Subaru Wide-Field Variability Survey

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Abstract

We present our survey for optically variable objects such as distant active galactic nuclei (AGN) and supernovae (SNe) with an optical wide-field imager, Suprime-Cam, on the prime focus of the 8.2-m Subaru telescope. By utilizing one of the Subaru large survey data in the Subaru/XMM-Newton Deep Survey (SXDS) field and combining with 50-100 ksec exposure X-ray data obtained with XMM-Newton, we confirmed that optical variability is a useful tool for finding AGN and found that it plays a complementary and important role especially for studying low-luminosity AGN with X-ray observation. We found that a significant fraction of optical-variability-selected AGN are below the X-ray detection limit, which was also shown by previous studies with the Hubble Space Telescope. The SN sample is used for cosmology and SN studies such as rates, its host galaxy properties, and its progenitors. We also briefly introduce the next-generation wide-field imager, Hyper Suprime-Cam (HSC), installed on the Subaru telescope in 2011 fall, our survey plan and expected results with Subaru/HSC.

Key words: optical, variability, wide-field, survey, supernovae, AGN

1. Introduction

Recently, a number of optical telescopes have been used for dedicated surveys for detecting transient phenomena. Although several telescopes in the world are dedicating or planned to dedicate wide-field variability surveys such as SkyMapper (Keller et al. 2007), Palomar Transient Factory (PTF; Rau et al. 2009), the Panoramic Survey Telescope & Rapid Response System (Pan-STARRS; Kaiser et al. 2002), Catalina Real-Time Transient Survey (CRTS; Drake et al. 2009), and Large Synoptic Survey Telescope (LSST; Ivezic et al. 2008), 8m-class telescopes with wide field-of-view imagers can give unique results among them because they investigate unprecedented parameter space which is not easily achieved by smaller aperture telescopes even if they dedicate their large surveys. The Subaru 8.2-m telescope and its prime-focus wide-field camera, Suprime-Cam (Miyazaki et al. 2002), is a very powerful combination in terms of exploring variable deep sky. Suprime-Cam has the widest field-of-view (34'×27') among imaging instruments on the current 8m-class and space telescopes. Although Subaru is a multi-purpose telescope, not dedicated for a kind of survey, and variability survey generally requires a lot of telescope time, we have succeeded in conducting large variability surveys due to the wide-field coverage of Suprime-Cam, and a combination of Subaru Observatory Projects and intensive observing programs. In this proceeding, we summarize our surveys for faint variable objects such as distant active galactic nuclei (AGN) and supernovae (SNe). The new wide-field imaging instrument, Hyper Suprime-Cam (Miyazaki et al. 2006), and transient object science cases achieved within its survey plan currently considered are introduced.

2. Optical Variability Survey with Subaru/Suprime-Cam

With Suprime-Cam on the Subaru telescope, two large surveys were carried out as the Subaru Observatory Projects. One is the Subaru Deep Field (SDF; Kashikawa et al. 2004) and another is the Subaru/XMM-Newton Deep Survey (SXDS; Furusawa et al. 2008). These surveys were done mainly for exploring high-z universe. In order to go as deeper as necessary for that study, several-hour or more integration imaging per filter was done over several years. A part of the observations were optimized for Type Ia SN studies. Then, we utilize these multi-epoch deep imaging data to investigate object variability. In this proceeding, we focus on our works on objects with flux variability in the SXDS (Morokuma et al. 2008a) although we succeeded in detecting small proper motions ($\mu \sim 0.01$ arcsec/yr) of stars using the same dataset (Richmond et al. 2009; Richmond et al. 2010).

The SXDS, (RA, Dec)=(02:18:00, -05:00:00), covers about 1.2 deg^2 with Suprime-Cam (Furusawa et al. 2008). This deep field has been observed in various wavelength regions from X-ray to radio and one of the deepest multi-wavelength fields. The XMM-Newton satellite data was taken down to depths of $f_{0.5-2.0\mathrm{keV}} = 1.0 \times 10^{-15}$ erg s^{-1} cm^{-2} and $f_{2.0-10.0\mathrm{keV}} = 3.0 \times 10^{-15}$ erg s^{-1} cm^{-2} (Ueda et al. 2008). We use imaging data in near-infrared by UKIDSS UltraDeep Survey (UDS; Lawrence et al. 2007) and mid-infrared by Spitzer Wide-field Infrared Extragalactic (SWIRE; Lonsdale et al. 2003, 2004) Survey, both of which cover most of the SXDS field.

Morokuma et al. (2008a) found 1,040 variable objects over 0.918 $\deg^2$ in the SXDS using multi-epoch deep Suprime-Cam i'-band data (8-10 epochs from 2002 to 2005 in the five Suprime-Cam pointings). The typical exposure and depth per epoch was 1 hour and 26 mag (5σ, 2.0 arcsec aperture). They classified these variable objects into stars, SNe, and AGN based on optical and optical-infrared colors and morphology of host objects, relative locations of variable components, and light curves. Number densities of variable stars, SNe, and AGN are 120 $\deg^{-2}$, 489 $\deg^{-2}$, and 579 $\deg^{-2}$, respectively. We show our results related to SNe and AGN in following sections.

One of difficulties in detecting object variability using ground-based images is changes of point spread functions (PSFs), or seeing, in time. We need some modification of images to detect variability of small amplitude and faint variable components on bright static host objects to subtract images from each other and find object variability anywhere in the images. Image subtraction methods (Alard & Lupton 1998, Alard 2000) are applied for these multi-epoch Suprime-Cam images and we can detect and measure flux variability of objects in the subtracted images.

3. Supernova Studies

Type Ia SNe (SNe Ia) have been used as a *standarzizable* candle, i.e., a cosmological distance indicator, and have provided the direct evidence of the accelerating cosmic expansion (Riess et al. 1998; Perlmutter et al. 1999). However, the nature of the progenitor systems of SNe Ia has not yet been resolved. It is widely believed that the progenitor of SNe Ia is a binary system containing a white dwarf. There are two plausible models, single-degenerate or double-degenerate, for the progenitor system. Measurements of SN Ia rate and its host galaxy dependence up to high redshifts, for example, are approaches giving a clue to understand the progenitors (e.g., Dahlen et al. 2008; Sullivan et al. 2006).

Delay time, defined as time of SN Ia explosion from formation of that progenitor star, is one of the key parameters to understand the SN Ia progenitor system because theoretical models for different progenitor systems provide different delay time. SN Ia delay time distribution (DTD) can be measured through the SN Ia rate measurement combined with cosmic star formation history and host galaxy properties of SNe Ia, but it is difficult to put strong constraints on SN Ia DTD with these methods and currently available data. Totani et al. 2008 succeeded in directly deriving SN Ia DTD in early-type galaxies at $0.4 < z < 1.2$ using 65 SN Ia candidates from the variable object sample in Morokuma et al. 2008a. They presented the DTD in $t_{\rm Ia} = 0.1 - 10$ Gyr is well described by a featureless power-law as $f_D(t_{\rm Ia}) \propto t_{\rm Ia}^{\alpha}$ with $\alpha \sim -1$. This index does not agree with the SNLS result ($\alpha \sim -0.5$; Pritchet et al. 2008), which was derived using a different approach, but agrees well with a generic prediction of the double-degenerate scenario. This may indicate that the single-degenerate progenitor system is not the major component of SNe Ia in an old stellar population. Okumura et al. (2011, in preparation) extend a study in Totani et al. 2008 using a SN Ia sample in every type of galaxies obtained by light curve fitting (Ihara et al. 2011, in preparation).

4. AGN Studies

AGN variability has been recognized just after its discovery and has been utilized to understand physics and emission mechanisms of the central engine which can not be spatially resolved with the current facilities. Variability has been also used as one of effective selection methods for AGN. There is an anti-correlation between luminosity and variability amplitude that less luminous AGN show larger variability amplitude using a large statistical sample (e.g., Vanden Berk et al. 2004), which has not been theoretically understood well. This motivates us to carry out variability surveys for less luminous AGN using deep imaging data. The HST/WFPC2 and ACS actually detected variability of low-luminosity AGN ($M_B < -20$ mag; Sarajedini et al. 2003) and found that a significant fraction of AGN were not detected in deep Chandra or XMM-Newton data (Sarajedini et al. 2006; Cohen et al. 2006). Recently several works to understand properties of variability-selected AGN have been published (Boutsia et al. 2009; Villforth et al. 2010) and they put importance on effectiveness and uniqueness of optical variability selections for AGN as well as other selections such as X-ray selection.

Morokuma et al. (2008b) reliably selected 211 optically variable AGN based on the locations of variable components and light curves using the variable object sample made by their Subaru Suprime-Cam observations (Morokuma et al. 2008a). They made three AGN samples; X-ray-detected optically non-variable AGNs (XAs), X-ray-detected optically variable AGNs (XVAs), and X-ray-undetected optically variable AGNs (VAs). We here focus on the properties of the VA objects, which are defined as variable AGNs without X-ray detections, and compare with those of the VA and XVA objects. The distributions of the variable component magnitude $i_{\rm vari}$ versus i-band total magnitude of the host objects for the XVA (filled circles) and VA (open squares) objects are shown in Figure 1. Significant differences between the XVA and VA objects are seen. There are VA objects which have a faint variable component ($i_{\rm vari} \sim 25$ mag) in bright galaxies ($i \sim 21$ mag), while there are only a few such objects seen in the distribution for the XVA objects. These galaxies have photometric redshifts $z_{\rm photo} \sim 0.5$ and they are relatively massive early-type galaxies. Assuming that AGN optical variability (differential) flux, not amplitude, is roughly proportional to optical luminosity of the AGNs, these 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 (right-bottom in the figure) 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 above the line 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 1. This difference should not be due to any selection effects because the selection cuts are along horizontal and vertical directions in this figure.

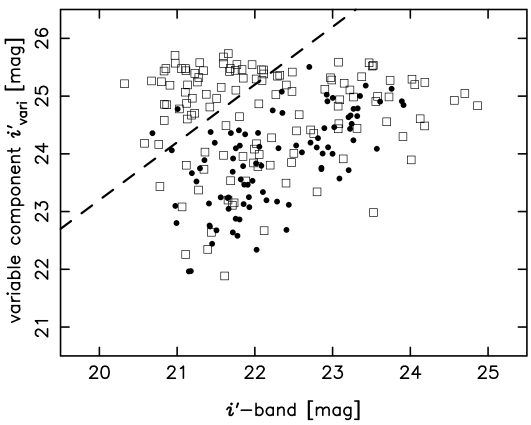

Fig. 1. Distributions of i'-band magnitude (total magnitude) versus variable component magnitude $i'_{\rm vari}$ (defined as differential flux between the maxima and minima) of the variability-selected AGN with (XVA objects, filled circles) and without (VA objects, open squares) X-ray detections. Dashed line indicates a constant ratio, 0.05, between i'-band magnitude and variable component magnitude $i'_{\rm vari}$.

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 radiatively inefficient accretion flows (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. 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, which should be clarified by more systematic observations. 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.

5. Hyper Suprime-Cam

The next-generation wide-field imager on the Subaru telescope, Hyper Suprime-Cam (HSC), is now being built (Miyazaki et al. 2006). The HSC has been designed to get images with seeing-limit quality in optical wavelengths. The HSC has 1.5-degree field-of-view in diameter and locate 116 Hamamatsu CCDs on the focal plane including 4 auto-guiding CCDs and 8 auto-focusing CCDs. The HSC field-of-view is about 7 times larger than that of Suprime-Cam. The first light is planned to get in 2011 fall and the large strategic survey with HSC will start in 2012 or 2013. The survey has 3 layers, *wide*, *deep*, and *ultradeep* and many science cases, including wide-field weak lensing survey taking advantage of good seeing in Mauna Kea and good image quality of the Subaru telescope and HSC, have been proposed.

Many science cases related to transient phenomena such as SNe Ia, core-collapse SNe, SNe IIn, SN shock breakouts, ultra-bright optical transients, gamma-ray burst orphan afterglows, variable stars, high proper motion stars, variability selection of quasars, variability-selected AGN evolution, tidal disruption events of supermassive black holes, have been discussed intensively to make an optimized survey design to maximize the science outputs in the HSC Japan-Taiwan-Princeton collaboration.

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