FAR-INFRARED AND NEBULAR STAR-FORMATION RATE OF DUSTY STAR FORMING GALAXIES FROM 
Herschel* AND 3D-HST AT z ~ 1

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ABSTRACT

We present results of a multi-band Spectral Energy Distribution (SED) and nebular emission line analysis of a sample of 1147 spectroscopically identified dusty star forming galaxies at 0.49 < z < 2.24 from Herschel/SPIRE and HST/WFC3 grism observations in the five CANDELS fields: AEGIS, GOODS-N, GOODS-S, COSMOS, and UDS. We use the spectroscopic redshifts measured from nebular lines to construct the SEDs of galaxies from the optical to the infrared using HST and Herschel photometry. We further utilize the 3D-HST grism Hα line flux measurements to measure the nebular star-formation rates after correcting for attenuation. We compare this with direct observations of the SFR measurements in the far-infrared from Herschel. Observation of the infrared excess (IRX) in this sample as a function of the UV spectral slope reveals that these DSFGs deviate towards bluer colors, thus sitting well above the expected relation for normal star-forming galaxies. The high-z dusty galaxies have a stellar mass distribution that is skewed towards larger masses, with M∗ = 2.6 × 10^{10} M⊙. However this population has star-formation rates consistent with the most massive tail of the main sequence, showing that these are both the most massive and the most star-forming galaxies during the peak epoch of formation.

Subject headings: dust, extinction – galaxies: general – galaxies: star formation – galaxies: evolution.

1. INTRODUCTION

Galaxies assemble their stellar mass by converting gas into stars within cold giant molecular clouds (Shu et al. 1987; Lada et al. 2010; Murray et al. 2010; Schneider et al. 2015). The rate at which the new stars are formed (the so-called star-formation rate or SFR; Schmidt 1959; Kennicutt 1998) is one of the key factors in determining the evolution of a galaxy (Hopkins et al. 2011; Muzzin et al. 2013; Lilly et al. 2013; González et al. 2014; Furlong et al. 2015). Dusty Star-forming Galaxies (DSFGs) for a recent review see Casey et al. (2014) are among the most star-forming galaxies in the universe (Riechers et al. 2014; Nayyeri et al. 2017b). These systems are bright in the far-infrared where the UV light emitted by young stars are re-emitted by dust in longer wavelengths (Reddy et al. 2012; Casey et al. 2014).

Herschel Space Observatory (Pilbratt et al. 2010) revolutionized studies of the far-infrared universe by allowing direct observations of dust in the local and distant universe (Magnelli et al. 2012; Elbaz et al. 2011; Gruppioni et al. 2013; Schreiber et al. 2015), characterization of rate of major mergers as a function of infrared luminosity and role of merger driven starburst activity (Rosario et al. 2012; Schreiber et al. 2015) and studies of the background far-infrared light (Berta et al. 2011; Cooray et al. 2012; Zemcov et al. 2014). Herschel observations of individual sources provided unique data sets to construct the far-infrared spectrum of dusty galaxies for the first time where previous such measurements were limited to indirect estimates, such as from the mid-IR (Reddy et al. 2010), with inherent uncertainties associated with the conversion and the dust heating (Elbaz et al. 2011; Reddy et al. 2010).

One of the main goals achieved with Herschel is probing the dust obscured star-formation activity in nearby and distant galaxies (Elbaz et al. 2011; Reddy et al. 2012; Overzier et al. 2011; Lee et al. 2012; Mancuso et al. 2016). Direct observations of the dust obscured systems in the far-infrared is used to constrain the universal infrared star-formation rate density budget and to investigate the relative importance of different populations of IR luminous galaxies to this as a function of redshift (Casey et al. 2014). Measurements of the star-formation rates from infrared observations (as a direct probe of obscured SFR; Elbaz et al. 2011; Whitaker et al. 2012) are calibrated from infrared luminosities (assuming an initial mass function; Shu et al. 1987; Kennicutt 1998) and could be directly compared to other SFR indicators (Reddy et al. 2010; Hao et al. 2011; Reddy et al. 2012; Burgarella et al. 2013). This comparison yields valuable information about not only the hidden modes of star-formation but also combined with the different diagnostics provide insight into the burstiness of the star-formation activity and hence time scales of star-formation and is a good diagnostic of the star-formation history of distant galaxies (Wuyts et al. 2011; Reddy et al. 2012; Madau & Dickinson 2014).

Another main indicator of star-formation activity in galaxies is nebular emission lines (Osterbrock 1989) – in particular, the Hydrogen Balmer line Hα at 6563 Å. The recombination emission line Hα is produced in ionized H II regions surrounding the most massive O stars and hence provides a direct probe of instantaneous and the bursty star-formation activity in galaxies at short time scales of ~ 10 Myr. On the other hand, underlying UV continuum in galaxies is produced by the less massive

* Herschel is an ESA space observatory with science instruments provided by European-led Principal Investigator consortia and with important participation from NASA.
young stars and traces star-formation activity over longer average time scales of \( \sim 100 \) Myr. Tracing these different modes of star-formation is crucial in forming a complete picture of total star-formation in a galaxy (Reddy et al. 2010). In particular, the different SFR diagnostics are affected differently by dust, given the wavelength, with the UV SFR being affected the most and IR the least. Hence comparison of these different diagnostics provide indirect probes of the attenuation in galaxies.

In this work, we use combined Herschel and 3D-HST (Brammer et al. 2012) observations of the five Cosmic Assembly Near-Infrared Deep Extragalactic Legacy Survey (CANDELS; Grogin et al. 2011; Koekemoer et al. 2011) fields with optical and near-infrared observations from HST/ACS and WFC3 to construct a complete census of dusty star-forming galaxies at \( z \sim 1 \). In particular, we use the Herschel far-infrared observations to measure the total far-infrared star-formation rates. We combine this with 3D-HST grism observations of the nebular lines and the HST/ACS and WFC3 photometry to get a full construction of the SED of DSFGs from optical to far-infrared and to study the different modes of star-formation from UV to FIR. Additionally, we use these observations to probe the different attenuations that drive different star-formation diagnostics.

This paper is organized as follows. In Section 2 we present the data used in this work, which includes observations by Hubble and Spitzer Space Telescopes and Herschel Space Observatory. We discuss our measurements of the physical parameters of the sources from multi-band SED fits and observed line fluxes in Section 3. The analysis of our results are presented and discussed in the context of dust attenuation in DSFGs in Section 4. We use a Chabrier initial mass function (IMF; Chabrier 2003) throughout this paper. We further assume a standard cosmology with \( H_0 = 70 \) km s\(^{-1}\) Mpc\(^{-1}\), \( \Omega_m = 0.3 \) and \( \Omega_{\Lambda} = 0.7 \). All magnitudes are in the AB system where \( m_{AB} = 23.9 - 2.5 \log(f_{\nu}/1\mu\text{Jy}) \) (Oke & Gunn 1983) unless otherwise noted.

2. DATA

Our sample consists of HST grism observations of \( z \sim 0.5 - 1.6 \) sources from the 3D-HST survey\(^2\) (Skelton et al. 2014; Momcheva et al. 2016) in the five major fields observed by HST Wide Field Camera 3 as part of the Cosmic Assembly Near-Infrared Deep Extragalactic Legacy Survey (CANDELS; Grogin et al. 2011; Koekemoer et al. 2011). Particularly, we take advantage of observations by the Herschel Space Observatory as part of the Herschel Multi-tiered Extragalactic Survey (HerMES; Oliver et al. 2012). This data-set includes photometric observations from Hubble and Spitzer Space Tele- scopes and Herschel Space Observatory from the optical to the infrared bands and spectroscopic observations with HST/WFC3 grism. As such, galaxies in our sample have ample ancillary observations that are used to construct their Spectral Energy Distributions (SEDs) and to measure their physical properties.

2.1. Herschel/HerMES

The Herschel Multi-tiered Extragalactic Survey (HerMES; Oliver et al. 2012), is a legacy survey program designed to study the evolution of galaxies in the distant universe and was the largest project on the European Space Agency’s (ESA) Herschel Space Observatory (900 hours; Pilbratt et al. 2010). In this work we used the fourth data release of the HerMES public photometric catalogs available on HeDaM\(^3\). This included observations at 250 \( \mu \)m, 350 \( \mu \)m and 500 \( \mu \)m bands by the Spectral and Photometric Imaging Receivers (SPIRE; Griffin et al. 2010). We used the XID250 catalogs which provides SPIRE photometry for objects whose positions are taken from catalogs extracted from Spitzer MIPS 24 \( \mu \)m maps (Roseboom et al. 2010, 2012). Furthermore, we used the COSMOS XID+ catalog which uses the XID+ tool (Hurley et al. 2017). This catalog uses 24 \( \mu \)m-detected sources from the MIPS 24 \( \mu \)m catalog (Le Floc’h et al. 2009) as a prior list for extracting SPIRE fluxes from the HerMES SPIRE maps (Oliver et al. 2012). The positional information determined from MIPS observations allows us to cross-match the Herschel observations with the near-infrared and optical data observed by HST as discussed below. MIPS Sky coordinates were matched with HST coordinates, allowing for a positional error of up to 2\( ^\prime \). About 5% of the cross-matches were misidentifications that were later removed.

2.2. 3D-HST Grism Observations

The 3D-HST near-infrared grism spectroscopic survey (Brammer et al. 2012; Skelton et al. 2014) covers roughly three-quarters (625 arcmin\(^2\)) of the area imaged by the CANDELS ultra-deep survey fields (Grogin et al. 2011; Koekemoer et al. 2011). The WFC3/G141 grism is the primary spectral element in the survey, and the G141 grism’s wavelength coverage (1.11 \( \mu \)m \( \leq \lambda \leq 1.67 \mu \)m) allows for the detection of H\( \alpha \) emission lines for sources at 0.7 \( < z < 1.5 \). We also used H\( \beta \) emission line fluxes from

\(^2\) http://3dhst.research.yale.edu

\(^3\) http://hedam.oamp.fr/HerMES/
observations provided a fairly comprehensive wavelength coverage from the near-UV to the near-IR, allowing us to constrain the stellar emissions. Note that not all of the listed HST filters are available in all five of the CANDELS fields.

2.3. CANDELS Photometry

The Cosmic Assembly Near-infrared Deep Extragalactic Legacy Survey (CANDELS; Grogin et al. 2011; Koekemoer et al. 2011) covers approximately 800 arcmin$^2$ of the sky over five main extragalactic fields (Grogin et al. 2011). In this work, we used Spitzer/IRAC 3.6 µm, 4.5 µm, 5.8 µm and 8.0 µm observations reported by CANDELS (Galametz et al. 2013; Guo et al. 2013; Nayyeri et al. 2017a; Stefanon et al. 2017) in the five fields in addition to the optical/near-infrared data discussed above. These observations employ TFIT (Laidler et al. 2007) which is a robust photometry measurement algorithm using prior information – such as position and light distribution profiles – from high-resolution images, to estimate the photometry in a low resolution band. This is crucial for measuring the Spitzer/IRAC photometry given the PSF is much wider than the high resolution HST observations and is essential in constraining the stellar mass of higher redshift sources in our sample.

2.4. Final sample

To construct our final sample, as discussed above, we used the fourth data release of the HerMES survey with coordinates matched to the 24 µm positions and including the 250 µm, 350 µm and 500 µm observations. These sources were matched with the 3D-HST catalogs also with MIPS 24 µm positions using a matching radius of 2″ in the five CANDELS fields of GOODS-S, GOODS-N, COSMOS, AEGIS and UDS. Our choice of matching radius is more conservative than the MIPS 24 µm PSF FWHM (at ~ 6″) and is more consistent with HST and Spitzer/IRAC observations. However, we find that the number of matched sources is not very sensitive to this choice and changes minimally upon choosing a 6″ matching radius. We find 6018 matched sources between the 3D-HST and Herschel/HerMES catalogs out of which 1147 have reported Hα line fluxes. These sources form the final sample used in this study. Table 1 summarizes the result of our matching in each of the five fields. The resulting catalog was cross-matched with the CANDELS photometric catalog (Galametz et al. 2013; Guo et al. 2013; Nayyeri et al. 2017a; Stefanon et al. 2017) to extract the Spitzer/IRAC photometry in the four bands at 3.6, 4.5, 5.8 and 8.0 µm. The final catalog consists of 1147 sources with multi-band photometric observations from the optical to the infrared and reported spectroscopic observations of the Hα and Hβ (when available) nebular emission lines.

3. PHYSICAL PROPERTIES

3.1. Physical Properties from Multi-band SEDs

We fit observed SEDs of our sources with the MAGPHYS package (Multi-wavelength Analysis of Galaxy Physical Properties; da Cunha et al. (2008)), which compares the observed values of flux density to a library of model SEDs at the same redshift, for the entire SED – from the UV to the far-IR range. We ran MAGPHYS in the default mode, wherein the library of reference galaxy spectra...
are generated using Bruzual & Charlot’s (2003) stellar population synthesis models in conjunction with Charlot & Fall’s (2000) dust attenuation libraries, and dust emission models from da Cunha et al. (2008).

The Bruzual (2007) version of the Bruzual & Charlot (2003) code was used to predict the spectral evolution of stellar populations at wavelengths ranging from 91 Å to 160 µm, aged from 1 × 10^5 to 2 × 10^9 yr. In these models, timescales of random bursts of star formation are distributed uniformly between 3 × 10^7 and 3 × 10^8 yr, galaxy ages between 0.1 and 13.5 Gyr, and stellar metallicities between 0.02 and 2 Z⊙ (solar metallicity). The probability density function of star formation timescale is nearly uniform over 0 to 0.6 Gyr−1 and drops around 1 Gyr−1. For each galaxy, both the dust-attenuated and dust-free spectra are calculated, the former using the angle-averaged two-component dust model of Charlot & Fall (2000), which accounts for the birth of stars in dense molecular clouds which dissipate in timescales of 10^7 yr. The dust attenuation model thus treats dust attenuation from both the natal birth clouds and the interstellar medium (ISM) and that from just the ISM separately. The da Cunha (2008) dust emission models combine SEDs of the power reradiated by dust in the IR and from dust emitted by the ambient ISM. For the birth clouds, three components contribute to the dust emission: polycylic aromatic hydrocarbons (PAHs), a mid-IR continuum consisting of hot grains at 130-250 K, and warm dust in thermal equilibrium, where the equilibrium temperature is distributed between 30 K and 60 K.

For our SED fitting, we used 13 photometric bands for UDS sources, 14 for AEGIS and COSMOS, 16 for GOODS-N and 17 for GOODS-S. These fits used a near-UV filter (~ 0.37 µm), at least 5 optical filters (0.5 – 1.5 µm), 4 mid-IR filters (3.6–8 µm), 3 far-IR filters (250, 350, and 500 µm), and with the exception of the UDS sources, the MIPS 24 µm mid-IR filter. Thus, we had a comprehensive coverage of wavelengths for fitting our observed SEDs to models at the same redshift. Figure 3 shows the MAGPHYS output SEDs for 8 representative sources in the five fields. About half of the fits were very good (χ^2 ≤ 3), 20% had χ^2 > 10, and 10% were poor fits with χ^2 > 20. MAGPHYS returns several physical parameters, including total infrared luminosity (L_{IR}; rest-frame 8 – 1000 µm), stellar masses (M⋆), and dust temperature (T_d). These are marginalized parameters, based on the likelihood probability distribution functions from the observed photometry. For the uncertainties, we report the 16% and 84% intervals from the probability distribution for each measured parameter. Figure 2 shows the measured total infrared luminosities for our sample of Herschel detected DSFGs as a function of redshift, with the spectroscopic redshifts derived from the 3D-HST matched catalogs. Our measured luminosities mostly lie above the Herschel detection limit of S_{250} > 10 mJy assuming a dust temperature of T_d = 35 K, and is in agreement with mid-infrared and millimeter selected samples of dusty galaxies (Casey et al. 2012). The scatter and deviations from the line is associated with the variations in the infrared SEDs of galaxies due to variations in the intrinsic dust temperatures and opacities.

### 3.2. The UV and Far-IR SFRs

MAGPHYS measured total infrared luminosities, L_{IR}, could be directly converted to total infrared star-formation rates, SFR(IR), using SFR(M⊙ yr−1) = 10−10 × L_{IR}[L⊙] conversion assuming a Chabrier IMF (Chabrier 2003). We further used the rest-frame UV luminosity, L_{UV}, measured by MAGPHYS at 1600Å, to estimate the UV star-formation rate, SFR(UV), using the Kennicutt’s prescriptions (Kennicutt 1998). We added up contributions from SFR(IR) and SFR(UV), derived from these luminosities, to estimate SFR(IR+UV), supposedly the true SFR indicator and compare this with SFR measurements from the HST grism observations.

### 3.3. The Hα SFR

The SFR(Hα) can be measured directly from the reported Hα flux densities assuming a given calibration (Kennicutt 1998). The HST/WFC3 grism observations lack the resolution necessary to separate the Hα from adjacent [N II] emission at λ6548 and λ6583. Hence, the reported Hα flux densities include contributions from both emission lines. Furthermore, light from the Hα and Hβ line includes contributions from atmospheric absorption lines from stars within the galaxy (Domínguez et al. 2013), which needs to be corrected. Finally, the observed Hα flux densities need to be corrected for dust attenuation before it can be scaled to SFR(Hα). At 6563 Å, Hα is less susceptible to dust attenuation than the SFR(UV) discussed above. However, this correction needs to be taken into account for a correct measurement of the nebular SFR (Erb et al. 2006).

To correct the reported Hα flux density for [N II] contamination mentioned above, we used a prescription based on equivalent widths (EWs) of the Hα line outlined in Sobral et al. (2012). We used the polynomial relation between log([N II]/Hα) and log(EW_{0}([N II]+Hα)) as outlined in Sobral et al. (2012) to correct the [N II] contribution.

To account for stellar absorption, we correct the reported emission-line measurements assuming the same equivalent width for Hα and Hβ fluxes (Osterbrock 1989). As outlined in Rosa-González et al. (2002), we use the observed ratio between Hα and Hβ emission line fluxes:

\[
\frac{F(\text{H}\alpha)}{F(\text{H}\beta)} = \frac{F_{+}(\text{H}\alpha) - F_{-}(\text{H}\alpha)}{F_{+}(\text{H}\beta) - F_{-}(\text{H}\beta)}
\]

where the + and - subscripts are used to denote the intrinsic fluxes of the emission lines and absorption lines respectively. Furthermore, we assumed an intrinsic Balmer decrement ratio of 2.86 (Osterbrock 1989) and used the measured equivalent widths of the nebular emission lines in order to determine the Balmer absorption, Q, i.e. the ratio of equivalent width of Hβ in absorption to emission \((EW_{-}(\text{H}\beta)/EW_{+}(\text{H}\beta))\) from the following equation:

\[
\frac{F(\text{H}\alpha)}{F(\text{H}\beta)} = \frac{2.86 \left(1 - Q \frac{EW_{+}(\text{H}\beta)}{EW_{-}(\text{H}\alpha)}\right)}{1 - Q}
\]

Using these ratios with proportionality relation of fluxes of emission lines to their EWs, we corrected Hα.
Figure 3. Best-fit model SEDs for eight representative sources in the five main fields observed with 3D-HST. The SEDs are constructed using MAGPHYS (da Cunha et al. 2008), with optical, near-infrared and infrared observations from HST, Spitzer and Herschel as outlined in the text. In each panel, the best-fit SED model is plotted in black while the intrinsic model without dust attenuation is plotted in orange. For each SED modeling we fix the redshift to the spectroscopic value, as determined by the 3D-HST and is also reported in each panel. The infrared luminosities (rest-frame 8–1000 µm) reported in each panel are measured with MAGPHYS from the modified black-body radiation observed by Herschel.

and Hβ fluxes for stellar absorption.

To correct the observed Hα fluxes for dust attenuation, we applied Calzetti’s (2001) prescription. We had 26 sources with S/N ≥ 3 for both Hα and Hβ fluxes, for which we could robustly utilize the Balmer decrement to calculate the dust attenuation of the Hα emission line. We computed the Balmer optical depth, the logarithmic ratio of observed to intrinsic Balmer decrement. Finally, assuming a Calzetti reddening curve, we computed the nebular attenuation.

To apply dust correction for sources that didn’t have secure detections for both Hα and Hβ, we used the V-band optical depth of each source, τ_v, output by MAGPHYS SED modeling and applied it to the definition of τ and A_λ: A_λ^0 = 1.086τ_λ, where A_λ^0 is the attenuation at the wavelength λ. Then, assuming the Calzetti et al. (2000) reddening curve for stellar extinction, we obtained the color excess, E_{star}(B − V).
Next, we applied a differential $f$-factor to convert the stellar color excess to a nebular color excess, $E_{\text{neb}}(B-V)$. Calzetti et al. (2000) defined this as a differential attenuation between nebular emission lines and the stellar continuum and parameterized this scaling factor as:

$$E_{\text{star}}(B-V) = f \times E_{\text{neb}}(B-V),$$

(3)

and, in a sample of local starbursts, found $f = 0.44 \pm 0.03$. Essentially, this implies that ionized gas is about twice as attenuated than stars. More recently however, in a study of Herschel sources at $0.7 < z < 1.5$ in the GOODS-S, Puglisi et al. (2016) derived a value of 0.93 for this $f$-factor. Puglisi et al. (2016)'s sample was also selected from Herschel and 3D-HST-matched galaxies and contains galaxies at similar redshifts to ours, in contrast to the nearby starbursts in Calzetti et al. (2000). They also obtained physical parameters from MAGPHYS SED-fitting. Due to the similarities in our samples and methodologies, we used the value reported in Puglisi et al. (2016) for our own calibration between nebular and stellar dust extinction.

Figure 5 shows the SFR(Hα) measured from the corrected Hα flux density as a function of the Balmer decrement for the sub-sample of dusty galaxies for which both lines were detected with a signal-to-noise ratio of at least 3. The increased attenuation as a function of star-formation activity is observed in dusty star-forming galaxies, similar to previous studies of star-forming systems at $z \sim 1 - 2$ (Reddy et al. 2015). We used this relation to estimate SFR(Hα) for the rest of the sources that had Hα and Hβ reported. This ensures that the correlation between total dust attenuation and star-formation rates has been observed at both low and high redshifts, and can be explained by the ISM of the galaxy being enriched in dust with increasing SFR activity (Reddy et al. 2015). To test this dependence, we observed the relationship of $(\text{H}\alpha/\text{H}\beta)$ – the Balmer decrement – with SFR(Hα), for the 26 sources for which we had secure (with S/ N $\geq 3$) Hα and Hβ observations. For this sub-sample we used the observed Balmer decrement directly to correct the measured SFR(Hα) for dust attenuation. Figure 4 shows the relation between measured star-formation activity and observed Balmer decrement. This yields a best-fit power-law relation:

$$\log(\text{SFR(H}\alpha)) = 2.98 \times \log((\text{H}\alpha/\text{H}\beta)_{\text{obs}}) + 0.50$$

(4)

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Herschel selected dusty star-forming galaxies. The DS-2016) and from observations of molecular gas reservoirs star-formation activity (Elbaz et al. 2011; Nelson et al. 2015). At higher redshifts galaxies of similar stellar mass tend to be more star-forming as demonstrated from direct observation of star-formation activity (Elbaz et al. 2011; Nelson et al. 2016) and from observations of molecular gas reservoirs (Genzel et al. 2015; Scoville et al. 2016).

Figure 7 shows the SFR versus $M_*$ for our sample of Herschel selected dusty star-forming galaxies. The DS-

4.2. The IRX-β Relation

To compare dust extinction from the UV to that of the IR, we studied the IRX-β relationship. Energy conservation demands that the photons absorbed in the UV and optical should be re-radiated in the infrared. Thus, for a measure of the total dust attenuation, we computed the IRX (Infrared Excess Ratio), defined as $L_{IR}/L_{UV}$ (Narayanan et al. 2018; Reddy et al. 2018). Assuming each deviation from the constant-shaped UV spectra of star-forming galaxies is produced by dust, we computed the UV slope, $β$, using Meurer et al. (1999) calibration, based on local starburst galaxies, and the continuum attenuation at rest-frame wavelength (1600 Å) following:

$$A_{1600} = 4.43 + 1.99β$$

Meurer et al. (1999)'s sample was among the first to produce a strong correlation between UV spectral slope – essentially a color – and IRX, indicating that dust absorption is directly related to UV reddening. Later studies confirmed the relation for both local (Seibert et al. 2005; Gil de Paz et al. 2007) and high redshift (Reddy et al. 2010, 2012; Casey et al. 2014) galaxies. Casey et al. (2014) also found that DSFGs with high star formation rates lie significantly above the expected IRX-β relationship. The IRX-β relationship is shown in Figure 6. The trend observed is similar to, but above, that expected of starburst galaxies. This is expected for Herschel detected galaxies that re-emit most of their UV light in infrared, as is the case for DSFGs.

4.3. The SFR – $M_*$ relation

The star-formation rate (SFR) and stellar mass ($M_*$) of star-forming galaxies (SFGs) are directly correlated across various cosmic epochs. This so-called main sequence of star formation (MS; Noeske et al. 2007), has been used extensively to test models of galaxy formation and evolution at different redshifts (e.g. Brinchmann et al. 2004; Elbaz et al. 2007; Guo et al. 2015; Shivaei et al. 2015). Observations, in general, show that star-formation activity increases as a function of stellar mass for SFGs and that this a strong function of redshift (Elbaz et al. 2011; Pannella et al. 2015). At higher redshifts galaxies of similar stellar mass tend to be more star-forming as demonstrated from direct observation of star-formation activity (Elbaz et al. 2011; Nelson et al. 2016) and from observations of molecular gas reservoirs (Genzel et al. 2015; Scoville et al. 2016).

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FGs sit above the MS relation at similar redshifts compared to that of normal star-forming systems (Speagle et al. 2014; Whitaker et al. 2014). This is consistent with recent studies of sub-millimeter bright galaxies pointing towards enhanced star-formation activity and/or larger molecular gas reservoirs accessible to these systems (Scoville et al. 2016). The scatter is mostly associated with diverse star-formation histories and uncertainties in dust correction assumptions and stellar mass derivations from multi-band SED modeling.

5. SUMMARY AND CONCLUSION

We presented a multi-wavelength study of 1147 spectroscopically-identified dusty star forming galaxies at 0.49 < $z$ < 2.24 in the five CANDELS fields. We constructed SEDs for each of these sources, from the UV to the far-IR, using photometry from HST and Herschel and spectroscopic redshifts measured from nebular emission lines. Physical properties of these galaxies, such as stellar mass, $M_*$, IR luminosity, $L_{IR}$, and V-band optical depth, $τ_V$, were obtained by comparing observed SEDs with SEDs at the same redshift predicted by Bruzual & Charlot’s (2003) population synthesis models. We used the 3D-HST Hα grism line measurements to infer SFR from nebular lines and IR and UV luminosities to infer SFR from the stellar continuum, having accounted for the dust attenuation for all these quantities.

Our main conclusions are as follows:

- The differential f-factor of 0.93 used by Puglisi et al. (2016) used to relate nebular dust extinction to that of the stellar continuum gave us good agreement between the Hα and IR+UV derived SFRs. This implies that the extinction of ionized gas is close to that of the stellar continuum, running counter to the generally accepted idea that nebular emission lines are about twice as attenuated as the stellar continuum.
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Figure 7. The main sequence of star-formation for our sample. The SFR report are measured from the corrected Hα flux densities assuming a Kennicutt (1998) conversion, as discussed in the text. The stellar masses are measured from the multi-band SED modeling using MAGPHYS including observations in the near-infrared from HST/WFC3 and Spitzer/IRAC. The near-infrared observations of these dusty systems was crucial in constraining the stellar masses. We see that the population of DSFGs at $0.5 < z < 1$ show elevated SFR at any given stellar mass compared to the main sequence of star-formation as observed for normal star-forming galaxies (Speagle et al. 2014; Whitaker et al. 2014).

- We observed a correlation between IRX and UV spectral slope, $\beta$, and our galaxies sit well above the established relation for normal star-forming galaxies. Dusty galaxies are observed to have preferentially bluer colors.
- We observe that star formation rates increase with increased dust attenuation, as is typical of DSFGs.
- We also studied the star formation main sequence relationship between SFR and $M_*$ of these high-$z$ galaxies. Our distribution, skewed toward higher masses, shows SFRs related relative to the well-established SFR-M$_*$ relation, and supports the idea that luminous galaxies have higher star formation rates.

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