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Dust attenuation on and off the galaxy Main Sequence at $z \geqslant 1$

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Abstract. Stellar masses are crucial ingredients for putting galaxies in the context of galaxy evolution and are commonly evaluated via Spectral Energy Distribution (SED)-fitting analyses which are hampered by dust attenuation. Observational constraints of attenuation in various galaxy classes provide key inputs for fitting a SED. I will present recent results about the attenuation properties of a sample of *Herschel*-selected galaxies at $0.7 \leqslant z \leqslant 1.6$ widely spanning the star-forming Main Sequence (MS). I will show that far-IR selected galaxies on the MS are well described with local attenuation recipes. Conversely, common recipes cannot recover the SFR of far-IR selected starburst galaxies well above the MS. The SFR of these outliers appears to be hidden by the ∼90% in optically thick cores. These findings pose challenges for SED-fitting codes based on energy balance assumptions that might break in these peculiar sources.

Keywords. galaxies: evolution, galaxies: high-redshift, galaxies: star formation, dust, extinction, infrared, galaxies: interactions, galaxies: ISM

1. Introduction

The so-called Main Sequence is a tight relation that roughly 90% of star-forming galaxies follow in the stellar mass ($M_\star$) versus Star Formation Rate (SFR) plane (MS, Speagle *et al.* 2014). Its existence since very high redshifts along with its small scatter (∼0.3 *dex*, Whitaker *et al.* 2014) has been often interpreted as an evidence that star formation events proceed smoothly with cosmic time and stochastic episodes (e.g. mergers) do not significantly contribute to galaxy growth. Nevertheless, outliers from this MS exist and might have a key role in the formation of massive elliptical galaxies despite contributing only ∼10% to the cosmic SFR density (Rodighiero *et al.* 2011).

Locating a galaxy on the MS plane implies to measure accurate $M_\star$ and SFR. Traditionally, $M_\star$ is inferred through Spectral Energy Distribution (SED) fitting codes by comparing simple stellar population models to UV- to-NIR observations after applying a dust attenuation correction (Conroy 2013, e.g.). Measurements of SFR from UV or optical emission lines also require to correct for dust attenuation.

There are several dust attenuation indicators allowing us to correct the spectrum of a galaxy for this effect. For example, one can use the slope of the spectrum in the UV (the so-call UV-slope β, Calzetti *et al.* 1994) to evaluate the *reddening* of the stellar continuum $E_\star(B-V)$. To quantify the dust attenuation in HII regions, $E_{\rm neb}(B-V)$, one can directly measure nebular line ratios such as the Balmer Decrement (i.e., the $H\alpha/H\beta$ line ratio, BD). Finally, the so-called IRX=$L_{\rm FIR}/L_{\rm UV}$ ratio quantifies the total dust attenuation of a galaxy by comparing the bolometric emission of the dust ($L_{\rm IR}$) and the observed radiation at UV wavelengths ($L_{\rm UV,obs}$). These indicators appear to be correlated through empirical relationship which are mainly calibrated on local galaxies. Exploring the validity of dust attenuation correction in the high-z Universe is crucial given that star-forming galaxies show evolving properties as a function of redshift. Moreover, most studies are conducted on "typical" MS galaxies representative of the star-forming population. Systematic works exploring the dust attenuation properties of starbursting MS outliers are missing although it is likely to expect some variations in these objects given their large gas and dust content.

In this proceeding I will summarize our recent efforts to study the dust attenuation properties of $z \geqslant 1$ star-forming galaxies selected from *Herschel* far-IR observations in various extragalactic fields for having spectroscopy covering the nebular emission lines.

2. Dust attenuation on the $z \sim 1$ MS

In Puglisi *et al.* 2016 we analyzed the near-IR spectra of 79 *Herschel*-selected star forming galaxies at $0.7 \leqslant z \leqslant 1.5$, acquired from the 3D-HST survey (Brammer *et al.* 2012). The 3D-HST spectra allowed us to detect the Hα emission for the full sample, from which we measured spectroscopic redshifts and Hα fluxes. The sources were selected in the GOODS-Southern field to secure a high quality multi-wavelength data-coverage including 21 bands from then near-UV to the far-IR ($0.23\ \mu m \leqslant \lambda \leqslant 500\ \mu m$). This wide ancillary coverage allowed us to derive robust estimates of $M_\star$, $L_{\rm IR}$, $L_{\rm UV,obs}$ and β via SED fitting with the MAGPHYS software (da Cunha *et al.* 2008). These galaxies span a SFR and $M_\star$ range of $10 \leqslant SFR_{\rm IR+UV} \leqslant 230 M_\odot yr^{-1}$ and $3 \times 10^9 \leqslant M_\star \leqslant 3.5 \times 10^{11} M_\odot$ thus being representative of the MS population above $M_\odot \sim 3 \times 10^{10} M_\odot$.

The left panel in Figure 1 reports the ratio $SFR_{\rm H\alpha}^{\rm uncorr}/SFR_{\rm UV}^{\rm uncorr}$ as a function of $E_\star(B-V)$, as evaluated from the IRX=$L_{\rm IR}/L_{\rm UV}$ ratio. The solid line highlights the relation between the two axis with a nebular-to-continuum attenuation ratio f=$E_{\rm neb}(B-V)/E_{\rm star}(B-V) = 0.93$ that is the best-fit value from the data distribution. This value turns out to be larger than the local value (f=0.58 Calzetti *et al.* 2000). We tested this dust attenuation correction in the right panel of Fig. 1 where we compared the $SFR_{\rm IR+UV}$ with $SFR_{\rm H\alpha}$ corrected for dust attenuation using the prescription derived in this work. This dust attenuation correction yields a good agreement between the two SFR indicators, with a median ratio $SFR_{\rm H\alpha}/SFR_{\rm IR+UV} = 0.88$ and a median relative scatter $|SFR_{\rm IR+UV} - SFR_{\rm H\alpha}|\ /(1 + SFR_{\rm IR+UV}) = 0.38$ whereas using the local f-factor would lead to overestimate the $SFR_{\rm H\alpha}$ by a factor of ~3.3 above $SFR_{\rm IR+UV} \geq 50 M_\odot yr^{-1}$. In both panel, data-points are color-coded according to the $M_\star$. The two panels suggest a possible trend with the $M_\star$: using $f \sim 0.93$ would overestimate $SFR_{\rm H\alpha}$ for galaxies with $M_\star \sim 10^{10} M_\odot$.

3. Dust attenuation off the MS at $z \sim 1.6$

In Puglisi *et al.* 2017 we studied the dust attenuation of dusty starbursting galaxies above the MS at $z \sim 1.6$ (SBs hereafter). These SBs were drawn from a *Herschel*-selected sample and have near-IR spectroscopy from the FMOS-COSMOS survey allowing to detect the Hα and Hβ emission lines at $1.4 \leqslant z \leqslant 1.7$. SB sources analyzed in this work were selected as outliers from the MS, with $SFR \geqslant 4 \times SFR_{\rm MS}$, following Rodighiero *et al.* 2011.

Figure 2-left shows the dust attenuation on the Hα emission, $A_{\rm H\alpha}$, as a function of $M_\star$ for this sample. We use two methods for estimating $A_{\rm H\alpha}$ in this SB sample: the BD (cyan diamonds) and the IRX ratio (red circles). The BD yields an average value $A_{\rm H\alpha,BD} \sim 0.89 \pm 0.69$ mag, consistent with the value measured on the MS at the same redshift. The IRX gives $A_{\rm H\alpha,IRX} \sim 3.3 \pm 0.51$, much larger than the former. The trend seen in Fig. 2 suggests that the optical light (from which $A_{\rm H\alpha,BD}$ is measured) comes from relatively un-obscured lines of sight, whereas the bulk of the SF is almost completely obscured at optical wavelengths. The right panel of Fig. 2 illustrates this configuration,

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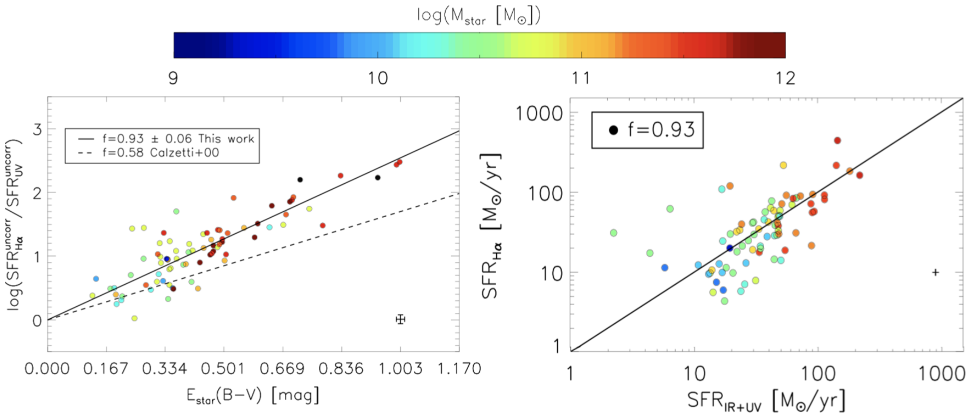

Figure 1. *Left:* Ratio of Hα to UV-based SFR (not corrected for dust extinction) as a function of $E_{\rm star}(B-V)$. The dashed line highlights the relation between these quantities adopting the local f-factor. The continuum line marks our estimate of the f -factor. *Right:* Comparison between $SFR_{\rm IR+UV}$ and $SFR_{\rm H\alpha}$ with the latter corrected for dust attenuation by using $f = 0.93$. The black solid line is the 1:1 correlation line. In both panels, the color-code corresponds to $M_{\star}$.

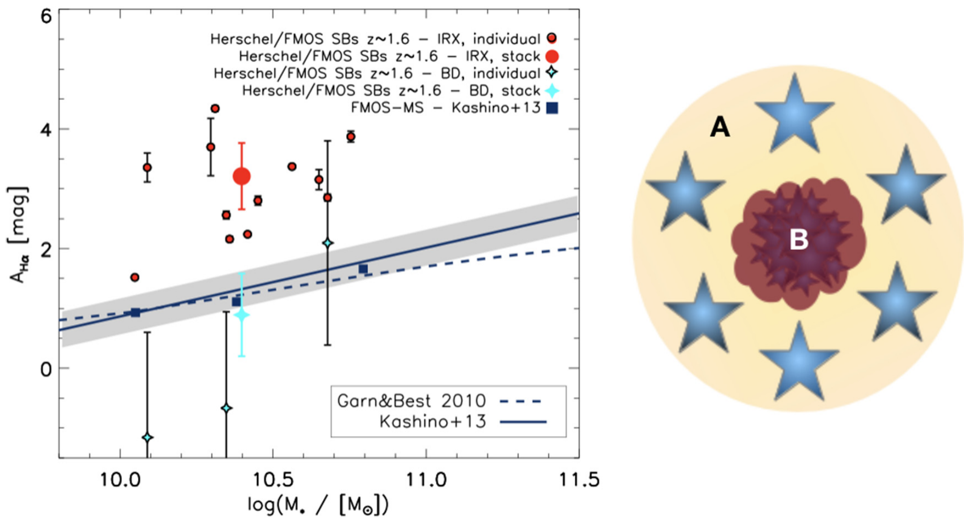

Figure 2. *Left:* Hα attenuation as a function of $M_{\star}$ for the twelve SBs at $z\sim1.6$ presented in Puglisi *et al.* 2017. Red filled dots are measurements of dust attenuation from the IRX ratio whereas cyan diamonds are dust attenuation measurements as derived from the Balmer Decrement. The measurements are compared with the MS trend at $z\sim1.6$ and in the local universe (solid and dashed lines, respectively). *Right:* Cartoon sketching our two-component dust model, with the optically-thin component A highlighted in yellow and the starbursting, optically thick region B in dark red.

in which a SB galaxy is modeled with an optically-thin part and an optically-thick region corresponding to the starburst core. Both components contribute to $SFR_{\rm tot}$ and to our integrated measurements, with their relative contribution depending on their attenuation. By assuming that all the dust is spatially concentrated in the starbursting core region and the optically-thin component is dust free, we estimated a lower limit for the attenuation of the thick core $A_{\rm H\alpha,thick} = 4.5$ mag. In this limiting situation the thick component has its maximum possible contribution to the optical emission lines of $\sim 33\%$. ALMA

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high-resolution imaging of the CO(5-4) emission for one of our sources confirms that $L_{\rm FIR}$ mainly arises from a region barely detected at UV/optical wavelengths (Silverman *et al.* 2018).

These results prompted us to use Magellan FIRE to obtain spectroscopy of starbursts in the near-IR rest-frame. Our aim is to study SBs at longer wavelengths thus suffering less by dust attenuation effects, at least in principle. The first results of this effort are presented in Calabrò *et al.* 2018. In this work by using Paschen-to-Balmer line ratios compared with far-IR dust attenuation indicators, we showed that SBs are consistent with a model in which young stars and dust are homogeneously mixed and are not consistent with attenuation laws assuming a foreground dust screen. With this mixed model the dust attenuation of the heavily obscured core reaches up to $A_{\rm V} \sim 30$ mag, with a median value $A_{\rm V} \sim 9$ mag. In these conditions observed optical/near-IR emission comes from surface regions, while the starburst core is still invisible at near-IR wavelengths.

4. Implications for SED-fitting studies

The results presented in Puglisi *et al.* 2017 and Calabrò *et al.* 2018 suggest that SBs are a separate class off galaxies with different properties with respect to the MS population. In particular, they show peculiar dust attenuation properties due to the large dust content and inhomogeneous dust distributions. These large dust content and the peculiar dust distribution may have dramatic effects on the multi-wavelength SED of these galaxies (see also Hainline *et al.* 2011). Geometrical effects in the dust distribution can produce blue spectra even for a large dust content or may reduce the far-IR emission also for red optical colors (Popping *et al.* 2017). This implies that spatially integrated observations at different wavelengths sample effectively physically disconnected regions (Puglisi *et al.* 2017). The question of whether energy balance assumptions can hold true in these extreme configurations has yet to be proven. Testing the impact of these peculiar dust attenuation properties on SED-estimated stellar population properties seems a crucial next step to firmly establish the role of starburst galaxies in galaxy evolution.

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