Identification of variability in recent star formation histories of local galaxies based on Hα/UV ratio

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ABSTRACT
Because the timescale of Hα emission (several tens of Myr) following star formation is significantly shorter than that of UV radiation (a few hundred Myr), the Hα/UV flux ratio provides insight on the star formation histories (SFHs) of galaxies on timescales shorter than ~100 Myr. We present Hα/UV ratios for galaxies at z = 0.02–0.1 on the familiar star-forming main sequence based on the AKARI-GALEX-SDSS archive dataset. The data provide us with robust measurements of dust-corrected SFRs in both Hα and UV for 1,050 galaxies. The results show a correlation between the Hα/UV ratio and the deviation from the main sequence in the sense that galaxies above/below the main sequence tend to have higher/lower Hα/UV ratios. This trend increases the dispersion of the main sequence by 0.04 dex (a small fraction of the total scatter of 0.36 dex), suggesting that diversity of recent SFHs of galaxies has a direct impact on the observed main sequence scatter. We caution that the results suffer from incompleteness and a selection bias which may lead us to miss many sources with high Hα/UV ratios; this could further increase the scatter from SFHs in the star-forming main sequence.

Key words: galaxies: formation – galaxies: evolution – galaxies: general

1 INTRODUCTION
Large galaxy surveys have enabled extensive research on stellar mass assembly histories of galaxies over the last decade, including the derivation that galaxies follow a tight correlation between stellar mass and star formation rate (SFR), i.e. the star-forming main sequence (e.g. Brinchmann et al. 2004; Daddi et al. 2007; Elbaz et al. 2007; Noeske et al. 2007; Whitaker et al. 2012; Shi et al. 2015; Tomczak et al. 2016). This relation suggests that most galaxies evolve into more massive systems by approximately following this tight sequence. The current research focuses on the mechanisms that drive scatter in the main sequence beyond measurement errors, and how galaxies evolve on the mass–SFR diagram and quench their star-forming activities (e.g. Pannella et al. 2009; Peng et al. 2010; Lilly et al. 2013; Genzel et al. 2015; Sparre et al. 2015; Renzini & Peng 2015; Kurczynski et al. 2016; Tacchella et al. 2016).

In this context, the Hα/UV ratio offers a unique tool to constrain the mechanisms that scatter the star-forming main sequence (Sparre et al. 2017). The Hα/UV ratio is defined by the ratio of SFR from Hα luminosity (SFRHα) to that from UV flux density (SFRUV) based on the Kennicutt (1998) prescription. Observed Hα/UV (≡ SFRHα/SFRUV) ratios of galaxies basically exceed one since UV light is more severely affected by dust extinction (Koyama et al. 2015). More importantly, even if one corrects for dust attenuation, Hα/UV ratios of star-forming galaxies may have a considerable scatter (Iglesias-Páramo et al. 2004; Weisz et al. 2012; Guo et al. 2016) because of the time discrepancy of SFR traced by between Hα line (∼10 Myr) and UV radiation (∼200 Myr in FUV) (e.g. Fumagalli et al. 2011; Kennicutt & Evans 2012; Cerviño et al. 2016; Sparre et al. 2017). The commonly-used Kennicutt (1998) SFR calibration assumes continuous star formation history (SFH) lasting over 100 Myr. Thus, a variation of SFHs of galaxies in the last 100 Myr spreads intrinsic values of those Hα/UV ratios. Conversely, we can trace time evolution and variability of recent SFHs for galaxies by assessing the Hα/UV ratio.

This letter reports initial results based on the AKARI-GALEX-SDSS sources amounting to 1,050 objects at z =
0.02–0.1. We estimate dust-corrected SFR$_{H\alpha}$ by the Balmer decrement technique based on the SDSS library (the Sloan Digital Sky Survey; York et al. 2000). We also derive dust-corrected SFR$_{UV}$ by combining UV sources from GALEX (the Galaxy Evolution Explorer; Martin et al. 2005) and far-infrared (FIR) data from AKARI InfraRed Surveyor (Murakami et al. 2007). Our $H\alpha$/UV ratios, based on reliably measured SFR$_{H\alpha,corr}$ and SFR$_{UV,IR}$ values, enable an investigation on the short-time variability of recent SFHs of galaxies.

This letter addresses the effects of the variability in recent SFHs of local galaxies on the scatter of the well-known main sequence based on those dust-corrected $H\alpha$/UV ratios. We also discuss the validity of the often-used Kennicutt (1998) SFR prescription for low-mass objects and describe current issues and visions for the future. This work adopts the Kroupa (2001) initial mass function (IMF) by following the literature highly related to this letter (Kaufmann et al. 2003a; Tremonti et al. 2004; Koyama et al. 2015). We assume a cosmology parameters $H_0 = 70$ km s$^{-1}$Mpc$^{-1}$, $\Omega_M = 0.3$, and $\Omega_\Lambda = 0.7$.

2 DATA

This work is based on the data catalogue made by Koyama et al. (2015). The catalogue is established by the combination of the SDSS Data Release 7 (DR7; Abazajian et al. 2009), the UV source catalogue by GALEX (Martin et al. 2005), and the AKARI Far-Infrared Surveyor (FIS) bright source catalogue (Yamamura et al. 2010). Since the detail of cross-matching is fully explained in Koyama et al. (2015), this letter mainly describes specific information that could affect our key results and conclusions.

The procedures of catalogue matching begin with 135,813 SDSS sources meeting several requirements: redshift between 0.02–0.10, line detections above certain S/N criteria, pure star-forming population judged by the BPT diagram (Kaufmann et al. 2003b), and stellar masses higher than 10$^{5.5}$ M$_\odot$. We here employ stellar masses of the samples from the publicly-available catalogue by Kaufmann et al. (2003a) and Salim et al. (2007). Then, 78,731 galaxies are selected by matching with GALEX UV sources with both NUV and FUV detections. Finally, the sample size drastically decreases down to 1,200 by cross-matching with AKARI FIS sources. This sample is treated as the full AKARI-GALEX-SDSS catalogue in Koyama et al. (2015). Besides, this work only selects galaxies with detections of at least two band receivers (WIDE-S at 90 $\mu$m and WIDE-L at 140 $\mu$m) on AKARI whose total IR luminosities can be reliably measured by the Takeuchi et al. (2010) calibration. Obtained total IR luminosities are $<10^{10}$ (1 %), $10^{10} - 10^{11}$ (73 %), and $10^{11} - 10^{12}$ L$_\odot$ (26 %) in our sample, respectively. We also checked the effect of SDSS fibre corrections and then found that negative fibre corrections lead to exceptionally low $H\alpha$/UV ratios (< $-1$ dex). To avoid this error, we remove a few objects with total SFR$_{H\alpha}$ < fibre SFR$_{H\alpha}$ from the samples. Through these additional selection processes, 1,050 secure objects are finally employed in this letter.

We use the SFR$_{H\alpha,corr}$ and SFR$_{UV,IR}$ values derived by Koyama et al. (2015), based on the Kennicutt (1998) calibration. Dust corrections were made by using the Balmer decrement technique for the H$\alpha$ line assuming Case B recombination (Brocklehurst 1971) and the Calzetti et al. (2000) extinction law, and by adding SFR$_{IR}$ to SFR$_{FUV}$ for UV light (see Koyama et al. 2015 for details). Here, median SFR$_{IR}$/SFR$_{FUV}$ ratio and scatter are 1.22$^{+0.51}_{-0.42}$ dex, and thus, IR fluxes have major contributions to SFR$_{UV,IR}$ in our sample. Typical uncertainties of SFR$_{H\alpha,corr}$ and SFR$_{UV,IR}$ for individuals are 0.06 and 0.3 dex, respectively. Although these random errors affect the scatter in the main sequence and the $H\alpha$/UV ratios, we believe that those impacts on any systematic trend reported in this work should be minor (see §3). Figure 1 indicates a good agreement between obtained SFR$_{H\alpha,corr}$ and SFR$_{UV,IR}$ individually with a dispersion of 0.28 dex. When we first correct dust attenuation of SFR$_{UV}$ based on the FUV–NIR slope under the Calzetti et al. (2000) law, the scatter further increases to ~ 1 dex. Such a significant difference in scatter implies that our SFR estimations are well improved as compared to those more reliant on empirical extinction laws.

However, the cross-matching with AKARI sources (78,731 → 1,200) produces a critical completeness issue. We checked sample integrity as a function of H$\alpha$-inferred SFR in Fig. 1. The figure indicates that the completeness is only 2.6 and 24 per cent above SFR$_{H\alpha,corr}$ > 1 and 10 M$_\odot$/yr, respectively. When we only use the samples at $z = 0.02–0.05$, these values increase to 12 and 85 per cent, respectively, meaning that our data have better sampling coverage for galaxies at lower redshifts (see also Takeuchi et al. 2010). One should note that such a low completeness and a sampling bias might affect our results and conclusions. However, we stress that we could not find any apparent redshift dependence on obtained results in this letter.
3 RESULTS

Based on the selected samples, we investigate how closely the Hα/UV ratio correlates with scatter in the star-forming main sequence. Figure 2 represents stellar mass versus the Hα or UV+(IR) -based SFR for our sample. We see a clear trend in colour-coded Hα/UV ratios on this diagram in the sense that galaxies above/below the Hα-inferred main sequence tend to have higher/lower Hα/UV ratios. On another front, UV+(IR)-based main sequence shows the exact opposite of this trend. Such a tendency is broadly consistent with the correlation between SFRHα,corr/SFRUV and specific SFR found by Domínguez Sánchez et al. (2012). To evaluate this trend more quantitatively, we define the values of deviation from the main sequence (AMS) in the following,

\[
\log(\text{AMS}) = \log(\text{SFR}_{\text{Hα,corr}}/M_\odot \text{yr}^{-1}) - [0.758 \log(M_*/M_\odot) - 7.057],
\]

where the right-hand side indicates the formula of a median-fitted main sequence in SFRHα,corr for the entire sample. We then compare Hα/UV ratio with AMS in Figure 3.

In early star-forming phases, the Hα/UV ratio reaches ~0.5 dex and after quenching reduces to ~1 dex according to the simple model of SFH by Weisz et al. (2012). Indeed, 95 per cent of our obtained Hα/UV ratios fall between ~1 and 0.5 dex. We then explore the 68th percentile distributions of the Hα/UV ratio along the main sequence in two stellar mass bins (M∗ ≤ 1010 or > 1010 M⊙). Massive galaxies have a tight correlation between AMS and the Hα/UV ratio along the one-to-one relation with a dispersion of 0.26 dex (Fig. 3). The Spearman’s rank correlation coefficient shows \( r_s = 0.60 \) with 20σ. We recalculate the coefficient value by following the Jenkins et al. (1986) test (see Appendix B in the literature) to ensure the validity of this strong association since both variables (i.e. AMS and the Hα/UV ratio) depend on the common error of SFRHα,corr. We then confirm that the real correlation coefficient remains significant \( (r_s = 0.57) \). Another concern is the effect of the SDSS fibre correction (Koyama et al. 2015). We assess this impact by conducting the same analysis based on fibre-uncorrected SFRHα,corr, and also by checking fibre correction factors of galaxies and those trends on the main sequence. We then find that this effect seems to weaken the correlation rather than to produce the tight relationship artificially. Thus, the results indicate that the dispersion in the Hα/UV ratio (0.28 dex; Fig. 1) is not only caused by measurement uncertainty but also intrinsic variation in the Hα flux.

On the other hand, less massive galaxies tend to be more scattered (σ = 1.1 dex) and typical Hα/UV ratio declines by 0.14 dex. All these trends are in excellent agreement with past observations (Boselli et al. 2009; Weisz et al. 2012) and the simulation by Sparre et al. (2017) (see §4.2).
4 DISCUSSION AND SUMMARY

4.1 Impact of SFH variability on the main sequence scatter inferred from Hα/UV ratio

Understanding the scatter of the star-forming main sequence has been a controversial topic in recent times. This letter finds an explicit correlation between the dust-corrected Hα/UV ratio and deviation from the main sequence, suggesting that time variability of recent SFH in \( \lesssim 100 \) Myr is a causal factor in the spread on the main sequence. Galaxies in young burst phases tend to be located above the main sequence as inferred from those higher Hα/VU ratios. On the other hand, galaxies under the rapidly declining phase of star formation, expected from those lower Hα/UV ratios, tend to appear below the main sequence (Sparre et al. 2017). The results also could imply that galaxies oscillate across the main sequence by following a repetitive cycle of star formation and subsequent feedback in very short timescale (\( \lesssim 100 \) Myr). However, this scenario conflicts with the anticorrelation between DM and gas depletion timescale (Saintonge et al. 2012; Genzel et al. 2015; Tacchella et al. 2016) which suggests that the timescale of oscillation across the main sequence would be much longer (\( \sim 1 \) Gyr).

Moreover, we should note that the dispersion of Hα/UV ratios (\( \sim 0.3 \) dex) is considerably larger than those reported by past work (\( < 0.1 \) dex) (Weisz et al. 2012). One of the major factors for this inconsistency would be measurement errors of the Hα/UV ratio. Besides, our sample includes quite a few objects with specifically low Hα/UV ratios (\( < -0.5 \) dex), covering 6 per cent of the massive galaxies. Those are thought to be post dusty starbursts since they tend to have high SFR\(_{UV-IR}\) (Fig. 2). Taking account of our extensive survey area and the sampling bias limited to the AKARI detections, the inconsistency may also be due to the fact that past studies miss such unique populations while we preferentially select them.

To examine how SFH variance influences the scatter, we iteratively calculate values for the dispersion of the main sequence as a function of \( \gamma \) where \( \gamma \) is a correction factor defined by \( \log(\Delta MS) = \gamma \log(SFR_{Halpha,corr}/SFR_{UV-IR}) \). As a result, the standard deviation holds a minimum value of 0.32 dex when we employ the correction factor of \( \gamma = 1 \), which decreases by 0.04 dex from the original value (0.36 dex). It should be noted that this decrement is thought to be dependent on the measurement accuracy of the Hα/UV ratio. On the other hand, we still have 0.32 dex dispersion of the main sequence, and thus we think other physical parameters should be more responsible for the scatter, such as variation of gas fraction and concentration of stellar components.

4.2 Hα/UV flux ratios of low-mass systems

Hα/UV ratios of AKARI-detected lower-mass systems (\( M_\star < 10^{10} \) M\(_\odot\)) tend to be lower than those of massive galaxies. This suggests that UV-based SFR calibrations would potentially overestimate the SFRs in many lower mass systems. Such low Hα/UV ratios of less massive objects have been reported by several studies (Weisz et al. 2012; Guo et al. 2016) where they correct dust attenuation based on empirical extinction laws. For example, Weisz et al. (2012) have reported that their model can examine such systematically lower Hα/UV ratios by the burst duration of a few ten Myr by the time period of 250 Myr. This time period is two times longer than that of massive galaxies. Since low-mass galaxies are expected to have higher mass-loading factors due to those shallower potential wells (Muratov et al. 2015), more efficient stellar feedback makes those hard to maintain active star formation in longer timescale, leading higher fraction of temporarily (star formation-)suppressed systems (Sparre et al. 2017, but see also Meurer et al. 2009; Fumagalli et al. 2011). More periodic SFHs would also spread the Hα/UV ratio and may cause the large dispersion of Hα/UV ratios for a given AMS in our samples. However, we should note that our low-mass sample critically fails to catch faint UV(+(IR)) sources i.e. high Hα/UV objects (Fig. 2).

4.3 Hα/UV on the mass–metallicity relation

Comparison of the Hα-based SFR with the UV-inferred SFR reflects the discrepancy of the lifetime between H\(\alpha\) regions (a few ten Myr) and long-lived massive stars (a few hundred Myr). The former one is comparable with the timescale of chemical enrichment of a-elements by core-collapse supernovae. With this motivation, we test if Hα/UV ratios show any systematic trend in gaseous metallicity on the mass–metallicity relation (Tremonti et al. 2004). Gas-phase metallicities of the entire samples are derived from Tremonti et al. (2004), which is based on the line fitting of multi-optical emission lines ([O\textsc{ii}], H\(\beta\), [O\textsc{iii}], H\(\alpha\), [N\textsc{ii}], [S\textsc{ii}]) with the spectral model by Charlot & Longhetti (2001). Although our samples are limited to AKARI detections, it would be still worth discussing the effects of variability of recent SFH on the mass–metallicity relation.

Figure 4 shows gas-phase metallicities as a function
of stellar mass for our samples with high (> 0.3) and low (< -0.3) log Hα/UV ratios. Interestingly, those two groups with M⋆ > 10^{10} M⊙ do not belong to the same parent population according to the Kolmogorov-Smirnov test with 4σ confidence level (PKS = 1 × 10^{-7}), and galaxies with lower Hα/UV ratios tend to have lower Oxygen abundances. We actually expected the opposite trend since galaxies in burst phase might be subjected to metal dilution by inflow as suggested by e.g. Mannucci et al. (2010). However, the obtained result could suggest that metal removal by feedback in rapid declining phase more effectively reduces those Oxygen abundances. One should note that margin of those median values is only 0.05 dex, and thus, further investigation must be needed. We also confirm that such a statistical difference no longer can be seen if we estimate gaseous metallicities by using N2 index (Pettini & Pagel 2004), which could be attributed to the fact that N2 index more likely traces Nitrogen abundance rather than α-elements. In either case, we can claim that metallicity effect should be minor in the tight ΔMS– Hα/UV relationship identified by this work.

4.4 Concluding remarks

The clear trend of the Hα/UV ratio on the star-forming main sequence suggests that galaxies at bursting phase tend to be located on the upside of the main sequence while those at rapid declining phase apt to be on the downside of the main sequence for a given short time period. However, there remain some problems peculiarly related to the sample completeness and the sampling bias, and thus, we still need to improve the reliability of the results more quantitatively. Moreover, we should keep in mind that we could have another interpretation on the ΔMS– Hα/UV correlation (e.g. non-universality of IMF; Meurer et al. 2009). The following materials discuss on-going and future work so as to bring forward this study.

— The future release of the AKARI faint source catalogue will allow us to test any trend of the Hα/UV ratio with better completeness, including investigations of its dependence on such as stellar mass, morphology, and colour.

— Studying Hα/UV ratios on the main sequence distribution for high-z galaxies should be intriguing since higher mass-loading factors and more vigorous inflowing gas would enhance time variability of those SFHs (Muratov et al. 2015; Sparre et al. 2017). Indeed, we see a systematic difference in Hα/UV ratios in low mass systems that would be more severely affected by feedback than massive objects. In the meanwhile, lower metallicities and harder ionisation fields of high-z galaxies (Steidel et al. 2016) likely raise those intrinsic Hα/UV ratios (Stanway et al. 2016). Those unknown factors would make commonly-used SFR estimation invalid, and SFR_{Hα,corr} may no longer be equivalent with SFR_{UV,IR} at high redshifts. Even-increasing archive data of such ALMA might help us to test this hypothesis in the future.

— We demonstrate that analyses of dust-corrected Hα/UV ratio have a great benefit for studying last ~ 100 Myr of galaxy SFHs. Application of this technique to spatially-resolved Hα/UV observation would enrich our understanding of the morphological transition (Wuyts et al. 2011; Tacchella et al. 2016), which can be achieved by the combination of spatially resolved UV-to-FIR observations.
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