Star formation rates in type 1 AGN host galaxies

Irham Taufik Andika¹, Mochamad Ikbal Arifyanto¹, Wolfram Kollatschny²

¹Astronomy Study Program, Institut Teknologi Bandung, Jl. Ganesha No. 10, Bandung 40116, Indonesia
²Institut für Astrophysics, University of Goettingen, Friedrich-Hund-Platz 1, Goettingen 37077, Germany
E-mail: irham.andika@students.itb.ac.id

Abstract. We present a study of star formation rates of 3191 type 1 AGN host galaxies at z < 0.35, selected from Sloan Digital Sky Survey Data Release 12. We find that low ionization lines, [O II] λ3727, [N II] λ6548, [S II] λλ6717,6731 luminosities increase with increasing z while intermediate ionization lines, [O III] λ5007 luminosities does not increase with z, consistent with no evolution in AGN SED. We suggest the increasing luminosity of [O II] is caused by host galaxy contribution. The star formation rates that are estimated from [O II] luminosities show a flatter increase with z than non-AGN galaxies which indicates lower star formation activity across z in type 1 AGN host galaxies.

1. Introduction
The term of active galactic nuclei (AGN) is related to the compact region at the center of galaxy which emits stronger radiation than the rest of the host galaxy. The energy source of AGN is produced by accretion of gas onto supermassive black hole (SMBH; [1]) and then released in the form of radiation, winds, and/or jets. Circumnuclear gas at the center of AGN is photoionized by the energy and produces broad emission lines with typical width thousands of km s⁻¹, and narrow emission lines with typical width hundreds of km s⁻¹. The broad emission lines are believed to come from broad line region (BLR) while narrow emission lines are came from narrow line region (NLR). Type 1 AGN is a class of AGN which shows broad and narrow emission lines in their spectra.

There are several evidence that AGN and star formation activity are strongly related [2]. Most of AGN host galaxies in the low redshift universe contain significant amounts of molecular gas and dust. This makes nearby AGN host galaxies have the potential to undergo enhanced star formation. However, studies by [3] and [4] show that AGN activity somehow suppress star formation efficiency in these systems. NLR can be used as a proxy to study the property of gas in AGN host galaxies. It can be described as low-density and low-velocity gas extending from outer AGN torus up to thousands of parsecs along the general direction of ionization cones. This makes NLR emission not only driven by photoionization from accretion disk of AGN but also affected by the star formation activity in the host galaxy.

In this work we will investigate the NLR emission properties across a range of redshift by using new large sample of type 1 AGN from Sloan Digital Sky survey Data Release 12 [5]. Then,
star formation rates for each AGN host galaxies will be determined from NLR gas luminosity. We will also examine the correlation between star formation rates with redshift and compare the result with previous studies, including the case for non-AGN galaxies. Throughout this paper, we assume a Friedmann-Robertson-Walker cosmology with \( \Omega = 0.3, \Lambda = 0.7, H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1} \).

2. Data selection and processing
The data are selected from Sloan Digital Survey (SDSS) Data Release (DR) [5] in order to obtain type 1 AGN sample at low redshift \((z)\). Our search criteria are listed below:

(i) The spectrum of the objects is classified as quasi-stellar object or "QSO" by SDSS pipeline.
(ii) \(0.02 \leq z \leq 0.35\), to cover the Balmer series (especially H\(\beta\) and H\(\alpha\)), optical forbidden narrow lines \([\text{O II}], [\text{O III}], [\text{N II}], [\text{S II}]\), and optical Fe II complex in the spectral lines.
(iii) S/N > 10 in the spectrum based on median S/N of whole pixels covered by the spectrum (available in the SDSS database), to improve the accuracy of NLR/BLR decomposition.

A total 9184 spectra pass our criteria. The reduced one-dimensional spectral data are downloaded through SDSS Skyserver (http://skyserver.sdss.org/dr12/en). The data processing throughout this paper were done using custom Python codes. We use similar approach which as described by [6] with some modifications in continuum and emission lines fitting procedure. We separated the continuum windows into three parts: around \([\text{O II}], \text{H}\beta, \text{and H}\alpha\). For each region, we fit a local power-law continuum \((f_\lambda = A\lambda^{\alpha})\), an iron template, and host galaxy spectra to the wavelength region around the line that is not contaminated by the emission line.

We compare our results with the \(L_{\text{O III}}\) measurements of SDSS AGN in [7], who model \([\text{O III}]\) using multiple Gauss-Hermite (GH) functions. In the 2657 overlapping objects, the mean difference of our \(L_{\text{O III}}\) to their \(L_{\text{O III}}\) is 0.1 dex with dispersion of 0.08 dex. A total of 4293 objects with acceptable fits \((\text{reduced } \chi^2 < 2)\) pass these criteria. We note that our rejection criteria may have been too restrictive, and potentially excluded objects with an unusual broad line profile.

We utilize the diagnostic diagram to classify our sample and exclude objects other than AGN [8]. Therefore, our sample now contains 3191 type 1 AGN (T1 AGN) which reside at \(42.4 < \log L_{5100} < 45.3\) with median \(\log L_{5100} = 43.9\), where \(L_{5100}\) is averaged continuum luminosity at rest wavelength 5100 Å.

3. Result and analysis
3.1. Narrow lines luminosity and redshift
In this subsection, we will investigate the NLR emission across a range of redshift. First, we note that SDSS data is likely to miss high luminosity objects in low redshift and low luminosity objects in high redshift. This was expected because the flux limit of SDSS for AGN spectroscopy is \(i < 19.1\) and the evolution of AGN luminosity function. To overcome this problem, we group T1 AGN according to their \(\log L_{5100}\) into 10 luminosity classes \((L1 - L10)\). We thus divide each group into several subsets according to their redshift \((z)\) with bins of width 0.03. We only consider the subset that has more than 5 objects to get significant result. Based on this criteria, we only consider \(L4 - L7\) luminosity bins which spans more than 50% \(z\) range of 0.02 – 0.35. We will treat each bin separately and then average the measured correlation parameter.

There are four strongest forbidden narrow lines that we measured in T1 AGN spectral range: \([\text{O II}] \lambda\lambda 3727, [\text{O III}] \lambda\lambda 5007, [\text{N II}] \lambda 6548, \text{and} [\text{S II}] \lambda\lambda 6717, 6731\). We plot the luminosity of these lines against \(z\) to find if there is a correlation in Figure 1. We can see overall tendency of increasing \(L_{\text{NLR}}\) as \(z\) increases. To examine this quantitatively, we calculate the Spearman rank
Figure 1. The line luminosity versus redshift of the four narrow lines. In the each luminosity bin, the figure shows a clear increase in luminosity of each line towards higher redshift. The dots associated error bars mark the mean and the standard deviation of $\lambda L_{$ in each redshift bin.

Table 1. Overall result of the linear regression and the Spearman rank correlation coefficient for the lines luminosity and redshift for the four narrow lines.

| Line   | Slope (m) | Constant (c) | Std. Error | $\rho$   | $P$  |
|--------|-----------|--------------|------------|----------|------|
| [O III] | 0.129     | 41.374       | 0.300      | 0.250    | 0.252|
| [O II]  | 0.565     | 40.800       | 0.339      | 0.567    | 0.229|
| [N II]  | 0.531     | 40.552       | 0.289      | 0.526    | 0.260|
| [S II]  | 0.387     | 40.566       | 0.231      | 0.342    | 0.158|

correlation coefficient and slope in the Table 1 which is derived from least-squares regression in the form of equation:

$$\log L_{\text{NLR}} = mz + c$$  \hspace{1cm} (1)

As shown in Figure 1, the strongest correlation is found in $L_{\text{[O II]}}$ versus $z$ with Spearman correlation coefficient of $\rho = 0.567$ with $P = 0.299$ ($P$ is the probability of no correlation). A weaker correlation was found in [N II] ($\rho = 0.526$, $P = 0.260$) and [S II] ($\rho = 0.342$, $P = 0.158$). Basically, [O II], [N II], and [S II] have low ionization potential (IP). In the idea of stratified NLR, these lines are located in the outer region of NLR. On the other hand, [O III] which has higher IP and located in the inner region of NLR has weakest correlation ($\rho = 0250$, $P = 0.252$).

The slight increase in the luminosity of these narrow lines might be result of the host galaxy
contribution which undergoes enhanced star formation rates (SFR) at higher $z$. [O III] line that is located closest to the center of AGN will be strongly influenced by AGN radiation and less affected by host galaxy contamination. This was expected as we found the weak correlation in [O III]. The strong correlations which are found in [O II], [N II], and [S II] emissions show that these lines are more affected by the host galaxy contamination even while they are still driven by AGN photoionization.

The apparent increase in $L_{[\text{O II}]}$ as a function of $z$ could be also caused by different factors other than an increase in SFR of typical AGN host galaxy. For example, the 3-arcsec fixed-size aperture that is used by SDSS means the spectra potentially include a larger fraction of the host galaxy gas at high redshift than in lower redshift objects due to the larger projected physical size at higher redshift. More specifically, at $z = 0.02$ the physical size is 1.2 kpc and at $z = 0.35$ the physical size is 14.8 kpc. However, the typical size of entire NLR is probably less than 10 kpc, as found by [4]. This means apparent increase in $L_{[\text{O II}]}$ across $z$ cannot be caused solely by AGN photoionization.

3.2. Star formation rates and redshift

There are various methods to measure star formation rate (SFR) in galaxies. One of these methods is using [O II] line as reliable tracer. This line becomes particularly important for objects with $z > 0.5$ because the primary SFR tracer of H$\alpha$ has passed out of the optical bandpass. Unlike H$\alpha$, the [O II] line luminosity is not only influenced by electron temperature but also the degree of ionization and metallicity of the gas.

Assuming that [O III] is produced entirely by the AGN and is a good tracer of AGN bolometric luminosity as suggested by [5], we can use the $L_{[\text{O III}]}$ to constrain $L_{[\text{O II}]}$ contribution from star-forming region in the host galaxy. To estimate the SFR using [O II], we use $L_{[\text{O II}]}$ calibration equation from [9] for non-AGN galaxies:

$$\text{SFR}_{[\text{O II}]} = 8.4 \times 10^{-41} L_{[\text{O II}]} \ M_{\odot} \text{yr}^{-1}$$

This calibration equation is useful because it simplifies SFR calculation without directly involving assumptions about metallicity and intrinsic extinction that causes additional uncertainty. We first subtracted 10% of the $L_{[\text{O III}]}$ from the $L_{[\text{O II}]}$ to account the AGN contribution. This way we can estimate the excess of $L_{[\text{O II}]}$ contributed by star-forming region of host galaxy and calculate the upper limit SFR of T1 AGN.

We plot the result in Figure 2 which shows clearly that the SFR of T1 AGN increases with increasing $z$. The figure also shows that higher luminosity objects have higher SFR as expected from higher $L_{[\text{O II}]}$ in higher $L_{5100}$. Our least-squares regression shown in the figure with a slope of $m = 2.02 \pm 0.7$ which is notably consistent with [4] fit ($m = 2.3 \pm 0.4$) but somewhat smaller than the [9] fit ($m = 4.5$).

Study of star formation in AGN host galaxies using [O II] line also has been conducted by [3]. From a review of extant literatures, [3] concludes that SFR in type 1 AGN host galaxies are quiet modest, being no greater than $\sim 1 - 10 \ M_{\odot} \text{yr}^{-1}$. By using CO measurements, [3] also proved that the star formation efficiencies (SFR per unit gas mass) are also low, suggesting that the AGN somehow inhibits star formation. Another research was conducted by [2] who conducted detailed analysis of the narrow line spectrum of type 1 AGN. [2] also use [O II] line to constrain the ongoing SFR in the host galaxies and compared the measurement with a new set of photoionization models. They found [O II] line can be readily reproduced using conventional AGN parameters. This places strong constraints on any additional star-forming contribution to the [O II] luminosity. Their result also showed that the host galaxies of type 1 AGN evidently experience very modest star formation.

Therefore, we suggest that the smaller power-law slope of SFR we found compared with [9] indicates smaller star formation activity across $z$ in the type 1 AGN host galaxies compared
Figure 2. SFR calculated using Equation 2. The trend of increasing SFR towards higher redshift is clearly seen in the figure. The red line shows average linear regression of the luminosity groups.

with normal galaxies, at least up to $z = 0.35$.

4. Conclusion
In this paper, we derive a well-selected sample of type 1 AGN at low redshift using large sample SDSS DR 12 data to get the optical spectra of the sample. Spectral reduction and analysis to optical spectra carried out in order to derive emission lines parameters. We use the measured emission lines parameters to explore correlation and properties of type 1 AGN emission.

The luminosity of forbidden narrow lines increase with redshift. The strongest correlation was found in [O II] line. Because the [O II] line is known to be a reliable SFR estimator in normal galaxies, we interpret this result as evidence for higher SFR in the host galaxies of AGN at higher redshift. We calculate the SFR of T1 AGN sample by using the $L_{[O II]}$ scaling relation and find that the estimated SFR is increasing with redshift. The calculated power-law slope that we found ($m = 2.02 \pm 0.7$) is consistent with [5] but smaller than non-AGN galaxies ($m = 4.5$; [9]). Supported by [3] and [2] findings, we suggest that this smaller slope indicates smaller star formation activity across $z$ in type 1 AGN host galaxies compared with normal galaxies, at least up to $z = 0.35$.

References
[1] Netzer H., 2013, The Physics and Evolution of Active Galactic Nuclei
[2] Kim M. Ho Luis C., Im M., 2006, ApJ, 642, 702
[3] Ho Luis C., 2005, ApJ, 629, 680
[4] Tammour A., Gallagher S. C., Richards G., 2015, MNRAS, 448, 3354
[5] Alam S., et al., 2015, ApJS, 219, 12
[6] Shen Y., et al., 2011, ApJS, 194, 45
[7] Stern J., Laor A., 2012b, MNRAS, 426, 2703
[8] Kewley L. J., Dopita M. A., Sutherland R. S., Heisler C. A., Trevena J., 2001, ApJ, 556, 121
[9] Rosa-Gonzlez D., Terlevich E., Terlevich R., 2002, MNRAS, 332, 283