METALLICITY EFFECTS ON THE ISM OF DWARF GALAXIES - THE PROMISE OF THE HERSCHEL SPACE OBSERVATORY

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Abstract

The Herschel Space Observatory will offer the opportunity to study the gas and dust properties in dwarf galaxies of a wide variety of metallicities, even the extremely metal-poor galaxies, for the first time, using far infrared (FIR) and submillimeter (submm) wavelengths. The moderately metal-poor ($1/10 < z < 1/2$) galaxies that we have been studying to date in the FIR and submm using ISO and the KAO, exhibit striking effects on the observed gas and dust properties due to the low metallicity environments. These conditions may provide advantages in detecting more low metallicity dwarf galaxies in the local and the more distant universe. We find a striking enhancement of I[CII]/I(CO) in dwarf galaxies that can be explained by the lower dust abundance and conclude that FIR fine structure lines can be reliable probes of the molecular gas reservoir in dwarf galaxies. Additionally, the global dust properties differ from those of normal spiral galaxies or other starbursting galaxies. We find that most (up to 60%) of the global infrared luminosity is emitted from a small grain component which is the major contribution to the MIR continuum emission and is stochastically heated, while most of the dust mass resides in a very cold (~ 7K) component of dust, emitting in the submillimeter regime, not detected before now in galaxies. In spite of the striking dearth of the MIR aromatic band carriers, cooling in the photodissociation regions via [CII] is a very efficient process.

Key words: Galaxies: NGC1569 NGC1140 IIZw40 PDRs CII ISM dust – macros: LaTeX

1. Introduction

In spite of the fact that dwarf galaxies are the most numerous types of galaxies in the local universe, many aspects of their ISM properties have been difficult to ascertain owing to their low mass and low metallicity. While the atomic gas is relatively abundant, determination of the quantity and nature of the molecular gas reservoir remains uncertain since CO detections have been challenging, if possible at all, in many dwarf galaxies (e.g. Taylor et al. 1998). Alternatively, we approach the study star formation in dwarf galaxies and the subsequent effects on the ISM, through observations of the mid infrared (MIR) to submillimeter (submm) dust properties and the photodissociation region (PDR) properties via far-infrared (FIR) fine-structure lines.

2. FIR observations: [CII] emission from PDRs

The 158 μm $^2P_{3/2} - ^2P_{1/2}$ far infrared [CII] fine structure line is a valuable measure of the global star formation activity in galaxies in a variety of luminosity regimes up to at least 10^{10} $L_\odot$ (Stacey et al. 1991). In the case of very high luminosities, the interpretation of the [CII] line observations may not be as straightforward (Malhotra et al. 1997; Luhman et al. 1998). We have obtained Kuiper Airborne Observatory (KAO) and ISO observations of the [CII] fine structure line emission in 15 dwarf galaxies (Jones et al. 1997) with metallicities ranging from 0.1 to 0.5 solar. The ionisation potential of carbon is 11.3 eV, less than that of HI, allowing some photons to escape HII regions, dissociate molecules, and ionise 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. The observed [CII] 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 submillimeter wavelengths. 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 [CII] and the 63 μm [OI] transitions in PDRs. Therefore, the photoelectric effect 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 references in Kaufman et al. 1999).

In the context of PDR models, the C^+-emitting shell and CO core of a molecular cloud have similar beam filling factors. Therefore, the I[CII]/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[CII]/I(CO) ~ 6300, which is 3 times greater than that observed in more quiescent galaxies (Stacey et al. 1991). Our [CII] survey shows that for dwarf galaxies, this ratio ranges from 6000 to 70,000, which can be even up to 10 times greater than values for normal metallicity starburst

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galaxies (Figure 1). We also observe an overall enhancement in the I[CII]/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[CII]/FIR ratio is a direct measure of the fraction of the UV energy reemerging in the [CII] 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. While all these observational effects are probably 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[CII]/I(CO) and I[CII]/FIR ratios in our surveys simply with metallicity.

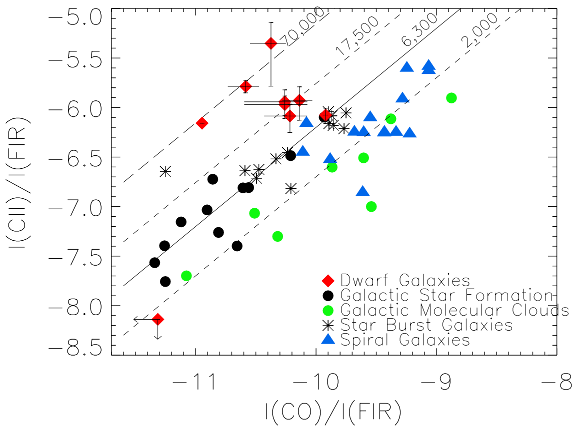

Figure 1. Comparison of [CII] emission in normal metallicity regions with low-metallicity galaxies. Lines of constant I[CII]/I(CO) ratios run diagonally across the plot and range from ~ *2000 for quiescent galaxies and Galactic molecular cloud regions (Stacey et al. 1991) up to* ~ *70,000 for some dwarf galaxies. The ratios of both axes are normalized to the local interstellar radiation field* ($1.3\times10^{-4} ergs\ s^{-1} cm^{-2} sr^{-1}$).

The reduced dust abundance in these environments allows the UV radiation to penetrate deeper than in the case of higher metallicity molecular clouds, leaving a smaller CO core surrounded by a larger C^+- emitting region, thus enhancing the I[CII]/I(CO) ratios (Maloney & Black 1988). Consequently, as the FUV photons travel further, the intensity suffers greater geometrical dilution, resulting in a lower beam-averaged FIR flux, which can account for the increased I[CII]/FIR ratios. However, due to the shelf-shielding properties of H_2, the presence of molecular gas in the C^+-emitting region, outside the CO core, can be non-negligible. The abundance of H_2 is a result of the competition between destruction by photodissociation in high radiation fields (G_o) and the formation of H_2 which can remain high when the column density (N) is sufficient. Self-shielding of H_2 is thought to take effect when $G_o/N < 0.01$ cm^{-2} (Kaufman et al. 1999) and can shift the HI/H_2 transition zone in the PDR closer to the surface of the cloud. In this case, the observed CO is not tracing all of the molecular gas. Based on [CII] observations in the low metallicity dwarf galaxy IC10, 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).

In principle, contributions to the [CII] emission, from sources other than PDRs, should also be considered. The diffuse warm ionised gas has been shown to be at most 50% in spiral galaxies (Madden et al. 1993). The Herschel Space Observatory will be sensitive enough to quantify more accurately, possible contributions to the total [CII] emission, particularly through observations of the 122 and 205 μm [NII] lines, which are expected to be about 10 times weaker than the [CII] line.

3. THE MIR AND SUBMM OBSERVATIONS

Some sources from our [CII] survey have been followed up with MIR observations, in order to trace the hot dust emission and the smallest particles thought to be primary agents for the photoelectric effect. In Figure 2 we show ISOCAM spectra covering 5 to 17 μm for the dwarf galaxies: NGC 1140, NGC 1569, IIZw40 (Madden et al. 2001), SBS0335-052 (Thuan et al. 1999) and the SWS spectra of NGC 5253 (Crowther et al. 1999). The MIR spectra of dwarf galaxies usually show steeply rising continua longward of ~ 10 μm, as often seen in dusty starburst galaxies (e.g. see M82 in Figure 2). This continuum is due to thermal emission from hot small grains with mean temperatures on the order of 100's of K. The carriers of 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, not in thermal equilibrium, (i.e. PAHs: polycyclic aromatic hydrocarbons; Léger & Puget 1984; Allamandola et al. 1989) and are observed to peak in the PDR zones around HII regions. Several ground state fine-structure nebular lines are present also in the MIR spectra, the most prominent being the 15.6 μm [NeIII] line (energy potential ~ 41 eV) and the 10.5 μm [SIV] line (energy potential ~ 35 eV). The MIR characteristics of these dwarf galaxy spectra differ globally from a normal dusty starburst galaxy, M82, also shown in Figure 2 for comparison, and bear remarkable resemblance to resolved HII regions.

In addition to the continuum and aromatic band emission in the MIR spectra, there is the possibility of absorption due to amorphous silicates at 10 and 18 μm. This has been taken into account in the spectrum of the very metal-poor (1/40 solar metallicity) galaxy SBS0335-052 (Figure 2) to determine an $A_v \sim 20$, raising the possibility of a significant amount of star formation that may be obscured from optical observations (Thuan et al. 1999). We determine an $A_v \sim 4$ for IIZw40, due to possible silicate absorption (Madden et al. 2001).

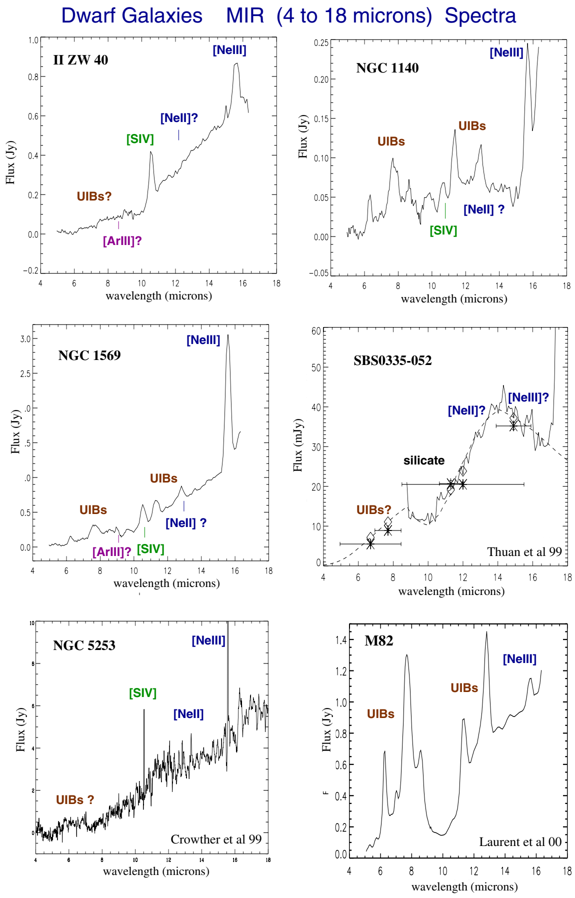

Figure 2. ISOCAM MIR spectra of dwarf starburst galaxies: IIZw40, NGC 1569, NGC 1140, SBS0335-052 and NGC 5253. Also shown for contrast, is the MIR spectrum of a normal metallicity starburst galaxy, M82. The horizontal lines in SBS0335-052 are broad band measurements; the dashed line is a blackbody fit with $A_v \sim 20$. (Note the absorption attributed to amorphous silicates at ∼ 10 and 18 μm).

In order to sample the more extreme range of the IR spectra, 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). With these data, along with the ISOCAM and IRAS data, we construct dust SEDs, 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. This model explains the dust emission spectra with three components: PAHs, (radii ∼ few − 10 Å) with emission bands corresponding to the MIR UIB carriers, carbonaceous very small grains (VSGs, radii ∼ 10 − few 100 Å) which are the primary source of the MIR continuum, and big grains (BG), peaking in the FIR wavelength regime, and composed of carbon-coated amorphous silicates (radii ∼ 100 − 1000 Å). The PAHs, and potentially 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, each component has a defined power-law size distribution, minimum and maximum grain size and dust mass, while the dust temperature distribution is calculated as a function of the input grain size distributions for a given input ISRF, dust composition, and the heating process (stochastic *vs.* thermal equilibrium). We use a stellar population synthesis model, PEGASE (Fioc & Rocca-Volmerange 1997), in conjunction with a photoionisation 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 3 to 20 Myr.

The normal Désert et al. model with 3 components alone does not allow us to fit the complete SEDs. To account for the excess submm emission, we add a 4th, cold grain (CG) component, using an emissivity index-modified blackbody emission with temperatures ∼ 7 K for NGC1569 and IIZw40 and emissivity indices ∼ 2 and 1 for IIZw40 and NGC1569, respectively (see Galliano et al. 2001 and Madden et al. 2001 for more model details).

One of the most dramatic results we find for the global spectra of dwarf galaxies is that the PAH abundance is decreased by several orders of magnitude to an almost negligible fraction compared to our Galaxy. 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 [NeIII]/12.8 μm [NeII], may have destroyed these smallest 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 spite of the reduction in abundance of PAHs, there is a good spatial correlation between the UIBs from the ISOCAM image and the 850 μm emission in NGC 1569 (Galliano et al. 2001). From a larger sample of broad band MIR observations in low metallicity galaxies, we find a higher [CII] luminosity to PAH luminosity (as traced by the 4.5 to 8 μm ISOCAM filter) for dwarfs then for normal galaxies. This suggests that there may be other grains, such as the VSGs, which might also be playing an important role in the photoelectric effect (Madden et al. 2001.

In IIZw40 and NGC1569 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 BGs or colder dust, presumably originating in the cirrus. Only a few percent of the IR luminosity arises from the cold grain component, yet the CGs harbors approximately 90% of the total dust mass, 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 IIZw40 and 4.0×10^5 $M_\odot$ for NGC1569. The submm data is absolutely 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 obtained using data out to only 100 μm. In spite of the major influence of the HII regions on the IR SEDs of the dwarf galaxies, there is a pervasive very cold dust component not commonly found in galaxies. 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. The Future of the Herschel Space Observatory

We are beginning to obtain some ideas of the effects of the low metallicity on the ISM in dwarf galaxies. It has never been an easy task to obtain much information on the dust and molecular gas content in dwarf galaxies owing to their intrinsically weak emission. Obtaining ground-based submm data has been possible, but a veritable challenge for the handful of dwarf galaxies that have been observed. We have not yet been able to sample the dust or molecular gas in very metal-poor galaxies through mm/submm wavelength. To address issues such as true molecular gas and dust content in dwarf galaxies, the dust-to-gas ratio as a function of metallicity, and the evolution of dust properties as a function of metallicity, the Herschel Space Observatory will be revolutionary. It will be the first time that statistically significant samples of galaxies covering a wide *range* of metallicities can be observed in submm and FIR wavelengths.

While the intensity of the 158 μm [CII] line seems to be reduced in ULIRGs, on the contrary, the [CII] line intensity is enhanced, relative to the CO intensity, in local low-metallicity dwarfs galaxies, over normal metallicity star forming regions and spiral galaxies, lending promise to detections of higher redshift low metallicity dwarf galaxies. Observations of the [CII] line with PACS, for local galaxies and SPIRE and HIFI with high-z galaxies, can provide a measure of the total molecular gas reservoir in low metallicity regions, where CO observations may miss a potentially significant mass of H_2. Other important FIR fine-structure lines can also be imaged, including the 63 and 145 μm [OI], 88 μm [OIII] and 122 and 205 μm [NII] lines which, together with the [CII] line will provide a measure of numerous physical quantities tracing the nature of the gas in low metallicity environments. We will be able to observe a statistically significant number of dwarf galaxies, beyond this current survey that we have conducted with the ISO/LWS and the KAO. Additionally, the nature of the dust variations and the evolution of dust *within* galaxies can be studied, given the photometric imaging capabilities of the Herschel Space Observatory. Completely mapping the dust emission in many dwarf galaxies in the PACS and SPIRE photometry bands at 60 to 500 μm, will be possible, giving us unprecedented spatial resolution *and* spectral coverage. These future studies with the Herschel Space Observatory will lead to very important steps in our understanding of the nature and origin of dwarf galaxies and their role in the overall picture of galaxy evolution.

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References

Allamandola, L.J., Tielens, A.G.G.M. & Barker, J.R. 1989, ApJS, 71, 733

Crowther, P.A., Beck, S.C., Willis, A.J., Conti, P.S., Morris, P.W. & Sutherland, R.S. 1999, MNRAS, 304, 645

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

Ferland, G.J. 1996, in Int. Rep. Dept. of Physics, U. Kentucky

Fioc, M. & Rocca-Volmerange, B., 1997, A&A, 326, 950

Galliano, F., Madden, S. C., Jones, A., 2001, in preparation.

Jones, A.P., Madden, S.C., Colgan, S.W.J. et al., 1997, in Extragalactic Astronomy in the Infrared, eds G. Mamon, T. Thuan, J.Tran Than, Editions Frontières, Paris, 1997, p.101

Kaufman, M.J., Wolfire, M.G., Hollenbach, D. J., Luhman, M. L., 1999, ApJ, 527, 795

Lagache, G., Abergel, A., Boulanger, F. & Puget, J.-L. 1998, A&A, 333, 709

Laurent, O., Mirabel, I.F., Charmandaris, V., Gallais, P., Madden, S.C., Sauvage, M., Vigroux, L.& Cesarsky, C. 2000, A&A, 359, 887

Léger, A. & Puget, J.-L. 1984, A&A, 137, L27

Luhman, M.L., Satyapal, S., Fischer, J., Wolfire, M.G., Cox, P., Lord, S. D., Smith, H.A., Stacey, G.J. & Unger, S.J., 1998, ApJ, 504, L11

Madden, S.C., Geis, N., Genzel, R., Herrmann, F., J. Jackson, J., Poglitsch, A., Stacey, G.J.& Townes, C.H., 1993, ApJ, 407, 579

Madden, S.C., Poglitsch, A., Geis, N., Genzel, R., Stacey, G.J.& Townes, C.H., 1997, ApJ, 483, 200

Madden, S. C., Galliano, F., Jones, A., 2001, in preparation.

Malhotra, S., Helou, G., Stacey, G. et al., 1997, ApJ, 491, L27

Maloney, P., & Black, J.H., 1988, ApJ, 325, 389

Mochizuki K., Nakagawa, T., Doi, Y. et al., 1994, ApJ, L37

Pak, S., Jaffe, D.T., van Dishoeck, E.F., Johansson, L.E.B. & Booth, R.S . 1998, ApJ, 498 735

Poglitsch, A., Krabbe, A., Madden, S.C., Nikola, T., Geis, N., Johansson, L.E.B., Stacey, G.J. & Sternberg, A., 1995, ApJ, 454 293

Reach, W. T., Dwek, E., Fixsen, D. J. et al., 1995, ApJ, 451, 188

Stacey, G.J., Geis, N., Genzel, R., Lugten, J.B., Poglitsch,A., Sternberg , A. & Townes, C.H., 1991, ApJ, 373, 423

Taylor, C.L., Kobulnicky, H.A. & Skillman, E.D. ,1998, AJ, 116, 2746

Thuan, T.X., Sauvage, M. & Madden, S.C., 1999, ApJ, 516, 783