Near-infrared Emission Lines in Starburst Galaxies at 0.5 < z < 0.9: Discovery of a Merger Sequence of Extreme Obscurations

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Received 2018 May 31; revised 2018 July 2; accepted 2018 July 10; published 2018 August 1

Abstract
We obtained optical/near-IR rest-frame Magellan FIRE spectra (including Paβ and Paγ) of 25 starburst galaxies at 0.5 < z < 0.9, with average star formation rates (SFRs) seven times above the main sequence (MS). We find that Paschen-to-Balmer line ratios saturate around a constant value corresponding to AV ∼ 2–3 mag, while line-to-IR-luminosity ratios suggest a large range of more extreme obscurations and appear to be uncorrelated with the former. This behavior is not consistent with standard attenuation laws derived for local and distant galaxies, yet is remarkably consistent with observations of starburst cores in which young stars and dust are homogeneously mixed. This model implies AV ≥ 2–3 mag attenuation to the center of starburst cores, with a median of ∼9 mag (a factor of 4000). X-ray hardness ratios for six AGNs in our sample and column densities derived from observed dust masses and radio sizes independently confirm this level of attenuation. In these conditions observed optical/near-IR emission comes from surface regions, while inner starburst cores are invisible. We thus attribute the high [N II]/Hα ratios to widespread shocks from accretion, turbulence, and dynamic disturbances rather than to AGNs. The large optical depths demonstrates that substantial diversity is present within the starburst population, possibly connected to different merger phases or progenitor properties. The majority of our targets are, in fact, morphologically classified as mergers. We argue that the extreme obscuration provides in itself smoking gun evidence of their merger origin, and a powerful tool for identifying mergers at even higher redshifts.

Key words: dust, extinction – galaxies: evolution – galaxies: high-redshift – galaxies: ISM – galaxies: starburst – infrared: galaxies

1. Introduction
Starburst galaxies (SBs), outliers from the main sequence (MS; e.g., Daddi et al. 2007; Noeske et al. 2007), might be key to solving a long-standing mystery in galaxy formation and evolution: the transition from star-forming galaxies to massive, passively evolving ellipticals. According to a popular scenario (e.g., Di Matteo et al. 2005; Hopkins et al. 2010), this transition is attributed to major mergers producing strong bursts of star formation in very dense cores and triggering obscured black hole accretion, which can both remove the gas and dust content in the galaxy.

Local ultra-luminous infrared galaxies (ULIRGs) are textbook examples of merger-induced starbursts, showing compact and heavily obscured cores (e.g., Soifer et al. 2000; Juneau et al. 2009) in agreement with the above scenario. Using standard attenuation recipes in ULIRGs (Cardelli et al. 1989; Calzetti et al. 2000) leads to UV-based, optical-based, and near-IR-based star formation rates (SFRs) being systematically underestimated compared to the total infrared luminosities, implying optically thick conditions for these tracers (Goldader et al. 2002; García-Marín et al. 2009; Rieke et al. 2009).

The nature and evolution of SBs in the distant universe is debated. While they might still be major merger events, there are also claims that they might be instead very gas-rich galaxies (e.g., Scoville et al. 2016), possibly due to exceptionally strong gas accretion events. This is supported by ideas that at higher redshifts, with higher gas fractions, major mergers might only rarely result in strong SFR enhancements (Fensch et al. 2017). Comparisons of both dust-free and dust-affected SFRs are required to study their degree of obscuration, providing clues to the ULIRGs/distant-SB connection. Puglisi et al. (2017) showed that on average, Balmer emission lines of Herschel-selected z ∼ 1.6 SBs are mainly coming from regions producing <10% of the total SFR, suggesting that rest-optical
lines cannot be used to infer the physical properties of the whole starburst system. These results prompted us to use Magellan FIRE to obtain spectroscopy of starbursts in the near-IR rest-frame with the aim of providing enhanced sensitivity and constraining power to study their attenuation properties (hence their nature). In this Letter we present the first results of this effort. We adopt Chabrier (2003) IMF, AB magnitudes, and standard cosmology ($H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_m = 0.3$, $\Omega_{\Lambda} = 0.7$).

2. Sample Selection

We select starbursts galaxies for observations with Magellan FIRE in the COSMOS field, with the following criteria:

1. Spectroscopic redshift $0.5 < z < 0.9$ (from optical surveys, Salvato et al. 2018, in preparation), placing Pa$\beta$ within the K band, and H$\alpha$ above 0.82 $\mu$m, thus observable with FIRE.19

2. SFR $> 4 \times$ SFR$_{M_S}$ (Rodighiero et al. 2011). SFRs are derived using the IR catalog from Jin et al. (2018).18 As shown in Figure 1, the MS for our sample, derived through a running median over 10 bins in $M_*$, agrees with the literature (Sargent et al. 2014; Schreiber et al. 2015). Our SFRs are decontaminated from AGN torus emission (3% median contribution to $L_{IR}$; see Liu et al. (2018) and Jin et al. (2018) for the procedure).

3. $M_* > 10^{10} M_\odot$, for sample completeness: above this mass limit and up to $z = 0.9$, all SBs would be Herschel-detected at $S$/N$_{FIR} > 5$ (see Figure 13 in Jin et al. 2018). Stellar masses are from Laigle et al. (2016).

These criteria yield a total of 152 starburst candidates for our Magellan observations (Figure 1). They represent 2%–3% of the whole star-forming population in the same mass range and redshift (see, e.g., Sargent et al. 2012, 2014; Schreiber et al. 2015).

3. Magellan FIRE Observations

FIRE is a single-slit near-infrared spectrometer mounted at the Magellan 6.5 m Baade Telescope, covering the wavelength range 0.82–2.4 $\mu$m. We observed in the cross-dispersed echelle mode, choosing a slit width of 1″ to maximize the incoming light from our targets. This configuration provides a spectral resolution $R \approx 3000$, which helps reducing the effect of OH sky-emission. We refer to Simcoe et al. (2013) for a complete description of the instrument and its performances.

Our observations were performed in two runs during the nights of 2017 March 17–18 and 2018 March 22–23. We prioritized targets for observations based on two criteria: (1) the presence of a nearby ($\lesssim 30''$ from the target) bright ($J < 19–20$ mag) star to facilitate acquisition, and (2) maximization of the ratio SFR$_{IR}/D_L^2(z)$, where $D_L$ is the luminosity distance. The latter condition selects galaxies with the intrinsically brightest emission lines, and tends to bias our observed sample toward the most massive objects (Figure 1). We observed 11 targets during the first run and 14 in the second, for a total of 25 starbursts. Integration times ranged between 30 and 80 minutes, longer for galaxies with lower H$\alpha$ S/N (from real-time reductions), to improve the detection of fainter lines.

The spectra were reduced using the FIRE pipeline (Gagné et al. 2015). Full details will be given in a forthcoming paper (Calabrò et al. 2018, in preparation) that also presents science results for the complete range of observed emission lines. In Figure 2, we show examples of H$\alpha$ and Pa$\beta$ (or Pa$\gamma$) for some

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**Figure 1.** Left: SFR–$M_*$ diagram for galaxies in our parent sample ($0.5 < z < 0.9$), where SFR$_{tot}$ is defined as SFR$_{UV,obs}$+SFR$_{IR}$ and is normalized to their median redshift (0.73) using the evolving trend from Sargent et al. (2014). For sources detected only at 24 $\mu$m, we estimated the SFR from their 24 $\mu$m flux using Magdis et al. (2012) templates. Right: SFR$_{tot}$ vs. redshift for the same sample.
of the galaxies with good detection (S/N > 5) of both lines. Double-Gaussian components were fitted to line profiles whenever single-Gaussian fits could be rejected based on χ² statistics, always resulting in good fits (χ²_red < 1.5). We attribute these double-Gaussians to either rotation or the presence of physically separated components.

The target list with the main physical properties is presented in Table 1, while i-band, H-band, and radio (3 GHz) cutout images of representative targets are shown in Figure 3.

### 4. Results

The wide spectral coverage of FIRE and the wealth of photometric data available for our targets makes this a unique sample to investigate attenuation through the use of different indicators as emission lines and the total infrared luminosity. In the left panel22 of Figure 4 we compare the ratio of Hα and Paβ (Paschen-Balmer decrement) to the ratio of SFRs derived from the observed Paβ and bolometric IR (A_Paβ/IRX = 2.5 × log₁₀(1 + SFR_IR/SFR_Paβ)).23 where SFR_Paβ is derived from the observed Paβ luminosity, adopting an intrinsic ratio Paβ/Hα = 0.057 and a standard Kennicutt et al. (1994) calibration, valid for case B recombination and T_e = 10⁴ K. We show that for our 25 starbursts, these two ratios, both independent measures of attenuation, do not generally scale as predicted by the Calzetti et al. (2000) and Cardelli et al. (1989) attenuation curves.24 The value of Paβ/Hα rather saturates at ~0.18 (with a dispersion of ~0.08 dex), qualitatively consistent with an optically thick “mixed model,” in which different lines probe different optical depths. As opposed to the foreground dust-screen, a mixed model is made of a uniform extended distribution of young stars and dust inside a volume. In the one-dimensional case, a simple analytic relation can be derived between the observed and intrinsic SFR by integrating along a segment of the luminosity contribution from each differential volume element, subject to the extinction of the full optical depth in front of it. This yields

\[
\frac{\text{SFR}_{\text{obs}}(\lambda)}{\text{SFR}_{\text{int}}(\lambda)} = \frac{L(\lambda)_{\text{obs}}}{L(\lambda)_{\text{int}}} = \frac{\log_{10}(e)}{0.4} \times \left(1 - 10^{-0.8A_{\lambda}(\lambda)}/2A_{\lambda}(\lambda)\right).
\]

where \(L(\lambda)\) is the luminosity of a line at a wavelength \(\lambda\) and \(A_{\lambda}(\lambda)\) is the total absolute attenuation at \(\lambda\) toward the center defined as \(k(\lambda)A_{\lambda}(\lambda)/R_\nu\). In the last expression, \(k(\lambda)\) and \(R_\nu\) correspond to the local extinction, for which we assumed two

22 This plot is equivalent to an IRX-β plot (Meurer et al. 1999).
23 For three galaxies in our sample where Paβ falls in nearly opaque atmospheric spectral regions or out of FIRE coverage, we use the Paγ line to infer the attenuation, estimating Paβ flux as 2.2 × Paγ (Table 1). Indeed, both in a mixed model and foreground dust-screen geometry, the expected observed ratio Paβ/Paγ ranges between 2.1 and 2.5, for all the attenuation values we use in our range.
24 The Cardelli relation is actually an extinction law.
Figure 2. Hα and Paβ (Paγ for ID 245158) emission lines for four representative galaxies. In each panel, the spectra around the lines are shown, together with their best-fit Gaussians in red, derived with MPFIT (Markwardt 2009). In the bottom panels we display the noise and the residual of the fit (data-model) normalized by the noise.

extreme cases of a Cardelli et al. (1989) and an SMC (Bouchet et al. 1985) law, yielding an asymptotic Paβ/Hα ratio of 0.17 and 0.2, respectively. Using Equation (1), we can predict the observed fluxes at all wavelengths as a function of a single parameter, $A_{V,\text{tot}}$. For small values of $A_{V,\text{tot}}$, this model coincides with the standard attenuation curves adopted. For large $A_{V,\text{tot}}$, the local extinction inside the starburst core increases toward the center until the photons are not able to escape anymore from the galaxy, and are fully absorbed by the outer layers of dust. This leads us to depict heavily obscured starbursts as made of a central optically thick core, invisible to us, and a surrounding skin, producing the observed optical and near-IR nebular lines.

This picture naturally explains both the larger attenuation and SFR fraction that can be recovered by near-IR observations with respect to optical studies (Puglisi et al. 2017), as near-IR wavelengths allow us to penetrate deeper in the system. Because only the less attenuated light from the skin comes out, from Paβ we can recover, on average, 30% of the total IR SFR (center panel of Figure 4). However, inside the skin the optical depth quickly becomes large, with median $A_{V,\text{tot,mixedmodel}} = 9$, corresponding to a suppression of $\times4000$ of V-band light from the starburst core centers and up to extreme cases with $A_{V,\text{tot,mixedmodel}} \sim 30 \times 10^{12}$ (in linear scale). Hence, we cannot directly see the starburst cores in the optical/near-IR.

5. Discussion

Can we conclude that $z \sim 0.7$ SBs contain extremely obscured cores that are well described by mixed stars/dust models? It is worthwhile to consider alternative explanations. It might be possible that the UV radiation from newly born massive stars is absorbed by dust within HII regions, before reaching to ionize H I outside. While strong stellar winds push the dust away to form a screen (Calzetti et al. 2000), a substantial amount of absorbing dust may still be trapped in the ongoing SF site (Caplan & Deharveng 1986; Bell & Kennicutt 2001), particularly in these very dust-rich galaxies. This would simulate the existence of an optically thick SB core, just reducing the fraction of photons seen by H I, and could still represent a mixed model scenario, with mixing occurring at smaller scales. Whether this is a viable option depends on geometry and is difficult to model in detail.

Alternatively, the discrepant SFRs (coming from the lines and IR bolometric luminosity) may be due to time-variation effects, as $L_{\text{IR}}$ probes longer SFR timescales than emission lines, due to the energy contribution of longer-lived B-type stars to ionizing O stars. In our case, this would require that most SBs have recently experienced a severe SFR truncation, which seems unlikely. Instantaneous and dust-free SFR tracers, like e.g., through CO[5-4] lines (Daddi et al. 2015), would shed light and help with definitively addressing this possibility.

Due to the optically thick cores, the mixed model also implies that it might not be possible to detect AGNs from optical and near-IR observations, if they are located in the coalescing center. Interestingly, Figure 4 shows that our SB galaxies often display high N2 ($= \log[N \text{II}]/H\alpha$) indexes, which might suggest highly ionizing, AGN-dominated emission. We also see a correlation, significant at >95% confidence level (Spearman correlation coefficient $r = 0.5$), between N2 and $A_{V,\text{tot,mixedmodel}}$. We argue that instead, in the majority of our targets with enhanced 26 This incidentally suggests that the four galaxies with Paδ upper limits are also very highly obscured, having relatively high N2.
[N II]/Hα (and relatively higher obscurations), the line emission may be driven by shocks, which were already shown to contribute up to 50% in local ULIRGs in latest merger stages (Rich et al. 2015). In case of shock contribution, the attenuations that we have inferred through $A_{\text{Pa}\beta}$, IRX would represent lower limits, but the line ratios will not be affected as Case B recombination regime still holds.

Nevertheless, it would be crucial to obtain independent estimates of actual attenuations toward the cores. One possibility is provided by AGNs. We searched for evidence of AGNs among our SBs using multiple dust-free multi-wavelength tracers in the radio and X-rays. While none of our SBs show significant radio excess, either following the criteria of Del Moro et al. (2013) and the less stringent requirements of Liu et al. (2018; all assuming an IR-radio correlation), six galaxies (ID 578239, 635862, 777034, 232171, 222723, and 911723) are detected by XMM-Newton, Chandra, or NuStar (Cappelluti et al. 2009; Civano et al. 2015; Marchesi et al. 2016) with luminosities much higher than what was expected from their SFRs (Ranalli et al. 2004). These objects also have a mid-IR dusty torus component detected through SED fitting. Their X-ray hardness ratios were converted in obscuring column densities ($N_{\text{H}}$) by Lanzuisi et al. (2017; see Figure 19 in LaMassa et al. 2016 for the method), which are $N_{\text{H}}$ upper limits for gas/dust obscurations to the cores (part of the obscuration would happen within the torus itself). The relation of Güver & Özel (2009) allows us to convert $N_{\text{H}}$ into total $A_V$ and ($N_{\text{H}}$(cm$^{-2}$) = 2.21 × 10$^{21}$A$_V$(mag)). This generally returns very high X-ray obscurations for the AGNs (Figure 4-right), supporting the presence of high obscuration in their center, as required by the mixed model.

As a further check, we computed the column density of gas in the SB cores using the total molecular mass $M_{\text{mol}}$ inferred as $M_{\text{mol}} = 8.05 + 0.81 \times \log(\text{SFR})$ (Sargent et al. 2014, assuming conservatively the starburst case) and the radio size, measured with GALFIT by fitting a Gaussian profile (convolved with the PSF) to their VLA (3 GHz) images (Figure 3). From the right panel Figure 4 we can see that for half of our sample, at relatively low-moderate obscurations within the probed range, the attenuation inferred from this method is consistent with the mixed model. On the other hand, toward the highest obscurations, this approach suggests even larger attenuations. Some fraction of the emission line fluxes might come from foreground regions unrelated to the

Figure 3. Left: HST-ACS F814W cutout images for the galaxies observed in the first Magellan run. Their FWHM resolution is 0.095. Center: H-band UltraVISTA images with the same field of view and with FWHM$_{\text{r}}$ ~ 0.75. Right: 3 GHz radio images from the VLA-COSMOS 3 GHz Large Project (Smolčić et al. 2017), FWHM ~ 0.75. For the galaxies 862072 and 893857, higher-resolution (0.2") H-band cutouts from the COSMOS-DASH program are shown (Momcheva et al. 2016).
starbursting cores, presumably residual material from the merging galaxies. Accounting for this extra, modestly attenuated component, would result in a substantial increase of the merging galaxies. Accounting for this extra, modestly attenuated component, would result in a substantial increase of the starbursting cores, presumably residual material from the merging galaxies.

What is the origin of these extremely obscured cores? Unsurprisingly (Figure 3), morphological classification was independently derived for 18 starbursts in our sample (Kartaltepe et al. 2010, see Table 1), and over 83% of them were identified as mergers: 11 as major mergers (61%), showing distorted or double nuclei, tidal tales, bridges, or overlapping disks; and 4 (22%) as minor mergers, characterized by at least slightly disturbed morphology (e.g., warped disks, asymmetric spiral arms, small companion at same z, etc.). Visual inspection for the remaining sources suggests that merger origin is at least plausible for the vast majority of our sample. Mergers are, in fact, more commonly identified among less obscured systems (Table 1), which is understandable given that in the later coalescence phases any remaining merger signature becomes subtle (see, e.g., two of the three morphologically non-merger objects in our sample classified as Ellipticals/S0 by Kartaltepe et al. (2010), and the three of them have $A_{V,\text{tot}}>9$). It is thus tempting to attribute the large range of observed properties apparently defining a sequence of obscurations as reflecting different merger phases, to varying progenitor properties (including, e.g., the gas fraction of merging galaxies and the impact geometry), or a combination of them. Nevertheless, we cannot definitely exclude with our data that the sequence may also be reflecting the amount of foreground contamination, which would make our data unrelated to the real obscuration of the core.

Our work suggests that deeply embedded merger events still largely dominate among sample of SBs galaxies at least to $z \sim 0.7$, which corresponds to a 6.3 Gyr lookback time, an epoch with galaxy specific SFRs that are on average $>5 \times$ larger than local rates. At even higher redshifts, it becomes much harder to identify mergers from their morphological signatures ,due to surface brightness dimming and widespread presence of clumpy/irregular galaxies. We argue instead that higher-$z$ mergers might be even more efficiently identified when searching for evidence of extreme levels of obscuration, given our results; also, consistent with simulations (e.g., Di Matteo et al. 2005), these mergers might represent a clear footprint of the origin of these obscurations. In fact, we are not aware of any viable alternative mechanism that could produce galaxy-wide obscurations of 10+ mag in the V-band: normal disk-like galaxies display much lower obscurations (see the orange lines in the left panel of Figure 4). Near-IR rest-frame spectra of galaxies will soon be easily accessible with JWST up to $z \simeq 7$ and down to much fainter levels, and will allow for tests and applications of this idea.

Figure 4. Left: diagram comparing the observed Pa$\beta$/H$\alpha$ ratio and $A_{\text{Pa}\beta/\text{H}\alpha}$. Upper and lower limits are shown with arrows for four galaxies in the sample, while a color-coding highlights their [NII]/H$\alpha$ values. Center: ratio of the SFR (relative to IR) derived from the observed Pa$\beta$ line (blue) and after correcting the Pa$\beta$ fluxes using the Balmer(H$\alpha$–Paschen/β) decrement and a Calzetti et al. (2000) attenuation law (red). We remark that the unobscured UV SFR represents $\sim 1\%$ of that derived from the IR, thus its contribution to the total SFR is negligible for our sample. Right: comparison between $A_{\text{Pa}\beta/\text{H}\alpha}$, which directly translates into the total $A_V$ toward the center of a mixed model (right axis) with: (blue circles) $A_{\text{Pa}\beta}$ derived from the dust column-density and (red crosses) $A_{\text{Pa}\beta}$ calculated from X-ray hydrogen column-density $N_\text{H}$ (Lanzuisi et al. 2017) for X-ray-detected galaxies, as explained in the text.

We thank the referee for useful suggestions; thank G.Rudie for assistance with Magellan observations, thank Nicolás Ignacio Godoy for data reduction, and thank Daniela Calzetti for discussions. We acknowledge support from FONDECYT regular programs 1150216, 1171710, and 1170618, ERC Advanced Grant 695671 “QUENCH”, JSPS KAKENHI grant No. JP17K14257, CONICYT D.N.21161487, the Brain Pool Program, funded by the Ministry of Science and ICT through the Korean National Research Foundation (2018H1D3A200902), and RadioNet conference funding.

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References
Bell, E. F., & Kennicutt, R. C., Jr. 2001, ApJ, 548, 681
Bouchet, P., Lequeux, J., Maurice, E., Prevot, L., & Prevot-Burnichon, M. L. 1985, A&A, 149, 330
Bruzual, G., & Charlot, S. 2003, MNRAS, 344, 1000
Calzetti, D., Armus, L., Bohlin, R. C., et al. 2000, ApJ, 533, 682
Calzetti, D., Kinney, A. L., & Storchi-Bergmann, T. 1994, ApJ, 429, 582
Caplan, J., & Deharveng, L. 1986, A&A, 155, 297
Cappelluti, N., Brusa, M., Hasinger, G., et al. 2009, A&A, 497, 635
Cardelli, J. A., Clayton, G. C., & Mathis, J. S. 1989, ApJ, 345, 245
Chabrier, G. 2003, PASP, 115, 763
Civano, F., Hickox, R. C., Puccetti, S., et al. 2015, ApJ, 808, 185
Daddi, E., Dannerbauer, H., Liu, D., et al. 2015, A&A, 577, A46
Daddi, E., Dickinson, M., Morrison, G., et al. 2007, ApJ, 670, 156
Del Moro, A., Alexander, D. M., Mullaney, J. R., et al. 2013, A&A, 549, A59
Di Matteo, T., Springel, V., & Hernquist, L. 2005, Nature, 433, 604
Draine, B. T., & Li, A. 2007, ApJ, 657, 810
Fensch, J., Renaud, F., Bournaud, F., et al. 2015, MNRAS, 465, 1934
Gagné, J., Lambrides, E., Faherty, J. K., & Simcoe, R. 2015, FireHose_v2: Firehose v2.0. Zenodo, doi:10.5281/zenodo.18775
García-Marín, M., Colina, L., & Arribas, S. 2009, A&A, 505, 1017
Genzel, R., Lutz, D., Sturm, E., et al. 1998, ApJ, 498, 579
Goldader, J. D., Meurer, G., Heckman, T. M., et al. 2000, ApJ, 568, 651
Güver, T., & Özel, F. 2009, MNRAS, 400, 2050
Hopkins, P. F., Bundy, K., Croton, D., et al. 2010, ApJ, 715, 202
Jin, S., Daddi, E., et al. 2018, ApJ, submitted (arXiv:1807.04967)
Juneau, S., Narayanan, D. T., Moustakas, J., et al. 2009, ApJ, 707, 1217
Kartaltepe, J. S., Sanders, D. B., Le Floc’h, E., et al. 2010, ApJ, 721, 98
Kennicutt, R. C., Jr., Tumlin, P., & Congdon, C. E. 1994, ApJ, 435, 22
Laigle, C., McCracken, H. J., Ilbert, O., et al. 2016, ApJS, 224, 24
LaMassa, S. M., Civano, F., Brusa, M., et al. 2016, ApJ, 818, 88
Lanzuisi, G., Dullech, I., Berta, S., et al. 2017, A&A, 602, A123
Liu, D., Daddi, E., Dickinson, M., et al. 2018, ApJ, 853, 172
Magdis, G. E., Daddi, E., Béthermin, M., et al. 2012, ApJ, 760, 6
Marchesi, S., Lanzuisi, G., Civano, F., et al. 2016, ApJ, 830, 100
Markwardt, C. B. 2009, adass XVIII, 411, 251
Meurer, G. R., Heckman, T. M., & Calzetti, D. 1999, ApJ, 521, 64
Momcheva, I. G., Brammer, G. B., van Dokkum, P. G., et al. 2016, ApJS, 225, 27
Mullaney, J. R., Alexander, D. M., Goulding, A. D., & Hickox, R. C. 2011, MNRAS, 414, 1082
Noeske, K. G., Weiner, B. J., Faber, S. M., et al. 2007, ApJL, 660, L43
Puglisi, A., Daddi, E., Renzini, A., et al. 2017, ApJL, 838, L18
Ranalli, P., Comastri, A., & Setti, G. 2004, in Proc. Guillermo Haro Conference 2003, Multiwavelength AGN Surveys, ed. R. Mújica & R. Maiolino (Singapore: World Scientific Publishing), 43
Rich, J. A., Kewley, L. J., & Dopita, M. A. 2015, ApJS, 221, 28
Rieke, G. H., Alonso-Herrero, A., Weiner, B. J., et al. 2009, ApJ, 692, 556
Rodighiero, G., Daddi, E., Baronchelli, L., et al. 2011, ApJ, 739, L40
Sargent, M. T., Béthermin, M., Daddi, E., & Elbaz, D. 2012, ApJL, 747, L31
Sargent, M. T., Daddi, E., Béthermin, M., et al. 2014, ApJ, 793, 19
Schreiber, C., Pannella, M., Elbaz, D., et al. 2015, A&A, 575, A74
Scoville, N., Sheth, K., Aussel, H., et al. 2016, ApJ, 820, 83
Scoville, N. Z., Evans, A. S., Dinshaw, N., et al. 1998, ApJL, 492, L107
Simcoe, R. A., Burgasser, A. J., Schechter, P. L., et al. 2013, PASP, 125, 270
Smolčič, V., Novak, M., Bondi, M., et al. 2017, A&A, 602, A1
Soifer, B. T., Neugebauer, G., Matthews, K., et al. 2000, AJ, 119, 509