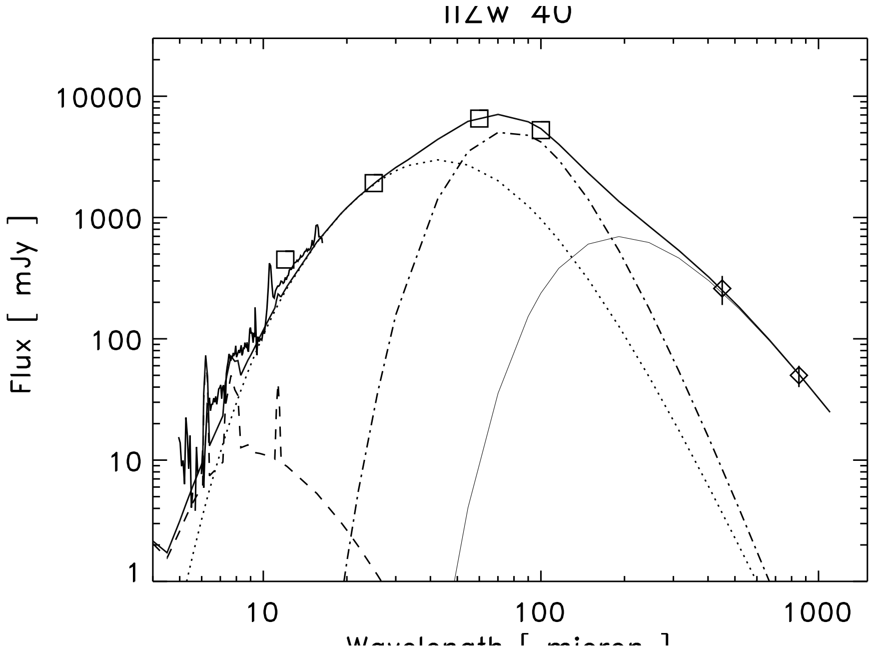

Figure 3: Example of the dust model results for II Zw 40 using the 3 component Désert et al (1990) model with the individual PAH (dashed line), VSG (dotted line), and BG (dash-dotted line) components shown with the resulting fit. The spectrum from 5 to 18 μm is the ISOCAM data, the open squares are the IRAS data and the open diamonds are the 450 and 850 μm SCUBA data. It it usually necessary to add an additional, cold grain (CG) component for the dwarf galaxies. In this case, II Zw 40 has a CG component with a temperature $\sim$ 10 K and $\beta \sim 2$ (Madden et al. 2001).

modeled this excess long-wavelength emission as an additional cold grain (CG) component, using an emissivity index-modified blackbody emission (Figure 3).

One of the most dramatic differences from Galactic dust characteristics is that the PAH abundance is decreased by several orders of magnitude down to an almost negligible fraction, as evidenced in the MIR observations (Figure 2). The decrease in carbon abundance due to the lower metallicity in these galaxies may explain the dearth of PAHs. On the other hand, the effect of the extremely hard radiation fields in these galaxies, indicated by the high ratio of 15.6 μm [Ne III]/12.8 μm [Ne II], may have destroyed these small particles. The global destruction of the PAHs can be facilitated by the decreased metallicity which results in the decreased attenuation of the photons and therefore larger photon mean free path.

In II Zw 40 and NGC 1569, for example, the VSGs contribute about half of the global IR energy, unlike the Galaxy, or other spirals, where the global energy budget is dominated more by the BG or colder dust emission, corresponding to the cirrus emission. Only a few percent of the IR luminosity arises from the cold grain component, yet the CG component harbors more than 1/2 of the total dust in these CG components, with the remaining mass shared by the BG and VSG components. This translates into total dust masses of 2.1×10^6 M$_\odot$ for II Zw 40. Having the submm data is crucial for the dust mass determination as we find up to an order of magnitude more dust mass with our 4 component model compared to results we calculate using only the IRAS data. The resulting gas to dust mass ratio for II Zw 40 is 210 and is now similar to that of the Galactic value. In spite of the major influence of the H II regions on the IR SEDs of the dwarf galaxies, there is a pervasive very cold, 7 to 10 K dust component not commonly found in galaxies. It appears to be very extended for these galaxies, more so than the hot dust emitting in the MIR, which is found primarily within and near to H II regions. The presence of a very cold 7 K component in our Galaxy was suggested from COBE data (Reach et al. 1995) but this component is still somewhat controversial (Lagache et al. 1998).

5 Summary

From a global point of view, there is a dearth of the aromatic stochastically heated particles in dwarf galaxies, due to the decreased abundance of metals and the hard, pervasive radiation field. We have found a large mass of very cold, $\sim$ 7 to 10 K, extended dust emission in dwarf galaxies. Observations of the [C II] line can provide a measure of the total molecular gas reservoir in low metallicity regions, where CO observations may not probe a potentially significant mass of H_2 in the C^+-emitting regions. In spite of the decreased abundance of PAHs in dwarf galaxies, the cooling via [C II] emission appears to be an efficient mechanism in dwarf galaxies. The I[C II]/I(CO) ratio in low metallicity regions is enhanced over normal metallicity star bursting regions and spiral galaxies by up to an order of magnitude.

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