# The Properties and the Structure of the ISM of Low Metallicity Dwarf Galaxies: From *Herschel* to *SPICA*

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**ABSTRACT**

*Herschel* has brought new light on the structure and properties of the gas and dust in low metallicity galaxies. The sensitivity of *SPICA* will leap beyond *Herschel* to revolutionise this study, where crucial observational constraints on the dust and gas properties of the extremely low metallicity galaxies has been lacking. We review our current knowledge of the low metallicity dust and gas properties in terms of where *Herschel* and *Spitzer* have brought us and how *SPICA* will go even further in this field.

## 1. INTRODUCTION: DWARF GALAXIES SURVEYS

The gas and dust spectral energy distribution (SED) that a galaxy presents today is its fossil footprint harboring clues to the processes governing its evolution through cosmic time. In order to reconstruct the history of the galaxy, in lieu of capturing snapshots of any one galaxy throughout its evolutionary history, we can study large numbers of galaxies possessing wide ranges of properties, including metallicity, star formation activity and morphology, for example, and attempt to reconstruct the effect of these variables on the evolution of galaxies. This requires characterising the various gas phases with the appropriate variety of tracers and sampling the dust emission over a wide range of wavelengths. Only then can we have enough constraints to follow the dust and gas evolution in galaxies.

While our comprehension of the gas and dust properties in metal-rich or moderately metal-poor galaxies has been growing at a fast pace due to the very successful infrared (IR) space missions *IRAS*, *ISO*, *Spitzer*, *AKARI* and *Herschel*, as well as recent ground-based millimetre (mm) and submillimetre (submm) telescopes, the number statistics of studies that include the low metallicity dwarf galaxies, in particular, have been suffering, mainly from lack of sufficient sensitivity. The Dwarf Galaxy Survey (DGS; Madden et al. 2013), has compiled a large observational data base of 48 low metallicity galaxies, motivated by the new PACS (Poglitsch et al. 2010) and SPIRE (Griffin et al. 2010) 55 to 500 $\mu$m photometry and spectroscopy observations onboard the *Herschel Space Observatory* (Pilbratt et al. 2010).

Surmising dust and gas properties of low metallicity galaxies has been an enigmatic undertaking. For one thing, assessing the molecular gas content in dwarf galaxies has been a difficult issue due to the formidable challenge in detecting CO in these galaxies (e.g. Schruba et al. 2012; Cormier et al. 2013, and references within). Also, even before *Herschel* the presence of a submm excess over the expected Rayleigh-Jeans behavior had been noted in the SEDs of some low metallicity galaxies detected at 850/870 $\mu$m with SCUBA on JCMT and with LABOCA on APEX (e.g. Galliano et al. 2003, 2005; Bendo et al. 2006; Galametz et al. 2009; Zhu et al. 2009; Galametz et al. 2011). The origin of this submm excess is still under investigation (see Galametz et al. 2011, for discussion).

## 2. DUST PROPERTIES AND METALLICITY

The dust properties of the DGS have been modeled by Rémy-Ruyer et al. (2013a) (Figure 1, for example) and compared with the *Herschel* KINGFISH survey, consisting of mostly metal-rich galaxies (Kennicutt et al. 2011; Dale et al. 2012). The full DGS + KINGFISH samples, 109 galaxies together ranging over 2 dex in metallicities, are modeled to determine the dust mass, dust temperature ($T_{\rm dust}$) and emissivity index ($\beta$) to investigate the effects of metallicity on the dust properties.

The overall $T_{\rm dust}$ of the low metallicity galaxies spans a broader range in temperature and a higher mean $T_{\rm dust}$ of 32 K, with a few extreme cases as high as 90 K. This is in contrast to the higher metallicity KINGFISH galaxies which span a narrower temperature distribution and a lower mean $T_{\rm dust}$ of 23 K. A trend of increasing $T_{\rm dust}$ with decreasing metallicity can be noted (Rémy-Ruyer et al. 2013a). In contrast, the distribution of $\beta$ is widely varying for both galaxy samples with no obvious trend in metallicity.

With dust masses accurately measured for galaxies of a broad metallicity range, it is possible to characterize the impact of metallicity on the gas-to-dust mass ratio (G/D). This was possible for the moderately low metallicity to more metal-rich galaxies (for $12+\log{\rm (O/H)} > 8$) before *Herschel*, but the behavior of metal enrichment in the ISM for the lower metallicity galaxies was uncertain due to observational constraints. Rémy-Ruyer et al. (2013b) show the broad scatter observed in G/D over 2 dex range of metallicity and a steep rise in the G/D for the lower metallicities, consistent with chemical evolution models, that require grain growth in the ISM as a source of dust production as well as episodic star formation history

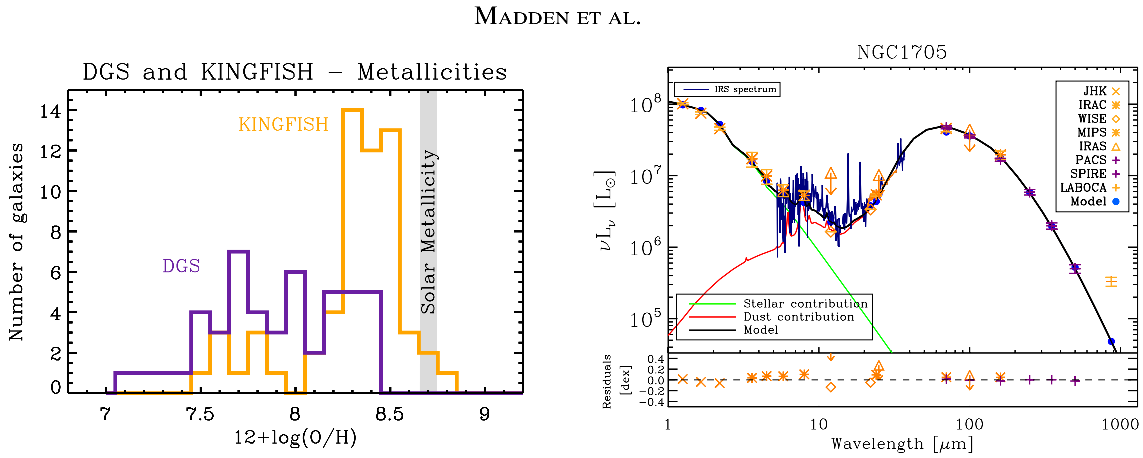


**Figure 1.** *Left*: Metallicity range of the DGS and KINGFISH samples. *Right*: The full SED of the dwarf galaxy, NGC 1705, modeled by Rémy-Ruyer et al. (2013a) using the Galliano et al. (2011) model. Note the excess beyond that of the SED model, appearing at 1.2 mm.

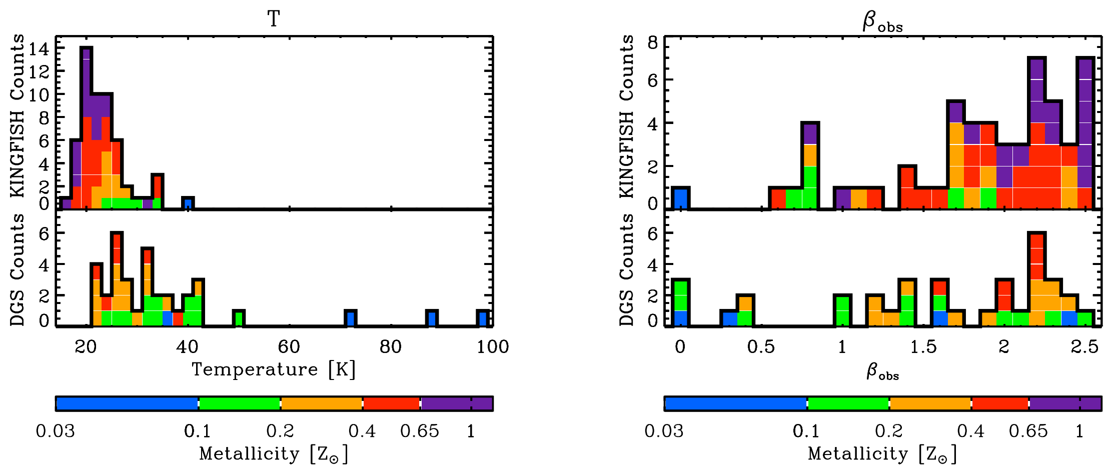


**Figure 2.** Dust properties of the DGS and KINGFISH samples. Histogram of $T_{\rm dust}$ distribution with metallicity (*left*) and $\beta$ (*Right*). The color scale represents the metallicity values.

(Asano et al. 2013, Zhukovska et al., in preparation): dust production becomes more efficient when enough dust can accumulate, and this occurs in the observations and models at around 12 + log (O/H) ∼ 7.5 (Figure 3).

## 3. FIR FINE STRUCTURE LINES AND LOW METALLICITY ISM

The DGS galaxies were surveyed in the most important FIR fine structure lines, such as 158 $\mu$m [C II], 63 and 145 $\mu$m [O I], 88 $\mu$m [O III] and more rarely, due to sensitivity limits, 57 $\mu$m [N III], 122 and 205 $\mu$m [N II] (see Madden et al. 2013, for more details of the DGS observations). These important cooling lines are diagnostics to probe the FUV flux, the gas density and temperature and the filling factor of the ionized gas and photodissociation regions (PDRs; e.g. Wolfire et al. 1990; Kaufman et al. 2006; Le Petit et al. 2006). The photoelectric effect is normally the dominant source of gas heating in PDRs and [C II] usually ranks foremost in the PDR cooling lines, followed by the 63 $\mu$m [O I]. Thus the [C II]/$L_{\rm FIR}$ (or ([C II]+ [O I])/$L_{\rm FIR}$) indicates the efficiency of photoelectric heating. Figure 4 (*left*) shows the ([C II]+ [O I])/$L_{\rm FIR}$ vs. $L_{\rm FIR}$ of dwarf galaxies is higher than those of galaxies in other surveys, of mostly metal-rich galaxies. These relatively larger efficiency factors, from 1 % to 2 %, can be a consequence of relatively normal PDR gas densities (often on the order of $10^3$ to $10^4$ cm$^{-3}$) and low average ambient radiation fields over full galaxy scales, resulting in a relatively low ionization parameter. Note, in contrast, the effect of the FIR line deficit seen in the most luminous sources (e.g. Luhman et al. 2003; Graciá-Carpio et al. 2011; Díaz-Santos et al. 2013; Farrah et al. 2013) where dustier H II regions are present leading to a high ionization factor globally. On the other hand, the 88 $\mu$m [O III] line is the brightest FIR cooling line in the dwarf galaxies — not the [C II] line, as in the normal metallicity galaxies. The predominance of the [O III] line which requires an ionization energy of 35 eV, demonstrates the ease at which such hard photons can traverse the ISM on full galaxy scales (see also Cormier et al. 2012; Lebouteiller et al. 2012), highlighting the different nature and structure of the ISM of low metallicity galaxies.

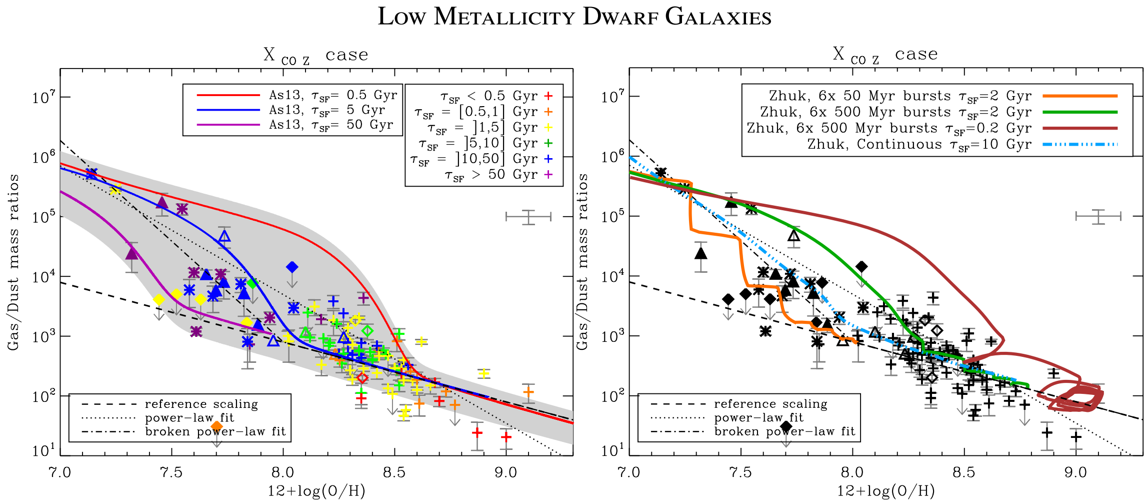


**Figure 3.** Comparison of the observed G/D for the DGS + KINGFISH galaxies compared to models of Asano et al. (2013) (*left*) and Zhukovska et al. (in preparation) (*right*) for various star formation time scales ($\tau$) and star formation histories. From the recent study of Rémy-Ruyer et al. (2013b).

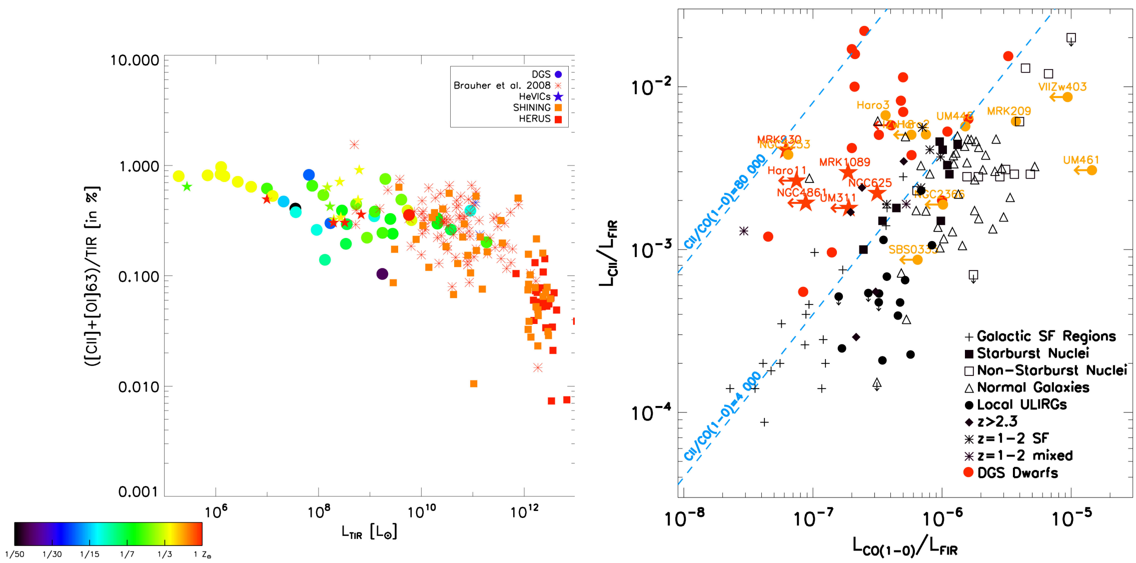


**Figure 4.** *Left*: ([C II]+[O I])/$L_{TIR}$ vs $L_{TIR}$ and *Right*: [C II]/$L_{FIR}$ vs CO(1–0)/$L_{FIR}$ for the dwarf galaxies and other more metal-rich samples.

The dwarf galaxies also show extreme [C II]/CO ratios (Figure 4 *right*): while most normal star forming galaxies are observed to have [C II]/CO ~ 1000 to 4000, the low metallicity galaxies can reach much higher ratios — up to an order of magnitude higher, or more, in [C II]/CO over galaxy-wide scales. Such relatively high [C II] values may be indicative of a reservoir of gas, possibly molecular, not traced by CO: the CO-dark molecular gas, which may be present in the $C^+$-emitting region, where the CO is photodissociated but the $H_2$ remains self-shielded from the dissociating photons (e.g. Glover & Jappsen 2007; Wolfire et al. 2010). This was first uncovered in a few low metallicity galaxies using [C II] (e.g. Poglitsch et al. 1995; Israel et al. 1996; Madden et al. 1997), but *Herschel* has increased the sample for deeper studies and *SPICA* will take the study of this phenomenon to much large samples of extremely low metallicity, where CO is very difficult to detect, if at all.

## 4. PROBING THE COMPLEX LOW METALLICITY ISM -THE *SPICA* DWARF GALAXY SURVEY

The challenge for *SPICA* is to take the next step to obtain the wide range of MIR and FIR cooling lines to be able to model the various phases of the gas and dust over full galaxy scales *as well as* obtaining much large sample of low metallicity dwarf galaxies, to obtain a more precise prescription of the role of metallicity in governing the evolution of galaxies. *Herschel* has successfully opened up wide the window into this subject and can be exploited to build a most comprehensive observing programs for *SPICA*. To execute this will entail reaching for a large number of the lowest metallicity galaxies. Due to sensitivity, *Herschel* was able to target only a handful of extremely low metallicity galaxies: less than 1/20 $Z_{\odot}$ in photometry ($12 + \log(O/H) < 7.8$; Figure 1) and of these 20 % were not detectable with PACS 160 $\mu$m. 10 % of our full sample was not detectable in spectroscopy at all, and only 20 % were detected with 5 FIR fine structure lines and only one or two of the brightest FIR fine structure lines, if at all, in the lowest metallicity galaxies. Having observational constraints for the MIR through FIR continuum to accurately model the dust properties (Figure 1) for large numbers of the lowest metallicity galaxies would be a breakthrough with *SPICA*. Many ambiguities remain in the interpretation of the behavior of the G/D ratio at these low metallicities, specifically metallicities less than 12 + log (O/H) (about 1/8 $Z_\odot$; Figure 3).

Using limiting MIR and FIR gas diagnostics to deduce the conditions for star formation and the structure of the galaxy is effectively averaging ensembles of PDRs and physically different gas phases mixed in a telescope beam. The challenge in moving forward with interpretation is to cover a range of diagnostics having varying critical densities and ionization potentials, to be able to characterise the PDRs and dense and diffuse ionized gas and neutral atomic and molecular gas which have very different filling factors even for the range of dwarf galaxies *Herschel* has surveyed. Analysis of these various phases comprising galaxies can not be done without considering the gas and dust tracers together. An example of one of the most thorough analysis that has been approached, given the wide selection of diagnostics for any one galaxy, is demonstrated in Cormier et al. (2012, 2013) with 17 FIR fine structure lines and CO observations as well as the photometry constraints to model the full dust SED of Haro 11. This is the brightest low metallicity galaxy in the DGS sample and 7 FIR lines were obtained with PACS as well as all of the higher energy ionic lines with the *Spitzer* IRS. Cormier et al. (2012) was able to determine the mass fraction of different phases of this unresolved galaxy. Only with sufficient observational constraints was this possible, but now will be possible for large numbers of galaxies, with the increased sensitivity of *SPICA*.

Statistical surveys with *SPICA* will follow from *Euclid* (launch expected 2018) which will survey 15000 sq degree, detecting $10^{12}$ galaxies of which about $10^5$ should be dwarfs: to as low as $10^6\,L_\odot$ out to 100 Mpc with a limiting magnitude, $M_B$, of −24.5 whereas *Herschel* was −20.0. If *SPICA* surveys 500 dwarf galaxies of similar characteristics as the lowest metallicity galaxies detected by *Herschel* (SBS0335−052 and IZw18), the FIR SAFARI spectrometer on *SPICA* would require 500 h to simultaneously detect the 7 brightest FIR lines and continuum. The MIR camera, MCS (12 to 28 $\mu$m), which would observe the PAH bands, $H_2$ lines, ionic lines plus warmer dust continuum, would use 100 to 500 h to complete the survey. Similarly, to map the extended Local Group galaxies, such as NGC 6822, NGC 4214, IC 10, would require on the order of ∼10 h with SAFARI while mapping galaxies the size of the SMC or M31 (5 deg ×2 deg) would use 300 to 500 h. The LMC (8 deg ×8 deg), on the other hand, would require more than 2 months if mapped completely. Mapping 1 deg ×1 deg pieces of the LMC with SAFARI would take ∼30 h, which would allow a wide rage of ISM and star formation properties to be probed in the LMC. Spectroscopy with PACS on *Herschel* and IRS on *Spitzer* acquired very limited regions in the LMC and SMC, each of several arcmin$^2$ at most. Only with large statistically-important surveys with *SPICA* observing a large array of important diagnostic MIR to FIR lines, and with more efficient mapping characteristics, will we be able to accurately assess the impact of metallicity on the evolution of the dust and gas of galaxies.

None of this research would be possible without the dedicated effort of the *Herschel* PACS GT and SPIRE GT SAG 2 teams in producing science-quality data, with particular acknowledgement to Maud Galametz, George Bendo, Hélène Roussel, Matt Smith, Marc Sauvage, Eckhard Sturm and Albrecht Poglitsch. This research was supported in part by the Agence Nationale de la Recherche (ANR) through the programme SYMPATICO (Program Blanc Projet ANR-11-BS56-0023).

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