THE SUBARU/XMM-NEWTON DEEP SURVEY (SXDS). VI. PROPERTIES OF ACTIVE GALACTIC NUCLEI SELECTED BY OPTICAL VARIABILITY

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ABSTRACT

We present the properties of active galactic nuclei (AGN) selected by optical variability in the Subaru/XMM-Newton Deep Field (SXDF). Based on the locations of variable components and light curves, 211 optically variable AGNs were reliably selected. We made three AGN samples; X-ray-detected optically nonvariable AGNs (XAs), X-ray-detected optically variable AGNs (XVAs), and X-ray-undetected optically variable AGNs (VAs). In the VA sample, we found a bimodal distribution of the ratio between the variable component flux and the host flux. One of these two components in the distribution, a class of AGNs with a faint variable component $i'_{\text{var}} \sim 25$ mag in bright host galaxies $i' \sim 21$ mag, is not seen in the XVA sample. These AGNs are expected to have low Eddington ratios if we naively consider a correlation between bulge luminosity and black hole mass. These galaxies have photometric redshifts $z_{\text{photo}} \sim 0.5$ and we infer that they are low-luminosity AGNs with radiatively inefficient accretion flows (RIAFs).

The properties of the XVA and VA objects and the differences from those of the XA objects can be explained within the unified scheme for AGNs. Optical variability selection for AGNs is an independent method and could provide a complementary AGN sample even deep X-ray surveys have not found.

Subject heading: galaxies: active

1. INTRODUCTION

Recent deep X-ray surveys have found many low-luminosity and obscured active galactic nuclei (AGNs) and revealed luminosity-dependent cosmological evolution of AGNs (Ueda et al. 2003; Barger et al. 2005). The obscured fractions of AGNs increase with decreasing X-ray luminosity (Ueda et al. 2003; La Franca et al. 2005; Akiyama et al. 2006). On the other hand, at optical wavelengths, many AGN surveys have been carried out by taking advantage of the blue optical colors of AGNs, which are a common characteristic of unobscured (or type 1) AGNs. However, the blue colors are difficult to recognize for AGNs with dust obscuration and host galaxy contamination. Optical variability has been observed in almost all luminous AGNs, i.e., quasars, on timescales of months to years (Hook et al. 1994; Giveon et al. 1999; de Vries et al. 2003, 2005; Vanden Berk et al. 2004; Sesar et al. 2006). AGN selection by optical variability is less affected by host galaxy contamination than selection by blue optical color if the variable components can be extracted. Several Sloan Digital Sky Survey (SDSS) results have showed that the optical variability of less luminous AGNs is larger and this illustrates the usefulness of optical variability as a tracer of low-luminosity AGNs. Variability studies using the Hubble Space Telescope (HST) actually found several tens of galaxies with variable nuclei down to $V, I, i' \sim 27–28$ mag (Sarajedini et al. 2000, 2003, 2006; Cohen et al. 2006). Although deep X-ray observations have been carried out with the Chandra and XMM-Newton satellites in the HST survey fields, there is a significant fraction (>70%) of optically variable AGNs without X-ray detection (Sarajedini et al. 2006; Cohen et al. 2006). These authors showed that most of these X-ray non-detections can be explained in terms of small X-ray-to-optical flux ratios of the nuclear components. The number densities of variable AGNs in their samples are comparable to those of X-ray-detected AGNs and these facts indicate that selection by optical variability is a powerful tool to find faint AGN populations which current deep X-ray observations may not be able to trace.

There are also important results indicating the usefulness of optical variability as a tracer for AGNs, especially for low-luminosity AGNs. Radiatively inefficient accretion flows (RIAFs; Quataert 2001) are considered to have an accretion rate $\dot{m} (\equiv M/M_{\text{Edd}})$ below a critical value in contrast with the standard disk model for luminous AGNs. The spectral energy distributions of some nearby low-luminosity AGNs have been explained in terms of RIAFs (Chiaberge et al. 2006; Nemmen et al. 2006). Totani et al. (2005) serendipitously found low-luminosity AGNs in apparently normal bright galaxies at $z \sim 0.3$ by optical variability in their cluster-cluster microlensing search using the images separated by several days and one month. This rapid and large fractional ($\sim 100\%$) variability could be of blazar origin, but their emission line spectra and number densities support the RIAF interpretations. The low luminosities are also consistent with RIAFs. Their result indicated that the flare-ups of Sgr A* are not special phenomena and may be common in low-luminosity AGNs in the distant universe. Multipech ultraviolet images with HST revealed that most of the nearby low-ionization nuclear emission-line region (LINER)
nuclei show significant variability with peak-to-peak amplitudes ranging from a few percent to 50% (Maoz et al. 2005). On the other hand, Maoz (2007) found that the properties of the SEDs of these LINERs and luminous AGNs show continuous distributions, suggesting that thin accretion disks may persist to low luminosity.

The optical continuum of AGNs mainly comes from an accretion disk. The main origin of optical variability is still under debate: disk instability (Rees 1984; Kawaguchi et al. 1998), bursts of supernova explosions (Terekhova et al. 1992), or microlensing (Hawkins & Veron 1993). However, if we assume that the optical variability of AGNs also originates from an accretion disk, type-1 AGNs should tend to show larger optical variability than type-2 AGNs because we can directly see the accretion disk without it being obscured by a surrounding dust torus.

In this paper, we investigate the X-ray, optical, and optical variability properties of faint variable AGNs in the Subaru/XMM-Newton Deep Field (SXDF). The data was obtained by the Subaru/XMM-Newton Deep Survey (SXDS) project (Sekiguchi et al. 2004; K. Sekiguchi et al. 2008, in preparation [Paper I in this series]). Morokuma et al. (2008, hereafter Paper V) succeeded in constructing a statistical variable object sample and a well-classified AGN sample. We describe the AGN sample selections in §2 and show the properties of optical-variability-selected AGNs in §§3 and 4. We summarize our results in §5. In this paper, we use cosmological parameters of $\Omega_M = 0.3$, $\Omega_L = 0.7$, and Hubble constant $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$. The AB magnitude system is used for optical photometry. We define $i_{\text{vari}}$ as the $i'$-band magnitude amplitude (minimum to maximum) of the variable components and $i'$ as the $i'$-band total magnitude.

2. AGN SAMPLE

In this section, we describe our AGN sample selection. Our survey field, the SXDF, is a multivavelength project covering $\sim 1.2 \text{ deg}^2$. We use deep optical imaging data (Furusawa et al. 2008, hereafter Paper II; Paper V) taken with Suprime-Cam (Miyazaki et al. 2002) on the 8.2 m Subaru Telescope for the optical variability investigation. X-ray imaging data with XMM-Newton satellite is also used for the AGN selection.

2.1. Optical Variability-Selected AGN Sample

Our AGN sample selected by optical variability is based on the variable object sample constructed by Paper V. By applying an image subtraction method (Alard & Lupton 1998; Alard 2000) to multiepoch ($8 \sim 10$ times from 2002 to 2005) $i'$-band deep ($i = 25.2 \sim 26.8 \text{ mag}$) imaging data obtained with Suprime-Cam, they found 1040 variable objects among $\sim 600,000$ objects, showing significant ($>5 \sigma$) variability over 0.918 deg$^2$. The detection limit for variable components is $i_{\text{vari}} \sim 25.5 \text{ mag}$, where $i_{\text{vari}}$ is defined as the magnitude of differential flux between the maximum and minimum. For almost all the variable objects, the host objects are unambiguous and their optical photometric properties such as magnitudes and colors cataloged in Paper II are used. These authors classified nonstellar variable objects (including point sources with nonstellar colors) as AGNs and supernovae (SNe) based on the locations of the variable components within the host objects together with their light curves in the three pointings of Suprime-Cam (0.56 deg$^2$, SXDF-C, SXDF-S, and SXDF-E) from 2002 to 2005. Well-classified variable AGNs have variable components at their centers of the host objects (offsets between variable components and their host objects $<1.2 \text{ pixel}^{12}$) and have non-SN-like light curves. Variable objects with these two properties are defined as in case 2 of Paper V. The baselines of the light curves were not long or dense enough to discriminate AGNs from SNe completely. There are many variable objects which have SN-like light curves and show variability lying at the centers of the host objects. These variable objects can be either SNe or AGNs, and we do not include such objects in our variable AGN sample. Hence, we use a variability-selected AGN sample consisting of 211 variable AGNs in the region which overlaps the X-ray imaging field. We note that the number of case 2 objects (228) in Paper V is slightly different from the number of variable AGNs used in this paper because we focus on objects only within the X-ray imaging field.

2.2. X-Ray-Selected AGN Sample

In the SXDF, deep X-ray imaging observations were carried out with European Photon Imaging Camera (EPIC) on board XMM-Newton satellite. One deep ($\sim 100 \text{ ks}$) pointing and six shallower ($\sim 50 \text{ ks}$) pointings covered almost the entire Suprime-Cam field of the SXDF (Ueda et al. 2007 [Paper III in this series]; M. Akiyama et al. 2008, in preparation). The detection limit is $1 \times 10^{-15} \text{ ergs}^{-1} \text{ cm}^{-2} \text{ s}^{-1}$ in the $0.5 \sim 2.0 \text{ keV}$ band and $3 \times 10^{-15} \text{ ergs}^{-1} \text{ cm}^{-2} \text{ s}^{-1}$ in the $2.0 \sim 10.0 \text{ keV}$ band, respectively. The X-ray sources which we use in this paper have detection likelihood higher than nine in either energy band. The X-ray flux is calculated assuming a power-law X-ray spectrum with photon index $\Gamma = 1.5$. In order to compare the properties of the X-ray-selected AGNs with those of the optical-variability-selected AGNs, we use 327 X-ray sources in the variability survey region where we selected 211 optically variable AGNs in §2.1.

2.3. AGN Sample Classification

We classify these two, optical-variability-selected and X-ray-selected, AGN samples into three categories: (1) X-ray-detected, optically nonvariable AGNs (238 objects, hereafter “XAs”); (2) X-ray-detected, optically variable AGNs (89 objects, hereafter “XVAs”); (3) X-ray-undetected, optically variable AGNs (122 objects, hereafter “VAs”). Matching between the optically variable AGNs and the X-ray-detected AGNs was done on the basis of the optical and X-ray positions, and the X-ray positional errors. We first assigned the nearest optical objects within $5 \sigma$ of the X-ray positional errors from the X-ray centroids as the potential optical counterparts of the X-ray-detected AGNs. Then, we defined objects as “XVAs” if the host objects of the optically variable objects are identical to the optical counterparts of the X-ray AGNs.

Spectroscopic redshifts were determined for 36, 35, and 9 objects in the XA, XVA, and VA samples. Our spectroscopic observations were biased to X-ray-detected objects and the number of VA objects with redshift determinations is small. For these three AGN samples, we calculated various statistical parameters such as the average, median, standard deviations, and the Kolmogorov-Smirnov (K-S) test probabilities between the samples. These values are summarized in Tables 1 and 2. Some of these values are discussed in §4.

2.4. Variability Detection Completeness

The detection efficiency of optical variability depends on not only the depth of the imaging data but also on observation time sampling. Variability detection itself depends on the depths of the images. All the Suprime-Cam images used in this paper have similar depths ($i' \sim 25.6 \sim 26.8 \text{ mag}$), and we can detect object variability down to component amplitudes of $i_{\text{vari}} \sim 25.5 \text{ mag}$. The optical variability behavior of AGNs differ from object to object, and the detection completeness calculations for AGNs are

$^{12}$ Pixel scale of Suprime-Cam is 0.202.
The fractions of X-ray sources showing optical variability are shown for observations with a four-year baseline from 2002 to 2005 for all objects which we use in this paper.

In the top panels of Figure 1, we show the X-ray flux versus $i'$-band magnitude distributions for the XA and XVA objects. The fractions of X-ray sources showing optical variability are shown in the bottom panels of Figures 1 and 2 as a function of $i'$-band magnitude. These figures indicate that the variability detection efficiency for X-ray sources decreases down to zero at $i' \sim 24$–25 mag, and it is difficult to detect optical variability of X-ray sources with high X-ray–to–optical flux ratios. Figure 1 is further discussed in § 4.

In Figure 1 we also plot the X-ray-detected optically nonvariable AGNs (25 objects) and the X-ray-detected optically variable AGNs (four objects) from one of similar studies (Sarajedini et al. 2006) for a comparison (these correspond to the XA and XVA objects in this paper). We plotted $I_c$-band magnitudes, which was available from Vogt et al. (2005) for the sample of Sarajedini et al. (2006). The difference of the bandpasses between $i'$ band and $I_c$ band is not large, and we do not apply any band transformations. The observational properties of the objects plotted in this figure are derived from their Tables 6 and 7. The X-ray flux in each band is calculated using the full-band (0.5–10 keV) X-ray flux.

### Table 1

**K-S Test Probabilities**

| Sample 1 | XA XVA | XA bright | XA VA | XA bright | XVA VA |
|----------|--------|-----------|-------|-----------|-------|
| Redshift | 1.33E–03 | 5.61E–04 | 3.30E–01 | 2.15E–01 | 2.55E–02 |
| $B - V$ | 3.20E–01 | 1.56E–02 | 1.27E–02 | 7.47E–02 | 1.47E–02 |
| $V - R$ | 3.91E–01 | 5.25E–03 | 4.97E–01 | 1.59E–01 | 2.16E–01 |
| $R - i'$ | 5.78E–05 | 1.27E–07 | 4.10E–04 | 7.96E–07 | 3.25E–01 |
| $i' - z'$ | 1.15E–04 | 9.87E–07 | 3.90E–07 | 4.21E–10 | 6.04E–01 |
| $i'$-band magnitude | 2.44E–20 | 4.12E–02 | 8.84E–23 | 2.30E–04 | 4.60E–02 |
| HR2 | 1.07E–07 | 7.93E–06 | ... | ... | ... |
| log ($f_{X,0.5-2.0keV}$) | 1.40E–06 | 3.27E–03 | ... | ... | ... |
| log ($f_{X,2.0-10.0keV}$) | 8.74E–01 | 8.58E–01 | ... | ... | ... |
| log ($f_{X,0.5-2.0keV}/f_{X}$) | 2.80E–10 | 2.83E–02 | ... | ... | ... |
| log ($f_{X,2.0-10.0keV}/f_{X}$) | 9.36E–10 | 1.77E–02 | ... | ... | ... |

Note.—K-S test probabilities between sample 1 and sample 2 for the parameters.

* The XA bright sample consists of 199 XA objects with $i' < 23.9$ mag.

### Table 2

**Averages (medians) and Standard Deviations of Parameters**

| Parameter | XA | XVA | VA |
|-----------|----|-----|----|
| Redshift | 1.479 ± 0.027 (1.180) | 1.815 ± 0.731 (1.623) | 1.358 ± 0.601 (1.152) |
| $B - V$ | 1.328 ± 0.903 (1.086) | 0.475 ± 0.560 (0.387) | 0.469 ± 0.335 (0.428) |
| $V - R$ | 0.375 ± 0.414 (0.327) | 0.307 ± 0.354 (0.329) | 0.431 ± 0.419 (0.379) |
| $R - i'$ | 0.454 ± 0.345 (0.461) | 0.278 ± 0.239 (0.289) | 0.349 ± 0.294 (0.303) |
| $i' - z'$ | 0.531 ± 0.279 (0.542) | 0.271 ± 0.194 (0.275) | 0.243 ± 0.198 (0.241) |
| $i'$-band magnitude | 0.483 ± 0.253 (0.489) | 0.223 ± 0.81 (22.04) | 22.04 ± 0.98 (21.85) |
| HR2 | -0.335 ± 0.501 (−0.506) | -0.599 ± 0.209 (−0.637) | ... |
| log ($f_{X,0.5-2.0keV}$) | -0.341 ± 0.465 (−0.501) | -0.434 ± 0.46 (−0.501) | ... |
| log ($f_{X,2.0-10.0keV}$) | -14.73 ± 0.46 (−14.68) | -14.45 ± 0.39 (−14.44) | -14.45 ± 0.39 (−14.44) |
| log ($f_{X,0.5-2.0keV}/f_{X}$) | -14.66 ± 0.44 (−14.63) | -14.45 ± 0.39 (−14.44) | -14.45 ± 0.39 (−14.44) |
| log ($f_{X,2.0-10.0keV}/f_{X}$) | -14.15 ± 0.37 (−14.13) | -14.20 ± 0.47 (−14.17) | -14.20 ± 0.47 (−14.17) |
| log ($f_{X,0.5-10.0keV}/f_{X}$) | -0.400 ± 0.745 (0.393) | -0.076 ± 0.408 (−0.054) | -0.076 ± 0.408 (−0.054) |
| log ($f_{X,2.0-10.0keV}/f_{X}$) | -0.149 ± 0.500 (−0.147) | 0.171 ± 0.491 (0.261) | ... |
| log ($f_{X,0.5-2.0keV}/f_{X}$) | 0.998 ± 0.810 (1.005) | 0.368 ± 0.554 (0.444) | ... |
| Variable component $i_{	ext{v}}$ | 23.90 ± 0.82 (24.03) | 24.69 ± 0.84 (24.96) | ... |
| log ($f_{X,v}/f_{X}$) | -0.666 ± 0.305 (−0.608) | -1.059 ± 0.512 (−1.069) | ... |

Note.—For the XA sample, upper rows are calculated using all the sample while lower rows are calculated using the objects with $i' < 23.9$ mag.
and hardness ratio (calculated as $f_{2.0-10.0\,\text{keV}} / f_{0.5-2.0\,\text{keV}}$) in their Table 6. The significance threshold for optical variability is set at 3.2 $\sigma$, which is the same value as Sarajedini et al. (2006) adopted. The differences in the distributions between our sample and their $HST$ sample can be due to the differences of the depths of the observations.

3. PROPERTIES OF AGNs WITHOUT X-RAY DETECTIONS

We first focus on the properties of the VA objects, which are defined as variable AGNs without X-ray detections, and compare with those of the XA and XVA objects.

The distributions of the variable component magnitude $i_{\text{vari}}$ versus $i'$-band magnitude of the host objects for the XA and VA objects are shown in Figure 3. Significant differences between the XVA and VA objects are seen. In the right panel of Figure 3, there are objects which have a faint variable component ($i_{\text{vari}} \sim 25$ mag) in bright galaxies ($i' \sim 21$ mag), while there are only a few such objects seen in the distribution for the XVA objects. In addition, histograms of the ratios between variable component flux $f_{i_{\text{vari}}}$ and total flux $f_i$ shown in Figure 4 marginally indicate a bimodal distribution suggesting that the VA objects may consist of two classes of AGNs. The low K-S test probability (6.67E−09, Table 1) of the flux ratio distributions also indicates that these distributions are different. Accordingly, we separate the VA sample...
into two classes by a dashed line, 

\[ i'_{\text{vari}} = 1.0 \times i + 3.2 \left( f_{\text{vari}} = 0.05 \times f'_i \right) \]

in Figure 3; HE-VA objects (73 objects, below the line) and LE-VA objects (49 objects, above the line). Assuming that AGN optical variability (differential) flux, not amplitude, is roughly proportional to optical luminosity of the AGNs, \(^{13}\) AGNs with faint variable components are considered to be faint AGNs. Given the correlation between supermassive black hole mass and bulge luminosity (Wandel 1999), AGNs with larger ratios between the variable component flux and total flux can be naively interpreted as AGNs with higher Eddington ratios. Thus it is expected that LE-VA objects have low Eddington ratios, while HE-VA objects have high Eddington ratios. The LE-VA sample produces the difference of the distributions between the XVA and VA objects in Figure 3. This difference should not be due to any selection effects because the selection cuts are along horizontal and vertical directions in this figure.

The LE-VA objects are AGNs with faint variable components in bright galaxies. These objects are similar to low-luminosity AGNs in bright elliptical galaxies which were found using optical variability on timescales of several days to a month by Totani et al. (2005). Totani et al. (2005) indicated that the rapid variability may be due to flare-ups in RIAFs rather than a blazar origin and noted the similarity to near-infrared flares of Sgr A* (Yuan et al. 2004). RIAF disks have low accretion rates and low Eddington ratios, and tend to show flare-ups on short timescales. We show four examples of Suprime-Cam images and light curves of these objects in Figure 5. These objects are randomly selected from the LE-VA sample. Some light curves are likely to be those of flare-ups. If the LE-VA objects are really equivalent to AGNs showing rapid variability as found by Totani et al. (2005), their variation timescales are expected to be shorter than those of the HE-VA objects on average. However, it is difficult to investigate the timescales of variability quantitatively because of the sparse time sampling. We tried evaluating two kinds of variability timescales: as the minimum time interval over which objects show significant (>5 \( \sigma \)) variability, and as the interval between maxima and minima. There are no significant differences for either timescale between the LE-VA and HE-VA objects. It is not clear which objects show variability on shorter timescales. However, this does not reject the RIAF interpretation for LE-VA objects.

Figure 6 shows the optical color-magnitude distributions for the LE-VA and HE-VA objects. The K-S test probabilities for these distributions and their averages are given in Tables 3 and 4, respectively. The LE-VA objects have significantly redder \( B - V \) colors than the HE-VA objects on average. In our sample, there are only a few objects which are selected as \( B \)-dropout objects. The intrinsically blue colors of AGNs should remain blue in the observed \( B - V \) colors even when redshifted. The red colors of LE-VA can be explained by large contamination by red host galaxies and might indicate that most of them are early-type galaxies at relatively low redshift. When we calculate the photometric redshifts for these galaxies without considering any AGN light...
Fig. 5.—Examples images and light curves of four LE-VA objects with faint variable components, $i'_{	ext{ori}} \sim 25$ mag, in bright galaxies. The left column shows the reference images before subtractions. The variable components in the subtracted images are seen in the right column images. Unreliable photometric points are plotted as open circles.

Fig. 6.—Optical color-magnitude diagrams of the LE-VA (left column, filled squares) and HE-VA (right column, right column) objects. The LE-VA objects are also plotted in the right column as gray squares for a comparison.
contribution, the optimal spectral templates and redshifts are early-type galaxies at z_{photo} \sim 0.5 for most of the LE-VA objects, also supporting a low luminosity for these AGNs.

The HE-VA objects also show a similar distribution to the XVA objects in Figure 3. Figure 7 shows the redshift distributions for the XA, XVA, and VA objects. We have no spectroscopic identifications for the LE-VA objects and all the VA objects plotted in this figure belong to the HE-VA subsample. Most of the spectroscopically identified AGNs in the XVA and VA samples are at high redshift (z > 1) and the HE-VA objects are expected to be similar objects to the XVA objects. We interpret the X-ray non-detections of the HE-VA objects as deriving from the intrinsically wide distributions of X-ray-to-optical flux ratios of AGNs (e.g., Anderson et al. 2007), as seen in Figure 1. If we assume that the X-ray-to-optical flux ratio distributions of the optically variable AGNs are independent of their brightness and the distributions for bright (i' < 23.9 mag) XVA objects are the same as those for fainter XVA objects, there should be N = 20 VA objects just below the X-ray detection limit. The number of HE-VA objects is 73, much larger than this estimate. However, many VA objects are as bright as i' \sim 21–22 mag and the X-ray-to-optical flux ratio distributions of our XVA sample may not represent the entire intrinsic distributions even in the bright magnitude range. There can be AGNs with lower X-ray-to-optical flux ratios for which we can detect their optical variability but cannot detect their X-ray emission.

Thus we infer that the VA sample consists of two classes: low-luminosity AGNs at relatively low redshift (LE-VA) and luminous AGNs at high redshift (HE-VA). Other similar studies of optical variability-selected AGNs with HST found that significant fractions (\sim 70%) of variable AGNs in their samples were not detected in deep X-ray imaging with the Chandra or XMM-Newton satellites (Sarajedini et al. 2006; Cohen et al. 2006). Our results, as well as HST results, indicate that optical variability can trace AGN classes that are not detected in deep X-ray surveys.

4. ARE OPTICAL-VARIABILITY-SELECTED AGNs TYPE-1?

As discussed in §1, it is natural to expect that objects showing optical variability are type-1 AGNs because optical variability of AGNs is considered to originate in their accretion disks.

We first compare the optical properties (magnitudes and colors) of the XA, XVA, and VA objects. Figure 8 shows the distributions of $B - V$ and $R - i$ colors, and $i'$-band magnitude. Figure 8, as well as Figure 1, clearly indicates that optical variability can be detected only for relatively brighter AGNs ($i' < 23.9$ mag) among X-ray-detected AGNs because of our variability detection limit. The distributions of only the XA sample go down to fainter magnitudes. The K-S test probabilities indicate that significant color differences are seen for red ($R - i'$ and $i' - z'$) colors in the observed frame while distributions of $B - V$ and $V - R$ colors are not different. However, the redshift distribution of the XA objects is different from those of the XVA and VA objects (Fig. 7) and the differences of observed colors should be affected by the redshift distribution differences.

We now focus on the X-ray hardness ratio distributions. We define the hardness ratio, HR2, as the ratio of count rates in the $0.5 - 2.0$ and $2.0 - 4.5$ keV bands; HR2 = (H - S)/(H + S) (H: count rate in the $0.5 - 2.0$ keV band). By definition, HR2 can have values of $-1 \leq$ HR2 $\leq 1$ and obscured, type-2, populations tend to have larger HR2 values because photons with higher energy can penetrate through the obscuring torus more efficiently. There may be a good correlation between AGN classification (type-1 or type-2) in X-rays and that deduced from optical spectroscopy (Ueda et al. 2003). Barger et al. (2005) showed that broad-line AGNs with emission-line widths above 2000 km s^{-1} are soft X-ray sources, while AGNs with emission lines below this width have a wide range of X-ray colors. The correlation between optical obscuration and X-ray obscuration may be biased because classification using optical spectra requires good signal-to-noise ratios, but the hardness ratio can be a good parameter for evaluating optical obscuration. Figure 9 shows the HR2 versus X-ray flux distributions for the XA and XVA objects. The HR2 distributions are significantly different. The XA objects tend to have higher HR2 values, while the HR2 values of the XVA objects concentrate around $-0.6$. This can be naturally understood by considering the unified scheme of AGNs because of obscured populations, in which we can see the nuclei directly, should show larger optical variability.

The variability detection completeness also shows the differences of the selection effects between optical variability and X-ray detection. Figure 1 indicates that the XVA objects (black circles) tend to have higher X-ray flux than the XA objects (gray circles). When we limit XA objects to those with $i' < 23.9$ mag, which is the $i'$-band magnitude of the faintest XVA object, this tendency becomes weaker but still exists. High X-ray-to-optical flux ratios can be attributed to both optical faintness and large X-ray flux. Objects with extremely high X-ray-to-optical flux ratios are candidates for highly obscured luminous AGNs, objects whose optical variability is more difficult to detect than unobscured AGNs. The decline of the detection completeness for variability toward fainter magnitudes also contributes to this tendency, as well as the inclusion of obscured populations in the XA sample.

| Parameter | XVA | VA | LE-VA | HE-VA |
|-----------|-----|----|-------|-------|
| $B - V$   | 0.360 ± 0.438 (0.357$^a$) | 0.535 ± 0.453 (0.499$^a$) | 0.734 ± 0.383 (0.683) | 0.401 ± 0.448 (0.400) |
| $V - R$   | 0.307 ± 0.354 (0.329$^a$) | 0.431 ± 0.419 (0.379$^a$) | 0.566 ± 0.307 (0.337) | 0.341 ± 0.459 (0.322) |
| $R - i'$  | 0.278 ± 0.239 (0.289$^a$) | 0.349 ± 0.294 (0.303$^a$) | 0.431 ± 0.255 (0.409) | 0.293 ± 0.306 (0.239) |
| $i' - z'$ | 0.271 ± 0.194 (0.275$^a$) | 0.243 ± 0.198 (0.241$^a$) | 0.253 ± 0.168 (0.269) | 0.237 ± 0.215 (0.230) |

$^a$ The same values as those in Table 2.
Fig. 7.—Redshift distributions of $i'$-band magnitudes and optical colors of the XA (left column, filled triangles), XVA (center column, filled circles), and VA (right column, squares) objects. The XVA objects are also plotted in the left and right columns in gray filled circles for comparison.

Fig. 8.—Optical color-magnitude diagrams for the XA, XVA, and VA objects. Symbols used are the same as those in Fig. 7.
distributions of the hardness ratio HR2 and X-ray flux as a function of redshift shown in Figure 10 also indicate that the XVA objects have lower hardness ratios and higher soft X-ray fluxes on average at any redshift.

Lines of constant X-ray luminosity are shown in Figure 10 assuming that the X-ray spectrum is well represented by a power law with photon index $\Gamma = 1.5$. Ueda et al. (2003) showed that the fraction of X-ray type-2 AGNs decreases with X-ray luminosity; this was also indicated in later studies (La Franca et al. 2005; Akylas et al. 2006). Ueda et al. (2003) also found a possible similar effect in that the fraction of optical type-2 AGNs increases with deceasing of X-ray luminosity although spectroscopic observational biases can affect this tendency because the host galaxy contaminations make it difficult to detect broad lines of AGN origin. Almost all of the XVA objects have X-ray luminosity higher than $\sim 10^{43}$ ergs s$^{-1}$ cm$^{-2}$, below which optical type-2 fraction of X-ray sources increases up to 0.4–1.0 (Ueda et al. 2003). The nondetections of optical variability for low-$z$ bright XA objects can be understood if they are obscured and low-luminosity populations.

Although spectroscopic redshifts are available for only part of our AGN sample, as described in § 2.3, the redshift distribution of XVA objects is biased toward slightly higher values than that of the XA objects, as is shown Figure 7. The median redshifts are $\langle z_{\text{XA}} \rangle = 1.18$, $\langle z_{\text{XVA}} \rangle = 1.48$, $\langle z_{\text{VA}} \rangle = 1.40$, respectively. There are not many low-$z$ ($z < 1$) XVA objects while there are many XA objects at such redshifts. The nondetections of optical variability from such bright XA objects can be explained if many of them are type-2 AGNs with lower X-ray luminosities, less than $\sim 10^{43}$ ergs s$^{-1}$ cm$^{-2}$.

The optical and X-ray properties of AGNs can be summarized as follows. Compared with the XA objects, the XVA objects have lower HR2 values, smaller X-ray–to–optical flux ratios, higher X-ray flux, and appear at higher redshifts. These differences can be explained within the unified scheme of AGNs considering the anticorrelation between luminosity and obscured fractions. We conclude that most of the optical-variability-selected AGNs are type-1.

5. SUMMARY

We investigated the X-ray, optical, and optical variability properties of X-ray-selected and optical-variability-selected AGN samples in the SXDF. Among the VA objects, we found a class of AGNs (LE-VA) with a faint variable component $i_{\text{opt}} \sim 25$ mag in bright host galaxies $i' \sim 21$ mag. In our definition the variability flux of these AGNs are less than 0.05 of their total flux, including host galaxy components. Our limited time sampling prevented us from determining the typical timescale of variability, but some of them show plausible flare-ups. They are similar to the low-luminosity AGNs that Totani et al. (2005) found. Therefore, we infer that they are low-luminosity AGNs with RIAF at low redshift. The photometric redshifts, $z_{\text{photo}} \sim 0.5$, and extended morphologies of the LE-VA objects supports the idea that these AGNs are low-luminosity objects. These low-luminosity AGN
candidates may be similar to Sgr A* and some of nearby Seyfert nuclei, whose properties can be described in terms of RIAF.

The XVA objects have lower X-ray hardness ratios than theXA objects on average. For the spectroscopically identified objects, XVA objects also have higher X-ray luminosity than theXA objects. These properties are consistent with those expected from the unified scheme for AGNs and dependence of obscured fraction on X-ray luminosity. The XVA and VA objects are mainly unobscured, type-1 AGNs.

Although X-ray observations can effectively trace even obscured populations of AGNs, optical variability selection for AGNs is a useful method which is independent of X-ray selection and could provide a new AGN sample that even deep X-ray surveys have not found.

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