The Spectral Energy Distribution of Galaxies
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Characterisation of the submillimeter excess in dwarf galaxies: Presentation of the *Herschel* Dwarf Galaxies Survey

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Abstract. The *Herschel* Space Observatory is revolutionizing our view of dust in galaxies with high sensitivity observations in the far infrared(FIR)/submillimeter (submm) regime from 70 to 500 μm. *Herschel* is confirming the submm excess that has been noted previously in low metallicity dwarfs. We present here the Dwarf Galaxies Survey sample through a *Herschel* colour-colour diagram. We will then focus on two galaxies, Haro11 and NGC4449 presenting different interesting behaviours in the FIR as revealed by *Herschel*.

Keywords. galaxies: dwarf, galaxies: ISM, ISM: dust, infrared: ISM, submillimeter,

1. The *Herschel* Dwarf Galaxies Survey

The Interstellar Medium (ISM) plays a key role in the evolution of a galaxy, being the repository of stellar ejecta and the site of stellar birth. The spectral energy distribution (SED) is a current snapshot with this historical information integrated over the lifetime of the galaxy. To understand star formation and its feedback on the ISM in conditions that may be representative of different stages of early universe environments, the *Herschel* Dwarf Galaxy Survey (DGS; P.I. Madden) is studying the gas and dust properties of a wide variety of 48 low-metallicity (Z) galaxies at far infrared (FIR) and submillimeter (submm) wavelengths. Our sample has been observed with both *Herschel* photometers : PACS (Poglitsch *et al.* 2010) at 70, 100 and 160 μm and SPIRE (Griffin *et al.* 2010) at 250, 350 and 500 μm spanning a wide range in metallicity : 12+log(O/H) = 7.2 to 8.5.

2. Far Infrared Colours

To obtain a better overall view of the DGS and its mid infrared (MIR) to submm behaviour, we constructed several *Herschel* colour-colour diagrams, and present one of them here (example : Fig. 1). Total fluxes were extracted from the maps to compute the various ratios (Remy *et al.* 2011, in prep). We eliminated galaxies with more than one upper limit in the considered bands. We then computed the theoretical *Herschel* flux ratios of simulated modified black bodies spanning a range in temperatures (from 10 to 100K) and emissivity index (from 1.0 to 2.5). The spread of galaxies in the diagram in Fig. 1 reflects variations in metallicity, T, and β in our survey. The submm SED for local and distant galaxies is commonly described by β = 2. The flattening of the submm slope (β<2) may signal possible excess emission appearing at or beyond 500 μm. Therefore, the $PACS_{70}/PACS_{160}$ vs $PACS_{160}/SPIRE_{500}$ diagram can be considered a

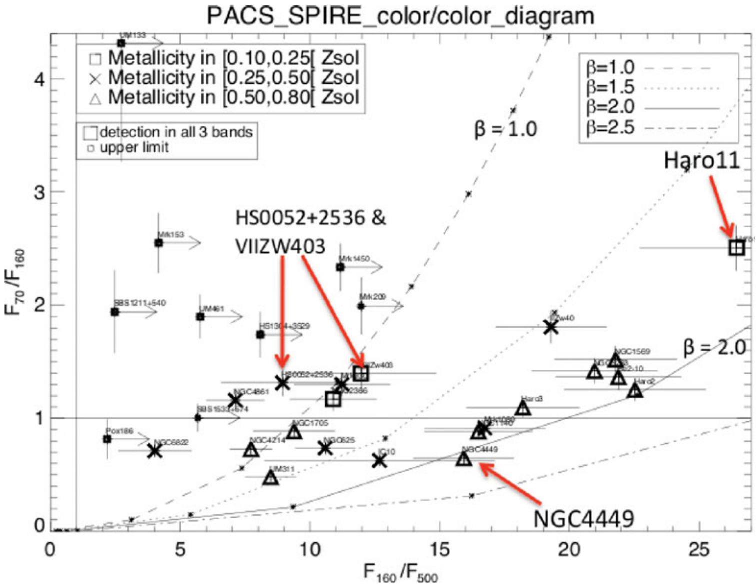

Figure 1. DGS colour colour diagram : $PACS_{70}/PACS_{160}$ vs $PACS_{160}/SPIRE_{500}$. The symbols delineate the metallicity bins for the galaxies. The large symbols are for galaxies with detections in all 3 bands; smaller ones are sources that are not detected at 500 μm. The four curves give theoretical *Herschel* flux ratios for simulated modified black bodies for β=1.0 to 2.5 and T=10 to 100K, increasing in 10K bins from left to right. Sources mentionned in the text are indicated by arrows.

good diagnostic tool, for example, to spot some potential "submm excess" galaxies (eg. Haro11, HS0052+2536 or VIIZw403).

3. Zoom on particular cases

From our diagnostic diagram, we select, for illustration, Haro11 (D$\sim$90 Mpc, Z=0.2$Z_\odot$) for its apparent submm excess, and NGC4449 (D$\sim$4.1 Mpc, Z=0.5$Z_\odot$) for its excess starting after 500 μm.

The Haro 11 MIR to submm SED was modelled by Galametz *et al.* (2009) with an additional Very Cold Dust (VCD) component (β=1, T=10 K) to explain the submm excess, and NGC 4449 has been modelled here with the Galliano *et al.* (2011) model.

Note how Haro11 SED peaks at $\sim$ 40 μm, shorter than metal rich starbursting galaxies, and typical of the very active starbursting dwarf galaxies (Fig. 2). Also note the submm excess seen in both galaxies : Haro 11 begins to show submm excess at 500 μm, as highlighted by the *Herschel* colour-colour diagram (Fig. 1). For NGC4449 however the excess is not apparent at 500 μm : NGC4449 falls on the $\beta = 2$ line when considering only the Herschel bands (Fig. 1). This is confirmed by the modelled SED (Fig. 2). The excess in dwarf galaxies is often only appearing at longer submm wavelengths and is not always detected with *Herschel*. This highlights the necessity of having submm constraints beyond *Herschel* for SED modelling.

Assuming a VCD component for Haro 11, the derived dust mass is $1.7\times10^7 M_\odot$. Haro11 only has an HI upper limit of $\sim10^8 M_\odot$ (Bergvall *et al.* 2000), and only an upper limit of CO(1-0) (D. Cormier, priv. com.), which, if we assume this traces the molecular gas, leaves little H_2. Therefore, the measured gas-to-dust mass ratio (G/D) is $\sim$5.8, much too low compared to that expected from chemical evolution models. Assuming a Galactic G/D $\sim$158 (Zubko *et al.* 2004) we should find G/D$\sim$790 for Haro11, considering its

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metallicity. Assuming that the dust mass determination is reliable, a large fraction of the gas mass seems to be missing and could exist as a large reservoir of CO-dark molecular gas (as suggested by Madden *et al.* 1997 for IC10, another dwarf irregular galaxy) or as a large reservoir of ionized gas. For NGC4449, we derive a dust mass of $1.9 \times 10^6 M_\odot$ from our modelled SED, which is comparable to that found by Böttner *et al.* (2003) using SCUBA 450 and 850 μm observations. Hunter *et al.* (1998, 2000) determined a total gas mass (HI and H_2) of $1.1 \times 10^9 M_\odot$, giving us a G/D of $\sim$578. The scaling from the Galactic value would be $\sim$316, considering NGC4449 metallicity. As we did not yet model the potential excess seen in NGC 4449, some cold dust could have been missed by our present dust mass estimate.

Other explanations have been proposed to explain the origin of the submm excess in addition to an extra VCD component. For example, the use of amorphous carbons instead of graphites, with a lower emissivity index, requires less dust mass to account for the same luminosity (Galliano *et al.* 2011). The electric dipole emission from fast rotating grains ("spinning dust", e.g. Bot *et al.* 2010) has also been suggested as a possible source of the submm excess. To date, no one explanation suffices. Further studies on the DGS may bring new answers on this present issue.

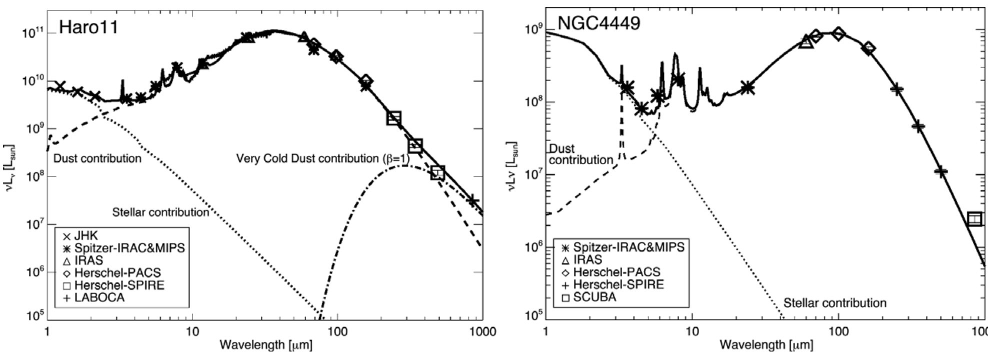

Figure 2. (left :) SED of Haro11 from Galametz *et al.* 2009, with *Herschel* points overlayed as diamonds and squares. (right :) The SED of NGC4449 has been obtained with the Galliano *et al.* 2011 model, including the new *Herschel* points. Other symbols are observational constraints from previous missions such as 2MASS, ISO, IRAS, Spitzer and IRS spectrum between 5-40 μm for Haro11. The total SEDs are the sum of the different contributions displayed here : stellar, dust and VCD for Haro11. The VCD hypothesis have been tested on Haro11 to explain the submm excess (Galametz *et al.* 2009) but led to extremely low G/D. NGC4449 however begins to show potential excess after 500 μm which is not detected with *Herschel*.

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