Probing the Stellar Contents of Star-Forming Galaxies at Re-Ionisation Era

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ABSTRACT

We propose a narrowband imaging survey of star-forming galaxies at re-ionisation era. The survey will exploit the wide-field imaging capability of *SPICA*/MCS by using narrowband filter to detect Hα emission from the redshift $7 \lesssim z \lesssim 10$. We estimated the feasibility of this survey, showing that the number of detectable sources highly depends on the IMF of the stellar population. Since the age constraints are fairly strong at such high redshifts, and extremely young star-forming galaxies are presumably less dusty, the survey should give the first direct and meaningful constraints on the IMF of population III (popIII) star formation.

1. BACKGROUD: DIFFICULTIES IN DERIVING THE STAR-FORMATION HISTORY WITH UV

Recent surveys in optical/NIR wavelengths have revealed star-formation history at high redshifts, now approaching to reionisation era (up to $z \sim 10$: e.g., Bouwens et al. 2011, 2013; Ellis et al. 2013; Oesch et al. 2013). The star-formation history of the universe revealed with these studies provides us with general understanding of galaxy-formation history up to $z \sim 10$, and thus reionisation history of the universe. Also, studies of Lyα emission from high-z galaxies are reaching to redshifts up to $z \sim 7.5$ (Schenker et al. 2012; Ono et al. 2012; Shibuya et al. 2012; Finkelstein et al. 2013). Combined with the UV continuum, the information from the Lyα provides with the neutral fraction of IGM in the high-z universe, leading to detailed measurements of the reionisation history, and search for the photon suppliers for the reionisation. Such studies should be further expanded to higher redshifts in the *JWST* era.

However, these studies are based on the rest-frame UV observations, and the star-formation rates (SFRs) are derived from their UV luminosities. Especially for the survey observations, *JWST* can only probe the rest-UV regime. The future large ground-based telescopes such as TMT or E-ELT cannot probe the rest-frame optical to NIR wavelengths either. In order to probe the *correct* star-formation history at such a high redshifts up to $z \sim 10$, we definitely need information of MIR. For instance, the UV continuum is the most commonly used to derive the SFRs. However, the conversion from the UV luminosity to the SFR usually assumes Salpeter's IMF, solar metallicity, and constant star formation over $\gtrsim 10^8$ yrs (Madau et al. 1998; Kennicutt 1998). These kinds of assumption should not be valid for reionisation era, in which the age of the universe is only several 10^8 yrs.

Even in the low redshifts up to $z \sim 2$, the SFRs derived from the UV luminosities seem to be different from those derived from the Hα luminosities. Figure 1 shows the difference of the SFRs derived from the UV and Hα luminosities in term of the luminosity functions (LFs). The axes on the top and the bottom in this plot are scaled so as to match the SFRs derived from the both quantities (local calibrations; see Figure 2). The difference between the UV- and Hα-based SFRs increases with increasing redshift. Although the dust attenuation is not corrected for these LFs, this tendency should hold at least qualitatively. Observing UV-selected galaxies may thus lead to a significant underestimate of the galaxy number density at high redshifts.

2. THE *SPICA* Hα SURVEY

2.1. Basic Ideas

SPICA/MCS has a wide-field imaging capability, $5' \times 5'$, and the survey speed exceeds that of *JWST* in almost the whole wavelength coverage. Here we propose the narrow-band imaging survey of Hα emitters at $z \gtrsim 7$ to fully exploit the high survey efficiency. This will construct a unique sample of Hα-selected star-formation galaxies, which cannot be surveyed with NIR imaging. Assuming the resolving power of the narrowband $R \sim 100$, we estimated the line sensitivity (5σ, 1 hr) to be $\sim 1 \times 10^{-17}$ erg s^{-1}. We here show the estimates for the $z = 7.0$ and $z = 10.5$ cases for example. Considering the limitation of the available observing time, we assumed the survey coverage to be an order of $\sim$deg^2 observed with $\sim 10^2$ pointings.

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Since the Hα line strength depends on the age, the metallicity, and the IMF, the detectability of the Hα emission strongly reflects these fundamental properties related to the star-formation history. First we show the simplest estimate of the detectability based on observational constraints from the UV LFs available in the literatures. Figure 2 shows the expected number of Hα emitters as a function of the detection limit. The simplest estimates from currently available observations suggests that the number of sources above the detection limit is almost zero: $\sim 10^{-10}$–10^{-8} sources per FoV for $z = 10.5$, and $\sim 10^{-5}$–10^{-4} sources per FoV for $z = 7.0$ if we use the UV LFs from the literatures.

2.2. Dependence of the Number Density of Hα Emitters

The calibration of the SFRs based on the UV continuum, however, may not be a good probe to predict the Hα luminosities (i.e., the detectability) of star-forming galaxies at very high redshifts. If we use the $z \sim 2$ Hα LFs scaled with the cosmic SFRD, the expected number raises to order of 10^{-2} per FoV for $z = 10.5$, and 10^{-1} for $z = 7.0$. Although the detectability

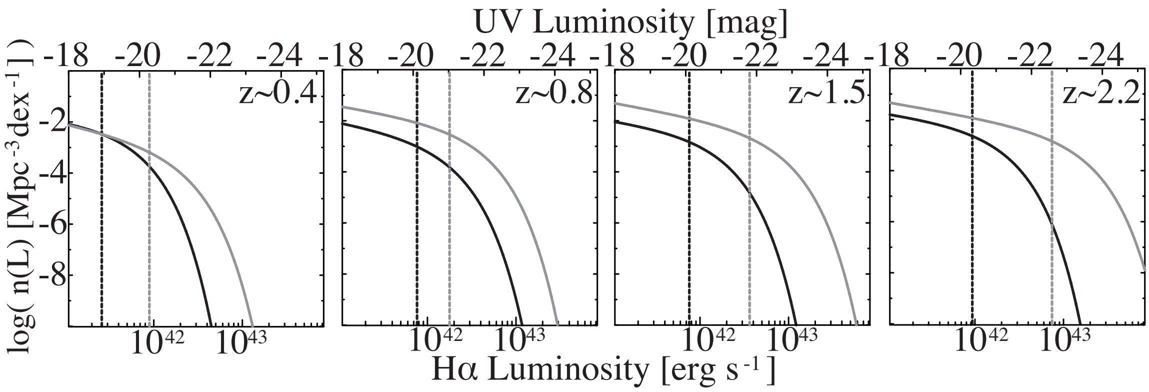

Figure 1. Comparison of the two SFR indicators at four redshift bins, z = 0.4, 0.8, 1.5, and 2.2. For each panel, the grey curve shows the Hα luminosity function (LF), and the vertical grey dotted line shows the L^* at the redshift noted on the upper-right corner (Sobral et al. 2013). The black curve and vertical dotted line show the UV LF and M^* at the corresponding redshift (Arnouts et al. 2005). The top and bottom axes are scaled so as to match the SFRs derived from the both quantities.

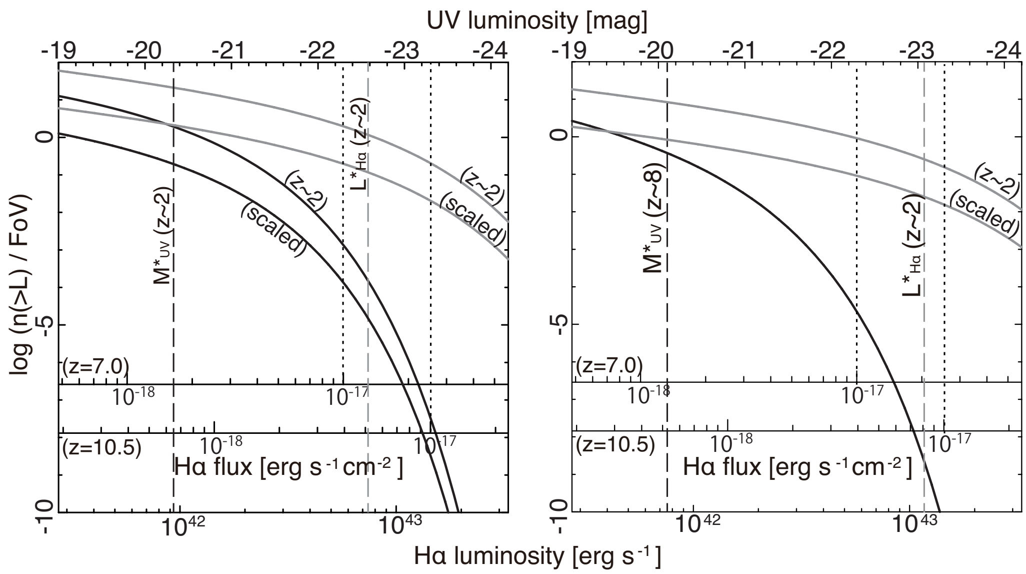

Figure 2. Expected number of Hα emitters at $z = 7.0$ and $z = 10.5$ as a function of the Hα luminosity (bottom axes) and UV luminosity (top axes). The Hα fluxes at $z = 7.0$ and 10.5 are shown on the two axes near the bottom of each panel. The *SPICA*/MCS detection limit at each redshift is shown with the vertical dotted line. (*Left*) Based on $z \sim 2$ observations. The grey curves are based on the Hα LF at $z \simeq 2.2$ from Sobral et al. (2013), and the black curves are based on the UV LF at $z \sim 2$ from Arnouts et al. (2005). The $L^*_{\mathrm{H}\alpha}$ and the M^*_{UV} are shown with the vertical dashed lines. The curves marked "scaled" show the LFs scaled with the cosmic star-formation rate density (SFRD) at $z \sim 10$, assuming that the SFRD is lower than $z \sim 2$ by a factor of ~ 10 as suggested by Hopkins & Beacom (2006). (*Right*) Based on $z \sim 2$ and $z \sim 8$ observations. The symbols are same as the left panel. The Hα LF is taken from Hayes et al. (2010), showing almost the same results as the left panel, and the UV LF is taken from the $z \sim 8$ result of Bouwens et al. (2011).

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might be highly overestimated in the case of using Hα LF at $z \sim 2$, there are some factors causing the significant underestimate of the number of Hα emitters when we use the UV LFs.

Inoue et al. (2011) suggest that low metallicity conditions give larger number of ionising photons, leading to larger Hα luminosities at the given SFRs. The zero-metallicity case gives a factor of ~ 3 larger Hα luminosity, and the LFs shifts rightward on the Figure 2. This gives the number of Hα sources detected here to be $\sim 10^{-4}$ for $z = 10.5$, and $\sim 10^{-2}$ for $z = 7.0$, if galaxies at these epochs are predominantly metal free. Although the number is still very small, the change is quite significant since we are looking at the very bright end of the LF.

Further significant boost of Hα luminosity comes from the stellar IMF. For example, Schaerer (2003) suggests that some cases of IMF with large stellar masses (50–500 $M_{\odot}$) give an Hα luminosity higher by a factor of ~ 10. This corresponds to $\sim 10^{-1}(10^{0})$ sources per FoV for $z = 10.5(7.0)$. If the galaxies at these epochs are dominated by those with IMF that prefer such large stellar masses, $\sim 10^{1}$ of Hα emitters should be detected in total even at $z \sim 10$, and $\sim 10^{2}$ or more at $z \sim 7$. The LF of the Hα emitters at such high redshifts should thus put meaningful constraint on the stellar IMFs of very early-phase star formation like popIII.

3. IMPORTANCE OF THE Hα SURVEY AT $Z > 7$

The number density (i.e., the LF) of Hα emitters thus strongly reflects the properties of star-forming galaxies that determines the correct star-formation history of the universe, especially the IMF. The popIII IMF is totally unknown, and the uncertainties to determine the SFRs or other properties should be much severer at higher redshifts.

Since the UV continuum may not trace correctly the star-formation activities especially at higher redshifts (e.g., Wilkins et al. 2012), studies of alternative SFR indicators should be quite essential. The Hα emission has been extensively used, and is the most well-calibrated SFR indicator. The SFR of galaxies in reionisation era has been studied almost only with the rest-frame UV lights, so that using Hα is quite essential.

Another advantage is that the age constraints are quite strong at such high redshifts. The age of the universe is ~ 0.7 (0.4) Gyr at $z = 7$ (10.5). Considering that the major epoch of popIII star formation is ~ 20, the typical duration of star formation activity is up to ~ 200–500 Myr. The short duration also implies that the amount of dust is presumably small. These facts help us to break the degeneracy between the IMF and the stellar age, and also dust contents. The Hα survey at $z \sim 7$–10 should give the first meaningful constraints on the popIII IMF from direct observations.

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