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Properties of LBGs with [OIII] detection at z > 3: The importance of including nebular emission data in SED fitting

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Abstract. At high redshift, the contribution of strong emission lines to the broadband photometry can cause large uncertainties when estimating galaxy physical properties. To examine this effect, we investigate a sample of 54 LBGs at $3 < z_{\rm spec} < 3.8$ with detected [OIII] line emissions. We use CIGALE to fit simultaneously the rest-frame UV-to-NIR SEDs of these galaxies and their emission line data. By comparing the results with and without emission line data, we show that spectroscopic data are necessary to constrain the nebular model. We examine the K-band excess, which is usually used to estimate the emissions of [OIII]+Hβ lines when there is no spectral data, and find that the difference between the estimation and observation can reach up to > 1 dex for some galaxies, showing the importance of obtaining spectroscopic measurements of these lines. We also estimate the equivalent width of the Hβ absorption and find it negligible compared to the Hβ emission.

Keywords. galaxies: high-redshift, galaxies: formation, galaxies: emission lines

1. Introduction

Lyman Break Galaxies (LBGs) are star-forming galaxies with relatively low dust attenuation. These galaxies are important tracers for cosmic star formation rate at high redshift. However, there are many uncertainties in deriving the properties of LBGs from the spectral energy distribution (SED) fitting. At high redshift, an important uncertainty is the contamination to broadband photometry from the strong nebular emission lines (de Barros *et al.* 2014). Stark *et al.* (2013) have shown that [OIII]5007, Hβ and $H\alpha$ can contaminate K, *Spitzer* IRAC1 (3.6μm) or IRAC2 (4.5μm) bands when redshift > 3. On the other hand, information from nebular emission may give additional constraints on properties such as star formation rate (SFR), stellar mass and dust attenuation.

However, detecting emission lines is non-trivial. Deep near-infrared spectroscopy with sufficient spectral resolution is needed. Due to the lack of spectroscopic data, many studies assume the observed flux excess compared to the SED model flux in K/IRAC1/IRAC2 band as the line emission redshifted to that band. This method may provide only a rough estimation of the emission lines, thus its accuracy should be examined more carefully.

To better understand the properties of high-z LBGs, we selected a sample of LBGs with detected emission lines ([OII], [NeIII], Hβ, [OIII]4959,5007) at $3 < z_{\rm spec} < 3.8$. We analyze the properties of these galaxies (e.g., SFR, stellar mass, dust attenuation) using the SED fitting that considers both broadband photometry and emission line data.

2. Data

Our sources are taken from the samples published by Schenker *et al.* (2013); Troncoso *et al.* (2014) and Holden *et al.* (2016). The observations are taken with the Keck I MOSFIRE or VLT SINFONI spectrographs. The detected lines include [OII], [NeIII], Hβ and [OIII]4959, 5007. The photometric data are collected from 3D-HST, GOODS-MUSIC and also from the work of Magdis *et al.* (2010), and cover the wavelength range from U-band to Mid-infrared (~850Å to 2μm at restframe). In total, we obtain photometric and emission line data for 54 galaxies.

Since our data are selected from different works, we need to control the data quality. We divided our sample into Sample-A and Sample-B. Galaxies in Sample-A should satisfy the following criteria: 1) The galaxy is a secure match between the line and photometric data; 2) At least five bands have a detection better than 3σ; 3) At least one of the four IRAC bands has a detection better than 3σ; and 4) At least one emission line has a detection better than 3σ. In total, we have 26 out of the 54 galaxies in Sample-A. The others are in Sample-B. Although Sample-B has a poorer quality than Sample-A, galaxies in Sample-B are detected in at least three bands. Upper limits are included in the SED fitting using the method presented by Sawicki (2012) (see also Boquien *et al.* 2018).

3. Method

The SED fitting is performed with CIGALE (Code Investigating GALaxy Emission, Burgarella *et al.* 2005; Noll *et al.* 2009; Boquien *et al.* 2018). This code adopts the energy balance strategy and is able to fit the star and dust emission simultaneously. It applies the Bayesian analysis to estimate the output parameters. In this work, we use a new version of CIGALE which enables fitting the photometric and the nebular emission data at the same time.

We use the Salpeter IMF (Salpeter 1955) and the stellar populations from Bruzual & Charlot (2003). The star formation history is assumed to follow the delayed form: $SFR \propto t\,\exp(-t/\tau)$. We assume that the dust attenuation for the stellar part obeys the Calzetti Law (Calzetti *et al.* 2000) with a modification on the slope (Noll *et al.* 2009).

The nebular emission is modelled based on the templates of Inoue (2011) using the CLOUDY code. The input parameters include the metallicity, the radiation strength U, the dust attenuation and the escape fraction of the Lyman continuum photons, $f_{\rm esc}$. The metallicity is assumed to be the same as that of stars (i.e. $0.02Z_\odot$ to $Z_\odot$). The radiation strength U is fixed to $\log U = -2.5$. We have tested different $\log U$ values following Inoue (2011), and find that the value of -2.5 gives minimum χ^2 for our fitting. The dust attenuation for the nebular emission is assumed to follow the Milky Way extinction curve, in which $R_V = 3.1$. The $f_{\rm esc}$ is fixed to 0.2 (e.g. Stark *et al.* 2013).

The nebular emission and stellar emission are connected through $f_{\rm esc}$ and $f_{\rm ebv}$. The parameter $f_{\rm ebv}$ is the ratio of the $E(B-V)_{\rm star}$ to the $E(B-V)_{\rm neb}$. Usually, the value is taken as 0.44. Many recent studies, however, have found that this factor can vary up to 1 (e.g., Puglisi *et al.* 2016; Yuan *et al.* 2018; Buat *et al.* 2018). In this work, we take this parameter as free (in the range 0.1–1.0) and find that the fitting is improved compared to that by using a fixed value.

We examine the degeneracies between different parameters using mock galaxies and the probability density function (Yuan *et al.* in preparation). We find that in the 'Withline' run, the output parameters (SFR, M_*, A_V and age) are better constrained than in the 'Noline' and 'Nonebular' runs.

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Table 1. Models and Data used for the 'Withline', 'Noline' and 'Nonebular' runs of CIGALE.

Name	Models	Data
Withline	stellar+nebular	photometric + line
Noline	stellar+nebular	photometric
Nonebular	stellar	photometric

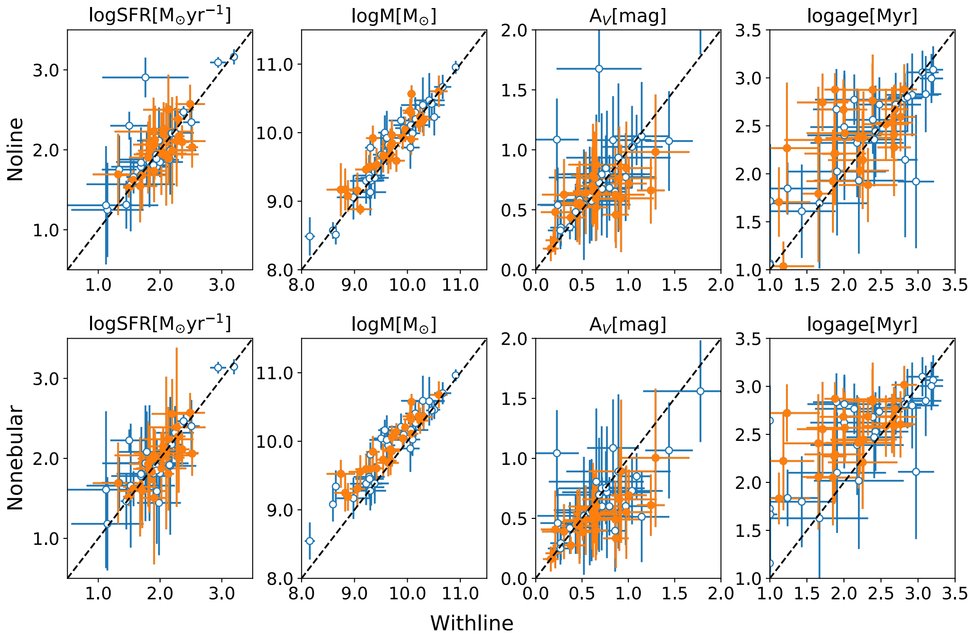

Figure 1. *Top*: Comparison of the results of the 'Withline' and 'Noline' runs. *Bottom*: Comparison of the results of the 'Withline' and 'Nonebular' runs. Orange dots are galaxies in Sample-A. Blue circles are galaxies in Sample-B.

4. Result

We investigate the influence of including nebular emission model and data in the fitting by comparing the results of three runs as listed in Table 1. First, we compare the results with and without line data (the 'Withline' and 'Noline' runs) and find that the SFR and stellar mass derived show no significant difference (Figure 1, *Top*). However, with no emission line data, the SED fitting is not able to predict line emission correctly (Figure 2).

If no nebular model is applied to the photometric data, the resulting stellar masses are systematically overestimated by 0.23 dex (Figure 1, *Bottom*). The fit results in a larger amount of aged stellar populations than those with nebular models. This is consistent with the fact that the K-band fluxes are boosted by the [OIII] emission.

The line emission can be estimated from the photometric data using SED fitting. The difference between the model predicted K-band flux and the observed one is attributed to the fluxes of the [OIII]+Hβ emission. We compared the results from this method with the observation. The average equivalent width estimated from photometric data is 503Å, while the observed value is 487Å, both with a large dispersion of 672Å, implying that although the estimation is systematically unbiased, it is not valid for an individual galaxy.

We calculate the Hβ absorption from the best model and find that the Balmer absorption is not significant for these galaxies. The equivalent width for this absorption is $\sim$1Å at rest-frame on average, comparing to the $\sim$20Å for the emission.

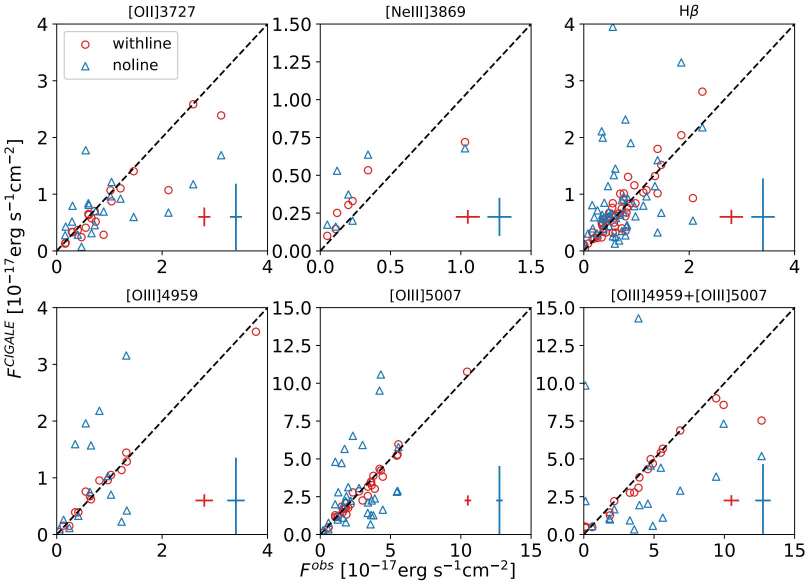

Figure 2. Comparison of the line fluxes derived from CIGALE SED fitting and those from observation. Circles show the results from the 'Withline' run, while triangles show the results from the 'Noline' run. The typical uncertainties are shown at the lower right corner of each plot.

To summarize, by comparing the SED fitting with and without emission line data, we find that both the SFR and the stellar mass values from broadband SED fitting are barely affected by the contamination from emission lines at $z \sim 3$. However, it is risky to predict line fluxes using photometric data alone. We also find that Balmer absorption plays an insignificant role in measuring the line fluxes, due to the fact that the stellar populations are not old enough to produce deep absorption features. Our UV-to-NIR SED and the emission line data together still cannot constrain the dust attenuation law and the star formation history very well. The Hα emission line data from JWST may help anchor the dust attenuation and thus better constrain the properties of these galaxies.

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Discussion

Kentaro Motohara: Why does the [OII]3427 estimate change according to model's $\log U$?

Yuan: Because in the fitting, the line ratios depend on $\log U$.

Tomo Goto: Without line data (photometry only), how much does it improve by including line model to the no line model?

Yuan: With the nebular model, the offset to the reference will decrease about 0.15 dex for stellar mass estimation. However, the scatters are not improved. Both are 0.20 dex compared to the reference run.

Helen Kim: Do your galaxies have any FIR detections? (e.g. Herschel)

Yuan: No, we do not have any restframe far-infrared data in our sample. Some of these galaxies have been observed by Spitzer MIPS, but only upper limits are obtained, because these galaxies are faint at FIR.

Daniel Ceverino: Did you try other SFR histories in your SED fit? Simulations of galaxies at these redshifts support increasing SFR with time.

Yuan: In the current stage, we only test the delayed and delay+burst star formation histories. From the fit assuming the delayed SFH, we find the shape close to an increasing SFH.