Abstract

We present a star formation rate function (SFRF) at \( z \sim 4.5 \) based on photometric data from the rest UV to optical of galaxies in the CANDELS GOODS-South field using spectral energy distribution (SED) fitting. We evaluate the incompleteness of our sample and correct for it to properly compare the SFRF in this study with those estimated based on other probes. The SFRF is obtained down to \( \sim 10 \, M_\odot \, \text{yr}^{-1} \), and it shows a significant excess compared to that estimated from the UV luminosity function and dust correction based on the UV spectral slope. As compared with the UV-based SFRF, the number density is larger by \( \sim 1 \) dex at a fixed SFR, or the best-fit Schechter parameter of the characteristic SFR, SFR* is, larger by \( \sim 1 \) dex. We extensively examine several assumptions on SED fitting to see the robustness of our result and find that the excess still exists even if the assumptions change such as star formation histories, dust extinction laws, and a one- or two-component model. By integrating our SFRF to \( 0.22 \, M_\odot \, \text{yr}^{-1} \), the cosmic star formation rate density (CSFRD) at this epoch is calculated to be \( 4.53_{-0.84}^{+0.94} \times 10^{-2} \, M_\odot \, \text{yr}^{-1} \, \text{Mpc}^{-3} \), which is \( \sim 0.25 \) dex larger than the previous measurement based on UV observations. We also find that galaxies with intensive star formation (\( > 10 \, M_\odot \, \text{yr}^{-1} \)) occupy most of the CSFRD (\( \sim 80\% \)), suggesting that star formation activity at this epoch is dominated by intensively star-forming galaxies.

Unified Astronomy Thesaurus concepts: Galaxy evolution (594); Galaxy formation (595); High-redshift galaxies (734)

1. Introduction

The star formation rate function (SFRF) is one of the key properties of galaxies. It directly describes the in situ evolution of galaxies at an epoch of the universe. The SFRF also provides the cosmic star formation rate density (CSFRD), which sheds light on the history of the universe. Therefore, revealing SFRFs at various redshifts is crucial for the understanding of the cosmological evolution of galaxies.

In the high-z (\( z \gtrsim 4 \)) universe, until recently, the SFRF and CSFRD had been investigated mainly based on rest-UV observations (see, e.g., a review by Madau & Dickinson 2014). In estimating the SFRF and CSFRD from the UV luminosity function (LF), dust extinction is a major concern. Because UV light emitted from massive stars can be easily attenuated by dust, it is important to correct for the loss of light due to the dust extinction. This correction is usually made by using a relation by Meurer et al. (1999), which links a rest-UV spectral slope \( \beta \) and the amount of dust extinction. Because FIR can probe dust-obscured star formation activity, FIR observations can also examine the CSFRD. Some studies claim that the dust-obscured galaxies contribute to the CSFRD largely in the high-z (\( z \gtrsim 4 \)) universe (e.g., Rowan-Robinson et al. 2016), while others claim that the contribution is negligible (e.g., Koprowski et al. 2017). Thus, consensus on the evolution of the CSFRD has not been reached yet, and an independent estimation of the SFRF/CSFRD is desirable.

Because dust extinction has much less effect on rest-optical light, utilizing not only rest UV but also optical data is expected to help properties of galaxies be derived more reliably. Thus, deriving the SFRF with data from the rest UV to optical can be an independent estimation. Recent deep observations by the Infrared Array Camera (IRAC) on Spitzer enable us to access the rest-optical information of high-z galaxies. To determine properties of a galaxy with data from the rest UV to optical, spectral energy distribution (SED) fitting is a common way. Previous such studies using the rest-UV to optical data also found an inconsistency between properties such as SFR or dust extinction derived from UV-based analysis and those from rest-UV to optical data (e.g., Shim et al. 2011; de Barros et al. 2014; Duncan et al. 2014). The inconsistency leads to a systematic difference in SFRFs.

However, the SFRF derived from the rest-UV to optical data has not been investigated extensively or statistically evaluated. In SED fitting, it is known that dust reddening and the red color due to the aging of the stellar population are degenerate, which makes the SFR derived from SED fitting less reliable. Furthermore, if strong emission lines such as H\( \alpha \) or [OIII] \( \lambda 5007 \) from high-z galaxies are reddshifted into the IRAC band, it can boost IRAC broadband photometry (e.g., Yabe et al. 2009; Stark et al. 2013). The excess in the IRAC band may be interpreted as the presence of dust reddening and/or an old stellar population (e.g., Katz et al. 2019). This may also lead to a larger and/or smaller SFR. These problems make it difficult to derive SFRF based on SED fitting, and the previous studies did not take into account these aspects well enough.

In this study, we aim to derive the SFRF based on the data from the rest UV to optical considering these problems. If an excess in emission line is seen in the IRAC 4.5 \( \mu \text{m} \) band, it would be hard to recognize it as an emission line because the sensitivities of the IRAC 5.8 \( \mu \text{m} \) and 8.0 \( \mu \text{m} \) bands are very much shallower than those in the 3.6 \( \mu \text{m} \) and 4.5 \( \mu \text{m} \) bands. To avoid this problem, targeting a redshift around 4.5 and including nebular emissions in the model spectrum are desirable. The excess in the 3.6 \( \mu \text{m} \) band due to strong H\( \alpha \) emission is expected to be recognized with 4.5 \( \mu \text{m} \) photometry. Furthermore, we extensively examine assumptions on SED fitting that can have effects on the SFRF, such as various star formation histories (SFHs), a two-component model (i.e., model composed of an old stellar population and young star-forming population), and dust
extinction law, to see the robustness of our result. The incompleteness of our sample is corrected to derive the SFRF, and the completeness limit of the SFRF is also evaluated. These enable us to derive the SFRF from SED fitting, which can be properly confronted with the SFRF estimated from the UV LF.

This paper is structured as follows. In Section 2, we describe the data and sample selection. In Section 3, details of the SED fitting are provided. In Section 4, we present the resulting SFRF and see the effects of changing several assumptions. Using the resulting SFRF, the CSFRD is calculated in Section 5. Section 6 gives the summary of this paper. Throughout this paper, all magnitudes are quoted in the AB system (Oke & Gunn 1983), and we assume the cosmological parameters of $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_m = 0.3$, and $\Omega_\Lambda = 0.7$.

2. Data

2.1. Photometric Catalog and Photometric Redshifts

Among the surveys conducted with Spitzer, the Great Observatories Origins Deep Survey (GOODS) South field is one of the deepest and widest fields (e.g., Bradač 2020). We focus on this field and use the photometry catalog given by Guo et al. (2013), which is a UV to mid-infrared multi-wavelength catalog in the Cosmic Assembly Near-infrared Deep Extragalactic Legacy Survey (CANDELS) GOODS-South field.

The details of the object extraction and photometry are presented by Guo et al. (2013), so here we briefly summarize the method. The catalog contains multiwavelength band photometry consisting of observations by the Advanced Camera for Surveys (ACS) and Wide Field Camera 3 (WFC3) on Hubble Space Telescope (HST), IRAC on Spitzer, and other ground-based observatories. The optical data from ACS contain observations in the F435W, F606W, F775W, F814W, and F850LP bands. The NIR data from WFC3 contain observations in the F098M, F105W, F125W, and F160W bands. From IRAC observations, 3.6 $\mu$m (Ch1), 4.5 $\mu$m (Ch2), 5.8 $\mu$m (Ch3), and 8.0 $\mu$m (Ch4) band photometries are available. In addition, the catalog contains VIMOS and CTIO $U$-band data and ISAAC and HAWK-I $K_s$-band data.

Photometry for HST bands was conducted by using SExtractor’s dual-image mode. The combined max-depth mosaic of the F160W-band image ($H_{160}$ hereafter) was used for object detection, and photometry in other bands was made with a point-spread-function-matched image. For the ground-based and Spitzer images, photometry was done through TFIT. In this work, we use all of the data from the 17 bands except for the CTIO $U$-band data from this photometry catalog, because the band was revealed to have a red leak (Guo et al. 2013).

As for the redshifts, we utilize the CANDELS Bayesian photometric redshift catalog (Dahlen et al. 2013). For entire objects in this catalog, photometric redshifts are derived based on a hierarchical Bayesian approach that combines the full $P(z)$ distributions derived via several manners.

2.2. Sample Selection

In this study, to make a sample of galaxies at $3.88 < z < 4.94$ whose $H_0$ emission is redshifted into the Spitzer/IRAC 3.6 $\mu$m band, we set the criteria composed of two steps. Figure 1 shows a flowchart of the criteria. We adopt the route indicated by red solid arrows.

The CANDELS GOODS-S catalog contains 34,930 objects. Among them, we extract objects whose redshift with $1\sigma$ confidence. The level is in the range of $3.88 < z < 4.94$; we pick out objects that meet the following criterion,

$$ (3.88 < l68) \land (u68 < 4.94), $$

where $l68$ and $u68$ are the lower and upper photo-$z$ 68% confidence limit, respectively. Here, we exclude active galactic nuclei (AGNs) identified by Hsu et al. (2014). The X-ray sensitivity limit of this AGN catalog is typically $3.2 \times 10^{-17}$, $9.1 \times 10^{-18}$, and $5.5 \times 10^{-17}$ erg s$^{-1}$ cm$^{-2}$ for the full (0.5–8 keV), soft (0.5–2 keV), and hard (2–8 keV) bands, respectively. With the redshift of $z = 4.5$, this limit corresponds to $\sim 6.5 \times 10^{-22}$, $\sim 1.9 \times 10^{-22}$, and $\sim 1.1 \times 10^{-21}$ erg s$^{-1}$, respectively.

A total of 605 objects pass the selection above (we refer to them as “target sample”). Next, we apply an additional cut to the target sample to ensure the SEDs of the galaxies in our sample are reliable to make the SED fitting. As we introduced in Section 1, detection in the 4.5 $\mu$m band of IRAC plays an important role in recognizing the excess in the 3.6 $\mu$m band due to $H_0$ emission. Thus, we require a signal-to-noise ratio (S/N) larger than 5 in the 4.5 $\mu$m band of IRAC. In addition, we remove all objects whose photometry can be contaminated by neighboring objects in IRAC images. Specifically, we first discard objects whose separation from the nearest object is $< 2''$ in the $H_{160}$ image. If the neighboring object is extended, photometry can be contaminated by the neighbor even if the separation from the nearest object is larger than $2''$. Thus, for the objects whose separation in the $H_{160}$ image is larger than $2''$, we conduct a visual inspection of the IRAC images to see whether the neighbors around the objects affect the photometry.

As a result, we create a sample containing 107 galaxies (we refer to this sample as the “final sample”).

3. SED Fitting

We then perform SED fitting to the final sample. To make the SED model, we use the population synthesis code PÉGASE.3 (Fioc & Rocca-Volmerange 2019). This code includes nebular emission and follows the chemical evolution of the galaxy, which is then used to determine the metallicity of...
the interstellar medium (ISM) and newly born stars at every time step. The Chabrier03 IMF (Chabrier 2003) with the mass range of 0.08–120 $M_\odot$ is adopted. As for the SFH, we adopt an exponentially declining ($\propto e^{-t/\tau}$) and delayed exponential ($\propto t^{-1}e^{-t/\tau}$) history with $\tau = 10$, 100, and 1000 Myr, and constant star formation (CSF). We also examine a two-component model later (Section 4.4.1). The universe at $z \sim 4.5$ is aged $\sim 1.4$ Gyr; we allow the age to vary from 1 Myr to 2 Gyr with 70 steps, which is not equally spaced in linear or logarithmic space. Dust extinction is modeled with the Calzetti law (Calzetti et al. 2000) with $R_V = 4.05$, but we will explore an alternative extinction law measured in the Small Magellanic Cloud (SMC; Pei 1992) later (Section 4.4.2). The color excess $E(B-V)$ is taken from 0.0 to 0.8 mag at an interval of 0.01 mag. The ratio between stellar and nebular extinction is assumed to be 1. We adopt the default value of PEGASE.3 for the escape fraction. Intergalactic attenuation by neutral hydrogen is applied following the prescription by Madau (1995). The redshift of the model galaxy is set from 3.8 to 5.0 at an interval of 0.1. Consequently, we make 5670 SED templates for each of the redshift steps and SFHs and search for the best-fit SED for each galaxy by $\chi^2$ minimization. Here, we do not fix the SFH but fix the redshift of the template to $z_{\text{best}}$ of the galaxy given by the CANDELS catalog. Here, $z_{\text{best}}$ is basically the photometric redshift but is the spectroscopic redshift when it is available. We do not use the photometry at the wavelengths shortward of Ly$\alpha$ in calculating the $\chi^2$.

Figure 2 shows the resulting color excess $E(B-V)$ against age, which is defined as the time since the onset of the star formation. The color excess tends to decrease with increasing age as expected. However, the color excesses are not so large for ages of less than $10^{5.5}$ Myr. This stems from the inclusion of the nebular continuum in our model spectra. The color of the nebular continuum is redder than that of a very young stellar component (e.g., Bouwens et al. 2010). Figure 2 (right) shows the SFR against stellar mass. The SFR is defined as the instantaneous value of the best-fit template. The distribution is basically similar to that at $z \sim 4.5$ derived by using SED fitting in the previous studies (e.g., Caputi et al. 2017; Faisst et al. 2019).

4. Star Formation Rate Function

In this section, we first describe the method for deriving SFRF using the result of SED fitting (Section 4.1). Next, we derive the SFRF and compare it with that estimated from UV LF (Section 4.2). In Section 4.3, the reason for the difference between our SFRF and UV-based one is examined. We also derive SFRF with various assumptions to see the effect by the difference of model assumption (Section 4.4). Finally, in Section 4.5, we present several further inspections related to the result derived in Sections 4.2–4.4.

4.1. Method for Deriving SFRF

In order to derive the SFRF, the incompleteness of the sample should be corrected properly. The final sample is affected by three factors: (i) detection rate in the H$_{160}$-band
image, (ii) S/N cut in the 4.5 μm band, and (iii) elimination of blended objects with neighbors.

To correct for (i), the detection rate in H_{160} is required. Duncan et al. (2014) derived the detection rate of the CANDELS GOODS-S catalog by conducting mock observations, so we use their result. Figure 3 (top panel) shows the detection rate against apparent magnitudes at H_{160}. Note that Duncan et al. (2014) estimate the rate by dividing the GOODS-S fields into four subregions according to the exposure time; HUDF, ERS, DEEP, and WIDE.

We evaluate the detection rate in the IRAC 4.5 μm band to correct for (ii). The exposure time in the surveyed region is inhomogeneous. Thus, we evaluate this effect as follows. In the CANDELS photometric catalog, 1σ limiting magnitudes at the position of all the objects in each band are also available. We calculate the 5σ limit at the location of the objects in our target sample and make a cumulative histogram of it. This can be used for correcting the difference of the limiting magnitudes because z ∼ 4.5 galaxies are almost randomly distributed in the whole survey region. Figure 3 (right panel) shows the distribution of the 5σ limit against apparent magnitudes in the 4.5 μm band.

As for (iii), blending occurs regardless of its SFR as far as their apparent size is similar, so we can correct for it by dividing the fraction of isolated objects. Therefore, we derive the fraction of isolated objects in the IRAC image f_{sel} at z ∼ 4.5. We first randomly pick out ∼ 100 objects from our target sample and see their images in the IRAC 4.5 μm band. We categorize the ∼ 100 objects into three groups: objects clearly detected and not blended with the neighboring objects (group A), objects clearly detected but heavily contaminated by the neighbors (group B), and objects that are faint and not detected. We then calculate the fraction f_{sel} by #(A)/(#(A)+#(B)), and obtain the value of f_{sel} ∼ 0.35.

By considering the effects of incompleteness due to these factors, the SFRF ϕ(M_{*}) [Mpc^{-3} dex^{-1}] for the bin of d(log M_{*}) can be estimated as follows:

ϕ(M_{*})d(log M_{*}) = \sum_{i}^{N_{sel}} \frac{1}{f_{det}(m_{ch2,i}) V_{i}^{eff}},

where the subscript i represents each of the galaxies in the bin, N_{sel} is their number, f_{sel} is the fraction of isolated objects in the IRAC image (iii), f_{det}(m_{ch2,i}) is the value in the cumulative histogram of 5σ limit in 4.5 μm band at the magnitude of m_{ch2,i} (ii), and V_{i}^{eff} is the effective volume of the survey for this galaxy i (i). This effective volume for a galaxy i can be calculated as

V_{i}^{eff} = \sum_{k}^{N_{reg}} f_{k}^{160}(m_{160,i}) \Omega_{k} \int_{r_{z=0}}^{r_{z=a}} r^{2} dr,

where the summation, k, is over the subregions in the field, N_{regions} is their number (n = 4), f_{k}^{160}(m_{160,i}) is the detection rate in the H_{160} band at the magnitude of m_{160,i}, \Omega_{k} is the solid angle of the subregion, and r_{z=0} is the comoving distance from z = 0 to z = a.

Additionally, we intend to estimate the completeness limit of the SFR. We apply an S/N cut in the 4.5 μm band, and the 4.5 μm magnitude of a galaxy at about this redshift is a good indicator of its stellar mass (e.g., Yabe et al. 2009). Thus, our sample is expected to be stellar mass limited. Because a rough correlation is seen between the SFR and stellar mass (Figure 2 right), this limit would also be the SFR limit. To see this, we examine the correlation between SFR and 4.5 μm magnitude. Figure 4 shows the SFR versus 4.5 μm magnitude. The trend of a brighter galaxy showing a larger SFR for SF galaxies is seen regardless of SFH. Because our detection limit in the 4.5 μm band is ∼ 26.0 mag (lower-right panel in Figure 3) and this magnitude corresponds to SFR ∼ 10 M_{\odot} yr^{-1} (Figure 4), the SFRF is constructed down to SFR ∼ 10 M_{\odot} yr^{-1} by correcting for the incompleteness discussed above. One might worry about the effect from an object that is bright enough to be detected in the 4.5 μm band, for which, in turn, its SFR can be larger than the SFR completeness limit 10 M_{\odot} yr^{-1}, but too faint in the H_{160} band. However, considering the distribution of the magnitudes in the H_{160} and 4.5 μm bands (lower-left panel in Figure 3), such objects should be rare and the effect on the SFRF is expected to be negligible.

4.2. Star Formation Rate Function

The resulting SFRF is shown in Figure 5. As we can see in Figure 5, the SFRFs with various SFHs agree well with each other in the complete region (> 10 M_{\odot} yr^{-1}). Given that their error bars are smaller than the differences among SFH models, we adopt the maximum and minimum value in each bin among these SFHs as the upper and lower limits of the uncertainty for SFRF, respectively, and adopt the average values of these maximum and minimum as the fiducial values of the SFRF. The fiducial SFRF is shown in Figure 6.

For comparison, we plot the SFRF at z ∼ 5 by Smit et al. (2012, S12 hereafter) converted to the same IMF as we use.
This SFRF by S12 is constructed by correcting for the observed UV LF with the Meurer et al. (1999) IRX–β relation. We also plot the SFRF presented by Smit et al. (2016, hereafter S16). S16 found a systematic offset between the Hα- and UV-based SFR at \( z \sim 4.5 \). To resolve this tension in the inferred SFRs, they examined the impact of the assumed dust extinction and stellar properties on the inferred SFRs. They consequently proposed two types of SFRFs: Meurer et al. (1999) type and SMC type. Because the Meurer et al. (1999) dust correction is almost identical to that with the Calzetti law, we plot the Meurer et al. (1999) type model for a fair comparison.

The SFRF obtained in this study obviously shows a large excess in the SFRF estimated from the UV LF by S12 and S16. The SFRF from the UV LF by S16 is made to reconcile the discrepancy between the SFRs derived from rest UV and Hα at this redshift, though it still seems to underestimate the number of galaxies with a large SFR. We will deal with this difference for comparison. We only use data points at SFR \( \geq 10^{-3} \, M_\odot \, yr^{-1} \) for the dust extinction. The black dotted line is a guide line corresponding to SFR \( = 10 \, M_\odot \, yr^{-1} \). The vertical error bars are 1σ Poisson uncertainties by Gehrels (1986).

We fit the Schechter function to our data for SFRF through \( \chi^2 \) minimization. The Schechter function can be written as

\[
\phi(M_*)d(\log M_*) = (\ln 10)\phi^* \left( \frac{M_*}{SFR^*} \right)^{\alpha+1} \exp \left[ -\frac{M_*}{SFR^*} \right] d(\log M_*),
\]

where SFR*, \( \alpha \), and \( \phi^* \) are the characteristic SFR, faint-end slope, and characteristic number density, respectively. Because our SFRF is complete only in the large SFR region, it is difficult to determine the parameter \( \alpha \). Thus, we tentatively fix the value as \( \alpha = -1.50 \), which is the same as that of SFRF at \( z = 5 \) estimated from the UV LF (S12). We also conduct fitting, leaving \( \alpha \) as a free parameter for comparison. We only use data points at SFR \( > 10^{-3} \, M_\odot \, yr^{-1} \) in the fitting. When the parameter \( \alpha \) is fixed to be \( -1.50 \), the best-fit Schechter parameters are \( \phi^* = 7.24^{+1.07}_{-1.36} \times 10^{-5} \, Mpc^{-3} \) and log \( (\text{SFR}^* [M_\odot \, yr^{-1}]) = 2.56^{+0.10}_{-0.12} \). If we allow \( \alpha \) to vary, the best-fit values are \( \alpha = -1.42^{+0.24}_{-0.34} \), \( \phi^* = 9.20^{+1.76}_{-2.28} \times 10^{-5} \, Mpc^{-3} \), and log \( (\text{SFR}^* [M_\odot \, yr^{-1}]) = 2.50^{+0.22}_{-0.28} \). The fixed value ...
of \( \alpha \) is within its uncertainties. These results are shown in Figure 6 and Table 1.

### 4.3. What Gives Rise to the Difference in the SFRF?

In the previous subsection, we have demonstrated that the SFRF from SED fitting shows a large excess compared to the SFRF from the UV LF. The main reason for this is considered to be the difference in the estimated dust extinction. Converting the observed UV LF to SFRF, the dust correction is made by using Meurer et al. (1999) IRX–\( \beta \) relation:

\[
A_{1600} = 4.43 + 1.99\beta. \tag{5}
\]

This relation links the observed spectral slope \( \beta \) in rest UV and the rest-UV extinction \( A_{1600} \). We measure the slope \( \beta \) for all the objects in our final sample. For the measurement of \( \beta \), we simply conduct a power-law fit to the photometry from the F814W band (\( i_{814} \) hereafter) to \( H_{160} \). We compare the attenuation derived from SED fitting and this relation.

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**Figure 6.** SFRF obtained from the SED fitting (black circles) and the best-fit Schechter function (red solid line). The black filled and open circles represent the data points that are used and not used in the fitting, respectively. Upper left: fixed \( \alpha \) with red shaded region representing 1\( \sigma \) error. Upper right: error contours for Schechter parameters \( \phi^* \) and \( \log_{10}(SFR_*) \). The black cross represents the best-fit values. Lower left: same as the upper-left panel but for fitting without fixing \( \alpha \). Lower right: same as the upper-right panel but for fitting without fixing \( \alpha \). Note that this contour in the lower-right panel is for the case where \( \phi^* \) is fixed to its best-fit value. Blue solid and dotted lines show the SFRFs converted from the UV LF at \( z \sim 5 \) (see text for details).

**Table 1**

| Redshift | \( \alpha \) | \( \log_{10}(SFR^*) \) (M\(_{\odot}\) yr\(^{-1}\)) | \( \phi^* \) (10\(^{-5}\) Mpc\(^{-3}\)) | \( \log_{10}(\phi^*/SFR) \) (M\(_{\odot}\) yr\(^{-1}\) Mpc\(^{-3}\)) | Note | Dust extinction |
|----------|-------------|---------------------------------|----------------|---------------------------------|------|----------------|
| 4.5      | -1.50 (fixed) | 2.56\(^{+0.10}_{-0.12}\) | 7.24\(^{+0.07}_{-0.06}\) | -1.34\(^{+0.08}_{-0.09}\) | Calzetti |                  |
| 4.5      | -1.42\(^{+0.24}_{-0.34}\) | 2.50\(^{+0.22}_{-0.28}\) | 9.20\(^{+0.16}_{-0.11}\) | -1.36\(^{+0.17}_{-0.19}\) | \( \alpha \) is varied | Calzetti |
| 4.5      | -1.50 (fixed) | 2.40\(^{+0.06}_{-0.10}\) | 11.0\(^{+0.16}_{-1.06}\) | -1.33\(^{+0.07}_{-0.09}\) | Two-comp. model | Calzetti |
| 4.5      | -1.56 (fixed) | 2.22\(^{+0.12}_{-0.12}\) | 3.89\(^{+0.00}_{-0.20}\) | -1.91\(^{+0.13}_{-0.16}\) | SMC |                  |
| 4.5      | -1.56 (fixed) | 2.10\(^{+0.08}_{-0.10}\) | 13.5\(^{+0.13}_{-2.33}\) | -1.50\(^{+0.10}_{-0.09}\) | Two-comp. model | SMC |

Note. The star formation rate density is calculated by integrating SFRF down to \( \sim 0.22 \) M\(_{\odot}\) yr\(^{-1}\), which corresponds to \( M_{UV} = -17 \) mag.
Figure 7. Left: color excess \((E(B-V))\) against SFR derived from SED fitting. The corresponding \(A_{1600}\) is also shown at the right ordinate. Right: \(A_{1600}\) from the SED fitting and that from the spectral slope \(\beta\). We use Equation (5) to convert the spectral slope \(\beta\) into the extinction \(A_{1600}\). Only the case of the exponentially declining SFH model with \(\tau = 100\) Myr is shown here, but the distribution does not change that much with the choice of SFH.

The results are shown in Figure 7. Galaxies with a larger SFR tend to show a larger color excess (left panel), and the dust extinction of such objects is especially underestimated when we use the IRX–\(\beta\) relation (right panel). We infer that, for a red galaxy, SED fitting gives a larger value of \(A_{1600}\) than that derived from the IRX–\(\beta\) relation, and hence the intrinsic rest-UV luminosity and SFR get larger.

4.4. SFRF with Other Assumptions

In this subsection, we derive the SFRF by changing the assumptions on SED fitting to see the robustness of our result.

4.4.1. Two-component Model

As we described in Section 4.3, the excess of SFRF is mainly due to the difference in the estimation of dust extinction. However, the red color of the SED can be explained not only by dust extinction but also by the aging of the stellar population. Therefore, we examine a two-component model composed of an old stellar population and a young star-forming population. If the red color of the high-SFR objects can be explained not only by dust but also by old stellar component to some extent, the best-fit value of \(E(B-V)\) and the discrepancy of SFRFs are expected to be reduced. In order to examine this, we conduct SED fitting using a two-component model. As for the old stellar population, we use the spectrum of a 1 Gyr old quenched galaxy. Details of this two-component analysis are presented in the Appendix. The resulting SFRF is shown in Figure 8 and Table 1. As seen in Figure 8 and Table 1, adopting a two-component model reduces the discrepancy only slightly, and the excess in a large SFR region still exists even with a two-component model.

Interestingly, adopting this model not only reduces the number density at the most intensive region (SFR \(\gtrsim 10^2 M_\odot\) yr\(^{-1}\)) but also increases at intermediate regions (SFR \(\sim 10^{1-2} M_\odot\) yr\(^{-1}\)) (c.f. Appendix), though the difference is not large.

4.4.2. Alternative Reddening Law

The assumption regarding the dust extinction curve can have a systematic effect on the estimated SFR. Thus, it is important to see the impact of the assumption regarding the extinction law on the SFRF. So far, we adopt the Calzetti law for dust extinction. However, some studies suggest that high-z galaxies prefer an SMC-like extinction curve (e.g., Fudamoto et al. 2020). Adopting the SMC extinction law systematically reduces the value of SFR derived from SED fitting compared to that with the Calzetti attenuation curve (e.g., Yabe et al. 2009). We conduct SED fitting with the same procedure as we did in Section 3 assuming the SMC extinction curve by Pei (1992) and derive SFRF in the same way as Section 4.2.

We show the resulting SFRF in the top panel of Figure 9. We also plot two SFRFs converted from UV LFs for comparison. In S12, the UV LF is converted into SFRF assuming the Meurer relation (Equation (5)). Because the Meurer et al. (1999) dust correction is different from that with the SMC law, we obtain an SFRF following the procedure described in S12 using an SMC-type relation, Equation (6),

\[
A_{1600} = 2.45 + 1.1\beta,
\]

instead of Equation (5), and plot it in Figure 9. We also plot the SMC-type model by S16.

The completeness limit of our SFRF (SFR \(\gtrsim 10 M_\odot\) yr\(^{-1}\)) does not change with the extinction law. Similar to the case of Calzetti attenuation, our result shows an excess to the SFRF estimated from the UV LF. We also fit the Schechter function to our result, fixing the faint-end slope to \(\alpha = -1.56\), which is the same as that in S12 with an SMC-type correction (Equation (6)). We present the result of this fitting in the top panel of Figure 9 and Table 1.

As we discussed in Section 4.4.1, it is meaningful to explore if this excess can be reduced with a two-component model. The result is shown in the bottom panel of Figure 9. Akin to the result in Section 4.4.1, this excess is reduced only slightly and still exists even with the two-component model. In the case of the SMC extinction law, the effect of increasing the value of the SFR by adopting a two-component model is distinctive, and the number density of galaxies with SFR \(\sim 10^{1-2} M_\odot\) yr\(^{-1}\) increases significantly.

We conclude that the SFRF derived from SED fitting shows a significant excess compared to that estimated from the UV LF in the large SFR (\(\gtrsim 10 M_\odot\) yr\(^{-1}\)), and this is robust regardless of the choice of dust extinction law or stellar composition models including various SFHs and the two-component model. The SFRF can vary especially with the assumption regarding the dust extinction curve, so we expect that the true value of the SFRF is located between the maximum and minimum among...
Figure 9. SFRF derived with the SMC extinction curve and the best-fit Schechter function (red solid line) for the one-component model (top) and the two-component model (bottom). In both panels, the red dashed–dotted line shows the best-fit Schechter function to the SFRF with the Calzetti extinction law with the corresponding model. Blue solid and dotted lines show the SFRFs converted from the UV LFs with SMC-type dust correction (see text for details).

the four SFRFs derived here. In Figure 10, we show all of these SFRFs and the region where we expect the true value is located.

4.5. Further Inspections of the Excess

4.5.1. Difference in UV Luminosity Function?

The difference in SFRF may have originated in the difference in the UV LF due to, e.g., field-to-field variance. We derive (dust-uncorrected) rest-UV LF using our samples to see whether the UV LF is the same as in the previous studies. The rest-UV magnitude $M_{UV}$ of each galaxy is calculated using the apparent magnitude in the $i_{814}$ band and its photometric redshift. We derive the UV LF with both the target sample and the final sample. With the final sample, the UV LF of $M_{UV}$ [Mpc$^{-3}$ erg$^{-1}$] is estimated using the same equation as we used for the SFRF (Equation (2)). With the target sample, because this sample is not affected by the S/N cut and elimination of blended objects in the IRAC 4.5 $\mu$m band, the UV LF is estimated without the corresponding corrections, $f^{\text{rel}}$ and $f^{\text{det}}(m_{\text{ch2}})$.

We show the result in Figure 11. Because the SFRFs in S12 and S16 are derived based on the (dust-uncorrected) UV LF given by Bouwens et al. (2007, 2015), respectively, we plot them for comparison. We can see that the UV LFs derived here are in good agreement with those we used for comparisons.

Furthermore, if we correct for the dust extinction using Equation (5) for each galaxy, the (dust-corrected) rest-UV LF is almost identical to that obtained by S12. These indicate that the excess of the SFRF is not caused by the difference in the UV LF. Note that the UV LF with the final sample is lower at $M_{UV} = -19.5$, but this is due to the incompleteness of our final sample. In addition, UV LFs with the final sample and target sample agree well with each other in the bright region ($SFR > 10 M_\odot$ yr$^{-1}$), which suggests that the incompleteness due to the S/N cut and elimination of blended objects in the IRAC 4.5 $\mu$m band is well corrected with our method.

4.5.2. Consistency with FIR Observation

It is important to see the consistency between our result and FIR observation. About one-third (~69 arcmin$^2$) of the CANDELS GOODS-South field is observed with ALMA band 6 in the GOODS-ALMA project (Franco et al. 2018, 2020). They presented a catalog of galaxies detected at 1.1 mm with a flux density limit of 640 $\mu$Jy (~3.5$\sigma$). At the redshift of $z \sim 4.5$, this corresponds to a monochromatic luminosity limit ($L_{\nu}$ units) of $9.2 \times 10^{10} L_\odot$ at $\nu_{\text{rest}} \sim 200 \mu$m. Using the SED template presented by Schreiber et al. (2018), this limit is converted into a total IR luminosity limit, and then into an SFR limit with the following equation by Madau & Dickinson (2014):

$$SFR = \kappa L_{\text{TIR}},$$

where $\kappa = 1.08 \times 10^{-10} M_\odot$ yr$^{-1}$ L$_\odot^{-1}$ for the Chabrier IMF. The resulting SFR limit is $\sim 270 M_\odot$ yr$^{-1}$.

Among galaxies in our final sample, 52 galaxies are located in the region covered by GOODS-ALMA observation. No counterpart is found in this ALMA-selected catalog. Considering the variety of SFRs with the assumption of models, there is no galaxy whose SFR is definitely larger than $\sim 270 M_\odot$ yr$^{-1}$ among the 52 galaxies. Therefore, the lack of a counterpart is consistent with the SFRs estimated in this study.

$^7$ We have seven models for SFHs, two models for dust extinction, and two models for stellar composition. Thus, we derived 28 values of SFR per one galaxy.
Recent studies from FIR observations by Bouwens et al. estimate the UV LF at lower redshift, e.g., Bouwens et al. (2020; Gruppioni et al. 2020; Khusanova et al. 2021). Results by Khusanova et al. (2021) and Gruppioni et al. (2020) are based on FIR observations, and that by Bouwens et al. (2020) is based on UV observations. For clarity, the result by Khusanova et al. (2021) at $z = 4.5$ is shifted $\Delta z = -0.15$.

As a result, the SFRF with this alternative sample of galaxies following the stellar component model, are

are shown in Table 2. These values are smaller than the CSFRDs obtained with the extrapolation by $\sim 0.1$ dex, but still larger than the CSFRD estimated from the UV LF by $\sim 0.2$ dex. $\rho_{\text{SFR}}^{\text{complete}}$ occupies $\sim 80\%$ of $\rho_{\text{SFR}}$ (Table 2), suggesting SF activity at this redshift is dominated by intensively star-forming galaxies, though the faint-end slope is not constrained well.

In addition, to examine the effect of the choice of dust extinction law on the CSFRD ($\rho_{\text{SFR}}^{\text{complete}}$ or $\rho_{\text{SFR}}$), we see the difference in CSFRDs when the assumption regarding the dust extinction changes while other assumptions, such as for the stellar component model, are fixed. With the one-component model, as can be seen in Table 2, adopting the SMC extinction law reduces $\rho_{\text{SFR}}^{\text{complete}}$ and $\rho_{\text{SFR}}$ by $\sim 0.6$ dex compared with that obtained from the Calzetti law (c.f. “C,1,f” and “S,1,f” models in Table 2). However, with the two-component model, the difference in the CSFRDs between the Calzetti and SMC extinction laws is only $\sim 0.2$ dex (c.f. “C,2,f” and “S,2,f” models in Table 2). Thus, the choice of dust extinction law seems to affect the CSFRD, but its amount is still uncertain. Note that these values of the difference ($\sim 0.6$ dex and $\sim 0.2$ dex) do not change with the range of integration, i.e., $\rho_{\text{SFR}}^{\text{complete}}$ or $\rho_{\text{SFR}}$, so this uncertainty is not due to the poor constraint of our SFRF on the faint-end slope.

Next, we intend to see the effect of our photo-$\alpha$ selection. As we described in Section 2.2, we extracted objects that meet the criterion of Equation (1). Only about half of the objects whose photometric redshift $z_{\text{best}}$ is nominally in our target redshift range $3.88 < z < 4.94$ can pass this criterion (Figure 1). Thus, our photo-$\alpha$ selection may have a non-negligible effect on our result.

To examine this, we set an alternative criterion as

$$3.88 < z_{\text{best}} < 4.94,$$

instead of Equation (1) (we show this alternative sample selection by the black dotted arrow in Figure 1) and derive the SFRF with this alternative sample of galaxies following the same procedure as we did in Section 4.2. As a result, the SFRF
The SFRF at $z \sim 4.5$ derived from SED fitting shows an excess compared to that estimated from the UV LF. As compared with the SFRF estimated from the UV LF, the number density is larger by $\sim 1$ dex at a fixed SFR, or the best-fit Schechter parameter of SFR is larger by $\sim 1$ dex (Section 4.2, Figure 6). This result does not change with the choice of models such as various SFHs and a one- or two-component model. (Section 4.4, Figure 8 and Table 1).

2. The SFRF varies with the choice of the dust extinction law, but the excess compared to the UV-based SFRF still exists (Section 4.4, Figure 9, and Table 1).

3. The CSFRD is calculated to be $4.53^{+0.94}_{-0.87} \times 10^{-2} M_{\odot} \text{year}^{-1} \text{Mpc}^{-3}$ with the Calzetti extinction law. The excess in the SFRF leads to an increase in the CSFRD by $\sim 0.25$ dex compared with that estimated from the UV LF at $z \sim 4.5$ (Section 5 and Figure 12). However, the CSFRD varies with the choice of the dust extinction law (Section 5 and Table 2).

4. The CSFRD is largely occupied (80%) by intensively star-forming (SFR $> 10 [M_{\odot} \text{year}^{-1}]$) galaxies regardless of the model assumption (Section 5 and Table 2).

We thank the anonymous referee for useful comments. K.O. is supported by JSPS KAKENHI grant No. JP19K03928. F.M. is supported by a Research Fellowship for Young Scientists from the Japan Society of the Promotion of Science (JSPS). This work is based on observations taken by the CANDELS Multi-Cycle Treasury Program with the NASA/ESA HST, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS5-26555.

Appendix

Two-component Model

In this appendix, we describe the two-component model used in Section 4.4.1. This model consists of a relatively old stellar population without star formation and a young star-forming population. As we discussed in Section 4.3, the large discrepancy in SFRFs is considered to be due to the large value of $E(B-V)$ derived from the SED fitting. Thus, we introduce the two-component model to see whether the red color of such objects can be explained not by dust extinction but the continuum jump by old stars. In the two-component SED fitting, it would be necessary to take the age of the old population and a fraction of the old population as additional free parameters. However, we do not intend to examine the details of the two-component analysis, and we just examine the rough behavior when we adopt the two-component model. Thus, we fix the age and fraction of the old population.

The age of the universe at $z \sim 4.5$ is $\sim 1.3$ Gyr, thus the age of the old component is less than 1.3 Gyr. We then see which SFH makes their continuum reddest with age of 1 Gyr old.8 We compare stellar continuum spectra at the age of 1 Gyr with five different SFHs: instantaneous burst and CSF with the duration of $\Delta t = 10, 50, 100$, and 500 Myr from the onset of star formation using the population synthesis code PÉGASE3. We show these spectra in Figure 13 (top panel).

Naively, the instantaneous SFH is expected to be the reddest. As shown in Figure 13 (bottom panel), this is the case when the stellar metallicity is fixed. However, the spectrum of CSF with the duration of $\Delta t = 100$ or 500 Myr is redder when we consider the chemical evolution. This is essentially because of their stellar metallicity. In PÉGASE3, the model SED is calculated following the chemical evolution, so the stellar population with instantaneous SFH has extremely low (almost zero) metallicity and the SED shows a very blue color. This effect is still seen for the CSF with $\Delta t = 10$ Myr, and the SED becomes the reddest when star formation continues for a reasonable duration. Therefore, we adopt the spectrum of the CSF model with $\Delta t = 500$ Myr aged 1 Gyr as the old population spectrum.

Next, we examine the fraction of the old component to the whole system at 4.5 $\mu$m. We test the fraction of 25%, 50%, and 75%, and find that the fraction of 25% is too small to affect the result, and 75% shows a larger effect than 50% to reduce the best-fit values of $E(B-V)$. Hence, we fix the fraction to 75%.

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8 The onset of star formation of the 1 Gyr old stellar population at $z \sim 4.5$ is $z \sim 13$.

9 If we take a much larger fraction, the SED of the young population shows an unrealistic shape.
We then subtract the old population from the observed SED and make the same SED fitting to the residual as we did in Section 3. Here, we assume that there is no dust extinction in the old component.

The results are shown in Figures 14 and 15. Note that the value of age and $E(B - V)$ in the two-component model is for the young population, not for the entire galaxy. As expected, galaxies that have a large value of $E(B - V)$ in the one-component model tend to show a lower value in the two-component model and show a lower SFR by $\sim 0.2$ dex. However, the difference is not that large—the two-component model can decrease the excess in SFRs only subtly. We present an example of this kind of galaxy in the top panel of Figure 16.

Interestingly, some galaxies show a larger $E(B - V)$ and SFR in the two-component model than in the one-component model. An example of such a galaxy is shown in the bottom panel of Figure 16. We find that this kind of galaxy is
interpreted as an almost passive galaxy in the one-component model because of its moderately red color from rest UV to optical, although there seems to be some excess in the 3.6 μm band. In the two-component model, most of its rest-optical light comes from the old population, thus the young population needs to be faint in the rest optical, which prefers a younger and bluer star-forming population. On the other hand, the young population must reproduce the moderately red color of the rest UV, thus the young population has a higher angular resolution and compare the spatial distribution between rest UV and optical, which is expected to correspond to the star-forming component and old component, respectively. JWST will enable us to conduct such observations.

**Figure 16.** Examples of the SED fitting. Top: an example galaxy whose best-fit $E(B-V)$ decreases in the two-component model. The left and right panels show the best-fit SED by one-component and two-component models, respectively. Bottom: an example galaxy whose best-fit $E(B-V)$ increases. In both panels, black points with error bars represent the observed SED of each object. The blue solid line represents the best-fit model spectrum of the entire galaxy, whose flux densities in each band are shown with red crosses. The blue and red dotted lines in the right panel shows the best-fit spectra of young and old populations, respectively. We only show the result in the case of an exponentially declining SFH model with $\tau = 100$ Myr and the Calzetti extinction law for the one-component model and the young population in the two-component model.

In conclusion, when the two-component model is adopted, there seem to be two groups of galaxies: in one group, the best-fit values of $E(B-V)$ and SFR decrease, while in the other group their best-fit values increase. Galaxies with SFR $\geq 10^{1.5} M_\odot$ yr$^{-1}$ by the one-component model tend to belong to the former, and the two-component model reduces their best-fit SFR values by $\sim 0.2$ dex. Galaxies with SFR $\leq 10^{1.5} M_\odot$ yr$^{-1}$ by the one-component model tend to belong to the latter, and the two-component model increases their SFR to $\sim 10^{1.1}$–$10^{1.5} M_\odot$ yr$^{-1}$. Therefore, adopting the two-component model reduces the number density of galaxies with the largest SFR ($\geq 10^2 M_\odot$ yr$^{-1}$) and increases that of galaxies with intermediate SFR ($\sim 10^{1.1}$–$10^{1.5} M_\odot$ yr$^{-1}$) (c.f. Figures 8 and 9).

To determine whether such a two-component model is the case or not, it is necessary to observe their rest-optical light with a higher angular resolution and compare the spatial distribution between rest UV and optical, which is expected to correspond to the star-forming component and old component, respectively. JWST will enable us to conduct such observations.

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