On the different levels of dust attenuation to nebular and stellar light in star-forming galaxies

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Abstract

As a science verification study of the newly released AKARI/FIS Faint Source Catalog ver.1, this paper discusses the different levels of dust attenuation toward stellar light and nebular emission lines within local star-forming galaxies at 0.02<z<0.10. By constructing an updated version of the AKARI–SDSS–GALEX matched galaxy catalog (with >2,000 sources), we compare the dust attenuation levels toward stellar light (from $L_{\text{IR}}/L_{\text{UV}}$ ratio) and nebular emission lines (from H$\alpha$/H$\beta$ ratio). We find that there is a clear trend that more massive galaxies tend to have higher “extra” attenuation toward nebular regions, while galaxies with higher specific star formation rates tend to have lower extra attenuation. We also confirm these trends by using the WISE mid-infrared photometry with a significantly large sample size of the WISE–SDSS–GALEX galaxies (>50,000 sources). Finally, we study how the levels of extra attenuation toward nebular regions change across the SFR–$M_*$ plane. We find that, even at a fixed stellar mass, galaxies located below the main sequence tend to have higher levels of extra attenuation toward nebular regions, suggesting the change in dust geometry within the galaxies across the star-forming main sequence during the course of star formation quenching process.

Key words: Galaxies: evolution — Galaxies: star formation

1 Introduction

Measuring the star formation rate (SFR) of galaxies is always an important task in the extra-galactic astronomy. A common approach to derive SFR is to observe the rest-frame UV light from young massive stars, or to measure the nebular emission line fluxes such as H$\alpha$ ($\lambda=6563$Å) line associated with young star-forming regions, applying a proper dust attenuation correction (e.g. Kennicutt 1998; Kennicutt et al. 2009; Hao et al. 2011; Kennicutt & Evans 2012). Because star-forming regions are dust-rich environment in general, the light emitted from those young star-forming (HII) regions are known to be heavily obscured by dust, and unfortunately, the dust attenuation correction has been one of the biggest sources of uncertainty when deriving the SFRs.

The H$\alpha$ line is recognized as one of the best indicators of SFR. The dust attenuation at H$\alpha$ line can ideally be estimated by observing H$\beta$ ($\lambda=4861$Å) line at the same time and translating the H$\alpha$/H$\beta$ line flux ratio (Balmer decrement) to the dust atten-
vation levels with an assumption of reddening curves. Although it is true that even H\(\alpha\) line could be heavily obscured in the case of extremely dusty sources (e.g. Poggianti & Wu 2000; Koyama et al. 2010), it is widely recognized that the dust-corrected H\(\alpha\)-based SFR is one of the most reliable estimators of SFR. The H\(\alpha\) line has been commonly used for SFR measurements of local galaxies, and with the recent improvements of near-infrared observational technologies, it has now become much easier to access to the (redshifted) H\(\alpha\) line of distant galaxies across environment (e.g. Geach et al. 2008; Garn et al. 2010; Sobral et al. 2013; Koyama et al. 2013; and many others).

However, because H\(\beta\) line is much fainter than H\(\alpha\), it is still very challenging to directly measure the dust attenuation to H\(\alpha\) line for a statistical sample of galaxies at high redshifts with the Balmer decrement; indeed, only a small fraction of high-redshift works successfully detect both H\(\alpha\) and H\(\beta\) lines of individual sources for a statistical sample of galaxies (e.g. Shivaei et al. 2015; Reddy et al. 2015). An alternative approach exploited in many studies is to use the dust reddening derived from the broad-band SED fitting to predict the dust attenuation to H\(\alpha\) line. However, in addition to the well-known degeneracy between age, metallicity, and dust reddening in the broad-band SEDs, this process accompanies a large uncertainty, because the dust reddening estimated from broad-band SEDs indicates the reddening toward stellar light, while the reddening toward nebular emission lines could be different (e.g. Reddy et al. 2015; Koyama et al. 2015; Zahid et al. 2017).

It should be noted that nebular emission lines from H\(\alpha\) regions tend to be more obscured by dust than the stellar continuum light averaged over the galaxies. Calzetti (1997) showed that stellar continuum light are a factor of \(\sim 2\times\) less reddened than the nebular emission lines on average, and established a relation between color excess toward stellar continuum and nebular emission lines with an equation of E(B−V)\(_{\text{stellar}}\)\(=0.44\times\text{E(B−V)}\)_gas (see also Calzetti et al. 1994; Calzetti et al. 2000). Although many studies apply this relation to convert the reddening to stellar light to that of ionized gas until recently, it should be noted that the factor “0.44” in the above equation is derived as an average value of a wide variety of galaxy population in the local universe (from starbursts to dwarfs; see Calzetti 1997), and it would not be a number applicable to all types of galaxies.

Some recent studies suggest that the factor of this “selective” attenuation (or “extra” attenuation) toward nebular emission lines is different for distant galaxies (e.g. Erb et al. 2006; Reddy et al. 2010; Kashino et al. 2013; Pannella et al. 2015), and a growing number of high-z studies do not blindly assume the same relation as for local galaxies (e.g. Förster Schreiber et al. 2009; Wuyts et al. 2013; Tadaki et al. 2013; Theios et al. 2018). It is often argued that the different levels of attenuation toward ionized gas is originated by the fact that stars and ionized gas do not occupy the same regions within the galaxies (e.g. Calzetti et al. 1994; Wild et al. 2011; Price et al. 2014; Reddy et al. 2015). The ionized gas requires the presence of young massive (short-lived) stars to ionize themselves (hence they are always located in the birth clouds), while stellar continuum light can also be contributed by long-lived, non-ionizing stars distributed throughout the galaxy; so-called “two-component” dust model composed of birth-clouds and diffuse ISM as described by Charlot & Fall (2000). It is of great interest to understand what determines the levels of extra attenuation toward nebular regions—this is not only to reduce the uncertainties of SFR estimates, but also to understand the link between star/gas geometry inside the galaxies along the process of galaxy evolution.

A method to study the extra attenuation toward nebular regions would be to compare the E(B−V)\(_{\text{gas}}\) and E(B−V)\(_{\text{stellar}}\) measured independently. The E(B−V)\(_{\text{gas}}\) can be measured with H\(\alpha\)/H\(\beta\) ratio as described above, and the E(B−V)\(_{\text{stellar}}\) can be estimated from UV attenuation measured by far-infrared (FIR) to UV luminosity ratio with an assumption of attenuation curve. The key observational data is therefore deep MIR–FIR photometry covering a wide area on the sky to directly trace the dust thermal emission from galaxies. The Wide-field Infrared Survey Explorer (WISE; Wright et al. 2010) performed all-sky survey to the MIR (3.4, 4.6, 12, 22 \(\mu\)m; W1–W4), and provides an excellent tool for this purpose. Also, the AKARI (Murakami et al. 2007) Far-Infrared Surveyor (FIS; Kawada et al. 2007) performed all-sky survey at 65, 90, 140, and 160 \(\mu\)m with high sensitivity and high angular resolution (Doi et al. 2015; Takita et al. 2015), and thus serves as another ideal tool for this purpose.

In Koyama et al. (2015), we constructed an AKARI–SDSS–GALEX star-forming galaxy sample, by cross-matching the sources in the AKARI-FIS Bright Source Catalog ver.1 (Yamamura et al. 2010) to SDSS (DR7) and GALEX (GR5) data. By comparing the A\(_{\text{UV}}\) (derived from L\(_{\text{IR}}\)/L\(_{\text{UV}}\) ratio) and A\(_{\text{H}\alpha}\) (derived from Balmer decrement), we find a hint that more massive galaxies and/or galaxies with low H\(\alpha\) equivalent widths (EW\(_{\text{H}\alpha}\)) tend to show higher levels of extra attenuation toward nebular regions. In this paper, as a science demonstration study of the newly released AKARI Faint Source Catalog ver.1 (Yamamura et al. 2018), we will revisit the issue of this extra attenuation toward nebular regions by constructing an updated version of the AKARI–SDSS–GALEX matched galaxy catalog.

This paper is organized as follows. In Section 2, we present our new AKARI–SDSS–GALEX star-forming galaxy catalog with the newly released AKARI Faint Source Catalog (Section 2.1), and derive their FUV-, H\(\alpha\)-, and FIR-based SFRs as well as the dust attenuation levels toward stellar and nebular emission (Section 2.2–2.4). In Section 3, we investigate how the “extra” attenuation toward nebular regions changes with various galaxy properties using the AKARI–SDSS–GALEX sample.
In Section 4, we verify our results by using WISE data as it also covers all sky and provides an independent measurement of IR-based SFRs. In Section 5, by using our AKARI–SDSS–GALEX and WISE–SDSS–GALEX sample, we show how the levels of extra attenuation to nebular regions changes across the star-forming main sequence. In Section 6, we describe caveats on the interpretation of our results by comparing the results when we use Hα-based SFRs instead of UV/IR-based SFRs. Finally, our conclusions are summarized in Section 7. Throughout the paper, we adopt the cosmological parameters of $\Omega_M = 0.3$, $\Omega_{\Lambda} = 0.7$, and $H_0 = 70$ km s$^{-1}$Mpc$^{-1}$, and we assume the Kroupa (2001) initial mass function (IMF). All magnitudes are given in the AB system.

2 New AKARI-SDSS-GALEX sample

2.1 Sample selection

In Koyama et al. (2015), we constructed a star-forming galaxy sample ($N=1,200$) in the local universe by matching the SDSS Data Release 7 (DR7; Abazajian et al. 2009) spectroscopic galaxy sample, UV sources from the All-sky Imaging Survey of GALEX fifth data release (GR5), and FIR sources from the AKARI FIS Bright Source Catalog ver.1 (BSCv1; Yamamura et al. 2010). We refer the readers to Koyama et al. (2015) for details of the source matching procedure, but we here briefly describe the process of our sample selection. We note that the dataset is the same as those used in Koyama et al. (2015), except that we replace our FIR data from the AKARI FIS Bright Source Catalog ver.1 to the newly released AKARI Faint Source Catalog ver.1 (FSCv1; Yamamura et al. 2018). The key observational quantities used in this paper are SDSS Hα and Hβ fluxes to derive Hα-based SFRs (Section 2.2), and GALEX FUV and AKARI FIR (90μm and 140μm) photometry to derive UV+FIR SFRs (Section 2.3).

The first step is to match the SDSS (DR7) spectroscopic catalog with the FUV-detected sources selected from GALEX (GR5) All-sky Imaging Survey (AIS) with a help of the SDSS (DR7)–GALEX (GR5) matched photometric catalog published by Bianchi et al. (2011). We use the Max Planck Institute for Astrophysics and Johns Hopkins University (MPA/JHU) catalog for spectroscopic measurements including the Galactic extinction correction, stellar absorption correction for emission line fluxes, and stellar mass estimates for individual galaxies with SED fitting (Kauffmann et al. 2003; Salim et al. 2007). We restrict the sample to those within the redshift range of $0.02 < z < 0.10$, and we also apply a stellar mass cut of $\log(M_*/M_{\odot})>8.5$. We further require detection of four major emission lines (Hα, [NII], Hβ, [OIII]) to select star-forming galaxies using the ’BPT’ diagram (Baldwin et al. 1981), following the standard criteria to distinguish star-forming galaxies from AGNs (Kauffmann et al. 2003; Kewley et al. 2006). We thus select 78,731 SDSS–GALEX sources satisfying all the above criteria.

We then match our SDSS–GALEX galaxy sample with the AKARI FIS Faint Source Catalog ver.1 (hereafter FSCv1; Yamamura et al. 2018). The AKARI FSCv1 contains 401,157...
point sources selected with a different detection policy from the AKARI FIS Bright Source Catalogs (ver.1/ver.2) to improve the sensitivity, particularly in the high ecliptic latitude regions where the number of scans is large (see Yamamura et al., 2018 for details). We note that the majority of the AKARI sources are Galactic objects distributed along the Galactic plane, and we find that \( \sim 15,000 \) galaxies are located within the SDSS survey area. Considering the PSF size of AKARI at \( 90 \mu \text{m} \) (\( \sim 40\text{-arcsec} \)), we use 20-arcsec radius aperture to search counterparts, and find 2,416 star-forming galaxies identified in all the AKARI, SDSS, and GALEX catalogs, with a median redshift of \( z = 0.043 \), and with a median separation of 5.1 arcsec (measured as angular distance between the positions of AKARI and SDSS coordinates).

In Fig. 1 (left), we compare the AKARI WIDE-S (90\( \mu \text{m} \)) photometry from AKARI/FIS BSCv1 and FSCv1 for galaxies identified in both of the catalogs. More detailed comparison between the catalogs will be presented in Yamamura et al. (2018), but we here confirm that the FIR flux measurements agree well between the BSCv1 and FSCv1 over a wide flux range for local star-forming galaxies. We also show in Fig. 1 (right) the 90\( \mu \text{m} \) flux distribution of the AKARI–SDSS–GALEX sample from our previous version (with BSCv1; red hatched histogram) and the updated version of the catalog (with FSCv1; blue filled histogram). It is clear that the increase of the total sample size mainly comes from the improved sensitivity at \( \log F_{90 \mu \text{m}} \lesssim -0.4 \) [Jy].

2.2 \( \text{H}\alpha \)-based SFRs and dust attenuation toward nebular regions

The key physical parameters that we use in this study are \( \text{H}\alpha \)-and UV/FIR-based SFRs and dust attenuation toward stellar and nebular light for individual galaxies. We derive these quantities basically following the same way as presented in Koyama et al. (2015), but here we provide a quick overview of the procedure.

To derive the \( \text{H}\alpha \)-based SFRs, we first calculate the dust attenuation at \( \text{H}\alpha \) line by using the \( \text{H}\alpha /\text{H}\beta \) flux ratio (Balmer decrement) with the following equation, assuming the Case B recombination at \( T = 10^4 \) K with an electron density of \( n_e = 10^2 \) cm\(^{-3}\):

\[
A_{\text{H}\alpha} = \frac{-2.5 k_{\text{H}\alpha}}{k_{\text{H} \beta} - k_{\text{H}\alpha}} \log \left( \frac{2.86 F_{\text{H}\beta}}{F_{\text{H}\alpha}} \right),
\]

\[
E(B-V)_{\text{gas}} = A_{\text{H}\alpha}/k_{\text{H}\alpha}.
\]

We here assume the Cardelli et al. (1989) Galactic extinction curve to determine the \( k_{\text{H}\alpha} \) and \( k_{\text{H} \beta} \) in the above equations, following the original derivation of the Calzetti et al. (2000) relation (see e.g. Steidel et al. 2014; Reddy et al. 2015; Shivaei et al. 2015). We emphasize that our conclusions are unaffected even if we apply the Calzetti et al. (2000) curve to both nebular and stellar light as assumed by many studies including our previous work (e.g. Garn & Best 2010; Sobral et al. 2012; Koyama et al. 2015), while it would bring a small systematic offset in the estimate of \( A_{\text{H}\alpha} \) by \( \sim 10\% \).

We derive the \( \text{H}\alpha \)-based SFRs (SFR\( _{\text{H}\alpha} \)) using the Kennicutt (1998) calibration assuming Kroupa (2001) IMF\(^3\):

\[\text{SFR}_{\text{H}\alpha} = 3.2 \times 10^{-21} \times \log(M_\star/M_\odot) \times F_{\text{H}\alpha}.\]

\(^3\) We follow Kennicutt et al. (2009) to reduce the SFR by a factor of 1.44 to...
SFR$_{\text{H}\alpha} = 5.5 \times 10^{-42} L_{\text{H}\alpha} \text{[erg s}^{-1}]$.  

We here correct for the dust attenuation effect based on the $A_{\text{H}\alpha}$ estimated above. We also apply aperture correction to the $\text{H}\alpha$ flux based on the difference between the total (petro) magnitudes and SDSS fiber magnitudes at $r$-band (i.e. $m_{r,\text{petro}} - m_{r,\text{fiber}}$), assuming that the dust attenuation levels measured in the 3$''$ aperture regions can be applicable to the outer regions. Although this approach might bring some uncertainties, we believe that our simple reproducible approach works reasonably well. We will show a comparison between the SFR$_{\text{H}\alpha}$ derived with this approach and the independently measured UV+FIR-based SFRs in Section 3.2 (see also Koyama et al. 2015; Shimakawa et al. 2017; Matsuki et al. 2017), and we will also discuss the potential effects of aperture correction in Section 3.4.

2.3 UV- and FIR-based SFRs and dust attenuation to stellar light

We derive dust-unobscured part of SFRs from GALEX FUV ($\lambda_{\text{eff}}=1516$ Å) photometry using Kennicutt (1998) calibration assuming the Kroupa (2001) IMF:

$$\text{SFR}_{\text{FUV}} = 9.7 \times 10^{-29} L_{\nu,\text{FUV}} \text{[erg s}^{-1} \text{Hz}^{-1}]$$

We use “FUV$_{\text{MAG, REST}}$” in the Bianchi et al. (2011) catalog as the total FUV magnitudes, and apply the foreground Galactic extinction correction using the Schlegel et al. (1998) dust map and the Galactic extinction curve of Cardelli et al. (1989) with $R_V = 3.1$. We also apply the $k$-correction by using a $k$-correction tool developed by Chilingarian et al. (2010) and convert the SFRs derived under the assumption of Salpeter (1955) IMF (i.e. the original Kennicutt 1998 prescription) to that derived with Kroupa (2001) IMF. We apply the same (a factor of 1.44) scaling when we derive SFR$_{\text{FIR}}$ and SFR$_{\text{IR}}$ in this work.

Chilingarian & Zolotukhin (2012), where the required correction values are predicted for individual galaxies based on their FUV−NUV and NUV−g colors. We note that the $k$-correction values applied to the FUV magnitude of our sample are very small (typically $\sim$0.02-mag).

We also derive the dust-obscured part of SFRs from AKARI FIR data. Following Koyama et al. (2015), we derive the total infrared luminosity ($L_{\text{FIR}}$) using the WIDE-S (90$\mu$m) and WIDE-L (140$\mu$m) photometry with the equation established by Takeuchi et al. (2010):

$$\log L_{\text{FIR}} = 0.9641 \log L_{\text{FIR, AKARI}}^{\text{2band}} + 0.814,$$

where $L_{\text{FIR, AKARI}}^{\text{2band}} = \Delta \nu_{90\mu m} L_{\nu}(90\mu m) + \Delta \nu_{140\mu m} L_{\nu}(140\mu m)$. We note that $\Delta \nu_{90\mu m} (=1.47 \times 10^{12}[\text{Hz}])$ and $\Delta \nu_{140\mu m} (=0.831 \times 10^{12}[\text{Hz}])$ denote the band widths of AKARI WIDE-S and WIDE-L bands, respectively. We realize that 187 out of 2,416 galaxies (7.7%) are detected only at WIDE-S (90$\mu$m) band, and we remove these sources from our sample (because we cannot estimate their $L_{\text{FIR}}$ with the above technique). We do not consider $k$-correction for the FIR photometry as the AKARI band widths are wide enough and its effect is negligible for our $z < 0.1$ galaxy sample. We then use Kennicutt (1998) equation with the Kroupa (2001) IMF to derive IR-based SFR:

$$\text{SFR}_{\text{IR}} = 3.1 \times 10^{-44} (1 - \eta) L_{\text{IR}} \text{[erg s}^{-1}]$$

where $\eta$ indicates the fraction of IR emission heated by old stars. We here adopt a constant $\eta=0.17$ for all our AKARI-detected sources, following the average $\eta$ value for local star-forming galaxies reported by Buat et al. (2011). We note that the $\eta$ value could be dependent on $L_{\text{IR}}$ or specific SFR of individual galaxies, while the reported $\eta$ values are different from studies to studies within a range of $\eta=0.1–0.4$ (e.g. Hirashita et al. 2003; Bell 2003; Buat et al. 2011). We stress that our conclusions are not affected even if we choose different $\eta$ values. Fig. 2 compares SFR$_{\text{FUV}}$, SFR$_{\text{FIR}}$, and the dust-corrected SFR$_{\text{H}\alpha}$. Fig. 4. Dust attenuation at H$\alpha$ ($A_{\text{H}\alpha}$) measured with H$\alpha$/H$\beta$ flux ratio (Balmer decrement) plotted against stellar mass (left), SFR (middle), and specific SFR (right). The red circles indicate our new AKARI–SDSS–GALEX sample, while the gray-scale density plots show the overall distribution of SDSS–GALEX matched SF galaxy sample. It can be seen that our AKARI-detected galaxies tend to be massive, highly star-forming population, and that they are heavily obscured by dust for their specific SFR.
Although there exists a relatively large scatter ($\sigma=0.31$ dex), these two independently measured SFRs show good agreement with each other (with a median difference of $\sim0.05$ dex). We note that we here further removed 101 sources (4.5%) having negative aperture correction in the SDSS $r$-band data (with $m_{r,\text{fiber}}<m_{r,\text{petro}}$), as these galaxies show unrealistically small SFR$_{H\alpha}$.

Finally, we derive dust attenuation at FUV ($A_{\text{FUV}}$) as well as the color excess toward stellar light ($E(B-V)_{\text{star}}$) by comparing the total (UV+FIR) SFRs and the observed UV-derived SFRs (without dust attenuation correction):

\begin{equation}
A_{\text{FUV}} = 2.5 \times \log(\text{SFR}_{\text{UV+FIR}}/\text{SFR}_{\text{UV}}),
\end{equation}

\begin{equation}
E(B-V)_{\text{star}} = A_{\text{FUV}}/k_{\text{FUV}},
\end{equation}

where we determine $k_{\text{FUV}}$ using the Calzetti et al. (2000) reddening curve. In summary, our final AKARI–SDSS–GALEX star-forming galaxy sample includes 2,128 sources with the measured SFRs and dust attenuation. The source catalog as well as our measurements of SFR and dust attenuation for individual sources will be published on the AKARI website.

2.4 General properties of AKARI-detected galaxies

Because we aim to study the dust attenuation properties of star-forming galaxies with our new AKARI–SDSS–GALEX sample, it is important to understand fundamental properties and any potential bias associated with the sample. We here briefly examine the nature of the AKARI–SDSS–GALEX sample selected in the previous sections.

In Fig. 3, we show our new AKARI–SDSS–GALEX galaxies on the SFR–$M_*$ diagram (red symbols) on top of the distribution of the parent SDSS–GALEX star-forming galaxy sample (gray-scale image plot). We here use SFR$_{H\alpha,\text{corr}}$ for both AKARI–SDSS–GALEX and SDSS–GALEX samples (as we cannot estimate SFR$_{\text{FIR}}$ for galaxies without AKARI detection). As expected, the AKARI-detected sources are relatively massive (mostly with $\log(M_*/M_\odot) \gtrsim 10.0$), and highly star-forming population (with SFR\gtrsim1 $M_\odot/yr$). We note that $\sim7\%$ of the AKARI–SDSS–GALEX galaxies have $>4\times$ higher SFRs with respect to the main sequence (hence starbursts), and so the majority of our samples are massive (normal) star-forming galaxies.

We then plot in Fig. 4 the H$\alpha$ dust attenuation ($A_{H\alpha}$) against their stellar mass (left), SFR (middle), and specific SFR (right). Again, our AKARI–SDSS–GALEX galaxies are shown with the red symbols, while the overall distribution of the SDSS–GALEX sample is shown with the gray-scale image plot. It seems that the distribution of the AKARI–SDSS–GALEX galaxies is similar to that of all the SDSS–GALEX sample on the $A_{H\alpha}$–$M_*$ and $A_{H\alpha}$–SFR diagrams (except that they are skewed to massive/high SFR side), while they tend to show high $A_{H\alpha}$ for their specific SFRs. This is not surprising considering the fact that low-mass galaxies (with $\log(M_*/M_\odot) \lesssim 10.0$) are not detected at FIR regardless of their specific SFR (Fig 3), and those with high specific SFR (but with low $A_{H\alpha}$) are dominated by low-mass galaxies. We should keep this potential bias in mind, but we believe that our conclusions will not be affected as we will show consistent results in Section 5 by using WISE MIR data which is much deeper in terms of IR-based SFRs.
creasing stellar mass, consistent with the visual impression that we recognized in Fig. 5. We therefore conclude that more E(B − V)\_gas/E(B − V)\_star ratio, plotted against stellar mass (left), SFR (middle), and specific SFR (right) for our AKARI–SDSS–GALEX sample. The gray circles indicate individual AKARI–SDSS–GALEX galaxies, and the red circles with error-bars show their median data points computed for a constant 0.3-dec bin, with the y-axis error-bars representing their 25%–75% distribution. We note that a wider bin size is adopted at the lowest-mass and highest sSFR bins so that each bin has sufficient (>15) number of galaxies. The error bars in x-axis indicate the adopted bin size. The dotted-line curve drawn in each panel shows the best-fit polynomial function computed for the median data points weighted by \sigma/\sqrt{N} of each bin, and the horizontal dashed line indicates the canonical value of E(B − V)\_star/E(B − V)\_gas = 0.44 for reference.

3 Different dust attenuation toward stellar and nebular regions with AKARI sample

In Fig. 5, we compare E(B − V)\_gas and E(B − V)\_star for our AKARI–SDSS–GALEX sample. It can be seen that there is a positive correlation between E(B − V)\_gas and E(B − V)\_star with a large scatter. In the left and right panel of Fig. 5, the color coding indicates stellar mass and specific SFR of individual galaxies, respectively; i.e. redder symbols show more massive galaxies in the left panel, while redder symbols indicate lower sSFR in the right panel. We find that galaxies with higher \textit{M}_\star and/or galaxies with lower specific SFR dominate the upper side of the overall distribution of the data points, suggesting that galaxies with higher \textit{M}_\star and/or lower sSFR tend to have higher levels of “extra” attenuation toward nebular regions at fixed E(B − V)\_star. We showed a similar plot in Koyama et al. (2015) (see their fig. 14), but we have now confirmed the results using a larger sample size with our updated (deeper) AKARI–SDSS–GALEX catalog.

We here quantify the levels of extra reddening toward nebular regions by calculating the E(B − V)\_gas/E(B − V)\_star ratio, and study the correlation between E(B − V)\_gas/E(B − V)\_star and various galaxy properties. In Fig. 6, we plot the E(B − V)\_gas/E(B − V)\_star ratio as functions of stellar mass (left), SFR (middle), and specific SFR (right). We also show the running median in each panel; red circles with error-bars representing the 25%–75% distribution in each bin. Although the scatter is large in all the panels, the left panel of Fig. 6 demonstrates the trend that E(B − V)\_gas/E(B − V)\_star increases with increasing stellar mass, consistent with the visual impression that we recognized in Fig. 5. We therefore conclude that more massive galaxies tend to have higher levels of extra attenuation toward nebular regions, and the best-fit relation between E(B − V)\_gas/E(B − V)\_star and the stellar mass of galaxies is provided with the following equation:

\[
E(B - V)_{\text{gas}} / E(B - V)_{\text{star}} = a_0 + a_1 X + a_2 X^2, \quad (9)
\]

where \(X = \log(M_\star / 10^{10} M_\odot)\), with the best-fit parameters of \(a_0 = 1.729 \pm 0.019\), \(a_1 = 0.464 \pm 0.039\), and \(a_2 = -0.249 \pm 0.048\).

The middle and right panels of Fig. 6 suggest that E(B − V)\_gas/E(B − V)\_star mildly decreases with increasing SFR, and as a combination of the trends with stellar mass and SFR, we find that E(B − V)\_gas/E(B − V)\_star sharply decreases with increasing specific SFR, again consistent with the results from Fig. 5. Our data suggests that more actively star-forming galaxies tend to have lower E(B − V)\_gas/E(B − V)\_star ratio, and E(B − V)\_gas/E(B − V)\_star becomes consistent with unity at the highest sSFR end; i.e. no extra attenuation is required for very actively star-forming population. By fitting the data points of the running median in the middle and right panels of Fig. 6, the best-fit relation between E(B − V)\_gas/E(B − V)\_star and SFR (\(Y = \log(\text{SFR}) \ [M_\odot \text{yr}^{-1}]\)) and specific SFR (\(Z = \log(\text{sSFR}) \ [1/\text{Gyr}]\)) are provided as follows:

\[
E(B - V)_{\text{gas}} / E(B - V)_{\text{star}} = b_0 + b_1 Y + b_2 Y^2, \quad (10)
\]

\[
E(B - V)_{\text{gas}} / E(B - V)_{\text{star}} = c_0 + c_1 Z + c_2 Z^2, \quad (11)
\]

with the best-fit parameters of \(b_0 = 1.865 \pm 0.049\), \(b_1 = 0.213 \pm 0.129\), \(b_2 = -0.273 \pm 0.079\), \(c_0 = 1.450 \pm 0.022\), \(c_1 = -0.798 \pm 0.050\), and \(c_2 = -0.244 \pm 0.048\). We believe that the above equations can be a convenient tool to provide a realistic estimate of the extra attenuation toward nebular regions (E(B − V)\_gas/E(B − V)\_star), but we caution that the equations should be used with care, in particular when one
A sanity check with WISE MIR photometry

The main goal of this paper is to use the newly released AKARI Faint Source Catalog ver.1 and show its scientific capability. It is therefore important to test the validity of our scientific results presented in this work with some independent dataset. The Wide-field Infrared Survey Explorer (WISE; Wright et al. 2010) all-sky MIR survey data can be an ideal tool for this purpose, because it can provide independent measurements of IR-based SFRs. We here use the GALEX-SDSS-WISE Legacy Catalog (GSWLC) published by Salim et al. (2016)\(^4\), in which they provide WISE 22\(\mu\)m-based SFRs (SF\(_{\text{MIR}}\)) for all galaxies detected at 22\(\mu\)m, by interpolating the Chary & Elbaz (2001) SEDs to match the observed 22\(\mu\)m flux densities. In this work, we use the SF\(_{\text{MIR}}\) from 22\(\mu\)m flux in “unWISE” catalog (Lang et al. 2016), recommended for low-\(z\) galaxies with large apparent size (see Salim et al. 2016). We note that Salim et al. (2016) assume Chabrier (2003) IMF when deriving the SF\(_{\text{MIR}}\), and we therefore rescaled their SF\(_{\text{MIR}}\) (by +0.03 dex) to account for the IMF difference.

Following the same strategy as that we performed in Section 2.1 to construct our AKARI–SDSS–GALEX catalog, we first match our SDSS–GALEX star-forming galaxy sample (at 0.02<\(z\)<0.1) with the “GSWLC-X” catalog\(^5\). We here reconstructed WISE–SDSS–GALEX catalog by matching our own SDSS–GALEX sample with the GSWLC catalog, to keep consistency in the data release versions of the SDSS and GALEX catalog used for the analyses. We restrict the sample to those detected at WISE 22\(\mu\)m band, and now we identify 50,353 WISE–SDSS–GALEX sample for which MIR-based SFRs are available. By matching the WISE–SDSS–GALEX sample with our AKARI–SDSS–GALEX sample constructed in Section 2.1, we find that 2,036 sources (>95\%) of the AKARI–SDSS–GALEX sample are also identified in the WISE–SDSS–GALEX sample constructed here.

In Fig. 7, we compare the FIR-based SFRs (derived with AKARI data in Section 2.2) and WISE 22\(\mu\)m-based SFRs (provided by Salim et al. 2016, after accounting for the IMF difference) for galaxies identified in both AKARI and WISE catalogs, showing a reasonable agreement between UV+FIR and UV+MIR SFRs (with a median difference of 0.01 dex and a scatter of \(\sigma=0.22\) dex). Following the good agreement between the FIR- and MIR-based SFRs, we will perform the same analysis presented in the previous sections with a significantly larger number of galaxies in the WISE–SDSS–GALEX sample.

We here apply the same method as we performed in Section 2.2 to derive \(E(B-V)_{\text{star}}\) from SF\(_{\text{FIR}}\) and SF\(_{\text{UV}}\), and we now calculate \(A_{\text{UV,WISE}}\) and \(E(B-V)_{\text{star,WISE}}\) with the following equations:

\[
A_{\text{UV,WISE}} = 2.5 \times \log(\text{SFR}_{\text{UV,MIR}}/\text{SFR}_{\text{UV}}),
\]

\(\text{Fig. 7. SFRs derived from AKARI FIR photometry (Section 2.2) plotted against SFRs from WISE 22\(\mu\)m data taken from the public GSWLC catalog by Salim et al. (2016) for galaxies identified in both our AKARI–SDSS–GALEX sample and the GSWLC catalog, taking into account the different IMF assumption. The two SFR measurements show good agreement with each other.}

\(4\) https://archive.stsci.edu/preps/gswlc/

\(5\) We note that Salim et al. (2016) published three versions of the catalog (GSWLC-A, M, D) depending on the GALEX survey depths used for the source matching, and they also publish a master catalog (GSWLC-X), in which they exploit the deepest data among GSWLC-A, M, and D. We decided to use this “GSWLC-X” which covers the largest fraction of SDSS survey area (see Salim et al. 2016 for more details).
In Fig. 8, we compare E(B−V)_{gas} and E(B−V)_{stellar,WISE}, with color coding based on stellar mass and specific SFR of galaxies. This is the same plot as Fig. 5, but considering the large sample size of the WISE–SDSS–GALEX sources. We show the average M_⋆ (left panel) and specific SFR (right panel) at each position on this diagram, rather than showing the individual data points. This plot clearly demonstrates that galaxies with higher stellar mass or lower specific SFR tend to have higher E(B−V)_{gas} at fixed E(B−V)_{stellar}, confirming the trend we reported in Fig. 5 by using AKARI–SDSS–GALEX sample.

We then quantify the extra reddening toward nebular regions by computing the E(B−V)_{gas}/E(B−V)_{stellar,WISE} ratio (as we did in the previous section), and we plot in Fig. 9 the derived E(B−V)_{gas}/E(B−V)_{stellar,WISE} against their stellar mass (left), SFR (middle), and specific SFR (right) for all WISE–SDSS–GALEX galaxies. Instead of showing the individual data points, we show the distribution of all WISE–SDSS–GALEX galaxies with the gray-scale density plot, and we show the running median with the orange squares with error-bars (indicating the 25%–75% distribution in each bin). It can be seen that the extra reddening level increases with increasing stellar mass, while it decreases with increasing specific SFR, consistent with the results we reported in Fig. 6.

The trend for SFR seems to be different from that shown in Fig. 6: we showed a mild decrease of the E(B−V)_{gas}/E(B−V)_{stellar} ratio with increasing SFR in Fig. 6, while in Fig. 9, E(B−V)_{gas}/E(B−V)_{stellar} increases at log(SFR) < −1.0–0.5 [M_⊙/yr] and decreases at log(SFR) ≥ 0.5–1.5 [M_⊙/yr]. However, it should be noted that the SFR range presented in Fig. 6 and Fig. 9 are different. As we showed in Section 3.1, most of the AKARI-detected samples have log(SFR) ≥ 0 [M_⊙/yr], whilst the WISE data goes an order of magnitude deeper than the AKARI data in terms of IR-based SFR. We note that the mild decrease of the E(B−V)_{gas}/E(B−V)_{stellar,WISE} ratio toward the high SFR end seen in Fig. 6 is consistent with our current analysis using WISE data (see the red circles in Fig. 9 showing the same data points as in Fig. 6). The reason of this different behavior at low-SFR and high-SFR side is unclear, but we speculate that the E(B−V)_{gas}/E(B−V)_{stellar} ratio increases following the increase of stellar mass at low-SFR side, while the effect of specific SFR becomes stronger at high-SFR end (the trend with stellar mass becomes almost flat at high-M_⋆ end as shown in the left panel of Fig 9).

### 5 Extra attenuation toward nebular regions across star-forming main sequence

We have shown that the extra dust attenuation toward nebular regions changes with stellar mass and (specific) SFR. In this section, we study how the E(B−V)_{gas}/E(B−V)_{stellar} ratio changes across the SFR–M_⋆ diagram. In Fig. 10, we show the SFR–M_⋆ diagram for AKARI–SDSS–GALEX sample (left) and for WISE–SDSS–GALEX sample (right) with color coding based on the E(B−V)_{gas}/E(B−V)_{stellar} ratio. For the right panel of this plot, we divide the diagram into 60×60 sub-grids and compute the average E(B−V)_{gas}/E(B−V)_{stellar} at each pixel (with requirement of the minimum sample size of N_{galaxy}=4 in each pixel).
Both of these plots demonstrate that, at fixed stellar mass, there remains a trend that galaxies with lower sSFR tend to have higher $E(B-V)_\text{gas}/E(B-V)_{\text{star}}$ ratio; i.e. galaxies located at the lower side of the star-forming main sequence tend to suffer from higher extra attenuation toward nebular regions.

Assuming that the levels of extra attenuation toward nebular regions with respect to the stellar continuum light reflects the different geometry of stars and gas/dust within the galaxies as argued by many authors (e.g. Calzetti 1997; Price et al. 2014; Reddy et al. 2015), the fact that the $E(B-V)_\text{gas}/E(B-V)_{\text{star}}$ ratio changes across the SFR–$M_\star$ diagram suggests that the geometry of stars and dust within the galaxies become more and more different as the SF quenching process proceeds. In other words, the distribution of star-forming regions becomes more distinct (patchy and/or centrally concentrated) from the distribution of stellar components.

To study the nature of galaxies with high $E(B-V)_\text{gas}/E(B-V)_{\text{star}}$ ratio, we show in Fig. 11 the attenuation at FUV measured with $L_{\text{IR}}/L_{\text{UV}}$ ratio plotted against the FUV–NUV colors (equivalent to the so-called “IRX–β” diagram; e.g. Meurer et al. 1999; Witt & Gordon 2000; Takeuchi et al. 2010; Reddy et al. 2010; Buat et al. 2011), with color coding based on the extra reddening toward nebular regions, $E(B-V)_\text{gas}/E(B-V)_{\text{star}}$. We show individual data points for AKARI–SDSS–GALEX sample, while we show the average of $E(B-V)_\text{gas}/E(B-V)_{\text{star}}$ ratio at each pixel for the WISE–SDSS–GALEX sample. This plot demonstrates that galaxies with “IR excess” sources (i.e. dusty galaxies) tend to have lower $E(B-V)_\text{gas}/E(B-V)_{\text{star}}$ ratio, suggesting that the FIR light and the ionized gas emission lines are coming from the same (star-forming) regions within the galaxies. On the other hand, galaxies with high $E(B-V)_\text{gas}/E(B-V)_{\text{star}}$ ratio are strongly clustered at the low $L_{\text{IR}}/L_{\text{UV}}$ side, demonstrating that galaxies with higher $E(B-V)_\text{gas}/E(B-V)_{\text{star}}$ ratio tend to be less dusty, moderately star-forming population, consistent with the results we showed in Fig. 10.

### 6 Caveats on the use of SFR$_{H\alpha}$ instead of SFR$_{UV+IR}$ and other uncertainties

In Fig. 12, we show the same SFR–$M_\star$ plot as Fig. 10 by replacing the SFR$_{UV+MIR}$ (or SFR$_{UV+IR}$) with the $H\alpha$-derived SFRs. It can be seen that the region showing the highest levels of extra reddening (with $E(B-V)_\text{gas}/E(B-V)_{\text{star}} \gtrsim 2$; i.e. red-color regions in the plot) is strongly concentrated at the very massive end ($\log(M_\star/M_\odot) > 10.5$), whilst we reported in Fig. 10 that the red-color regions are distributed along the bottom part of the SF main sequence over a wide stellar mass range. The physical reason of the different behavior between SFR$_{UV+MIR}$ and SFR$_{H\alpha,\text{corr}}$ is unclear, but we speculate that it is originated from disagreement between the SFR$_{UV+MIR}$ and SFR$_{H\alpha,\text{corr}}$ at the low-mass end. We investigate this possibility in Fig. 13 by comparing the SFR$_{H\alpha,\text{corr}}$ and SFR$_{UV+MIR}$, with the color code indicating the $E(B-V)_\text{gas}/E(B-V)_{\text{star}}$ ratio. It can be seen that galaxies with SFR$_{H\alpha,\text{corr}}$ > SFR$_{UV+MIR}$ tend to show significantly higher levels of extra attenuation.

We caution that the major source of uncertainties of our analysis would be the dust attenuation correction (and aperture correction) when we derive $H\alpha$-based SFRs. We performed a simple dust attenuation correction assuming that the distribution of $H\alpha$ and $H\beta$ line fluxes follow that of stellar continuum light measured in $r$-band (Section 2.2). In Fig. 14, we briefly test
the effects of aperture correction, by creating the same plots as Fig. 10, Fig. 12, and Fig. 13 with the color code (gray scale) indicating the average aperture correction at each position on these diagrams \((m_{\text{fiber}} - m_{\text{petro}})\). It can be seen that low-mass galaxies \((\log(M_*/M_\odot) \lesssim 10)\) with low SFR tend to require larger aperture correction, mainly because they are intrinsically faint sources and we can detect those low-mass, low-SFR galaxies only when they are located in the very nearby universe (hence with large apparent size). It should be noted that we need to apply \(\sim 2\)-mag or more aperture correction when we derive SFR_{H\alpha} for these low-mass, low-SFR galaxies. We note that the amount of aperture correction is not directly linked to the uncertainties of the derived SFR, but it might be unrealistic to assume the completely uniform dust attenuation levels over the galaxies (e.g. Kreckel et al. 2013; Hemmati et al. 2015; Nelson et al. 2016; Tacchella et al. 2018), and therefore our results at the low-mass/low-SFR end should be interpreted with care.

Finally, we comment that another source of uncertainty is regarding the choice of dust attenuation curves. In particular, we should note that the results must be interpreted with care in case one applies variable attenuation curve depending on galaxy properties (e.g. Kriek & Conroy 2013; Salim et al. 2018). A recent study by Salim et al. (2018) suggests that lower-mass galaxies or galaxies with low specific SFR tend to have steeper attenuation curve slopes. For those galaxies with steeper slopes, the observed UV attenuation tend to be translated into smaller \(E(B-V)_{\text{stellar}}\) (hence higher \(E(B-V)_{\text{gas}}/E(B-V)_{\text{stellar}}\) ratio). This is qualitatively consistent with our results, and may partly explain the trend we reported in this work that the \(E(B-V)_{\text{gas}}/E(B-V)_{\text{stellar}}\) ratio is higher for galaxies below the SF main sequence. We believe that our conclusions of this work are robust because most of the results are unchanged even if we use SFR_{H\alpha} or SFR_{UV+IR}, but a more detailed, systematic spatially-resolved studies for a statistical sample of galaxies selected from above/below the SF main sequence would be needed to obtain a more conclusive evidence for the changing star/dust geometry as well as the changing dust attenuation curve across the SFR–\(M_\star\) diagram.

7 Summary

In this study, we constructed an updated version of our AKARI–SDSS–GALEX star-forming galaxy catalog at 0.02<z<0.10 using the newly released AKARI/FIS all-sky Faint Source Catalog ver.1 (FSCv1). With the improved sensitivity of the Faint Source Catalog, the number of the matched sources is increased by a factor of \(\sim 2\times\) compared to the previous version of the catalog presented by Koyama et al. (2015) using the AKARI Bright Source Catalog (ver.1).

We derived SFRs from dust-corrected H\alpha luminosities and from UV+FIR luminosities, and find a reasonable agreement between the two independent measurements of SFRs. We then derived the dust attenuation levels toward stellar light (from IR/UV ratio; SFR_{UV+FIR}/SFR_{UV}) and nebular emission lines (from H\alpha/H\beta ratio), to discuss the different dust attenuation levels toward stellar and nebular regions within local star-
forming galaxies. We quantify the “extra” attenuation toward nebular regions by \( E(B-V)_{\text{gas}}/E(B-V)_{\text{star}} \) ratio, and find that the levels of extra attenuation increase with increasing stellar mass, while it decreases with increasing specific SFR. At the high specific SFR end, no extra reddening is required (i.e. \( E(B-V)_{\text{gas}}/E(B-V)_{\text{star}} \approx 1 \)).

If we assume that the different levels of dust attenuation toward stellar and nebular regions is attributed to the different star/dust geometry within the galaxies as often argued by previous studies, we suggest that more massive galaxies tend to have more patchy (or centrally concentrated) distribution of dust within the galaxies, while the HII regions tend to be more uniformly distributed over the galaxies in low-mass galaxies (or those with high specific SFRs). Our results are also confirmed by using the WISE 22\( \mu \)m photometry, with the GSWLC catalog published by Salim et al. (2016).

We then study how the extra attenuation toward nebular re-
gions, \(E(B-V)_{\text{gas}}/E(B-V)_{\text{star}}\), changes on the SFR–\(M_\star\) diagram, by using the AKARI–SDSS–GALEX and WISE–SDSS–GALEX samples. We find that, even at a fixed stellar mass, there is a clear trend that galaxies located below the star-forming main sequence tend to have higher levels of extra attenuation, suggesting that the change in the \(E(B-V)_{\text{gas}}/E(B-V)_{\text{star}}\) ratio is related to the galaxy transition or SF quenching process, and that the distribution of stars and dust becomes more and more different as the SF quenching process proceeds.

Our results based on the new AKARI FSCv1, helped by SDSS, GALEX, and WISE data, demonstrate interesting trends between the \(E(B-V)_{\text{gas}}/E(B-V)_{\text{star}}\) ratio and various galaxy properties. However, considering the potential large uncertainty regarding the derivation of \(H_\alpha\) SFR (which is inevitable as long as we rely on the SDSS data), more detailed, systematic spatially-resolved studies for a statistical sample of galaxies selected from above/below the SF main sequence would be necessary to obtain a conclusive evidence of the change in the dust geometry across the SFR–\(M_\star\) diagram.

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