Search for Hα Emitters at \(z \sim 7.8\): A Constraint on the Hα-based Star Formation Rate Density

Yoshisasa Asada© and Kouji Ohta©

Department of Astronomy, Kyoto University, Sakyo-ku, Kyoto 606-8502, Japan; asada@kusastro.kyoto-u.ac.jp

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Abstract

We search for H\(\alpha\) emitters at \(z \sim 7.8\) in four gravitationally lensed fields observed in the Hubble Frontier Fields program. We use the Lyman break method to select galaxies at the target redshift and perform photometry in the Spitzer/IRAC 5.8 \(\mu\)m band to detect H\(\alpha\) emission from the candidate galaxies. We find no significant detections of counterparts in the IRAC 5.8 \(\mu\)m band, and this gives a constraint on the H\(\alpha\) luminosity function (LF) at \(z \sim 7.8\). We compare the constraint with previous studies based on rest-frame UV and far-infrared observations using the correlation between the H\(\alpha\) luminosity and the star formation rate. Additionally, we convert the constraint on the H\(\alpha\) LF into an upper limit for the star formation rate density (SFRD) at this epoch assuming the shape of the LF. We examine two types of parameterization of the LF and obtain an upper limit for the SFRD of \(\log_{10}(\rho_{\text{SFR}} [M_\odot \text{yr}^{-1} \text{Mpc}^{-3}]) \lesssim -1.1\) at \(z \sim 7.8\). With this constraint on the SFRD, we present an independent probe into the total star formation activity including dust-obscured and unobscured star formation at the Epoch of Reionization.

Unified Astronomy Thesaurus concepts: High-redshift galaxies (734); Strong gravitational lensing (1643); Galaxy evolution (594); Galaxy formation (595)

1. Introduction

One of the ultimate goals of extragalactic astronomy is the accurate quantification of the cosmic star formation history. Clarifying how many stars formed across cosmic time reveals the mass assembly of galaxies, which is crucial to understand galaxy formation and evolution. So far, a rough consensus has been reached that the cosmic star formation was most intensive at \(z \sim 2-3\), 2–3 billion years after the Big Bang, and got weaker with time to the present universe (e.g., Madau & Dickinson 2014).

However, the evolution of the star formation rate density (SFRD) before the peak at \(z \sim 2-3\) is still controversial. In this redshift range, most investigations have made use of rest-frame UV observations. Since UV light can be easily attenuated by dust, the correction for the loss of light due to this attenuation is essential to properly evaluate the total star formation rate (SFR). Based on the dust-corrected rest-frame UV observation, the total SFRD beyond \(z \sim 3\) is thought to decrease as the redshift increases (e.g., Bouwens et al. 2020). SFRD measurements through far-infrared (FIR) observations in this redshift range have also become available recently. The FIR can probe the dust-obscured star formation (SF) activity; thus comparing the results based on rest-frame UV and FIR observations enables us to see whether the correction for the dust extinction is appropriate. In Rowan-Robinson et al. (2016), the dust-obscured SF activity at \(3 \leq z \leq 6\) is estimated to be dominant over the dust-unobscured SF, and the total SFRD is suggested to be as large as that at \(z \sim 2\). Recent Atacama Large Millimeter/submillimeter Array observations also suggest that the contribution of dust-obscured SF is significant particularly in UV-bright galaxies even at \(z \geq 7\) (Schouw et al. 2021). By contrast, in Koprowski et al. (2017), the dust-obscured SF activity at \(3 \leq z \leq 5\) is estimated to be small and its contribution is negligible, which is consistent with the estimation based on the dust-corrected rest-frame UV observation. Therefore, an independent investigation is desired to measure the SFRD at \(z \geq 3\) more robustly.

As an independent tracer of the SF activity, the H\(\alpha\) emission line is one of the most ideal indicators. There is a tight correlation between the H\(\alpha\) luminosity and the SFR among star-forming galaxies (see e.g., a review by Kennicutt 1998) and dust extinction has much less of an effect on the H\(\alpha\) emission than on the rest-frame UV light. Therefore, H\(\alpha\) emission is expected to give an independent assessment of the SFRD.

At \(z \geq 3\), H\(\alpha\) emission is redshifted and observed at \(\lambda \gtrsim 2.5 \mu\m\), so it is difficult to observe it with ground-based telescopes, and observations with a space telescope are needed. With the current facilities, Spitzer/IRAC is the most suitable for the observation of this wavelength range, and H\(\alpha\) emission is strong enough to boost IRAC broadband photometry and thus can be detected with IRAC (e.g., Yabe et al. 2009; Stark et al. 2013). To recognize H\(\alpha\) emission with broadband photometry, not only is photometry at the broadband where the line falls needed, but photometry at longer wavelengths free from any other emission lines is also crucial. Without an observation at a longer wavelength, the flux boosting by emission lines can also be interpreted as the presence of the dust reddening and/or old stellar continuum emission.

IRAC has four broadband filters (3.6, 4.5, 5.8, and 8.0 \(\mu\m\) bands), and the H\(\alpha\) emission from \(z \sim 4.5, 5.8, 7.8\), and 11 galaxies falls into each filter, respectively. However, for \(z \sim 11\) galaxies, an observation at the wavelength longward of the H\(\alpha\) emission cannot be conducted with IRAC, and it would be difficult to measure the H\(\alpha\) flux as mentioned above. Thus, H\(\alpha\) emission from \(z \sim 4.5, 5.8,\) and 7.8 can be probed with IRAC. Very recently, in Asada et al. (2021), the SFRD at \(z \sim 4.5\) has...
been estimated based on spectral energy distribution (SED) fitting by taking into account the effect of H\(\alpha\) emission, but an H\(\alpha\)-based SFRD at \(z \sim 5.8\) and 7.8 have not been probed yet. In particular, the H\(\alpha\) emission from a galaxy at \(z \sim 7.8\) has never been reported due to its faintness.

To investigate distant and/or less luminous galaxies, the gravitational lensing effect is a powerful tool. Massive matter overdensities such as galaxy clusters can deflect the light ray from sources behind, which works just as a lens does and brightens the apparent magnitude. The Hubble Frontier Fields (HFF; P.I.: Lotz et al. 2017) program conducted the deepest observations toward six massive clusters with the Hubble Space Telescope (HST): A2744, MACSJ0416, MACSJ0717, MACSJ1149, AS1063, and A370 (Lotz et al. 2017), and these cluster regions are also observed with Spitzer. A number of studies of high-\(z\) galaxies have been published using the HFF data and it has been shown that strong gravitational lensing is effective to investigate the properties of galaxies down to intrinsically faint regions (e.g., Atek et al. 2015; Bhatawdekar et al. 2019; Kikuchihara et al. 2020).

In this paper, we aim to investigate the SFRD using the H\(\alpha\) emission line at \(z \sim 7.8\), which is the highest redshift that can be probed with IRAC. H\(\alpha\) emission is probed by the 5.8 \(\mu\)m band at this redshift. To investigate intrinsically faint galaxies, we utilize the gravitational lensing effect. This paper is structured as follows. In Section 2, we describe the data and perform the photometry to make a sample of galaxies. Using the photometric catalogs, we search for H\(\alpha\) emitters at \(z \sim 7.8\) and present the resulting constraint on the H\(\alpha\) luminosity function (LF) and the SFRD in Section 3. Discussions are given in Section 4. Section 5 gives the summary of this paper. Throughout this paper, all magnitudes are quoted in the photometric catalogs, and we use the Salpeter initial mass function (IMF). We also assume the cosmological parameters of \(H_0 = 70\) km s\(^{-1}\) Mpc\(^{-1}\), \(\Omega_m = 0.3\), and \(\Omega_{\Lambda} = 0.7\).

### 2. Data

Among the six clusters in the HFF, images in the 5.8 \(\mu\)m and 8.0 \(\mu\)m bands are available for four clusters (A2744, MACSJ0717, AS1063, and A370), and thus we focus on these cluster regions. The mosaic and weight images of Spitzer/IRAC observations are also available. As for the mass distribution model, we use the latest model created by The Clusters As Telescopes (CATS) team (Richard et al. 2014; i.e., Version 4 model for A370 and Version 4.1 model for the other three clusters).

#### 2.1. Photometric Catalog

We use the Lyman break method to create a sample of galaxies at 6.9 < \(z\) < 8.6, where the H\(\alpha\) emission line falls into the 5.8 \(\mu\)m band. This target range of redshift can be covered by \(i_814\)- and \(Y_{105}\)-dropouts. Thus, we first construct photometric catalogs to obtain these Lyman Break Galaxy (LBG) candidates.

To measure the HST color accurately, we homogenize the point-spread function (PSF) of the HST images. Using IRAF, we measure the sizes of the PSF in HST images at the \(i_{814}\), \(Y_{105}\), \(J_{125}\), \(H_{140}\), and \(H_{160}\) bands and convolve them with a Gaussian kernel to match the PSF sizes to the largest one. In addition, we also make a stacked image of \(B_{435} + V_{606}\). We then run SExtractor (version 2.19.5; Bertin & Arnouts 1996) in dual-image mode to perform the photometry in each band. The \(J_{125}\) and \(H_{140}\) images are used as the detection images, and two photometric catalogs are constructed for each cluster field (we refer to them as the J-selection catalog and the JH-selection catalog, respectively). We use aperture magnitudes with a diameter of 0\(\prime\)36 for the PSF homogenized images, and 0\(\prime\)20 for the unconvolved images (i.e., \(B_{435}\), \(V_{606}\), and \(B_{435} + V_{606}\) images). The limiting magnitudes are also measured with this diameter and are shown in Table 1.

#### 2.2. Sample Selection and IRAC Photometry

Using the photometric catalogs, we make a sample of candidate galaxies whose H\(\alpha\) emission falls into the IRAC 5.8 \(\mu\)m band. For \(i_814\)-dropout, we use the J-selection catalog and adopt the selection criteria that are used by Ishigaki et al. (2018; 118, hereafter):

\[
i_{814} - Y_{105} > 0.8, \tag{1}\]
\[
Y_{105} - J_{125} < 0.8, \tag{2}\]
\[
i_{814} - Y_{105} > 2(Y_{105} - J_{125}) + 0.6. \tag{3}\]

We require the signal-to-noise ratio (S/N) in both the \(Y_{105}\) and \(J_{125}\) bands to be larger than 5\(\sigma\). In addition, we exclude any object whose S/N in both the \(B_{435}\) and \(V_{606}\) bands or in the \(B_{435} + V_{606}\) stacked image is larger than 2\(\sigma\). The detection threshold in the \(i_{814}\) band is set to be 3\(\sigma\).

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1. https://archive.stsci.edu/prepds/frontier/
2. https://doi.org/10.17909/T9KK5N
3. https://irsa.ipac.caltech.edu/data/SPITZER/Frontier/overview.html

### Table 1

| Band | \(B_{435}\) | \(V_{606}\) | \(B_{435} + V_{606}\) | \(i_{814}\) | \(Y_{105}\) | \(J_{125}\) | \(H_{140}\) | \(H_{160}\) | [3.6] | [4.5] | [5.8] | [8.0] |
|------|-------------|-------------|-------------------|-------------|-------------|-------------|-------------|-------------|-----------|-----------|-----------|-----------|
| Diameter | 0\(\prime\)20 | 0\(\prime\)20 | 0\(\prime\)20 | 0\(\prime\)36 | 0\(\prime\)36 | 0\(\prime\)36 | 0\(\prime\)36 | 0\(\prime\)36 | 2\(\prime\)64 | 2\(\prime\)76 | 2\(\prime\)52 | 2\(\prime\)64 |
| A370  | 29.61       | 29.72       | 30.28            | 28.85       | 28.91       | 28.65       | 28.75       | 28.93       | 25.05      | 24.89      | 23.13      | 24.05     |
| A2744 | 29.79       | 29.78       | 30.33            | 28.79       | 29.05       | 28.83       | 28.83       | 28.87       | 25.12      | 25.07      | 22.49      | 22.16     |
| MACSJ0717 | 29.40       | 29.76       | 30.16            | 28.72       | 28.71       | 28.50       | 28.53       | 28.36       | 24.31      | 24.47      | 20.97      | 20.93     |
| AS1063 | 29.47       | 29.59       | 30.36            | 28.88       | 29.10       | 28.86       | 29.03       | 28.67       | 25.10      | 24.89      | 22.14      | 22.29     |

**Note.**

- Limiting magnitudes are measured for the PSF homogenized images.
For $Y_{105}$-dropout, we use the $JH$-selection catalog and adopt the selection criteria that are used by I18 again:

\begin{align}
Y_{105} - J_{125} &> 0.5, \quad (4) \\
J_{125} - H_{140} &< 0.5, \quad (5) \\
Y_{105} - J_{125} &> 1.6(J_{125} - H_{140}) + 0.4. \quad (6)
\end{align}

We require the S/N in both the $J_{125}$ and $H_{140}$ bands to be larger than 5σ. In addition, we exclude any object whose S/N in the $B_{435}$, $V_{606}$, or $i_{814}$ band image is larger than 2σ. The detection threshold in the $Y_{105}$ band is set to be 3σ.

The selection efficiency against redshift is shown in Figure 1 for both the $i_{814}$-dropout and $Y_{105}$-dropout selections (a detailed explanation of Figure 1 is given in Section 4.2). As seen in Figure 1, these selections are insensitive to galaxies at $z \sim 7$. To supplement our LBG sample with galaxies at $z \sim 7$, we set additional criteria as follows:

\begin{align}
i_{814} - J_{125} &> 1.0, \quad (7) \\
i_{814} - J_{125} &> 10(J_{125} - H_{140}) - 0.2. \quad (8)
\end{align}

The criterion of Equation (7) is applied only to galaxies that are detected in the $i_{814}$ band. We require the S/N in both the $Y_{105}$ and $J_{125}$ bands to be larger than 5σ. In addition, we exclude any object whose S/N in both the $B_{435}$ and $V_{606}$ bands or in the $B_{435} + V_{606}$ stacked image is larger than 2σ. The detection threshold in the $i_{814}$ band is set to be 3σ. The selection efficiency of the additional criteria is also shown in Figure 1.

A total of 229 galaxies are selected as our sample by the three color–color criteria. Among the $i_{814}$-dropout or $Y_{105}$-dropout galaxies reported in the four cluster regions by I18, 33 galaxies are not included in our sample of galaxies, mainly because a stacked deep image was used as the detection image in I18 but not in this study. Therefore, we add the 33 galaxies detected in I18 to our sample of galaxies. A visual inspection is conducted to remove spurious sources for each galaxy, and about half of them are removed. Most of the spurious sources are misidentifications of the tails of bright stars or the bad pixels at the edge of the image. We also exclude galaxies whose redshift is spectroscopically confirmed not to be in the range of our target redshift (Hu et al. 2002; Richard et al. 2014; Vanzella et al. 2014; Karman et al. 2015; Lagattuta et al. 2017; Mahler et al. 2018). As a result, a total of 125 galaxies are selected as our sample.

For each galaxy in the sample, we measure the photometry in the Spitzer/IRAC bands. To prioritize detection, we use aperture photometry with the optimum radius ($r_{\text{opt}} \sim 0.673\text{FWHM}$), which results in the S/N best for point sources. The center of aperture photometry is fixed to the position in the HST image that is used for detection. The systematic difference in the astrometry between the HST and Spitzer images is typically less than $\sim0''.1$. The limiting magnitudes for each IRAC image with this aperture photometry are performed and are also shown in Table 1.

3. Results

3.1. Constraint on H$_\alpha$ LF

We find no significant detection in the IRAC 5.8 μm band at each position of the sample galaxies. Four examples are shown in Figure 2. Nevertheless, the H$_\alpha$ LF at $z \sim 7.8$ can be constrained by the fact that no H$_\alpha$ emitter at $z \sim 7.8$ is found by this survey. To derive the constraint, in this section, we first derive the limiting luminosity of the H$_\alpha$ emission, and put a constraint on the H$_\alpha$ LF considering the gravitational lensing effect.

Using the flux density that corresponds to the detection limit of the 5.8 μm band ($F_{\text{lim}}^\text{cont}$) and the bandwidth of the 5.8 μm band ($W_\lambda$), the limiting flux of the 5.8 μm band can be written as $F_{\text{lim}}^\text{all} = F_{\text{lim}}^\text{cont} W_\lambda$. This limiting flux is attributed to the continuum ($F_{\text{lim}}^\text{cont}$) and the H$_\alpha$ emission ($F_{\text{lim}}^\text{line}$), and thus the following equation holds:

$$F_{\text{lim}}^\text{all} = F_{\text{lim}}^\text{cont} + F_{\text{lim}}^\text{line}. \quad (9)$$

Considering that the maximum rest-frame equivalent width (EW) of H$_\alpha$ is 4000 Å (e.g., Inoue 2011), we obtain

$$\text{EW}_{\text{obs}} = \frac{F_{\text{lim}}^\text{line}}{F_{\text{cont}}^\text{line}} < 4000(1+z) \sim 35000 \text{ Å}. \quad (10)$$

Since the contribution of the continuum to the limiting flux can be calculated as $F_{\text{lim}}^\text{cont} = F_{\text{lim}}^\text{all} W_\lambda$, the ratio of contributions must obey the following inequality:

$$F_{\text{lim}}^\text{line} < 35,000 F_{\text{cont}}^\text{line} = \frac{35,000}{W_\lambda} F_{\text{lim}}^\text{all}. \quad (11)$$

Therefore, the limiting flux of H$_\alpha$ emission can be evaluated as follows:

\begin{align}
F_{\text{lim}}^\text{line} &= \frac{F_{\text{lim}}^\text{line}}{F_{\text{lim}}^\text{all}} F_{\text{lim}}^\text{all} \\
&= \frac{1}{1 + (F_{\text{lim}}^\text{cont}/F_{\text{line}}^\text{all})} F_{\text{lim}}^\text{all} \\
&< \frac{1}{1 + (W_\lambda/35,000)} F_{\text{lim}}^\text{all} \approx \frac{5}{7} F_{\text{lim}}^\text{all}. \quad (12)
\end{align}

Here, we use the value of the bandwidth of the 5.8 μm band $W_\lambda = 14,000$ Å. In the following, we use the maximum value for $F_{\text{lim}}^\text{line}$ to define the (apparent) limiting luminosity of the H$_\alpha$ emission.
emission line in this observation as

\[
L_{\text{line}}^{\lim} = \frac{5}{7} 4\pi d_L^2 F_{\text{all}}^{\lim},
\]  

(13)

where \(d_L\) is the luminosity distance to \(z = 7.8\).

No H\(\alpha\) emission is detected with the observation whose limiting line luminosity of the H\(\alpha\) emission is \(L_{\text{line}}^{\lim}\); thus the H\(\alpha\) LF can be constrained. The constraint on the LF at an intrinsic H\(\alpha\) luminosity \((L_{\text{H}\alpha}^{\text{int}})\) is

\[
\phi(L_{\text{H}\alpha}^{\text{int}}) < \frac{1}{V_{\text{eff}}(L_{\text{H}\alpha}^{\text{int}})}. 
\]  

(14)

Here, \(V_{\text{eff}}(L_{\text{H}\alpha}^{\text{int}})\) is the effective volume in which we search for galaxies with an H\(\alpha\) luminosity of \(L_{\text{H}\alpha}^{\text{int}}\). Using the comoving volume per unit solid angle from \(z = 6.9\) to \(z = 8.6\) \((dV)\), this effective volume can be calculated as

\[
V_{\text{eff}}(L_{\text{H}\alpha}^{\text{int}}) = \int_{\mu_{\text{lim}}}^{\mu_{x}} d\mu \int_{L_{\text{H}\alpha}^{\text{int}}}^{L_{\text{H}\alpha}^{\text{int}}} dL_{\text{H}\alpha}^{\text{int}} \Omega_{\mu \geq x} d\Omega, 
\]  

(15)

where \(\Omega_{\mu \geq x}\) is the solid angle in the source plane where the magnification factor \(\mu\) is larger than \(x\), and \(\mu_{\text{lim}}\) is the minimum magnification factor to detect the H\(\alpha\) emission of \(L_{\text{H}\alpha}^{\text{int}}\). Here, we assume the source plane to be at \(z = 7.8\), and use 2\(\sigma\) limiting magnitudes at the 5.8 \(\mu\)m band. We show the \(\Omega_{\mu \geq x}\) for each cluster region in Figure 3.

The result is shown in Figure 4. The red shaded region is ruled out by our nondetection. If the intrinsic H\(\alpha\) luminosity is larger than the apparent limiting luminosity \((L_{\text{H}\alpha}^{\text{int}} < L_{\text{H}\alpha}^{\text{int}})\), such a galaxy can be detected with this observation wherever it is located; thus the effective volume and the upper limit for the number density do not change with \(L_{\text{H}\alpha}^{\text{int}}\). However, if the intrinsic H\(\alpha\) luminosity is smaller than the apparent limiting luminosity \((L_{\text{H}\alpha}^{\text{int}} < L_{\text{line}}^{\lim})\), such a galaxy must be located in a region whose magnification factor is larger than \(\mu_{\text{lim}}\) to be detected with this observation. Thus, the effective volume for such a galaxy changes with \(L_{\text{H}\alpha}^{\text{int}}\). As can be seen in Figure 3, a larger minimum magnification factor corresponds to a smaller effective volume. Therefore, the upper limit for the number density of galaxies with \(L_{\text{H}\alpha}^{\text{int}}\) becomes less tight as \(L_{\text{H}\alpha}^{\text{int}}\) becomes smaller.

We compare this result to previous works using rest-frame UV observations and FIR observations through the SFR. In the conversion, we use the following relations:

\[
L_{1500} = \left( \frac{8.0 \times 10^{27}}{\text{erg s}^{-1} \text{Hz}^{-1}} \right) \left( \frac{\text{SFR}}{M_{\odot} \text{yr}^{-1}} \right), 
\]  

(16)
The SFRF based on FIR observation at $z \sim 5$ The SFRF based on FIR observations is not currently probed at $z \sim 5$.

Equations (16) and (17) are given by Madau et al. (1998) and Kennicutt (1998), respectively. These conversion factors can change with an assumption of a different IMF (e.g., a Chabrier03 IMF, Chabrier 2003) or a lower stellar metallicity. However, both conversion factors change similarly. For example, when the Chabrier03 IMF is assumed instead of the Salpeter IMF, both conversion factors get larger by $\sim 0.2$ dex. When a lower stellar metallicity ($Z = 0.1 Z_\odot$) is assumed, both conversion factors get larger by $\sim 0.1$ dex. This indicates that our comparison shown in Figure 4 does not change even if a different IMF or metallicity is assumed because the offsets on the conversion factors cancel out.

We first compare the forbidden region to the dust-obscured SFRF based on an FIR observation at $z \sim 6$ by Rowan-Robinson et al. (2016),\(^5\) which is shown by a red solid line in Figure 4. If we assume that the dust-obscured SFRF does not evolve from $z \sim 6$ to $z \sim 7.8$,\(^6\) we can see that the SFRF at $z \sim 6$ is marginally consistent, or is likely to overestimate the number density and/or the SFR value. Considering that this SFRF at $z \sim 6$ is derived using extremely high SFR galaxies ($SFR \sim 10^5 M_\odot$ yr$^{-1}$ at $L_{H\alpha} \sim 10^{45}$ erg s$^{-1}$) and extrapolating it fainter, the comparison suggests the extrapolation is invalid. However, the FIR LF is obtained at $z \sim 6$ and not at $z \sim 7.8$, and thus the comparison can also suggest a negative cosmological evolution of the dust-obscured SFRF from $z \sim 6$ to $z \sim 8$.

To compare the forbidden region with the previous studies based on rest-frame UV observations, we correct the rest-frame UV LF for dust extinction following the procedure presented by Smit et al. (2012). We use the relation between the rest-frame UV spectral slope $\beta$ and the amount of dust extinction at rest-frame UV $A_{1600}$ given by Meurer et al. (1999) and a relation between $\beta$ and the (dust-uncorrected) rest-frame UV absolute magnitude $M_{UV}$ at $z \sim 8$ by Bouwens et al. (2014) to calculate the amount of dust extinction, and to correct the (dust-uncorrected) rest-frame UV LF at $z \sim 8$ by Bouwens et al. (2015). As can be seen in Figure 4, the dust-corrected UV LF does not violate the forbidden region, which suggests that the dust correction with this method is acceptable.

3.2. Constraint on the SFRD

With the nondetection of H$\alpha$ emitters at $z \sim 8$, we can put a constraint on the total SFRD at this epoch. To calculate the upper limit for the SFRD from the forbidden region for the H$\alpha$ LF, it is necessary to assume a shape for the LF. In this work, two types of parameterization of the LF are assumed: the Saunders et al. (1990) functional form and the Schechter function, which are often used in the context of FIR and rest-frame UV observations, respectively.

3.2.1. Saunders Function

To parameterize FIR LFs, a functional form that behaves as a power law in the low luminosity region and behaves as a Gaussian in the high luminosity region is commonly adopted (Saunders et al. 1990):

$$\phi(L) d(log L) = \ln(10) \phi^s \left( \frac{L}{L_s} \right)^{1-\alpha} \exp \left[ -\frac{\log^2 \left(1 + \frac{L}{L_s}\right)}{2\sigma^2} \right] d(log L).$$

In Rowan-Robinson et al. (2016), this functional form is used to fit to the FIR LF, and the parameters of $\alpha$, $\sigma$, and $\phi^s$ are found to be constant at $z > 3.5$. Thus, we fix $\alpha$, $\sigma$, and $\phi^s$ to those values found by Rowan-Robinson et al. (2016) and examine the upper limit for $L_{H\alpha}^*$ using the forbidden region to obtain the upper limit for the SFRD with this functional form. Consequently, we obtain the upper limit for $L_{H\alpha}^*$ of $4.65 \times 10^{42}$ erg s$^{-1}$ (Figure 5(a)) and for the SFRD we find $\log_{10}(\rho_{SFR} [M_\odot$ yr$^{-1}$ Mpc$^{-3}$]) $< -1.19$. The lower bound of the integration to calculate the SFRD is set to be $L_{H\alpha} = 4.44 \times 10^{40}$ erg s$^{-1}$, which corresponds to SFR $\sim 0.34 M_\odot$ yr$^{-1}$ or $M_{UV} \sim -17$ mag. The result is shown in Figure 5(c).

3.2.2. Schechter Function

To parameterize (dust-uncorrected) rest-frame UV LFs, a Schechter function is commonly used:

$$\phi(L) d(log L) = \ln(10) \phi^s \left( \frac{L}{L_s} \right)^{\alpha+1} \exp \left[ -\frac{L}{L_s} \right] d(log L).$$

To derive the upper limit for the SFRD at $z \sim 8$ with this functional form, we use a (dust-uncorrected) rest-frame UV LF at $z \sim 8$ parameterized with this function, and examine the upper limit for the amount of dust extinction using the forbidden region by converting the dust-corrected UV LF to the H$\alpha$ LF through the SFR.
The amount of dust extinction depends on the rest-frame UV luminosity. Observations and simulations reported that brighter galaxies tend to suffer from heavier dust extinction (e.g., Smit et al. 2012; Yung et al. 2019; Asada et al. 2021). Thus, we assume that the correction factor \( \eta \) can be written as

\[
\eta = aL^b, \tag{21}
\]

where \( L \) and \( L_{\text{int}} \) are the dust-uncorrected and dust-corrected rest-frame UV luminosities.\(^7\) For simplicity, we also assume that the correction factor is unity at the faint-end region, i.e., there is no dust extinction in the faintest galaxies, which leads to the following relation:

\[
1 = a \left( \frac{3 \times 10^{26}}{\text{erg s}^{-1} \text{Hz}^{-1}} \right)^b. \tag{22}
\]

With these formulations, the dust-corrected rest-frame UV LF can be written as

\[
\phi(L_{\text{int}})d(L_{\text{int}}) = \ln(10)\phi_{\text{int}}^\ast \left( \frac{L_{\text{int}}}{L_{\text{int}}^\ast} \right)^{\alpha_{\text{int}} + 1} \exp \left[ - \left( \frac{L_{\text{int}}}{L_{\text{int}}^\ast} \right)^{1/b} \right] d(L_{\text{int}}), \tag{23}
\]

where \( \alpha_{\text{int}} \), \( \phi_{\text{int}}^\ast \), and \( L_{\text{int}}^\ast \) are defined using the Schechter parameters of \( \alpha \), \( \phi^\ast \), and \( L^\ast \) for the dust-uncorrected UV LF as

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\(^7\) Even if we use the Meurer relation and the \( \beta - M_{\text{UV}} \) relation to estimate the amount of dust extinction, the luminosity dependence of the correction factor can be expressed as Equation (21).
the parameters of obtaining the upper limit for the dust-corrected rest-frame UV LF with SFRD. Here, we use the Schechter parameters for the dust-corrected UV LF at \( z \approx 8 \) given by Bouwens et al. (2015). We obtain the upper limit for the dust-corrected rest-frame UV LF with the parameters of \( (a, b) = (1.37 \times 10^{-17}, 0.637) \), which gives the limit for the SFRD of \( \log_{10}(\rho_{\text{SFR}} [M_\odot \text{ yr}^{-1} \text{ Mpc}^{-3}]) < -1.04 \). The result is shown in Figures 5(b) and (c).

We can immediately see that the upper limits from the two types of parameterization show similar values. This suggests that the constraint on the total SFRD from the nondetection does not change significantly with the assumption of the functional form of the \( H_\alpha \) LF. Comparing these constraints with the estimation by Rowan-Robinson et al. (2016), even if the dust-obscured SF significantly dominates at \( 3 \lesssim z \lesssim 6 \) and the total SFRD is as high as that at \( z \approx 2 \), the total SFRD must decrease moderately by \( z \approx 8 \).

It is worth noting that the result persists with changing assumptions. Recent observational studies suggest the double power-law (DPL) function describes the (dust-uncorrected) rest-frame UV LF at \( z \gtrsim 8 \) better than the Schechter function (e.g., Bowler et al. 2020). Even when a DPL is used instead of the Schechter function to parameterize the dust-uncorrected rest-frame UV LF, the upper limit does not change significantly. Further, even if we fix \( b \) instead of fixing the relation of \( a \) and \( b \), the result is still similar.

4. Discussion

4.1. Effect of Rest-frame UV Selection

In this study, we used the Lyman Break method to make a sample of galaxies at the target redshift, so the rest-frame UV selection can lead to an incompleteness of our sample and affect the result. However, the observations in the \( J_{125} \) and \( H_{140} \) bands by HST that we used for the source extraction are much deeper than that in the IRAC 5.8 \( \mu m \) band that we used to measure the \( H_\alpha \) flux. Thus, the incompleteness originating from the rest-frame UV selection is expected to have a negligible effect on the result.

To quantify this, in the parameter space of the (dust-corrected) rest-frame UV luminosity \( L_{1500}^{\text{int}} \) versus the color excess \( E(B - V) \), we compare the region that can be detected with HST to that which can be detected in the IRAC 5.8 \( \mu m \) band. We assume the redshift of the source to be \( z = 7.8 \), and use Equations (16) and (17) to convert the rest-frame UV luminosity to an \( H_\alpha \) luminosity. We also take into account the contribution by the continuum assuming a value for the rest-frame EW of the \( H_\alpha \) emission line, and calculate the IRAC 5.8 \( \mu m \) band magnitude for a given rest-frame UV luminosity.

\[
\alpha_{\text{int}} = \frac{\alpha - b}{1 + b},
\]

\[
\phi_{\text{int}}^* = \frac{\phi^*}{1 + b},
\]

\[
L_{\text{int}}^* = \eta L^* = aL^{\beta + 1}.\]

Using these equations, we examine the upper limit for the dust-corrected UV LF by changing \( a \) and \( b \) under the relation of Equation (22), which is in turn used to obtain the upper limit for the SFRD. The Astrophysical Journal, 1999

Equation (1980)

\( \alpha \) is 8. The relation between the stellar mass and the \( H_\alpha \) EW by Reddy et al. (2018) is derived for star-forming galaxies at \( z \approx 2.3 \), and the redshift is largely different from that in this study. However, this relation has not been probed above \( z \approx 2.3 \), and thus we use the relation as the fiducial one.

To determine what value to assume for the EW, we roughly estimate the range of EWs for galaxies that are expected to be detected by this survey. First, we set the upper limit for the EW to be 4000 \( \text{Å} \) (e.g., Inoue 2011). There is an anticorrelation between the stellar mass and the EW of the \( H_\alpha \) emission among star-forming galaxies (e.g., Reddy et al. 2018), and thus we can estimate the minimum EW that is expected to be detected by estimating the maximum stellar mass. The effective volume surveyed in this study is \( \sim 10^4 \text{Mpc}^3 \). Considering the galaxy stellar mass function at \( z \approx 8 \) (Song et al. 2016), the expected value for detecting a galaxy with a stellar mass of \( M_* > 10^8 M_\odot \) is below unity. Thus, the stellar mass of a galaxy that is expected to be found in this survey is no larger than \( 10^8 M_\odot \), which corresponds to the \( H_\alpha \) EW of 250 \( \text{Å} \) (Reddy et al. 2018). As a result, the expected range of the \( H_\alpha \) EWs is estimated to be 250 \( \text{Å} \) \( \lesssim \text{EW} \lesssim \text{4000} \text{Å} \).

The comparison is shown in Figure 6. When we make a sample of galaxies based on the rest-frame UV observations with HST, galaxies located below the blue line in this figure will be selected. By contrast, the constraint obtained in this study is derived from the lack of galaxies below the red (or green) line in this figure. Thus, if we consider the amount of dust extinction of the \( H_\alpha \) emission line up to \( ~2 \text{mag} (\sim 1 \text{mag}) \) assuming the Calzetti (SMC) dust extinction law, the effect of missing galaxies due to the rest-frame UV selection on our result is expected to be negligible.

4.2. The Additional LBG Criteria

In Section 2.2, we use additional criteria (Equations (7) and (8)) to complement our sample with galaxies at \( z \approx 7 \). In this subsection, we show how the redshift dependence of the selection efficiency by the criteria is evaluated, and discuss the properties of the sample used in this study.

We first assume the rest-frame UV apparent magnitude and the spectrum of the galaxy (Im-type spectrum by Coleman et al. 1980), and calculate the position in the color–color diagram for each redshift. Intergalactic attenuation by neutral hydrogen is modeled following the prescription by Madau (1995). For each position in the diagram, we then mock the observation taking into account the photometric errors (Gaussian error) 10,000 times and we obtain the 10,000 mock colors of the galaxy to calculate the fraction of mock colors that meet the criteria we used in Section 2.2. We examine this fraction for several values of rest-frame UV apparent magnitude and obtain the effective selection efficiency by taking the weighted mean of them. Here, we adopt the weight according to the apparent magnitude distribution of galaxies in our sample, resulting in an effective rest-frame UV magnitude of \( ~27.9 \text{mag} \).

The result is shown in Figure 1. For comparison, the redshift dependence of the selection efficiency by \( b_{14\text{L}} \) and \( Y_{105\text{drop}} \) selection are also examined in the same way and shown in this figure. We can see that the additional criteria cover the redshift range where both of the \( b_{14\text{L}} \) and \( Y_{105\text{drop}} \) selections are insensitive.

It is worth noting that we do not exclude low-z interlopers or active galactic nuclei (AGNs) from our sample of galaxies. Particularly, the additional criteria can pass low-z interlopers, because we do not set the criteria to exclude local brown

\footnote{Assuming there are linear relations between \( A_{1600} \) and \( \beta \) (e.g., Meurer et al. 1999), and between \( \beta \) and \( M_{14\text{L}} \) (e.g., Bouwens et al. 2014), the parameter \( b \) can be analytically determined.}
4.3. Other Possible Uncertainties on the Result

In the IRAC photometry, we do not conduct any subtraction of foreground sources. If an H$_\alpha$ emitter at $z \sim 7.8$ is blended with a foreground source and obscured in the 5.8 $\mu$m band image, such H$_\alpha$ emission can be missed, which would decrease the effective volume of this survey. However, the effect of foreground sources is expected to be negligible. Among the 123 LBG candidates, only a few galaxies are potentially blended with a foreground source, and none of them are heavily blended and obscured. This indicates that the effect of blending decreases the effective volume of this survey only slightly ($\lesssim 2\%$). The reason for such a small effect is mainly due to the very low depth in the 5.8 $\mu$m band image.

The presence of foreground sources can also have some effect on LBG detection. If a low-z source lies in the projection of a $z \sim 7.8$ LBG, it prevents us from identifying the LBG. Such a projection effect can also reduce the effective volume of this survey.

To quantify this effect, we place 10,000 apertures randomly and examine the fraction of those that meet the shortward wavelength detection criteria ($S/N > 2$ in both the $B_{435}$ and $V_{606}$ bands or in the $B_{435} + V_{606}$ stacked image for $i_{814}$-dropout selection, and $S/N > 2$ in $B_{435}$, $V_{606}$, or $i_{814}$ band images for $Y_{105}$-dropout selection). The fraction of apertures that meet these criteria is determined to be $\sim 6.4\%$ and $\sim 17\%$ of the solid angle in the source plane for $i_{814}$-dropout and $Y_{105}$-dropout selection, respectively. The latter fraction is too large to be ignored. However, our sample is complemented with the additional criteria (Equations (7) and (8)), which use the same criteria for the shortward wavelength detection as for the $i_{814}$-dropout and covers up to $z \sim 8.2$ (Figure 1). Therefore, the effect of projection is expected to be small ($\sim 10\%$).

It is worth noting that both effects of blending and projection move the forbidden region not as a whole. These effects depend on the spatial distribution of the foreground sources, and thus the degree of these effects changes depending on the magnification factor and the intrinsic H$_\alpha$ luminosity (for a fixed observed H$_\alpha$ luminosity).

Finally, cosmic variance is also a source of uncertainty on the result. The area probed by this work is relatively small ($V_{eff} \sim 10^4 Mpc^3$), so the uncertainty that stems from the cosmic variance may be large. However, since we find no H$_\alpha$ emitters, it is difficult to quantitatively estimate the impact of the cosmic variance.

4.4. Constraint on the H$_\alpha$ EW at $z \sim 7.8$

The forbidden region in Figures 4 and 5 depends on the assumed value for the H$_\alpha$ EW: if a larger value is assumed for the H$_\alpha$ EW, the forbidden region moves to the right as a whole. This is because the larger H$_\alpha$ EW we assume, the larger the flux in the 5.8 $\mu$m band is attributed to the H$_\alpha$ emission. Thus, for a fixed limiting flux in the 5.8 $\mu$m band observation, the limiting flux of H$_\alpha$ emission gets larger (smaller) if a larger (smaller) value is assumed for the H$_\alpha$ EW. In this study, we take the maximum value to estimate the most conservative constraint on the H$_\alpha$ LF.

By contrast, the minimum value for the H$_\alpha$ EW can be evaluated by changing the assumed value. Given that the H$_\alpha$ LF converted from the (dust-uncorrected) UV LF (blue solid line in Figure 4) is the lower limit for the H$_\alpha$ LF, the forbidden region must not violate this H$_\alpha$ LF. We examine how small the

dwarfs. However, in this work, we make the sample contain all of the galaxies at the target redshifts, even though the sample can be contaminated with low-z interlopers or AGNs, and perform the photometry in the IRAC 5.8 $\mu$m band for each galaxy in the sample. Because no sample galaxy is detected in the 5.8 $\mu$m band, the contamination with low-z interlopers or AGNs does not affect on the result.

Moreover, in calculating the constraint on the H$_\alpha$ LF, we do not take into account the effect of the selection efficiency (see Equations (14) and (15)), and we assume the selection efficiency to be unity for galaxies whose redshift is in the target range ($6.9 < z < 8.6$). As shown in Figure 1, the selection efficiency is less than unity, and thus taking the effect into account can lead to a decrease in the effective volume and the forbidden region moves up as a whole. However, the shift is only slight (less than 0.1 dex), and the upper limit for the SFRD gets larger only by <0.1 dex.
Hα EW can be such that the forbidden region does not exclude this Hα LF. The minimum value of the Hα EW is determined to be $\sim 60$ Å. This indicates that the Hα EW of the SF galaxies at $z \sim 7.8$ is typically larger than $\sim 60$ Å.

5. Summary

The amount of the contribution by dust-obscured SF to the total SF activity in the high-$z$ universe is still controversial. The SFRD in the high-$z$ universe is mainly probed through rest-frame UV or FIR observations; thus using the Hα emission line can provide an independent constraint. In this study, we search for Hα emitters at $z \sim 7.8$ in several gravitationally lensed fields observed in the HFF program. We make a sample of galaxies at the target redshift with the Lyman break method, and use the IRAC 5.8 μm band to detect Hα emission from galaxies in the sample.

Our main results are as follows:

1. We find no significant detection of counterparts in the 5.8 μm band. This nondetection gives a constraint on the Hα LF at $z \sim 7.8$. We compare this constraint with results of previous studies based on rest-frame UV LFs at $z \sim 8$ and FIR LFs at $z \sim 6$ through the SFR. The dust-corrected rest-frame UV LF is consistent with the constraint. The FIR LF at $z \sim 6$ is not consistent with the constraint if we assume the FIR LF does not evolve from $z \sim 6$ to $z \sim 7.8$. Even if we assume the FIR LF evolves from $z \sim 6$ to $z \sim 7.8$, the FIR LF at $z \sim 7.8$ should not violate the constraint, and this may suggest a negative evolution of the FIR LF from $z \sim 6$ to $z \sim 7.8$ (Section 3.1 and Figure 4).

2. We put a constraint on the SFRD at $z \sim 7.8$ assuming the shape of the Hα LF. We examine two types of functional form and obtain an upper limit for the SFRD of $\log (\rho_{\text{SFR}} [M_\odot \text{yr}^{-1}\text{Mpc}^{-3}]) \lesssim -1.1$ (Section 3.2 and Figure 5).

3. With the constraint on the SFRD at $z \sim 7.8$, even if dust-obscured SF dominates significantly at $3 \lesssim z \lesssim 6$ and the total SFRD at this epoch is as large as that at $z \sim 2$–3 (e.g., Rowan-Robinson et al. 2016), the total SFRD must decrease moderately by $z \sim 8$ (Section 3.2 and Figure 5).

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Software: SExtractor (Bertin & Arnouts 1996), IRAF (Tody 1986, 1993), Astropy (The Astropy Collaboration et al. 2013), APLpy (Robitaille & Bressert 2012).

ORCID iDs

Yoshihisa Asada 🏥 https://orcid.org/0000-0003-3983-5438
Kouji Ohta 🏥 https://orcid.org/0000-0003-3844-1517

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