Near-infrared MOSFIRE Spectra of Dusty Star-forming Galaxies at $0.2 < z < 4$

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Abstract

We present near-infrared and optical spectroscopic observations of a sample of 450 and 850 μm -selected dusty star-forming galaxies (DSFGs) identified in a 400 arcmin² area in the COSMOS field. Thirty-one sources of the 114 targets were spectroscopically confirmed at $0.2 < z < 4$, identified primarily in the near-infrared with Keck MOSFIRE and some in the optical with Keck LRIS and DEIMOS. The low rate of confirmation is attributable both to high rest-frame optical obscuration in our targets and limited sensitivity to certain redshift ranges. The median spectroscopic redshift is $\langle z_{\text{spec}} \rangle = 1.55 \pm 0.14$, comparable to $\langle z_{\text{phot}} \rangle = 1.50 \pm 0.09$ for the larger parent DSFG sample; the median stellar mass is $(4.9^{+2.1}_{-1.4}) \times 10^{10} M_{\odot}$, star formation rate is $160 \pm 50 M_{\odot} \text{ yr}^{-1}$, and attenuation is $A_V = 5.0 \pm 0.4$. The high-quality photometric redshifts available in the COSMOS field allow us to test the robustness of photometric redshifts for DSFGs. We find a subset (11/31 $\approx$ 35%) of DSFGs with inaccurate ($\Delta z / (1 + z) > 0.2$) or non-existent photometric redshifts; these have very distinct spectral energy distributions from the remaining DSFGs, suggesting a decoupling of highly obscured and unobscured components. We present a composite rest-frame 4300–7300 Å spectrum for DSFGs, and find evidence of $200 \pm 30 \text{ km s}^{-1}$ gas outflows. Nebular line emission for a subsample of our detections indicate that hard ionizing radiation fields are ubiquitous in high- z DSFGs, even more so than typical mass or UV-selected high- z galaxies. We also confirm the extreme level of dust obscuration in DSFGs, measuring very high Balmer decrements and very high ratios of IR to UV and IR to H α luminosities. This work demonstrates the need to broaden the use of wide bandwidth technology in the millimeter to spectroscopically confirm larger samples of high- z DSFGs, as the difficulty in confirming such sources at optical/near-infrared wavelengths is exceedingly challenging given their obscuration.

Key words: galaxies: evolution – galaxies: high-redshift – galaxies: starburst – infrared: galaxies – submillimeter: galaxies

1. Introduction

The most challenging observational hurdle in the study of extremely obscured galaxies has been obtaining accurate spectroscopic redshifts (Chapman et al. 2003, 2005; Swinbank et al. 2004). These redshifts present a major bottleneck in understanding the physics of these extreme star formers and limit our ability to test evolutionary models derived from simulations (e.g., Lacey et al. 2016; Narayanan et al. 2015). Gaining insight into the physics of Dusty Star-forming Galaxies (DSFGs) is of crucial importance in constraining massive galaxy formation and the build-up of stellar mass at early times, when these systems dominate cosmic star formation (see reviews of Blain et al. 2002 and Casey et al. 2014a).

Since the first identification of submillimeter-luminous galaxies with the Submillimeter Common User Bolometric Array (SCUBA) instrument (Smail et al. 1997; Barger et al. 1998; Hughes et al. 1998), the characterization of DSFGs has been a top priority of extragalactic astrophysics. The large beam size of SCUBA at the James Clerk Maxwell Telescope made the immediate identification of DSFGs' multiwavelength counterparts difficult. However, the correlation between radio and FIR luminosity in starburst galaxies (Helou et al. 1985; Condon 1992) provided a means of using radio interferometric positions to identify the likely source of

FIR/submillimeter emission (Yun et al. 2001; Chapman et al. 2004, 2005). However, redshift identification was still a challenge. Optical/near-infrared photometric redshifts are often out of reach for these highly obscured galaxies, and obtaining spectroscopic redshifts required the most sensitive optical and near-IR spectrographs on the largest telescopes, such as the Low Resolution Imaging Spectrometer (LRIS) on Keck (Oke et al. 1995). With star formation rates exceeding $100 M_{\odot} \text{ yr}^{-1}$, only $\lesssim 0.5\%$ of rest-frame UV/optical starlight and optical/ultraviolet emission features are unobscured by dust (Howell et al. 2010; Casey et al. 2014b).

The most comprehensive survey of spectroscopic redshifts for DSFGs was presented in Chapman et al. (2005). They present 75 redshifts for submillimeter galaxies (SMGs⁸) peaking at $z \sim 2.5$. This sample was the primary sample pursued for follow-up, from CO molecular gas studies (Greve et al. 2005; Tacconi et al. 2006, 2008; Bothwell et al. 2010, 2013; Engel et al. 2010; Casey et al. 2011), rest-frame optical follow-up (Swinbank et al. 2004; Alaghband-Zadeh et al. 2012; Menéndez-Delmestre

⁸ In this paper and in recent years, we have adopted the term DSFG as a more general name for SMGs. SMGs have been formally defined in the past as having an 850 μm flux density in excess of $\sim 2 \text{ mJy}$, while DSFG represents any galaxy directly detected at wavelengths $\sim 70 \mu\text{m}$ –2 mm with current and past facilities, with the exclusion of ALMA, which is much more sensitive.

Table 1
Details of MOSFIRE Observations

Slitmask Name	Obs. Date	Mask Position	Exp. Time <i>K</i> -band (s)	Exp. Time <i>H</i> -band (s)	N_{S2}	N_{all}	$N(z)$ DSFGs	% DSFGs conf. (%)
cosm1	2012 Dec 21	10:00:10.25+02:19:44.71	2880	1920	12	25	3	25%
cosm2	2012 Dec 21	10:00:18.94+02:24:28.70	2520	1200	10	24	4	40%
cosm3	2012 Dec 21	10:00:23.39+02:30:37.29	2520	720	12	24	1	8%
cosm4	2013 Dec 31	10:00:31.91+02:20:13.00	3600	2880	16	21	9	56%
cosm5	2014 Jan 19	10:00:51.13+02:20:57.92	3240	1440	10	25	4	40%
cosm6	2013 Dec 31	10:00:01.15+02:24:35.91	3600	1920	13	23	3	23%
cosm7	2013 Dec 31	09:59:51.54+02:21:07.69	2880	1320	14	25	6	43%
cosm8	2014 Jan 19	10:00:15.16+02:16:38.68	3600	2400	15	26	4	27%
cosm9	2014 Jan 19	10:00:00.67+02:28:15.20	3600	2880	16	24	5	31%
cosm10	2014 Jan 19	10:01:00.05+02:24:59.20	2880	—	10	24	0	0%
Total					102		31	29.8%

Notes. Our MOSFIRE observations consisted of 10 slitmask configurations, nine of which were observed in both *H*- and *K*-bands. The exposure time and number of targets per mask varied as a function of real-time observing decisions based on accessibility of the field, intermittent cloud cover, and higher-priority vs. lower-priority targets. The number of SCUBA-2 sources that were targeted per slitmask is given in N_{S2} while the total number of targets on that slitmask is given in N_{all} . The number of DSFGs that were spectroscopically confirmed on the slitmask, a subset of N_{S2} , is given in the “ $N(z)$ DSFGs” column. The percentage of DSFGs with spectroscopic confirmations on the given slitmask, ranging from 0% to 56%, and averaging 29.8%, is given in the last column.

et al. 2013), to mid-infrared follow-up from *Spitzer* IRS (Pope et al. 2008; Menéndez-Delmestre et al. 2009; Coppin et al. 2010), and high-resolution radio continuum mapping (Biggs & Ivison 2008; Casey et al. 2009). These studies pointed out that the 850 μ m-selected DSFG population is primarily made up of major galaxy mergers at the tip of the luminosity function and could be more heterogeneous in triggering mechanism at intermediate luminosities. Nevertheless, they exhibit exceptional star formation rates that are predominantly short-lived (Bothwell et al. 2013; Swinbank et al. 2014) and result in the formation of the most massive galaxies in the Universe.

Though those with spectroscopic identification have proved very valuable to DSFG research, there are still few constraints on the $\sim 50\%$ of the population of DSFGs that have not been detected via Ly α emission or other rest-frame ultraviolet tracers. Do they lie at higher redshifts? Are they significantly more obscured by dust? Are their physical triggering mechanisms different from those with detectable UV/optical emission features? To address the unknown selection bias the UV/optical (and radio detected) subsample may place on our interpretation of DSFGs, the ALESS Survey has set out to meticulously characterize an unbiased population of 870 μ m-selected DSFGs with rest-frame UV/optical spectroscopy and submillimeter interferometry from the Atacama Large Millimeter Array (ALMA; Weiß et al. 2009; Wardlow et al. 2011; Hodge et al. 2013). Spectroscopic success rates for DSFGs with known interferometric positions is $< 50\%$ using optical/near-infrared (A. Danielson 2017, in preparation). While ALMA has ushered in a new era of spectroscopically confirming DSFGs via direct emission of CO and [C II] at long wavelengths, this unfortunately is still prohibitively expensive for large samples of unlensed galaxies (c.f. Vieira et al. 2013).

We have embarked on an independent spectroscopic follow-up campaign of DSFGs selected at 450 and 850 μ m using the SCUBA-2 instrument in the COSMOS field (Casey et al. 2013). Due to the extreme obscuration present in DSFGs at rest-frame UV wavelengths, our spectroscopic campaign has primarily focused on rest-frame optical features detectable with the superbly sensitive MOSFIRE instrument on Keck (McLean et al. 2012). Though only a subset of DSFGs in this sample have interferometric measurements from ALMA and the

Plateau de Bure Interferometer, 62% of the DSFGs in the sample are detected at 450 μ m, which has a significantly smaller beam size ($7''$) than the 850 μ m ($15''$) or 870 μ m on LABOCA ($19''$).

Here we present the results of this spectroscopic survey. In Section 2, we describe the spectroscopic data. In Section 3, we present an analysis of the sample’s redshifts, contrasting photometric and spectroscopic identifications, and we discuss individual source characteristics in Section 4. In Section 5, we present a composite rest-frame optical spectrum comprised of 20 $z = 1.26$ – 2.55 DSFGs, and we compare to previous composites presented for DSFG samples. In Section 6, we present an analysis of the sample’s active galactic nuclei (AGNs) using X-ray coverage in the field. In Section 7, we present nebular line diagnostics for a handful of galaxies and use them to analyze possible physical drivers of line emission. In Section 8, we discuss the H α luminosities of the DSFGs we sample, in relation to their SFRs measured at long wavelengths. In Section 9, we present our conclusions. Throughout this paper, we assume a Λ CDM cosmology with $H_0 = 71$ km s $^{-1}$ Mpc $^{-1}$ and $\Omega_m = 0.27$ (Hinshaw et al. 2009). We also assume a Chabrier initial mass function (IMF; Chabrier 2003).

2. Observations and Data

The parent sample for spectroscopic follow-up we use in this analysis is the full set of 165 SCUBA-2-identified DSFGs in COSMOS, as summarized in Casey et al. (2013). The $1\text{-}\sigma$ sensitivity of the SCUBA-2 maps used were 4.13 mJy and 0.80 mJy at 450 μ m and 850 μ m, respectively. Of the 165 independent sources identified, 78 were detected above 3.6σ at 450 μ m and 99 above the same threshold at 850 μ m. An additional eight sources were identified at marginal $3 < \sigma < 3.6$ significance at both 450 and 850 μ m. About two-thirds of the sample are detected in both 450 and 850 μ m bands. With positional uncertainties of $1''$ – $2''$, optical/near-infrared counterparts were identified directly from submillimeter positions weighted by a *p*-value. Sixty-one percent of the entire sample have “high confidence” OIR counterparts identified using this method, with $< 5\%$ contamination; the remaining 39% of the parent sample are less well-matched. The targets that were

observed spectroscopically were not biased toward either secure or low confidence populations. We discuss the relationship of the spectroscopic sample to the parent sample more in Section 3 and refer the reader to Casey et al. (2013) for more details.

Our near-infrared spectroscopic follow-up campaign was carried out on the Keck I MOSFIRE instrument on 2012 December 21, 2013 December 31, and 2014 January 19. Observing conditions for these nights were all favorable, with clear skies and $0''.5$ – $0''.7$ seeing. We observed 10 MOSFIRE masks, all designed in the MAGMA mask design software package for MOSFIRE in the K -band, and nine of the same masks in H -band all using an ABBA $1''.5$ nod pattern. Individual exposures in the H -band were 120 s while individual exposures in the K -band were 180 s. Observation details are given in Table 1. Total on-source integration times varied from 720–2880 s in the H -band and 2520–3600 s in the K -band. No Y -band or J -band observations were taken. To maximize the number of high-priority targets per mask, we made some minor sacrifices in spectral coverage; on average, each primary target had complete wavelength coverage from 1.45 to $1.75\ \mu\text{m}$ in the H -band and from 1.92 – $2.40\ \mu\text{m}$ in the K -band. We used the MOSPY Data Reduction Pipeline (DRP) package for spectral reduction. In total, 102 DSFG targets were observed with MOSFIRE.

We also present observations obtained with the DEIMOS instrument on Keck II, following-up the same SCUBA-2 selected sample at optical wavelengths. DEIMOS observations were carried out on 2012 December 10–11, 2013 February 07, and 2014 October 28. Conditions were suboptimal on 2012 December 10–11 with intermittent cloud cover and $1''.1$ – $1''.3$ seeing. Conditions on 2013 February 07 were poor and completely weathered out during the LST when the COSMOS field was accessible. We used the 600 lines mm^{-1} grating with a $7200\ \text{\AA}$ blaze angle (resulting in a dispersion of $0.65\ \text{\AA}$) and the GG455 filter to block out higher-order light. Wavelength coverage varied with the sources' positions on the slitmask, averaging 4800 – $9500\ \text{\AA}$. Twelve sources observed with DEIMOS were not observed with MOSFIRE, but the majority of DEIMOS observations overlapped with MOSFIRE targets.

All spectra, from MOSFIRE and DEIMOS, were extracted using the IRAF routine APALL. Apertures were set interactively, depending on the seeing and whether or not the galaxy is spatially resolved on the slit, and background is subtracted using simultaneously fit sky apertures. Sources are corrected for a trace only when continuum emission has significant signal-to-noise ratio (S/N) across the entire spectral region, otherwise a fixed aperture is assumed. Optimal extraction is set with variance weighting.

Figure 1 compares the characteristics of the parent sample of SCUBA-2 galaxies with the sources that have been spectroscopically confirmed. While one might expect the strongest correlation with the K -band magnitude (as this is the wavelength regime of the MOSFIRE spectroscopy), we see a relatively uniform distribution in magnitude for the confirmed sources. Though this does suggest a lower fraction of confirmations at fainter magnitudes, the distributions are not statistically inconsistent with the parent sample. The distribution in $24\ \mu\text{m}$ flux densities is similarly uncorrelated with spectroscopic confirmation. The statistics for the $1.4\ \text{GHz}$ radio emission is similar, yet has fewer sources than our $24\ \mu\text{m}$ distribution. We attribute the lack of correlation to our spectroscopic follow-up strategy, which was intended to not

Figure 1. Comparison of sources' magnitudes in the V-, K- and $3.6\ \mu\text{m}$ bands and flux densities at $24\ \mu\text{m}$ between the parent sample of 165 SCUBA-2 sources and those with spectroscopic redshifts described in this paper.

be biased with relative near-infrared or optical luminosity. The selection of targets was focused on maximizing the number of SCUBA-2 targets per mask and so represents a spatial selection on $6'$ scales, not noticeably biased with respect to sample characteristics.

We also make use of the extensive multiwavelength ancillary data available in the COSMOS field (Capak et al. 2007), including over 30 optical and near-infrared photometry and associated photometric redshifts (Ilbert et al. 2013; Lagache 2015), spectroscopic redshifts (Lilly et al. 2009), X-ray imaging from *Chandra* (Civano et al. 2012), *Herschel* PEP/PACS and HerMES/SPIRE 100 – $500\ \mu\text{m}$ catalogs (Lutz et al. 2011; Oliver et al. 2012; Lee et al. 2013), and deep radio continuum mapping at $1.4\ \text{GHz}$ (Schinnerer et al. 2007) and $3.0\ \text{GHz}$ (Smolcic et al. 2017). It should be emphasized that the quality of photometry in the COSMOS field is superb and provides a unique opportunity to test the reliability of high-quality photometric redshifts for highly obscured galaxies. Seven of our spectroscopically confirmed sources also have $1.1\ \text{mm}$ ALMA dust continuum maps available from the ALMA archive, programs #2013.1.00118.S, 2013.1.00151.S, and 2011.0.00539.S (published in Bussmann et al. 2015). Five of the seven sources were correctly identified using multi-wavelength counterparts (71%), as we discuss further in Section 4.1. Those that were incorrectly identified were still detected, but submillimeter counterparts were misidentified. The ALMA $1.1\ \text{mm}$ maps range in rms from 0.08 – $0.15\ \text{mJy/beam}$, sources are detected with a median S/N = 10, and the median ratio between $850\ \mu\text{m}$ flux density and $1.1\ \text{mm}$ flux density is 3.9 ± 0.6 .

3. Photometric Redshift Analysis

Since COSMOS has some of the most precisely constrained photometric redshifts for even the faintest sources, we are able to assess the quality of those photometric redshifts for highly obscured sources like DSFGs (e.g., Wardlow et al. 2011).

Figure 2. Distribution in photometric redshifts for the parent sample of SCUBA-2 sources in COSMOS (selected from Casey et al. 2013; gray), the sample targeted by MOSFIRE (red, primarily determined by spatial configuration on the sky with respect to slitmasks), the sample that has been targeted but is *not* spectroscopically confirmed (blue hashed region), and those that have been confirmed (black distribution). In this depiction, each galaxy’s photometric redshift is represented by an asymmetric Gaussian with area under the curve equal to one. This more accurately portrays the photometric redshift constraints than a simple histogram. The total number of sources depicted here is 162 (total sample), 102 (targets selected for MOSFIRE follow-up), 71 (unconfirmed sources), and 31 (confirmed sources). We include targets without photometric redshift fits (inside the dashed box) for comparison.

While our original sample in Casey et al. (2013) made use of the then-current COSMOS team photometric redshift catalog (Ilbert et al. 2013), in this analysis we update those photometric redshifts to the most current catalog (Laigle et al. 2016).

Figure 2 shows the distribution of photometric redshifts (phot- z ’s) for the parent sample of 162 SCUBA-2 sources in the COSMOS field. This includes both 450 μ m- and 850 μ m-selected sources, as well as “marginal” detections identified at both wavelengths (denoted with a preceding “m”), at an S/N of $3 < \sigma < 3.6$ in both filters (see Casey et al. 2013). It should be noted that this redshift distribution is significantly different than the distribution of either the 450 μ m or 850 μ m sources, who peak at $\langle z_{450} \rangle = 1.95 \pm 0.19$ and $\langle z_{850} \rangle = 2.16 \pm 0.11$, respectively. The median of this parent distribution is $\langle z \rangle = 1.46 \pm 0.14$, similar to the results of Roseboom et al. (2013). We attribute this to the inclusion of the marginally detected 450 and 850 μ m sources to our spectroscopic follow-up sample: these sources are less submillimeter luminous and so are likely at lower redshifts (see also Béthermin et al. 2015).

Figure 2 also shows the phot- z distribution for sources targeted by our MOSFIRE campaign (102 sources), and those that have not been confirmed (71 sources) and confirmed (31 sources). Those sources that have been spectroscopically confirmed do trend toward redshift ranges that are well-suited to the identification of strong emission and absorption features in the observed H - and K -bands (i.e., $z \sim 1.2$ – 1.7 and $z \sim 2.0$ – 2.5). Many sources with photometric redshifts outside of this range did show continuum emission in our H - and K -band observations, but the lack of discernible emission or

Figure 3. Comparison of spectroscopic and photometric redshifts for SCUBA-2 galaxies in COSMOS. Dashed lines show the $\Delta z/(1+z) = 0.05$ level of accuracy, which is the average of this data set. Note that this comparison excludes five sources that lack photometric redshift estimates. On occasion, there was a slight positional offset between the photometric and spectroscopic sources, yet no larger than $0''.4$. The inset plot shows a histogram of $\Delta z/(1+z)$. As discussed in the text, Section 3, the outliers have significantly higher IR luminosities than their optical/near-infrared emission would imply (also see Figure 4).

absorption feature makes redshift identification not possible. Sources with photometric redshifts in our optimum range without spectroscopic confirmations are on average 1 mag fainter in the near-infrared than those that have been spectroscopically confirmed. The lack of spectroscopic confirmation, however, is probably attributable to a mix of luminosity, geometry, and inaccurate photometric redshifts for dust-obscured sources.

Figure 3 illustrates the correlation of photometric redshift with spectroscopic redshift. For confirmed DSFGs with photometric redshifts in COSMOS, these photometric redshifts prove to be fairly reliable, with an average $\Delta z/(1+z) = 0.05$, only moderately worse than the average for “normal,” less obscured galaxies. This is encouraging, as it demonstrates that high-quality photometric redshifts and a broad range of templates that include a range of star formation histories can accurately reflect a DSFG’s redshift. However, the distribution of $\Delta z/(1+z)$ is broadened relative to normal galaxies with many examples of catastrophic failures: four sources have $\Delta z/(1+z) > 0.2$ and seven lack any photometric redshift solution.

What gives rise to such inaccuracies in DSFGs’ photometric redshifts in some cases but not others? We investigate the possible causes of such inaccuracies by fitting spectral energy distributions (SEDs) to the UV through millimeter photometry using the MAGPHYS code (da Cunha et al. 2008). We use the updated version (da Cunha et al. 2015), equipped to fit SEDs of high-redshift, potentially burst-dominated galaxies like DSFGs. The SED fits are shown in Figure 4.

Geometric effects are the most likely culprit causing significant photometric inconsistencies, leading to poorer photometric redshift estimation. For example, we identify five galaxies with MAGPHYS fits that are not well-matched from the UV through IR in Figure 4: 450.23, 450.25, 450.49, 450.63,

Figure 4. UV through submillimeter photometry for the DSFGs in our sample with confirmed spectroscopic redshifts; spectral energy distribution fits come from Bruzual & Charlot (2003) models using the MAGPHYS energy balance code (da Cunha et al. 2008). 450.14 is excluded due to its multiple redshift solution, and thus blended photometry. The corresponding unobscured SED is shown in light blue. In addition, we fit simple modified blackbodies plus mid-infrared power laws to the photometry longward of $20\ \mu\text{m}$ (green dotted-dashed lines) to compare to the best-fit MAGPHYS SED output. While often consistent, several galaxies show a strong disconnect between the best-fit simple FIR SED and an SED that takes the rest-frame UV and optical into account, indicating a complete decoupling of UV-emitting and submillimeter-emitting regions.

Figure 4. (Continued.)

and 850.59. Despite the balance of UV attenuation with IR luminosity used in MAGPHYS to match photometry across all bands, the IR luminosity in these systems is dramatically underestimated by the best-fit Bruzual & Charlot (2003) templates. Of these sources, only 450.23 has an adequate

photometric redshift estimate ($\Delta z/(1+z) = 0.03$), and it sits at $z < 1$. The other sources all have very poor photometric redshift estimates ($\Delta z/(1+z) \approx 0.60$) or none at all. While two of these sources only have far-IR identifications at $450 \mu\text{m}$, and so could be false identifications as DSFGs, three are

robustly identified at both far-IR and optical/near-IR wavelengths. Thus, we attribute the cases of catastrophic photometric redshift failures primarily to a geometric decoupling of unobscured and obscured emission.

Included in Figure 4 are far-infrared/millimeter SED fits generated using a modified blackbody plus mid-infrared power law as an independent assessment of the infrared luminosity, dust temperature, and dust mass. We use the SED-fitting procedure outlined in Casey (2012), using an emissivity spectral index of $\beta = 1.8$. When there are fewer than four far-IR photometric points, the mid-infrared power-law slope is fixed to $\alpha = 2.5$, and when there are fewer than two far-IR photometric points, the dust temperature of the fit is fixed to $T_{\text{dust}} = 35$ K. A number of galaxies, particularly those highlighted in the previous paragraph, are not well fit at long wavelengths using the MAGPHYS energy balance approach but are much better characterized at those wavelengths with this simple SED approach. We use these simple SEDs to characterize the IR luminosities, dust temperatures, and dust masses of the sample, as given in Table 2.

4. Characteristics of the Spectroscopic Sample

In this section, we describe some of the unique characteristics of the spectroscopically confirmed COSMOS DSFGs listed in Table 2. The sample is naturally heterogeneous, and thus requires some individual and subset remarks to fully capture the physical nature of their evolution and the source of their obscured emission. We group sources by common characteristics, and include some remarks on ambiguous and misidentifications at the end of this section.

4.1. Unlensed DSFGs Above $L > 10^{11} L_{\odot}$

DSFGs that have intrinsic infrared luminosities exceeding $L > 10^{11} L_{\odot}$ can be characterized as bona fide DSFGs: luminous dusty galaxies, predominantly at a redshift beyond $z > 1$. Twenty-nine galaxies in our sample fall into this luminosity regime and range in redshift from 450.24 at $z = 0.166$ to 850.89 at $z = 3.584$, with a median redshift of $\langle z \rangle = 1.6$. Their luminosities, dust temperature constraints, dust masses, and $L_{\text{IR}}/L_{\text{UV}}$ ratios are shown in Figure 5. The median peak of the rest-frame far-infrared SED is $116 \pm 9 \mu\text{m}$, which translates to ~ 36 K dust temperature using our model assumptions. On average, the sample is 130^{+40}_{-30} times more luminous in the far-infrared/submillimeter than in the UV/optical, consistent with most luminous DSFGs. Figure 5 also compares our spectroscopic sample with the ALESS photometric sample of da Cunha et al. (2015); our sample sits at lower redshifts, and thus reaches to slightly lower luminosities, slightly cooler dust temperatures, lower dust masses, and yet higher obscurations of their rest-frame UV emission.

The median dust mass is $(4.4 \pm 1.0) \times 10^8 M_{\odot}$, which is about $0.9\% \pm 0.4\%$ of the median stellar mass, $(4.9 \pm 2.1) \times 10^{10} M_{\odot}$. Assuming an average gas-to-dust ratio of 100 (Scoville et al. 2014), this would imply molecular gas reservoirs averaging $4 \times 10^{10} M_{\odot}$. With a median star formation rate of $220 \pm 60 M_{\odot} \text{ yr}^{-1}$, the inferred representative gas depletion time for this population is ≈ 180 Myr, though we stress the importance of measuring this directly with emission from cold molecular gas. Five sources in this category also have archival ALMA 1.1 mm dust continuum data pinpointing their submillimeter emission to the positions of our MOSFIRE follow-up and are shown in

Figure 6. Two additional sources have ALMA 1.1 mm imaging, which reveal misidentifications, as discussed in Section 4.4.

4.2. Low-redshift DSFGs

Two sources identified in our sample sit at very low redshifts, $z < 0.3$. 850.36 has a measured spectroscopic redshift of $z = 0.224$ from the zCOSMOS survey (Lilly et al. 2007); its identification as the origin of the submillimeter emission is unambiguous. The optical morphology is clearly consistent with a major merger with double nuclei and an extended, asymmetrical disk. While we did target this source with MOSFIRE on the same mask as other higher priority DSFGs, the wavelength coverage failed to overlap with expected prominent features like $\text{Pa}\alpha$ and $\text{Pa}\beta$.

Source 450.24 also has a prior spectroscopic confirmation at $z = 0.1661$ (Lilly et al. 2007), and here we obtained a near-infrared spectrum that is more consistent with a redshift of $z = 0.1657$ based on the detection of $\text{Pa}\alpha$, $\text{Pa}\beta$ and H_2 features. We measure a Paschen decrement between $\text{Pa}\alpha$ and $\text{Pa}\beta$ of 8.7 ± 2.5 , with the significant uncertainty caused by flux calibration between bands and the $\text{Pa}\beta$ detection near the edge of the H -band close to telluric features. While highly uncertain, this ratio is still significantly higher than the expected theoretical intensity ratio of 2.16 for the case B recombination temperature of 10^4 K, suggesting significant dust obscuration.

Source 450.21 has a strong emission line detection at $2.087 \mu\text{m}$, though this is not in agreement with a previously reported spectroscopic redshift of $z = 0.837$ (J. Silverman 2017, private communication). We assign this source a tentative redshift of $z = 0.628$.

4.3. Spatially Superimposed

One DSFG in our sample is an ambiguous potential overlap of two sources at different redshifts. The optical/near-infrared counterpart to the submillimeter source is shown in Figure 7; it consists of a central compact source with two fainter arcs to the north and south. We have unequivocally identified the central compact source at a redshift of $z = 1.523$. The arcs are much more visible in the WFC3 imaging of the source, suggesting a higher redshift solution might be more plausible. This target was placed on two different MOSFIRE masks, and one happened to align with the faint southern arc. We tentatively suggest that this fainter arc is a background source sitting at $z = 2.462$ as identified by two anomalous emission features in the K -band spectrum consistent with $\text{H}\alpha$ and $[\text{N II}]$ at this alternate redshift. Figure 7 also shows the sources' 2D spectrum, zoomed in to the $\text{H}\alpha$ features in the H - and K -bands for the respective redshifts of the central source and potential background source. Though the detection of $\text{H}\alpha$ and $[\text{N II}]$ are only tentative for the $z = 2.462$ identification, there is also a tentative corresponding detection of $[\text{O III}]$ in the H -band at the same redshift. This source will require more substantial follow-up to determine if the spatial superposition is genuine. Other similar spatially overlapping sources have been found in submillimeter redshift surveys (e.g., the ALESS sample; A. Danielson 2017, in preparation).

4.4. Misidentifications

Inevitably, the positional uncertainty in bolometer maps will lead to some misidentifications and ambiguities, which propagate to spectroscopic follow-up campaigns. Here we

Table 2
Redshifts and Physically Derived Characteristics for MOSFIRE-confirmed DSFGs

Source	z_{spec}	Identifying Features	$M_{\star}$ ($M_{\odot}$)	M_{dust} ($M_{\odot}$)	L_{IR} ($L_{\odot}$)	SFR ($M_{\odot} \text{ yr}^{-1}$)	λ_{peak} (μm)	log(IRX)
450.05	2.551	H α , Ly α	$(3.4^{+0.1}_{-0.9}) \times 10^{11}$	$(1.4^{+3.7}_{-2.9}) \times 10^9$	$(6.3^{+2.4}_{-1.7}) \times 10^{12}$	593^{+226}_{-163}	104 ± 14	5.4 ± 3.2
450.06	2.092	H α , [N II], S II, C III], Fe II, Mg II	$(1.1^{+0.1}_{-0.2}) \times 10^{11}$	$(4.9^{+0.8}_{-0.7}) \times 10^8$	$(7.7^{+1.2}_{-1.0}) \times 10^{12}$	724^{+112}_{-97}	84 ± 6	2.32 ± 0.06
450.09	2.473	H α , H β	$(2.2^{+0.1}_{-0.4}) \times 10^{11}$	$(3.0 \pm 0.5) \times 10^8$	$(8.3^{+2.6}_{-2.0}) \times 10^{12}$	783^{+243}_{-186}	73 ± 11	2.91 ± 0.13
450.14	1.523	H α , [N II]	$< 2.8 \times 10^{11}$	$< 2.7 \times 10^8$	$< 1.4 \times 10^{11}$	< 128	108 ± 43	2.30 ± 0.38
	2.462	H α , [N II]	...	...	...	...	...	...
450.21	0.628	Pa β	$(3.1^{+0.4}_{-0.8}) \times 10^{10}$	$(2.8^{+5.4}_{-1.8}) \times 10^8$	$(1.4^{+1.1}_{-0.6}) \times 10^{11}$	13^{+10}_{-5}	176 ± 30	1.50 ± 0.24
450.23	0.9104	[O II]	$(5.7^{+1.0}_{-1.0}) \times 10^8$	$(3.2^{+15.6}_{-2.7}) \times 10^8$	$(7^{+30}_{-5}) \times 10^{11}$	63^{+282}_{-52}	182 ± 38	2.76 ± 0.74
450.24	0.1658	Pa α , Pa β , H $_2$	$(4.0^{+0.6}_{-1.0}) \times 10^{10}$	$(1.7^{+0.6}_{-0.5}) \times 10^7$	$(5.6 \pm 0.4) \times 10^{12}$	5.2 ± 0.4	132 ± 4	3.76 ± 0.20
450.25	1.516	H α , [N II], S II	$(3.4^{+0.1}_{-0.4}) \times 10^{11}$	$(9.0^{+2.0}_{-1.6}) \times 10^7$	$(1.7^{+0.9}_{-0.6}) \times 10^{12}$	157^{+80}_{-53}	84 ± 13	1.75 ± 0.18
450.27	1.535	H α , [N II], S II, Fe II, Mg II	$(3.0^{+0.3}_{-0.6}) \times 10^{11}$	$(4.5^{+0.8}_{-0.7}) \times 10^8$	$(4.0 \pm 0.5) \times 10^{12}$	373^{+51}_{-45}	97 ± 6	2.39 ± 0.06
450.28	2.472	H α , H β	$(6.6^{+0.3}_{-0.7}) \times 10^{10}$	$(3.8^{+2.9}_{-1.6}) \times 10^9$	$(2.4^{+1.9}_{-1.2}) \times 10^{12}$	229^{+476}_{-99}	147 ± 40	1.78 ± 0.25
450.37	2.109	H α , S II, [O III], H β	$(2.0^{+0.5}_{-0.2}) \times 10^9$	$(9.0^{+4.9}_{-3.2}) \times 10^7$	$(1.4^{+8.4}_{-1.2}) \times 10^{12}$	132^{+787}_{-113}	66 ± 34	1.59 ± 0.84
450.49	1.554	H α	$(2.3^{+0.1}_{-0.1}) \times 10^9$	$(9.0^{+4.9}_{-3.2}) \times 10^7$	$(8^{+63}_{-7}) \times 10^{11}$	75^{+593}_{-66}	66 ± 34	2.23 ± 0.95
450.58	2.464	H α	$(2.1^{+0.1}_{-0.3}) \times 10^{10}$	$(7.1^{+0.3}_{-1.4}) \times 10^8$	$(3.2^{+1.5}_{-1.0}) \times 10^{12}$	302^{+145}_{-98}	293 ± 14	> 3.9
450.59	0.4768	[O II], H β , H γ	$(2.3^{+0.2}_{-0.8}) \times 10^{10}$	$(6.8^{+4.5}_{-2.7}) \times 10^7$	$(1.1^{+0.7}_{-0.4}) \times 10^{11}$	11^{+6}_{-4}	105 ± 19	1.66 ± 0.20
450.63	1.358	H α	$(4.8^{+0.3}_{-1.0}) \times 10^8$	$< 9 \times 10^6$	$(6^{+57}_{-5}) \times 10^{11}$	59^{+541}_{-53}	$\equiv 90$	1.91 ± 1.00
450.77	1.566	H α	$(4.9^{+0.5}_{-1.2}) \times 10^{10}$	$< 9 \times 10^6$	$(8^{+89}_{-7}) \times 10^{11}$	79^{+836}_{-72}	$\equiv 90$	2.85 ± 1.07
850.04	1.436	H α	$(3.0^{+0.4}_{-0.7}) \times 10^{10}$	$(2.8^{+4.7}_{-1.7}) \times 10^9$	$(1.1 \pm 0.2) \times 10^{12}$	106^{+21}_{-17}	167 ± 10	2.00 ± 0.08
850.20	2.484	H α , [N II]	$(3.2^{+0.1}_{-0.8}) \times 10^{10}$	$(3.2^{+0.3}_{-0.4}) \times 10^8$	$(1.2 \pm 0.2) \times 10^{12}$	1096^{+166}_{-144}	67 ± 5	2.59 ± 0.07
850.25	2.438	H α	$(2.8^{+0.1}_{-0.4}) \times 10^{11}$	$(1.1^{+0.3}_{-0.2}) \times 10^9$	$(5.5^{+2.2}_{-1.6}) \times 10^{12}$	514^{+211}_{-150}	103 ± 15	2.10 ± 0.15
850.36	0.224	H α , [O II]	$(2.8^{+0.1}_{-0.5}) \times 10^8$	$(1.3^{+3.2}_{-0.9}) \times 10^8$	$(8.2^{+9.7}_{-4.5}) \times 10^9$	$0.77^{+0.92}_{-0.42}$	271 ± 46	2.04 ± 0.34
850.44	2.470	H α , [N II], [O III], H β , H γ , Ly α	$(1.8^{+0.1}_{-0.4}) \times 10^{10}$	$(2.0^{+0.8}_{-0.6}) \times 10^8$	$(2.8^{+2.1}_{-1.2}) \times 10^{12}$	263^{+202}_{-114}	91 ± 26	1.41 ± 0.25
850.45	1.258	H α , [N II]	$(4.7^{+0.5}_{-1.0}) \times 10^{10}$	$(4.3^{+1.9}_{-1.3}) \times 10^8$	$(5.4^{+3.4}_{-2.1}) \times 10^{11}$	51^{+32}_{-20}	140 ± 25	2.22 ± 0.22
850.59	3.584	Ly α	$(5.8^{+0.3}_{-1.1}) \times 10^{10}$	$(5.1^{+1.6}_{-1.2}) \times 10^8$	$(3.5^{+4.2}_{-1.9}) \times 10^{12}$	333^{+395}_{-181}	92 ± 40	1.49 ± 0.34
850.60	1.457	H α , [N II], SII	$(2.1^{+0.1}_{-0.2}) \times 10^{11}$	$(2.4 \pm 0.4) \times 10^8$	$(2.3^{+0.4}_{-0.4}) \times 10^{11}$	218^{+42}_{-35}	96 ± 8	2.96 ± 0.09
850.82	2.508	H α	$(1.8^{+0.2}_{-0.3}) \times 10^{11}$	$(2.8^{+0.7}_{-0.6}) \times 10^8$	$(5.0^{+3.4}_{-2.0}) \times 10^{12}$	471^{+323}_{-191}	80 ± 24	2.71 ± 0.23
850.89	2.104	H α , [N II], [O III], H β	$(1.8^{+0.1}_{-0.4}) \times 10^{11}$	$(6.8^{+2.0}_{-1.5}) \times 10^8$	$(3.7^{+1.8}_{-1.2}) \times 10^{12}$	347^{+173}_{-115}	104 ± 19	1.54 ± 0.18
850.95	1.556	H α , [N II], NaD	$(3.8^{+0.4}_{-1.0}) \times 10^{10}$	$(2.8^{+1.0}_{-0.7}) \times 10^8$	$(2.0^{+1.4}_{-0.8}) \times 10^{12}$	189^{+131}_{-77}	102 ± 28	1.66 ± 0.29
850.97	0.731	[O II]	$(1.5^{+0.1}_{-0.3}) \times 10^{11}$	$(4.7^{+6.3}_{-4.3}) \times 10^8$	$(2.8^{+29.7}_{-2.5}) \times 10^{11}$	$5.8^{+26.1}_{-4.7}$	109 ± 15	2.9 ± 1.1
m450.87	2.282	H α , [O III]	$(2.0^{+0.4}_{-0.8}) \times 10^{11}$	$(6.5^{+1.4}_{-1.2}) \times 10^8$	$(5.4^{+1.7}_{-1.3}) \times 10^{12}$	512^{+161}_{-122}	94 ± 13	3.21 ± 0.18
m450.133	0.728	Pa β , H β , [O III], [O II], Mg II	$(6.3^{+5.5}_{-1.1}) \times 10^{10}$	$(7.5^{+2.7}_{-2.0}) \times 10^7$	$(2.5^{+1.5}_{-0.9}) \times 10^{11}$	23^{+14}_{-9}	127 ± 24	0.73 ± 0.21
m450.173	1.003	[O II], Ne V, Ne III, H δ , Mg II	$(2.2^{+0.3}_{-0.4}) \times 10^{10}$	$(1.6^{+0.7}_{-0.5}) \times 10^8$	$(6.5^{+5.2}_{-2.9}) \times 10^{11}$	61^{+49}_{-27}	116 ± 20	1.38 ± 0.26

Note. Source names are as in Casey et al. (2013), and the positions of the sources are given in their Tables 6–7; in all of the cases above, the most likely multiwavelength counterpart was chosen (counterpart 1/ N). The redshift identification is given to three significant digits unless the source was particularly low redshift with bright emission features, which allow for a more precise redshift constraint. The “Identifying Features” column indicates which spectral features were used as the primary lines in identifying the sources’ spectroscopic redshift. Stellar mass estimates are generated with the help of the MAGPHYS energy balance code as described in Section 3. M_{dust} , L_{IR} , SFR, and λ_{peak} are all derived using a simple modified blackbody plus mid-infrared power law (Casey 2012), as shown in Figure 4. We quote λ_{peak} instead of the dust temperature T_{dust} as the former is more directly tied to observational constraints and the latter is heavily dependent on model assumptions. The SFR quoted here is derived from L_{IR} using a Chabrier IMF (Kennicutt & Evans 2012). The last column, log(IRX), is the log of the IRX ratio, defined as $L_{\text{IR}}/L_{\text{UV}}$. For example, a DSFG with log(IRX) = 2 will have an IR luminosity 100 times its UV luminosity.

present two misidentifications, along with two ambiguous cases that are likely misidentifications. All are shown in Figure 8.

Source 450.03 (Figure 8, left) is best known as AzTEC-2 in the literature (Younger et al. 2007, 2009) and has extensive follow-up, both interferometric and spectroscopic. Unfortunately, spectroscopic efforts to date have failed to yield a redshift identification. At the time of our MOSFIRE and DEIMOS campaigns, it seemed like the interferometric source (at 1.1 mm) was inconsistent with the 450 μm position identified in Casey et al. (2013), so the possibility remained that they were separate sources. More recent high-frequency follow-up from ALMA at 850 μm indicates this is not the case, however, and the position of the DSFG sits about $1''$ – $1''.5$ to the

north of our spectroscopic target. While we have confirmed that our original target sits at $z = 1.123$, and there is a possible detection of a CO line at the same redshift (E. F. Jimenez-Andrade et al. 2017, in preparation), our confirmation does not spatially align with the DSFG, and so we do not include it in further analysis for this paper or sample. The possibility remains that this DSFG is associated with the system at $z = 1.123$, but this requires further analysis.

Source 450.28 (Figure 8, middle left) is a member of a complex blend of submillimeter sources; the prior measurements of this area at 850 μm and 1.2 mm only reveal a single source (see Bertoldi et al. 2007; Casey et al. 2013), while 450 μm imaging breaks the emission into two distinct peaks. Our MOSFIRE

Figure 5. Basic measured physical characteristics of the spectroscopically confirmed DSFG sample from this paper (navy) against a comparison sample of photometric sources from the ALESS survey (da Cunha et al. 2015). In the top panel, total IR luminosity ranges from a few times $10^{10} L_{\odot}$ to $10^{13} L_{\odot}$. The peak rest-frame SED wavelength falls toward high redshifts; the $450 \mu\text{m}$ flux density points are crucial to the measurement of this quantity. Dust masses average several times $10^8 M_{\odot}$, about 0.1% of the galaxies’ stellar masses; compared to the ALESS sample, this SCUBA-2 sample seems slightly less massive in dust for comparable stellar masses. In the bottom panel, the IRX, or the ratio of $L_{\text{IR}}/L_{\text{UV}}$, is quite high compared to the ALESS sample, converted from A_V to IRX.

follow-up targeted the most likely counterpart for the western source, 450.28, and confirms a redshift for that source of 2.472 (a member of the protocluster discussed in Casey et al. 2015). However, more recent ALMA follow-up reveals this source is misidentified, and instead, three sources dominate the ALMA emission to the north and east. While formally resulting in a misidentification, this complex is physically associated with the structure identified at $z \approx 2.47$, confirmed through multiple transitions of CO at $z = 2.494$. This region is discussed at length in Wang et al. (2016) as a potential virialized protocluster core at $z = 2.51$, where they present an extended X-ray detection and 11 possible CO(1-0) detections in the broader redshift range of the protocluster. Further CO(1-0) observations of this region are being analyzed to determine redshifts and further map this complex region (J. Champagne et al. 2017, in preparation).

Source 450.55 (Figure 8, middle right) is likely a blend of a background galaxy, which is exceedingly faint, even at near-infrared wavelengths, and a foreground galaxy, confirmed at $z = 0.36$. The submillimeter source is more consistent with the background source to the west of the bright foreground source,

yet the foreground source is $24 \mu\text{m}$ bright, and so was earlier identified as the likely submillimeter counterpart. Deblending of this source was unfortunately not attempted before the spectroscopic campaign was underway, so we have not obtained a secure redshift for this DSFG.

The last case of a misidentification is 850.77. This submillimeter source is offset to the north of a very bright foreground spiral galaxy at $z = 0.1088$. The spiral is clearly the dominant source of $24 \mu\text{m}$ emission in the region, and so was mistaken as a potential counterpart to the $850 \mu\text{m}$ source. Deep imaging does not reveal any obvious optical/near-infrared counterpart, and so this source remains ambiguous and without a redshift identification; it is also not detected at $450 \mu\text{m}$.

5. DSFG Composite Spectrum

With many rest-frame optical spectra of DSFGs in hand, stacking provides a useful means of inferring the aggregate spectral characteristics of the DSFG population, including features that are too weak to measure in individual DSFG spectra. We construct a rest-frame optical spectrum for the 20 DSFGs with $\text{H}\alpha$ detections by first shifting all spectra into the rest frame using the systemic redshift measured from $\text{H}\alpha$ emission. The redshifts for the galaxies included in the composite range from 1.26–2.55, with a median redshift of $z = 2.1$. Because the continuum emission varies dramatically from source to source, we first remove continuum emission before stacking. For high S/N continuum (>10), we fit the continuum using a third-order polynomial, and for low S/N continuum, we use a linear fit. Continuum-subtracted spectra are combined using an unweighted co-addition. We test several combination methods, including weighting individual spectra by the strength of $\text{H}\alpha$ emission, weighting by the S/N of $\text{H}\alpha$, weighting by the spectrum’s inverse-variance (measured using each spectrum’s extracted 1D flux error array), and co-adding the spectra without special weighting. All combinations produce similar spectra, but the unweighted spectrum, scaled by flux, produces the most uniform, high S/N result. We check to ensure the final spectrum is not dominated by the brightest sources; the brightest $\text{H}\alpha$ source, 850.44, contributes 16% to the final stack. The median contribution is 3.5%, and the minimum contributor (faintest) contributes 1%.

The resulting rest-frame optical composite for DSFGs is shown in Figure 9, extending from rest-frame wavelengths ~ 4300 – $7300 \text{ \AA}$. We compare this fit to a similar composite derived in Swinbank et al. (2004) for 23 $850 \mu\text{m}$ -selected DSFGs (i.e., SMGs). Given the spectral coverage of Keck NIRSPEC, which was used for the SMG sample, the Swinbank et al. composite covered a much narrower rest-frame wavelength range. We simultaneously fit $\text{H}\alpha$ and $[\text{N II}]$ emission in the range 6550 – $6600 \text{ \AA}$ using four co-added Gaussian fits, with the narrowband component of $\text{H}\alpha$ and the two $[\text{N II}]$ features at a fixed width. The $\text{H}\alpha$ line is best fit with both a broad and narrow component, rather than a single fit. The narrow component has an FWHM of $\Delta v = 253 \pm 6 \text{ km s}^{-1}$ (comparable to the results of Swinbank et al.), while the broad component is $\Delta v = 2000 \pm 80 \text{ km s}^{-1}$. The narrow-to-broad flux ratio is 0.61 ± 0.03 , nearly identical to the ratio found in the Swinbank et al. composite.

The $[\text{N II}]/\text{H}\alpha$ ratio for the composite is 0.33 ± 0.02 , consistent with a star formation origin. We detect both $[\text{S II}]$ features at 6716 and $6731 \text{ \AA}$, and measure the $[\text{S II}]/\text{H}\alpha$ ratio

Figure 6. Sources from our spectroscopic sample with ALMA observations, confirming their positions align with those identified via prior multiwavelength techniques (in Casey et al. 2013). Cutouts range in size from $4''$ to $7''$ to a side, as indicated by the inset arcsecond marker. The first four cutouts are from *HST* F125W imaging from the CANDELS survey (Grogin et al. 2011; Koekemoer et al. 2011), and the last cutout is from ground-based UltraVISTA *H*-band imaging. ALMA band 6 (1.1 mm) dust continuum contours are shown in blue, MOSFIRE slits in yellow, and LRIS slits in green. From left to right, source 450.05, source 450.27, source 850.04, source 850.20, and source 850.59. While the submillimeter emission in source 850.04 is offset from its OIR counterpart, we present a further morphological and kinematic analysis of this source in P. Drew et al. (2017, in preparation), which lead us to tentatively conclude that the two components are associated.

Figure 7. Top: *HST* ACS and WFC3 cutouts around 450.14, an ambiguous case of a potentially superimposed pair of sources at $z = 1.523$ and $z = 2.462$. Source A is identified unequivocally at $z = 1.523$ via detection of $H\alpha$ and $[N II]$, shown in the lower panel. Source B is tentatively at $z = 2.462$. We overplot the two different MOSFIRE slits we used to observe this source (though vignetting prevents us from comparing the *K*-band spectra of the two). Bottom: spectra around the $H\alpha$ emission for Source A (left) and Source B (right). $H\alpha$ and $[N II]$ emission are marked at the measured redshifts.

at 0.15 ± 0.01 , consistent with an H II region origin (Veilleux & Osterbrock 1987). We also use the ratio of the two sulfur lines to infer the mean electron density in DSFGs. A ratio of $[S II]6716/[S II]6731 = 0.86 \pm 0.12$ implies an electron density of $n_e \sim 900 \pm 300 \text{ cm}^{-3}$. This density is well above the $\lesssim 10 \text{ cm}^{-3}$ low-density regime (see Figure 5.8 of Osterbrock & Ferland 2006) of many lower luminosity galaxies, and even the

$\sim 200 \text{ cm}^{-3}$ densities seen in high- z star-forming galaxies (Strom et al. 2017), implying a dense interstellar medium (ISM) consistent with DSFGs' relatively compact, high SFR-density, and high gas-density characteristics. The measured ratio of $H\alpha$ to $H\beta$ emission in the composite, i.e., the Balmer decrement, is 21.0 ± 2.4 , which translates to an $A_V = 6.8 \pm 0.5$. This is, of course, substantially higher than the theoretically expected $H\alpha/H\beta = 2.86$ from case B recombination, and the dramatic difference is directly attributable to the extreme obscuration present in the DSFG population.

The composite spectrum also shows notable Na absorption blueshifted by $-200 \pm 30 \text{ km s}^{-1}$, indicative of gas outflows. This blueshift is consistent with the measured $-240 \pm 50 \text{ km s}^{-1}$ blueshift observed in the Mg II and Fe II features in slightly lower redshift DSFGs (Banerji et al. 2011), indicative of large-scale outflowing interstellar gas and consistent with the momentum-driven wind model. This is also broadly consistent with the local relation of SFR to ISM outflow velocity from Martin et al. (2005).

In Figure 10, we compare the line profiles of $H\alpha$, $[O III]$, $H\beta$, and Na I from the composite spectrum. The measured $[O III]$ 5007 Å width is notably narrower than the width of $H\alpha$, at $74.0 \pm 3.7 \text{ km s}^{-1}$, though the $H\beta$ line width is consistent with the $H\alpha$ width. The $[O III]/H\beta$ ratio is 5.17 ± 0.78 . As we show in the next subsection, we use both the $[N II]/H\alpha$ and $[O III]/H\beta$ ratios to place our composite spectrum, as well as individual DSFGs with bright features, on a nebular emission line diagram, and compare it to literature sources at low and high redshift.

Figure 8. Characterization of four misidentifications. Left: source 450.03, known as AzTEC-2 in the literature, was initially thought to be associated with the source at the center of the frame, aligned in both the MOSFIRE (yellow) and DEIMOS (pink) slits, and confirmed to be at $z = 1.123$. Long-wavelength interferometric follow-up suggested the source sat farther to the north, though these positions were thought to be inconsistent with the positional constraint at $450\ \mu\text{m}$. However, further higher-frequency ALMA follow-up (blue contours) reveals that indeed, the DSFG sits farther to the north. The background image is WFC3 $1.25\ \mu\text{m}$ imaging from CANDELS (Grogin et al. 2011; Koekemoer et al. 2011). Middle left: source 450.28 is part of a complex region of submillimeter blends, now revealed by ALMA to consist of multiple sources. Unfortunately, the source targeted in our MOSFIRE observations, confirmed at $z = 2.472$, is not properly identified as one of the submillimeter sources. However, the brightest of the submillimeter sources has been spectroscopically confirmed at $z = 2.494$ (Wang et al. 2016). Middle right: source 450.55 was matched to a fairly bright $z = 0.36$ galaxy which dominates the $24\ \mu\text{m}$ emission (dashed gray contours) of the area. This counterpart is not very well aligned with the submillimeter emission (dotted cyan contours) and is likely to be a foreground contaminant. Unfortunately, our spectroscopic program failed to account for this foreground source before carrying out observations. Right: source 850.77 is a submillimeter source without an obvious multiwavelength counterpart, centered on the outskirts of a nearby spiral galaxy.

6. AGN Content

AGN can significantly impact rest-frame optical line diagnostics. Here we summarize the contribution of AGNs to the spectroscopically confirmed population of DSFGs. Only 4 of the 31 spectroscopically confirmed sources are X-ray detected: 450.58, 850.36, 850.89, and m450.133. Their integrated rest-frame $0.5\text{--}8\ \text{keV}$ luminosities are $8.0 \times 10^{43}\ \text{erg s}^{-1}$, $3.1 \times 10^{41}\ \text{erg s}^{-1}$, $2.0 \times 10^{44}\ \text{erg s}^{-1}$, and $1.1 \times 10^{44}\ \text{erg s}^{-1}$, respectively. The low luminosity for 850.36 (at $z = 0.224$) is consistent with a star formation origin, while the other sources are consistent with luminous AGNs. Sources not detected in X-ray data but showing signatures of bright AGNs include 450.09, discussed in Casey et al. (2015) as being radio-loud, just under the classic FR II classification luminosity. As shown in Figure 4, 450.09 is one of two sources with a clear power law through mid-infrared wavelengths, consistent with AGN-heated torus dust. The other is 850.59. Together, these rather clear AGN indicators in the X-ray and radio account for $\sim 10\%$ of the confirmed DSFG sample, a noticeably lower fraction than found at higher luminosities.

While most of our DSFGs lack obvious AGN signatures, some of the remaining DSFGs in our sample may contain AGNs that contribute at a lower level to a galaxy’s bolometric luminosity. While we do have 20 DSFGs for which an $N_2 \equiv [\text{N II}]/\text{H}\alpha$ ratio is measurable, nearly half the sample (9) have $\log([\text{N II}]/\text{H}\alpha) > -0.5$, consistent with solar or super-solar metallicity, shock-heating or AGN. As revealed from our composite spectrum in Figure 9, there is an underlying broad $\text{H}\alpha$ line profile with $2000\ \text{km s}^{-1}$ width confirming the presence of AGNs, albeit at a level that does not dominate the bolometric luminosity of our sources, but further demonstrates the link between luminous starbursts and their nuclear activity.

7. Nebular Emission Diagnostics

Five DSFGs have sufficiently high-S/N spectra with independent detections of $\text{H}\alpha$, $[\text{N II}]$, $[\text{O III}]$, and $\text{H}\beta$ to place in the context of the strong-line Baldwin–Phillips–Terlevich (BPT) classification (Baldwin et al. 1981) used to infer the dominant mode of excitation for strong nebular emission in both low- and high-redshift galaxies. While this sample is

insufficient to independently fit as a population, it does provide some context for a handful of typical high- z DSFGs, and provides some promise that future MOSFIRE surveys of larger DSFG samples could become a useful technique for understanding the galaxies’ internal physical drivers. This is particularly useful in understanding the origins of HII region ionization, either from AGNs or UV radiation from young stars (Kewley et al. 2001).

Figure 11 shows our DSFGs in context with other high- z samples. The largest $z \sim 2$ galaxy samples with these nebular line diagnostics are drawn from the Keck Baryonic Sky Survey (KBSS; Steidel et al. 2014; Strom et al. 2017) and from the MOSFIRE Deep Evolution Field (MOSDEF; Shapley et al. 2015). Both populations show elevated $[\text{O III}]/\text{H}\beta$ ratios, with differences between the star-forming tracks due to sample selections: in the rest-frame UV for KBSS versus in the observed near-IR for MOSDEF. We also draw comparisons with $z \sim 1.5$ BzK-selected star formers (Silverman et al. 2015) and *Herschel*-PACS-selected DSFGs (Kartaltepe et al. 2015). Our composite spectrum and 3/5 individual sources are on the upper envelope of the Steidel et al. (2014) sample fits and the Kewley et al. (2013) $z = 2.2$ model. While the Kartaltepe et al. (2015) work presents the largest sample of DSFGs with these optical line characteristics to date, our DSFGs here are more in line with $z = 1.5$ BzK galaxies and seem to probe a different regime. Indeed, AGNs are a significant contributor to the IR luminosity for *Herschel*-PACS samples, and as our selection is at $450\ \mu\text{m}/850\ \mu\text{m}$, this work is more sensitive to pure starbursts. The general observation of higher $[\text{O III}]/\text{H}\beta$ ratios, in excess of those observed by Steidel et al. (2014) and Shapley et al. (2015), is attributed to even harder ionizing radiation fields in these starbursting systems with low metallicity.

As discussed in Masters et al. (2016) and Strom et al. (2017), the N/O ratio seems to be rather fundamental, holding a tight relation with mass and metallicity. At high stellar masses (which our DSFGs are), we observe an even higher $[\text{N II}]/\text{H}\alpha$ ratio at a given $[\text{O III}]/\text{H}\beta$. Our results are also consistent with those of Stanway et al. (2014), who argue that high $[\text{O III}]/\text{H}\beta$ ratios can be accounted for with binary stellar evolution models in short-lived ($\sim 100\ \text{Myr}$) starbursts.

Figure 9. Composite optical DSFG spectrum, comprised of 20 DSFGs within the redshift range $1.26 < z < 2.55$. The median redshift of the stack is $\langle z \rangle = 2.1$. The composite is Gaussian-smoothed to a spectral resolution of ~ 1200 (dark red) from the original $R \sim 3600$ (gray). There are significant detections of $H\alpha$, $H\beta$, $[N II]$, $[O III]$, and $[S II]$ in emission, and $Na I$ in absorption. We compare our composite to that of Swinbank et al. (2004), shown in blue offset in flux. A zoom-in of the region surrounding $H\alpha$ and $[N II]$ emission is shown in the inset. See the text, Section 5, for more details. This spectrum is available for download at www.as.utexas.edu/~cmcasey/downloads.html.

8. Extinction in DSFGs

DSFGs are known to be among the most heavily extinguished sources at rest-frame ultraviolet and optical wavelengths, and here we explore where this sample of DSFGs sit with respect to other DSFG samples in terms of $H\alpha$ extinction. Figure 12 plots the integrated infrared-based star formation rate against the $H\alpha$ -based star formation rate, as inferred directly from $H\alpha$ line luminosity (Kennicutt 1998). Compared to the Swinbank et al. sample of $850 \mu\text{m}$ -selected DSFGs, our sample is a bit less luminous at far-infrared wavelengths, yet similarly bright (or brighter) in $H\alpha$ luminosity. Swinbank et al. attribute the factor of 14 ± 7 discrepancy between IR and $H\alpha$ SFR indicators to obscuration of the rest-frame optical, albeit not as significant as the much stronger discrepancy between IR and rest-frame UV, which is typically a factor of ~ 120 ($IRX \equiv L_{IR}/L_{UV}$; Chapman et al. 2005). As our sample is, on average, less luminous and less extreme than the Swinbank sample, the average $H\alpha$ SFR deficit we measure is only 1.3 ± 0.1 , in comparison. In other words, the $H\alpha$ in our sample is recovering about 77% of the total SFR of our DSFGs, while in the more luminous Swinbank et al. DSFG sample, only $\sim 7\%$ is recovered. This type of extinction is reminiscent of similar effects seen at rest-frame UV wavelengths. For example, in Casey et al. (2014b), we showed that the IRX ratio (or more specifically the deviation from the IRX- β relationship) is a strong function of galaxies' total star formation rates. As SFR increases, attenuation becomes more severe due to geometric effects decoupling UV and IR emission. In Figure 13, we show that the $H\alpha$ SFR deficit tracks the IRX ratio well, with the highest-obscuration UV sources those DSFGs whose $H\alpha$ emission most dramatically underestimates the total SFR.

9. Conclusions

This paper has presented new spectroscopic observations of DSFGs in the COSMOS field, which were initially selected via their emission at submillimeter wavelengths, at 450 and $850 \mu\text{m}$. Of the 114 sources initially targeted by both DEIMOS and MOSFIRE observations, we have spectroscopically confirmed 31. The vast majority of the sources identified were through MOSFIRE near-infrared spectroscopy (where we targeted 102 sources), with a few sources revealed by LRIS and DEIMOS optical spectroscopy.

The vast majority (71/102) of our MOSFIRE spectroscopic targets did not yield redshift identifications. From their photometric redshifts, we estimate about 60% of these failures are likely caused by the sources sitting outside the optimum redshift range where bright emission lines are detectable in the MOSFIRE H - and K -bands, while the other 40% are likely too obscured at rest-frame optical wavelengths to be detected in, e.g., $H\alpha$ emission. Archival ALMA dust continuum data exist for seven sources from our spectroscopic survey; five of the seven sources (71%) were correctly identified using multi-wavelength counterparts.

Because the COSMOS field has some of the highest quality photometric redshifts available thanks to 30+ bands of deep imaging, we assess the quality of photometric redshifts in DSFGs and conclude that half are high quality, $\Delta z/(1+z) < 0.05$, the other half are poor fits (no photometric redshift or $\Delta z/(1+z) \approx 0.6$), which we attribute to geometric decoupling of the galaxies' unobscured and obscured emission. Indeed, the sources whose photometric redshifts fail catastrophically have the most significant offset between rest-frame optical/near-infrared SED characteristics and far-infrared/submillimeter characteristics.

Figure 10. Velocity offset and width comparison across different line tracers in the stacked spectrum, including $H\alpha$ (from which the systemic redshifts are inferred), $[O\ III]$, $H\beta$, and finally Na B absorption. The Na B absorption is slightly blueshifted, indicative of winds.

Figure 11. BPT diagram for the DSFGs of this sample and the composite spectrum (so labeled). For comparison we show the $z = 0$ SDSS cloud (gray; Kewley et al. 2001), the $z = 1.5$ (dotted-dashed) and $z = 2.2$ (dashed) model predictions of Kewley et al. (2013) in light blue, the best-fit star formation track from KBSS (orange; Steidel et al. 2014) and MOSDEF (purple; Shapley et al. 2015), and $z \sim 1.5$ BzK galaxies (green diamonds; Silverman et al. 2015) and $z \sim 1.5$ *Herschel*-PACS DSFGs (red stars; Kartaltepe et al. 2015).

Figure 12. $H\alpha$ star formation rates against IR star formation rates for both local and high-redshift sources. The Swinbank et al. (2004) DSFGs (blue points) sit at slightly higher luminosities than the sample of this paper (black points). Both high- z DSFG samples exhibit substantial extinction, rendering the $H\alpha$ luminosity-to-SFR scaling inaccurate. This is reminiscent of more nearby galaxies (Franceschini et al. 2003; Flores et al. 2004). While the $H\alpha$ luminosities of the Swinbank et al. sample underestimate the total SFRs by factors of ~ 14 , our lower luminosity sample only underpredicts the total SFR by factors of ~ 1.3 .

Figure 13. IRX ratio, or the ratio of IR to UV luminosity (a tracer of relative obscuration of a galaxy), against the ratio of measured star formation rates from $H\alpha$ and IR. In these galaxies, IR can be viewed as the total SFR. It is clear that at higher obscurations, the $H\alpha$ SFR is less and less representative of the total SFR of the system, even though $H\alpha$ emission itself is relatively unobscured compared to the rest-frame UV continuum emission, probed by the IRX measurement.

We have constructed a composite spectrum of 20 DSFGs in the rest-frame optical spanning 4300–7300 Å, a much wider wavelength coverage than the previous DSFG composite spectra thanks to the sensitivity of the MOSFIRE instrument and our deep spectroscopic observations in both H - and K -bands. We detect $H\alpha$, $[N\ II]$, $[S\ II]$, Na D, $[O\ III]$, and $H\beta$ in

our composite and conclude that the DSFGs, in aggregate, are star formation dominated as measured from their $[\text{N II}]/\text{H}\alpha$ ratio, have relatively high electron densities $\sim 1000 \text{ cm}^{-3}$, and unsurprisingly are significantly obscured, with a Balmer decrement of 21.0 ± 2.4 . A handful of individual sources are detected at high-S/N across several nebular emission tracers to allow characterization on the BPT diagram. We find our sample of DSFGs more skewed toward star formation-driven ionization rather than luminous AGNs, but with harder ionizing radiation fields than lower redshift galaxies and lower-SFR galaxies at similarly high redshifts.

In line with the observation that our sample is, on average, less extreme than previously studied samples of DSFGs with $\text{H}\alpha$ observations, we find that their $\text{H}\alpha$ star formation rates only underestimate the total SFR of the system by a factor of 1.3 ± 0.1 , in contrast to much larger factors >10 . The most extreme $\text{H}\alpha$ SFR deficits align with the most extreme IRX, or $L_{\text{IR}}/L_{\text{UV}}$, ratios.

Overall, this survey, like the ALESS survey (A. Danielson 2017, in preparation), has revealed that spectroscopic redshifts—the classic “bottleneck” of DSFG analysis—are just as elusive today as they have been in the past decade. While newer, sensitive wide-bandwidth technology has come online at long wavelengths in recent years (most notably the Atacama Large Millimeter Array), there have not yet been large spectroscopic programs pursued in the millimeter to ease pressure from optical/near-infrared facilities in spectroscopically characterizing DSFGs. Until then, optical/near-infrared facilities will still be the most efficient source of DSFG spectroscopy despite the population’s high obscuration.

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