UNDERSTANDING AGN–HOST CONNECTION IN PARTIALLY OBSCURED ACTIVE GALACTIC NUCLEI. III. PROPERTIES OF ROSAT-SELECTED SDSS ACTIVE GALACTIC NUCLEI

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ABSTRACT

As the third paper of our series of studies that aim at examining the AGN–host co-evolution by using partially obscured active galactic nuclei (AGNs), we extend the broad-line composite galaxies (composite AGNs) into ROSAT-selected Seyfert 1.8/1.9 galaxies based upon the ROSAT All Sky Survey/Sloan Digital Sky Survey Data Release 5 (SDSS-DR5) catalog given by Anderson et al. The SDSS spectra of a total of 92 objects are analyzed by the same method used in our previous studies, after requiring the signal-to-noise ratio in the SDSS r' band to be larger than 20. Combining the ROSAT-selected Seyfert galaxies with the composite AGNs reinforces the tight correlation between the line ratio \([O\ I]/H\alpha\) versus \(D_n(4000)\), and establishes a new tight correlation between \([S\ II]/H\alpha\) versus \(D_n(4000)\). Both correlations suggest that the two line ratios are plausible age indicators of the circumnuclear stellar population for typical Type I AGNs in which the stellar populations are difficult to derive from their optical spectra. The ROSAT-selected Seyfert galaxies show that the two correlations depend on the soft X-ray spectral slope \(\alpha_X\), which is roughly estimated from the hardness ratios by requiring that the X-ray count rates within 0.1–2.4 keV be larger than 0.02 counts s\(^{-1}\). However, we fail to establish a relationship between \(\alpha_X\) and \(D_n(4000)\), which is likely caused by the relatively large uncertainties of both the parameters (especially for \(\alpha_X\) because of the AGN intrinsic obscuration). The previously established \(L/L_{\text{Edd}}-D_n(4000)\) evolutionary sequence is reinforced again by the extension to the ROSAT-selected Seyfert galaxies. These X-ray-selected Seyfert galaxies are, however, biased against the two ends of the sequence, which implies that the X-ray Seyfert galaxies present a population at a middle evolutionary stage.

Key words: galaxies: active – galaxies: evolution – galaxies: nuclei

Online-only material: color figures

1. INTRODUCTION

Active galactic nuclei (AGNs) are now widely believed to co-evolve with their host galaxies. The co-evolution scenario is based upon two observational facts. One is the firmly established tight Magorrian relationship (i.e., the \(M_{\text{BH}}-\sigma\) or \(M_{\text{BH}}-L_{\text{bulge}}\) relationship, e.g., Magorrian et al. 1998; Tremaine et al. 2002; Ferrarese & Merritt 2000; Greene & Ho 2006; Greene et al. 2008; Haring & Rix 2004). The other is the fact that the global evolutionary history of the growth of the central supermassive black hole (SMBH) and star formation history trace each other closely from the present to redshift \(z \sim 5\) (e.g., Nandra et al. 2005; Silverman et al. 2008; Shankar et al. 2009; Hasinger et al. 2005). Over the past decade, many theoretical and observational efforts have been made to understand the elusive evolutionary connection between AGNs and their host galaxies. For example, young stellar populations and enhanced ongoing star formation activities are prevalently identified in host galaxies of many Seyfert galaxies and quasars (e.g., González Delgado 2002; Silverman et al. 2009; Zuther et al. 2007; Canalizo & Stockton 2001; Stockton et al. 2007; Riffel et al. 2008; Cid Fernandes et al. 2001, 2005; Davies et al. 2007; Canizolo et al. 2007; Wang & Wei 2006; Zhou et al. 2005; Mao et al. 2009; Heckman & Kauffmann 2006). In addition, many authors established a relationship between the black hole accretion properties (e.g., \(L/L_{\text{Edd}}\)) and the properties (e.g., age and star formation rate) of the stellar population of the bulge of AGN host galaxies (e.g., Kewley et al. 2006; Wild et al. 2007; Wang et al. 2006; Wang & Wei 2008; Watabe et al. 2008; Davies et al. 2007). Theoretical simulations indicate that a major merger between two gas-rich disk galaxies is a plausible model for the co-evolution of AGNs with their host galaxies (e.g., Di Matteo et al. 2007; Hopkins et al. 2005, 2007; Granato et al. 2004). Finally, there is accumulating evidence supporting detectable AGN activity delays of \(\sim 10^8\) Myr after the onset of star formation activity (e.g., Hopkins et al. 2005; Wang & Wei 2006; Wang et al. 2009b; Schawinski et al. 2009; Reichard et al. 2008; Li et al. 2008).

Nevertheless, the details of the co-evolution of AGNs with their host galaxies are still far from being fully understood at the current stage. The main difficulty in understanding this co-evolution is due to the orientation effect caused by the AGN’s torus (see reviews in Antonucci 1993 and Elitzur 2007). We refer the readers to Wang & Wei (2008, hereafter Paper I, and references therein) for a brief comment on the several approaches that were adopted to overcome this difficulty. In Paper I, the spectra of partially obscured AGNs were used to simultaneously measure the properties of both AGNs and the stellar populations in an individual object. By examining the spectral properties of the 85 composite AGNs\(^1\) selected from the Sloan Digital Sky Survey Data Release 4 (SDSS-DR4) Max Planck Institute for Astrophysics/Johns Hopkins University (MPA/JHU) catalog (see Heckman & Kauffmann 2006 for a review), we identified an \(L/L_{\text{Edd}}-D_n(4000)\) evolutionary sequence and a tight correlation between the spectral break at 4000 Å (\(D_n(4000)\)) and the line flux ratio \([O\ I]/H\alpha\).

The study in Paper I is, however, far from a complete understanding of the co-evolution. At first, Paper I only focused on the composite galaxies whose narrow emission lines are believed

\(^1\) These composite AGNs with broad \(H\beta\) emission lines are selected from the composite galaxies that are located in the \([O\ I]/H\alpha\) versus \([N\ II]/H\alpha\) diagnostic diagram between the empirical and theoretical demarcation lines that separate AGNs from star-forming galaxies.
to contain significant contributions from both star formation and AGNs. The stellar populations in the composite galaxies are found to be systematically young (e.g., Kewley et al. 2006; Wang & Wei 2008; Schawinski et al. 2009), which naturally cause the composite AGNs studied in Paper I to tend toward clustering around the small \( D_\alpha (4000) \) end in the two relationships. Based upon the narrow emission-line galaxies from the MPA/JHU catalog, Kewley et al. (2006) suggested that the composite galaxies might evolve to Seyfert galaxies (see Section 3.2 for details). The star populations in the composite galaxies naturally contain significant contributions from both star formation and AGNs. The evolutionary role of X-ray emission is also indirectly suggested by the study of the eigenvector I (EI) space of AGNs. The EI space was first introduced by Boroson & Green (1992) who analyzed the optical spectra of 87 bright Palomar-Green quasars, and was subsequently extended to soft X-ray spectral slope \( T_{\text{soft}} \) (e.g., Wang et al. 1996; Grupe 2004; Xu et al. 2003; and see Sulentic et al. 2000 for a review). By examining the optical spectra of a sample of IRAS-selected Seyfert 1.5 galaxies, Wang et al. (2006) first extended the EL space into middle–far-infrared colors \( \alpha \), which implies a relation between the essential EI space and the age of the circumnuclear stellar population.

A sample of X-ray-selected Seyfert galaxies is therefore not only appropriate for the extension of the two relationships (i.e., the \( L/L_{\text{Edd}} \)–\( D_\alpha (4000) \) sequence and \( [O I]/H\alpha \) versus \( D_\alpha (4000) \) correlation) to Seyfert galaxies, but also required for the study of the speculated evolutionary role of X-ray emission. It is widely accepted that luminous X-ray emission is a common property of typical AGNs. Typically, the X-ray luminosity in AGNs contributes a fraction of about 5%–40% of the bolometric luminosity. A large fraction of the counterparts of the X-ray sources are optically spectroscopically identified as AGNs (e.g., Stocke et al. 1991; Obric et al. 2006; Anderson et al. 2007; Kollatschny et al. 2008; Mahony et al. 2010; Wei et al. 1999). Obric et al. (2006) found that the number of AGNs is six times more than that of star-forming galaxies for SDSS–ROSAT narrow emission-line galaxies according to the \( [O I]/H\beta \) versus \( [N II]/H\alpha \) diagnostic diagram. Because the properties of stellar populations are required in our study, we focus on partially obscured AGNs again by following the same approach used in Paper I since their spectra have the advantage of a balance between the contribution of AGNs and starlight.

With these motivations, we extend the study in Paper I to soft X-ray-selected partially obscured Seyfert galaxies by selecting these galaxies from the combination of the SDSS–DR5 spectroscopic survey and ROSAT All Sky Survey (RASS; hereafter ROSAT-selected Seyfert galaxies). The cross-match was originally done by Anderson et al. (2007). The selected sample is combined with the composite AGNs studied in Paper I to provide a complete understanding of the co-evolutionary issue, except for the analysis in which the X-ray properties are required. The paper is structured as follows. Section 2 describes the sample selection and data reduction. The physical properties of both AGNs and stellar populations are obtained in Section 3. Sections 4 and 5 present our analysis and discussion, respectively. A \( \Lambda \) cold dark matter (ΛCDM) cosmology with parameters \( h_0 = 0.7, \Omega_M = 0.3 \), and \( \Omega_\Lambda = 0.7 \) (Spergel et al. 2003) is adopted throughout the paper.

2. SAMPLE AND DATA REDUCTION

2.1. The Sample of SDSS-DR5/RASS Seyfert 1.8/1.9 Galaxies

Anderson et al. (2007, and references therein) recently carried out a RASS/SDSS program to identify the optical counterparts of the ROSAT X-ray sources from the SDSS-DR5 catalog, simply because the depths of the two surveys are well matched. The updated catalog contains about 7000 quasars/broad-line AGNs and 500 narrow-line AGNs (including Seyfert 1.5–1.9 galaxies) with plausible X-ray emission. These AGNs were classified by Anderson et al. (2007) through a visual examination of their SDSS spectra. We only focus on the Seyfert 1.8/1.9 galaxies in this paper. Among these Seyfert 1.8/1.9 galaxies, we further require the redshifts to range from 0.03 to 0.3, which is comparable with the study in Paper I. In order to ensure that our results are not affected by poor quality spectra, only objects with signal-to-noise ratios larger than 20 in the \( r' \) band image are considered in our subsequent analysis. There are a total of 93 ROSAT-selected Seyfert galaxies that are listed in our final sample.

RASS surveyed nearly all sky down to a limiting sensitivity \( \sim 10^{-13} \) erg s\(^{-1}\) cm\(^{-2}\). The sensitivity limit therefore results in a selection effect that causes us to miss AGNs with low X-ray emission (both intrinsic and obscured, see Section 4.2 for details).

The position error circles are about 10”–30” for RASS. The probability of a true match between SDSS and RASS strongly depends not only on the angular distance between the SDSS main galaxy sample and RASS sources, but also on the spectral types of galaxies. The simulation in Parejko et al. (2008) indicates that (1) the probability of a reliable cross-match between SDSS galaxies and RASS sources is larger than \( \sim 40\% \) when the separation is within \( \sim 30'' \), (2) this probability is greatly enhanced to \( \sim 95\% \) if the galaxies can be classified as AGNs with broad emission lines (see also Anderson et al. 2007), and (3) an X-ray counterpart could always be reliably identified for LINERs, Seyfert 2s, transitions, and unclassified galaxies, except for star-forming galaxies. The cross-match radius adopted in Anderson et al. (2007) is 27.5 away from each of the bright X-ray sources. Our spectral analysis shows that none of the ROSAT-selected galaxies used in the current study is classified as a star-forming galaxy. The redshifts are displayed per spectral type in Figure 1 for the ROSAT-selected Seyfert galaxies. The mean and median values are marked by open triangles and squares, respectively, for each of the spectral types. We classified these galaxies as transitions (T), Seyfert galaxies (S), LINERs (L), and unclassified galaxies (U) following the recent classification scheme proposed in Kewley et al. (2006) using the Baldwin–Phillips–Terlevich (BPT) diagrams (see Section 3.2). All four types of galaxies show similar mean and median redshifts at around \( z \sim 0.1 \).

2.2. Spectral Analysis

The SDSS spectra are reduced by following the identical method that was described in detail in Paper I. Briefly, the
Galactic extinction is first corrected for each spectrum by using the color excess $E(B-V)$ taken from the Schlegel, Finkbeiner, and Davis Galactic reddening map (Schlegel et al. 1998). The extinction law with $R_V = 3.1$ is adopted for the correction (Cardelli et al. 1989). Each extinction-corrected spectrum is then transformed to the rest frame, along with the $k$-correction, given the redshift measured by the SDSS pipelines (Glazebrook et al. 1998; Bromley et al. 1998).

Among the whole sample, the continuum of the majority of the spectra (90% = 83 objects) is dominated by stellar absorption features. For each of these objects, a pipeline based on the principal component analysis (PCA) method has been developed by us to separate the starlight from the observed spectrum. We refer the readers to Paper I for the details of the PCA method. The modeling and removal of the starlight component is illustrated for one typical object in the upper panel of the left column of Figure 2. However, the starlight component cannot be correctly separated from the observed spectra for the remaining 13 objects because their continuum is dominated by the featureless emission from central AGNs. In these cases, the continuum is instead modeled by a power law through a $\chi^2$ minimization. The minimization is carried out in the rest-frame wavelength ranging from 4000 Å to 7000 Å, except for the regions around the strong AGN emission lines: e.g., Balmer lines, $[\text{O} \text{III}]\lambda\lambda 4959, 5007$, $\text{He} \text{II}\lambda 4686$, $[\text{N} \text{II}]\lambda \lambda 6583, 6548$, $[\text{S} \text{II}]\lambda \lambda 6716, 6731$, $[\text{O} \text{III}]\lambda 4363$, and possible $\text{Fe} \text{II}$ complex from 4200 Å to 4500 Å. In fact, the $\text{Fe} \text{II}$ blends are not included in the continuum modeling and in the subsequent analysis, because the $\text{Fe} \text{II}$ blends are too weak to be detectable in these spectra. The lower panel in the left column of Figure 2 shows an illustration of the power-law continuum modeling.

The emission lines are modeled and measured by the SPECFIT task (Kriss 1994) in the IRAF package$^3$ in the $H\beta$ and $H\alpha$ regions, after the starlight/power-law continuum is removed from the observed spectra. In each spectrum, the observed profile of each emission line is modeled by a set of Gaussian components through their linear combination. The emission-line modelings in the $H\beta$ and $H\alpha$ regions are schemed in the middle and right columns of Figure 2, respectively. The flux of the $[\text{O} \text{I}]\lambda 6300$ emission line is measured by a direct integration in each spectrum through the SPLIT task in IRAF. Although the broad $H\alpha$ emission can usually be well modeled by a single Gaussian component in most objects, an additional very broad $H\alpha$ (with FWHM $\sim 10,000$ km s$^{-1}$) is required to adequately model the broad $H\alpha$ emission in five objects (see Paper I and references therein, and recently in Zhu et al. 2009). We determine the FWHM of the broad $H\alpha$ emission in these particular cases as follows. We first model the observed $H\alpha$ profile by a set of Gaussian components including the additional very broad component. A residual profile is then produced by subtracting the modeled $H\alpha$ narrow component from the observed profile. The line width of the broad $H\alpha$ emission is finally measured on the residual profile through the SPLIT task. The starlight around $H\beta$ is usually oversubtracted, especially for the objects associated with old stellar populations, which results in a 2%–7% underestimation in the $H\beta$ flux (see Paper I and Asari et al. 2007). The oversubtraction is probably caused by the calibration in the STELIB library (Asari et al. 2007). In this paper, we slightly enhance the continuum level around the $H\beta$ emission line from zero by assuming that all the $H\beta$ emission is above the zero level to account for the small underestimation. Although the small underestimation is corrected here, the results given in this paper are still comparable with our study in Paper I where the small underestimation is ignored, both because the correction is too small to affect the main results and because the composite AGNs are mainly associated with relatively young stellar populations.

The results of the emission-line measurements are tabulated in Tables 1 and 2 for the objects whose continuum is dominated by starlight and power-law emission, respectively. For each object in Table 1, Column 1 lists the SDSS identification and Column 2 the corresponding redshift. The line ratios in the logarithm of $[\text{N} \text{II}]\lambda 6583/\text{He} \text{II}\alpha$, $[\text{S} \text{II}]\lambda 6716/\text{He} \text{II}\alpha$, and $[\text{O} \text{III}]\lambda 4959/\text{H} \text{II}\alpha$ are listed in Columns 3–6. Columns 7 and 8 show the FWHM of the $H\alpha$ broad component and intrinsic luminosity ($L_{H\alpha}$), respectively. The luminosity is corrected for local extinction. The extinction is inferred from the narrow-line ratio $H\alpha/H\beta$ for

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$^3$ IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.
| SDSS Name   | $\alpha$ [J2000] | $\delta$ [J2000] | $V$ [mag] | $B-V$ [mag] | $J-K$ [mag] | $\text{FWHM}$ [km s$^{-1}$] | $L_\text{(H$\alpha$)}$ [erg s$^{-1}$] | $D_{\text{L}}$ [Mpc] | $M_\text{HI}$ [M$_\odot$] | $\alpha X$ [0.1-4 keV] |
|-------------|-----------------|-----------------|--------|----------|--------|-----------------|-----------------|-----------------|-------------------|-----------------|
| 095623.68+564806.30 | 0.075 | 0.176 | 0.377 | 0.1352 | 0.530 | 0.265 | 0.432 | 0.1576 | 0.03 | 0.19 | 0.67 |
| 100514.90+49085.89 | 0.071 | 0.265 | 0.432 | 0.1576 | 0.030 | 0.265 | 0.432 | 0.1576 | 0.03 | 0.19 | 0.67 |
| 095623.68+564806.30 | 0.075 | 0.176 | 0.377 | 0.1352 | 0.530 | 0.265 | 0.432 | 0.1576 | 0.03 | 0.19 | 0.67 |
| 100514.90+49085.89 | 0.071 | 0.265 | 0.432 | 0.1576 | 0.030 | 0.265 | 0.432 | 0.1576 | 0.03 | 0.19 | 0.67 |
| 095623.68+564806.30 | 0.075 | 0.176 | 0.377 | 0.1352 | 0.530 | 0.265 | 0.432 | 0.1576 | 0.03 | 0.19 | 0.67 |
| 100514.90+49085.89 | 0.071 | 0.265 | 0.432 | 0.1576 | 0.030 | 0.265 | 0.432 | 0.1576 | 0.03 | 0.19 | 0.67 |

Note: The table provides properties of ROSAT-selected Seyfert galaxies with determined stellar population ages.
For the objects whose continuum is modeled by a power law, we refer the readers to the analysis mentioned above. The calculation is briefly described in Paper I. Based upon the results in Table 1, the co-evolution of AGNs and their host galaxies is supported by the B-band brightness of the AGN, the AGN bolometric luminosity, and the total luminosity of the host galaxy.

3. ANALYSIS AND RESULTS

Based upon the spectral measurements given above, the multiwavelength properties of the ROSAT-selected Seyfert galaxies are derived and analyzed in this section. The ROSAT-selected Seyfert galaxies are then combined and compared with the composite AGNs previously studied in Paper I to give us a complete understanding of the co-evolution of AGNs and their host galaxies.

### 3.1. Deriving Physical Properties

The black hole mass \((M_{\text{BH}})\), Eddington ratio \((L/L_{\text{Edd}})\), soft X-ray spectral slope, and optical indices being sensitive to the age of stellar population are calculated based upon the spectral analysis mentioned above. The calculation is briefly described as follows, because some methods that are adopted here are the same as those used in Paper I. We refer the readers to Paper I for the details of the calculation and discussion about the uncertainties.

#### 3.1.1. \(L/L_{\text{Edd}}\) and \(M_{\text{BH}}\)

Two arguments allow us to believe that the detected emission of the \(H\alpha\) broad components is mainly contributed by central AGNs. First, the detectable X-ray emission strongly supports the presence of an AGN at the center of the galaxies. Moreover, the minimal value of the measured luminosity of the broad \(H\alpha\) component is \(1.59 \times 10^{40} \text{ erg s}^{-1}\). The average and median values are \(6.32 \times 10^{41} \text{ erg s}^{-1}\) and \(3.32 \times 10^{41} \text{ erg s}^{-1}\), respectively, which are far larger than the values that could be produced by other mechanisms (e.g., Wolf-Rayet stars and luminous blue variables with \(L_{\text{bol}} \sim 10^{46} - 10^{47} \text{ erg s}^{-1}\); see Izotov et al. 2007, Izotov & Thuan 2008 and references therein, and discussions in Paper I).

Following the study in Paper I, the two basic parameters of black hole accretion (i.e., \(L/L_{\text{Edd}}\) and \(M_{\text{BH}}\)) are directly estimated from the AGN broad \(H\alpha\) emission lines, because the continuum of these objects is highly contaminated by the emission from their host galaxies. Based upon the revised luminosity–radius relation provided by Bentz et al. (2009), Greene & Ho (2007) derived an updated estimator of mass of the central SMBH. In order to compare the results given in the table...
current paper with those reported in Paper I, we estimate \( L/L_{\text{Edd}} \) and \( M_{\text{BH}} \) by using the same equations used in Paper I, i.e., the calibrations provided in Greene & Ho (2005). The estimated values of \( L/L_{\text{Edd}} \) and \( M_{\text{BH}} \) are listed in Columns 11 and 12 of Table 1 for each object, respectively. \( L/L_{\text{Edd}} \) and \( M_{\text{BH}} \) are not available for 14 objects in which the very weak broad H\( \alpha \) components prevent us from estimating the values. As stated in Paper I, the estimated \( L/L_{\text{Edd}} \) and \( M_{\text{BH}} \) are likely systemically underestimated in the partially obscured AGNs. The upper limit of the underestimation is roughly \( \sim 70\% \) for \( M_{\text{BH}} \) and \( \sim 50\% \) for \( L/L_{\text{Edd}} \).

3.1.2. \( D_n(4000) \) and H\( \delta_A \)

As was done in Paper I, we use the 4000 Å break (\( D_n(4000) \)) and equivalent width of H\( \delta \) absorption of A-type stars (H\( \delta_A \)) as indicators of the ages of stellar populations of AGN host galaxies (e.g., Heckman et al. 2004; Kauffmann et al. 2003; Kewley et al. 2006). The two indices are measured in the removed starlight spectrum for each object. The measured values of both indices are tabulated in Columns 9 and 10 of Table 1. Figure 3 compares the number distribution of the measured \( D_n(4000) \) of the ROSAT-selected Seyfert galaxies with that of composite AGNs. The stellar populations of the ROSAT-selected Seyfert galaxies are systematically older than those of the composite AGNs, which agree with previous studies (e.g., Kewley et al. 2006). The Gehan’s generalized Wilcoxon two-sample statistical test shows that the two distributions are drawn from the same parent population at a confidence level of 1.2%. This conclusion is further confirmed by a two-side Kolmogorov–Smirnov test that yields a maximum discrepancy of 0.21 with a corresponding probability of 5.6% that the two distributions will match.

3.1.3. Soft X-ray Spectral Slope \( \alpha_X \)

The X-ray spectral properties are estimated from the ROSAT hardness ratios HR1 and HR2\(^4\) (Voges et al. 1999) by assuming a single power law (i.e., \( F_\nu \propto \nu^{-\alpha_X} \)) modified by the foreground absorption resulting only from our own Galaxy (e.g., Xu et al. 2003; Yuan et al. 2008; Grupe et al. 1998). The Galactic hydrogen column density \( N_H \) is transformed from the color excess \( E(B-V) \) through the calibration \( N_H = (5.8 \pm 2.5) \times 10^{21} E(B-V) \text{ cm}^{-2} \) (Bohlin et al. 1978) for each object, where \( E(B-V) \) is adopted again from the Schlegel, Finkbeiner, and Davis Galactic reddening map (Schlegel et al. 1998). The soft X-ray opacity is calculated from the effective absorption cross sections given in Morrison & McCammon (1983) by assuming a solar abundance.

Previous studies have suggested that this method is reliable and robust if the intrinsic X-ray spectra can indeed be described as a simple power law (e.g., Brinkmann & Siebert 1994; Schartel et al. 1996). The X-ray spectral slope \( \alpha_X \) is estimated for objects whose X-ray count rates within the 0.1–2.4 keV band are larger than 0.02 counts s\(^{-1}\). We list the estimated \( \alpha_X \) in Column 13 of Table 1 and Column 7 of Table 2. The estimated \( \alpha_X \) ranges from 0.1 to 5, which statistically agrees with the previous studies that focused on typical Type I AGNs (e.g., Xu et al. 2003; Grupe 2004). Although it is the best approach for a large AGN sample at present, strictly speaking, local absorption (and obscuration) from AGNs and their host galaxies should be involved in the spectral model for these partially obscured AGNs, because X-ray and optical absorptions are statistically correlated in AGNs (e.g., Garcez et al. 2007; Silverman et al. 2005). In fact, one can see from below that such a simple approach greatly degrades our results.

3.2. BPT Diagnostic Diagrams

The refined BPT diagrams (Baldwin et al. 1981; Veilleux & Osterbrock 1987) are commonly used to diagnose the central energy sources in narrow-line emission galaxies (see recent review in Groves et al. 2006). According to the classification scheme recently suggested in Kewley et al. (2006), we classified the 80 ROSAT-selected Seyfert galaxies for which all four line ratios have been measured. There are in total 13 transitions, 38 Seyfert galaxies, 1 LINER, and 28 uncategorized galaxies. The uncategorized galaxies mean that they are differently classified in the three diagrams.

Recent studies indicate that BPT diagrams reflect not only the dominant central energy sources, but also an evolutionary sequence of AGNs. Using the large spectral database of narrow-line emission galaxies selected from the SDSS, Kewley et al. (2006) found that the properties (e.g., \( D_n(4000) \)) of AGN host galaxies change with distance from the star-forming sequence. Wang et al. (2009b) recently pointed out that the traditionally classified LINERs consist of two populations likely at different evolutionary stages, with different power sources (see also Stasinska et al. 2008).

The distributions on the three traditional BPT diagrams are shown in Figures 4 and 6 for the ROSAT-selected Seyfert galaxies. In each figure, the three panels correspond to the

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\(^4\) The ROSAT hardness ratios HR1 and HR2 are defined as HR1 = \((B - A)/(B + A)\) and HR2 = \((D - C)/(D + C)\), where \(A\), \(B\), and \(D\) are the count rates in the energy bands 0.1–0.4, 0.5–2.0, 0.5–0.9, and 0.9–2.0 keV, respectively.
three different methods for classifying emission-line galaxies using two pairs of line ratios. The galaxies with measured $D_4(4000)$ are shown by red open squares and the galaxies whose spectra are dominated by AGN continuum by blue open circles. At first glance, as compared with the composite AGNs studied in Paper I, a majority of the ROSAT-selected Seyfert galaxies are located above the theoretical curves discriminating between AGNs and star-forming galaxies in all three BPT diagrams (Kewley et al. 2001). In Figure 4, the size of each point is scaled to be proportional to the value of $D_4(4000)$, if possible. All three panels indicate a trend that stellar populations that evolve as Seyfert galaxies, deviate from the star-forming sequence, which confirms the conclusion drawn in Paper I and possible. All three panels indicate a trend that stellar populations change from young to old as the AGNs deviate from the star-forming sequence, which confirms the results given in previous studies (e.g., Wang & Wei 2008; Kewley et al. 2006). The green star in each panel marks the empirical point used to calculate the distance from the star-forming sequence.

(A color version of this figure is available in the online journal.)

Figure 4. Three BPT diagnostic diagrams for the ROSAT-selected Seyfert galaxies. The red solid points present the galaxies whose continuum is dominated by the starlight component and the blue open circles the galaxies whose continuum is dominated by a featureless AGN power law. The theoretical demarcation lines separating AGNs from star-forming galaxies proposed by Kewley et al. (2001) are shown by the solid lines and the empirical line proposed by Kauffmann et al. (2003) by the dashed line. The dot-dashed lines drawn in the [S ii]/Hα vs. [O III]/Hβ and [O I]/Hα vs. [O III]/Hβ diagrams show the empirical separation scheme of LINERs proposed in Kewley et al. (2006). The size of each point is proportional to the corresponding value of $D_4(4000)$. Clear trends with $D_4(4000)$ can be identified in all three panels. The stellar populations change from young to old as the AGNs deviate from the star-forming sequence, which confirms the results given in previous studies (e.g., Wang & Wei 2008; Kewley et al. 2006). The green star in each panel marks the empirical point used to calculate the distance from the star-forming sequence.

(A color version of this figure is available in the online journal.)

Figure 5. Correlations between the index $D_4(4000)$ and the distance from the star-forming sequence (see the definition in the main text) in the three BPT diagrams for the ROSAT-selected Seyfert galaxies. From left to right, Spearman rank-ordered tests yield correlation coefficients $r_s = 0.379$, 0.367, and 0.482, and corresponding significance levels $P = 0.0006$, 0.0021, and $< 10^{-4}$.

(A color version of this figure is available in the online journal.)

Figure 6. Three diagnostic BPT diagrams, the same as in Figure 4. The size of each point is set to be proportional to the corresponding value of the soft X-ray spectral slope $\alpha_X$, instead of $D_4(4000)$.

(A color version of this figure is available in the online journal.)

3.3. [O I]/Hα Versus $D_4(4000)$ and [S II]/Hα Versus $D_4(4000)$ Correlations

We found a tight correlation between the line ratio [O I]/Hα and $D_4(4000)$ in Paper I for the first time. Here, we re-examine the correlation by extending the sample to ROSAT-selected Seyfert galaxies (typically with older stellar populations compared with the composite AGNs, see Section 3.1). Figure 7 shows the [O I]/Hα versus $D_4(4000)$ correlation in the left panel along with the [S II]/Hα versus $D_4(4000)$ correlation in the right panel. The ROSAT-selected Seyfert galaxies are shown by red open circles and the composite AGNs by green solid circles. The two tight correlations between the two line ratios and $D_4(4000)$ can be clearly identified not only for the ROSAT-selected Seyfert galaxies or composite AGNs, but also for the combination of the two samples. Taking only the ROSAT-selected Seyfert galaxies into account, Spearman rank-ordered tests yield a correlation coefficient $r_s = 0.661$ at a significance level of $P < 10^{-4}$ for the [O I]/Hα versus $D_4(4000)$ correlation, and $r_s = 0.693$ with $P < 10^{-4}$ for the [S II]/Hα versus $D_4(4000)$ correlation. After combining the two samples, similar tests provide better statistics with the corresponding correlation coefficients $r_s = 0.661$ ($P < 10^{-4}$) and $r_s = 0.681$ ($P < 10^{-4}$). An unweighted least-squares fitting results in two calibrations:

$$\log D_{4000} = (0.24 \pm 0.01) + (0.09 \pm 0.01) \log ([O I]/H\alpha)$$

(1)

and

$$\log D_{4000} = (0.20 \pm 0.01) + (0.14 \pm 0.01) \log ([S II]/H\alpha)$$

(2)

Similar significant correlations can be still identified for cases with $H\delta_{\lambda}$:

$$r_s = -0.583, P < 10^{-4} \text{ for } [S II]/H\alpha, \text{ and } r_s = -0.574, P < 10^{-4} \text{ for } [O I]/H\alpha.$$

5 Similar correlations can be found in the case of Hα instead of $D_4(4000)$. The corresponding Spearman rank-order correlation coefficients $r_s$ are $-0.471$, $-0.490$, and $-0.623$. All the correlations are significant at a level $P < 10^{-4}$.
with a value of standard deviation \( \sigma = 0.04 \) for both fittings. The best-fitted calibrations are shown by dashed lines in both panels of Figure 7. The 1\( \sigma \) deviation is marked by dotted lines in each panel.

3.4. \( L/L_{\text{Edd}} - D_n(4000) \) Sequence

One of the aims of this third paper is to extend the \( L/L_{\text{Edd}} - D_n(4000) \) sequence established in Paper I to ROSAT-selected Seyfert galaxies. \( D_n(4000) \) is plotted against \( L/L_{\text{Edd}} \) in Figure 8 by red solid squares for the ROSAT-selected Seyfert galaxies. The composite AGNs studied in Paper I are presented by blue open circles. The three green open stars mark the position of the three intermediate-\( z \) hybrid quasi-stellar objects (QSOs) studied recently in Wang & Wei (2009). The ROSAT-selected Seyfert galaxies follow the evolutionary sequence that was established previously in the composite AGNs. The correlation coefficient is \( r_s = -0.400 \) \( (P < 10^{-4}) \) for the combination of the two samples, although the statistics is poor \( (r_s = -0.142, P = 0.2464) \) when only the ROSAT-selected Seyfert galaxies are considered. The poor statistics is most likely caused by the relatively narrow dynamic range (see the discussion below).

The inset panel in Figure 8 shows the \( D_n(4000) - \text{H}\delta_4 \) diagram for the ROSAT-selected Seyfert galaxies. Again, we find consistency with what was reported in Paper I. The mass building in the ROSAT-selected Seyfert galaxies could be described by a continuous star formation history with an exponentially declining star formation rate.

4. DISCUSSION

4.1. Evolutionary Significance of \( \alpha_X \)?

The sample of the ROSAT-selected Seyfert galaxies allows us to examine the evolutionary significance of the properties of soft X-ray emission of AGNs. We directly plot the two line ratios \( ([\text{O}\text{I}]/\text{H}\alpha \text{ and } [\text{S}\text{II}]/\text{H}\alpha) \) and \( D_n(4000) \) as a function of \( \alpha_X \) in Figure 9. The top and middle panels show two marginal anti-correlations between the two line ratios and \( \alpha_X \). According to the Spearman rank-ordered tests, the correlation coefficients are \( r_s = -0.274 \) with \( P = 0.0355 \) for \([\text{O}\text{I}]/\text{H}\alpha \) versus \( D_n(4000) \), and \( r_s = -0.316 \) with \( P = 0.0171 \) for \([\text{S}\text{II}]/\text{H}\alpha \) versus \( D_n(4000) \). We argue that these dependences agree with the theoretical photoionization models. The photoionization calculations in Kewley et al. (2006) suggested that a hard ionizing field with a power-law index \( \alpha < 1.4 \) is required to produce the strong \([\text{O}\text{I}] \) line emission \( \log([\text{O}\text{I}]/\text{H}\alpha) \approx -0.6 \). This scenario seems to be plausible since various high-energy instruments have observed hard X-ray spectra in dozens of LINERs that are typical of high \([\text{O}\text{I}]/\text{H}\alpha \) ratios and old stellar populations (e.g., Flohic et al. 2006; Gliozzi et al. 2008; Rinn et al. 2005).

Given the strong correlation between the two line ratios and \( D_n(4000) \), \( D_n(4000) \) is expected to be related with \( \alpha_X \). However, no correlation can be identified between \( D_n(4000) \) and \( \alpha_X \) in the current sample from the bottom panel of Figure 9 \( (r_s = -0.107, P = 0.4184) \). The non-detection of the expected correlation might be caused by the uncertainties of both parameters. First, we ignore the local soft X-ray absorption in our estimation of \( \alpha_X \). Second, the measurement of \( D_n(4000) \) is model dependent, and highly depends on the signal-to-noise ratios of the spectra at the blue end. By contrast, the two line ratios can be accurately determined from the observed spectra.

In summary, we fail to find direct evidence supporting the evolutionary significance of \( \alpha_X \) from the sample of the ROSAT-selected Seyfert galaxies, albeit the evolutionary significance could be indirectly supported by the combination of the strong

\[ * \text{The Spearman correlation coefficient for the correlation between } \alpha_X \text{ and } \text{H}\delta_4 \text{ is } r_s = -0.134, P = 0.3122. \]
Figure 9. Direct dependence of the soft X-ray spectral slope $\alpha_X$ estimated from the \textit{ROSAT} hardness ratios on the two line ratios ([O\textsc{i}]/H\textalpha: upper panel and [S\textsc{ii}]/H\textalpha: lower panel) and on the $D_n(4000)$ index. The galaxies with and without determined stellar population ages are shown by red open and green solid circles, respectively.

(A color version of this figure is available in the online journal.)

[O\textsc{i}]/H\textalpha ([S\textsc{ii}]/H\textalpha) versus $D_n(4000)$ correlation and the identified marginal dependence of [O\textsc{i}]/H\textalpha ([S\textsc{ii}]/H\textalpha) on $\alpha_X$: AGNs with a soft X-ray spectrum might evolve to ones with a hard X-ray spectrum as the circumnuclear stellar population continually ages.

4.2. $L/L_{\text{Edd}}$ Versus $\alpha_X$

Although the physical origin of the soft excess is still uncertain (see, e.g., Walter & Fink 1993; Kawaguchi et al. 2001; Schurch & Done 2007; Turner & Miller 2009, for a review), it was known for a long time that there is a strong dependence between soft X-ray emission and optical spectroscopic properties (and also $L/L_{\text{Edd}}$). Brandt et al. (1997) found a strong anti-correlation between the photon index $\Gamma (N(E) \propto E^{-\Gamma})$, i.e., $\alpha_X = \Gamma - 1$ in the soft X-ray regime and the FWHM of AGN broad H\textalpha emission lines (see also Leighly 1999; Reeves & Turner 2000). Direct correlation analysis and PCA analysis indicated that $\alpha_X$ is related to the optical spectroscopic properties (e.g., [O\textsc{iii}] emission and RFe = optical Fe\textsc{ii}/H\beta) that define the EI space (e.g., Grupe 2004; Xu et al. 2003; Laor et al. 1997; Vaughan et al. 1999). Briefly, the larger the $\alpha_X$, the stronger the Fe\textsc{ii} blends and [O\textsc{iii}] emission will be.

As suggested early in Pounds et al. (1995), a high $L/L_{\text{Edd}}$ state tends to produce a steep soft X-ray spectrum. Thanks to the great progress made in the reverberation mapping technique (e.g., Kaspi et al. 2000, 2005; Peterson & Bentz 2006), Boroson (2002) indicated that the EI space is mainly physically derived by $L/L_{\text{Edd}}$. With this progress in $M_{\text{BH}}$ estimation, Grupe (2004) subsequently found a direct correlation between $\alpha_X$ and $L/L_{\text{Edd}}$ in a sample of \textit{ROSAT} soft X-ray-selected Type I AGNs. This correlation was recently confirmed in Desroches et al. (2009) for AGNs with intermediate $M_{\text{BH}}$.

We fail to identify a correlation between $\alpha_X$ and $L/L_{\text{Edd}}$ ($r_x = -0.127, P = 0.3725$) in the current sample, however. In fact, this is not a surprising result considering that both the parameters have relatively large uncertainties. In addition to the large uncertainties in the estimation of $\alpha_X$ (see the discussion above), the estimation of $L/L_{\text{Edd}}$ is still affected by the orientation effect of AGNs. Paper I stated that the upper limit of the underestimation of $L/L_{\text{Edd}}$ is $\sim 50\%$ due to both intrinsic extinction in the broad-line region and torus obscuration. In fact, Grupe (2004) found a direct correlation between $\alpha_X$ and $L/L_{\text{Edd}}$ in a sample of \textit{ROSAT} soft X-ray-selected Type I AGNs whose spectra are predominated by AGN emission, which was recently confirmed in Desroches et al. (2009) for AGNs with intermediate $M_{\text{BH}}$. To avoid the strong absorption in the soft X-ray band, we need to extend our future study to the hard X-ray ($\geq 2$ keV) regime. At present, the relationship between hard X-ray photon index $\Gamma$ and $L/L_{\text{Edd}}$ is still a controversial issue (e.g., Shemmer et al. 2008; Constantin et al. 2009).

Currently available hard X-ray surveys seem to be strongly biased toward bright Type I AGNs due to their limited sensitivity (e.g., Wang et al. 2009a). A deep, well-defined hard X-ray survey is therefore necessary for establishing a better understanding of the evolutionary significance of high-energy emission of AGNs in the future.

4.3. $L/L_{\text{Edd}}$–$D_n(4000)$ Sequence

There is accumulating observational evidence supporting that $L/L_{\text{Edd}}$ plays an important role in the evolution of AGNs. By combining the current sample with the composite AGNs studied in Paper I, we reinforce the $L/L_{\text{Edd}}$–$D_n(4000)$ sequence in which $L/L_{\text{Edd}}$ and the age of the stellar population are estimated directly from the H\alpha broad emission lines and starlight components, respectively. Similar relationships were found by other authors who used $L\text{[O\textsc{iii}]}/\sigma_\text{Fe}^4$ as a proxy for $L/L_{\text{Edd}}$ (e.g., Kewley et al. 2006; Wild et al. 2007; Kauffmann et al. 2007). Chen et al. (2009) found a tight correlation between $\text{[O\textsc{iii}]}/\sigma_\text{Fe}^4$ and the specific star formation rate obtained through modeling the continuum and absorption lines by the single stellar population models. Watabe et al. (2008) evaluated circumnuclear starburst luminosity in AGNs by the near-infrared polycyclic aromatic hydrocarbon (PAH) emission, which establishes a close correlation between the circumnuclear star formation rate and $L/L_{\text{Edd}}$.

The \textit{ROSAT}-selected Seyfert galaxies studied here are clustered in the middle range of the sequence, which is likely caused by a selection effect due to the sensitivity limit of RASS $\sim 10^{-13}$ erg s$^{-1}$ cm$^{-2}$. The sensitivity limit therefore leads us to miss some less-luminous X-ray AGNs. On one hand, the less-luminous X-ray emission is intrinsic in some AGNs that are typically associated with relatively old stellar populations and with low $L/L_{\text{Edd}}$ (e.g., Shemmer et al. 2008; Panessa et al. 2006; Hickox et al. 2009). On the other hand, there is accumulating evidence that AGNs with both young stellar populations and high $L/L_{\text{Edd}}$ tend to be heavily obscured by the plentiful surrounding gas at the beginning of their lives. The gas is required to not only fuel the central AGN activity, but to also rapidly form circumnuclear stars. The heavy obscuration causes the AGNs to be faint in the X-ray and optical bands, but...
typically luminous in the infrared (e.g., Sanders & Mirabel 1996). Numerical simulations of the merger of two gas-rich galaxies including SMBHs indicate that the central AGN activities are likely heavily obscured by the surrounding gas for most of the time of the starburst (e.g., Di Matteo et al. 2005; Springel et al. 2005; Hopkins et al. 2005). Mao et al. (2009) recently identified three H II-buried Seyfert galaxies from the SDSS MPA/JHU DR4 catalog by analyzing their optical spectral properties. Despite the broad Balmer emission lines, the narrow emission lines of the three Seyfert galaxies are found to be mainly ionized by the power from hot stars. Daddi et al. (2007) studied the X-ray spectral properties of X-ray-undetected IR luminous galaxies at $z \sim 2$ using the X-ray stacking analysis. The complex X-ray analysis suggested that there are heavily obscured AGNs in these galaxies with intensive star formation activities.

In fact, the soft X-ray survey is an efficient way to select narrow-line Seyfert galaxies (NLS1s) that are characterized by high $L/L_{\text{Edd}, \text{BH}}$, small $M_{\text{BH}}$, and the steepest X-ray spectra (e.g., Boroson & Green 1992; Boroson 2002; Sulentic et al. 2000; Boller et al. 1996; Brandt et al. 1997). Mathur (2000) argued that NLS1s might be young AGNs that are in the growth phase of their central SMBH (see also, e.g., Mathur et al. 2001; Grupe & Mathur 2004). Recent studies found that post-starburst stellar populations are frequently identified in NLS1s (e.g., Wang & Wei 2006; Zhou et al. 2005). In addition to the young stellar populations, Sani et al. (2010) recently pointed out that NLS1s are associated with higher ongoing star formation activities (using 6.2 $\mu$m PAH emission as a tracer) as compared with typical broad-line AGNs.

Comparing the $L/L_{\text{Edd}} - D_n(4000)$ sequence defined by the ROSAT-selected AGNs with that defined by the optically selected AGNs implies that AGNs with strong X-ray emission represent a population at a particular evolutionary stage (see also Hickox et al. 2009). The central SMBH is required to be active at this stage to produce the amount of high-energy emission. Meanwhile, in order to detect the X-ray emission, the central activity cannot be heavily obscured by the surrounding bulge star formation activity. A similar evolutionary scenario was recently proposed in Hickox et al. (2009) through a comprehensive comparison between radio-, X-ray-, and IR-selected AGNs. Compared to the radio-selected AGNs with extremely low $L/L_{\text{Edd}}$, the X-ray-selected AGNs have higher $L/L_{\text{Edd}}$. Although we cannot totally exclude selection effects, Wang et al. (2009a) indicated that the RXTE/INTEGRAL hard X-ray-selected AGNs have a narrow distribution of $L/L_{\text{Edd}} \sim 0.01-0.1$, and low column densities ($<10^{22}$ cm$^{-2}$). Moreover, the GALEX/SDSS NUV–optical color–magnitude diagram shows that the distribution of X-ray-selected AGNs prefers to distribute in the “green valley” located between the red sequence and the blue cloud (e.g., Schawinski et al. 2009; Hickox et al. 2009; Treister et al. 2009).

5. SUMMARY

In this third paper of the series, we examine the co-evolutionary issue of AGNs and their host galaxies by extending the studies in Paper I to ROSAT-selected Seyfert 1.8/1.9 galaxies. These galaxies are selected from the RASS/SDSS-DR5 catalog that was originally presented by Anderson et al. (2007). Using a similar analysis method as adopted in Paper I allows us to draw the following two main conclusions.

1. Two tight correlations, [$O I$/H$\alpha$] versus $D_n(4000)$ and [S II]/H$\alpha$ versus $D_n(4000)$, are firmly established not only in the ROSAT-selected Seyfert galaxies, but also in the combination of the current soft X-ray sample with the composite AGNs studied in Paper I. The ROSAT-selected Seyfert galaxies show that the two line ratios depend on the soft X-ray spectra slopes $\alpha_X$ estimated from the hardness ratios.

2. The ROSAT-selected Seyfert galaxies are well consistent with the $L/L_{\text{Edd}} - D_n(4000)$ sequence established in the composite AGNs studied in Paper I. The ROSAT-selected galaxies are, however, not uniformly distributed along the sequence. They are clustered in the middle range of the sequence, which could be explained by an observational bias. Because of the X-ray count rate threshold of RASS, the sample is biased against not only objects with heavy absorptions (at the end with high $L/L_{\text{Edd}}$ and young stellar population), but also ones with intrinsically low high-energy emission (at the end with low $L/L_{\text{Edd}}$ and old stellar population).

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