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NEW RESULTS FROM THE HERSCHEL REFERENCE SURVEY

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Abstract. The *Herschel* Reference Survey is a SPIRE guaranteed time key project aimed at studying the properties of the interstellar medium of a K-band selected, volume-limited ($15 \leq D \leq 25$ Mpc) complete sample of 322 galaxies spanning a large range in morphological type and stellar mass. We study the far infrared colours of the late-type galaxies of the cluster with the purpose of tracing with an empirical approach the relationships between the shape of the observed spectral energy distribution (SED) and different physical parameters such as the star formation rate, the birthrate parameter (or specific star formation rate), here taken as a tracer of the hardness of the inciding radiation, the intensity of the ionising and non ionising radiation, the metallicity and the Hα and FUV attenuation. We also show that the far infrared shape of the SED cannot be fitted with a modified black body with a fixed grain emissivity parameter β. All this analysis is a brief summary of a work presented in Boselli et al. (2012).

Keywords: Galaxies: ISM; dust; spiral; Infrared: galaxies

1 Introduction

Dust plays a major role in the matter cycle within galaxies. Formed by the aggregation of metals produced and injected into the interstellar medium (ISM) by stars during their evolution, dust is heated by the stellar radiation and re-emits in the infrared spectral domain. Dust is important in the process of star formation because acts as catalyst in the formation of molecular hydrogen inside giant molecular clouds, where star formation takes place. At the same time, absorbing the stellar radiation, and in particular the one emitted by the youngest, massive stars, its infrared radiation can be used as a direct tracer of star formation. The far infrared emission is also of paramount importance for quantyfing the amount of dust attenuation, and is thus necessary in the study of the different stellar populations in galaxies (e.g. Boselli (2011)).

With the purpose of studying the physical properties of the ISM of galaxies of different type and luminosity, the SPIRE extragalactic consortium has defined a guaranteed time key project, the *Herschel* Reference Survey (HRS), to observe 322 nearby galaxies in the bands at 250, 350 and 500 μm (Boselli et al. (2010)). The HRS is a complete, K-band selected, volume-limited ($15 \leq D \leq 25$ Mpc) sample suitable for any kind of statistical study. The SPIRE data of the HRS sample have been presented in Ciesla et al. (2012). We present here the most recent scientific results based on the analysis of the SPIRE data, in particular those relative to the far infrared colours of late-type galaxies. To avoid any possible effect related to the interaction of galaxies with the surrounding environment, we limit our analysis to unperturbed galaxies selected according to their HI-deficiency parameter $HI-def \leq 0.4$ (see Boselli & Gavazzi (2006) for the definition and the scientific interpretation of this parameter). These results have been recently published in Boselli et al. (2012) and Boselli et al. (2010). This work takes benefit from the large amount of multifrequency data that the team has acquired in these last years which are critical for defining the physical properties of the observed galaxies. These include gas metallicities obtained from integrated spectroscopy (Hughes et al. 2013; Boselli et al. 2013), atomic and molecular gas data (Boselli et al. 2013b), GALEX UV and optical photometry (Boselli et al. 2011; Cortese et al. 2012a), Halpha imaging (Boselli et al., in prep.). Most of these data have been made available to the community through our dedicated database at http://hedam.lam.fr/. Other interesting results on the analysis of the HRS far infrared data can be found in Cortese et al. (2010), Sauvage et al. (2010), Pohlen et al. (2010), Gomez et al. (2010), Eales et al. (2010), Boquien et al. (2012), Cortese et al. (2012b), Smith et al. (2012), Eales et al. (2012), and Boquien et al. (2013).

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2 The far infrared colours of normal galaxies

The multifrequency data in our hands allow us to define several physical variables to characterise the properties of the HRS galaxies. These variables are the star formation rate SFR, determined as in Boselli et al. (2009), the birthrate parameter b (Boselli et al. 2001) here taken as a tracer of the hardness of the inciding radiation, the Hα surface brightness, tracer of the density of the ionising radiation, the H-band effective surface brightness $\mu_e(H)$, tracer of the density of the general interstellar radiation field, the metallicity 12 + log(O/H) and the Hα $A(H\alpha)$ and FUV $A(FUV)$ attenuation, this last determined as in Cortese et al. (2008). Figure 1 shows the relationship between different far infrared colours, defined as the ratio of the far infrared flux densities measured in different bands, and these different physical parameters.
The widely used $S60/S100$ IRAS colour is often adopted as a direct tracer of the starburst activity of the target galaxies. This index is sensitive to the emission of the warm dust component principally heated by young stars and is thus a *warm dust sensitive index*. The colour indices $S60/S250$, $S100/S250$ and $S100/S500$ are sensitive to the relative weight of the warm and cold dust component since the peak of the emission of normal, star forming galaxies such as those analysed in this work lies in between 100 and 200 μm, thus in between the two photometric bands used to define these indices. They are related to the wavelength position of the peak of the dust emission, and are thus *dust peak sensitive indices*. The SPIRE colour indices $S250/S350$, $S250/S500$ and $S350/S500$ are indices tracing the emitting properties of the coldest dust component (*cold dust sensitive indices*). Indeed they sample the Rayleigh-Jeans tail of the dust emission dominating in mass in normal galaxies.

Figure 1 shows that the warm dust sensitive index $S60/S100$ is not related to the direct tracers of the star formation activity (SFR, $\Sigma(H\alpha)$), while it is only correlated to the birthrate parameter b. Galaxies still active in forming stars at the present epoch ($b \geq 1$) have, on average, $S60/S100$ flux density ratios ($S60/S100 \simeq 0.6$) slightly larger than quiescent objects ($b \leq 1$; $S60/S100 \simeq 0.4$). This indicates that, whenever integrated values are used, the contribution of the warm dust component to the total emission of late-type galaxies is principally controlled by the history of star formation (or the hardness of the radiation field) rather than by the present day activity. Figure 1 also shows poorly defined and dispersed relations between the peak sensitive $S100/S500$, $S100/S250$ and $S60/S250$ colour indices and the surface brightness of the ionising ($\Sigma(H\alpha)$) and non-ionising ($\mu_e(H)$) interstellar radiation field and the FUV attenuation ($A(FUV)$). Among these colour indices, only $S60/S250$ and $S100/S250$ correlate very mildly with the birthrate parameter. This evidence suggests that the position of the peak of the dust emission, or in other words the mean temperature of the dust, is governed, as expected, by the general interstellar radiation field. We also see strong correlations between the cold dust sensitive $S250/S350$ and $S250/S500$ colour indices and $\Sigma(H\alpha)$, $\mu_e(H)$ and $A(FUV)$. Warmer colours are observed in those galaxies with higher radiation fields and higher extinction. The same colour indices are only barely related to the present day star formation activity and the metallicity. Again, these plots indicate that the emission of the cold dust component is also controlled by the general interstellar radiation field and partly by the metallicity. What is surprising, however, is that the correlations with these cold dust sensitive indices are significantly stronger than with the peak sensitive indices which are sampling a warmer dust component. The first presentation of these results and their interpretation are extensively given in Boselli et al. (2012).

The relationships observed between the different far infrared colour indices can be due either to variations of the mean temperature of the emitting dust or to variations in the dust grain emissivity properties that might change in different types of galaxies. Assuming that dust grains are in thermal equilibrium with the radiation, which is probably the case for $\lambda \geq 250$ μm, the far infrared emission of galaxies is generally approximated by one (or more) modified black body $B(\nu, T)$, with a resulting emitted flux density:

$$S_{dust}(\nu, T) \propto \nu^{\beta} B(\nu, T) \tag{2.1}$$

where β is the grain emissivity index whose value ranges between ~ 1.5 and ~ 2 (Hildebrand 1983). Although not physical, this simple analytical prescription is often used both in extragalactic and cosmological studies since it reproduces fairly well the observed far infrared spectral energy distributions of galaxies. Our new homogeneous and complete set of data, in particular those obtained by SPIRE in the spectral domain 250-500 μm, can be used to see whether this simple modified black body assumption is realistic. At the same time this dataset can help us to understand which of the two main parameters regulating the dust emissivity, the grain emissivity index β or the dust temperature T, is the main driver of the observed colour-colour far infrared relations and for their scatter. To this aim we plot in Fig. 2 the SPIRE colour-colour indices $S250/S350$ vs. $S350/S500$ for galaxies coded according to the different physical parameters already used in the previous figure

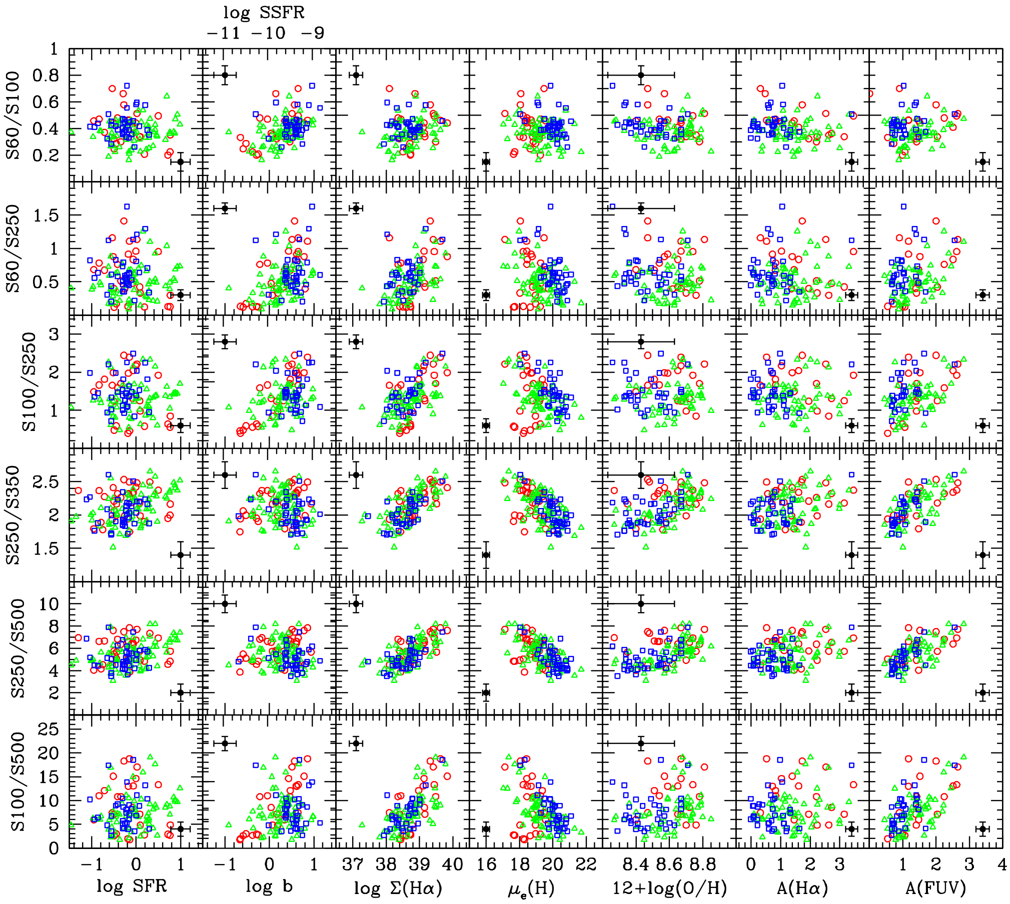

Fig. 1. The relationship between the far infrared colour indices and different tracers of the physical properties of the interstellar medium, from left to right: first column: the logarithm of the star formation rate (in $M_{\odot}yr^{-1}$) measured as described in Boselli et al. (2009); second column: the logarithm of the birthrate parameter b (or the specific star formation rate $SSFR$); third column: the logarithm of the Hα effective surface brightness (in erg s^{-1} kpc^{-2}); fourth column: the H-band effective surface brightness (in AB mag $arcsec^{-2}$); fifth column: the metallicity index 12+log(O/H); sixth column: the Balmer extinction $A(H\alpha)$ (in magnitudes); seventh column: the FUV attenuation $A(FUV)$ (in magnitudes). Red open circles for Sa-Sb, green empty triangles for Sbc-Scd and blue open squares for Sd-Im-BCD. The typical error bar is indicated with a black symbol (from Boselli et al. (2012)).

and compare them to the expected values obtained for a modified black body with a grain emissivity index β = 2 (solid line) and $\beta = 1.5$ (dotted line). Clearly, the observed relations can not be represented by a modified black body with a dust grain emissivity index of $\beta = 2$, but are better reproduced when $\beta = 1.5$.

The observed relationship between the two colour indices has a slope slightly flatter than the one predicted by a single modified black body of fixed grain emissivity index. We can thus not exclude values of $\beta > 1.5$ in galaxies with the highest flux density ratios. Similarly, in the objects with the lowest flux density ratios, β might be < 1.5. This evidence might indicate that both β and T vary along the sequence. Indeed, there is a quite strong degeneracy between β and T given that at these low temperatures a variation of T of ~ 5 K is almost equivalent to a variation of β of ~ 0.5. Furthermore, we have to remember that β and T might also be inversely correlated (Désert et al. 2008; Shetty et al. 2009; Veneziani et al. 2010; Anderson et al. 2010; Bracco et al. 2011).

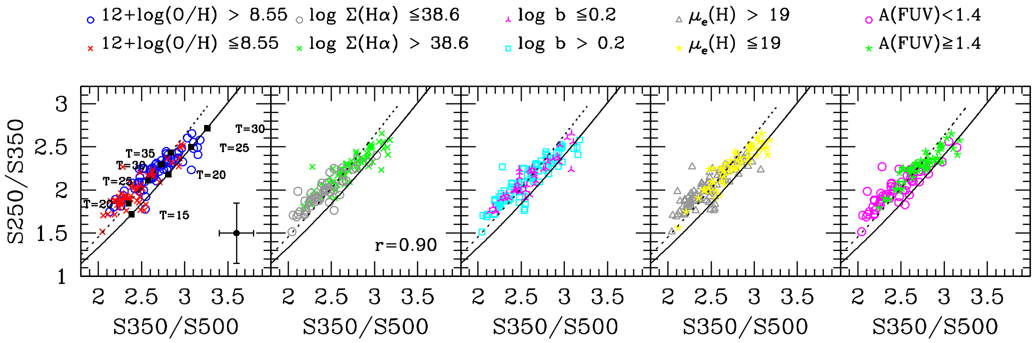

Fig. 2. The relationship between the SPIRE colour-colour indices $S250/S350$ vs. $S350/S500$ for galaxies coded according to their different physical parameters (from Boselli et al. (2012)). The colour-colour relation is compared to the expected relations obtained for a modified black body with a grain emissivity index $\beta = 2$ (solid line) and $\beta = 1.5$ (dotted line). Black squares indicate different temperatures for the two modified black bodies (left panel). The Spearman correlation coefficient of this relation is r=0.90.

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