MCSED: A Flexible Spectral Energy Distribution Fitting Code and Its Application to $z \sim 2$ Emission-line Galaxies

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Abstract

We present MCSED, a new spectral energy distribution (SED) fitting code that mates flexible stellar evolution calculations with the Markov Chain Monte Carlo algorithms of the software package emcee. It takes broad-, intermediate-, and narrowband photometry, emission-line fluxes, and/or absorption-line spectral indices and returns probability distributions and covariance plots for all model parameters. It includes a variety of dust attenuation curves with parameters for varying the UV slopes and bump strengths, a prescription for continuum and polycyclic aromatic hydrocarbon emission from dust, models for continuum and line emission from ionized gas, options for fixed and variable stellar metallicity, and a selection of star formation rate (SFR) histories. The code is well suited for exploring parameter interdependencies in sets of galaxies with known redshifts for which there is multiband photometry and/or spectroscopy. We apply MCSED to a sample of $\sim 2000 \, 1.90 < z < 2.35$ galaxies in the five CANDELS fields that were selected via their strong [O III] $\lambda 5007$ emission, and we explore the systematic behavior of their SEDs. We find that the galaxies become redder with stellar mass due to both increasing internal attenuation and a greater population of older stars. The slope of the UV extinction curve also changes with stellar mass, and at least some galaxies exhibit an extinction excess at 2175 Å. Finally, we demonstrate that below $M < 10^8 M_\odot$, the shape of the star-forming galaxy main sequence is highly dependent on the galaxies’ assumed SFR history, as calculations that assume a constant SFR produce stellar masses that are $\sim 1$ dex smaller than those found using more realistic SFR histories.

Unified Astronomy Thesaurus concepts: Galaxy formation (595); Galaxy evolution (594); Galaxy stellar content (621); Astrophysical dust processes (99); Observational cosmology (1146)

1. Introduction

Our primary source of information for understanding the evolutionary state of a distant stellar population is its integrated light as a function of wavelength, i.e., its spectral energy distribution (SED). Indeed, a galaxy’s ultraviolet (UV) through far-infrared (far-IR) SED contains insights into its current star formation rate (SFR), past history of star formation, and present-day stellar mass, dust content, and chemistry. Consequently, much of what is known about the galaxies of the $z \gtrsim 2$ universe is based on SED fits, and numerous programs now exist to perform this analysis (e.g., Acquaviva et al. 2011; Han & Han 2014; Chevallard & Charlot 2016; Leja et al. 2017; Wilkinson et al. 2017).

The reason SED modeling is effective is that different physical processes leave their imprint on different regions of the electromagnetic spectrum. For example, estimates of the present-day SFR and dust attenuation are obtained primarily from the UV, stellar masses and metallicities are derived largely from the optical and near-IR, and dust emissivity and the reradiation of the light from young stars follows from measurements in the mid- and far-IR. Unfortunately, this decoupling is not complete, which renders the process of extracting information from a galaxy’s SED a nonlinear problem, with many local minima, covariances between parameters, and highly non-Gaussian uncertainties. (For extensive discussions of this topic, see Walcher et al. 2011 and Conroy 2013.)

One therefore must employ a numerical procedure that can handle complex behavior for large numbers of parameters.

One such method is the Markov Chain Monte Carlo (MCMC) technique, which is designed to explore all regions of a multidimensional parameter space while honing in on the highest-likelihood parts of the probability distribution function. Over the past decade, MCMC algorithms have been employed for a myriad of problems in astronomy and astrophysics, including stellar population synthesis for galaxies and active galactic nuclei (AGNs), in both the near and distant universe (i.e., Acquaviva et al. 2011; Serra et al. 2011; Leja et al. 2017).

Inspired by several recent works (e.g., Acquaviva et al. 2011; Leja et al. 2017; Carnall et al. 2018), we introduce MCSED, a modular stellar population synthesis code that takes libraries of simple stellar populations (SSPs) and mates a flexible method of creating composite populations with the MCMC fitting program emcee (Foreman-Mackey et al. 2013). The combination of these components provides an inference framework for the creation of models with parameters with well-characterized uncertainties for a galaxy’s full UV through far-IR SED. To demonstrate the capabilities of MCSED, we apply the code to the sample of 1952 optical emission-line galaxies (oELGS) identified by Bowman et al. (2019) via the luminosity of their rest-frame optical emission lines. These $1.90 < z < 2.35$ systems have vigorous ongoing star formation, with a young ($\lesssim 100$ Myr) population that far outshines the contribution of older ($\gtrsim 1$ Gyr) stars. Moreover, because these galaxies were originally identified on Hubble Space Telescope (HST) grism frames, they make an excellent test set for exploring the systematics of the types of galaxies that will be found by next-generation space-based grism surveys, such as those planned.
for Euclid and WFIRST (Maciaszek et al. 2014; Gong et al. 2016).

Section 2 briefly describes our galaxy sample and the archival photometry and spectrophotometry available for analysis. Section 3 lists the parameters used for modeling the galaxies' UV through near-IR SEDs and introduces our new SED fitting code, MCSED. Section 4 explores the basic properties of the Bowman et al. (2019) sample, the systematics of the data set, and the effect that various assumptions have on the results. Section 5 extends our analysis to the mid- and far-IR and tests the ability of MCSED to explore the balance between the sight-line attenuation of the UV stellar continua by dust and its isotropic reradiation at longer wavelengths. Finally, in Section 6, our results are placed in the context of other work at these redshifts and within the framework of simulations.

Throughout this paper, we assume a ΛCDM cosmology, with \( \Omega_L = 0.7, \quad \Omega_M = 0.3, \quad \text{and} \quad H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1} \) (Bennett et al. 2013).

2. The Sample

At present, the largest samples of \( z \gtrsim 2 \) galaxies have been constructed from broadband photometry and color selection via the use of photometric redshifts (e.g., Reddy et al. 2012; Bouwens et al. 2015; Ono et al. 2018). However, in the near future, space missions such as Euclid/NISP (Maciaszek et al. 2014) and WFIRST (Gong et al. 2016) will detect millions of emission-line galaxies via near-IR slitless grism spectroscopy. Since the selection criteria for these galaxies will differ substantially from those identified using broadband photometric techniques, we can expect the distribution of the galaxies' physical properties to differ as well.

To prepare for this era, we can study the objects found by the pathfinding 3D-HST survey, a 625 arcmin\(^2\) set of two-orbit observations taken with the Wide Field Camera 3 (WFC3) and the G141 grism on the HST (GO programs 11600, 12177, and 12328; Momcheva et al. 2016; Weiner & AGHAST Team 2014). This data set consists of \( R \sim 130 \) near-IR (1.08 \( \mu \)m < \( \lambda < 1.68 \mu \)m) slitless spectroscopy within the deep CANDELS fields of AEGIS, COSMOS, UDS, GOODS-N, and GOODS-S (Giavalisco et al. 2004; Davis et al. 2007; Lawrence et al. 2007; Scoville et al. 2007). Tens of thousands of objects are detectable on these frames, but of special interest are galaxies in the redshift range 1.90 < \( z < 2.35 \). In this window, the emission lines of [O ii] \( \lambda 3727, \quad \text{[Ne iii]} \lambda 3869, \quad \text{H}_\beta \); and, the distinctively shaped [O iii] blended doublet \( \lambda 4959, \lambda 5007 \) are simultaneously present in the bandpass. This set of observable emission lines, which includes two different ionization states of oxygen, not only enables the determination of unambiguous redshifts but also allows for the direct detection of galaxies over an extremely wide range of metallicities and ionization parameters.

Bowman et al. (2019) recently created a sample of 1952 such oELGs by vetting the list of 1.90 < \( z < 2.35 \) objects in the 3D-HST database (Momcheva et al. 2016) and removing spurious detections, line misidentifications, and known AGNs. These systems, which generally have [O iii] as their brightest feature, have sizes \( R \lesssim 5 \) kpc, [O iii] \( \lambda 5007 \) fluxes brighter than \( F \sim 4 \times 10^{-17} \text{ erg cm}^{-2} \text{ s}^{-1} \) (50% completeness limit), and rest-frame near-IR magnitudes (IRAC 3 + IRAC 4) in the range 21.8 < \( m_{IR} < 26.0 \). A full description of the demographics of this sample is given by Bowman et al. (2019).

2.1. Photometry

To define the galaxies' SEDs, we began with the SExtractor-based photometric catalog of Skelton et al. (2014). This data set starts with deep coadded F125W + F140W + F160W images from HST and then matches the data to the results of ~20 distinct ground- and space-based imaging programs. The result is a homogeneous, point-spread function (PSF)–matched set of broad- and intermediate-band flux densities covering the observed wavelength range of 0.35–8.0 \( \mu \)m over the entire region surveyed by the HST grism. The poorest wavelength coverage is in the UDS field, which has photometry through 18 different bandpasses; the best data set is in COSMOS, which has imaging through 44 separate filters, including 12 intermediate-band (\( R \sim 20 \)) filters distributed between 4250 and 8240 \( \AA \) (Skelton et al. 2014). For \( z \sim 2 \) systems, these data cover the rest-frame far-UV through the rest-frame near-IR and form a homogeneous set of measurements for galaxies with F140W magnitudes as faint as ~26 mag.

In addition to adopting the Skelton et al. (2014) measurements, we examined the Rainbow Cosmological Surveys Database (Barro et al. 2011) for photometric data in the mid- and far-IR. Formally, 93 of the GOODS-S and COSMOS galaxies in the Bowman et al. (2019) sample have detections at 24 \( \mu \)m from the Spitzer/MIPS instrument, and 57 have data at longer wavelengths (via Spitzer/MIPS and Herschel/PACS observations). However, the utility of many of these measurements is uncertain, due to their low signal-to-noise ratio (S/N) and possible confusion with superposed foreground sources. Consequently, we do not use these data in our analysis, except for a proof-of-concept study described in Section 5.

Finally, there is one additional constraint that can be applied to our SED fits: emission-line fluxes from the 3D-HST reduction of the WFC3 grism data (Momcheva et al. 2016). A significant fraction of the Bowman et al. (2019) sample has H\( \beta \) measurements (70% with S/N > 1 and 25% with S/N > 3), which can be used to constrain the galaxies' present-day SFRs (e.g., Kennicutt 1998; Kennicutt & Evans 2012). In addition, most of the systems have measurements (or limits; 70% with S/N > 1 and 20% with S/N > 3) on the excitation via the [O iii]/H\( \beta \) ratio (e.g., Kewley et al. 2001). These fluxes can be used by MCSED to better constrain the state of the galaxies’ star-forming populations.

3. SED Modeling

The SED fitting involves a considerable number of parameters. Generally speaking, these can be divided into four categories: star formation history (SFH), stellar metallicity, dust attenuation, and dust emission. We describe them in detail below.

The first category involves the galaxies’ SFH. Several studies have shown that for systems at \( z \gtrsim 2 \), constant or declining SFHs are generally inappropriate (Reddy et al. 2012; Pacifici et al. 2013; Salmon et al. 2015). More realistic approaches model the SFH rate with three or four parameters (e.g., Behroozi et al. 2013; Simha et al. 2014), use discrete SFR histories binned into physically motivated age intervals (Leja et al. 2017), or adopt a dense basis approach, where nonmonotonic and/or starbursting behavior is reproduced using semianalytic models that use cosmological simulations as a guide (Iyer & Gawiser 2017). The assumptions made about the SFH will affect the estimates of a galaxy’s stellar mass and age.
The second class of SED variable involves stellar metallicity. Broadband photometry generally provides only a weak constraint on the metal abundance(s) of a stellar population, as its effect is largely degenerate with those of other parameters, such as the system’s SFH and dust attenuation (Worthy 1994; Bell & de Jong 2001). However, if the data include high-S/N measurements of emission-line ratios and/or absorption-line indices, tighter constraints on the metallicity may be possible. Thus, depending on the goal of an investigation, metallicity may be fixed, treated as a free parameter, or tied to another property, such as stellar mass (e.g., Peng & Maiolino 2014; Ma et al. 2016).

The third type of SED variable involves the UV/optical attenuation by dust. This issue is complicated; not only do different types of galaxies have different attenuation laws (e.g., Calzetti et al. 2000; Conroy et al. 2010; Wild et al. 2011), but it is likely that the properties of the dust that affects young ($\lesssim10^7$ yr) stellar populations differ from those that attenuate older stars (e.g., Charlot & Fall 2000). As a result, the choice of attenuation law propagates into estimates of other physical quantities, such as the recent SFR, stellar metallicity, and total V-band absorption. The final category parameterizes the emission from warm and cold dust. The energy budget of many star-forming galaxies includes a significant contribution from emission in the mid- and far-IR, so these components must be included in the SED fitting process. Such models are complicated, however, as they need to include the behavior of graphites, olivine silicates, and polycyclic aromatic hydrocarbon (PAH) molecules as a function of photon, ion, and electron irradiation. Nevertheless, several prescriptions for long-wavelength emission are available in the literature, including those of Draine & Li (2007) and Jones et al. (2017).

Each of these parameter classes dominates the SED at a different set of wavelengths. Measurements in the rest-frame UV primarily carry information about dust absorption and recent star formation. In contrast, data in the rest-frame optical and near-IR constrain a galaxy’s SFH, metallicity, and stellar mass, while photometry in the mid- and far-IR reflects the emissivity of dust. It is due to this near decoupling that SED fitting can be successful, even if complete spectral coverage is not available. For example, if far-IR measurements do not exist, one can still use data in the rest-frame UV, optical, and near-IR to gain valuable insights into a galaxy’s stellar populations and dust content.

### 3.1. MCSED

As described above, a full UV through far-IR SED modeling of a galaxy may involve 10 or more parameters. One therefore requires an SED fitting program that is (1) sufficiently general to handle a diverse range of inputs, (2) powerful enough to efficiently search through a multidimensional space and obtain realistic uncertainties on each parameter, and (3) flexible enough to allow the user to easily tailor the code to a specific problem or set of observational constraints. These conditions require the program to have many of the most commonly used astrophysical relations built in and be capable of accepting a wide variety of data, such as photometric measurements through broadband and intermediate-band filters, emission-line fluxes from recombination and collisional excitation, and absorption-line spectral indices. Indeed, in the era of space missions such as Euclid and WFIRST, galaxies with both broadband photometry and emission-line spectrophotometry will be the rule, rather than the exception.

We construct MCSED to handle dust-free spectra from a library of SSPs. The code creates a composite stellar population (CSP) for a given SFR history, adds nebular emission, modifies the resulting spectrum using an assumed attenuation law, adds in mid- and far-IR emission from dust, and finally redshifts the composite spectrum to the observed distance. Since MCSED is built to be modular, users can easily change the basic fitting assumptions to suit their needs. Many of the most commonly used SED fitting prescriptions (e.g., those pertaining to the SFH or dust attenuation) are already built into the program, and additional options (such as alternative libraries for stellar and nebular emission) can be incorporated with relative ease.

The current version of MCSED includes the library of SSPs from the flexible stellar population synthesis (FSPS) code (Conroy et al. 2009; Conroy & Gunn 2010; Foreman-Mackey et al. 2014) and the prescription for nebular line and continuum emission given by the grid of CLOUDY models (Ferland et al. 1998, 2013) generated by Byler et al. (2017). One noteworthy feature of this combination of SSP and nebular models is their self-consistency; the prescription for nebular line and continuum emission as a function of age, stellar metallicity, and ionization parameter is based on the same SSP spectra that are used in FSPS. In total, these SSPs consist of a grid of 22 metallicities ($-1.98 \leq \log\left(Z/\text{Z}_\odot\right) \leq -0.20$) and 84 ages (6 $\leq \log\left(t(\text{yr})\right) \leq 10.15$), while nebular emission is modeled via a grid containing 11 metallicities ($-2.0 \leq \log\left(Z/\text{Z}_\odot\right) \leq -0.2$), seven ionization parameters ($\leq 4 < \log\left(U - 1\right) < 0.5$), and nine ages ($0.5 < \tau(\text{Myr}) < 10$).

Included in MCSED are several prescriptions for dust extinction and attenuation (e.g., Cardelli et al. 1989; Calzetti et al. 2000; Noll et al. 2009). There are options for linking the attenuation of birth clouds and the diffuse dust component via a coefficient that can be set by the user (e.g., $E(B-V)_{\text{diffuse}} = 0.44E(B-V)_{\text{b Vick}}$) or adopting separate attenuation laws for the two populations. A variety of options for SFH are also provided in this release of MCSED, including constant and exponentially increasing/decreasing SFHs, a double power-law SFH (Behroozi et al. 2013), and an SFH defined via a set of user-defined age bins.

Dust emission is included using the parameterization of Draine & Li (2007) and Draine et al. (2007). This formulation is defined by the lower cutoff of the starlight intensity distribution ($U_{\text{min}}$), the fraction of dust heated by starlight with $U > U_{\text{min}}$ ($\gamma$), and the PAH mass fraction ($\alpha_{\text{PAH}}$). The total dust mass ($M_{\text{dust}}$) can be either treated as a free parameter to be fit via the normalization of the dust emission or constrained via the energy balance of attenuation. While the Draine & Li (2007) models are based on Milky Way dust, they have been successfully applied to high-redshift objects (Utomo et al. 2014).

For a given set of SED parameters, MCSED begins by constructing a set of CSPs from a linear combination of SSPs defined by the SFH. Following Mitchell et al. (2013), MCSED minimizes biases in stellar mass and other inferred quantities by avoiding the use of a single metallicity for this initial grid and instead introduces a small spread in abundance defined by a Gaussian kernel with dispersion $\sigma = 0.15\log\left(Z/\text{Z}_\odot\right)$ centered on the SED input metallicity. After creating the CSP, MCSED attenuates its spectrum, adds dust emission, redshifts the model to the observers’ frame, and compares the result to the list of observational constraints, which can include
photometry, emission-line fluxes, and absorption-line spectral indices. Because some emission lines, such as those produced by collisional excitation, are more difficult to model than others, the relative contribution of these lines to the overall likelihood can be adjusted by the user.

To perform the multidimensional parameter search, MCSED uses the Python package emcee (Foreman-Mackey et al. 2013), an MCMC algorithm that employs an affine-invariant ensemble sampler (Goodman & Weare 2010). Such an approach is insensitive to covariances in the fitted parameters and is thus well suited for efficiently exploring the high dimensionality and oddly shaped likelihood distributions that often occur in SED fitting. In addition, emcee generally requires no manual input or running period to tune the proposal distributions, as is common in Metropolis–Hastings MCMC algorithms. As emcee is written in Python, it nicely fits into the collection of Python packages used here.

As describe above, the many runtime options built into MCSED allow the user to select from a wide variety of SFHs and dust attenuation curves or implement their own parameterizations for these variables. Configuration options are also available for the inclusion of new photometric filters and SSP models. Finally, MCSED features a test mode, where the user can create and “observe” model galaxies and compare their inferred parameters to the input “truth.” Details about MCSED are given in Appendix A. Appendix B uses MCSED’s test mode to evaluate the precision of recovering input parameters.

An example of MCSED’s output is shown in Figure 1. Displayed are the probability distributions for a typical \( z \sim 2 \) emission-line galaxy, along with covariance plots, fitted SFR histories and attenuation curves, best-fit SEDs, and modeled and observed filter fluxes and emission-line strengths. The example shown uses a simplified set of fitting assumptions, i.e., a constant SFR, a Calzetti et al. (2000) dust attenuation law, a

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**Figure 1.** Diagnostic figure for a \( z = 2.14 \) emission-line galaxy (GOODS-S 43481), including the parameter covariances and marginalized probability distributions for the history of star formation, the dust attenuation curve, and the best-fit SED. This example adopts a simplified set of fitting assumptions, including a constant SFH, a Calzetti et al. (2000) attenuation law, and a fixed stellar metallicity of 40\% solar. The rightmost panel of each row displays the likelihood histogram for the captioned variable, with the most likely value (and its 1\( \sigma \) confidence interval) denoted by dashed lines. The three panels in the top right corner show randomly drawn realizations of the posterior distributions.
Attenuation of the diffuse component

Table 1
Free and Fixed Model Parameters

| Parameter | Description | Priors         |
|-----------|-------------|----------------|
| SFH       |             |                |
| sfr1      | log(SFR) [M$_\odot$ yr$^{-1}$] in the range 6.0 $\leq \log t$(yr) $< 8.0$ | $[-5, 3]$ (Uniform) |
| sfr2      | log(SFR) [M$_\odot$ yr$^{-1}$] in the range 8.0 $\leq \log t$(yr) $< 8.5$ | $[-5, 3]$ (Uniform) |
| sfr3      | log(SFR) [M$_\odot$ yr$^{-1}$] in the range 8.5 $\leq \log t$(yr) $< 9.0$ | $[-5, 3]$ (Uniform) |
| sfr4      | log(SFR) [M$_\odot$ yr$^{-1}$] in the range 9.0 $\leq \log t$(yr) $< 9.3$ | $[-5, 3]$ (Uniform) |
| $\delta$  | UV slope    | $[-1, 1]$ (Uniform) |
| $E_B$     | Depth of 2175 Å feature | $[-0.2, 6.0]$ (Uniform) |
| $E(B-V)$  | Total attenuation | $[-0.05, 1.50]$ (Uniform) |
| $E(B-V)_{\text{diffuse}}$ | Attenuation of the diffuse component (relative to the birth cloud) | 0.44 (Fixed) |
| $t_{\text{birth}}$ | Age separating the birth cloud and diffuse components | 10 Myr (Fixed) |
| log($Z_{\text{stars}}/Z_\odot$) | Metallicity | $[-1.98, 0.20]$ (Uniform) |
| $U_{\text{min}}$ | Lower cutoff of the starlight intensity distribution | 2.0 (Fixed) |
| $\gamma$  | Fraction of dust heated by starlight with $U > U_{\text{min}}$ | 0.05 (Fixed) |
| $q_{\text{PAH}}$ | PAH mass fraction | 2.5 (Fixed) |
| $Z_{\text{gas}}$ | Log ionization parameter | $-2$ (Fixed) |
| $w(\lambda 3727)$ | Weight of [O II] $\lambda\lambda 3727, 3729$ doublet | 0.5 (Fixed) |
| $w(\lambda 3727)$ | Weight of H$\beta$ line flux | 1.0 (Fixed) |
| $w(\lambda 5007)$ | Weight of [O III] $\lambda 5007$ line | 0.5 (Fixed) |

fixed stellar metallicity of $Z = 0.0077$ (40% solar), a fixed nebular ionization parameter of $\log U = -2$, and a fixed Draine & Li (2007) dust emission model with $U_{\text{min}} = 2.0$, $\gamma = 0.05$, and $q_{\text{PAH}} = 2.5$. One can easily reconfigure MCSED to accommodate a more realistic set of fitting assumptions. In addition to the diagnostic plot shown in Figure 1, many other MCSED outputs are available on demand, including a summary table of the best-fit model parameters and (user-defined) confidence intervals, the full posterior probability distributions of the model parameters, modeled and observed filter and emission-line fluxes, the best-fit SED, and a log file detailing the full set of parameters and fitting assumptions that were adopted for the run.

4. Fitting Emission-line Galaxies from 3D-HST

As described in Section 2.1, all of the galaxies in the five CANDELS fields have comprehensive multiwavelength photometry that extends from the atmospheric cutoff near 3500 Å to the Spitzer/IRAC 3.6, 4.5, 5.8, and 7.9 μm bands (Skelton et al. 2014). In the Bowman et al. (2019) redshift window of $1.9 < z < 2.35$, there are also measured fluxes (or limits) for the strong emission lines within the spectral range $\sim 3700$ to $\sim 5100$ Å from the WFC G141 grism spectroscopy of the 3D-HST team (Momcheva et al. 2016). These grism data provide an important constraint for fitting the galaxies’ SEDs, as the relative strengths of [O III] $\lambda\lambda 4959, 5007$, [O II] $\lambda\lambda 3727$, and H$\beta$ reflect the metallicity of the galaxy’s interstellar medium (ISM) and, implicitly, the metallicity of the latest generation of stars. At the same time, the absolute strengths of these emission lines indicate the amount of star formation currently taking place in the galaxy ($t < 10^7$ yr). What the Bowman et al. (2019) sample lacks is information in the mid- and far-IR; only $\sim 15\%$ of the galaxies have measurements with the Spitzer/MIPS detector at 24 μm (rest-frame wavelength near 8 μm), and just 143 objects (7%) have data at longer wavelengths. Thus, we start our analysis by reducing the dimensionality of the problem by fixing the dust emissivity variables to $U_{\text{min}} = 2.0$, $\gamma = 0.05$, $q_{\text{PAH}} = 2.5$, and $M_{\text{dust}} = 10^7 M_\odot$. We will return to this point when we examine the SEDs of two galaxies that have reliable longer-wavelength data.
4.1. Fitting Assumptions

As discussed by Walcher et al. (2011), Conroy (2013), and references therein, the physical properties one obtains from SED fitting depend in a nontrivial manner on the fitting assumptions one uses in the analysis. Moreover, these trends may change from population to population, as the systematics one obtains for relatively quiescent galaxies may be substantially different from those of starburst galaxies. Because of this behavior, it is useful

![Figure 3. The MCSED solutions for (left to right) the current SFR, differential reddening, and stellar mass for the Bowman et al. (2019) sample of $z \sim 2$ emission-line galaxies. Top row: comparison of the results for fixed metallicity ($x$-axis) with measurements where the system metallicity is left as a free parameter, while assuming a constant SFH and a Calzetti et al. (2000) attenuation law. Middle row: comparison of the results for a constant SFR ($x$-axis) with the four age bin SFH ($y$-axis), while assuming a Calzetti et al. (2000) attenuation law and leaving stellar metallicity as a free parameter. Bottom row: comparison of the results based on the Calzetti et al. (2000) attenuation law ($x$-axis) with those based on the Noll et al. (2009) law ($y$-axis), while adopting a constant SFH and leaving stellar metallicity as a free parameter.](image-url)
to explore the effect that each of our underlying assumptions has on the derived properties of moderate-redshift ($z \sim 2$) emission-line galaxies, as many millions of such objects will be identified by upcoming missions such as Euclid and WFIRST.

While many studies have demonstrated that simplified fitting assumptions (e.g., a constant SFH, a fixed stellar metallicity, and a Calzetti et al. (2000) attenuation law) overconstrain galaxy properties across a range of redshifts and galaxy types (e.g., Reddy et al. 2012; Pacifici et al. 2013; Salmon et al. 2015), the “optimal” set of fitting assumptions for $z \sim 2$ emission-line galaxies remains an open question. Fortunately, the wealth of data available in the CANDELS fields allows a relaxation of these assumptions. Our baseline analysis begins by dividing the galaxies’ SFH histories into four bins with log ages (in years) in the ranges [6.0–8.0], [8.0–8.5], [8.5–9.0], and [9.0–9.3], with a constant SFR within each bin. As noted by Conroy (2013) and Leja et al. (2017), fits with parameterized forms of the SFH may be susceptible to poorly quantified systematic uncertainties. We adopt the Noll et al. (2009) formulation for dust attenuation internal to the galaxies, allow stellar metallicity to be a free parameter, and, motivated by the high $\text{[O III]}/\text{[O II]}$ and $\text{[O III]}/\lambda\beta$ ratios present in the Bowman et al. (2019) sample, set the ambient ionization parameter to $\log U = -2$. This procedure leaves eight unknowns: one for each age bin of the SFH, three for attenuation (the slope of the UV wavelength dependence, the strength of the 2175 Å bump, and the total amount of extinction, which we parameterize via $E(B-V)$), and one for stellar metallicity. We adopt a coefficient (0.44 mag; Calzetti et al. 2000) to link the total attenuation of young stars still enshrouded in their birth clouds ($t \lesssim 10^7$ yr) to that affecting older stars. A list of the eight free parameters and their priors is given in Table 1, along with several values that are held fixed throughout the fitting. Sample SSP spectra, which contribute to each age bin in our SFH, are presented in Figure 2.

### 4.2. The Effects of Assumptions on MCSED Results

Before analyzing the global properties of our galaxy sample, we investigate how the parameterizations listed above affect the best-fit solutions found by MCSED. This issue can be examined by modifying our assumptions and, one by one, seeing what effect each has on the inferred properties of the galaxies. The results of this exercise are shown in Figure 3, where three fundamental outputs of MCSED are compared: the current SFR, the total dust attenuation as parameterized by $E(B-V)$, and the total stellar mass. The three rows each vary one fitting assumption (stellar metallicity, SFH, and dust attenuation law in the top, middle, and bottom rows, respectively) while holding the other two assumptions fixed. The top row compares parameter estimates inferred for fits with fixed metallicity at $Z = 0.0077$ (x-axis) to those where metallicity is kept as a free parameter (y-axis), while assuming a constant SFH and a Calzetti et al. (2000) attenuation law. In the middle row, where metallicity is left as a free parameter, we adopt a Calzetti et al. (2000) attenuation law and compare the results for a constant SFH history (x-axis) with the four age bin SFH (y-axis). Finally, the bottom row leaves metallicity as a free parameter, assumes a constant SFH, and compares the results from the Calzetti et al. (2000) attenuation law (x-axis) to those from the more general Noll et al. (2009) formulation (y-axis). Histograms and differential diagrams of these comparisons are presented in Figure 4.

Figure 3 displays how the inferred SFR, dust attenuation, and stellar mass depend upon the SED fitting assumptions. While there are systematics and biases between the parameter estimates (discussed in more detail below), an examination of the figure demonstrates that the properties derived by MCSED
for our sample of vigorously star-forming galaxies are, broadly speaking, consistent across the various assumptions about SFH, attenuation law, and stellar metallicity. The exact value of the best-fit recent SFR does depend on the systems’ assumed SFR history (Figure 3, middle row) and (to a lesser extent) metallicity (Figure 3, top row), but these systematics are generally small. Interestingly, the choice of attenuation law does not cause a significant systematic shift in the SFR estimates, and the internal uncertainties in the measurements, as estimated by a series of resampling experiments with each point perturbed by its measurement error, are consistent with the panel’s observed scatter about the 1:1 relation at the 90% confidence level.

Figure 3 also demonstrates that, while our assumptions about stellar metallicity have little effect on our conclusions, the best-fit $E(B-V)$ value does depend upon what one chooses for the SFR history and attenuation law (middle and bottom rows of Figure 3). This systematic is not due to incorrect fitting by MCSED (see Appendix B) and is expected, as the Noll et al. (2009) expression contains a parameter, $\delta$, that changes the wavelength dependence of the relation. For $z \sim 2$ galaxies, the bulk of the photometric measurements are in the rest-frame UV, so the added flexibility provided by $\delta$ propagates into a change in the optical reddening. The dependence of $E(B-V)$ on SFH is less straightforward but still apparent; more realistic SFHs with four age bins produce slightly lower values of

![Figure 5](image-url)
$E(B - V)$, independent of which attenuation law is used. For $\sim$90% of the galaxies, however, the reddening parameter is consistent to $D_E < 0.1$ (Figure 4(a)).

Perhaps the most interesting dependence shown in Figure 3 is that for stellar mass. Not surprisingly, the stellar mass estimates have little dependence on attenuation (Figure 3, bottom row), as the former is mostly derived from the near-IR, while the latter’s effect is predominantly in the UV. Similarly, system metallicity has a relatively minor effect on stellar mass, especially for systems with $M \gtrsim 10^9$ $M_\odot$, although there are obvious systematics for a subset of the objects (Figure 3, top row). However, at lower masses, the assumption of a constant SFR produces mass estimates that are up to $\sim$1 dex lower than those derived using the four age bin SFH. Clearly, the oversimplified assumption of a constant SFH can result in strong systematic shifts in low-mass galaxies. A similar result appears when using a constant SFH and varying the systems’ ionization parameter.

Both sets of fitting assumptions yield a similar quality of fits to the data (with similar $\chi^2$ values). However, the diagnostic summary for one of the galaxies shown in Figure 5 illustrates the unavoidable difficulty associated with estimating some aspects of $z \sim 2$ oELGs. In this example, the recent SFR ($t < 100$ Myr), $E(B - V)$, and stellar mass are fairly well constrained, as they are closely linked to the available data. (The emission-line fluxes and the wealth of rest-frame UV photometry strongly constrain the recent SFR and $E(B - V)$, while the rich data set at rest-frame wavelengths $\lambda \gtrsim 6000$ Å define the stellar mass.) Other properties, such as the distant-past SFR and the strength of the 2175 Å extinction bump, are, at best, weakly constrained.

4.3. The Physical Properties of oELGs

Our flexible fitting assumptions are next used to explore the variation of the dust attenuation curve, the SFR history, and the behavior of the SED across nearly 3 orders of magnitude in stellar mass. We divide our galaxy sample into four stellar mass bins (each containing $\gtrsim 200$ objects), with bin 1 having $\log M/M_\odot \lesssim 9.0$, bin 2 having $9.0 < \log M/M_\odot \lesssim 9.5$, bin 3 having $9.5 < \log M/M_\odot < 10.0$, and bin 4 having

Figure 6. Average spectrum, dust attenuation curve, and SFR history of $z \sim 2$ emission-line galaxies spanning nearly 3 orders of magnitude in stellar mass. As stellar mass increases, the energy budget shifts toward longer wavelengths, due to an increase in the overall dust content and a higher distant-past SFR.
dependence of attenuation can vary from galaxy to galaxy. For each bin, a representative spectrum is computed by finding the best-fitting SED of each galaxy and taking the mean of the distribution. Similarly, we calculated the dust-corrected, normalized SED of each bin by dereddening each galaxy (using its best-fitting attenuation parameters), normalizing its spectrum to the flux at 4500 Å, and taking the bi-weight of the distribution. Finally, to compute representative attenuation curves and SFHs, we stacked all of the parameter estimates from each realization of the posterior distribution of each galaxy in the bin and computed the bi-weight of the distribution. The 1σ uncertainties (and 90% confidence intervals) were found by bootstrapping these data. Figure 6 displays the results of this analysis.

It is obvious from Figure 6(a) that the SEDs of \( z \sim 2 \) emission-line galaxies vary systematically with mass; as the stellar mass increases, the galactic emission is shifted toward longer wavelengths. This unsurprising result can be explained by two effects: an increase in the amount of attenuation due to dust and a rise in the contribution of older, redder stars. The former effect is demonstrated in Figure 6(b), which displays the dust attenuation curves computed from the bi-weight of the Noll et al. (2009) parameters. This figure reveals that galaxies with stellar masses greater than \( \sim 10^{10} M_\odot \) have a magnitude more near-UV attenuation than lower-mass (\( M \lesssim 10^9 M_\odot \)) systems. Dereddening the best-fit spectra prior to stacking (using the best-fit attenuation law parameters for each galaxy) produces Figure 6(c), which presents the dust-free and flux-normalized version of the stacked SEDs. This panel illustrates the different mix of stellar populations, with higher-mass galaxies having a relatively larger amount of flux in the near-IR. Figure 6(d) confirms this result by showing the SFRs inferred for each of the four age bins; the highest stellar mass galaxies have relatively larger SFRs at older look-back times.

Beyond the increase in total dust content with higher stellar mass, several studies have shown that the wavelength dependence of attenuation can vary from galaxy to galaxy. We address this through use of the Noll et al. (2009) law, which contains three parameters: \( \delta \), which is the grayness/tilt of the wavelength dependence of attenuation relative to the Calzetti et al. (2000) law; \( E_b \), which represents the \( \sim 350 \) Å FWHM “bump” of excess attenuation at 2175 Å; and the total amount of extinction, parameterized by \( E(B - V) \). The mass-dependent trends shown in Figure 6(b) are primarily due to an increase in \( E(B - V) \), but we can also use our SED analysis to test for variations in \( \delta \) and \( E_b \).

In the AEGIS, UDS, and GOODS-N fields, the tests discussed in Appendix B demonstrate that \( \text{MCSED} \) can recover \( \delta \) to a precision of \( \sigma \lesssim 0.15 \). In COSMOS and GOODS-S, the results are even better; in these fields, the extensive photometric coverage in the rest frame enables \( \delta \) to be measured to \( \sigma \lesssim 0.11 \). Figure 7 places this smaller dispersion in context by comparing it to the observed distribution of \( \delta \) values. Clearly, the spread in \( \delta \) for the galaxies in the COSMOS and GOODS-S fields is broader than would be expected solely from measurement error, implying a physical variation in the intrinsic slope of the attenuation curve. Figure 8(a) shows the full probability distributions for \( \delta \) across the four stellar mass bins. While several studies have found that the slope of the attenuation curve changes with stellar mass (Buat et al. 2012; Kriek & Conroy 2013; Zeimann et al. 2015), the probability distributions for our fits do not show a significant correlation between the two properties.

Our \( \text{MCSED} \) analysis also suggests that the 2175 Å extinction bump may be present in the SEDs of \( z \sim 2 \) star-forming galaxies. Using the dust models of Silva et al. (1998), Granato et al. (2000) demonstrated that in local systems dominated by young stars, no 2175 Å bump is visible. Conversely, in more “normal” star-forming galaxies, where a significant fraction of UV photons are emitted by stars outside their birth clouds, an extinction bump is present. Hence, the Calzetti et al. (1994) observations of local starburst galaxies provide no evidence of a 2175 Å extinction feature, while observations of less extreme systems (e.g., Burgarella et al. 2005; Conroy et al. 2010; Hoversten et al. 2011; Battisti et al. 2017) exhibit the feature.

The 2175 Å bump has been reliably measured in the stacked spectra of high-\( z \) star-forming galaxies (e.g., Kriek & Conroy 2013; Zeimann et al. 2015). However, in contrast to \( \delta \), our SED analysis is not particularly sensitive to \( E_b \) (see Appendix B), and for individual galaxies, the bump is virtually undetectable. Figure 8(b) shows the probability distributions of \( E_b \) for the four stellar mass bins and demonstrates the difficulty in constraining the strength of the dust bump.

The main reason for the poor constraints on the 2175 Å bump is the nature of the photometric data being analyzed. Most of the filters used to survey the CANDELS fields have bandpasses that are significantly broader than the 350 Å width of the extinction feature. Unless high-S/N observations are taken through an intermediate bandpass filter centered near the 2175 Å rest frame and two bracketing filters, an accurate measurement of \( E_b \) is nearly impossible.

4.4. Spectrophotometric SED Fitting

Using \( \text{MCSED} \) allows us to explore the degree to which our SED fits and parameter estimates are improved by including emission-line fluxes as input data. It is well known that emission lines can provide information about a galaxy’s current SFR, metallicity, and warm ISM (density, pressure, and ionization parameter) that photometric measurements are unable to access (e.g., Xiao et al. 2018; Kewley et al. 2019). Moreover, Euclid (Maciaszek et al. 2014) and WFIRST (Gong et al. 2016) will soon make the availability of such data commonplace, providing a new resource for understanding the properties of star-forming
galaxies at high-$z$. The question is, how much do the bright emission lines of [O III] $\lambda\lambda 5007, 5007$, [O II] $\lambda\lambda 3727$, and H$\beta$ improve our ability to recover information about the physical properties of these galaxies? In what follows, nebular emission (both continuum and line emission) is included in all of our SED fits; the difference is only whether the observed emission-line fluxes (courtesy of 3D-HST; Momcheva et al. 2016) are employed to constrain the models.

Emission lines are handled by MCSED in an analogous way to photometry. Input line fluxes are compared to the predictions of a grid of CLOUDY models, and the resultant $\chi^2$ term contributes to the goodness of fit of the SED. Because some emission lines are more difficult to model than others, MCSED allows users to weight each line’s contribution. In our case, we weight the H$\beta$ line measurement equal to a photometric measurement and give half-weight to the strengths of the collisionally excited [O II] and [O III], since such features depend as much on the physical conditions of the ISM as they do on the ionization flux of bright stars (e.g., Kewley & Dopita 2002; Shapley et al. 2015). Although the precise weights given to these emission lines have minimal impact on the overall results, this particular weighting scheme typically produces better $\chi^2$ values than other formulations.

Before investigating the impact that emission lines have on our fits, we first compare our model SEDs and line strengths to observations from the 3D-HST survey (Momcheva et al. 2016). Figure 9 shows several examples of this comparison, and Figure 10 plots the modeled fluxes against the observed values.

Both figures demonstrate that the modeled strength of H$\beta$ agrees very well with the flux estimates from 3D-HST. Given the relative insensitivity of the hydrogen recombination lines to the physical conditions of the ISM (e.g., Osterbrock & Ferland 2006), this agreement is not surprising. In contrast, the collisionally excited [O II] and [O III] lines are consistently underpredicted by our models, and to compensate for this underprediction, the surrounding stellar continuum is slightly overpredicted. As a result, the modeled and observed fluxes integrated over the 3D-HST spectral range are in good agreement (typically within 10%–20%; see Figure 11) and do not exhibit any obvious systematic behavior.

The primary reason that our SED fits consistently underpredict [O III] $\lambda\lambda 4959, 5007$ to H$\beta$ as a function of metallicity and ionization parameter. None of the models have [O III]/H$\beta$ ratios greater than 6. Yet, as is evident from Figure 12(b), the typical [O III]/H$\beta$ ratio seen in our sample of $z \sim$ 2 emission-line galaxies is $\sim$4, and the distribution exhibits an extended tail toward more elevated ratios. This is not a new result: high [O III]/H$\beta$ ratios have been widely observed in the $z \gtrsim$ 1 universe (e.g., Maseda et al. 2014; Steidel et al. 2014; Dickey et al. 2016), but the reason behind the phenomenon has yet to be fully understood (see Kewley et al. 2019, and references therein).

As noted by Byler et al. (2017), other combinations of ionizing spectra and photoionization codes, such as those presented in Dopita et al. (2013) using STARBURST99 (Leitherer & Heckman 1995) and MAPPINGS III (Sutherland & Dopita 1993), can produce [O III]/H$\beta$ ratios that more closely resemble our sample. Similarly, population synthesis models that include binary evolution (i.e., BPASS; Eldridge et al. 2008) have also proven successful at reproducing elevated [O III]/H$\beta$ line ratios (Stanway et al. 2014). Nevertheless, the Byler et al. (2017) grid of CLOUDY models does have the advantage of self-consistency, as it employs the same FSPS SEDs that we use to model the galaxies’ broadband colors. Thus, in what follows, we use the Byler et al. (2017) grid, accepting that their collisionally excited line fluxes are systematically smaller than the observed values.\footnote{We note that AGNs are known to play a role in creating [O III]-to-H$\beta$ ratios (e.g., Baldwin et al. 1981; Shapley et al. 2015), and, as currently configured, MCSED does not model this emission. However, Bowman et al. (2019) already removed the vast majority of AGNs from the sample and, based on the exceedingly deep X-ray data of the Chandra Deep Field South, estimated the fraction of low-luminosity AGNs to be no more than $\sim$5%. Hence, this source of emission should not affect our line ratios.}

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**Figure 8.** The KDE curves for the full posterior distributions of $\delta$ (left) and $E_b$ (right) across the four stellar mass bins. We find no significant correlation between the slope of the attenuation curve and stellar mass; the narrowing of the distributions toward higher mass is likely due to higher S/N in the photometry and an increase in the overall dust content, both of which allow for a more precise estimate of the dust law parameters. The probability distributions for $E_b$ are much broader and exhibit a similar increasing precision toward higher masses. The low-mass bin just reflects the prior on the parameter, while the higher-mass bins show increasing sensitivity to the variable.
Our rest-frame optical emission-line measurements primarily constrain three physical properties. The first, the ISM’s ionization parameter, is implicitly taken into account by our choice of assumptions. As noted above, the nebular models cannot reproduce the elevated line ratios that are ubiquitous in the high-redshift universe. Nonetheless, as Figure 12(a) illustrates, the high value of ionization parameter that we adopt here ($\log U = -2$) does a reasonable job of fitting the high-excitation line ratios that are exhibited by our sample.

The second property constrained by our emission-line measurements is star formation. All three of our fitted emission lines provide some indication of the flux of ionizing photons currently being produced within a galaxy, and this quantity is directly tied to the very recent ($t \lesssim 10$ Myr) rate of star formation (e.g., Kennicutt 1998; Kennicutt & Evans 2012). However, each line has its drawbacks. The Hβ is most directly tied to star formation, since for Case B recombination, Balmer-line fluxes directly measure the photoionization rate. However, in the majority of our $z \sim 2$ galaxies, Hβ is only marginally detected ($\sim 60\%$ have an S/N less than 2), and, at a rest-frame wavelength of 4861 Å, the effects of attenuation cannot be ignored. Alternatively, one can translate the collisionally excited oxygen lines into an SFR estimate. However, in both the local (Moustakas et al. 2006) and distant (Teplitz et al. 2000) universe, the scatter between $[\text{O III}]$ and Balmer-line based SFRs is more than a factor of 2, and, although $[\text{O II}] \lambda 3727$ is often used as a

Figure 9. Comparison of the modeled SEDs (red) to the observed spectra (gray) for eight emission-line galaxies in the 3D-HST survey. The Hβ line fluxes are generally well modeled, while the collisionally excited oxygen lines are typically underpredicted. (The $[\text{O III}]$ fluxes printed on the panels refer to the $\lambda 5007$ line alone.) The integrated fluxes within the 3D-HST bandpass are generally consistent to within $\sim 20\%$. 

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from the stellar continuum. Nevertheless, when taken together, these lines do provide a redshift and are sensitive to the effects of both metallicity and Kennicutt & Evans. The solid integrated collisionally excited oxygen lines are systematically underpredicted. The solid (dotted) red line shows the scatter about the 1:1 relation within the 68% (95%) confidence interval that is expected solely from uncertainties in the line flux measurements. Objects with larger internal reddening are more susceptible to offsets in the modeled vs. measured line fluxes, but that is not the only (or dominant) effect contributing to the discrepancy.

Figure 10. Comparison of the modeled and observed line fluxes for [O II] λ3727, Hβ, and [O III] λ5007. The Hβ shows excellent agreement, while the strengths of the collisionally excited oxygen lines are systematically underpredicted. The solid (dotted) red line shows the scatter about the 1:1 relation within the 68% (95%) confidence interval that is expected solely from uncertainties in the line flux measurements. Objects with larger internal reddening are more susceptible to offsets in the modeled vs. measured line fluxes, but that is not the only (or dominant) effect contributing to the discrepancy.

Figure 11. Comparison of the modeled and observed fluxes integrated over the 3D-HST spectral range (1.08 μm < λ < 1.68 μm). The fractional change in the integrated flux is calculated as the difference between the modeled (B9CSED) and observed (3D-HST) flux, normalized by the observed flux. The systematic underprediction of the [O II] and [O III] emission-line fluxes is compensated for by a mild overestimate of the surrounding continuum. This brings the integrated fluxes predicted by the models into good agreement with the photometry.

local SFR indicator (Kewley et al. 2004; Moustakas et al. 2006; Kennicutt & Evans 2012), the line is generally weak at high redshift and is sensitive to the effects of both metallicity and dust. Nevertheless, when taken together, these lines do provide a measure of the recent SFR that complements that based on light from the stellar continuum.

Figures 13(a) and 14(a) demonstrate this agreement by showing how the posterior probability distributions are narrower when well-measured emission lines are included as inputs to the fits. By extension, the inclusion of emission lines also helps to constrain E(B − V) (Figures 13(b) and 14(b)), as they help break the strong degeneracy between star formation and dust attenuation (see Figure 5). The largest improvement is exhibited in systems where the emission lines have the highest S/Ns.

The third galaxy property improved by the inclusion of emission lines is metallicity. While measurements of absorption-line indices can constrain the metal abundance of a stellar population (e.g., Worthey 1994; Maraston & Strömbäck 2011), none of these features are strong enough to be detected via grism spectroscopy or broadband photometry. In contrast, emission-line ratios can provide strong constraints on the metal abundance of a galaxy’s ISM, and, by extension, its current generation of stars. Figures 13(c) and 14(c) demonstrate this effect. When emission-line fluxes are not included as inputs to the fits, the metallicity posterior probability distributions are extremely broad. In contrast, when emission lines are included (and well measured), these same distributions are strikingly narrow. Interestingly, the inclusion of emission lines in the χ² fits does not significantly affect where the peak of the distribution lies, suggesting that the use of broadband and intermediate-band photometry alone can do a reasonable job of estimating mean metallicity. This behavior may be unique to galaxy samples with strong emission lines (e.g., in the case of our z ∼ 2 sample, line fluxes can contribute up to ~50% of the total flux in a given filter) where the broadband photometry implicitly contains useful information about emission-line strengths. Nonetheless, including emission-line fluxes in the χ² calculation significantly improves the metallicity measurement.

5. Fitting Galaxies in the Mid- and Far-IR

Mid- and far-IR dust emission in starbursting galaxies arises from the reradiation of the UV stellar continuum and thus can trace dust attenuation. Observationally speaking, however, this principle of energy balance may not always hold: while the IR emission from dust is roughly isotropic, an attenuation measurement is valid only for a specific line of sight (e.g., Hayward & Smith 2015). This situation complicates any analysis that relies upon a galaxy’s IRX, i.e., the IR-to-UV flux ratio (see da Cunha et al. 2008). Furthermore, since the only observables of a galaxy at z > 4 may be the UV luminosity and spectral slope (e.g., Bouwens et al. 2009; Finkelstein et al. 2015), it is
important to understand how well energy conservation and dust attenuation can predict the IR luminosity of high-$z$ galaxies. The Bowman et al. (2019) galaxy sample is not ideal for answering this question. At $z \sim 2$, these systems are generally too faint to have Herschel/PACS and SPIRE far-IR measurements, and, even in the mid-IR, reliable photometric measurements are difficult, due to the blending of nearby sources induced by the large instrumental PSFs at these long wavelengths. Nevertheless,

The Bowman et al. (2019) galaxy sample is not ideal for answering this question. At $z \sim 2$, these systems are generally too faint to have Herschel/PACS and SPIRE far-IR measurements, and, even in the mid-IR, reliable photometric measurements are difficult, due to the blending of nearby sources induced by the large instrumental PSFs at these long wavelengths. Nevertheless,
we can explore the capabilities of MCSED by analyzing one galaxy whose photometry appears to be reliable. We used the CANDELS images and data products of Barro et al. (2019) to select a galaxy whose mid- and far-IR photometry appears to be relatively unaffected by blending issues and image confusion. We then ran MCSED twice, only changing the treatment of dust mass. For our first run, the dust mass was treated as a free parameter that set the normalization of the dust emission; for the second calculation, we assumed that all of the energy attenuated by dust was reradiated in the IR (i.e., using the energy balance argument).

The results of this experiment are shown in Figure 15. For the galaxy AEGIS-31956, the best-fit SED using the energy balance argument is essentially identical to that generated when the long-wavelength part of the SED is fit independently of the far-UV. As the SEDs illustrate, for this $z \sim 2$ galaxy, there are few photometric measurements in the mid- and far-IR, and those data that do exist have large uncertainties. To take advantage of MCSED’s long-wavelength capability, one must target lower-redshift objects with better MIPS and PACs photometry that reach the peak of the IR emission.

6. Discussion

We have presented MCSED, a new SED fitting code designed to model rest-frame UV through IR galaxy spectra. The code is built for both efficiency and flexibility; the former is made possible by MCMC algorithms in the Python package emcee (Foreman-Mackey et al. 2013), while the latter is achieved using several easily adjustable prescriptions for dust attenuation, SFR history, stellar metallicity, and dust emission. The code accepts a range of observational constraints, including photometry, emission-line fluxes, and absorption-line spectral indices, and is suitable for a wide range of galaxy types and redshifts.

We tested our code on a sample of $z \sim 2$ emission-line galaxies identified by Bowman et al. (2019) from HST grism data of the CANDELS fields. These galaxies, which span over 3 orders of magnitude in stellar mass ($M > 10^9 M_\odot$), can be characterized as having low dust content and active star formation and enable crucial pathfinding studies for upcoming large-scale surveys. In particular, missions such as Euclid and WFIRST will soon make such systems the dominant population of known $z > 1$ galaxies.

The CANDELS fields, with their extensive set of observational data, are the perfect locations for investigating the physical...
properties of $z \sim 2$ emission-line galaxies and exploring systematic errors induced by fitting assumptions. In this analysis, we adopted a flexible framework for our investigation, including a four age bin SFR history and a three-parameter model for dust attenuation (Noll et al. 2009). We confirm that our estimates for stellar mass, recent SFR, and dust content are all generally consistent with the simplified fitting assumptions that appear widely in the literature. However, our investigation also suggests that biases can be introduced when using simplified assumptions; in particular, the use of a constant SFR history tends to underestimate stellar masses for systems with $M \lesssim 10^9 M_\odot$. Figure 16 shows the stellar mass–SFR relation using UV-based SFRs (estimated in Bowman et al. 2019) and the updated stellar mass estimates provided by the more flexible fitting assumptions. Furthermore, there is compelling evidence to suggest that variations exist in the dust attenuation curve, even within our relatively homogeneous set of $z \sim 2$ emission-line galaxies. Clearly, caution should be exercised when applying a single set of assumptions to sets of galaxies with a wide range of types and redshifts.

Because most of our $z \sim 2$ emission-line galaxies are quite faint, measurements of the physical properties of individual systems typically carry large uncertainties. To circumvent this issue, we exploited the size of our sample ($\sim 2000$ galaxies) to estimate the galaxies’ mean properties as a function of stellar mass. We divided the sample into four stellar mass bins spanning $\sim 3$ dex ($10^8 \lesssim M/M_\odot \lesssim 10^{11}$) and computed the galaxies’ mean UV through IR spectra, SFR histories, and dust attenuation curves. Our emission-line galaxies exhibit a systematic shift in their SEDs, with the energy moving toward longer wavelengths with increasing stellar mass. This behavior is due to both an overall increase in the dust content of the galaxies and the greater importance of older stars. There is evidence that the shape of the attenuation curve (namely, the intrinsic grayness of the curve and the strength of the 2175 Å bump) varies across the sample, though specific trends with stellar mass are marginal at best. Nonetheless, it is clear that a universal attenuation law should not be assumed across the sample, and a flexible attenuation law is more appropriate.

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Facility: HST (WFC3).
Software: MCSED (Bowman et al. 2020), numpy (van der Walt et al. 2011), astropy (Astropy Collaboration et al. 2013, 2018), emcee (Foreman-Mackey et al. 2013), scipy (Virtanen et al. 2020), matplotlib (Hunter 2007), corner (Foreman-Mackey 2016), seaborn (Waskom et al. 2014), dustmaps (Green 2018), logging (Sajip & Mick 2002).

Appendix A
MCSED Description

Written in Python 2.7, MCSED was created with simplicity in mind. The code is modular in nature and allows users to edit and expand the initial base to include new SFHs, dust attenuation laws, and stellar population models. It is publicly available in Bowman et al. (2020).

The SFHs for MCSED are found in the sfr.py module (Bowman et al. 2020). Included in the package are algorithms for constant and exponentially declining (or increasing) SFR histories and a double power-law parameterization first proposed by Behroozi et al. (2013):

$$\text{SFR}(t) = A \left( \frac{t}{\tau} \right)^B \left( \frac{t}{\tau} \right)^{-C}^{-1}. \quad (A1)$$

This three-parameter formula has the flexibility to model both recent star-forming activity and star formation at older epochs and is sufficiently general to be applicable over a wide range of redshifts and stellar masses. We also include an option that allows the user to fit an arbitrary SFR history using a table with bins in log age. The default age bins in log years are [6.0–8.0], [8.0–8.5], [8.5–9.0], and [9.0–9.3], adopted from Leja et al. (2017).

A number of laws are included to reproduce the extinction and attenuation of starlight due to dust. Foreground extinction is handled via the inclusion of the Cardelli et al. (1989) relation, with the default parameter of $R_V = 3.1$. Options to model the attenuation that occurs internal to galaxies include the starburst galaxy dust model proposed by Calzetti et al. (2000), the Noll et al. (2009) generalization of the Calzetti et al. (2000) law, a Conroy et al. (2010) law that is parameterized by bump strength, and the high-z attenuation law of Reddy et al. (2015) that parameterizes attenuation as a function of specific SFR. These relations are found in the dust_abs.py module (Bowman et al. 2020).
Strong emission lines and nebular continuum can contribute significantly to some bandpasses, and these are included in MCSED via a grid of CLOUDY models generated by Byler et al. (2017). This emission does not necessarily see the same attenuation as the stars. Indeed, it is well known that the light from a galaxy’s H II regions will be extinguished more than the light from its stars (e.g., Calzetti et al. 2000; Battisti et al. 2016; Molina et al. 2020). This is handled by MCSED by allowing the user to attenuate young objects (i.e., nebular emission and stars younger than a certain age) differently from older stars.

Finally, MCSED also contains the Draine & Li (2007) prescription for dust emission. This law is parameterized by the lower cutoff of the starlight intensity distribution ($U_{\text{min}}$), the fraction of dust heated by starlight with $U > U_{\text{min}}$ ($\gamma$), and the PAH mass fraction ($g_{\text{PAH}}$). The total dust mass can be either directly derived from these quantities (using the assumption of energy balance) or computed via the independent normalization of far-IR data. The code for this is located in the dust_emission.py module (Bowman et al. 2020).

To create a new SFH, dust attenuation law, or dust emission prescription, the user simply defines a new class of the following structure. The class must initialize the parameters, define the range allowed for the parameters, and provide the MCMC initialization, delta. (This last variable is equivalent to the dispersion of an initial Gaussian distribution.) Thus, if the name of a parameter is dummy, the class must initialize values for dummy, dummy_lims, and dummy_delta. For parameters associated with star formation, the class must also include the following required functions: set_agelims, get_params, get_param_lims, get_param_deltas, get_names, prior, set_parameters_from_list, plot, and evaluate. The description of each of these functions can be found in one of the existing SFH classes.

Appendix B
Mock Galaxy Tests

To determine the accuracy of MCSED, we synthesized photometry for 120 mock galaxies in each of our five fields using the MILES spectral library, the PADOVA isochrones (Bertelli et al. 1994; Girardi et al. 2000; Marigo et al. 2008), a Kroupa (2001) initial mass function (IMF), a tabular SFR history of four age bins, and a Noll et al. (2009) reddening law. For each synthetic photometric measurement, we added a random error based on the image depths given by Skelton et al. (2014) and then attempted to recover the input parameters, such as stellar mass, coefficients for dust attenuation, and stellar metallicity.

The results are summarized in Figure B1. For each of the five fields, MCSED captures the input dust attenuation law, stellar mass, and stellar metallicity quite accurately. Specifically, the log of the stellar mass is recovered with a mean offset of −0.01 dex and a standard deviation of 0.16 dex, while the color excess, $E(B - V)$, is returned with a mean offset of −0.004 and a standard deviation of 0.04. The code does a reasonably good job of inferring the power-law deviation from a Calzetti et al. (2000) law, $\delta$, as the mean input of the simulations is offset by −0.03 with a standard deviation of 0.13; however, the dust law parameters will always be difficult to estimate when the total dust content is low. More poorly modeled is the 2175 Å bump, which has a small mean offset of −0.14 but a large standard deviation of 0.88. This result is not surprising given the weakness of the absorption and (for the AEGIS, UDS, and GOODS-N fields) the limited amount of photometry measurements bracketing the feature. Finally, the stellar metallicity is recovered moderately well (mean offset of −0.01), though with a large standard deviation of 0.26. It is no surprise that the GOODS-S and COSMOS fields, which have data in over 40 photometric bandpasses, produce the most accurate recovery of the input parameters. The overall results are also quite good for the GOODS-N, AEGIS, and UDS fields.

As an additional test, we also compared the MCSED stellar masses for the Bowman et al. (2019) set of $z \sim 2$ emission-line-selected galaxies with those measured by the FAST code (Kriek et al. 2009) by Skelton et al. (2014). For consistency, we adopted an exponentially declining SFH and a Calzetti et al. (2000) dust law and fixed the stellar metallicity to solar. The Skelton et al. (2014) catalog used mostly photometric redshifts for calculating stellar mass, so we restricted the comparison to sources whose photometric redshifts are within 0.02 of their grism redshifts (given by Momcheva et al. 2016). The remaining differences between the two inferred sets of models are the IMF (we used a Kroupa 2001 law, while Skelton et al. 2014 adopted a Chabrier 2003 IMF), the SSP code (we employed FSPS, while Skelton et al. 2014 used Bruzual & Charlot 2003), and the general fitting methodology. The results of the comparison are shown in Figure B2. The two inferred stellar mass distributions have a mean offset in log stellar mass of +0.17 and a standard deviation of 0.12. In stellar mass, the systematic expected from the differing IMFs is +0.03, while the systematic associated with the different stellar population models is +0.05 (Conroy 2013; Moustakas et al. 2013). The remaining difference of +0.09 can be accounted for by the best-fit ages, which are systematically higher for MCSED. If we add a prior that the e-folding time, $\tau$, must be less than the age of the galaxy, we find excellent agreement between the two stellar masses (once the offsets from the IMF and SSP code are included). The stellar mass comparison between MCSED and 3D-HST illustrates the systematics related to fitting methodology and the inclusion of priors.
Figure B1. Input SED parameters vs. best-fit output values produced by using MCSED in its test mode. The results for each survey field are given in an individual row of panels. From left to right, the columns represent the log of the stellar mass, the three dust attenuation parameters of the Noll et al. (2009) dust law, and the stellar metallicity. The mean offset and standard deviation between the input and output are noted in each panel.
stellar mass from differences in the IMF and SSP code is inferred ages and stellar masses.

The input parameters were used in the SED modeling, although different IMFs and SSP codes were employed. The individual points are colored by the difference in the comparison is for all five CANDELS fields but includes only those sources with $z_{\text{photo}}$ within 0.02 of the emission-line redshift (Momcheva et al. 2016). The same input parameters were used in the SED modeling, although different IMFs and SSP codes were employed. The individual points are colored by the difference in the log ages (Gyr) of the systems. Right: difference in the log stellar mass for CANDELS and 3D-HST. The expected offset in log stellar mass from differences in the IMF and SSP code is +0.08 and is shown with a red square. There is a clear monotonic trend in the differences between the inferred ages and stellar masses.

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Figure B2: Left: log of the stellar mass inferred from MCSED compared to that computed by Skelton et al. (2014) for the galaxy sample of Bowman et al. (2019). This comparison is for all five CANDELS fields but includes only those sources with $z_{\text{photo}}$ within 0.02 of the emission-line redshift (Momcheva et al. 2016). The same input parameters were used in the SED modeling, although different IMFs and SSP codes were employed. The individual points are colored by the difference in the derived log ages (Gyr) of the systems. Right: difference in the log stellar mass for CANDELS and 3D-HST. The expected offset in log stellar mass from differences in the IMF and SSP code is +0.08 and is shown with a red square. There is a clear monotonic trend in the differences between the inferred ages and stellar masses.
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